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Heritage Sites of Astronomy and Archaeoastronomy in the context of the UNESCO World Heritage Convention

A Thematic Study

June 2010

Heritage Sites of Astronomy and Archaeoastronomy in the context of the UNESCO World Heritage Convention

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Clive Ruggles and Michel Cotte

with contributions by

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Preface

This Thematic Study results from a collaborative project between the International Council on Monuments and Sites (ICOMOS), an advisory body to UNESCO for cultural heritage, and the International Astronomical Union (IAU), the world's foremost professional organization for astronomy, through its Working Group on Astronomy and World Heritage. It is published jointly by ICOMOS and the IAU

The main aims of the project are to gain an improved understanding of the character and composition of different forms of astronomical heritage and to identify optimal methods for, and potential problems in, defining this type of heritage in the context of the World Heritage Convention. As a result of the collaboration, the international team of authors is drawn from two complementary scientific and professional communities both of whom have provided invaluable input and expertise. The need to combine methodologies and develop common lines of approach has presented a range of challenges and each of the contributing authors named on various chapters and case studies has played a vital role in helping us to rise to them. Where no author is named on a case study, it has been provided by the author of the chapter that contains it.

These contributing authors provided the first drafts of their articles working to a common specification that we had supplied. Subsequently we assessed these contributions in detail and, in some cases, heavily reorganized and amended them in order to impose a suitable degree of consistency of approach and style and depth of analysis (as well as of length).

Where substantial cuts have been made to the individual authors' reports and case studies, it is our intention to make fuller versions available on the website of the Astronomy and World Heritage Initiative http://www.astronomicalheritage.net/ following the publication of this Thematic Study. Updates, together with and further reports and case studies, will also be posted on the Initiative's website in due course, forming part of an electronic resource that will continue to be developed into the future.

As with all ICOMOS Thematic Studies, the case studies presented do not in any sense constitute a 'provisional list'. They include a mixture of properties already inscribed on the World Heritage List, sites included on national Tentative Lists, and others. It must be emphasized, especially in the last case, that the presence or absence of any property as a case study in this volume carries no implications whatsoever regarding the outcome of the nomination process should it ever be put forward for inscription to the List, either alone or through a serial nomination.

CR and MC, June 2010

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Illustrative materials

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Further Information

Further information relating to astronomy and archaeoastronomy and/or the context of the World Heritage Convention can be found on the following websites:

UNESCO World Heritage Centre	whc.unesco.org
International Council on Monuments and Sites (ICOMOS)	www.icomos.org
International Astronomical Union (IAU)	www.iau.org
UNESCO Astronomy and World Heritage Initiative	www.astronomicalheritage.net
IAU Working Group on Astronomy and World Heritage	www.astronomicalheritage.org
Inter-Union Commission on the History of Astronomy	www.historyofastronomy.org
International Union for the Conservation of Nature (IUCN)	www.iucn.org
International Society for Archaeoastronomy and Astronomy in Culture (ISAAC)	www.archaeoastronomy.org

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Introduction

Michel Cotte and Clive Ruggles

Background to the ICOMOS–IAU Thematic Study

This ICOMOS–IAU Thematic Study was conceived in 2008 following a period of intensive activity relating to Astronomy and World Heritage, driven mainly by the UNESCO World Heritage Centre (WHC) and by the International Astronomical Union (IAU).

The central aim of this study is to extend these efforts by presenting a global survey of astronomical heritage from the standpoint of the identification and evaluation of heritage sites relating to astronomy and archaeoastronomy that might have the potential to demonstrate outstanding universal value (OUV)—the term of recognition for the value properties need to manifest in order to be inscribed on the World Heritage List.

UNESCO's Astronomy and World Heritage Initiative commenced in 2004 following a decision reached by the World Heritage Committee at its 28th session (28 COM 9). It reflected a recognition that astronomical heritage was underrepresented both on the World Heritage List itself and in the Tentative Lists of the various State Parties to the Convention. It also followed an expert meeting on 'World Heritage and Monuments of Astronomy' held in Venice on 17–19 March 2004, organised by the UNESCO Regional Bureau for Science in Europe (ROSTE) with the support of several State Parties.

The 29th session of the World Heritage Committee confirmed its interest and involvement in this thematic initiative particularly "as a means to promote … nominations which recognize and celebrate achievements in science" (July 2005).

At the outset, the Astronomy and World Heritage Initiative proposed the following types of cultural property associated with astronomical heritage:

- Properties which by their concept and/or the environmental situation have significance in relation to celestial objects or events;
- Representations of the sky and/or celestial objects or events;
- Observatories and instruments;
- Properties with an important link to the history of astronomy.

The initiative benefited initially from the creation of a database of sites and properties connected with astronomy, supported financially by the Royal Astronomical Society (UK) and hosted on the website of the World Heritage Centre.

In January 2008, the Inter-Union Commission on the History of Astronomy (ICHA)—a joint Commission of the IAU and the Division for the History of Science and Technology (DHST) of the International Union for the History and Philosophy of Science (IUHPS)—produced its own preliminary list of important ancient and historical cultural properties relating to astronomy.

In October 2008, UNESCO and the IAU signed a formal Memorandum of Understanding (MoU) committing them to work together to implement and progress the Astronomy and World Heritage Initiative. This provided a strong and secure framework for further progress. Shortly afterwards, the IAU created a Working Group on Astronomy and World Heritage in order to discharge its responsibilities under the Memorandum.

The decision by both UNESCO and the IAU to proclaim 2009 as the International Year of Astronomy served to raise the public profile of the initiative.

Meetings Throughout this period there have been various meetings that have served and continue to serve to implement, progress, and publicise the initiative. These include:

- A regional round table related to the Astronomy and World Heritage Initiative organised by the Institute of Astronomy of the Russian Academy of Sciences in May-June 2005.
- An international conference on 'Astronomy and Heritage' organised by the European Society for Astronomy in Culture in Sardinia, Italy, in June-July 2005.
- An international symposium on 'Cultural Heritage: Astronomical Observatories (around 1900) from Classical Astronomy to Modern Astrophysics', organized by ICOMOS Germany in Hamburg, October 2008.
- An international conference on 'Astronomy and World Heritage: Across Time and Continents', organized by the Russian National Commission for UNESCO, held in Kazan, Russian Federation, in August 2009.
- An international seminar on 'Astronomy and World Heritage: Across Ages and Continents', organized by the Egyptian National Commission for UNESCO, held in Cairo, Egypt, in February 2010.

Broader context and significance The words posted on the UNESCO WHC website emphasise the context and what is at stake:

> "As there are few properties related to science on the World Heritage List, and the scientific value of cultural properties related to astronomy is not always recognized, the World Heritage Centre, in close collaboration with the State Parties and ICOMOS, have developed the thematic initiative Astronomy and World Heritage in response to the ever-growing concept of World Heritage, and the Global Strategy for a Balanced, Representative and Credible World Heritage List adopted by the World Heritage Committee in 1994." http://whc.unesco.org/en/astronomy

In order to aid the recognition of global astronomical heritage and to help promote the inscription of the most outstanding astronomical heritage sites on to the World Heritage List, it is essential to undertake a scientific study of such heritage. A natural step, therefore, was for representatives of the IAU and ICOMOS to meet together, and such a meeting took place in October 2008. The decision was taken at that point to undertake a joint project of Thematic Study, taking as broad and open a view as possible, and the current publication is a direct result of this collaboration.

Aims, objectives and broad methodology

This Thematic Study sets out to undertake a wide-ranging survey of astronomical heritage, i.e. the material evidence relating to astronomy and to social uses and representations of astronomy. It suggests tools for the definition, identification, and assessment of the significance and, potentially, OUV of this specific type of heritage. It also gives examples of the identification, protection, conservation, management and promotion of such heritage. Since astronomical heritage represents scientific heritage in its cultural context, the Thematic Study thus aims to implement and develop one of the main objectives of the Astronomy and World Heritage Initiative.

Like all ICOMOS Thematic Studies (http://www.icomos.org/studies/), it has been produced in order to support possible nominations to the World Heritage List[1] by summarising the available documentation in a specific field. It aims to highlight the potential of all regions to contribute to the World Heritage List, especially in association with the global strategy for a 'balanced, representative and credible List'. It does not aim to identify OUV in individual sites, as this might compromise the subsequent process.

The list of themes we are proposing (see below) aims to provide a short and clear overview of the recognised evidence relating to astronomical heritage. It is an open list that acts as an initial framework for promoting and supporting the global recognition of astronomical and archaeoastronomical sites of possible significance, including those with potential OUV. It defines the main fields now well recognised by the international community and encourages State Parties to the World Heritage Convention to identify potential astronomical and scientific sites in their Tentative Lists.

The case studies aim to provide short examples of the methodological process of recognising heritage properties in astronomy and/or archaeoastronomy. The intention is to help State Parties identify potential sites and undertake comparative studies. We also hope to show how the value of the sites might be demonstrated and the World Heritage criteria met. Sites are inscribed on the List only if they are of outstanding universal value and have a broader significance than simply at the local, regional or national level. The evaluation process is based on the clear identification of the attributes that substantiate the OUV of the site.

A crucial step for every nominated property is the comparative study. In general terms this serves to define the true value of a property in an international and trans-cultural perspective. More specifically, its purpose is to demonstrate that there is room on the World Heritage List for the property and that there are no other comparable sites that might be nominated. This needs good specialists in the thematic field aware of the specific aspects of heritage evaluation and management constraints. This ICOMOS–IAU Thematic Study intends to provide some well-structured examples produced in this way. It has benefited from the professional advice of a range of specialists identified by the IAU, including many members of the ICHA and the Working Group on Astronomy and World Heritage, together with recognised specialists in the History of Astronomy and Archaeoastronomy/'Cultural astronomy', university academics, and members of the International Society for Archaeoastronomy and Astronomy in Culture (ISAAC). The advice of ICOMOS' experts was required for the value assessment of the various examples studied.

Some preliminaries about the nature of astronomical and archaeoastronomical heritage

In this section we propose some initial approaches to preparing and assessing evidence for the heritage of astronomy. The aims are to provide guidance in

- preparing an inventory of the astronomical heritage associated with a given place;
- understanding the issues inherent in identifying a potential astronomical World Heritage site; and
- developing a suitable methodological approach for undertaking preliminary studies and, if these are encouraging, to prepare a nomination dossier.

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[1] See the *Convention Concerning the Protection of the World Cultural and Natural Heritage* (UNESCO, 1972) and the *Operational Guidelines for the Implementation of the World Heritage Convention* (UNESCO, 2008), particularly para. 45 (definition of cultural heritage) and para. 77-78 (criteria for the inscription of properties on the UNESCO World Heritage List.

A vital starting point is to consider both the tangible and the intangible heritage of astronomy. The interplay between the tangible and the intangible is an inherent and fundamental aspect of astronomical heritage, as indeed it is of science heritage in general, and to a lesser degree of all properties on the World Heritage list.

Global methodology

There are three main aspects of the 'astronomical system' associated with a given place and thus contributing to the value of a site:

- material evidence of the astronomical place in the form of fixed property and/or moveable objects;
- the results of scientific activities (in the broadest sense), including but not restricted to astronomical observations; and
- socio-cultural applications and uses of astronomy at a given moment or over a given period for the site.

Each of these three main categories gives rise to both tangible evidence and intangible heritage. Following the World Heritage Convention, the tangible evidence must be divided into two subcategories: moveable heritage and immoveable heritage. Immoveable heritage is central to the application of the Convention but moveable heritage is not, strictly speaking, covered by the Convention.[2]

Thus, for example:

	Tangible immoveable heritage	**Tangible moveable heritage**	**Intangible heritage**
Property / objects	Architecture; permanent constructions and structures, fixed instruments	Plans; moveable artefacts; moveable instruments	Practical/technical expertise; rules of use and maintenance; structural/ architectural history of the site
Results of scientific activities (in the broadest sense)	Stone carvings; wall paintings; iconography; palaeography; symbolic representations	Records/accounts of observations; printed and digital data; sky maps; scientific publications	Knowledge and understanding; calculations and theories
Socio-cultural applications and uses	Astronomically aligned architecture; light-and-shadow hierophanies; urban planning and landscapes constructed using astronomy	Archives; drawings; maps and plans, tools or instruments using astronomical properties[3]	Calendars; ideology; predictions of the future (whether rational or irrational from modern perspectives)

While incomplete and begging many issues, such as the imprecise boundaries between certain types of evidence, the table suffices at this stage to highlight the important question of the relationships between material evidence, as the main focus of the application of the World Heritage Convention at the present time, and intangible heritage, as evidence for the value of material manifestations. Within the tangible category, we must also examine the relationships between fixed (immoveable) and moveable objects: again, only the first of the two is currently relevant to the World Heritage Convention.

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[2] The term 'immoveable' is used in a juridical sense, to mean something that has not been globally displaced from its position in the soil, in other words something that has permanent links with the architectural framework of its construction or of its natural foundation. In this sense, it actually means 'fixed in its original position' or 'not moved [yet]'. On the other hand, 'moveable' has its common-sense meaning.

[3] For example, sextants for maritime purposes or moveable sundials in social use.

In this Thematic Study we seek to understand what characterises the specificity and originality, and hence contributes to the outstanding universal value, of astronomical sites. In order to do this it is important, on the one hand, to clarify the boundaries between the types of evidence and, on the other, to have an open discussion of the continual exchange that exists on many levels between astronomical endeavour and material evidence, both fixed and moveable. Similar considerations apply to scientific heritage in general (and to a lesser degree to all heritage), and we intend that this study of astronomical heritage will provide a paradigmatic example that informs the broader discussion.

Themes

In the following chapters we have attempted to identify a set of themes that span the wide range of types of astronomical heritage but nonetheless provide a coherent framework for the development of case studies

In the main, the principal themes are related to a broad chronology of the major human cultures and to different types of astronomical discovery, knowledge and practice, including but not confined to recognisable stages in the development and use of modern scientific astronomy.

It is recognised that the scope and boundaries of each theme are often unclear.

The topics are:

- Earlier prehistory,
- Later prehistoric Europe,
- Pre-Columbian America,
- Indigenous uses of astronomy,
- Ancient and medieval Far East,
- India,
- Mesopotamia and the Middle East,
- Ancient Egypt,
- The Classical World,
- Islamic astronomy,
- Medieval astronomy in Europe,
- Astronomy from the Renaissance to the mid-twentieth century,
- The development of radio astronomy,
- Applied astronomy in modern times,
- Space heritage, and
- ‘Windows to the universe’—starlight, dark sky areas, and observatory sites.

Each chapter presents a general overview of the theme in accordance with the particular disciplinary competence and experience of the author(s) concerned. The chapter authors were also invited to co-ordinate, under their scientific responsibility, a limited number of case studies that would provide significant examples of methodology in the context of their thematic essays. Some have been written by the chapter authors themselves, and some by independent authors.

Astronomical heritage as tangible heritage: inventory and identification

The following may be identified as the principal types of tangible astronomical heritage:

- Observatories as ‘scientific monuments’. In most respects normal, well-accepted practices can be followed, but a critical question may arise with the section on authenticity (see below). The architectural approach may only be a limited part of the assessment of a scientific site.

- Fixed and moveable instruments. Tangible astronomical heritage raises the question of the borderline between fixed property and moveable artefacts, i.e. portable instruments, moveable domes or floors, etc. This is not a straightforward issue, since an instrument in the form of a fixed 'monument' could serve exactly the same purpose as a personal portable instrument or a 'semi-moveable' instrument located in specific places for observation. This issue in not peculiar to astronomy but applies to science and technology heritage in general. Concerning collections of moveable instruments, the UNESCO initiative 'Movable Heritage and Museums' may be relevant to some aspects of this type of heritage.
- Material representations of the results of astronomical observations and cognitive understanding:
    - Tangible representations of observations, events and predictions (calendars, time measurements, predictions of eclipses, zodiacs, celestial representations, etc);
    - Cosmological and symbolic representations (iconography, palaeography).
- The material products of the application of astronomy: constructions, architecture and urbanism related to applied astronomy and/or bearing astronomical information.
- Properties whose design and/or landscape setting have significance in relation to celestial objects or events.
- Cultural landscapes related to the history of astronomy and/or human cultural practices related to astronomy.
- Dark night sky areas where the ability to see natural starlight preserves the visual links to the sky that have connected humankind to the cosmos throughout history.

The distinction between property and moveable objects is important from the juridical and heritage perspective, but has no real significance for astronomers. What is important is the scientific function of the instrument and its technical performance. The distinction between a fixed instrument and a moveable instrument is only a question of dimension, technology and materials, precision of observation, stability, the necessity of moving the instrument for observation, etc. It is merely a practical and technical consequence of a scientific project. What is more pertinent is the distinction between a 'collective instrument', shared by a professional group of astronomers in some context, and an individual instrument. The notion of the personal use of astronomical instruments—for example, not only for scientific research but also for navigation, leisure purposes, etc.; or not only for astronomical observations but also for decoration, collection, etc—could easily be linked with the broader application and/or social use of astronomy, but only more rarely with a decisive improvement in observational techniques and/or theoretical progress at the level of universal exceptional value.

A collection of rare or unique moveable instruments authentically associated with the history of an observatory is obviously a major part of the latter's heritage value. The task of assessment must therefore involve making a detailed study of the functionality and of the construction and use of each instrument, exactly as would be necessary for a moveable part of a technological monument or for a 'machine-tool' in industrial heritage. For the scientist, this is the real core of the material value of the observatory, perhaps more than walls and architecture, which could be really poor in some major examples of the history of astronomy.

A remark arises here about the materiality of the celestial objects that we observe. Are stars and planets themselves part of our natural heritage? In one sense, yes, but it is more important to recognize that the sky is a cultural resource common to all of humanity. In consequence, astronomy forms part of the efforts by all human beings to comprehend the observable world—the cosmos—within which they dwell and to understand their place within it. At any level, the quest to make sense of the cosmos by imposing a perceived order upon it—whether by registering associations, recognising patterns and cycles, making predictions, or identifying generic relationships expressible as mathematical laws—can be regarded as a form of 'science'. Consequently, astronomy has been characterised by the observation and coherent interpretation of celestial objects and events from the earliest stages of human evolution through to the modern world, including (but not confined to) the history of contemporary science. In heritage terms, human scientific understanding of the sky and its links with cultural practices invariably represents the production of meanings by human beings and hence the production of 'intangible heritage' in context.

In assessing the material heritage of astronomy, it is clearly impractical to include the celestial objects and events themselves, even though this creates an epistemological difficulty in heritage terms. However, we cannot dissociate astronomical sites from the celestial objects studied by them: it is therefore important to recognise and, where possible, to strive to preserve, the visible link between the two. It is also conceivable that, just as some mixed properties derive their outstanding universal value from a combination of their cultural and natural heritage, so some properties may combine a cultural heritage of astronomy with the natural heritage of the dark night sky.[4]

Archives and documents: links between tangible and intangible scientific heritage

The scientific corpus that represents the core heritage of astronomy comprises the material sources of the history of astronomy: its archives and documents, in the broadest sense. An item of this type could be a tangible drawing or engraving on a monument or a palaeographic inscription, but it is frequently a 'moveable legacy' such as a written document, map or printed matter. The recording and transmission of information has certainly been a crucial issue throughout the history of astronomy. It is manifested in cave art, papyri, cuneiform tablets, paper-books of observations, paper archives, books and ephemerides, photos in visible and non-visible wavelengths, spectra, and digital databases.

Obviously, a major part of the evidence for the development of ideas in astronomy exists in the form of moveable documentation contained in archives, collections and bibliographies. Such documentation provides material support for the recording of observational results, prediction, calculation, theory, the use of astronomy, etc.

These documents are the product of scientific activities in their cultural context. The core of scientific knowledge is mainly intangible. It is an intellectual framework of the human spirit using specialised languages (written language, mathematics, etc) and images (drawings, maps, photographs, physical information such as spectra, and so on).

Archaeoastronomical and astronomical documentation is mainly related to:

- records of observations and events, tables of observations;
- physical images and information (photos, spectra, radio maps, etc);
- interpretation and theories (physical laws of the universe), cosmology (global theories and interpretations of the sky and universe);
- calculations and predictions (ephemerides, calendars, astronomical interpretations and predictions);
- social uses of astronomy, whether or not rational in modern scientific terms (calendars, navigation, agricultural practices related to the moon, astrology);
- symbolism, faith and religious uses of astronomy; and
- art and decoration.

In fact, the production and retention of archives could be considered the very heart of the scientific productivity of a laboratory or observatory. They are moveable underpinnings for collections of data emanating from sky observations, calculations, predictions and theoretical interpretations. It is in this way that the 'intangible property' represented by archives in a

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[4] 'Inscribing the sky' itself is a nonsensical concept, since the 'sky' is something that one sees/perceives from a place on the Earth, so is an attribute of the place. The physical universe and the objects within it are another matter, but not what is under discussion here.

broader sense is most directly linked with the scientific activities and reputation of the 'astronomical property'.

Links between buildings, instruments and archives are clearly important for documenting sites but are also crucial in order to demonstrate their outstanding universal value through the justification of the criteria. For instance, beyond the material and static starting point of its architecture and instruments, one measure of the importance of a given site could be how influential were the data contained in its archives. The scientific OUV of a site could certainly be demonstrated in this way. A global approach focusing upon the contents of value at an observatory/laboratory site should consider it as a stable node within a regional (and, more recently, global) network of astronomers. The conservation of archives and the sharing of the data and information contained within them has always been a crucial part of the international activities of scientists, in every geographical and historical context. For example, when NASA was preparing to conquer the moon with the Apollo missions, it gathered together all the old data and calculations in the papers and manuscripts of the best astronomers from the 17th century through to the 1950s, preserved in the archives of the main European observatories. The aim was to confirm and verify NASA orbital calculations. Other examples also exist of a living archive being used in astronomy.

Such facts offer a specific link between past and present, and between modern projects and the past compilation of data preserved in archives. In heritage terms, astronomical archives have considerable importance as well as the potential for further use while they are in the hands of astronomers inside observatories. This parallels the archaeological value of objects in their material context and the enormous decrease in the value when the objects are removed from that context. Furthermore, this archival material taken in context constitutes an inter-regional/international network of knowledge in astronomy, as a global scientific achievement during a given historical period. A similar network approach could be proposed for instruments, with the notion of specialisation of sites and subdivision of work between astronomers. The contribution of a site to these global regional networks through its 'intangible' and 'moveable' evidence must be taken into account in order to assess its value.

In heritage analysis terms, the various types of heritage typically involved in sites related to astronomy may call to mind serial nominations in their precise geographical and cultural context. In this case, a specific systemic link must be established following the sequence:

- Celestial object/subject of observation,
- Site/observatory monuments/landscapes,
- Instruments/scientific and technical system,
- Archives/products of intellectual and symbolic human activity;
- Networks of sites/ instruments/ archive centres, etc.

Links between astronomical heritage and other types of cultural heritage

The material evidence of astronomical practices and uses is often associated with tangible heritage and social value lying outside the domain of science in the modern sense. The legacy of astronomy is rarely isolated but forms part of a broader cultural legacy. Often, the tangible heritage of astronomy must be understood within a broader category of global material legacy of properties, such as a particular type of instrument or observatory, or the places related to astronomy located within a particular historical city or cultural landscape.

This immediately raises the fundamental question of the re-evaluation of sites now on the World Heritage List. Properties—such as monuments, group of monuments, urban sites or cultural landscapes—or individual elements within those properties could have important astronomical value even though the OUV at the time of inscription did not reflect this value. For example, Ulugh Beg's observatory in Samarkand is one of many elements within an historic city of outstanding civil, military and religious buildings. Such sites might be re-nominated and re-evaluated as major heritage places of the history of astronomy and for astronomical practices among civilizations, with their own outstanding universal value.

Frequently, human beliefs and practices form a fundamental part of astronomical heritage even where they do not constitute ‘rational behaviour’ as judged in modern scientific terms. The question of rationality (as we would judge it) is a secondary question because in each age, and each cultural context, astronomy operates within and is constrained by in a framework of cultural and ideological paradigms that define their own rationality. The definition of intangible cultural heritage—cultural practices and human behaviour—could be far from the modern definition of astronomical laws and facts. We have to take account of human attitudes to astronomical observations and predictions that have crossed many human cultures. For example, astrological practices based upon the complex but predictable movements of the sun and planets within the zodiac have been a common theme in many cultures over the centuries. They are far from today’s rational astronomical attitude derived from the ‘scientific revolution’ of Western civilisation, but remain a cultural fact within human history. Other examples of the relationship between astronomy and culture are not so black and white, but all must be understood as part of the historical anthropology of astronomical practices and eventually linked with the assessment of sites.

Such links between astronomical sites and human cultures could be summarised as:

- Cosmologies, theories and beliefs about the universe, sun, Earth, moon, planets, stars, etc.;
- (Modern/contemporary) Scientific paradigms, ‘rational’ (in the above sense) laws governing celestial objects;
- False/’non-rational’ (in the above sense) astronomical determinations for predictions or astrology;
- The cultural influence of celestial objects on daily-life and human attitudes; and
- The ‘magic’ and the religious dimension of astronomy in cultural and historical contexts.

The intellectual process of astronomy in the context of any particular cultural property always operates in a broader social context and in some cases in the context of global culture. It may or may not conform to modern scientific logic. A framework of processes that characterise the historical anthropology of human practice in the field of astronomy might be as follows:

- The progression from astronomical observations themselves to the results of those observations;
- The progression from raw results to notation, understanding and interpretations of those results;
- The integration of interpreted results into a cosmological system and/or global human thinking and knowledge;
- The compilation and transmission of knowledge;
- The eventual application, practical uses and material consequences of that knowledge;
- The eventual influence within social practices and spiritual beliefs; and
- The social, political and scientific context and decisions regarding observation projects and their organisation (which leads back to the top of the list).

Astronomy is characterised by a continual interplay between tangible and intangible aspects, and between facts and culture, within a given human society. Analysis of this network of relationships provides an indispensable basis for the assessment of a site’s value, helping to justify the selected criteria and eventually to demonstrate OUV.

The issues of 'integrity and authenticity' in the context of scientific heritage

Generally speaking, it is essential to tackle these two issues in order to give a credible demonstration of the OUV of cultural properties nominated for inscription on the World Heritage List. In this section we briefly examine integrity and authenticity issues that are specific to the evaluation of an astronomical site and, by extension, to any scientific site.

At the outset, we must emphasize the close connections that exist between technological sites and scientific sites. Innovation and modification are traditional and necessary in science as in the development of technology. A technical achievement, an industrial production process or a scientific tool are designed and frequently constructed to evolve, to change, and to take account of innovations and improvements in science and technology. The capacity for change and evolution typically forms part of the value of material devices in science and technology. This distinguishes science and technological heritage, as a class, from many other forms of heritage for the purposes of integrity–authenticity analysis, and suggests that it may be productive to develop particular ways of approaching these two concepts for this class.

Integrity concerns the completeness of all the attributes that contribute to the value (and, potentially, the OUV) of a site. Focusing on astronomical heritage, physical integrity is manifested in different and complex ways for mechanical, optical, or electronic instruments, computer software, etc., and the complexity of the physical and technical attributes increases rapidly when we reach modern and contemporary astronomy. Added to this, attributes may include not just physical objects but also their uses, innovation, and types of maintenance. Integrity analysis must take into account the logic of maintenance and innovative evolution of instruments, in the context of the duration of their uses for continuing and successive astronomical objectives. In order to support the concept of integrity at a science or technological heritage site in general, it may be useful to regard the site as a *global scientific instrument*, demonstrating its integrity through a typological analysis of the evolution of the site and its constituent instruments (components of the whole 'instrument'). Moreover, through the Convention and the *Operational Guidelines*, the material attributes of the property need to be identified as supporting its OUV; the integrity issue then is whether they are all within the site and none is under threat.

Attributes such as the architecture and the landscape skyline of the site are merely a part of the overall integrity of the property. Of course, they do form an important and symbolic element of popular landmark recognition, an example being the traditional European 'dome observatory'. Furthermore, the architecture and the completion of the landscape are important attributes that contribute to the assessment of the value of the laboratory/observatory, but they may not be the most important. On the other hand, in the case of archaeoastronomy or modern astronomy when applied to monuments and territory management, the architectural and cultural landscape attributes remain crucial components of integrity.

There is a similar situation for the concept of authenticity, which relates not only to the architectural components of the laboratory/observatory but also to each element of the machine or instrument. Authenticity is about the ability of the attributes of OUV to convey their meaning truthfully. In terms of scientific sites, the use of the instruments and the buildings that encompass them could be key attributes of OUV, in which case authenticity relates to how well they still display those uses. Questions could also be raised about the authenticity of design of the laboratory/observatory itself, viewed as a global contrivance, through its evolution and changes.

In order to maintain its efficacy, a working machine/instrument must be maintained over a period of time under strict conditions. For example, fragile or dynamic elements must be carefully checked, and in some cases regularly adjusted, or replaced with new spare parts. If not, the use and consequently the 'living state' of the instrument could be compromised.

Furthermore, the use of astronomical instruments with a high level of scientific efficiency must follow the innovations and improvements regularly offered through the availability of new technical components that are stronger, more precise, etc., and sometimes through radically new individual or collective technical solutions to existing astronomical problems. The renewal of materials and instruments, and sometimes their rebuilding and/or complete replacement to make a 'new' instrument/machine, is a living aspect of science/technology in general, and of instrumental astronomy in particular. A key question, then, is how the value of a property is balanced between its original components and the ability of each instrument to continue functioning. This is a question that every potential dossier must study in depth, in relation to the other attributes of the site's value.

At the same time, outside the sphere of modern scientific astronomy and its precursors, regular reinforcement by direct observation may not be necessary to the continued perception of, say, a sacred or religious site as directly connected with the sky or with particular celestial objects or phenomena. Thus modifications to a structure that render impossible a direct observation do not necessarily detract from the meaning of the site that derives from that observation. Indeed, in some cases a direct observation that is perceived to underlie the value of the site may never need to have been made at all.

These dimensions of change must be carefully studied through site authenticity analysis. In the case of modern scientific instruments the issues are typical of science heritage in general, and of movable objects in particular. But there are also significant consequences for traditional architecture. From the science heritage perspective, architecture might well be seen as an environmental aspect of the materiality of science, and not as the core attribute of the property. The relevant concept would then become that of 'architecture as part of a global machine', in other words as a protective envelope for the core process. The leading principle of the evolution of buildings is firmly imposed by the strategy of the group of astronomers in charge of the property with a clear scientific mission. The terms used for naming theses constructions—observatory, great telescope dome, spectroscopy lab, hall of heliometers, etc —are also important, and totally justified, in terms of the meanings of the property. The buildings certainly have a specific architectural function, but their historical role and value is directly dependent upon the scientific purposes of the site. They need to be assessed in the material and instrumental context of their construction and in their history of use, not just for their architectural associations and for the way the form of the buildings displays their purpose.

The complete history of the property should pay careful attention at every stage to the correlations between scientific purpose and architectural choices. Thus a building analysis of an astronomical property that is only couched in terms of the history of architecture and urbanism, referring only to dimensions, harmony of forms and landscapes, is totally insufficient. Conversely, a detailed chronology of use and evolution of the site is an essential prerequisite. Thus giant and monumental forms of construction that lack appropriate materials such as (in the historical or modern case) associated documentation, or whose function was relatively limited, or where only secondary scientific results were achieved (for whatever reason—such as a poor strategic scientific decision) might not reach outstanding universal value. In the case of archaeoastronomical sites, the appropriate materials would need to include strong archaeological/archaeoastronomical evidence supporting the case for astronomical significance.

In these ways, astronomical heritage sites, and science heritage sites in general, require. professional evaluation of the material and intangible issues to which these dual concepts give rise. Authenticity of use is probably a central issue in assessing the level and quality of the scientific operation of instruments by important astronomers, for a significant region, nation or internationally, and for a clearly identified historical period. The relevant notion may be 'authenticity in its scientific context and use'.

Management: general considerations

Measures for the protection, conservation and management of properties nominated to the World Heritage List need to be set out in the nomination dossier. They should be presented as an overall management system, and may be set out in the form of a Management Plan for the property, put into practice with the engagement of stakeholders and the approval of the State Party who will need to respect and apply it. The *Operational Guidelines* for the implementation of the Convention give a range of advice on this matter (items 96 to 98, 108 to 119 and 132–5; see also items 99–102 [the property] and items 103–7 [the buffer zone]). 'Protection' involves national, regional and local laws and planning regulations. A relevant and efficient juridical system must be presented to protect the property against all types of threat to the attributes that contribute to its outstanding universal value, both in the property itself, in its setting, and in relation to particular environmental issues that could affect its scientific function. The central idea is to maintain the integrity and authenticity of the property for the present and for the future—to sustain its OUV.

The overall management should rely upon professional competence in a range of different fields, such as architecture, construction, urbanism, archaeology and history, or whatever is relevant for the property.

The various aspects of protection and conservation should each be combined with the other aspects of property management—such as tourism organisation and facilities, and education, interpretation and outreach—with regard not only to the property itself, but also covering neighbour relationships, etc. For management to be effective, there must be sufficient and guaranteed funds to support the overall process.

It is worth emphasizing that for an astronomical heritage property the various general components of the dossier should be formulated in exactly the same way as they are for all other properties, with the same professionalism in addressing the different aspects of juridical protection of the property and its setting, and in the management system. The specificities of astronomical heritage management must be included in the management system as a separate topic, fully coordinated with the general issues and addressing, for example, the conditions for careful use and maintenance of the astronomical instruments, the availability of advice from astronomers the need for controlled scientific interpretations, and programmes of scientific education linked to the particular significance of the property.

Chapter 1: Earlier Prehistory

Michael Rappenglück

Since the early 20th century, and especially during the last few decades, interdisciplinary research has strengthened the evidence that during earlier prehistory (35,000–9,000 BP) people observed certain celestial phenomena and reflected about the spatiotemporal structure of the world they perceived themselves as dwelling within. What appear to be traces of very early systems of time-reckoning and visions of the cosmos can be found in depictions on both fixed and transportable objects (parietal/mobile art) within and outside of caves or related to other distinctive natural or man-made places. While interpretations of such evidence have often proved controversial, in broad terms there is little doubt that astronomy played an important and integral part in the early cognitive development of humankind.

The evidence suggests that there existed during earlier prehistory an archaic form of astronomy that included such components as simple natural calendars, more complex 'palaeo-almanacs', and the knowledge of certain asterisms. The motivations for watching the sky may have been both practical and philosophical: a suitable 'cosmovision' would have helped give meaning to life. In order to transform basic astronomical knowledge into suitable systems of time-reckoning and cosmographic models, people would not only have needed a first-rate imagination and the ability to conceive abstractions, but also a degree of technical ingenuity.

Table 1.0.1 presents a brief chronology of earlier prehistory from the Lower Palaeolithic to the Epipalaeolithic. The available archaeological evidence and the hitherto discussed palaeo-astronomical evidence restrict the geographical area of interest to Africa, Australia and Eurasia.

The archaeological record from earlier prehistory in general can be divided into fixed and mobile artefacts. Rock-art—paintings, engravings, and sculptures—exists within deep caves as well as at particular places outdoors, such as river valleys and rock shelters. Thematic 'maps' have been identified on bones and in caves, demonstrating that people were aware of landscape features. Caves and rock shelters, as well as other landscape features, had both practical and symbolic significance. The construction of dwellings, the structure of open-air campsites, tools, and mobile artwork set up further cognitive categories. Among the graphical representations found in parietal and mobile artwork there exist both abstract symbols and naturalistic depictions.

From at least the Aurignacian period (c. 32,000–26,000 BP), hunter-gatherer cultures depicted the periodic annual phenomena of flora and fauna, both in fixed contexts and on mobile objects. As hunters, they were surely well aware of the biological rhythms of animals, such as their diurnal and nocturnal activities, the mating season, the duration of their pregnancy, their time of birth and incubation, their change of fur, the formation and dropping of their antlers, their annual migration (particularly in the case of birds), and the production of spawn. And as gatherers they could not fail to be familiar with the periodic rhythms in the development of plants. The seasonal change between summer and winter camps is clear from the remains of the fauna and flora that were either consumed or used in other ways. Some local cave-sanctuaries also seem only to have been visited at certain times, since the creation and renewal of graphic art only occurred during 'special' time periods. In addition, there exists

Palaeolithic Periods	
Lower Palaeolithic (ca 2.6 Ma–100 ka)	Olduwan (2.6–1.8 Ma)
	Acheulean (1.7–0.1 Ma)
	Clactonian (0.3–0.2 Ma)
Middle Palaeolithic (300–30 ka)	Mousterian (300–30 ka)
	Aterian (82 ka)
Upper Palaeolithic (50–10 ka)	Baradostian (36 ka)
	Châtelperronian (35–29 ka)
	Aurignacian (32–26 ka)
	Gravettian (28–22 ka)
	Solutrean (21–17 ka)
	Magdalenian (18–10 ka)
	Hamburgian (14 ka)
	Ahrensbergian (13 ka)
Epipaleolithic	Swiderian (10 ka), Azilian (10 ka)

Table 1.0.1. A brief chronology of earlier prehistory. Ma = million years ago; ka = thousand years ago.

some evidence that the illumination of caves and rock shelters by sunlight on certain days of the year may have been significant, an example being the solstitial illumination of the innermost chamber of El Parpalló, a cave-sanctuary near to Gandía in Spain that was occupied in the Solutrean and Magdalenian periods.

Palaeoastronomical research has indicated the existence, within both parietal and mobile art, of astronomical/natural calendars using systems of images and signs to denote certain time periods. Observations of the moon appear to have been particularly important, with both its phase cycle and its changing position along the horizon recorded over periods up to several years. People not only reckoned time using the moon; there are also notations that evidently related to solar cycles and even luni-solar cycles. An example of the latter is the elaborate Thaïs Bone (Case Study 1.1). Among mobile objects dating from the Aurignacian to the Azilian have been found several tally sticks and tally pebbles (Azilian) that illustrate different kinds of time-reckoning.

Earlier prehistoric parietal and mobile art contains many representations of animals (mammals, birds, reptiles and even insects), as well as occasional depictions of plants. Many of these representations appear to have correlated the biological rhythms of certain animals and/or human women (menstruation, pregnancy) with astronomical periods. The term ‘almanac’ is probably appropriate. An example comes from the Geißenklösterle cave in Germany, where an ivory plate dating to 35,000–32,000 BP contains one of the oldest known representations of a human figure. This appears to relate to the constellation Orion and a lunar and pregnancy calendar (Case Study 1.2). In some of the more complex examples, especially those that span longer periods, a clearly structured system of counting—a so-called 'arithmetical' notation—has been used to indicate astronomically significant time units (for an example see Case Study 1.3).

There is evidence that during the Upper Palaeolithic certain asterisms, including Corona Borealis, the Pleiades and the Hyades, were not only recognized but were important for time reckoning or well-suited for the purpose of determining orientation. Perhaps the best publicised examples of possible representations of the Pleiades and Hyades are from the aurochs (no. 18) in the Hall of the Bulls at Lascaux cave in France, although the real significance of this site is the breadth and complexity of possible astronomical associations amongst what is undoubtedly a supreme assemblage of Upper Palaeolithic art (see Case Study 1.4).

The astronomical heritage of earlier prehistory is diverse and fragmentary and its identification, substantiation and evaluation raise a number of serious issues of credibility. Scientific rigour can only be achieved through the integration of methods from the humanities, natural sciences and experimental archaeology, but there is also a need for phenomenological methodology. The interpretation of iconography involves the concurrence of syntactic, semantic and pragmatic aspects, and the recognition of multiple levels of meaning.

To date, Palaeolithic astronomical heritage has not been promoted or protected in any consistent way. Some museums specifically point out the astronomical significance of mobile artefacts in their collections but there is not a single in-situ indication of the astronomical connotations of fixed items such as rock art; for some years it has been left to broader media coverage (in the form of printed matter, audio-visual material, electronic media and planetarium programs) to raise awareness of proto-astronomy (as well as proto-mathematics and other proto-sciences) during Palaeolithic times. Palaeolithic astronomical heritage is not explicitly protected, although fixed items are often implicitly included within existing measures to preserve historic buildings and monuments of broader significance.

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Case Study 1.1: The Thaïs Bone, France

Presentation and analysis of the object and its place of discovery

Geographical position: The Thaïs cave (Grotte de Thaïs, variants Thaï/Taïs/Taï) is situated in Saint-Nazaire-en-Royans, Département de la Drôme, France.

Location: Latitude 45º 3´ 53˝ N, longitude 5º 16´ 24˝ E. Elevation 220m above mean sea level.

General description: The Thaïs cave is located close to the confluence of the rivers Bourne and Isère, at the foot of the Vercors limestone massif. It consists of two dry sections and continues down into a large and deep system of water-filled galleries.

Inventory of the remains: Bone fragment no. 450, hereinafter 'the Thaïs bone', was excavated from the cave in 1968–69. Its archaeological context indicates a date around 12,000 BP, in the early Azilian period. It is part of a bovine rib, measuring 87 mm × 27 mm, and is engraved on both faces. The 'main face' contains seven long incised lines running more or less parallel to the longer edges. Connecting lines evident in one corner indicate that these actually formed a single line criss-crossing the face in boustrophedon style. Engraved perpendicular to this principal line, both above, below and over it, are large numbers of shorter strokes grouped into distinct sets 1–2 cm long. Microscopic analysis shows that the sets of marks were made using various tools at different times. The sequence is characterized by clustering, variation, and periodicity. The reverse contains one further line crossed by shorter strokes, together with a small remaining part of a second. It also contains six broader strokes in the perpendicular direction.

History of the site: A limited exploration of the cave was undertaken in 1878, according to dated graffiti the speleologists left behind. The first of several siphons was discovered in 1957, enabling access to the water-filled galleries. Excavations were carried out 1968–69 by J.É. and J.L. Brochier. In the 1970s the cave was set up for visits by tourists.

Cultural and symbolic dimension: The engraving on the Thaïs bone is a non-decorative notational system of considerable complexity. The cumulative nature of the markings together with their numerical arrangement and various other characteristics strongly suggest that the notational sequence on the main face represents a non-arithmetical record of day-by-day lunar and solar observations undertaken over a time period of as much as 3½ years. The markings appear to record the changing appearance of the moon, and in particular its crescent phases and times of invisibility, and the shape of the overall pattern suggests that the sequence was kept in step with the seasons by observations of the solstices. The latter implies that people in the Azilian period were not only aware of the changing appearance of the moon but also of the changing position of the sun, and capable of synchronizing the two.

Comparative Analysis: The markings on the Thaïs bone represent the most complex and elaborate time-factored sequence currently known within the corpus of Palaeolithic mobile art. The artefact demonstrates the existence, within Upper Palaeolithic (Azilian) cultures c. 12,000 years ago, of a system of time reckoning based upon observations of the phase cycle of the moon, with the inclusion of a seasonal time factor provided by observations of the solar solstices.

Authenticity and integrity: The Thaïs bone was discovered *in situ* in 1968–69 with the sequence of markings intact. None of them could have occurred naturally, demonstrating conclusively that this rib fragment was engraved by people in the Azilian period.

Fig. 1.1.1. The ‘main face’ of the Thaïs bone, after Marshack 1991, fig. 1.

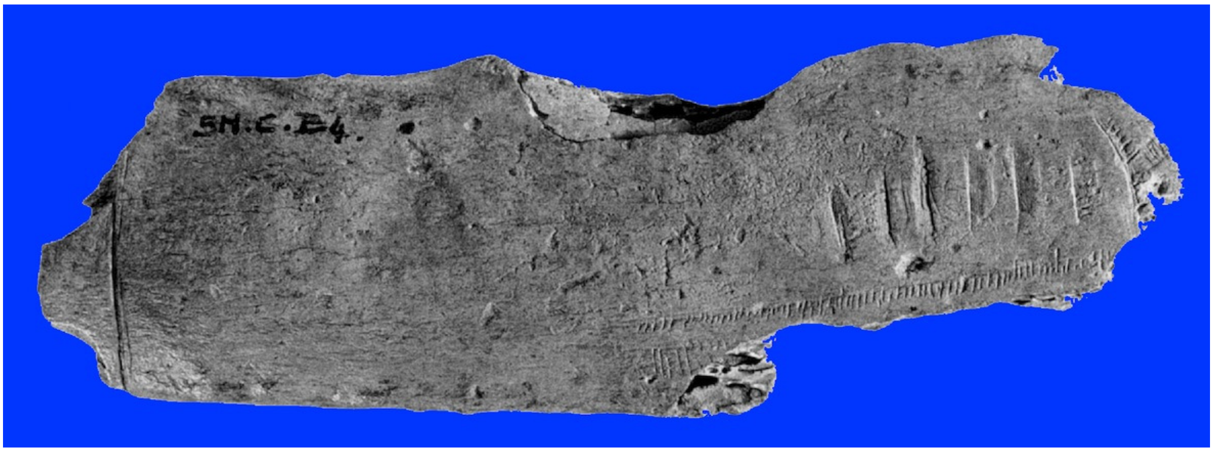

Fig. 1.1.2. The reverse of the Thaïs bone, after Marshack 1991, fig. 1.

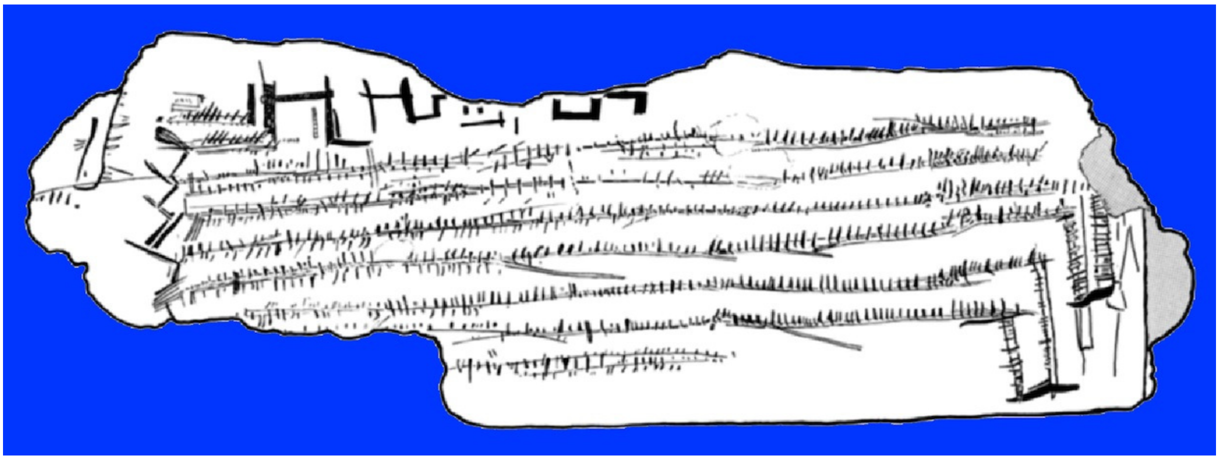

Fig. 1.1.3. Line drawing of the front face of the Thaïs bone, showing the boustrophedon sequence and groupings of markings, after Marshack 1991, fig. 5.

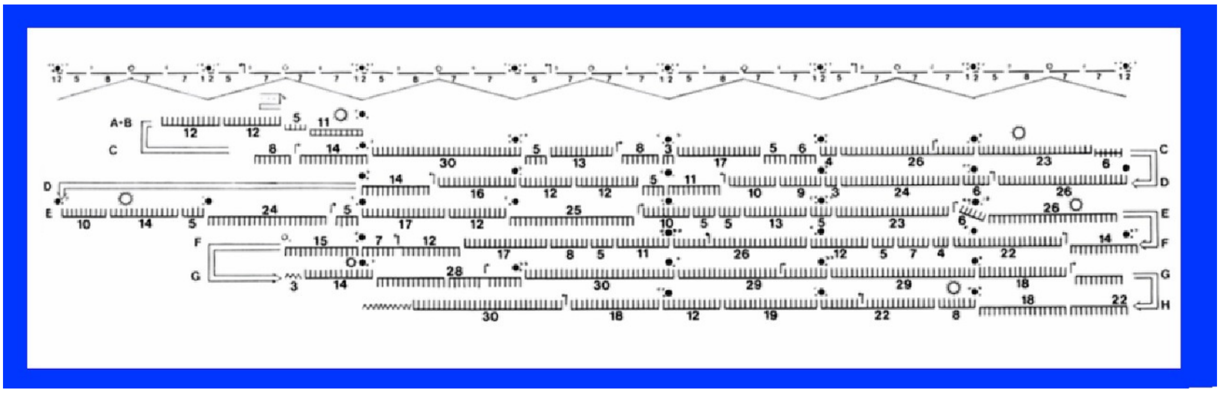

Fig. 1.1.4. The luni-solar time-reckoning model, after Marshack 1991, fig. 7.

Present management of the object

Present use: The Thaïs bone is in the collection of the Musée de Valence, France (inventory no. 792-33). The museum is closed to the public from 2006 to 2012 for renovation work.

Context and environment: The Thaïs cave is situated close to the Campalou rock shelter (Abri de Campalou). This contained a rich archaeological layer dating to the Late Magdalenian (12,800 ± 300 BP) and Epipalaeolithic–Azilian, where engravings on bone artefacts have also been found.

Archaeological/historical/heritage research: Initial studies of the Thaïs bone were undertaken by J.-É. and J.-L. Brochier in the early 1970s, following its discovery in their excavations of 1968–69. The substantive analysis and interpretation was carried out by Alexander Marshack in the course of his own meticulous microscopic examination of the object during the 1970s and 1980s.

Main threats or potential threats to the site: There are no potential threats to the object within the scope of normal storage, apart from damage resulting from *force majeure*.

Management: There are no special management arrangements relating to this object.

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Case Study 1.2: The Decorated Plate of the Geißenklösterle, Germany

Presentation and analysis of the object and its place of discovery

Geographical position: The cave ruin of Geißenklösterle is situated near to the village of Weiler in the Ach valley, close to the town of Blaubeuren in the Blau valley, region of Alb-Donau, Baden-Württemberg, Germany.

Location: Latitude 48º 23′ 53″ N, longitude 9º 46′ 17″ E. Elevation 580m above mean sea level.

General description: The cave ruin of Geißenklösterle is situated at the Bruckfels rocks, c. 60 m above the present floor of the Ach valley, which is part of the widespread drainage basin of the Proto-Danube river system and a pronounced karst area. The Geißenklösterle is a vestige of a once much more widespread cave system, which had already collapsed long before the first human occupation, in the Middle Palaeolithic (Mousterian) epochs. The remains of a large rock cavern including a rock arch are visible today. The Upper Palaeolithic archaeological strata yielded several works of figurative art: half reliefs of a bison and an anthropoid, and full reliefs of a mammoth and a bear, all made of mammoth ivory; two fragments of sculptures, possibly of animals; and a painted fragment of limestone.

Inventory of the remains: A small rectangular plate made of mammoth ivory, measuring just 38 mm × 14.1 mm × 4.5 mm, was excavated in 1979. Its archaeological context indicates a date within the Aurignacian, probably 35,000–32,000 BP. The artist cut, smoothed and carved one side (*A*) and finely notched the other side (*B*) and the edges. Side *A* contains the half-relief of an anthropoidal figure, either human or a human-feline hybrid, known as the 'adorant' because its arms are raised as if in an act of worship. On side *B* together with the four edges is a series of notches that are clearly set in an intentional pattern. The edges contain a total of 39 notches in groups of 6, 13, 7 and 13. A further 49 notches on side *B* are arranged in four vertical lines of 13, 10, 12 and 13 respectively plus a further notch that could be in either of the middle two lines.

History of the site: Excavations took place at Geißenklösterle between 1973 and 1991 and have continued since 2001. The archaeological layers contained well-preserved materials from the Mesolithic back to the Upper Palaeolithic (Magdalenian, Gravettian and Aurignacian periods), but earlier, Middle Palaeolithic artefacts were found to have been damaged by soil liquefaction. The ivory plate itself was excavated in 1979.

Cultural and symbolic dimension: The grouping of the notches on the plate suggests a time-related sequence. The total number of notches (88) not only coincides with the number of days in 3 lunations (88.5) but also approximately with the number of days when the star Betelgeuse (α Ori) disappeared from view each year between its heliacal set (about 14 days before the spring equinox around 33,000 BP) and its heliacal rise (approximately 19 days before the summer solstice). Conversely, the nine-month period when Orion was visible in the sky approximately matched the duration of human pregnancy, and the timing of the heliacal rise in early summer would have facilitated a 'rule of thumb' whereby, by timing conception close to the reappearance of the constellation, it could be ensured that a birth would take place after the severe winter half-year, but leaving enough time for sufficient nutrition of the baby before the beginning of the next winter. There is a resemblance between the anthropoid on side A and the constellation Orion.

Fig. 1.2.1. The two sides of the Geißenklösterle ivory plate. Based upon an image from the Landesmuseum Württemberg, Stuttgart.

None of these factors is convincing when taken in isolation, because of the high probability that apparently significant structural and numerical coincidences might have arisen fortuitously. However, taken together they suggest that the anthropoid represented an asterism equivalent to today's constellation of Orion, and that the ivory plate as a whole related to a system of time reckoning linked to the moon and to human pregnancy. If so, then ethnographic comparisons would suggest that the Geißenklösterle culture related their 'anthropoid' asterism to perceived cycles of cosmic power and fertility.

Comparative Analysis: The Geißenklösterle ivory plate is an exceptional artwork illustrating the highly developed cognitive and aesthetic abilities of early Upper Palaeolithic cultures. It is, to date, the oldest identifiable visualization of an asterism combined with denotations relating to time reckoning according to the moon and to the human pregnancy period. It also provides a clue to the kind of mythical conception that underlay these ideas and practices.

Authenticity and integrity: The plate was discovered *in situ* in 1979 in an original dwelling layer, beneath a 5cm-thick bone-ash stratum, unburned and close to a concentration of tools and other artwork—probably near to a fireplace. The layer was sealed by a collapse of the ceiling. The object had been shifted a small amount (by a few cm) from its original position by movements of the soil. The fact that the sculpture is complete and the fact that notches exist on all the edges prove that the small plate is complete and not a part of a larger object. Side *B* contains tiny spots of manganese and ochre, which must have been applied intentionally. Apart from a small repair to a tiny part of side *B* that had chipped away, no restoration work has been carried out on the plate.

Present management of the object

Present use: The original object is accessible only for scientific examination. There are replicas available for public display and private ownership.

Protection: The plate is deposited at the Landesamt für Denkmalpflege (LDA) Baden-Württemberg in Tübingen (accession number G 58.264).

State of conservation: The object is generally well preserved. Most of the surface of the figure on side A is only weathered from its original use, although during the excavation a tiny piece (c. 1mm) of the left upper corner was broken off. The uppermost thin ivory lamination on this side was also slightly damaged during the excavation. A tiny part of side B was chipped off, and has been restored.

Context and environment: The nature of the original weathering indicates that the piece may have been carried in a bag. The embedding of the object in a layer spotted with ochre, a mineral often used during Palaeolithic rituals, emphasizes the importance of the bas-relief for the original owner.

Archaeological/historical/heritage research: The plate has been examined and described in detail on several occasions since its discovery.

Main threats or potential threats to the site: The object is well and safely preserved.

Management: The original plate is only shown to the public in very rare cases. Replicas of it are displayed at several museums around the world.

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Case Study 1.3: The Ishango Bone, Democratic Republic of the Congo

Presentation and analysis of the object and its place of discovery

Geographical position: The object was found at an open-air site within Virunga National Park, near the town of Goma, Democratic Republic of the Congo.

Location: Latitude 0º 7´ 37˝ S, longitude 29º 36´ 2˝ E. Elevation 912m above mean sea level.

General description: The terrace named Ishango (or alternatively Isango-Isoro/Isanga-Isoro) is located on the north-western shore of Lake Rutanzige (Lake Edward) close to the outflow of the Semliki River. Fishermen and gatherers settled here during the Upper Palaeolithic, and excavations have revealed small ivory points, barbed bone points, fish bones, bones of different species of mammals, quartzite tools, and a decorated haft made of a baboon bone, as well as human remains.

*Inventory of the remains***:** The 'Ishango bone' is a slightly curved fibula of a baboon, about 10 cm long and dark brown in colour, which was discovered on the terrace in 1950. A short piece of quartz is fixed to one head of the bone, protruding by only 2 mm, and served as a blade. The tool was engraved with groups of notches arranged in three columns running the length of the bone. The first column (*G*) consists of 60 notches divided into four groups, containing 11, 13, 17, and 19 respectively; the second column (*M*) consists of 48 notches divided into eight groups containing 3, 6, 4, 8, 10 (9+1), 5 (1+4), 5, and 7 respectively; and the third column (*D*) consists of 60 notches divided into four groups containing 11, 21, 19, and 9 respectively.

History of the site and object: Geological surveys in the 1930s in the area of the Semliki River resulted in the incidental discovery of archaeological remains from the Middle and Upper Palaeolithic and the establishment of a basic Upper Semliki stratigraphy. Although presented in an excavation report of 1957, the Ishango bone was first interpreted as an example of proto-mathematics in 1962. A subsequent re-evaluation of the archaeological dating places the bone between c. 25,000 BP and 16,000 BP.

Cultural and symbolic dimension: Evidently the Ishango bone was designed as a tool for making incisions, but its bone handle was itself incised. The arrangement of the notches engraved on the handle, and the numbers in each group, are clearly not casual. Analysis of their numerological properties has led several investigators to conclude that the artefact is not a simple tally stick, but a kind of calculator based on special number systems. Each of the groupings in the left and right columns (*G*, *D*) contains an odd number of notches (9, 11, 13, 17, 19, and 21), while the numbers contained in the first column (*G*) are precisely the four prime numbers between 10 and 20. Certain adjacent groupings in column (*D*) contain 10 or 12 notches in total. From facts such as these it is supposed that the groupings represented numbers and the whole design represented a system of reckoning based upon counting by digits. The column totals (60, 48 and 60) suggest that a mixed base of 10 and 12 was used. It has also been suggested that the bone could have been used for time reckoning, following the observable course of the moon over a period of about 5½ synodic (lunar phase cycle) months, based on a period of a double lunation of 59–60 days.

Comparative Analysis: This interpretation of the Ishango bone provides evidence that people during earlier prehistory could have developed significant proto-mathematical knowledge beyond simple counting. This includes the selection of certain numeral bases (10, 12), specific kinds of numbers (odd, even, prime numbers), and rules of multiplication and division by two. An object such as the Ishango bone could have been used for time reckoning, for special games or other purposes.

Another decorated bone handle was discovered in 1957 from a similar archaeological context, but notes on this only became available in 1998. This object also contains engraved notches, in this case forming six groups, two of which are subdivided into a series of longer and a series of shorter grooves. The numerical sequence (20 [14 long, 6 short], 6 [long], 18 [long], 6 [long], 20 [long], 8 [6 long, 2 short]) has been interpreted as a kind of reckoning using a mixed base of 6 and 10.

Authenticity and integrity: The Ishango bone comes from a secure archaeological context and is well preserved. The artefact is fossilized and its surface shows only minor changes due to water and to the chemical effects of the surrounding soil.

Present management of the site and object

Present use: The Ishango bone is on permanent display in l'Institut Royal Belge des Sciences Naturelles, Brussels, Belgium. At least one international scientific conference (in 2007) has been dedicated exclusively to the interpretation of this unique artefact.

Protection: Virunga National Park was inscribed on the World Heritage List in 1979 (no. 63) and in 1994 it was placed on the List of World Heritage in Danger. The Ishango bone is well protected according to the usual standards of deposition and exhibition in a modern museum.

State of conservation: For the bone, normal procedures of conservation are applied, following international standards.

Context and environment: The landscape of Virunga National Park (c. 300 km × 150 km) is characterised by Lake Kiwu and Lake Edward, the Volcanoes of Virunga, the Ruwenzori Range which contains the peak of Mount Stanley (5109 m), and the Great Rift Valley. Its exceptional flora and fauna include one third of the world's remaining mountain gorillas.

There exist several open air sites close to Ishango on the banks of the Upper Semliki River and along the northern shore of Lake Rutanzige: examples are Kabale, Katanda, and Kasaka. They reveal artefacts dating to the Lower, Middle and Upper Palaeolithic as well as to the Neolithic epoch (8,000–1,300 BP).

Archaeological/historical/heritage research: The archaeological context was first researched and documented by a team led by Jean de Heinzelin in the 1950s; Alison Brooks and colleagues undertook a re-evaluation of the Ishingo site during the 1980s and 1990s and provided modern dating evidence. The ethnomathematical interpretation of the Ishango bone was first presented by de Heinzelin in 1962 and has since been pursued by Dirk Huylebrouck and others. A palaeoastronomical interpretation was introduced by Alexander Marshack in 1972 and subsequently elaborated by Claudia Zaslavsky.

Main threats or potential threats to the site: There are no potential threats to the object apart from damage caused by *force majeure*.

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Fig. 1.3.1. Left: The Ishango bone. Based upon an image from the Royal Institute for Natural Sciences of Belgium in Brussels. **Right:** The numerology of the countable notches arranged on the stick. After D. Huylebrouck, "Afrika, die Wiege der Mathematik", *Ethnomathematik, Spektrum der Wissenschaft* 2 (2006), 10–15.

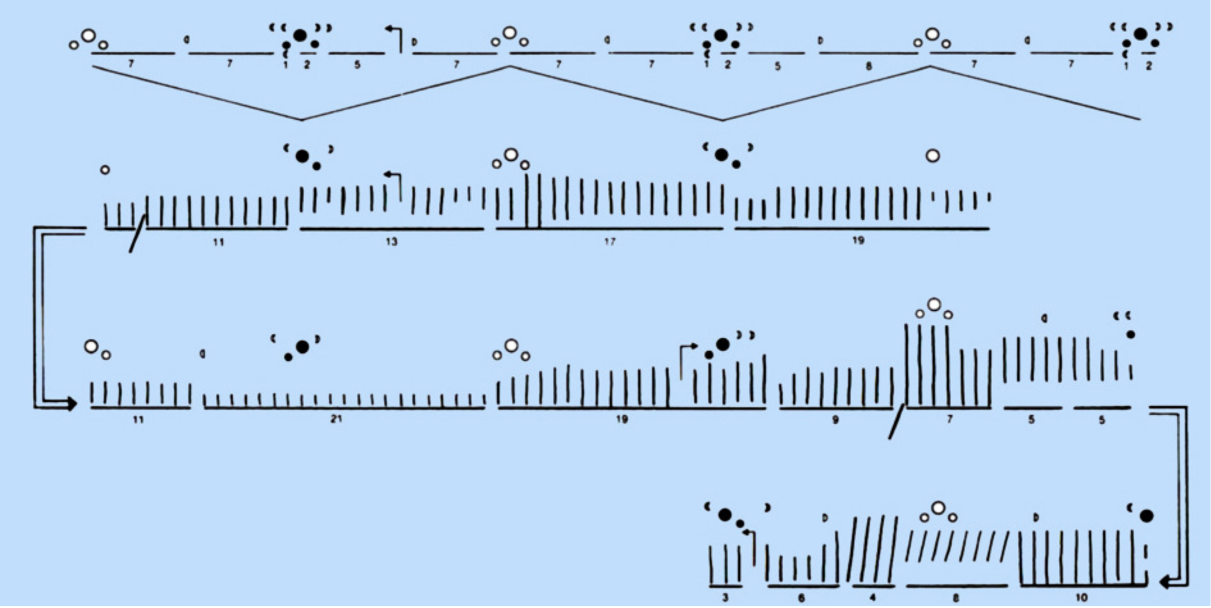

Fig. 1.3.2. The sequence of notches interpreted in terms of lunar time reckoning. After A. Marshack, *The Roots of Civilization* (New York, 1991), fig. 3.

Case Study 1.4: The Astronomical Rock Panels in the Lascaux Cave, France

Presentation and analysis of the site

Geographical position: The Lascaux cave (Grotte de Lascaux) is situated in the valley of the river Vézère, 1200 m south-east of Montignac, Département de la Dordogne, France.

Location: Latitude 45º 3´ 17˝ S, longitude 1º 10´ 44˝ E. Elevation 185m above mean sea level.

General description: The Lascaux cave is embedded in the Santon limestone massif, its entrance being just below the top of Lascaux hill, c. 90 m above the valley floor of the Vézère. It comprises three long and narrow subterranean galleries in the form of a letter 'K' and measuring almost 250 m in length, including what have become known as the Axial Gallery, the Hall of the Bulls, the Chamber of Felines, the Nave, the Apse, and the Shaft. Covering most parts of the cave are numerous monochrome and polychrome paintings and engravings. The published corpus lists 1963 figures including animals (horse, aurochs, bison, ox, stag, ibex, feline, woolly rhinoceros, bird, bear), an anthropoid, a chimera, some possible abstract representations of plants, and symbols (geometric figures, series and sets of dots etc). Carbon-14 dates (from charcoal used sparingly for painting), pollen analysis and stylistic evaluations suggest that the majority of the rock pictures should be associated with the Lower Magdalenian, c. 17,000-15,000 BP, although it is possible that a few were created much later, in the Mesolithic (up c. 5000 BC).

*Inventory of the remains***:** A number of the Lascaux pictures have a possible astronomical significance. These include the 'Chinese horse' and 'fronting ibex' in the Axial Gallery and the 'crossed bison' in the Chamber of Felines (natural calendars); the stag-and-horse motif and related dots in the Axial Gallery and the five 'swimming stags' in the Nave (astronomical almanacs); the aurochs (no. 18) in the Hall of the Bulls with its clusters of dots (representations of asterisms); and two pictograph panels in the Shaft (cosmography). See also 'Cultural and symbolic dimension' below.

History of the site: The cave was discovered on 12 September 1940 and rapidly started to attract large numbers of visitors. In 1948 it was opened to the public, but serious deterioration due to biological contamination resulted in it being closed again in 1963. A detailed three-dimensional replica of the cave's most impressive galleries, the Axial Gallery and the Hall of the Bulls, was created just 200m away and has been open to the public since 1983. Meanwhile, efforts to halt the continuing deterioration of the original cave continue through to the present time.

Cultural and symbolic dimension: The suggested astronomical associations fall broadly into four categories:

- *Natural calendars*. The majority of the animals depicted at Lascaux show seasonal characteristic features: the deer are represented in their rutting season at the start of autumn, the horses at their time of mating and foaling in late winter/early spring, the ibexes at the time when they congregate in same-sex herds during the late summer/early autumn, and so on. These indications of particular seasons are sometimes enhanced by the addition of stylized plants: an example is the 'Chinese horse' in the Axial Gallery that is shown in its summer fur, highly pregnant and surrounded by stylized branches, illustrating the time of foaling around summer solstice.
- *Astronomical almanacs*. Some abstract designs associated with 'seasonal' animals may relate to astronomical calendars. For example, it is argued that a set of 13 dots and another of 26 appearing beneath a roaring stag and a pregnant horse (representing autumn and spring respectively) in the Axial Gallery represent the 13- and 26-week intervals from the summer solstice to the autumn equinox and then to the spring equinox, each spot counting 7 days.
- *Representations of asterisms, particularly the Pleiades and Hyades*. A cluster of dots above the back of the aurochs (no. 18) in the Hall of the Bulls resembles the Pleiades, while the animal's eye and surrounding dots resemble Aldebaran (α Tau) and the Hyades, suggesting that the aurochs may be a distant forerunner of the constellation Taurus.
- *Archaic cosmography*. Two pictograph panels in the Shaft have been interpreted as representing the sky panorama as perceived by Magdalenian people from the top of the Lascaux hill at, for example, around midnight around the time of summer solstice in c. 16,500 BP.

Comparative Analysis: If these interpretations are upheld, then Lascaux cave not only represents an extraordinary repository of Upper Palaeolithic Art but also contains the most elaborate and complex astronomical notations in earlier prehistory so far recognised, and the only known representation of the cosmos as perceived by Upper Palaeolithic hunter-gatherers possessing an archaic totemistic-shamanistic world-view.

Authenticity and integrity: At the time of its discovery in 1940 the cave was in a state of geological and climatic integrity. However, by the time it was closed to the public in 1963 it had undergone extensive modifications in order to create a safe environment for tourists: the cave entrance had been enlarged and the floor lowered, electric lighting and air conditioning had been installed, and sluices had been constructed to drain off standing water.

Documentation and archives: The Lascaux cave paintings have been extensively researched and catalogued. See Aujoulat 2005 and http://www.lascaux.culture.fr/.

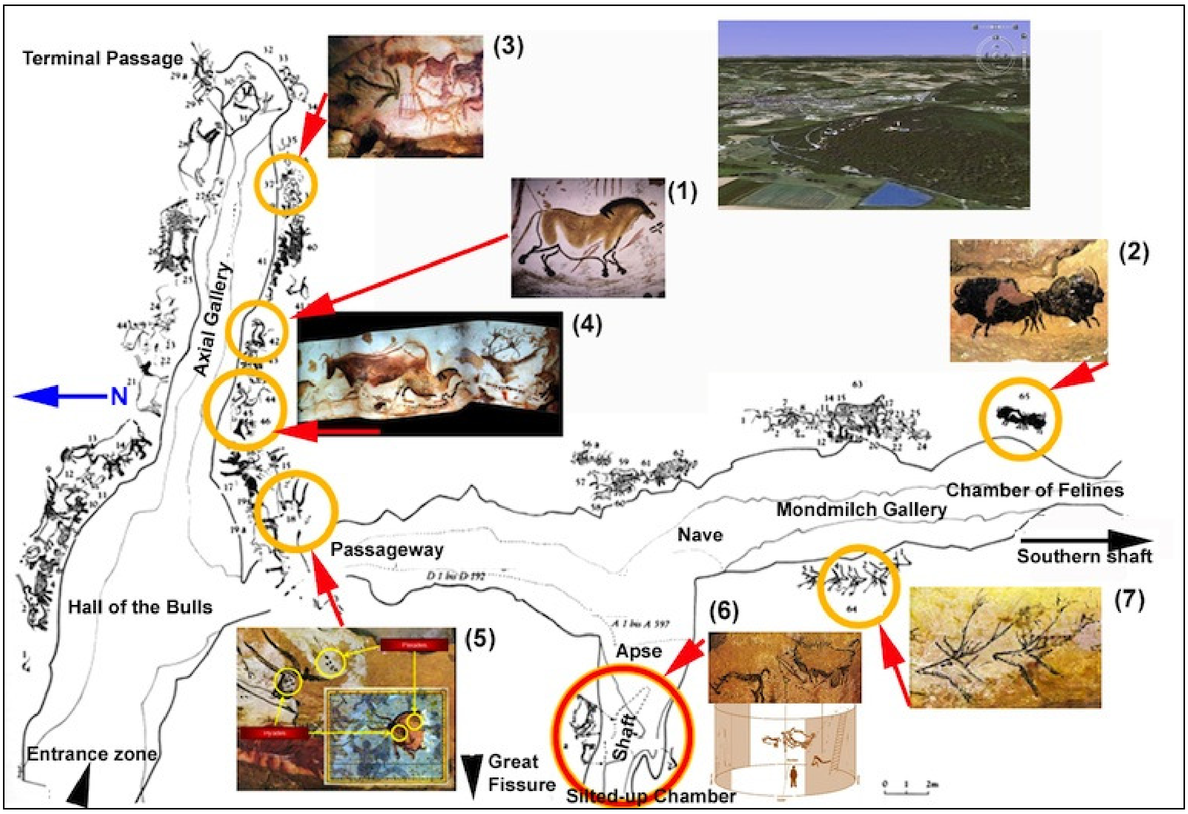

Fig. 1.4.1. Rock panels with possible astronomical associations in Lascaux cave. (1) The 'Chinese horse'; (2) the 'crossed bison'; (3) the 'fronting ibex'; (4) the 'roaring stag and pregnant horse motif'; (5) the aurochs (no. 18) and associated clusters of dots; (6) two pictograph panels of possible cosmographic significance; and (7) the 'five swimming stags'. Adapted from a graphic by Michael Rappenglück.

Present management of the site

Present use: At present the cave is closed to all non-essential visitors.

Protection: On 27 December 1943, Lascaux cave was declared a historic monument of France and since 1979 it has been inscribed on UNESCO's World Heritage List as part of 'Prehistoric sites and decorated caves of the Vézère valley' (no. 85). The site is in the care of the French Ministry of Culture and Communication.

State of conservation: From the late 1940s onwards, the effects of mass tourism and the measures put in place to support it upset the cave's fragile ecological balance. Despite the closure of the cave to the public in 1963 the biological contamination of the soil and rock walls has caused a series of irreversible changes, and since 2001 further fungal attacks have caused renewed and rapid deterioration. The French Ministry of Culture has held scientific meetings and sponsored major programmes in order to comprehend the situation and to take appropriate conservation decisions.

Context and environment: Lascaux cave is situated within an area rich in earlier Prehistoric sites—caves, rock shelters, and settlements—along the valleys of the Beune, Vézère, and Dordogne rivers and in the surrounding hills. Many of these sites contained parietal and mobile art, dating from all Upper Palaeolithic epochs.

Archaeological/historical/heritage research: There exist numerous authoritative archaeological, historical and heritage studies concerning the cave and its artwork. Many of the astronomical interpretations, by contrast, have been unscientific and highly speculative, arguably undermining more serious research in this area.

Main threats or potential threats to the site: The growth of micro-organisms (fungi, lichens and algae) seriously threatens the likelihood that the cave's art will survive undamaged. In February 2009, French government statements, and monitoring procedures within the World Heritage Centre and ICOMOS (as the relevant advisory body) indicated that the biological contamination had been halted, although not removed.

Management: Although the Lascaux cave ('Lascaux I') is closed, the replica ('Lascaux II') attracts more than 250,000 tourists each year. Detailed copies of some of the important frescoes not replicated in Lascaux II, including those in the Shaft, are on display at the Musée d'Art Préhistorique du Thot (Tonac, Dordogne, France) and the Musée d'Aquitaine (Bordeaux, France). Since 2009 a virtual display of the Lascaux cave has been available on the internet at http://www.lascaux.culture.fr/.

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Chapter 2: Later Prehistoric Europe

Clive Ruggles

The later prehistoric period within Europe, and particularly around the Atlantic façade, marks the widespread construction of large, evidently communal, structures built predominantly of earth, timber and/or stone. The vestiges of many earthworks and stone monuments dating to this period remain conspicuous in today's landscape. People have long identified tangible connections with the sky at such monuments, mostly in the form of alignments upon the rising and setting points of particular celestial objects, such as the sun at the summer or winter solstice. Such alignments remain the focus of much attention among both professional archaeoastronomers and enthusiastic amateurs.

In dealing with such alignments one must take account of three fundamental issues. First, every oriented structure must point somewhere, whether intentionally or not. Second, several different factors might have influenced a structural orientation, of which only a few are related to the sky. Third, there are many potential astronomical targets, some of which may have shifted significantly within the chronological timeframe that can be identified from the broader archaeological evidence. There is, therefore, a strong likelihood of being able to fit a fortuitous astronomical alignment to almost any structural orientation, which is increased still further if one is prepared to choose the 'best fit' date.

One way to establish the intentionality of an alignment and to sustain a plausible astronomical explanation is to identify repeated trends. Fortunately, among European later prehistoric monuments there exist several geographically and chronologically well-defined clusters of architecturally similar constructions where systematic analyses can be, and have been, undertaken. A prerequisite is that the type of monument in question should have a clearly identifiable 'principal axis' or other major structural orientation whose importance can be convincingly argued on *a priori* grounds.

Even where an astronomical connection can be reliably established through its repetition among a group of monuments, one still needs to consider the broader archaeological context in order to interpret its cultural significance: why it was constructed, how it functioned and what social purposes it may have served. It is clear, for example, that burial tombs, even if astronomically oriented, were not 'observatories' if that is taken to mean that they were constructed primarily to facilitate astronomical observations. Instead, we should view the astronomical connection encapsulated in the monument as a tangible reflection of a connection existing in people's minds between ancestors and/or ancestral spirits and the astronomical body in question. Its significance to us rests largely in revealing that connection. Similarly, astronomical alignments encapsulated in other types of monument such as enclosures and free-standing 'temples', even if periodically confirmed by observation, should be seen as secondary, albeit important and perhaps vital, aspects of the symbolism of those structures, whose interpretation inevitably leads to the consideration of issues such as ideology and cosmology.

Despite their continued predominance in discussions on the topic, tangible manifestations of astronomy in later prehistoric Europe are not confined to monumental alignments upon the horizon rising and setting points of celestial bodies. Other aspects of spatial patterning in the material record, as well as consideration of the situation of monuments within the landscape and human movement and experience in relation to the monuments, have become increasingly important in recent years.

Geographical and chronological context

In Europe, the term 'later prehistory' broadly refers to the period from the first appearance of farming communities (i.e. those who practised cultivation and/or animal husbandry) and lasted until the emergence of the classical civilizations and the Roman Empire. This covers the periods conventionally referred to as the Neolithic, Copper Age/Chalcolithic/Eneolithic, Bronze Age and Iron Age. The chronology varies from region to region: it stretches back as far as the 7th millennium BC in south-east Europe, as shown by the existence of numerous 'tells'—mounds containing the remains of fixed settlements lasting for many generations—and lasts into the early centuries AD in places like Ireland and northern Europe where there was no Roman conquest.

The monuments that survive to characterise this period so prominently in today's landscape include

- burial structures, typically stone chambers and passages covered, or once covered, in large earthen mounds;
- round enclosures or constructions, such as 'henges' and other circular earthworks, and stone circles;
- linear constructions, such as the earthen 'cursus monuments' concentrated in southern England, and the huge stone rows at Carnac in Brittany, France.

The main concentrations of these are around the Atlantic seaboard of western Europe, but they are also found in parts of central Europe, the Caucasus and the Russian steppes. Some, such as chambered tombs, were clearly places for the dead but may also have served a variety of functions for the living. The various purposes of others such as earthen enclosures, linear earthworks, stone circles and stone rows are much debated but they remain widely characterised as 'ceremonial' and/or 'ritual' monuments.[1]

Excavations have shown that many such monuments were altered and remodelled over time, Stonehenge being a famous example; another is the gradual 'closure' of various Scottish stone circles and their re-use as focal points for later burials. In other cases, constructions were destroyed and their component materials used for building new monuments. This is evident, for example, in Brittany, in the reuse of two adjacent pieces of a large menhir, presumably once standing, as the capstones in two large tombs (La Table des Marchand and Gavrinis) some 4 km apart.

Regional groupings of monuments

Fortunately, there exist many regional groupings of relatively modest monuments with evident similarities in construction technique and design, and presumably purpose, that can be shown, or can reasonably be assumed, to have been constructed within a relatively short period of time. The common characteristics of such monuments often include aspects of their landscape situation. Many types of monument also manifest a clear directionality, such as (in an enclosed structure such as a tomb) the direction faced by the entrance or (in the case of a standing monument) an axis of symmetry running through a distinctive feature such as the 'recumbent' stone (a stone set on its side rather than upright) found in certain Scottish and Irish

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[1] A variety of local terms is used to refer to such monuments: for example, single-chamber megalithic tombs with large capstones are known variously as dolmens, quoits, cromlechs, antas, and Hunebedden; earthen mounds as barrows, tumuli, and kurgans; and standing stones themselves as megaliths, menhirs, and orthostats.

Fig. 2.0.1. Top: Loanhead of Daviot, Aberdeenshire, United Kingdom: one of 97 Scottish recumbent stone circles. **Centre left:** Gurranes, one of 92 short stone rows in south-west Ireland. **Centre right:** One of c. 200 oriented tombs at Río Gor, Granada, Spain. **Bottom left:** Talatí de Dalt, one of 25 taula sanctuaries in Menorca, Spain. Photographs © Clive Ruggles

stone circles. These principal directions are typically confined to an arc of about 120° (i.e. one third of all possible directions) or less, demonstrating beyond doubt that orientation was a factor of considerable importance to the builders. The range of directions concerned—the orientation ‘signature’, varies from group to group, along with other aspects of monument design.

Many different factors can influence a structural orientation, including constraints of the local topography (e.g., the earthen long barrows of Cranborne Chase in Dorset, southern England, whose predominantly south-easterly orientation apparently results from the long axes being preferentially oriented along natural ridges), terrestrial ‘targets’ such as other tombs (as is quite common among Neolithic passage tombs in Ireland), or prominent landscape features; even, simply, the direction of the prevailing wind. However, in most cases—given a scatter of monuments over an area with significant topographic variability—such consistency could only have been achieved by reference to the north-south line defined by the diurnal motion of the heavens. This provides the most crude, but also the most fundamental, evidence for an astronomical connection among a wide range of later prehistoric monuments in Europe.

Systematic surveys of over 3000 tombs and 'temples' in western Europe, from France to the Mediterranean, provide the first refinement of this evidence. Virtually no monuments face the northerly quadrant, where heavenly bodies such as the sun, moon and planets are never seen. The remaining directions can be split into four arcs: the solar rising (SR) arc to the east, corresponding to the part of the horizon where the sun rises at some time in the year; the 'sun climbing' (SC) arc to the SSE, corresponding to those directions where the sun is seen to climb in the sky as it passes across; the 'sun descending' (SD) arc to the SSW, and the sun setting (SS) arc to the west. The orientation signatures of local monument groups typically correspond to two of these arcs, namely SR/SC, SC/SD, or SD/SS. This supports the idea that the principal association was with the sun, although such conclusions are critically dependent upon the outlying orientations in the sample. Others argue for a lunar association, but this is more difficult to prove owing to the greater complexity of the lunar motions. The seven-stone antas of central Portugal and central-western Spain are of particular importance in that their orientations lie exclusively in the SR range (see Case Study 2.2).

A number of groups of British and Irish monuments have been studied more closely. While many of these have orientation signatures broadly similar to those just mentioned, these studies have revealed more subtle differences. In particular, certain groups of monuments at more northerly latitudes, such as the 'recumbent stone circles' of the Grampian region of eastern Scotland, have a clear relationship with the moon. This is thought to relate to the fact that, at these latitudes, the moon on occasion passes low across the southern sky, at which times it is especially prominent. The orientation of the site (and especially, the positioning of the recumbent stone) apparently related to observations of the full moon, and particularly its setting position, at midsummer. In other cases, such as the 'axial stone circles' of Counties Cork and Kerry in south-western Ireland, there is a clear orientation trend but no obvious association with any particular astronomical body.

Some of the most important groups of monuments with clear orientation trends are listed in Table 2.0.1.

Alignments in context

Countless astronomical interpretations have been put forward of individual prehistoric monuments all over Europe, and an overview will not be attempted here. If there is no statistical backing one has to provide evidence from the broader archaeological context that supports the argument that a given alignment or other astronomical association was in fact intentional. The advantage of this 'contextual' approach over a purely statistical one is that it can also address the question of the meaning(s) and significance of the associations to the people who created and used them, making use of theoretical approaches and interpretative tools developed within archaeology as a whole.

At Stonehenge, for example (see Case Study 2.1), not only is the intentionality of the solstitial alignment confirmed by the fact that it is shared by a number of contemporary monuments in the vicinity, but archaeological evidence concerning the timing of feasts, and landscape features such as a solstitially aligned avenue at nearby Durrington Walls, provide plausible interpretations in terms of seasonal processions and rituals. More interestingly still, the recent discovery that the Stonehenge avenue seems to overlie natural geological striations in the landscape, which are themselves solstitially aligned, suggests that what seems to us an accident of nature may, for Neolithic people, have provided the ultimate cosmological confirmation of the special nature of this place and be the reason that Stonehenge was eventually built here.

Things are not so clear in the Boyne valley, where the famous midwinter sunset alignment of Newgrange passage tomb is not repeated at the nearby large passage tombs of Knowth and Dowth, although their passages (two in each case) are all aligned within the solar rising and setting ranges. 'Satellite' tombs surrounding Knowth, oriented inwards towards the larger tomb,

Type	Date (M BC)	Location	Country	No. of sites	Orientations	Azimuths (°)	Astronomy	Ref
Short stone rows	3rd/2nd?	Co. Cork, Co. Kerry	Ireland	92	SSW/NNE–WSW/ENE	200/20–250/70	Moon?	R
Short stone rows	3rd/2nd?	Western Scotland	UK	44	SE/NW–SW/NE	120/300–230/50	Moon	R
Clava Cairns	Early 2nd	Inverness-shire	UK	28	S–SW	170–230	Moon	R
Recumbent stone circles	Late 3rd	Grampian region	UK	97	SSE – SW	150–235	Moon	B,R
Earthen long barrows	4th	Salisbury Plain	UK	65	NE–S	c. 50–180	Sun (SR/SC)	R
Hunebedden	4th/ early 3rd	Drenthe, Groningen	Nether-lands	76	NE–S*	50–170*	Sun (SR/SC)	G
Bas-Rhône-type dolmens	3rd	Provence, W Languedoc	France	110	S–NW	170-300	Sun (SD/SS)	H
Languedoc-type dolmens	3rd	East Languedoc	France	103	SSE–NW	160-300	Sun (SD/SS)	H
All tombs	4th/3rd	Iberia + W & cent. France	Portugal, Spain, France	1576	NE–S	40–190	Sun (SR/SC)	H
All tombs	4th/3rd	Iberia + Pyrenees	Portugal, Spain, France	935	NE–S	60–190	Sun (SR/SC)	H
All tombs	4th/3rd	West Iberia	Portugal, Spain	324	ENE–ESE	60–140	Sun (SR)	H
Seven-stone antas	4th – late 3rd	Alentejo; Extremadura	Portugal, Spain	177	ENE–ESE	60–130	Sun (SR)	H
Taula sanctuaries	Late 2nd – early 1st	Menorca	Spain	25	ESE – SSW	110– 210	S Cross & Centaurus	H
Tombe di giganti	3rd	Northern Sardinia	Italy	158	NE–S	50–190	Sun (SR/SC)	H

Table 2.0.1. Some examples of groups of standing monuments whose principal orientations demonstrate an astronomical connection. In the lists of orientations and azimuths, outliers are excluded where they form less than 2% of the total. Key to references: R = Ruggles (1999); B = Burl (2000); H = Hoskin (2001); G = González-García, César and Lourdes Costa-Ferrer (2003). "Orientations of the Dutch Hunebedden", *Journal for the History of Astronomy* 34, 219–226. * = The azimuths quoted are those of the chamber which is different from that of the passage.

remind us that as far as determining orientation was concerned, astronomy was just one possible factor among many.

In the case of the Clava cairns, a small group of Bronze-Age monuments around Inverness, Scotland, the two approaches are in conflict: a 'statistical' study of the orientations of the group as a whole suggests that they are associated with the setting position of the midsummer full moon, whereas an archaeological excavation of the largest site, Balnuaran of Clava—where two tombs are aligned very closely on the setting midwinter sun (which is in the middle of the lunar range)—has uncovered evidence that the architectural construction was compromised in order to incorporate the precise solstitial alignment. In other words, in this one case the solar alignment was clearly deliberate, yet it is not repeated at the other sites. This paradox can only resolved by surmising that a particular (solar) practice was developed at this 'special' site in the midst of a more general local (lunar) tradition.

In a few cases, the alignment evidence deserves particular attention despite the lack of any wider corroboration. A good example is a rectangular setting of standing stones at Crucuno, Brittany—something that is highly unusual in itself—whose sides are aligned in the cardinal directions but whose diagonals are aligned solstitially. In other cases, wider arguments are brought to bear. For example, the solstitial alignment of the 'large sanctuary' at the Dacian fortress at Sarmizegetusa Regia, Romania (1st century AD), is 'theoretical' rather than efficacious in that it pays no attention to the altitude of the horizon in the sunrise direction; however, the existence of what is thought to be a sundial and apparent calendrical symbolism in the numbers and patterns of the kerbstones, together with the possibility of contact with Hellenistic Greece, renders it more likely that the sacred centre did have a geometrical and astronomical significance.

* * *

All of the astronomical alignments discussed so far are thought to be related to the sun or moon. Alignments upon the rising and setting positions of the planets, if they existed, are unlikely to be distinguishable from the archaeological evidence alone. This is because the 'extreme' rising and setting positions of the planets are complex, giving rise to many equally plausible 'targets'; and in any case all the possible positions are close to those of the sun and moon, since the planets' motions are confined to a region close to the ecliptic plane, and not easily distinguishable from them.

It is generally difficult to prove the intentionality of stellar alignments on the basis of archaeological evidence alone. This is because of the large number of stars and the fact that their rising and setting positions shift significantly on a timescale of centuries owing to the precession of the equinoxes. This means that it is all too easy to fit a putative stellar alignment by positing a date that falls within the chronological range suggested by the other archaeological evidence. Speculations about alignments upon the rising and setting positions of stars are further complicated by complex and often unpredictably variable effects such as atmospheric refraction and extinction.

Nonetheless, plausible contextual arguments for a stellar association have been made in a few cases. One is the pre-talayotic sanctuary of Son Mas in Mallorca, Spain, from which the stars of the Southern Cross and 'Pointers' (α and β Centauri) would have made a brief but spectacular appearance in a prominent valley to the south up until about 1700 BC, the date at which archaeological evidence suggests the site was abandoned. One interpretation is that the abandonment—for which the archaeological evidence suggests no other reason—took place *because* the critical stars disappeared. Another example is the Thornborough henges (3rd millennium BC) in Yorkshire, UK, which archaeological evidence suggests was an important pilgrimage centre; the alignment evidence backs the idea that the appearance of certain asterisms (the stars of Orion's Belt) provided the 'trigger' for people to set out from considerable distances in order to arrive at the appropriate time for the autumn festival.

* * *

It remains necessary to caution against unsupportable interpretations, typically based upon astronomical 'alignment hunting' without regard either for statistical underpinning or, most crucially, for the archaeological context. Stonehenge itself, although recognised throughout the world as an icon of ancient astronomy, epitomises such problems. Its continuing public perception as some sort of 'ancient observatory' owes much to arguments for multiple solar and lunar alignments made in the 1960s, ideas which are thoroughly undermined by the archaeological evidence as well as statistically unsupportable. Modern political and nationalist agendas can sometimes overemphasize the importance of putative alignments at ancient sites (ironically, sometimes publicised as local 'Stonehenges') in support of interpretations that emphasize ancient 'achievements'; this is misguided because the achievements concerned are conceived and measured in modern terms. The most notorious example is the use of the Odry site in northern Poland (see Case Study 2.3) for propaganda purposes by the Nazis in the 1930s.

Alignments upon horizon rising and setting positions of astronomical objects have dominated the discussion of astronomy in later European prehistory for many decades. To some extent this is inevitable from the nature of the evidence, but it should not close our eyes to other possible sky associations in the immovable material heritage of this period. Nonetheless, interpretative caution is needed in all areas. For example, astronomical interpretations of rock art have generally proved highly controversial.

Fixed monuments do not provide the only form of evidence for an interest in the skies within later prehistoric Europe. For example, sun symbols are found on a range of Neolithic and Bronze-Age artefacts from all over the continent, while moon symbols are found on a number of Iron-Age anthropomorphic hilted short swords from France and Germany. The discovery of the Nebra Disc, a bronze disc 32cm in diameter, inlaid in gold with depictions of the sun, moon and a scattering of stars, has caused controversy since 2002: claims that it was a star map or surveying device have been hotly disputed but at the least it was a high-status object whose prestige was enhanced by symbolic representations of the cosmos.

Meaning of astronomical associations

The likely meaning and significance, in broad terms, of tangible associations between prehistoric monuments and the sky—and particularly of alignments with horizon rising and setting events—is well demonstrated by the example of Newgrange passage tomb. Newgrange clearly wasn’t an observatory, in any sense of the term: people did not go to the lengths of building such a huge and impressive monument just so that someone could sit inside in the dark, among the bones of the dead, waiting to find out if the shortest day of the year had arrived. What Newgrange communicates to us is that in the minds of a group of people more than 5000 years ago, there existed a link between (on the one hand) the sun and seasonality and (on the other) death and the ancestors. While we can never know exactly how they conceptualised this link, it is reasonable enough to speculate that it related to notions of regeneration and seasonal renewal. What is clear is that the astronomical alignment of this great tomb—its tangible connection to the sky—reflects a connection that already existed in the minds of our ancestors. It is a nugget of information that tells us something about Neolithic peoples’ way of understanding the world—the cosmos—that they perceived themselves as dwelling within.

Ever since the antiquarians and proto-archaeoastronomers of the 19th and early 20th centuries started to discover large numbers of astronomical alignments amongst groups of standing stones, people have been tempted to see free-standing monuments such as these as some kind of ‘observatory’ or ‘monument to the sun’. Yet taking Stonehenge as the obvious example, its solstitial connection should almost certainly be viewed in symbolic terms like that at Newgrange; recent excavations lend support to the idea of an annual cycle of processions to and fro through the landscape and seasonal feasts—a seasonal series of activities related to propositioning the ancestors for fertility and the success of the annual harvest.

Cosmological symbolism may or may not be reflected in ritual practices for the living, and hence in direct ‘observations’ continuing to take place after the time of construction. Thus, at the Scottish recumbent stone circles it seems likely that the moon appearing over the recumbent stone formed a key moment in appropriate ceremonies within the circle. However, recent excavations have shown that many of these sites may have undergone a complex sequence of changes rendering the alignments unviewable. Related monuments in the region seem to have been purpose-built as cairns rather than as open enclosures, yet relate to the recumbent stone circle tradition and keep the same pattern of orientation.

Excavations at the Neolithic village of Barnhouse in the Orkney Islands, Scotland, have shown that the houses generally faced one of the intercardinal directions, in other words one of the four solstitial directions, a fact that is reflected in the orientations of the contemporary passage tombs in the area. This reinforces other evidence suggesting that the tombs were conceived as 'houses' for the dead, and implies that practices of astronomical orientation that are obvious to us in tombs in many regions (because they were built of more durable materials) may have reflected common practice among more 'everyday' activities—activities that have generally left little or no trace in the material record.

An obvious question to which this leads is whether astronomical practices in more domestic contexts were principally 'practical' or symbolic in nature. For example, there have been arguments as to whether the predominantly south-easterly orientation of some groups of British Iron-Age roundhouses is better explained in terms of ritual symbolism to do with the midwinter sun or practical expediency to do with the warmth of the early-morning sun entering the house in wintertime. The truth may well have been: a bit of both. The dichotomy that we see between the ritualistic and the pragmatic was not one that existed in the minds of people in later prehistory.

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Case Study 2.1: Stonehenge World Heritage Site, United Kingdom

Amanda Chadburn

Presentation and analysis of the site

Geographical position: County of Wiltshire, England, United Kingdom.

Location (Stonehenge): Latitude 51° 10′ 44″ N, longitude 1° 49′ 34″ W. Elevation 103m above mean sea level.

General description: The Stonehenge World Heritage Site (WHS), one half of the "Stonehenge, Avebury and Associated Sites" WHS (no. 373) inscribed in 1986, comprises an area of 2,665 ha (26.6 km^2) with Stonehenge stone circle approximately at its centre. Stonehenge is the most architecturally sophisticated prehistoric stone circle in the world and, in addition, the WHS around it contains many hundreds of archaeological sites and monuments, many of which are also prehistoric. These monuments and their associated landscapes help us to understand Neolithic and Bronze Age ceremonial and mortuary practices in England and indeed in north-west Europe. They demonstrate around 2,000 years of continuous use and monument building between c. 3700 and c. 1600 BC.

One of the most important features of Stonehenge is that it is aligned along the midwinter sunset-midsummer sunrise solstitial axis (approximately SW–NE). We now know that a number of other prehistoric sites in the Stonehenge WHS also have astronomical significance, with a number of monuments aligned along this same solstitial axis and others along the opposite midsummer sunset-midwinter sunrise solstitial axis (approximately NW–SE).

Brief inventory: The Stonehenge WHS contains more than 700 archaeological features, including more than 350 burial mounds, and a number of key monuments such as the Cursus (c. 3600–3400 BC); Woodhenge (c. 2300 BC), Durrington Walls henge (c. 2500 BC) and the Stonehenge Avenue (c. 2500–1700 BC). A new henge has recently been discovered at West Amesbury (c. 2400 BC) at the end of the Stonehenge Avenue.

A number of these monuments appear to have been deliberately aligned along the midwinter sunset-midsummer sunrise solstitial axis: Stonehenge stone circle, the 'final approach' of the Stonehenge Avenue, Coneybury henge, and Woodhenge. By contrast, a number of other monuments appear to have been aligned along the midsummer sunset-midwinter sunrise solstitial axis, including the timber circle known as Durrington Walls 68 and possibly the timber Northern Circle at Durrington Walls. There are also two further definite examples on significantly sloping ground, thus permitting us to identify their directionality: these are the recently discovered Durrington Walls Avenue, which is aligned on the midsummer sunset, and the Durrington Walls Southern Circle (another timber circle), which is aligned on the midwinter sunrise.

History of the site: The first 'monument' at Stonehenge comprised an alignment of three Mesolithic pits (c. 8000 BC), which apparently contained huge timber posts. But the area became more heavily used from the early and middle Neolithic onwards (c. 4000–3000 BC), with the construction of a number of funerary and ceremonial monuments such as long barrows (communal burial mounds) and two long earthwork enclosures known as Cursuses.

The lengthy history of Stonehenge itself started around 3000 BC with the construction of a circular enclosure formed by a bank and ditch, and containing 56 pits known as the Aubrey Holes. Later, stones—'bluestones' dragged from distances up to 240km away and 'sarsens' weighing up to 40 tonnes—were added to the monument, culminating in the construction of the stone circle in c. 2500 BC. After the stone circle was built, many burial mounds known as round barrows were constructed, particularly on the tops of the ridge-lines overlooking Stonehenge.

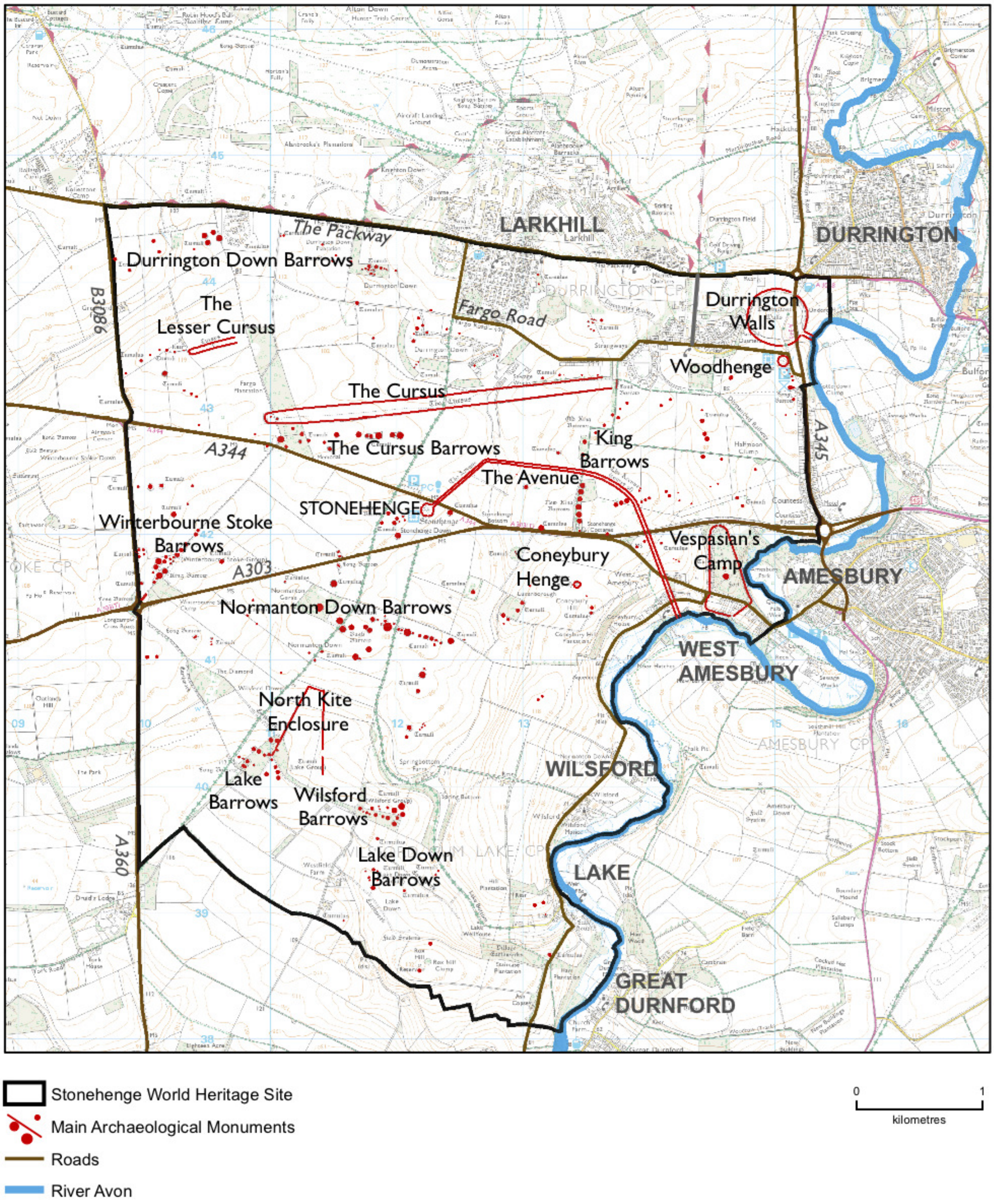

Fig. 2.1.1. Map of the Stonehenge World Heritage Site. Based on scheduled monument information from the English Heritage GIS combined with features drawn from Ordnance Survey mapping data. © English Heritage.

Fig. 2.1.2. The midwinter sunset at Stonehenge taken from the Stonehenge Avenue, and showing the solstitial axis through the monument. Photograph by James O Davies, © English Heritage (Photo Library N030018).

Stonehenge and many of other monuments remained conspicuous in the landscape during the ensuing centuries and millennia, and could hardly have gone unnoticed or ignored during all this time. However, it was only in the 18th century that the antiquarian William Stukeley (re)discovered the axial alignment of Stonehenge upon midsummer sunrise. It subsequently became, and remains, the main focus for modern celebrations at the site.

Cultural and symbolic dimension of the site: Stonehenge is one of the most famous prehistoric monuments in the world, revered and marvelled even today. It is an icon of our prehistoric past and a testament to the skills of ancient peoples. Since the 12th century, when Stonehenge was considered one of the wonders of the world by chroniclers such as Henry of Huntington and Geoffrey of Monmouth, it has excited curiosity and speculation. It has influenced generations of antiquarians, archaeologists, artists, authors, architects, historians and others, and today is an icon of ancient astronomy.

It is difficult to be precise about the uses of the WHS and the many monuments within it, particularly as they were sometimes in use for many hundreds of years. It is certainly the case that large numbers of monuments in the area have funerary associations—the long barrows and round barrows were places of burial and Stonehenge itself was used as a cremation cemetery, with the ashes of the dead placed in the Aubrey Holes. But the primary function of other monuments such as the Cursuses, timber circles and henges is more likely to have been as ceremonial centres or meeting places. Within this context, the astronomical alignments are likely to have had cosmological rather than practical significance.

Authenticity and integrity: Many of the astronomically significant monuments are now largely or wholly buried (e.g. Woodhenge). While their astronomical significance is not readily apparent on the ground, their remains are preserved underground and their authenticity is not affected. All the main elements of archaeological monuments that have astronomical significance (e.g. Stonehenge Stone Circle, Stonehenge Avenue) are well preserved given their great age, and therefore their integrity is good. The solstitial alignments have not been impaired by intrusive modern structures, with two exceptions: the relatively modern A344 road, which cuts the Stonehenge Avenue off from Stonehenge itself, and the A345 road, embanked in the 1960s, that cuts across Durrington Walls.

Documentation and archives: There are a number of important museum and archive collections relating to the WHS, most notably at Salisbury and South Wiltshire Museum and at Wiltshire Heritage Museum in Devizes, where a number of antiquarian archives are housed, along with important finds from the WHS. There are also very important collections of data in the Wiltshire and Swindon History Centre (including the Wiltshire Sites and Monuments Record), the National Monuments Record of English Heritage and The National Archives.

Present site management

Present use: The WHS is a living landscape under multiple ownership. Much of it is in private hands, and most of it is farmland. The National Trust, a national conservation body, owns 827 ha. Another part of the WHS forms part of Larkhill military garrison and is owned by the Ministry of Defence. There are also a number of private houses within the WHS at Amesbury, Durrington and the Woodford Valley.

Stonehenge itself is run by English Heritage, the UK government's statutory body for the historic environment in England, and is visited by over 900,000 paying visitors a year, not including those visiting free of charge at the summer solstice.

Protection: The Stonehenge WHS is protected as a 'material consideration' in UK planning law, and many individual elements within it are also protected. For example, there are 180 scheduled monuments which include over 415 archaeological sites and monuments within the scheduled areas, and there are also various listed buildings, registered parks and gardens, and conservation areas within the WHS.

State of conservation and main threats: The Stonehenge WHS is in a stable or improving condition. During the last decade, 520 ha of arable land (20% of the WHS) have been changed from arable land to pasture, with the help of government grants. This has directly benefited 105 archaeological monuments, which have been removed from the plough. The adverse impact of roads and traffic in the WHS remains a key issue, and does making adequate provision for managing the large number of visitors. These are being addressed by a new project, the Stonehenge Environmental Improvements Project, which aims by 2012 to close the A344 that runs beside Stonehenge, to build new visitor facilities, and to decommission the existing ones.

Context and environment: The Stonehenge WHS is surrounded to the north by the Army Training Estate Salisbury Plain (ATE SP), to the west and south by open countryside, and to the east by the town of Amesbury and Boscombe Down airfield. The ATE SP is heavily protected by its designation as a Site of Special Scientific Interest and a Special Area of Conservation, and there are strong planning laws protecting the open countryside to the south and west. The town of Amesbury has been growing fast in recent years, but planning policies prevent the WHS or its setting from being damaged. The Stonehenge WHS has no buffer zone, although this will be reviewed over the next few years.

Archaeological/historical/heritage research: Over the last decade, there has been a great deal of archaeological research at Stonehenge. Sustainable archaeological research is encouraged in the *Stonehenge WHS Management Plan 2009*, and the results of this have been very apparent. In recent years, the first Neolithic houses have been revealed by the Stonehenge Riverside Project (led by the University of Sheffield), and major new sites discovered at West Amesbury and Durrington Walls by the same team. The SPACES project (led by the University of Bournemouth) has discovered a major new Roman phase at Stonehenge, and has been researching the context of the Stonehenge bluestones. Other major research projects are also under way.

Management, interpretation and outreach: The WHS is managed by its owners and no single body has overall responsibility for the whole WHS. The *Stonehenge WHS Management Plan 2009* sets out main, agreed overall goals for managing the WHS and a Stonehenge World Heritage Committee (comprising key stakeholders) oversees this management framework. At present, there is very limited interpretation, although English Heritage is planning to build a new visitor centre at the edge of the WHS by 2012, where new interpretation and education facilities are planned.

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Case Study 2.2: Seven-stone Antas, Portugal and Spain

Presentation and analysis of the sites

Geographical position: 177 separate locations in the central Alentejo region, Portugal, and the provinces of Badajoz and Cáceres, Extremadura region, Spain.

Location: Latitude 37.8° to 39.6° N, longitude 8.2° to 7.0° W. Elevation from c. 200m to 580m above mean sea level.

General description: The seven-stone antas are a distinctive form of megalithic tomb. The 177 examples whose principal orientation can be reliably determined all, without exception, face within the arc of sunrise (the part of the horizon where the sun rises at some time during the year).

Brief inventory: Seven-stone antas are distributed over an area approximately 100km east to west, from about 50km from the coast near Lisbon to the Spanish border provinces, and a little over 200km from south to north, from Ourique to the River Tejo. The main concentrations of sites within the group are around the towns of Évora and Elvas (Portugal) and Valencia de Alcántara (Spain).

The seven-stone antas (dolmens) were mostly constructed using tall blocks of granite, typically 3m or more in height. In some areas the builders used smaller blocks of schist. Seven-stone antas are distinguished from other megalithic tombs found in the same region by the presence of a passage and by their distinctive method of construction. This involved erecting a backstone and then leaning three uprights in succession on each side so as to form a chamber typically some 4m to 5m in diameter with a clearly defined entrance to which a short passage of smaller orthostats was attached.

History of the sites: These tombs are thought to have been constructed from c. 4000 BC onwards, with longer corridors appearing around 3200 BC.

Cultural and symbolic dimension of the site: The range of orientations of the 177 monuments corresponds almost exactly to the range of possible rising positions of the sun. In other words, each tomb in the group without exception is oriented within the arc of sunrise, corresponding to about one sixth of the available horizon. In almost cases the orientations fall between azimuths of 61° (29° north of east) and 122° (32° south of east); there are two exceptions, which are oriented more towards the south (azimuth 128°–129°), but these are within a deep valley with a higher eastern horizon, and so still face sunrise. This remarkable statistic provides the strongest possible indication of an association between these tombs and the sun.

If the tombs were oriented to face sunrise on the day when construction began, then the distribution of azimuths would suggest that this took place predominantly in the spring or autumn, but the fact that orientations span the entire solar rising range implies that in some cases construction was commenced in the middle of summer or winter. The ‘exactness of fit’ between the range of tomb orientations and the arc of sunrise suggests that the tombs were aligned with a precision of about 1–2 degrees (2–4 solar diameters).

Fig. 2.2.1. The seven-stone anta at Mellizo, near Valencia de Alcántara, Spain. Photograph © Clive Ruggles.

Authenticity and integrity: A number of the examples near Valencia de Alcántara (e.g. Cajirón I, and Zafra I and II) have been reconstructed. In some cases these reconstructions raise serious authenticity issues regarding the orientation.

Present site management

Present use: Most of the sites are on privately owned farmland and only accessible to the public with the landowner's permission.

Protection: In Portugal, archaeological sites are protected by the Ministério da Cultura under Heritage Law no. 107/2001. In Spain, they are protected under Articles 14–25 of Law 16/1985 on Spanish Historical Heritage.

State of conservation: The sites are in various states of repair. Some of the Spanish examples, such as Cajirón I, have been reconstructed since their orientations were determined in the 1990s.

Main threats or potential threats to the sites: A set of small, isolated monuments in a variety of land-use situations face various potential threats, but are generally safe from the damage that might be caused by large numbers of visitors. An additional danger specific to the astronomical significance of these sites is reconstructions such as those mentioned above. If these disturb the orientation, then they could lead to misunderstandings about the individual and collective significance of these monuments.

Archaeological/historical/heritage research: Some of the tombs in both countries have been excavated. The orientations of the seven-stone antas were first systematically measured by Michael Hoskin between 1994 and 1998, as part of a 12-year fieldwork campaign measuring the orientations of many hundreds of tombs and temples in the western Mediterranean.

Management, interpretation and outreach: Most of the tombs are on privately owned farmland. Some local authorities, such as those at Évora, Castelo de Vide, Valencia de Alcántara and Cedillo, have produced booklets or pamphlets for tourists with information about the nature and whereabouts of some of the sites in their area.

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Case Study 2.3: The Stone Circles at Odry, Poland

Stanisław Iwaniszewski

Presentation and analysis of the site

Geographical position: About 2.5 km from the kashebe village of Odry (kashebe Òdrë, german Odri), commune (gmina) of Czersk, county (powiat) of Chojnice, in the southern part of the Pomorskie (Pomerania) province (voivodeship), Poland.

Location: Latitude 53º 53´ 54˝ N, longitude 17º 59´ 35˝ E. Elevation 140m above mean sea level.

General description: The "Stone Circles at Odry" Archaeological and Natural Reserve is located on the right bank of the Wda River and extends over an area of 16 ha. It contains the greatest concentration of stone circles in Poland, and was the focus of one of the pioneering archaeoastronomical investigations of the early 20th century. It later became notorious when the archaeoastronomical interpretation became used to justify nationalist claims in Germany and Poland in the years preceding World War II.

*Brief inventory***:** The reserve contains 10 completely preserved and 2 partially damaged stone circles, ranging from 15m to 33m in diameter. Each of them comprises between 16 and 29 upright boulders, whose heights range from 20cm to 70cm above ground level. Most of the circles contain 1 or 2 larger monoliths, generally placed roughly at the centre. The interior of several of the circles was covered with stone pebbles.

The stone circles form part of a huge cemetery. Within and between the circles, beneath some of the stones, and inside nearby kurgans (barrows), archaeologists have discovered no fewer than 602 burials. Most of the kurgans contain 1 to 3 inhumations.

History of the site: The site was investigated in the second half of the 19th century by two amateur archaeologists, Wilhelm Stryjkowski and Abraham Lissauer, who excavated several burials, removed some of the stones, and concluded that the remains were Neolithic in date. Paul Stephan, a geodesist from Poznan, surveyed the site in 1915 and was the first to propose astronomical alignments. Jozef Kostrzewski (Poznan University) excavations the site in 1926 and was the first to date the stone circles correctly to the 1st and 2nd centuries AD.

Stephan discovered that sightlines connecting the central stelae of 4 of the stone circles point to the solstitial points, and also identified various stellar alignments on the (false) assumption that the construction date was in the 18th century BC. He therefore proposed that the Odry circles were carefully designed so as to establish a precise calendar, needed for tribal festivities. In the 1930s, Stephan's interpretation of the Odry site was used by some Nazi archaeologists to demonstrate the supposed intellectual superiority of the Germanic tribes, and in 1940, after Germany's capture of western Poland, the site was declared a 'Germanic sanctuary' under the curatorship of the special SS unit for archaeological excavations. One of the ramifications of this was to deter serious research for many years. In 1963, the historian of astronomy Jerzy Dobrzycki demonstrated conclusively that Stephan's conclusions were undermined by Kostrzewski's chronology.

The Odry site was systematically investigated in the 1960s by an archaeological team led by Jerzy Kmiecińsk (Łódź University). Following this, the site once again became a focus for archaeoastronomical research, and in the 1970s and 1980s Mirosław Dworak, Ludwik Zajdler, Mariusz Ziółkowski, Karol Piasecki and Robert Sadowski proposed different hypotheses regarding site's astronomical alignments. Unfortunately, they never arrived at final and definite statements. In the 1990s and 2000s a new generation of archaeoastronomers have proposed that even the solstitial alignments might be fortuitous.

Cultural and symbolic dimension of the site: The Odry site is associated with the cultural activities of the peoples who created the Wielbark Culture (German Willenberg-Wielbark Kultur). This archaeological culture, which is attributed to the appearance of Goths and Gepids from Southern Scandinavia, emerged during the early years of the 1st century AD in what are now Eastern Pomerania and the Lower Vistula. They also created several other stone circle sites, including Węsiory, Grzybnica, and Leśno. In the first half of the 3rd century, the people of the Wielbark culture abandoned their settlements in Eastern Pomerania and migrated or expanded eastwards and southwards.

Present site management

Present use: The site is open to the public daily, except for Mondays, throughout the year. Well-marked routes allow tourists to approach the circles without damaging the forest. The Reserve can be reached on foot or by bicycle (using the green tourist route across the Tuchola Forest), or by kayak along the Wda River.

Protection: A state decree of 1958 declared the site a Natural Reserve in order to protect at least 86 different species of moss and lichen that were found on more than 300 hundred stones and boulders. Today it is Archaeological and Natural Reserve protected under Polish laws relating to archaeological and natural monuments and covers an area of 17 ha (delimited in the foundation decree). The site is fenced.

Main threats or potential threats to the site: Although the site is well protected, its use by various 'New Age' groups poses some potential threats. It is utilized both by groups who congregate here at the summer solstice for gatherings and rituals, and by people such as dowsers, 'bioenergotherapists' and others who believe it to be a source of cosmic energy.

Context and environment: The stone circles are located within a sparse pine forest near to the river Czarna Woda, a tributary to the Vistula. This forms part of the large Tuchola Forest (Bory Tucholskie), which covers 4789 ha (47.9 km^2) between the Brda and Wda rivers in central-northern Poland. The forest contains sand dunes, small morainal hills and narrow postglacial lakes formed after the last (Würm) glaciation. In 1996, the most scenic core of the spruce and pine forest that covers the area today was designated the Tuchola Forest National Park. It contains wild boar, fox, fallow, deer, red deer, polecat, badger, wood grouse (in the more inaccessible thickets), herons, white and black storks, eagle owls, eagles and cranes.

Management, interpretation and outreach: Tourist information and services are located in a kiosk by the site entrance. A guide service is available if requested in advance by telephone.

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Fig. 2.3.1. General views of the site. Photographs © Clive Ruggles.

Chapter 3: Pre-Columbian America

Stanisław Iwaniszewski

Broadly speaking, our understanding of indigenous astronomical knowledge in the Americas through the ages is derived from historical accounts by Spanish chroniclers, reports by ethnographers and anthropologists working among native groups during the last 150 years, several well-presented archaeological and historical sites, numerous rock-art sites and the living traditions of indigenous peoples.

North and South America

As in other parts of the world, observations of the recurrent phenomena perceived in the sky aided the development of time reckoning among all Native American groups. The methods of time reckoning used by Native Americans often consisted of a crude designation of different periods of time arranged in a definite succession. The calendars they used were not intended for recording the number of days, months or years from any particular date; they only served to mark the passage of time within the current year.

Most populations in the Americas used a lunar calendar. While all native populations doubtless used a variety of natural events and also the stars for the determination of time, the observation of the phases of the moon might well have been instrumental in shifting attention from irregular time indicators to continuous time reckoning. Generally, two types of lunar time reckoning were used: the descriptive lunar series and the astronomical lunar series. The first type refers to a series of lunations named after the events or activities that served to be synchronized with them. People kept track of the succession of lunations with their distinguishing names, but not of the number of days in one lunation or the number of lunations within one year. In several cases, however, the counting of the moons became attached to a fixed point in the year, which served to mark the beginning of the annual cycle. Some Native Americans employed landmarks to fix the place on the horizon where the solstitial sunrise or sunset occurred; such an event would be followed by a sequence of lunations, twelve or thirteen of which would pass before the sun reached the solstitial point again.

In some cases, shadows cast by, or light-and-shadow phenomena produced by, a range of natural or artificial features were employed to mark the solstices. In many places, houses made of perishable materials such as wood, cane, and hide functioned as rudimentary solar calendars, with arrangements of posts or holes allowing for the accurate determination of the solstices, dates of zenith passage, or other dates especially important for their inhabitants. Since almost nothing remains of such structures above the ground, only careful archaeological excavations can inform us about their specific alignments with the sun. Only a small number of native populations recognized the importance of the equinoxes, and this knowledge was not used in their time-reckoning systems.

Another astronomical method of reckoning the time derived from observations of the stars or planets. The (heliacal) rising of specific constellations or asterisms (most commonly the Pleiades or the stars of Orion) served to mark the beginning of the year.

The creation of order is a feature common to all Native American societies and its physical manifestations may be perceived in a wide range of material remains left by them. A common characteristic is that actions such as centring settlements, ordering dwellings and aligning burials stem from a shared knowledge of origins ('origin myths') and communal world-views that embody a variety of astronomical and cosmogonic principles. The ability to design and orient dwellings, shrines, temples, palaces or burials according to the annual movements of the sun is testimony to the knowledge of the sky possessed by many Native American groups.

While Amerindian societies had notions of days, months and even years, these were not usually clearly bounded units, and time reckoning tended to be in terms of qualitatively distinct types of recurring events. There is really no evidence that time was conceived as a uniform, abstract and continuous flow; qualitative aspects are always present in Native American notions of time. In other words, time concepts are concerned with the succession of events or the relation of these successive events with the present. There is no evidence of the development of the idea of abstract time as a dimension within which several processes may be coordinated.

Many Amerindian societies recognized the division of space into four quarters. These were usually conceived statically, based on the rising and setting positions of the sun at the solstices. The division of the surrounding world into four quadrants is a common feature of all Native American groups, up to the present (see Chapter 4). The cardinal points were (and are) not so much abstract directions as value-laden localities associated with different supernatural entities and ordering principles. Even astronomical-calendrical cycles are seen as embedded in the life-space of Native American groups, since they are often represented by a symmetrical space of cardinal (or inter-cardinal) directions modelled after the sun (and the stars).

North America

In broad terms, solstitial-lunar calendars existed among the hunters and gatherers of the Northwest, the horticultural and hunting communities within the Mississippi River valley, the agricultural groups of the Southwest, and the nomadic groups in northern Mexico. A variety of solstitial observation stations have been discovered in each of these areas.

A few claims have been made that some North American groups noted the 18.61-year (node) cycle of the moon.

The constellation of Ursa Major, the Pole Star, the belt of Orion, the Pleiades and the Hyades were known among North American communities, as were several bright stars such as Sirius, Aldebaran, Antares, Altair and Fomalhaut, together with the planets. In spite of this, most Northern American communities seem to have paid less attention to the stars, knowing the names only of a few.

Although all North American groups possessed some knowledge of the sky, in several cases specialized time-keepers or star-gazers were needed to observe the exact time of the rising of a star. Sometimes specialists were required to watch the sun. In most cases, it was the duty of a few elderly men, who represented the wisdom of a whole society, to watch the sky. In other communities the timekeepers were the priests, who used their observations of the sun or moon to determine the proper time for agricultural activities as well as for religious ceremonies. In many cases these religious officials made anticipatory observations to forecast ceremonial dates ahead of time.

Several observation stations have been recorded and described in the specialist literature. Sometimes they consisted of rock art depictions of the sky as it was perceived by native groups. These rock art representations deserve attention, since they can inform us about native constellations, asterisms, and bright stars and planets.

The starting point for counting of the days of the lunar month was the first appearance of the lunar crescent in the western sky just after the sunset. The lunar month was commonly divided into two halves, but some North American groups who used the decimal system of counting divided the lunar month into three ten-day periods. Although lunar calendar sticks and rock-art tallies are extremely rare, they nevertheless tell us about the methods used by specialized skywatchers to track the lunar cycle over larger time intervals (see Case Study 3.1).

South America

South American communities, like their North American counterparts, used the moon to reckon time. Descriptive sequences of lunations, similar to one another, are found among Amerindian societies living in the tropical forest of Amazonia and in Patagonia. However, the observation and naming of the lunar phases remained quite unsystematic. Three divisions of the lunar month were generally identified—waxing, culmination, and waning—with numerous activities being tied to them, while the period of the dark (invisible) moon was avoided.

Unlike North American groups, Amazonian and Patagonian communities frequently used constellations and asterisms to determine the time of important seasonal activities or to mark the starting point of subsistence activities. The Pleiades signalled the rainy season and the need to start clearing for planting. The stars of Orion marked the manioc season. Among other stars known in Amazonia are Sirius, Aldebaran, Capella, Castor and Pollux, the stars of Auriga, the Southern Cross, Scorpio and Centaurus. The Milky Way was particularly important, with its dark rift located near Scorpio and Sagittarius, as were the Magellanic Clouds. In short, the determination of time from the stars seems to have been much more common in South America than in North America.

Moreover, Amazonian societies often used interior light-and-shadow effects and shadow casting to determine the time of day. Their buildings were designed so that beams of sunlight could be observed moving across the walls and floors. The course followed by such beams also changed gradually from day to day, corresponding to the seasonal changes in the sun's trajectory across the sky.

Anthropological studies show that knowledge of the sky was important because of the relationship they perceived between human societies and celestial objects. Amazonian Indians perceived themselves to be a part of a universe in which humans, animals, plants and astronomical objects formed a single community, constantly intercommunicating. Astronomical objects were used to mediate between the individual and subjects of concern to all. Activities such as stargazing or time-keeping were seen as part of the collective life of the community and often used to designate individual and collective identities. Calendrical and astronomical knowledge was embedded in a variety of religious rituals, agricultural ceremonies, political discourses and world-view beliefs, and was embedded in mythological storytelling, ceremonial dances, the organization of domestic space and other social activities. Some social organizing principles may also have been derived from the material surroundings and embodied in the dwellings and burials of various American groups.

Mesoamerica

The painted codices and manuscripts of prehispanic Mesoamerica are perhaps the best examples of calendrical-astronomical speculations and computation ever made by the populations of ancient America. The Mesoamerican calendrical system is displayed in the form of many different permutations, which are usually connected to divinations; but besides tracking temporal cycles these codices are aimed at the explanation of temporal and supernatural forces that gave form and structure to the surrounding world. In a sense, they expressed the universal laws governing the world as it was then conceived. Different sections of these codices refer to astronomical observations of the planets, eclipses, computations of the tropical year, and native cosmogonies. Astronomical practices by the Maya or by the Aztecs sometimes attain the level of systematic observations and theoretical modelling of celestial movements. There is no doubt that they should be regarded as examples of non-Western systems of knowledge.

The Mesoamerican system of time-reckoning is exceptional. A period of 260 days in combination with the 365-day year cycle, producing a ‘Calendar Round’ (cycle of roughly 52 years), is a method of marking the passage of time unique in the history of humankind. So also is the vigesimal system of time-reckoning that produces the Long Count, a continuous count of the days from mythical beginnings (and is responsible for current fears that the end of the world will occur in 2012).

Our knowledge of the astronomical practices of prehispanic peoples in Mesoamerica derives from prehispanic written records as well as the other sources mentioned at the beginning of the chapter—Spanish historical reports, numerous well-preserved archaeological sites, and the living cultural traditions of indigenous populations. A number of Mesoamerican sites with important astronomical connections are already inscribed on the World Heritage List, including:

- *Pre-Hispanic city of Chichen Itza, Yucatan, Mexico, no. 483, inscribed in 1988 under criteria (i), (ii) and (iii).* A regional civic-ceremonial polity by the end of the 6th century AD. It developed towards the Late Classic and the Terminal Classic periods (roughly 10th and 11th centuries). It declined after 1221 (because of a civil war). Visitors come in considerable numbers on the day of the spring equinox.

  Archaeoastronomical elements: **El Castillo** (*Temple of Kukulcan*) which displays the equinox phenomenon**; El Caracol** (solstice sunset alignments, sunset on the day of zenithal passage, the northernmost setting position of Venus, sunset at the equinoxes, sunsets on April 29 and August 13, etc—there are multiple orientation possibilities); the **Great Ball Court** (***Temples of the Jaguar*** – pointing to the sunsets on April 29 and August 13); **Las Monjas** (pictorial representations of the Maya zodiac); **Temple of Venus** (iconographic representation of 8 solar years equalling 5 Venus cycles); etc.
- *Maya Site of Copan, Honduras, no. 129, inscribed in 1980 under criteria (iv) and (vi).*
- *El Tajin Pre-Hispanic city, Veracruz, Mexico, no. 631, inscribed in 1992 under criteria (ii) and (iv).* A Totonac ceremonial-civic polity that developed around the 1st century AD and peaked between 600 and 900.

  Archaeoastronomical elements: the **Pyramid of the Niches,** an architectural model of the world (it contains a series of 365 niches).
- *Historic Centre of Oaxaca and Archaeological Site of Monte Albán, Mexico, no. 415, inscribed in 1987 under criteria (i), (ii), (iii) and (iv).* A ceremonial-administrative centre situated on the top of an artificially-levelled ridge over the valley floor. The city was founded around 500 BC and later became the capital of a Zapotec polity that interacted with other regional states such as Teotihuacan. Largely abandoned around 900–1000 AD.

  Archaeoastronomical elements: the unusually oriented **Structure J** towards the stars of the Southern Cross and Centaurus on one side and towards the heliacal rising position of Capella on the other; vertical shaft (zenith sighting tube) of **Structure P** (for observations of the zenith passage of the sun); several astronomically oriented stelae; **Stelae 12 and 13**, with first inscriptions referring to a solar year, orientations attesting the division of a 260-day calendar into 4 minor cycles (*cocijos*) of 65 days each, etc. Examples of Zapotec hieroglyphic writing (*Danzantes* stones).
- *Pre-Hispanic City and National Park of Palenque, Chiapas, Mexico, no. 411, inscribed in 1987 under criteria (i), (ii), (iii) and (iv).* One of the most important Mayan sites, it reached its height between 500 and 750 AD.

  Archaeoastronomical elements: inscriptions referring to the conjunction of planets (Jupiter, Saturn, and Mars and the Moon) and the birth of three ancestor patron gods I, II, and III and the First Mother, in July 690; the **Temple of Inscriptions** (with the tomb of Janaab´ Pakal); the **Palace** and the **Group of the Cross**.

Fig. 3.0.1. El Caracol, Chichen Itza. Photograph © Clive Ruggles.

- *Archaeological Park and Ruins of Quirigua, Guatemala, no. 149, inscribed in 1981 under criteria (i), (ii) and (iv).*
- *Pre-Hispanic City of Teotihuacan, Mexico, no. 414, inscribed in 1987 under criteria (i), (ii), (iii), (iv) and (vi).* Founded before 150 BC and collapsed after 550 AD.

  Archaeoastronomical elements: the **Pyramid of the Sun** related to the mythical origins of the current era (on August 11–13, 3114 BC), to the dates (April 29–30, August 11–13) of the zenith passages of the sun at latitude 15° (e.g. at Izapa, Edzna or Copan in southern Mesoamerica) or to the days defining the agricultural year (February 11, October 29). Orientation pattern later diffused over the great part of Mesoamerica. Other astronomically oriented structures are: the **Avenue of the Dead,** the **Pyramid of the Moon**, the **Ciudadela** (Citadel, with calendar symbolism) and **cross-circle figures** pecked in stucco floors.
- *Tikal National Park, Guatemala, no. 64, inscribed in 1979 under criteria (i), (iii), (iv), (ix) and (x).*
- *Pre-Hispanic Town of Uxmal, Yucatan, Mexico, no. 791, inscribed in 1996 under criteria (i), (ii) and (iii).* A major Mayan centre, built between about 700 and 1100.

  Archaeoastronomical elements: the **Governor's Palace** (alignments to the Venus extreme positions, (eastward or westward), iconographic representations of the Venus cycle and of the Mayan zodiac; the **Nunnery Quadrangle** (astronomical imagery), visual relationships between the most important structures as viewed from the top of the **Adivino** (Pyramid of the Magician).

Fig. 3.0.2. The Pyramid of the Sun at Teotihuacan. Photograph © Clive Ruggles.

- *Archaeological Monuments Zone of Xochicalco, Morelos, Mexico, no. 939, inscribed in 1999 under criteria (iii) and (iv).* Developed around 200 BC and flourished between 700 and 1000 AD.

  Archaeoastronomical elements: **Temple of the Feathered Serpent** (iconographic imagery referring to hypothetical calendar reform in the 7th century AD) with calendrically significant alignments; **vertical shaft** facilitating observations of the zenith sun or moon (latitude 18º 43´); one of the **ballcourts** permits equinox observations; stelae with calendrical inscriptions; etc.

A site not on the List but worthy of mention is *Uaxactun (Waxaktun), Guatemala*. Its **Group E** is the oldest architectural complex in the Americas ever analyzed from an archaeo-astronomical point of view (in 1924).

It is also important as having become the ‘type site’ for a group of structures now known as ‘Group E structures’. These are Mayan structures of distinctive form—one western pyramid with two or three in a north-south line located to the east—that are found in the Petén and, like the one at Uaxactun itself, appear to have been associated with observations of sunrise at the solstices and equinoxes. Their importance as a group, if so, derives from the fact that some were clearly functional while others were, or became, non-functional, thus showing how actual observations may have become transformed into purely symbolic astronomy.[1]

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[1] Paragraph added by CR.

The Andean area

The various Andean populations in South America had a good knowledge of the sky, though less advanced than those of Mesoamerica. All the Andean peoples used the decimal system of time-reckoning, were able to describe various astronomical phenomena such as eclipses and the heliacal risings of Venus and the stars, and constructed temples to display alignments with the sky.

In Inca times, the *ceque* system consisted of 41 lines emanating from the Inca Temple of the Sun called Coricancha in the Inca capital Cuzco. The ceque system defined 328 sacred places (*huacas*) and it has been argued that this was associated with the use of a lunar sidereal calendar.

In several cases, observatory devices were built to permit precise sun-watching. In the region of Cuzco a pair of vertical pillars located on a ceque line was observed from Coricancha. The pillars marked the course of the sun along the horizon. Several systems consisting of standing pillars are reported in the literature, including one—Chankillo—that predates the Inca empire by some 1500 years (see Case Study 3.3).

Around the Inca empire, platforms known as *ushnus* seem to have served to symbolize the authority of the Inca in various ways, and specifically as places for performing rites related to the sun and the calendar together with sacred elements in the surrounding landscape such as prominent mountain peaks (for an example see Case Study 3.4).

Our knowledge of the astronomical practices of prehispanic peoples in the Andean region derives from prehispanic ‘written records’ (such as the knotted string devices known as khipu) as well as the other sources mentioned at the beginning of the chapter.

Central America and the Caribbean

Unfortunately, all the indigenous groups that practiced sky-watching and calendar-making in this region in the remote past have disappeared. Very little information has been left by Spanish, French, Dutch or British chroniclers and archaeological research has not been directed to the study of astronomical alignments. Today the Caribbean is populated by diverse African-American groups that are culturally connected with African traditions. This means that their astronomical lore is likely to derive from the traditions of that continent rather than from the knowledge of the indigenous American populations. Only the south Caribbean area, which is connected to the South American tradition, has received significant attention from ethnoastronomers.

The traditional skylore of the ancient Caribbean shows that important celestial events were associated with seasonal meteorological phenomena and agricultural activities. The Pleiades, Sirius and the constellations of Orion and Ursa Major appear to have been important in marking the onset of the cyclone season and the periods suitable for fishing, hunting and gathering. Unfortunately, the potential of stellar observations for the purposes of navigation has not been fully researched.

The calendar lore and astronomical activities of Central American peoples have not received adequate attention from scholars and, with just a few exceptions, have not been studied in a systematic way.

General considerations

‘Western’ scientific knowledge stems from the ‘way of knowing’ that characterised European societies from the 16th century onwards. It follows that each type of non-Western knowledge can only be reduced to the Western model (i.e., examined by those working within the Western tradition) at the cost of losing of some of its non-Western cognitive elements, traditions or frameworks of thought. Non-Western sky-lore and astronomical knowledge, from the Western perspective, are bounded by their cultural frameworks, and were not meant to transcend any regional, cultural, ethnic or national boundaries. Astronomical knowledge in non-Western America is strictly connected to numerous cultural values and should be regarded as ethnocentric rather than as an abstract and universal system. By contrast, the scientific method developed by the West is a universal method. Unfortunately, among historians of science in general and historians of astronomy in particular, the influence of positivist thought still prevails—in other words, the model of Western science provides the standard against which all other non-Western science is judged. This model of science continues to impede the development of suitable frameworks within which non-Western science can be adequately understood. Only a post-positivist orientation in the history of science can offer a proper epistemological context within which the UNESCO astronomical heritage project can be adequately addressed.

In this context it must be emphasized that Native Americans developed various systems of sky-lore, perceived different objects and events in the sky from previously chosen observation stations, encoded celestial alignments in architectural structures, and studied the solar and lunar cycles to anticipate and regulate economic and ceremonial activities. Some of those societies needed specialists responsible for watching the sky, and celestial knowledge and the art of calendar-making were used to generate and sustain relations of power and social inequality. The astronomical knowledge of Native Americans has always been bounded by culture.

The study of astronomical properties in the Americas shows that numerous celestial objects may be depicted in rock-art sites. Most of them are in the form of motifs that represent lunar crescents, sun-discs or star-like objects. Rock-art motifs are often interpreted through mythical narratives, and relate implicitly to mythological storytelling that describes the concepts of the world, including origin myths. These mythical narratives are often connected to other ceremonial activities such as dance and rituals performed on specific occasions. These are often used to present origin myths (like the famous Deer-Dance in northern Mexico) in which different stories of the birth of the sun, moon and stars are recounted. There are songs intoned to the first visible lunar crescent, to the heliacal rise of a brilliant star, and so on. This intangible heritage related to astronomy is particularly abundant in areas where very little material heritage remains, such as the tropical rain forest areas of Central America, the Caribbean, and the Amazonian and Patagonian regions (for an exception see Case Study 3.2).

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Case Study 3.1: Boca de Potrerillos, Mexico

Stanisław Iwaniszewski and William Breen Murray[3]

Presentation and analysis of the site

Geographical position: Municipality of Mina, State of Nuevo León, Mexico.

Location: Latitude 26º2´40˝N, longitude 100º38´40˝W. Elevation 700m above mean sea level.

General description: The Boca de Potrerillos site is one of the most important petroglyph sites in Mexico. It consists of more than 4000 rock boulders and rock panels containing numerous petroglyphs located on mountain slopes within an attractive landscape typical of the deserts of north-eastern Mexico.

Inventory of the remains: The site covers approximately 435 ha and the archaeological remains are distributed within three main topographical features:

a. An extended alluvial fan located on the eastern part of the site with the remains of hundreds of prehispanic hearths called *fogones* and thousands of carved lithic and grinding artifacts, which are widely dispersed on the surface.
b. Another alluvial fan located on the western part of the site with the same kinds of dispersed artefacts, but on a minor scale.
c. The eastern flank of the El Antrisco and La Zorra mountains where there are thousands of rock boulders and loose rocks, all of them covered with petroglyphs on one or more sides.

History of the site: The site was first reported in 1963, by María Antonieta Espejo, an archaeologist from the Instituto Nacional de Anropología e Historia (INAH). In the 1980s it

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[3] With notes supplied by Moisés Valadez Moreno, Regional Centre, National Institute of Anthropology and History, Monterrey, Nuevo León, Mexico.

was studied by several rock-art specialists, most notably Jon Olson, Ma. Guadalupe DeWitt and William Breen Murray. Archaeological activities were initiated in 1991 when INAH and the University of Texas at Austin started a joint ‘Boca de Potrerillos Project’, directed by Moisés Valadez Moreno, Solveigh A. Turpin and Herbert H. Eling. Archaeological investigations were continued by Valadez later. The site was officially opened in November 1995.

Cultural and symbolic dimension: The site contains different astronomical motifs in rock-art depictions showing lunar calendar tallies and displaying alignments towards the solstitial and equinoctial positions of the sun on both horizons. Some rock tallies suggest, particularly, that the lunar count was connected to the cycles of deer reproduction. The site is extremely important for studies of the use of calendars and astronomy by hunter-gatherer peoples in the past.

Documentation and archives: Scientific conclusions have been made public and disseminated through diverse publications: a book, a dozen of scientific papers published in national and international academic journals, three Licenciatura Degree theses, a mini-guidebook to the site, a video, a movie and numerous papers and conferences presented at national and international meetings.

Present site management

Present use: The site is open to the public daily between 8 a.m. and 5 p.m.

Protection: The site is on the Public Register of Monuments and Archaeological Zones. Its extent is legally defined, and marked on the ground by 10 boundary markers in form of piles of stone. It is enclosed by a mesh fence, with two entrances on opposite sides. Two permanent jobs have been created by INAH for people from the adjacent rural communities who serve as site guardians and watchmen.

Meetings were held with the local population of Potrerillos to inform them about the judicial and legal measures that protect the archaeological heritage. At present, the total site area covers 6 km^2, which mainly comprises the buffer zone, since only an area of 600×400 m^2 (24 ha) is opened to visitors. The buffer zone both guarantees protection against damage and degradation and facilitates any future archaeological investigation.

Context and environment: The site is located between two mountains, El Antrisco and of La Zorraca, forming a ‘mouth’ (*boca*) or entrance to ‘Potrerillos Canyon’. It is within one of the most beautiful desert landscapes of the Mexican north-east and contains the remains of the natural environment that was inhabited by various nomadic groups over a period of some 8000 years.

State of conservation: The environment has badly degraded recently owing to the overexploitation of the underground aquifer resources during the last 40 years to meet the water supply demands of the city of Monterrey. The degradation is exacerbated by natural desertification processes.

Archaeological/historical/heritage research: Archaeological work has revealed important material evidence attesting to the socio-economic development of local indigenous groups. The occurrence of hundreds of prehispanic hearths called fogones, together with a huge number of lithic artefacts and the thousands of images depicted in the rock petroglyphs, testify to the long-term socio-economic, cultural and ritual development of the communities who exploited natural resources and maintained ecological equilibrium in the region prior to European contact.

Management: The site is administered by INAH. A small pavilion has been built that contains a small museum room, an electric generator with an electric pump, and restrooms.

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Fig. 3.1.1. Top left: The ‘altar’. **Top right:** General view of the site. **Bottom left:** The ‘seat’, an observatory site. **Bottom right:** The Boca monolith. Photographs © Stanisław Iwaniszewski.

Case Study 3.2: Caguana, Puerto Rico

Angel Rodriguez

Presentation and analysis of the site

Geographical position: Barrio Caguana, Utuado, Puerto Rico

Location: Latitude 18°17′41″N, longitude 66°46′52″W. Elevation 310m above mean sea level.

General description: The Caguana Ceremonial Ball Courts Site is considered one of the most important archeological sites in the West Indies.

Inventory of the remains: Approximately 13 ball courts (*bateyes*) have been identified. Monoliths and petroglyphs carved by the Taínos can be seen among the rocks and stones. Some of the monoliths weigh over a tonne, and were most likely brought from the Tanama River located adjacent to the site.

History of the site: Studies estimate that the site is over 700 years old, built by the Taíno in around 1270 AD.

Cultural and symbolic dimension: The plan of the site indicates that the plazas were aligned according to specific astronomical events. The site evidently functioned as a place to observe or predict astronomical events. There are symbolic representations of astronomical objects as rock engravings on rock slabs. The cultural landscape surrounding the site (and particularly its topography of mountains and rivers) represents the cosmovision of the builders.

Authenticity and integrity: The site was found *in situ* with all the plazas in their original context. Furthermore, a plan of the site was made to help in the reconstruction.

Documentation and archives: The archaeostronomical documentation of the site is mainly related to (i) the social use of astronomy—ritual and ceremonies during astronomical events; and (ii) art and decoration represented on the rock engravings.

Present site management

Present use: The site is open to visitors as an interpretative park.

Protection: The National Park Service has placed the Caguana site on the National Register of Historic Places, and designated it as a National Historic Landmark. This means it is a monument protected under law.

State of conservation: Many of the ball courts have been restored to their original state.

Context and environment: The site is located near to the Cemí Mountain (Montaña Cemí) which was believed by the Taínos to be the home of the gods. This is the reason they built the ball courts in this area.

Archaeological/historical/heritage research: Current research related to astronomy at the site focuses on: (i) its use for astronomical observations; (ii) symbolic representations (rock art).

Management: The Institute of Puerto Rican Culture manages and maintains the site as a park called the Caguana Indigenous Ceremonial Center (Centro Ceremonial Indígena de Caguana). The park includes a small museum containing Taíno artifacts, archaeological exhibits and a botanical garden featuring the plants the Taínos harvested for food, such as sweet potatoes, cassava, corn, and yautía. Many of the trees used by the Taínos to construct their homes (*bohíos*), such as mahogany and ceiba can be seen throughout the park.

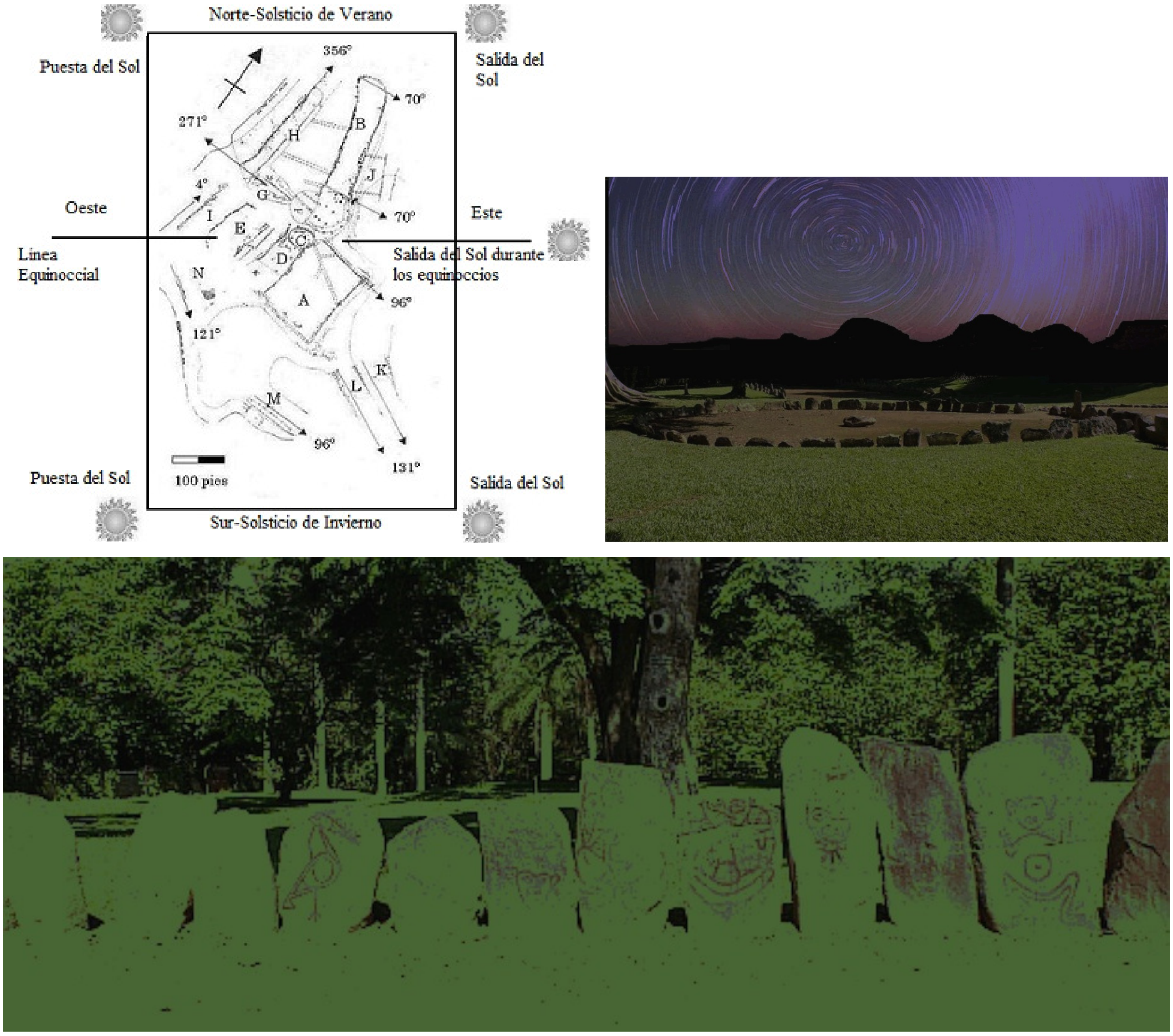

Fig. 3.2.1. Top left: General plan of Caguana. **Top right:** The view from Plaza C towards Polaris. **Bottom:** A row of stones aligned upon the equinoxes with reliefs displaying human figures. All figures © Angel Rodriguez

Case Study 3.3: Chankillo, Peru

Ivan Ghezzi

Presentation and analysis of the site

Geographical position: San Rafael, Casma district, Casma province, Ancash region, Peru.

Location: Latitude 9º 33´ 18˝ S, longitude 78º 14´ 13˝ W. Elevation 300m above mean sea level.

General description: Chankillo is a ceremonial centre with ritual, administrative and defensive attributes located in the coastal desert just outside the flood-plain of the Casma-Sechín river basin.

Inventory of the remains: Chankillo is characterized by its standing architecture, of which the principal elements are the hilltop Fortress; the solar observatory (the Thirteen Towers and observing points to the east and west; the Plaza area, with an administrative complex and several other buildings; and a geoglyph group. Prominent among the artefact collections are ceramic warrior figurines.

History of the site: Radiocarbon dates range from 350 BC to 100 BC, placing occupation in the late Early Horizon. The site appears have been dedicated to regulating seasonal events such as religious festivals and to sun worship, and possibly to maintaining a seasonal calendar through solar observations. Excavations indicate an abrupt disruption by warfare, marked by the destruction of its main temple and religious symbols, its entombment, and its abandonment. There was no significant re-occupation, save for looted burials that may date to the Early Intermediate and Middle Horizon, and an Inca offering placed at the base of a tower during the Late Horizon.

Cultural and symbolic dimension: Unlike the architectural alignments upon a single astronomical target found at many ancient sites around the world, Chankillo's Thirteen Towers span the entire annual solar rising and setting arcs as seen from the two observing points, not only giving direct indications of all four solstitial rising and setting points but also the means to identify every other day in the year by observing sunrise or sunset against the intervening towers. In this sense, Chankillo is unique worldwide as a functioning solar observatory and an extraordinary example of native landscape timekeeping.

Authenticity and integrity: Archaeological research confirms the authenticity of the standing architecture at Chankillo. It also underlines its integrity as a ceremonial centre. There is no evidence of modifications in the past or present (restoration). The Temple of the Pillars, a sacred building inside the Fortress, was partially destroyed and buried after the conflict around 100 BC. Further research is needed to confirm its full extent, in particular to the east.

Documentation and archives: A 1970 earthquake destroyed Casma, along with official records. Rosa Fung and Victor Pimentel led a research project in 1968–69 (the state of their records is unknown). The Chankillo Archaeological Project has carried out research since 2001; its documentation is stored at the Pontificia Universidad Católica del Perú in Lima.

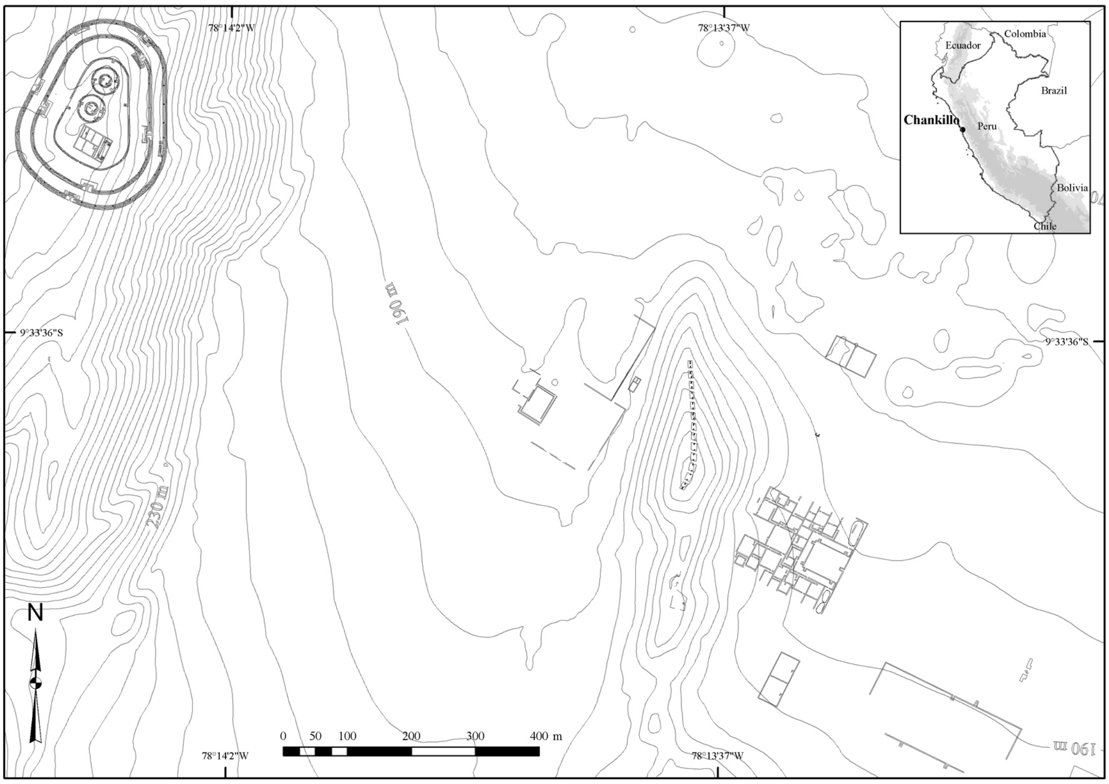

Fig. 3.3.1. Plan of Chankillo. © Ivan Ghezzi.

Present site management

Present use: Chankillo is a cultural resource in Casma province, and a site of ongoing archaeological research since 2001. It is often visited by parties from local schools and by national and international tourists; these visits have increased markedly since 2007, when the (inter)national media highlighted it as 'America's earliest observatory'. However, there is no infrastructure to manage visits. Communities in the vicinity consider it part of their cultural heritage, protect its boundaries, and keep an eye on tourists.

Protection: Chankillo is officially recognized as national cultural heritage, and its limits have been defined. It is administered by the Peruvian National Institute of Culture (INC) from local offices (Sechín Museum, Casma). Nevertheless, there is no INC infrastructure nor staff presence. Its buffer zone can only be used for the purposes approved by the INC.

State of conservation: In regard to its state of conservation, Chankillo can be subdivided into three areas: the Fortress (25% deterioration, plaster and mortar loss); the Thirteen Towers area (60% deterioration, plaster and mortar erosion, serious cracks, risk of total collapse); and the Plaza area (15% deterioration due to protective sand coverage). No conservation intervention is documented or visible. Artefacts recovered by the Chankillo Archaeological Project have received preventive conservation, and are stored at the Sechín Museum in Casma.

Context and environment: Chankillo is located in the coastal landscape of Peru, one of the world's driest desert areas, 400 km north of Lima and 15 km from the Pacific coast. Lying to the west of the Andes mountain range, this landscape of foothills, valleys, and plains has remained geologically stable for thousands of years. The site itself lies adjacent to the irrigated and fertile southern branch of the Casma-Sechin river basin, amidst rock outcrops and sand ramps, near the rugged foothills of the western slopes of the Andes. Like many other coastal valleys, the Casma-Sechin river basin has long been an 'oasis' for settlement in an otherwise inhospitable desert.

Archaeological/historical/heritage research: Chankillo was first reported by explorers Ephraim Squier and Antonio Middendorf, and naturalist Antonio Raimondi, in the late 19th century. In the early 20th century Roosevelt, Tello, Kroeber, Collier, and Thompson discussed its function and chronology. Fung and Pimentel's synthesis of their 1968–69 excavations remains the most comprehensive description of the site to date. Later, Pozorski, Topic, and Wilson reported it in their surveys. Since 2001, Ghezzi has led the investigations of the Chankillo Archaeological Project. There is a consensus on the date and function of the most significant features (the Fortress and the Thirteen Towers).

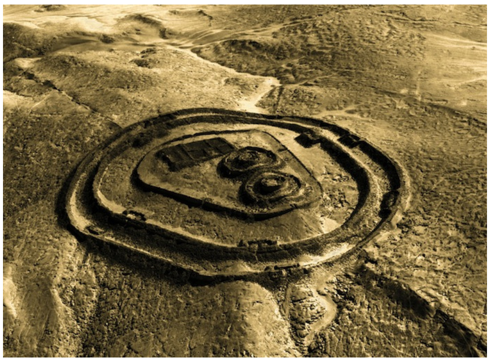

Fig. 3.3.2. Aerial view of the Fortress. Photograph © Servicio Aerofotografico Nacional, Lima.

Main threats or potential threats to the site: Chankillo is increasingly exposed to threats of cultural origin, such as the robbery of stones for use as building material, the dumping of construction debris and city rubbish, and uncontrolled tourist visits. It is also affected by the damaging action of winds, daily thermal variation, seasonal humidity and earthquakes. Wind erosion causes the loss of mortar, which weakens the stone masonry, causes cracks to appear and stones to fall, and thus brings about the gradual collapse of walls. The structural instabilities caused by these physical-mechanical flaws compound the risk of collapse due to earth tremors, a common occurrence in Peru. The general neglect of the site causes greater exposure to all the factors mentioned, and significantly increases the rate at which deterioration occurs, as does damage caused by unsupervised tourism.

Management: The implementation of a Management Plan, which will include a Master Conservation Plan, an Interpretation Centre, and outreach programs, is one of the long-term goals of the Chankillo archaeological project.

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Fig. 3.3.3. The Thirteen Towers as seen from the Fortress. © Ivan Ghezzi.

Case Study 3.4: The Metallurgical Centre of Viña del Cerro, Chile

Ricardo Moyano

Presentation and analysis of the site

Geographical position: Tierra Amarilla, III Atacama Region, northern Chile.

Location: Latitude 27º 54´ 9˝ S, longitude 70º 1´ 51˝ W. Elevation 1090m above mean sea level.

General description: Viña del Cerro is a *Diaguita-Inka* metallurgical centre dating to approximately 1400 AD. The site is located in the middle of the Copiapó river valley, or *Camasquil*, on a rocky hill at the foot of the *Calquis* Mountain, near the ancient Indian town of *Painegue*.

Inventory of the remains: The site is composed of four well-defined architectural units: a group of *huayras* (founding ovens), a control unit, a water-provisions construction, and a large plaza or *kancha* (see Fig. 3.4.2). The *kancha* or unit A, which is located on a large flat section of a rocky hill, is an area of 58.5 × 52 m constructed of mud, stone and adobe. It is composed of two architectural units: the camp and the *ushnu* platform. The platform is located on the eastern corner of the large plaza or *kancha*. It is trapezoidal in form, with a 6 m wall of mud and stone. The platform has seven steps that are 1.4 m wide, located on the east side of the south wall.

The access gates to the residential structures and the *kancha* are oriented towards the summits of two prominent mountains, Potro mountain in the south-east and Calquis Mountain to the north-east (Fig. 3.4.3). The *ushnu's* walls and diagonals are also aligned on these mountain peaks, together with the positions of sunrise on the two solstices (line segments 4–1 and 4–2 in Fig. 3.4.4). These and other alignments suggest that the platform that was part of the *ushnu,* and the access doors of the *kancha* and other structures, could have served for the creation and adjustment of a solar horizon calendar using specific mountains in the local landscape as reference points.

History of the site: In 1958 Jorge Irribarren described what for him were 'Indian constructions' and undertook the first topographical survey of this site with the help of Hans Niemeyer, who later began the first archaeological excavations at the end of the 1960s. Between 1979 and 1980, Niemeyer executed a new topographic survey of Viña del Cerro along with another archaeologist. The site was studied from the perspective of archaeo-astronomy between 2004 and 2006.

Cultural and symbolic dimension: Ushnus have been interpreted in various ways: as platforms for military parades, places where military leaders swore obedience to the Inca, places for *capac hucha* ceremonies, places where the Sapa Inca or his representatives spoke about politics and justice, podiums where local authorities carried out their responsibilities, platforms for ceremonies to fertility worship, places for astronomical observations, and centres for architectural planning in the principal provincial towns of the Inca empire.

Analysis of the orientations of the reconstructed architecture at Viña del Cerro provides strong evidence that the site—in addition its to political and administrative functions relating to accounting and to the production of copper and silver—served as a place for performing activities related to sun and mountain worship. In Viña del Cerro, the construction of a complex *ushnu* may have been a response to the Incas' need to highlight the pre-existing qualities of the place. These include landscape markers of the solstices, and the visibility of the Calquis and Potro mountains, likely considered sacred places (*huacas*).

Viña del Cerro is also connected with the 'Main Incan Trail', in its section through the Copiapó River Valley between La Puerta and Iglesia Colorada.

Viña del Cerro, with its *ushnu,* was a place that symbolized the authority of the Inca as well as Andean complementarity and reciprocity. It served as a form of ideological coercion and subordination of local groups to the solar deity and the Inca empire, through the incorporation of all potentially sacred elements from the local topography.

Authenticity and integrity: An architectural restoration was carried out in 1982 by the Institute of Archaeological Investigations and Monumental Restoration of the University of Antofagasta, Chile, under the supervision of Hans Niemeyer.

Fig. 3.4.1

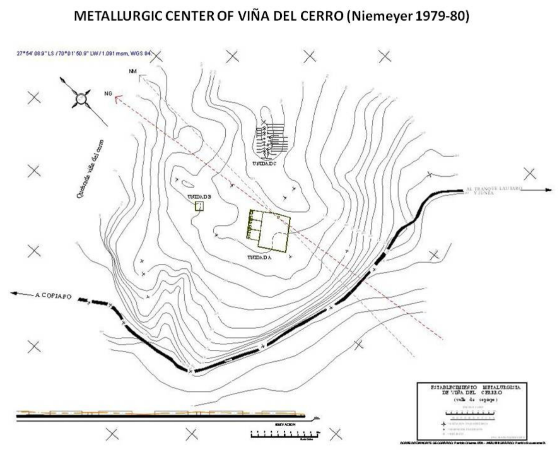

Fig. 3.4.2

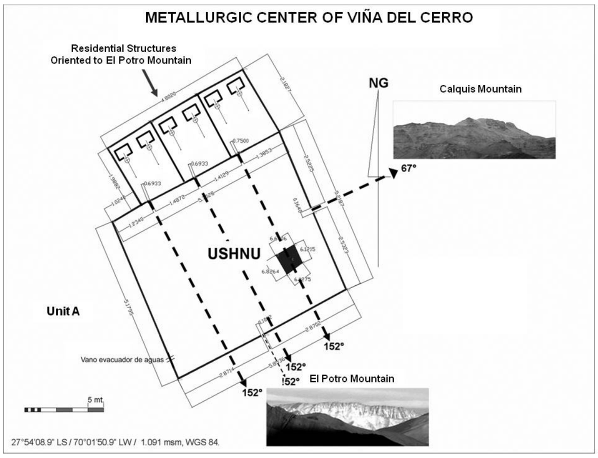

Fig. 3.4.3

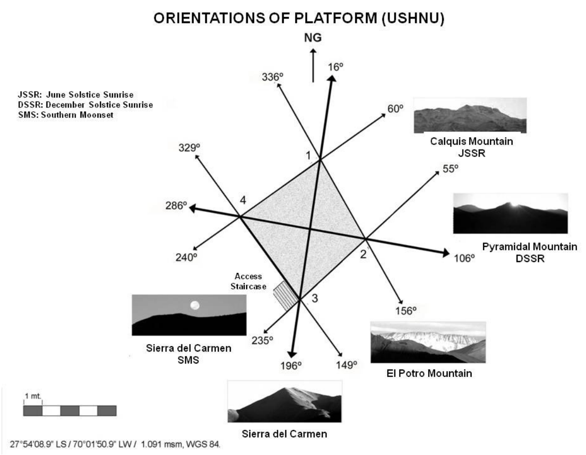

Fig. 3.4.4

Fig. 3.4.1. Location of Viña del Cerro. **Figs. 3.4.2–3.4.4.** See text. Drawings by Ricardo Moyano.

Present site management

Archaeological/historical/heritage research: Viña del Cerro is part of the World Cultural Heritage project '*Qhapaq Ñan*' (Main Andean Trail) of UNESCO and the University of Chile.

Main threats or potential threats to the site: Human disturbance and natural agents (wind, sun, and water).

Management: The site is a national historical and archaeological zone. Outreach is provided by the Atacama Regional Museum.

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Chapter 4: Indigenous Uses of Astronomy

Jarita Holbrook, Stephen McCluskey and Clive Ruggles

In one sense, all cultural uses of astronomy are indigenous, whether past or present. In practice, though, the term ‘indigenous’ is commonly taken to apply only to people outside the ‘Western’ framework of thought, given the global nature of modern science. This introduces a dichotomy that parallels the differences of approach between historians of astronomy—who tend to focus upon places, discoveries and people significant in the development of modern scientific astronomy—and those such as archaeoastronomers who generally take a more anthropological perspective, striving to recognise human achievements in their own terms and to emphasize cultural diversity.

There is no hard-and-fast boundary between practices among indigenous communities in the present or recent past and those in the more distant past. It might seem that the obvious dividing line is the existence, or not, of ethnographic evidence: evidence from ‘live informants’. However, ethnographic data does not remain current: it itself ages, and then becomes historical. The ‘ethnohistoric’ evidence of the European chroniclers who recorded the vestiges of Native American traditions shortly after the conquest is a key factor in interpreting many pre-Columbian sites in the Americas (see Chapter 3).

The existence of ethnographic data does not remove the need to consider other forms of evidence in interpreting cultural sites. Ethnographic evidence in the form of a reliable informant giving direct information about the meaning and use of a place is a virtually unattainable ideal, for a variety of reasons: some of the more obvious ones are the ethnographer’s bias in selecting what questions to ask, or not understanding the answer in their own terms because of not sharing the world-view of the informant, or not having the privilege to be given sacred information. As ethnography ages into ethnohistory, all this is compounded with additional problems of historical interpretation. Finally, if one is interested in the cultural significance and meaning of a site at some time in the past, then it is questionable how relevant the ‘living tradition’ is to the practices that defined the place at a (possibly considerably) earlier time.

In this chapter we focus on places where some element of ‘modern’ ethnography (not more than, say, two centuries old) is considered relevant to the interpretation of sites. As we shall see, this does not eliminate the sort of methodological issues inherent in the interpretation of archaeoastronomical evidence—such as the possibility of fortuitous occurrences of impressive alignments and hierophanies—encountered in the preceding chapters. Forming the most sustainable interpretation involves a suitable balance between these different types of evidence—ethnographic, historical, archaeological and statistical.

In such an interdisciplinary field of enquiry, terminology is a significant issue, since the term used can carry unfortunate and unintentional overtones. For example, if ‘observatory’ is taken to mean a place constructed for the exclusive, or main, purpose of astronomical observations then it is likely to be inappropriate in almost any indigenous context; however, the term ‘observatory’ is generally acceptable if it is taken to mean any place where astronomical observations were actually carried out (for whatever purpose). We adopt the latter meaning here. Likewise, ‘astronomy’ makes more sense in the indigenous context if it is taken in a broad sense to encompass activities, artwork, and measurements related to the sky carried out by people who would not be considered 'astronomers' in any modern sense (i.e. specialists). In this case, the term 'indigenous astronomy', or even 'indigenous astronomies', is to be preferred to 'indigenous uses of astronomy'. In what follows, we refer to 'indigenous astronomy' in this latter sense.

Examples of indigenous astronomy can be found on every continent. Mindful of the four categories of cultural property associated with astronomical heritage that were identified by the Astronomy and World Heritage Initiative at its outset (see Page 1), it is helpful to distinguish (i) physical sites that are connected to indigenous astronomy; (ii) practices and activities such as navigation that are connected to indigenous astronomy; and (iii) indigenous astronomy concepts found in oral forms and other intangible forms such as origin stories, songs, dances, and rituals, and calendars. Only the first represents fixed tangible heritage, the other two categories being intangible.

Physical sites connected to indigenous astronomy

In contrast to the observatories used for scientific astronomy, the places where people made regular observations of the night sky in an indigenous context reflect the cultural applications of those observations, such as timekeeping, setting the local calendar, or the needs of religion.

For example, the Ngas people of Nigeria follow a calendar based on regular observations of the moon. The moon is important to the Ngas and their monthly activities and agricultural activities are based on this lunar calendar. They look for the first crescent moon to appear on the western horizon every month, and their biggest festival is based on observing the first crescent moon of their New Year. The week-long festival activities include ritually cleaning their homes and their village, gift giving, and drinking 'the moon's beer'. A ceremony with the 'sons of the moon'— young boys whose faces are decorated with the full moon—involves the boys shooting arrows into the sky to kill the old moon in order for the new crescent moon to be born. The timing of their shooting the moon is precise: the first crescent moon must be sighted the next evening. If the timing is wrong, the villagers will fall ill. The priest who determines the calendar has an exact location where he stands to make the moon observations, and so there is a physical site connected to his moon-watching.

It is more challenging to interpret the evidence where traditional practices have been substantially modified, forgotten or lost, and conclusions must be derived from historical or archaeological evidence alone. For example, there is a group of Native North American sites that seem to combine petroglyphs or rock art and physical obstructions that together create light-and-shadow events marking certain days of the year. An example is the 'sun dagger' of Fajada Butte, New Mexico, USA, where a dagger of sunlight cast by a gap between two slabs of rock bisects a large spiral carving around noon on the summer solstice. Unfortunately, while there has been a lot of research on these sites, there is still debate and controversy as to whether these light and shadow events were intentionally designed by the people who constructed each site, or simply coincidence.

This sort of methodological issue has already been encountered in the preceding chapters. Similar remarks apply to the other well studied way in which places may directly reflect indigenous practices relating to astronomy: the alignment of buildings and structures upon the rising and setting positions of celestial bodies. It is generally accepted, for example, that some of the great cities of pre-Columbian America contained astronomical alignments serving purposes connected both to religious practices and political control; in many cases, observations of celestial events reinforced the divine right of the kings to rule.

Unlike the well-known and richly documented astronomical traditions of Mesoamerica, the astronomical traditions of the indigenous peoples of North America left no written historical record, a comparatively scant physical record, and only few 'astronomical' monuments. Thus archaeological records, combined with early ethnographic accounts, provide the principal evidence of these astronomies. The accounts tell us that the native peoples saw the land as sacred, and in some cases an element of this sacred landscape was the way in which it joined the Earth and the Sky. Holy places that joined the Earth and Sky sometimes memorialized celestial beings; sometimes marked the times of the planting and ceremonial calendar. Sun-watching sites were numerous: some Sun shrines, although well attested historically, are associated with living pueblo peoples and therefore, because of their current ritual uses, not available for public inspection. However, one group of sites, the star ceilings created by the Navajo (see Case Study 4.1), are not known to be subject to current ritual uses and memorialize the astronomical concerns of the Navajo.

Practices and activities that are connected to indigenous astronomy

Navigation is perhaps the most obvious example of a practice with strong connections to indigenous astronomy. Navigation by the stars, especially mid-ocean, required a good knowledge of the night sky and its daily and seasonal motions. Elements of the navigational knowledge and skills of several ethnic groups in the Pacific have been recorded in the mid- to late 20th century, including peoples in Micronesia, Melanesia, and Polynesia. In some cases navigation practices are directly linked to physical sites, such as navigation temples and voyaging stones with directional markers. They are also linked to indigenous concepts such as the ‘star compass’ of the Caroline Islands—a mental construct whereby the navigator memorises the relative rising and setting positions of about 15 stars and, at any time or place, observes those few that are actually close to the horizon and ‘imagines’ the rest.

Fig. 4.0.1. Navigation temple (*heiau*) at Holo Moana, Island of Hawai‘i, Hawaiian Islands. Photograph © Clive Ruggles.

Many other practices and activities are connected to indigenous astronomy through local calendars. Observations of celestial bodies help to regulate calendars that are also connected to the timing of planting, irrigation, harvesting and other agricultural activities on the one hand, or tied to determining the religious or ceremonial calendar on the other.

Indigenous astronomy concepts found in intangible forms

Calendars themselves are intangible concepts related to indigenous astronomy. Some have particular significance because of their unique characteristics. One such example is the calendar of the Mursi, a community of transhumant herders and cultivators from the lower Omo valley region of south-west Ethiopia. The Mursi reckoned time using lunar cycles (but also some observations of the sun and stars) in a way that, to Western sensibilities, appears haphazard but in practice 'self-adjusted' so that it was wholly fit for purpose. From a perspective that is keen to explore the diversity of indigenous astronomy the Mursi calendar is significant because it counters virtually every assumption that those who extrapolate the 'path of progress' approach too incautiously tend to make about the way in which calendars inevitably developed. Another example is the extraordinary 'luni-stellar' calendar of the Borana of southern Ethiopia and northern Kenya, which makes extensive use of the faint constellation Triangulum.

The fragility of this type of heritage is emphasized by the changes that have occurred since the Mursi calendar was recorded in the late 1960s and early 1970s, before it came into contact with external calendars.

Indigenous astronomy concepts include a range of ideas, beliefs, and understandings connected to the sky that may not be attached to a physical site. These include weather prediction; celestial deities such as solar, lunar, and stellar gods and goddesses; and 'sun kings' as an example of rulers who attribute the right to rule to a direct connection to a celestial body. Cosmological concepts may also be made real in physical structures such as the planning of cities and tombs.

Returning to the example of the Ngas of Nigeria, in addition to focusing on the moon to establish their calendar, they look at the tilt of the first crescent moon each month to determine the strength of the seasonal rains. Although there is no underlying physics to explain it (in other words, it doesn't make sense in 'our' western rationality) it is as much a part of 'their' rationality as the calendrical observations mentioned earlier. The importance of the moon to the Ngas is also expressed in the form of drawn and painted images of the moon that are found throughout their society. This includes those painted annually on the face of young boys during their new-year ceremony—another level of intangible heritage.

The 'value' of indigenous astronomy

Indigenous astronomy is a challenge for the Astronomy and World Heritage Initiative because there are often no material remains or tangible heritage associated with it, and where there is tangible heritage it is often several steps removed from the actual act of observing the sky. This makes it all the more important to try to comprehend the nature of these indirect links where they do exist.

Members of the IAU's Astronomy and World Heritage Working Group have examined the World Heritage List for sites that are connected to astronomy, including those connected to indigenous astronomy. The resulting list is shown in Table 4.0.1.[1] What perhaps stands out most is that the great majority of the sites listed do not have a connection with modern scientific astronomy or its history. In other words, most are connected to indigenous astronomy in its broadest sense (i.e. stretching back into the remote past).

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[1] It is not exhaustive: among the other sites that might be added is Strasbourg Grande Île (Case Study 11.3).

Table 4.0.1. Sites on the World Heritage List identified by the IAU Astronomy and World Heritage Working Group as having a connection to astronomy or indigenous astronomy.

Country	**Established World Heritage Site With Possible Connections to Astronomy**	
	No.	**Name**
Argentina	936	Cueva de las Manos, Río Pinturas
Australia	447	Uluru-Kata Tjuta National Park
Bolivia	567	Tiwanaku: Spiritual and Political Centre of the Tiwanaku Culture
Bolivia	883	Fuerte de Samaipata
Botswana	1021	Tsodilo
Cambodia	668	Angkor
Chile	715	Rapa Nui National Park
China	881	Temple of Heaven: An Imperial Sacrificial Altar in Beijing
China	441	Mausoleum of the First Qin Emperor
China	1003	Longmen Grottoes
China	439bis	Imperial Palaces of the Ming and Qing Dynasties in Beijing and Shenyang
China	707ter	Historic Ensemble of the Potala Palace, Lhasa
Columbia	744	San Agustín Archeological Park
Columbia	743	National Archeological Park of Tierradentro
Egypt	88	Nubian Monuments from Abu Simbel to Philae
Egypt	86	Memphis and its Necropolis - The Pyramid Fields from Giza to Dahshur
Egypt	87	Ancient Thebes with its Necropolis
Ethiopia	12	Tiya
Ethiopia	15	Aksum
France	83bis	Palace and Park of Versailles
France	85	Prehistoric Sites and Decorated Caves of the Vézère Valley
Greece	392	Temple of Apollo Epicurius at Bassae
Greece	595	Pythagoreion and Heraion of Samos
Greece	530	Delos
Greece	941	Archaeological Sites of Mycenae and Tiryns
Greece	517	Archaeological Site of Olympia
Greece	491	Sanctuary of Asklepios at Epidaurus
Greece	393	Archaeological Site of Delphi
Greece	404	Acropolis, Athens
Guatemala	64	Tikal National Park
Guatemala	149	Archaeological Park and Ruins of Quirigua
Honduras	129	Maya Site of Copan
India	246	Sun Temple, Konârak
India	243	Ellora Caves
India	244	Elephanta Caves
Indonesia	592	Borobudur Temple Compounds
Ireland	659	Archaeological Ensemble of the Bend of the Boyne
Iran	114	Persepolis
Italy	787	The *Trulli* of Alberobello
Italy	94	Rock Drawings in Valcamonica
Italy	829	Archaeological Areas of Pompei, Herculaneum and Torre Annunziata
Italy	831	Archaeological Area of Agrigento
Kenya	801bis	Lake Turkana National Parks

Korea	977	Gochang, Hwasun and Ganghwa Dolmen Sites
Lebanon	294	Baalbek
Mali	119	Timbuktu
Mali	516	Cliff of Bandiagara (Land of the Dogons)
Malta	132bis	Megalithic Temples of Malta
Mexico	714	Rock Paintings of the Sierra de San Francisco
Mexico	415	Historic Centre of Oaxaca and Archaeological Site of Monte Albán
Mexico	791	Pre-Hispanic Town of Uxmal
Mexico	414	Pre-Hispanic City of Teotihuacan
Mexico	483	Pre-Hispanic City of Chichen-Itza
Mexico	411	Pre-Hispanic City and National Park of Palenque
Mexico	412	Historic Centre of Mexico City and Xochimilco
Mexico	631	El Tajin, Pre-Hispanic City
Mexico	939	Archaeological Monuments Zone of Xochicalco
Mexico	1061	Ancient Maya City of Calakmul, Campeche
Norway	352	Rock Art of Alta
Peru	548	Río Abiseo National Park
Peru	700	Lines and Geoglyphs of Nasca and Pampas de Jumana
Peru	274	Historic Sanctuary of Machu Picchu
Peru	273	City of Cuzco
Peru	330	Chavin (Archaeological Site)
South Africa	985	uKhahlamba / Drakensberg Park
Sudan	1073	Gebel Barkal and the Sites of the Napatan Region
Sweden	557	Rock Carvings in Tanum
Syria	23	Site of Palmyra
Togo	1140	Koutammakou, the Land of the Batammariba
Turkey	448	Nemrut Dağ
United Kingdom	373bis	Stonehenge, Avebury and Associated Sites
United Kingdom	795	Maritime Greenwich
United Kingdom	514	Heart of Neolithic Orkney
USA	27	Mesa Verde National Park
USA	353	Chaco Culture
USA	198	Cahokia Mounds State Historic Site
Uzbekistan	603	Samarkand – Crossroads of Cultures
Zimbabwe	306	Matobo Hills
Zimbabwe	364	Great Zimbabwe National Monument

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Case Study 4.1: Navajo Star Ceilings, USA

Stephen McCluskey and Von Del Chamberlain

Presentation and analysis of the sites

Geographical position: 'Four corners' region, States of New Mexico, Arizona, Colorado and Utah, USA.

Location: Latitude 35º 5´ to 37º 17´ N, longitude 109º 36´ to 105º 56´ W. Elevation c. 1500m to 2500m above mean sea level.

General description: Star ceilings are scattered throughout the Navajo region. They consist of clusters of stars painted or stamped on the overhanging ceilings of natural rock shelters. Each star in the pattern is depicted as an equal-armed cross, in black, red, or white or occasionally in orange, yellow or green. These characteristics distinguish star ceilings from depictions of stars on vertical rock faces and from star images incised or drilled into the rock. The star ceilings vary in detail from a single star to a cave ceiling filled with the imprints of several hundred stars.

Inventory of the remains: Eighty sites have been identified so far: about 66 percent of these are concentrated in the Canyon de Chelly National Monument, 15 percent in the original *Dinétah* heartland, and the remainder widely scattered throughout the four-corners region.

History of the sites: The Navajo (or *Diné*) were originally a Southern Athapaskan—or Apachean—people and are relative newcomers to their current homeland in the four corners region, where the states of New Mexico, Arizona, Utah, and Colorado meet. The exact date of their arrival in this region is uncertain, with scholarly estimates ranging between 1000 and 1525 AD. During this period of settlement the Navajo interacted with their puebloan neighbours and came to exchange many traditions with them. By the 16th century, Spanish explorers had already described them as a semi-sedentary people who hunted and raised maize and other crops in the *Dinétah* region south of the San Juan River in what is now Northern New Mexico. In addition to maize-based agriculture, they acquired from the pueblos a cosmology based on the association of colours with the four directions, and particularly with sacred mountains at the cardinal points, while the Navajo are said to have contributed their characteristic depiction of four-pointed stars to their puebloan neighbours.

Cultural and symbolic dimension: Star ceilings document the Navajo interest in the stars. Navajo astronomy differs substantially from that of their puebloan neighbours : unlike the puebloan peoples, who developed an astronomy centred on observations of the changing places of sunrise and sunset against the local horizon, Navajo astronomy was primarily stellar, marking the seasons by the changing appearances of the starry sky at different times of the year. The Navajo thus developed an extensive knowledge of constellations and commemorated these stellar patterns in mythology, ritual, and a wide range of ceremonial artefacts.

Despite early attempts to identify specific constellations in these star ceilings, subsequent investigations have found no convincing evidence that actual star patterns are displayed in the star ceilings. In other words, these stellar patterns do not depict specific identifiable Navajo constellations but are representations of a generic starry sky.

Present site management

Present use: These sites are not generally recognized as visitor attractions.

Protection: Those sites on tribal and federal lands are protected by the Antiquities Act of 1906 (16 USC, §431–433), the Archeological and Historic Preservation Act (16 USC, §469-469c) and Federal Regulations on the Protection of Archaeological Resources (43 CFR 7); sites on Navajo lands are additionally protected by the Navajo Nation Cultural Resources Protection Act (19 NNC 1001 *et seq.*); sites within the National Parks and Monuments are further protected by the Park Service's Cultural Resource Management Guideline (NPS 28); and sites on private lands are protected by the National Historic Preservation Act of 1966 (16 USC, §470 *et seq.*).

State of conservation: Most of the sites are intact and well-preserved, sometimes because of their isolated location and limited public knowledge of them, others because they are physically located in National Parks and Monuments.

Main threats or potential threats to the sites: Because of the simple nature of their iconography, they have not been as threatened by collectors as have more artistically attractive rock art. Nonetheless, some isolated sites have been vandalized by graffiti and effort is needed to further preserve them.

Management: The star ceilings are on land under many different and overlapping jurisdictions. The vast majority of them are on Navajo tribal lands; many are in National Parks and Monuments; others are on Federal Lands (chiefly under the Bureau of Land Management), and a few are on private lands.

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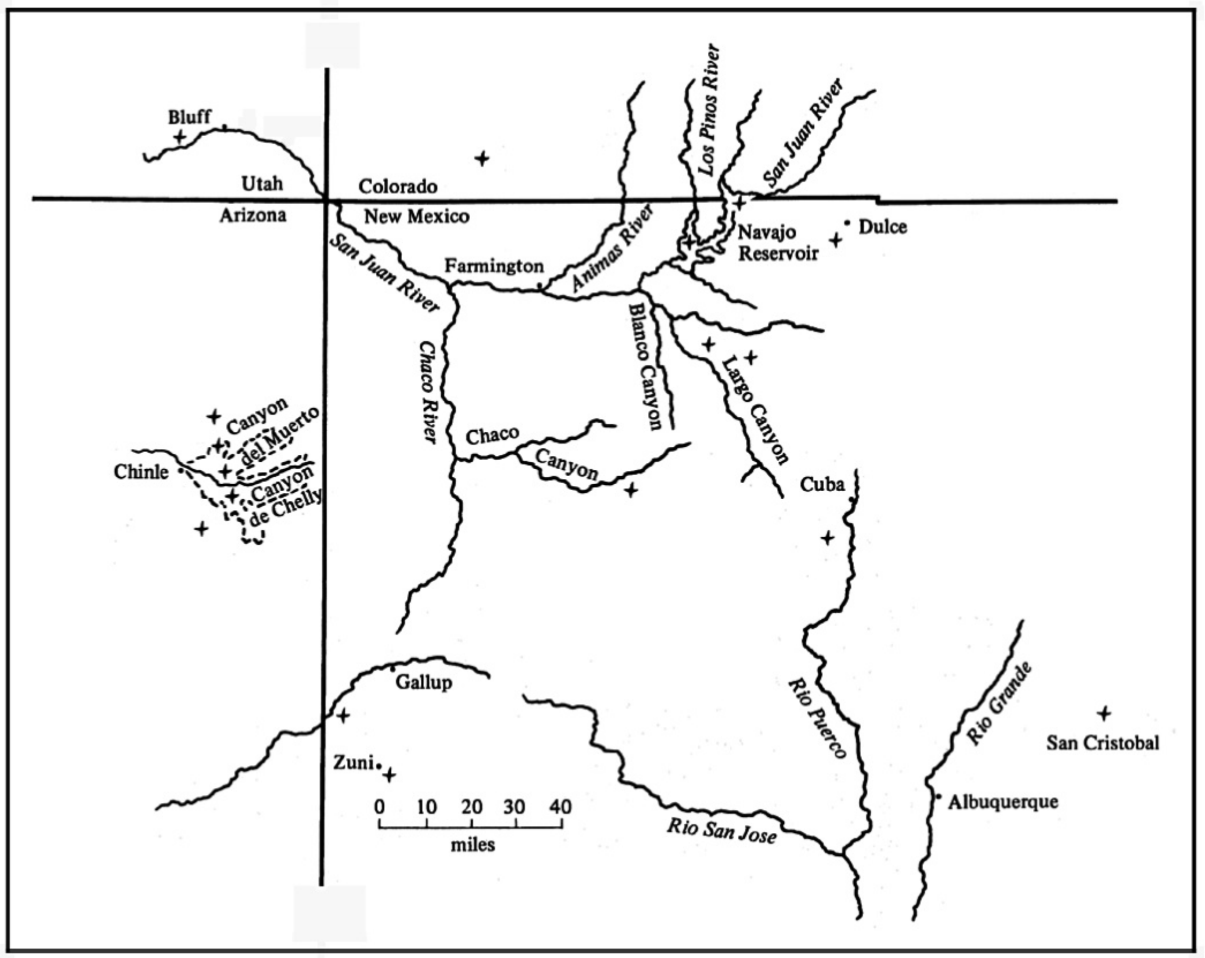

Fig. 4.1.1. The geographical distribution of star ceiling sites.

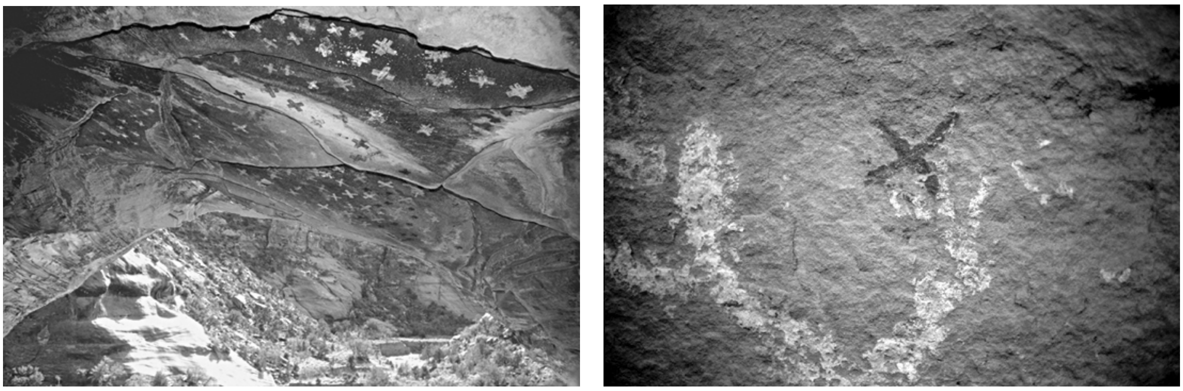

Fig. 4.1.2. Left: Many Stars Site; Middle Trail Canyon. **Right:** Single Star, Red Star Ceiling; Slim Canyon. Photographs © Von Del Chamberlain.

Case Study 4.2: Atituiti Ruga, Mangareva, French Polynesia

Clive Ruggles

Presentation and analysis of the site

Geographical position: Atituiti subdistrict, Rikitea district, Island of Mangareva, Gambier Archipelago, French Polynesia.

Location: Latitude 23º 7´ 58˝ S, longitude 134º 58´ 14˝ W. Elevation 90m above mean sea level.

General description: The plateau of Atituiti Ruga occupies the southernmost part of the island of Mangareva, between the coastal plain (Atituiti Raro) to the south and the peak of Auorotini (Mount Duff) (441m) behind sheer cliffs to the north. There are extensive settlement remains on the plateau, including a large platform identified locally as Te Rua Ra ('the pit of the sun'). The archaeoastronomical data confirm ethnohistoric accounts extending back to the mid-19th century showing that the platform was a key location used for solstitial observations that helped to calibrate the lunar calendar, determine the transitions between the two main seasons of the year, and to make predictions about the coming year's breadfruit harvest.

Inventory of the remains: The Atituiti Ruga plateau contains numerous structures including terraces, walls, platforms, and upright stones. The largest structure, 190-06-ATU-1A, is a stone-faced, earth-filled platform, broadly rectangular in form, with sides c. 23m long, aligned in the cardinal directions. It has clear views out over the Mangareva lagoon to the east, south and west, and sheer 200m-high cliffs to the north, rising up to the peak of Mount Duff.

History of the site: Radiocarbon evidence suggests that the platform was constructed around AD 1450. Traditions describing its use for solstitial observations were first recorded by Catholic missionaries in the mid-19th century, so such observations may have continued right up until traditional practices were abandoned following European contact. As observed from the platform, the cliff of Ana Tetea on the northern end of Agakauitai Island, clearly visible beyond the lagoon, marked the position of sunset on the December (summer) solstice. There was also a clear view out to reefs that may have marked the position of sunrise on the same day. A flat boulder in the centre of the platform may well have marked the exact observing spot. The shadow cast by the peak of Mount Duff to the north passed across the platform around noon on days around the June (winter) solstice, and informants' accounts refer to a stone being set up to mark the farthest limit reached by the shadow on the solstice itself.

The ethnohistoric evidence also attests to the former existence of other specific observing sites from which Margarevans not only observed the range of rising positions of the sun over the islets of the outer reef to the east but also indicated the limits of the sun's course using man-made markers—pairs of stones set up on mountain ridges.

The plateau fell into disuse and became thickly overgrown. The platform remained undocumented until 2001, when it was rediscovered by an international archaeological survey and excavation team.

Fig 4.2.1. Island of Mangareva, Gambier Archipelago: view from the lagoon showing the plateau with Mount Duff and its cliff behind, and Mount Mokoto further away on the right. Photograph © FRED at fr.wikipedia, Creative Commons Licence

Cultural and symbolic dimension: There is a good deal of ethnohistoric and linguistic evidence for the existence throughout Polynesia of local variants of a calendar based on the phase cycles of the moon and divided into two main seasons marked by the heliacal and acronychal rising of the Pleiades. In contrast, there are only a few records of ancient Polynesians using systematic observations of the rising or setting position of the sun to mark the seasons, and virtually no actual sites reliably identified where such observations took place. The platform at Atituiti Ruga is exceptional in being the only surviving structure known unequivocally (from both ethnohistoric and archaeological/archaeoastronomical evidence) to have been used for systematic solar observations in Polynesia prior to European contact.

Documentation and archives: The practice of solstitial observation was witnessed by the Belgian missionary Honoré Laval and recorded in an unpublished manuscript started in 1856, never completed, rediscovered in 1936 in the Archives of the Maison des Pères des Sacrés-Coeurs in Braine-le-Comte, Belgium, and eventually published by the Bishop Museum in Honolulu, Hawaii in 1938. This account describes several aspects of Te Rua Ra in Atituiti district, one of the most important locations where such observations were carried out, including detailed descriptions of foresights. In 1934, the ethnologist Te Rangi Hiroa (Sir Peter Buck) acquired further information from native informants and written accounts, including that observations were made from a flat rock. In 2001, elderly local informants identified the vicinity of the platform as bearing the toponym Te Rua Ra.

Authenticity and integrity: The fact that, as seen from the platform, Ana Tetea cliff does indeed mark December solstice sunset, and the shadow of the summit of Mount Duff does indeed mark noontime on the June solstice, identifies 190-06-ATU-1A beyond any serious doubt as the solstitial observing site described by Laval and Hiroa. The surviving memory of the Te Rua Ra toponym, and the presence of a flat rock in the centre of the platform, in accordance with Te Rangi Hiroa's description, provide corroborating evidence.

Present site management

Present use: Numerous monumental stone structures in Mangareva, including several temples (*marae*), are known to have been dismantled or destroyed by French missionaries in the nineteenth century, the stone being reused in other buildings. Owing, presumably, to its comparative isolation, many structures on the Atituiti Ruga plateau survived. The plateau is largely covered today in dense high vegetation including Java plum and other non-indigenous trees, but much of the eastern façade of the Te Rua Ra platform has been damaged in the last ten years during the construction of a nearby road.

Protection: The sheer cliffs rising up to Mount Duff, and a steep bluff descending sharply down to the coastal plain, provide natural barriers to the north and south respectively.

State of conservation: The site appears to have been largely, if not completely, neglected since traditional practices were abandoned. The horizon in the direction of December solstice sunrise is currently obscured by high vegetation.

Archaeological/historical/heritage research: The island was studied in 1934 by the Polynesian archaeologist K.P. Emory, but the structures on the Atituiti Ruga plateau went unrecorded. An archaeological survey of the area, including test excavations, was carried out by an international team between 2001 an 2003.

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Case Study 4.3: Wurdi Youang, Australia

Ray Norris

Presentation and analysis of the site

Geographical position: Near the village of 'Little River', between Geelong and Melbourne, Victoria, Australia.

Location: Latitude 37º 52′ 30″ S, longitude 144º 27′ 28″ E. Elevation 80m above mean sea level.

General description: The Wurdi Youang site is one of a number of stone arrangements known in the state of Victoria that were built by Aboriginal people before European settlement. It is on land traditionally owned by the Wathaurong Aboriginal people and may be an initiation site.

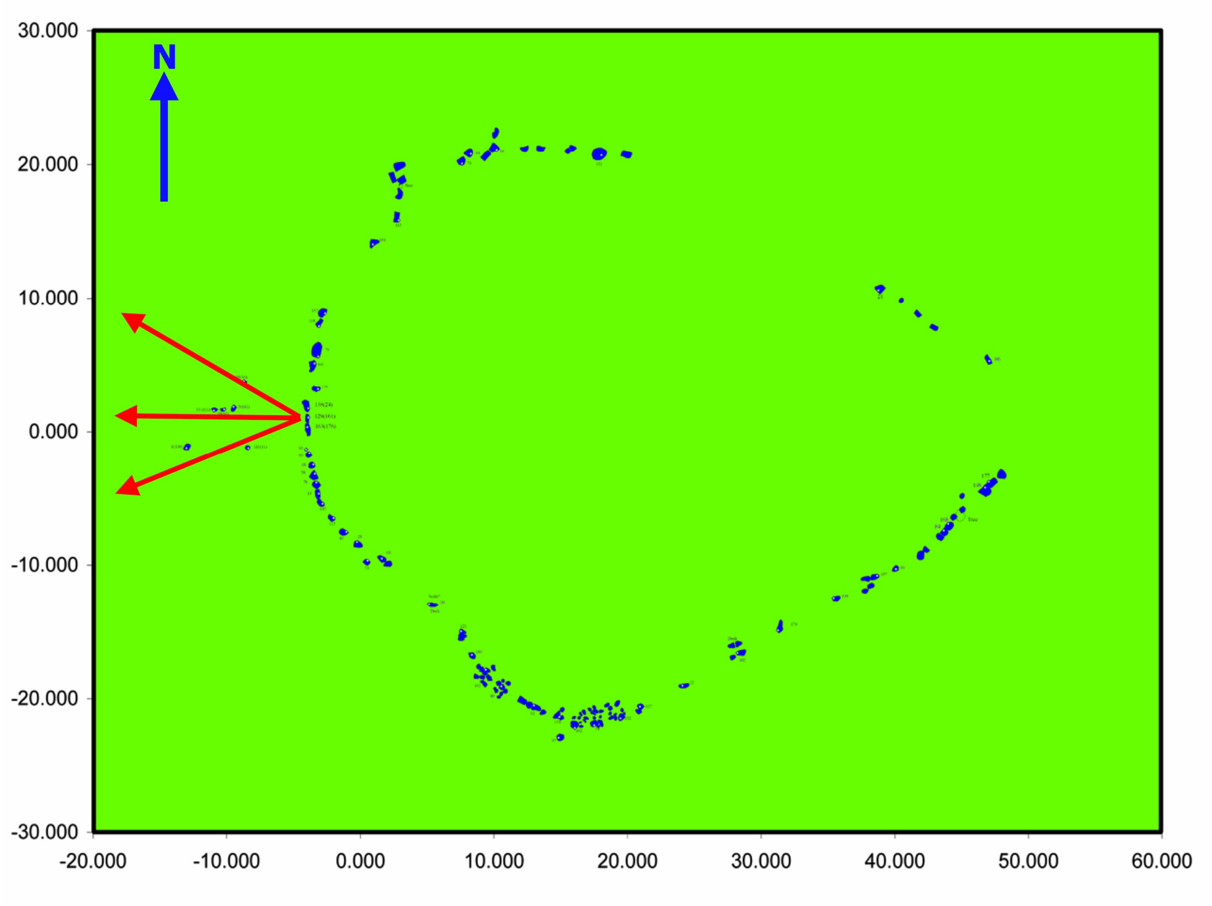

Fig. 4.3.1. Plan of the Wurdi Youang site showing the solstitial and equinoctial alignments from the westernmost stones. The scales are in metres. © Ray Norris.

Its construction date is unknown, and could be anywhere in the range c. 25000BC to about 1835AD. All records of its use have disappeared. Archaeoastronomical surveys indicate that it was related to observations of the changing setting position of the sun on the western horizon.

Inventory of the remains: The Wurdi Youang Aboriginal stone arrangement, also known as Wada Wurrung and the Rothwell Archaeological site, consists of a roughly egg-shaped circle, about 50m in diameter, of about 100 basalt stones. The stones range from small rocks about 20cm in diameter to standing stones about 1m high—some of which appear to be supported with 'trigger stones'—with an estimated total mass of about 23 tonnes.

The three largest stones in the circle are placed together at the western end, from which a number of small outlying stones indicate the setting position of the Sun at the solstices and at the Equinox, to an accuracy of a few degrees. The straight segments on the north-east and south-east sides of the ring also indicate the sun's setting points at the two solstices when viewed from the eastern apex of the ring.

History of the site: The area has been occupied by the Wathaurong hunter-gatherer Aboriginal people from about 25000 BC until their culture was destroyed in about 1835. Since then, the area has been farmed by European settlers, although the Wurdi Youang site itself has been untouched.

Cultural and symbolic dimension: Aboriginal cultures have long been neglected, and until the last few decades there were systematic attempts by the European majority to suppress them (e.g. children were punished for speaking their indigenous language in school). That repression has thankfully largely disappeared, and both Indigenous and non-Indigenous groups are now working to consolidate and rebuild the indigenous cultures. While Aboriginal

Fig. 4.3.2. The view to the west from the westernmost part of the circle, including the three largest stones. Photograph © Clive Ruggles.

art, music, and dancing are well known, only recently has attention been paid to other aspects of indigenous culture, such as astronomy. The study of astronomy in Aboriginal cultures is in its infancy, but there has been much interest in it both from indigenous and European groups, resulting in a great deal of media coverage and related activities.

Alignments in the cardinal directions are common among stone arrangements in Victoria, which implies that the Wurdi Youang alignments are not fortuitous.

Authenticity: The site is classified as an Aboriginal Heritage Site by the relevant department in the State government, Aboriginal Affairs Victoria. This is based on the fact that:

- similar stone arrangements are known elsewhere in Victoria, although none exactly resembles Wurdi Youang;
- the stone arrangement is on a property that has been owned by one family since first settlement, and the family tradition rules out a European origin; and
- the arrangement has no known counterpart among colonial structures. It is on rocky ground with no commercial or agricultural value, and it would not have been suitable for defining the boundaries of a sheep dip, sheep pen, or cattle dip. There is no evidence that it ever formed part of a fence or building.

Integrity: Some stones may have been removed, but in general the site is probably in a similar condition to when it was last used by the Wathaurong people in about 1835.

Documentation and archives: Aboriginal Affairs maintains a site register, which includes all known accounts of the site.

Present site management

Present use: Wurdi Youang is situated in rural agricultural land, with unadvertised public access to the stone configuration. There is no current agricultural or other use of the land at the site, but arable farming takes place within 50m.

Protection: Wurdi Youang is a protected Aboriginal Heritage site. The ‘tradition owners’ are the Wathaurong Aboriginal Cooperative Limited.

Fig. 4.3.3. The view to the west from the eastern side of the circle, showing the solstitial alignment of the straight sections. Photographic and graphic © Ray Norris.

Archaeological/historical/heritage research: The existence of a tangible astronomical connection at the site was recognised by John Morieson in the 1990s, and has been recently confirmed by archaeoastronomical surveys by Ray Norris and others.

Main threats or potential threats to the site: There are no obvious threats at present, but the imminent publication of its astronomical significance introduces potential threats from vandalism if the site receives publicity.

Outreach: There are no interpretative signs at present at the site.

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Chapter 5: Ancient and Medieval Far East

Ancient and Medieval China *by Shi Yun-li*

Geologically, China occupies a large and central position in East Asia. It is one of the first places in the world where agricultural civilization originated, and it remained an agriculture-dominated culture until the end of the imperial period in 1912. For this reason, Chinese people became keen observers and worshippers of celestial phenomena from very early times. For them, these phenomena high above were mandates from Heaven *tian* (天), revealing sacred regulations and admonishments important not only for their agricultural economy but also for all social activities centred upon this economy. They called the regular motions and cycles of the celestial bodies Calendrical Phenomena *lixiang* (历象), and the general astronomical and meteorological sky, as well as any occurrences in this sky, Heavenly Patterns *tianwen* (天文). For Calendrical Phenomena they developed and continued to improve systems of Calendrical Method *lifa* (历法) as a way to describe and predict the motions of the sun, the moon and the five major planets and thus to regulate economic, political and even daily activities in accordance with the rhythm of the heavens. In the meantime, vigilant eyes were kept on Heavenly Patterns in order promptly to discover any omens and portents meaningful to the rulers. This gave rise to the two core branches of traditional Chinese studies of Heaven which, in modern terms, can be portrayed roughly as calendrical astronomy and astrology.

These two branches of heavenly studies helped give rise to two central concepts of traditional Chinese philosophy, the Uniformity of Heaven and Man *tianren heyi* (天人合一) and the Sympathy between Heaven and Man *tianren ganying* (天人感应), which support the idea that Man and Heaven are made of and connected with the *qi* (气), a kind of ether or pneuma, and therefore influence each other. The ancient Chinese created a sophisticated system of rituals founded on these concepts, which constituted the ideological cornerstone of their politics and administration. The system consisted of a series of activities and ceremonies carried out by various official institutions devoted to calendrical astronomy, sky-watching, astrology and celestial worship. It continued uninterrupted for thousands of years from the origin of Chinese civilization, leaving behind an abundant succession of cultural heritage, including a number of heritage sites. These attest to the long and continuous evolution of an extraordinary tradition of cultural astronomy.

Documentary evidence for the existence of this ritual system and its institutional basis can be traced back to the first Chinese dynasty Xia (夏), from the 23rd to the 17th century BC, as recorded in *The Book of Documents*, or *Shujing* (书经). This is a Confucian classic believed to have been composed between 550 and 200 BC but which incorporated materials from very early times. The first article, “The Canon of Yao”, contains a lengthy description of how Yao, an ancestral king of the Xia dynasty, ordered the brothers Xi (羲) and He (和) “reverently to conform themselves to august heaven, to calculate and plot the sun, the moon, the stars and the celestial houses, and respectfully to submit a calendar for humankind”. The brothers Xi and He then went in four directions and used four constellations as indicators of the approach of the equinoxes and solstices. The Small Calendar of the Xia, or *Xia xiaozheng* (夏小正), now preserved in the Confucian classics, is believed to be a calendar of the Xia dynasty. The book not only describes the celestial and biological-meteorological phenomena that indicate each month, but also the agricultural and social activities that should be carried out in each month.

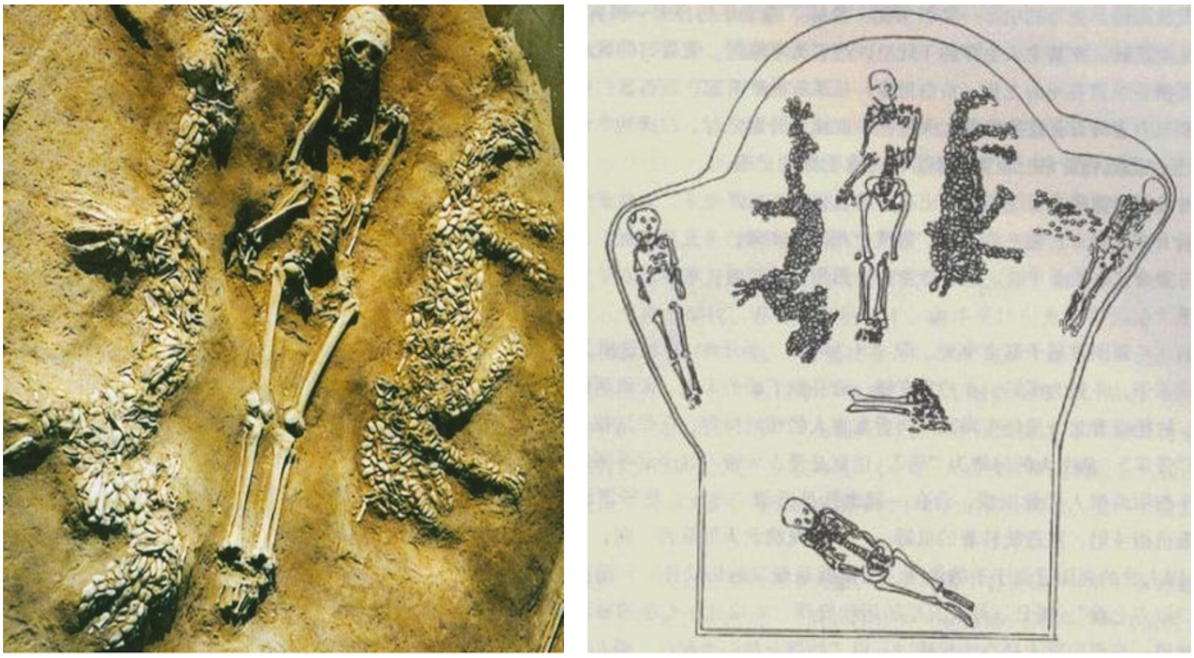

Fig. 5.0.1. The Tiger and Dragon Grave from Puyang. © Authorised for non-profitable use

Archaeological discoveries have confirmed the special role of astronomy in the early history of Chinese civilization. In 1988, a tomb dating to 4000 BC was excavated in Puyang County, Henan province. Its occupant was surrounded by a group of figures made up of clam shells: a dragon to the east, a tiger to the west, and a ladle to the north. Archaeologists believe that this configuration is a representation of the Chinese sky developed between 770 BC and 221 BC: the ladle represents Ursa Major, a major constellation in the circumpolar region; the dragon is the eastern asterism Blue Dragon; and the tiger the western asterism White Tiger.

During the 1970s, archaeologists excavating at Juxian, a late Neolithic site (Dawenkou Culture) in Shangdong province dating from 4040 to 2240 BC, unearthed some pottery decorated with a special symbol. Since then, pottery with the same symbol has also been found at contemporary sites nearby, as well as the Yuchisi site in northern Anhui province. Archaeologists differ in their interpretations of the symbol's exact meaning, but its connection with celestial phenomena is undisputed.

Fig. 5.0.2. The special symbol on the pottery from the Juxian site. © Authorised for non-profitable use

In 2003, archaeologists excavated a sacrificial area at Taosi (see Case Study 5.1), a site in the southern central part of Shanxi province, which is now known to be a large city of about 3.0 km^2 surrounded by a long wall, dating to between 2300 and 1900 BC. A terrace with three concentric semi-circular levels built from rammed earth, which forms the main part of the sacrificial area, seems to have been an altar. On the rims of the innermost two terraces are 13 small, rammed earth blocks (one rectangular and twelve square) which archaeologists believe to be the foundations of 13 pillars. When viewed from an observing point close to the centre of the altar, the 12 gaps between the pillars created a set of special alignments with the skyline, which is formed by a chain of distant mountains. Calculations and experimental observations indicate that 4000 years ago the sun would have risen in the northernmost slot at the June solstice, and in the slot next to the southernmost at the December solstice. This means that the altar could also have functioned as an observatory.

During the second Chinese dynasty *Shang* (商), between the 18th and 12th centuries BC, astronomical rituals became more sophisticated. Oracle-bone inscriptions that have been discovered since the end of the 19th century contain valuable information in the form of calendar tables and records of celestial phenomena such as eclipses and the names of stars. The calendar was now based more upon mathematical rules than upon direct observations as had been the case in the Xia dynasty. Instruments such as gnomons and clepsydrae are believed to have been widely used for observations and time-keeping.

From at least the time of the Zhou dynasty (mid 11th century to 256 BC), astronomical rituals became wholly controlled by the central government. The emperors named themselves the Son of Heaven, or *tianzi* (天子), and the rituals became a symbol of their authority. This meant that only the emperor had the right to maintain the institutions responsible for astronomical rituals, and in particular the Platform for Heavenly Communication, or *lingtai* (灵台), an observatory for sky-gazing. According to the political geography of the time, the territories of the emperor formed the whole world under heaven, or *tianxia* (天下), and the capital, the seat for the Son of Heaven, including his Platform for Heavenly Communication, had to be built in the centre of this world. In consequence, the initial task for 'political astronomy' was to determine where the centre was. In Dengfeng County, Henan province, is a site called Duke Zhou's Terrace for Gnomon Measurement, or *Zhouggon ceyingtai* (周公测影台). Historical records assert that this was centre of the world as determined from gnomon observations by Duke Zhou, a founding duke of the Zhou dynasty. For this reason, the site became a sacred place and remained so throughout the later history of Chinese astronomy. A monumental stele was erected here in AD 723 by an astronomical official of the Tang dynasty (AD 618–970) (See Case Study 5.2).

The institutional control of astronomical rituals established during the Zhou dynasty became the norm during all the later Chinese dynasties. Each of them maintained a similar system centred on an official observatory, although this was not always located at the place considered to be the 'centre of the world'. The remains of one of these later observatories are located in Luoyang (洛阳), Henan province, the capital city of the Eastern Han dynasty (AD 25–220). The Dengfeng observatory was built in about AD 56 and functioned for over 250 years. The site, which was excavated in 1974–75, covers an area of some 44,000 m^2 surrounding a square terrace of compacted earth. The base of the remaining part of the terrace measures about 41m from south to north, 31m from east to west, and 8m in height. The terrace had two levels, with buildings on the upper level. The remaining walls reveal that the rooms in the east, west, south and north were painted in blue, white, red and black respectively, corresponding to the colours assigned to the four directions in ancient Chinese cosmology.

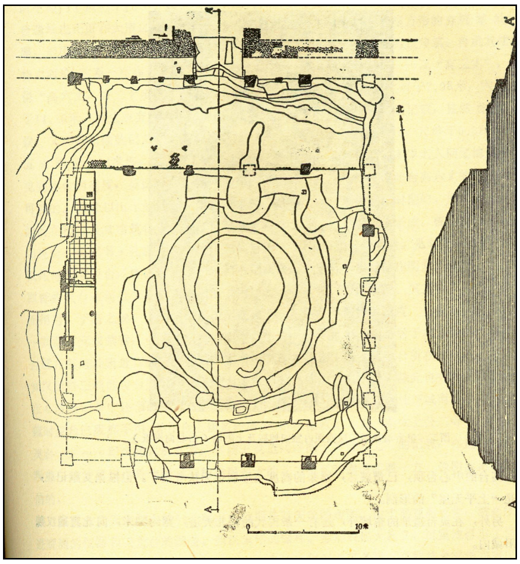

Fig. 5.0.3. The remains of the observatory in Luoyang. © Authorised for non-profitable use

The Luoyang observatory is famous for Zhang Heng 张衡 (AD 78–139), one of the greatest astronomers in ancient China who was the Head Grand Historian, i.e. the chief astronomer, from AD 115 to 120 and again from AD 126 to 133. During these periods, he invented the world's first seismograph and constructed a new type of large armillary sphere driven and controlled by water, which is the first astronomical clock in China.

From at least the Spring and Autumn period (722–481BC) onwards, the precision of the system of calendrical astronomy was considered a key factor in ensuring the peace and prosperity of the country. Maintaining a precise calendar became a measure of the power, capacity and legitimacy of a monarch. Given this motivation, calendrical astronomy became a leading science in every dynasty and continued to be expanded and improved, finally reaching its apex in the Yuan dynasty (1271–1368). In 1276, the Yuan government launched a large-scale project of calendar reform and entrusted it to a group of astronomers and mathematicians including Guo Shoujin 郭守敬 (1231–1316). Charged with the responsibility of making observations, Guo Shoujing invented a number of ingenious instruments, such as the famous 'simplified instrument', the high gnomon and the shadow definer, and obtained the most accurate values for the basic astronomical constants of all the traditional Chinese astronomers. Nonetheless, the most important observational work carried out by Guo Shoujing was undoubtedly a nationwide programme of observation at different latitudes. For this purpose, he built 26 observational stations across the country in addition to a spectacular observatory in the capital Dadu (大都), which is now Beijing. On the old site of Duke Zhou's Terrace for Gnomon Measurement in Dengfeng, he built a large observatory, which still stands intact and has become a permanent monument to traditional Chinese astronomy (see Case Study 5.2).

With the fall of the Yuan dynasty in 1368, some of Guo Shoujing's instruments in Beijing were transported all the way south to Nanjing by the Yangtze River, the capital of the newly established Ming Dynasty, where a new observatory was built on top of the Purple Mountains, or *Zijin shan* (紫金山). The Ming government also constructed two sets of new armillary spheres to equip the observatory. All these instruments were still on the site in 1598, but they mysteriously disappeared after the fall of the Ming dynasty in 1644.

In 1406 the Ming government moved its capital to Beijing, and in 1442 a new observatory was built near the site of the old Yuan observatory, which gave birth to the present Beijing Ancient Observatory. In 1438, a 'simplified instrument', an armillary sphere and a high gnomon were constructed according to the designs of the same instruments on top of the Purple Mountains. They had been in use for nearly 130 years when, in 1669, the Flemish Jesuit Ferdinand Verbiest (1623–1688) re-equipped the observatory with six new instruments based on Tycho Brahe's designs. The old Ming instruments were moved from the top of the observatory and finally transported in 1933 to the Purple Mountains, where they still remain today.

From 1583 onwards, European astronomy and instruments were systematically introduced into China by generations of Jesuit missionaries like Verbiest. However, while traditional Chinese techniques were superseded, the entire system of Chinese astronomical rituals remained unchanged. Given this historical context, the Old Observatory in Beijing—itself a hybrid of Chinese and European astronomical culture (see Case Study 5.3)—serves as an example of how European techniques were used in the service of Chinese ideology in the Qing dynasty (1644–1912), the last imperial dynasty in China.

Since the establishment of the People's Republic of China, the central government has paid great attention to the preservation of cultural relics and heritage, including astronomical heritage. The Old Observatories in Dengfeng and Beijing have both been developed into museums. In 1986, a new museum was built in Puyang city to house the Tiger and Dragon Tomb in Puyang. While the Chinese economy has been booming in recent years, the government has launched a series of projects for the preservation and effective presentation of both material and intangible heritage. One of these projects is the 'Compass Plan for the Exploration and Exhibition of the Value of Ancient Chinese Inventions and Creations', launched in 2008 through the National Bureau for Cultural Relics. Its objective is to incorporate the most important cultural heritage in science, technology and engineering into museum exhibitions.

Fig. 5.0.4. The old instruments at the Purple Mountain Observatory. © Authorised for non-profitable use

At the same time, local governments have begun to increase their investment in promoting the development of culture- and heritage-related facilities in their regions. In this context, the preservation of astronomical heritage has received renewed emphasis.

Japan and Korea *by Clive Ruggles*

For over a millennium and a half, Japanese culture has continually absorbed influences from mainland Asia and yet retained a distinct identity. Even the Japanese language, when it was first written down in the middle of the first millennium AD, used kanji characters imported from the Chinese.

From the fourth century until the end of World War II, the principles of Shinto religion forged unbreakable links between cosmology, political structure, and the sun. Successive emperors traced their ancestry directly back to the Sun Goddess, helping to forge a national identity linked with the sun that is still evident in the national flag. Shinto persisted despite the strong influence of Buddhist traditions from China that have coexisted in this island nation from the 6th century onwards. This coexistence involved some remarkable compromises, for instance, in locating and aligning temples and palaces. In the Shinto tradition this would be done with respect to places of spiritual power in the landscape, whereas in the Chinese tradition they would typically be aligned cardinally, reflecting the principle that spiritual and imperial power derived from the north celestial pole as the pivot of the heavens, and ensuring that the emperor would be approached, like the celestial pole itself, from the south. The plan of ancient Kyoto, for example, built in 794, with its palace complex approached from due south, reflected such principles every bit as faithfully as Beijing itself.

Aside from institutionalized astronomy, elements of star lore and folk calendars have been transmitted through countless generations of ordinary people, and some have persisted in rural areas despite the introduction of the Gregorian calendar. For example, the changing patterns of appearance of the Pleiades (Subaru), Hyades, and Orion's belt provided a succession of seasonal rules of thumb for rice farmers. One of these was that when Subaru—which resembled a collection of rice seedlings—set progressively earlier in the evening sky in the spring, this indicated the time for planting the actual rice seeds in the ground.

Archaeoastronomy is in its infancy in Japan. The Asuka plain, to the east of Osaka, contains several tombs (*kofun*) of high-status individuals that were erected in the 7th and early 8th centuries. Two of them, only about 1km apart—Takamatsu Zuka Kofun, excavated in 1972, and Kitora Kofun, probed in 1998 using a miniature camera—contain paintings with strong astronomical associations. The ceilings depict the 28 lunar 'mansions' (known in Japan as *shuku*) and other constellations, while the walls show the animal gods associated with each of the cardinal directions. The two tombs demonstrate clear but nonetheless different Chinese and Korean influences. The region also contains a number of granite megaliths carved in the shape of human figures. These are of uncertain origin, date, and purpose, and while some have attracted archaeoastronomical interest, they are far more speculative.

The development of astronomy in Korea was also heavily influenced by China. For two thousand years, astronomical (and also meteorological) events were seen as portents with strong political implications.

Korean history is divided into three major dynastic periods: the Three Kingdoms period (56 BC–AD 916), the Koryo dynasty (early 10th century – late 14th century), and the Choson dynasty (1392–1910). Historical records of astronomical observations go back to the early Three Kingdoms period. A remarkable 67 records of solar eclipses exist from this first period, stretching over nine centuries. There are also records of comets, lunar occultations of planets, and other unusual events. The 12th-century *Samguk sagi* (*Chronicles of the Three Kingdoms*), documents hundreds of observations.

The best known astronomical structure from the Three Kingdoms period is the Cheomseongdae observatory at Gyeongju (see Case Study 5.4). In fact, the word *cheomseongdae* means 'star-gazing tower' and Korean historical records mention at least three *cheomseongdae*, of which another survives in good condition in the outskirts of Gaeseong, North Korea.

The first Korean calendars were probably introduced from China early in the Three Kingdoms period, and Korea started to influence Japan in its turn during the 6th and 7th centuries, as Japanese sources attest.

Extensive records of observations also exist from later periods, and it is clear that continual exchanges with China had a very significant and positive effect on the subsequent development of Korean astronomy—and in particular observation methods, the production of star maps, improvements in calendar systems, and the construction of ever better instruments.

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Case Study 5.1: Taosi Observatory, China

Xu Fengxian and He Nu

Presentation and analysis of the site

Geographical position: Xiangfen County, Shanxi province, China

Location: Latitude 35° 52′ 55.9″ N, longitude 111° 29′ 54.9″ E. Elevation 573m above mean sea level.

General description: Taosi ancient observatory forms part of the Taosi archaeological site, one of the most famous of the eighty or so Longshan Culture (c. 3000–2000 BC) sites in north

China. At the Taosi site, a small walled-town of the Early Taosi Period (23rd and 22nd centuries BC) was superseded by two walled-towns of the Middle Period (21st century BC), the larger of which occupied 2.8km^2 and is the largest known walled-town in prehistoric China. The observatory is located within the lesser Middle Period walled-town, close to the inner south-eastern wall of the larger one.

Inventory of the remains: A semi-circular platform about 1,000m^2 in area, measuring 40m across from east to west and about 29m from north to south, appears to have consisted of three concentric terraces. The innermost, with a radius of about 21m, has a rammed-earth retaining wall 22.5m long, 1.1m wide and 2.7m high, which contains a series of eleven rammed-earth pillars arranged along the arc. These were formed by cutting ten U- or V-shaped slots into the top of the wall foundation, which survive to a depth of about 4–17 cm and are filled with soft earth. Most are 15–20 cm in width, the southernmost two being slightly wider. A rammed-earth block on the second terrace has been slotted in a similar manner, to form two further pillars.

Slightly to the west of the geometrical centre of the platform archaeologists have found a round foundation-pit and three concentric rammed-earth circles. As viewed from this point, the series of 11 pillars with 10 slots on the third terrace and the 2 pillars with 1 slot on the second terrace appeared to form a single line of 13 pillars and 12 slots (the gap between the south pillar on the second terrace and the north pillar on the third terrace forming the additional slot) against the skyline formed by Taer Hill, or Chong Hill, a prominent chain of peaks (up to 1493m in elevation) about 7 to 10km to the east.

Calculations and experimental observations indicate that 4000 years ago the sun would have risen in the northernmost slot at the June solstice, and in the slot next to the southernmost at the December solstice. Slot no. 7 (counting from south to north) could possibly have been used to determine the spring and autumn equinoxes: nowadays the sun can be seen as rising in this slot on March 18 and September 25. The southernmost slot could not have been used to observe sunrise, although it did indicate the position of southernmost (‘major standstill’) moonrise.

The fact that a clear archaeological structure has been discovered at the point where the centre-lines of the 12 slots converge implies that the twelve slots and the observation point must have been designed carefully and formed an integrated observation system.

History of the site: The observatory was constructed and used during the Middle Taosi Period (21st century BC) and was deliberately demolished during the Late Taosi Period (20th century BC).

Cultural and symbolic dimension: According to Chinese classical literature, the tradition of ‘observing the phenomena to bestow the seasons’ goes back to ancient times. The earliest historically recorded method for determining the seasons is by measuring the lengths of the sun’s shadow at noon. Little was recorded about the method of observing the direction of sunrise in order to determine the seasons, but the Taosi observatory implies that a tradition of making such observations had already been established for a very long time.

The Taosi site is believed to be the capital of King Yao, who ruled before the time of the Xia Dynasty, the first Dynasty in Chinese history. About a third of the *Yao Dian [Canon of Yao]*, a classical Chinese text said to be King Yao’s document, is devoted to describing the Great King’s policy and achievements in astronomy. In particular, he commanded astronomical officials to “make a calendar to delineate the regularities of the sun, moon, stars, and constellations, and to bestow respectfully to the people the seasons for observance” and accordingly he sent four of them to observe the culminating stars at the two equinoxes and the two solstices. The Taosi observatory could have been used to identify these four special days, thus demonstrating that the ancient Chinese carried out astronomical observations carefully as long as 4100 years ago.

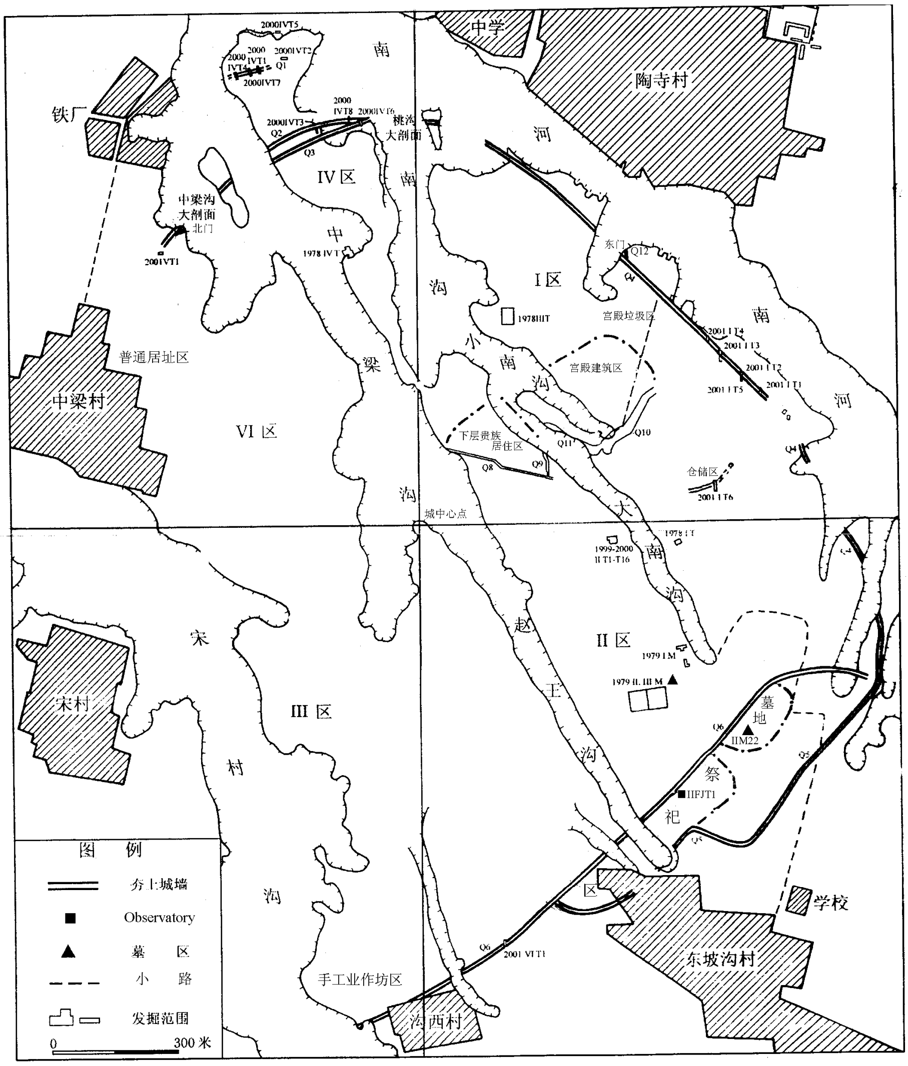


Fig. 5.1.1. Location of Taosi Observatory (identified as feature IIFJT1) within the Taosi site. After He Nu and Shanxi Xiangfen (2009), "Taosi chengzhi zhongqi wang ji da mu IIM22 chutu qigan guichi gongneng shitan [On the gnomon shadow template function of the lacquer stick from the royal tomb IIM22 at Taosi walled-town of Middle Period]", *Ziran kexueshi yanjiu [Studies in the history of natural sciences]*, 28(3), 261–276.

Authenticity and integrity: The foundations of the pillars have been preserved under the ground surface for 4000 years until rediscovered by excavation in 2003–04. At that time, the top of the rammed-earth was about 1m under the ground surface.

Documentation and archives: Historical records and local traditions demonstrate that the Taosi area was the hinterland of the territory of the King Yao and the Xia dynasty. Given this, the astronomical rituals documented in such ancient books as *The Canon of Yao* and the *Small Calendar of the Xia* may well have been performed at this site.

Present site management

Present use: The Taosi observatory site is used by several local villagers as a wheat field. Archaeologists and historians of astronomy have reconstructed a temporary building on the site with brick structures imitating the ancient pillars and slots. The aim is to simulate observations and further research.

Fig. 5.1.2. Top: Aerial view of the observatory. North is to the right. **Bottom left:** Foundations of the pillars and slots. **Bottom right:** The observation point. Photographs © He Nu.

Protection: After the excavation and surveys were completed, the observatory site was buried some 2–3 m beneath the ground surface.

State of conservation: See above.

Context and environment: The Taosi site is situated on the south-eastern part of the Yellow Earth Plateau, between five modern villages including Taosi Village, from which it took its name.

Archaeological/historical/heritage research: The Taosi site was first discovered in the 1950s. During the late 1970s and early 1980s, archaeologists excavated nine chiefly tombs with rich grave goods, together with large numbers of common burials and dwelling foundations. Archaeologists first discovered the walled towns of the Early and Middle Periods in 1999.

The remains of the observatory were first discovered in 2003 and totally uncovered in 2004. Archaeoastronomical surveys were undertaken in 2005. This work has been published in a variety of Chinese journals.

Chinese archaeoastronomers and archaeologists are currently conducting further collaborative research at Taosi Observatory, sponsored jointly by the Committee of Natural Science of China and the Academy of Science of China. The project, which is due to finish in 2011, has purchased the right to occupy the main field of the observatory site for two years.

Main threats or potential threats to the sites: The most critical potential threat to the observatory site itself is from the burials of native villagers, which are placed randomly.

The skyline formed by Taer Hill, which is a crucial part of the visual landscape since it contains the sunrise points, is potentially threatened by mining, which could cause the collapse of parts of the top of the hill. The government of Xiangfen County is currently trying to shut down some of the mines, but it is unclear whether a ban on mining could be policed effectively in the longer term.

Management, interpretation and outreach: The county government is trying to purchase the land from the local farmers in order to carry out a conservation project as soon as possible. The buffer zone is handled by the Cultural Relics Bureau of Xiangfen County, but it has no right to control the use of this land. The Legal General Conservation Project of the entire Taosi Site, which includes the Observatory site, has been ready since 2003 but has not yet been implemented. In this project, the entire Taosi Site would be designated an archaeological park, and the observatory would be reconstructed permanently, for both public and scientific use, in a manner that would ensure the conservation of the original remains.

Case Study 5.2: Dengfeng Observatory, China

Xu Fengxian

Presentation and analysis of the site

Geographical position: The observatory lies to the north of Gaocheng Town, 12 km south-east of Dengfeng City, Henan Province, China.

Location: Latitude 34° 23´52˝N, longitude 113° 8´44˝E. Elevation 253m above mean sea level.

Heritage context: Dengfeng Observatory forms a part of a property that has been on China’s Tentative List since 2008, under the general name ‘Historic Monuments of Mount Song’. This includes the ancient architectural complex at Mount Song and the site of the Xia-dynasty capital. They are situated in and around Mount Songshan in Henan Province in China. The complex consists of the following 13 ancient structures and sites: Taishi, Shaoshi and Qimu Towers; the pagodas of Songyue and the pagoda of Master Jingzang; the Observatory itself; the Chuzu Temple; the pagoda forest of Shaolin Monastery; the Huishan Temple and the Songyang Academy; the Zhongyue Temple; the Shaolin Monastery; and the site of the Xia-dynasty capital at Wangchenggang. A great many different attributes of cultural value merge together inside the Mount Song site.

General description: The site is 37m wide from east to west and 150m long from north to south, covering 5550 m^2. Two astronomical monuments remain at this spot: an observatory of the Yuan Dynasty (1279–1368) and a stele of the Tang Dynasty (618–960). The main feature of the Yuan Dynasty Observatory is a device for measuring the length of the sun's shadow at noon and tracing its variation through the year. It functioned by casting the shadow of a horizontal bar down onto a large horizontal scale extending to the north. This innovative design effectively created a gnomon five times the height of the standard gnomon used for the same purpose through Chinese history.

The earlier stele marked this place as a key node in a remarkable 8th-century geodetic survey that established the length of a degree of the meridian.

*Inventory of the remains***:** The main structures forming the observatory are a brick-built platform in the shape of truncated pyramid and a horizontal scale extending to the north.

The platform is 9.45m high and its sides are over 16m long at the base and over 8m long at the top. On the northern part of the platform stand two rooms separated by an opening. Each of the two rooms has one window facing the other room and a second window facing north. The two rooms and the opening are covered by an elongated roof, which is 12.62m above ground level. A horizontal rod connects the two rooms through their facing windows, and directly below this a groove with vertical sides runs down the centre of the north side of the platform. Two stairways lead up to the platform from the bottom of the north side, one running up the east side and one up the west side. The stairways and the platform are contained within low walls 1.05 m in height.

The scale, which is called the sky-measuring scale, was built using 36 stone blocks. It measures 31.19m in length and runs due north-south, its south end continuing into the groove on the north side of the platform. Two parallel troughs run along the top of the scale; they are linked at the ends and would have held water to form a level surface. According to historical records, the length of the sky-measuring scale was 128 *chi*, the *chi* being one of the basic Chinese units of length; the height from the surface of the scale to that of the bar between the two rooms on the platform, 9.75m, was exactly 40 *chi*.

On either side of the scale at its north end are two reconstructed astronomical instruments that were originally invented by Guo Shoujing. On the eastern side is the *zheng fang an*, or 'square meter', while to the west is the *yang yi*, a type of sundial using a spherical surface.

The Tang Dynasty stele lies to the south of the Yuan Dynasty observatory. It consists of a stone gnomon mounted truncated stone base, both the gnomon and the base being 1.98m in height, exactly 8 *chi* according to the metrology in use during the Tang Dynasty. The base is nearly rectangular in cross-section at the bottom (1.8–1.9m from east to west by 1.70m from north to south), and nearly square at the top (width 0.88–0.89m). The gnomon consists of a 1.64 m-high standing stone and a 0.34 m-high cap. The stele is so arranged that the sun at noon on the summer solstice casts no shadow beyond its heavy truncated pyramidal base.

Between the Yuan Dynasty observatory and the Tang Dynasty stele is the later Zhou Gong's Temple, built during the Ming Dynasty.

History of the site: Gaocheng occupies a special place in Chinese history as well as in the history of Chinese astronomy (for which, see below). Before the Tang Dynasty its name was Yangcheng, and according to classical Chinese texts, Emperor Yu the Great, founder of the Xia Dynasty, the first Dynasty in Chinese history, made Yangcheng his capital in the 21st century BC.

The Tang Dynasty stele was erected in AD 723 by Nangong Yue, a Tang Dynasty astronomer who responsible for the survey of four sites in Henan as part of Yixing's geodetic survey (see below).

Fig. 5.2.1. The Yuan Dynasty Observatory. Photograph © Xu Fengxian.

The Yuan Dynasty observatory was originally built in 1279 by Guo Shoujing (1231–1316). It was repaired in 1542 during the Ming Dynasty (1368–1644). Zhou Gong's Temple was also built in the Ming Dynasty, in commemoration of Zhou Gong, who is believed to have carried the earliest measurement of the sun's shadow in Yangcheng.

Cultural and symbolic dimension: Ever since ancient times, Chinese people had believed that the world has a centre. According to the ancient text *Zhou li*, the founders of the Zhou Dynasty in the mid 11th century BC used a gnomon to determine the site of their capital. Observations of the lengths of the sun's shadow were used to determine the latitude in order to fix provincial and other territorial boundaries, but only the place where an 8-*chi*-long gnomon cast a 1.5-*chi*-long shadow at noon on the summer solstice was the centre of the world. By at least the 1st century BC, astronomical authors were identifying this place with Yangcheng, i.e., today's Gaocheng. From then on, astronomers considered Yangcheng the best place for astronomical observations, and especially for measuring the length of the sun's shadow. Since the summer and winter solstices, and hence the length of the tropical year, were determined in this way, traditional Chinese calendars paid special attention to the sun's shadow. Generations of astronomers measured the sun's shadows at Yangcheng, or used the results from Yangcheng, to make calendars.

Before about the 5th century AD, Chinese astronomers believed that the sun's noontime shadow length on any given day of the year increased in proportion to the distance north of the earth's centre at Yangcheng, and decreased similarly in proportion to the distance south. This is not actually true because of the curvature of the earth's surface. A number of experiments during the 5th and 6th centuries disproved this idea and between AD 721 and 725 Yixing, a Tang Dynasty monk, organised a geodetic survey using thirteen stations running from latitude 52° in the north down to latitude 17.4° in the south, including Yangcheng, which was regarded as the standard against which all the other data were compared. This is perhaps the most remarkable piece of organized field research carried out anywhere in the early Middle Ages. Yixing obtained a complete set of values for the altitude of the celestial north pole and the length of the sun's shadow at noon on the two solstices and the equinoxes, and concluded that the altitude of the north pole changes in proportion to the distance along the meridian, thereby determining the length of a degree of the meridian.

Measuring the sun's noontime shadow was the main method used in China to determine the seasons and calculate the length of a tropical year. Traditionally the gnomon was 8 *chi* long, which meant that the length of the gnomon was close to a person's height. At the start of the Yuan Dynasty, the astronomer Guo Shoujing was asked to make a new calendar. He designed many new astronomical instruments and organized a large-scale survey. Gou Shoujing found that the taller the gnomon, the more precise the results of the measurements, and the 40-*chi*-long gnomon is one of his most important innovations. The instrument at Dengfeng was one of two built by Guo, the other being in Dadu (today's Beijing). Guo's Shoushi Calendar was not only used until the end of the Yuan Dynasty; it continued to be used, with only a small adjustment, throughout the Ming Dynasty.

Present site management

Present use: The site belongs to Dengfeng Municipal Bureau of Culture Relics and is open to the public as a historical monument.

Protection: In 1961, Dengfeng Observatory was included among the first group of the nation's key sites needing protection to be identified by the State Council of China.

State of conservation: The site is generally in a good state of preservation and management. Most of the bricks used in building the platform are in good condition.

Context and environment: Mount Song lies to the north, the Ji hill lies to the south, and the Ying River runs past on the south side, flowing from north-west to south-east.

Management, interpretation and outreach: This will be developed inside the future management plan for the 'Historic Monuments of Mount Song'.

Fig. 5.2.2. The Tang Dynasty stele. Photograph © Xu Fengxian.

Case Study 5.3: Beijing Ancient Observatory, China

Shi Yun-li

Presentation and analysis of the site

Geographical position: The Beijing Ancient Observatory is located in Beijing, the capital city of the Jin (1115-1234CE), Yuan (1271-1368CE), Ming (1368-1644CE) and Qing (1644-1912CE) dynasties. The name of the city was Yanjing (燕京) in the Jin dynasty, and Dadu (大都), the Great Capital, in the Yuan dynasty.

Location: Latitude 39º 54´ 43˝ N, longitude 116º 25´ 22˝ E. Elevation 49m above mean sea level.

General description: The observatory site covers an area of 10,000m^2. The brick platform of the observatory is 14m high and the top measures 20.4m from north to south and 23.9m from east to west. It used to be a part of the city wall once surrounding Beijing.

*Inventory of the remains***:** On top of the platform are eight bronze instruments constructed in the Qing dynasty. Six of them were built by the Flemish Jesuit Ferdinand Verbiest (1623–88) in 1669:

(1) *Chidao jingwei yi* 赤道经纬仪, literally the instrument for equatorial longitude and latitude, or the equatorial armillary sphere;

(2) *Huangao jingwei yi* 黄道经纬仪, literally the instrument for ecliptic longitude and latitude, or the ecliptic armillary sphere;

(3) *Tianti yi* 天体仪, literally the instrument of the celestial body, or the star globe;

(4) *Diping jingyi* 地平经仪, literally the instrument for azimuth, or the azimuthal ring;

(5) *Xiangxian yi* 象限仪, literally the quadrant instrument, or the quadrant; and

(6) *Hushi yi* 弧矢仪, literally bow and arrow instrument, or the sextant.

The other two instruments are:

(7) *Diuping jingwei yi* 地平经纬仪, literally the instrument for azimuth and altitude, or the azimuth quadrant; and

(8) *Jiheng fucheng yi* 玑衡抚辰仪, literally the divine instrument for pacifying luminaries.

The first of these was constructed by the Portuguese Jesuit Kilian Stumpf (1655–1720) between 1713 and 1715, while the maker of the latter is not clear. The seven instruments made by the two Jesuits are based on Tycho Brahe's design but with Chinese decorations, while the last one belongs to the Chinese tradition but with a European system of graduation and sighting. Overall, the observatory is now the only example in the world that is equipped with Tychonic instruments.

History of the site: The first observatory in Beijing was built in the Jin dynasty, but its position is not clear now. In 1279, by order of Kublai Khan, Wang Xun (王恂) and Guo Shoujing (郭守敬) built a new observatory just north of the present observatory. After the Ming capital moved from Nanjing to Beijing in 1406, a temporary observatory was set up on the city wall. The present brick platform was built in 1442 on a portion of the city wall that used to encircle the city. The whole city wall was removed after 1949 when the construction of the 'new Beijing' began, but the platform and some important gate towers have been preserved intact up to today except minor refurbishments. The observatory remained in use throughout the rest of the Ming and the whole of the Qing dynasties. After the founding of the Republic of China in 1911, it became the seat of the Central Observatory of the Kuomingtang government until 1927 when the Central Observatory moved to the Purple Mountains in Nanjing.

Authenticity and integrity: Today, the top of the platform is almost the same as in 1669 when Verbiest published the first illustration of the observatory, except for the addition of the two instruments built after 1713.

Documentation and archives: The history of the observatory, including the structure and usage of the eight instruments atop of it, is well documented in Chinese literature from the Ming, Qing and the Republic of China periods. Most of the original observational reports to the throne in the Qing dynasty are now well preserved in the First National Archives in Beijing.

Present site management

Present use: In 1982, the observatory was put on the list of key national cultural properties. Since 1983, it has been open to the public and has become a tourist destination in Beijing. Since 2008, it has been open to tourists free of charge. Presently the observatory forms part of the Beijing Planetarium.

Protection: The government provides regular funding for the observatory's preservation, study and maintenance.

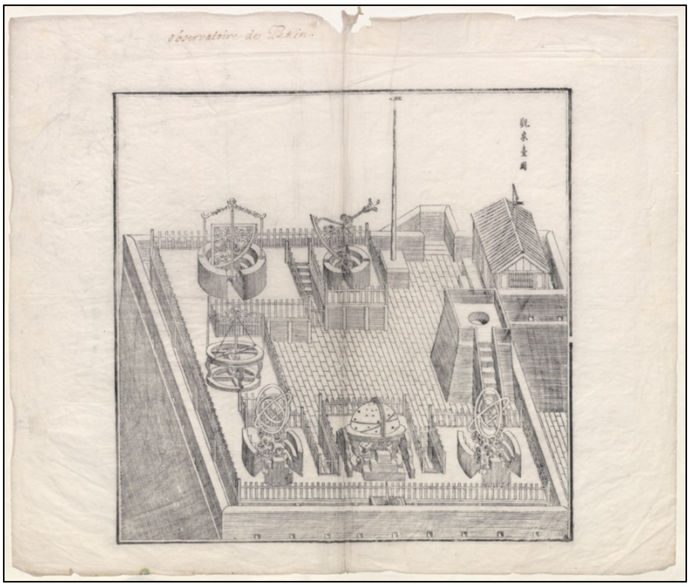


Fig. 5.3.1. Top left: Plan of the site. © Authorised for non-profitable use. **Top right:** The brick platform. © Authorised for non-profitable use. **Bottom:** Verbiest's illustration of the observatory (from a 17th-century European manuscript). Creative Commons Licence.

Case Study 5.4: Cheomseongdae Observatory, Republic of Korea

Park Jeong Eun

Presentation and analysis of the site

Geographical position: 839–1, Inwang-dong, Gyeongju City, North Gyeongsang Province, Republic of Korea.

Location: Latitude 35º 50´ 7˝ N, longitude 129º 13´ 9˝ E. Elevation 44m above mean sea level.

General description: Cheomseongdae is a 9.17m-high stone tower that has long been renowned as the oldest astronomical observatory in the Far East. Dating back to the Silla period (57 BC–AD 935), it is comprised of three parts: a stylobate, a cylindrical body resembling a bottle, and a top whose shape when viewed from above is that of the Chinese character 井. It is located near to the royal tomb of King Naemul of Silla

Inventory of the remains: The cylindrical body consists of 27 layers of stones, each stone resembling a fan. A square hole in the middle three (13th to 15th) tiers faces slightly east of south. In contrast to the skilfully trimmed exterior, the inside wall is not elaborately carved, with the rear parts of stones sticking out. Below the hole the interior is entirely filled with rubble, while the upper part is empty. From each of the four corners on the top, the ends of two interlocking stones protrude. There are also protruding ends on the 19th to 20th and 25th to 26th tiers, making it possible to set up a ladder in and out of the building for observation.

History of the site: It was constructed during the reign of Queen Seondeok (AD 632–647).

Cultural and symbolic dimension: The body of the tower comprises 365 stones, symbolising the days of a year, and the 27 tiers probably reflect that fact that Queen Seondeok was the 27th monarch of the Silla Kingdom. Twenty-eight, the number generated when the stylobate is included, corresponds to the 28 constellations of East Asia, and if the two-tier top is also added, the number increases to 30, which is the number of days in a lunar month. Each of the sections above and below the central hole comprises 12 tiers, which calls to mind the 12 months and the 24 solar terms.

Given that seasonal change was highly important in making decisions on agriculture, astronomy was particularly significant at the time when Cheomseongdae was constructed. Also, given the importance of astrology at the time, astronomical observation was surely closely linked to politics. Accordingly, there would have been great interest in astronomical observations in Silla, and Cheomseongdae was constructed against this background.

Authenticity and integrity: Cheomseongdae has retained its original appearance for about 1300 years since its establishment in the 7th century. The structure is now slightly tilted to the north-east but the original shape is mostly intact. However, the instruments used for observation and observatory records have not been passed down, so the exact methods of taking observations are not known today.

Documentation and archives: According to an old document, “the structure is made for men to climb up by entering through the centre”. This implies that one could enter the structure with a ladder, climbing in and out of the building to observe the sky.

Fig. 5.4.1. Cheomseongdae observatory viewed from the north-east. © National Research Institute of Cultural Heritage, Republic of Korea

Present site management

Present use: The site is open to visitors.

Protection: Cheomseongdae is designated National Treasure no. 31 and under government protection according to Korea's Cultural Heritage Protection Act. Any kind of construction activity taking place within a 500m radius, and hence which could affect the historic site, has to gain the approval of the head of the Cultural Heritage Administration in consultation with the Cultural Heritage Committee.

State of conservation: The site is well preserved and managed. The National Research Institute of Cultural Heritage, an organization affiliated to the Cultural Heritage Administration of Korea, has conducted a variety of safety inspections at annual intervals since 1981. The institute's strategy for conserving Cheomseongdae is concerned with structural displacement and cracks, the vertical displacement of foundation stones, and ultrasound compressive strength. In 2007, a system was installed that takes measurements every hour and, in 2009, an overall survey was carried out with a three-dimensional scanner. In addition, the exterior of the structure is washed regularly and the moss removed.

Context and environment: Cheomseongdae forms part of a provincial historical district that includes several major historic sites such as Half Moon Fortress (Banwolseong), Heavenly Horse Tomb (Cheonmachong), and the Pond of Geese and Ducks (Anapji), all of which reveal the scenic beauty of the thousand-year-old capital of Silla.

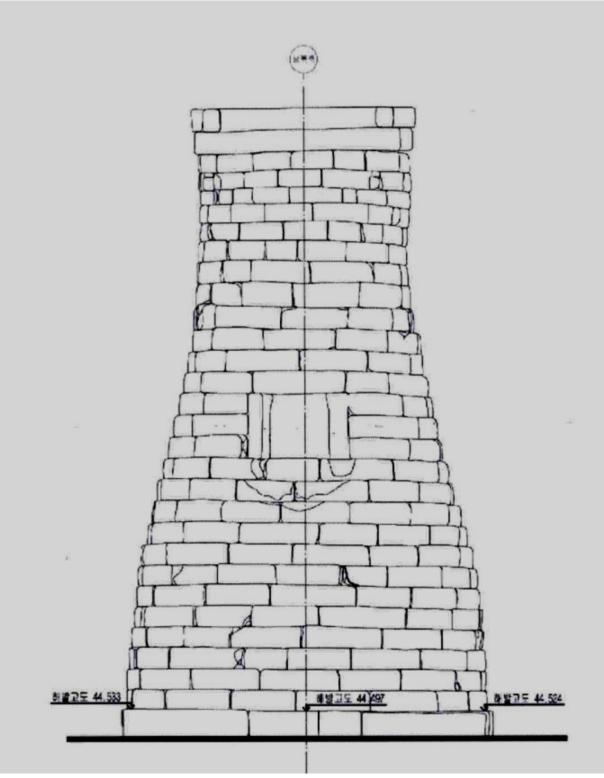
Archaeological/historical/heritage research: The stone tower at Cheomseongdae was first recognised as an observatory by Wada Yuji, a Japanese meteorologist, in the early 20th century. In a report entitled “A theory for Cheomseongdae in Gyeongju”, published in *Joseon Observatory Academic Report* in 1910, he presented a theory that people might have set up an observation balloon such as Honcheoneui, an astronomical clock, on a wooden structure at the edifice.

A Korean scholar, Hong i-seup, argued in his book *Science History of Joseon* that the Silla Kingdom made their astronomical observations independently and presented Cheomseongdae as evidence, saying that it was the oldest observatory of its kind extant in the East. Hong Sa-jun, who was the first to survey and study the stone building using scientific techniques, argued that people made observations of astronomical phenomena lying on their backs inside the building.

At first, Cheomseongdae was firmly believed to have been an astronomical observatory. However, some dissenting views emerged in the 1960s. Yi Yong-beom argued instead that it was simply an altar modelled on Mount Sumi, which is of great importance in Buddhism. Park Seong-rae, while acknowledging Cheomseongdae to be an observatory in the broad sense, argued that it was actually an altar constructed to respect the sacred god of agriculture.

Main threats or potential threats to the sites: Thanks to its location near to several major historic sites in Gyeongju, Cheomseongdae is relatively safe from landscape damage caused by development projects in the city. However, the observatory is affected by aging and weathering, in common with other cultural properties built in stone. Among the main causes of damage are environmental changes such as air pollution, weathering caused by chemical interactions between the rock and water, and structural imbalance caused by ground subsidence.

Management, interpretation and outreach: The observatory structure is now owned by the Korean government, and the Gyeongju municipal government is primarily responsible for its management. Along with signboards and leaflets, a year-round tour guide service is provided free of charge, with an aim to enhancing visitors’ understanding of the observatory.



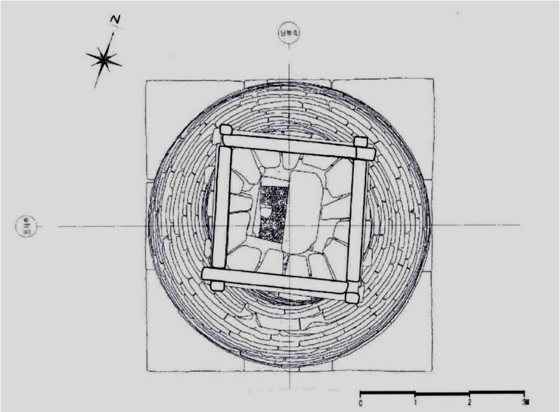


Fig. 5.4.2. Drawings of Cheomseongdae. **Left:** Site elevation viewed from the south. **Right:** Floor plan of the roof. © National Research Institute of Cultural Heritage, Republic of Korea

Chapter 6: India

Subhash Kak

Our understanding of archaeoastronomical sites in India is based not only on a rich archaeological record and texts that go back thousands of years, but also on a living tradition that is connected to the past. Conversely, India has much cultural diversity and a tangled history of interactions with neighbouring regions that make the story complex. The texts reveal to us the cosmological ideas that lay behind astronomical sites in the historical period and it is generally accepted that the same ideas also apply as far back as the Harappan era of the third millennium BC.

In the historical period, astronomical observatories were part of temple complexes where the king was consecrated. Such consecration served to confirm the king as the foremost devotee of the chosen deity, who was taken to be the embodiment of time and the universe. For example, Udayagiri, located a few km from Vidisha in central India, is an astronomical site connected with the Classical age of the Gupta dynasty (320–500 AD). The imperial Guptas enlarged the site, an ancient hilly observatory going back at least to the 2nd century BC, at which observations were facilitated by the geographical features of the hill, into a sacred landscape to represent royal authority.

Indian astronomy is characterised by the concept of ages of successively longer durations, which is itself an instance of the pervasive general idea of recursion, or repetition of patterns across space, scale and time. An example of this is the division of the ecliptic into 27 star segments (*nakshatras*), with which the moon is conjoined in its monthly circuit; each of these segments is further divided into 27 sub-segments (*upa-nakshatras*), and the successive divisions of the day into smaller measures of 30 units. The idea of recursion underlies the concept of the sacred landscape and it is embodied in Indian art, providing an archaeo-astronomical window on sacred and monumental architecture.

Chronological overview

The archaeological record in the north-west of India demonstrates a continuity of tradition extending back to about 7500 BC at Mehrgarh, and some of the abundant rock art of the region may extend back to the Upper Paleolithic.

The archaeological phases of the Indus (or Sindhu-Sarasvati) tradition have been divided into four eras: the early food-production era (c. 6500–5000 BC), the regionalisation era (5000–2600 BC), the integration era (2600–1900 BC) and the localisation era (1900–1300 BC). The early food-producing era lacked elaborate ceramic technology. The regionalisation era was characterized by styles in ceramics, lapidary arts, glazed faience and seal making that varied across regions. In the integration era, there is significant homogeneity in material culture over a large geographical area and the use of the so-called Indus script, which is not yet deciphered. In the localisation era, patterns of the integration era are blended with regional ceramic styles, indicating decentralisation and the restructuring of networks of interaction.

The cultural mosaic in the third millennium BC is characterised by the integration of the Harappan civilization of north-west India, copper- and copper-bronze-age cultures of central and northern India, and Neolithic cultures of south and east India. Five large cities of the integration phase are Mohenjo-Daro, Harappa, Ganweriwala, Rakhigarhi, and Dholavira. Other important sites of this period are Kalibangan, Rehman Dheri Nausharo, Kot Diji, and Lothal.

The majority of the towns and settlements of the Harappan period were in the Sarasvati valley region. Hydrological changes, extended period of drought, and the drying up of the Sarasvati River following an earthquake in 1900 BC led to the abandonment of large parts of this area, and the Harappan phase underwent various stages of decline during the second millennium BC. A second urbanization began in the Ganga and Yamuna valleys around 900 BC. The earliest surviving records of this culture are in Brahmi script. A continuous series of cultural developments, which can be traced in the characteristic ceramic assemblages, links the two early urbanizations of India. There is also continuity in the system of weights and lengths between the Harappan period and the later historic period.

The main setting for the hymns of the *Rigveda*, which is India's most ancient literary text, is the area of Sapta Saindhava, the region of north India bounded by the Sindh and the Ganga rivers. The *Rigveda* describes the Sarasvati River to be the greatest of the rivers, flowing from the mountains to the sea. The archaeological record, suggesting that this river had turned dry by 1900 BC, indicates that the *Rigveda* is prior to this epoch. The *Rigveda* and other early Vedic literature have astronomical references that indicate epochs of the fourth and third millennium BC, which is consistent with the hydrological evidence.

The foundation of Vedic cosmology is the notion of *bandhu* (homologies or bindings between the outer and the inner). For example, in the Ayurveda, a medical system associated with the Vedas, the 360 days of the year were linked to the 360 bones of the developing foetus.

Some of the astronomical information in the Vedic texts allows them to be tentatively dated. Various of the Vedas contain lists of the 27 nakshatras, either listed directly or under their presiding deities, and one may conclude that their names have not changed. Twelve 'solar months' are also listed, implying that Vedic astronomy used a luni-solar calendar with an intercalary month being used to keep in step with the solar year. Correlations between the nakshatra segment and the 'solar month' constrain the date. Thus, nakshatra lists of the late Vedic period begin with Krittikā (Pleiades) whereas those of astronomy texts after 200 AD begin with Ashvini (α and β Arietis), indicating a transition through 2 nakshatras, or a time span of about 2000 years. The *Vedānga Jyotisha*, for instance, mentions that winter solstice was at the beginning of Shravishthā and the summer solstice at the mid-point of Ashleshā, which implies that this particular text dates to 1300 BC.

Texts of the Vedic and succeeding periods provide a crucial understanding of the astronomy of the historical period throughout India. This is complemented and strengthened by the archaeoastronomical evidence.

According to the *Vāstu Shāstra*, the traditional Hindu system of architectural design, the structure of a building mirrors the emergence of cosmic order out of primordial chaos through the act of measurement. The universe is symbolically mapped onto a square, *vāstu-mandala*, that emphasizes the four cardinal directions. The basic forms of this square are used as the basic plan for the house and the city. There exist further elaborations of this plan, some of which are rectangular.

The medieval period was characterised by pilgrimage centres that created sacred space mirroring conceptions of the cosmos. Over a long period, sacred temple architecture served both religious and political ends.

The instruments (*yantra*) that were used in Indian astronomy include the water clock (*ghati yantra)*, gnomon (*shanku*), cross-staff (*yasti yantra*), armillary sphere (*gola-yantra*), board for determining the time from the sun's altitude (*phalaka yantra*), sundial (*kapāla yantra*), and astrolabe. The culmination of the Indian tradition of instrument-making occurred between 1724 and 1734, when the ruler of Jaipur, Maharaja Sawai Jai Singh II, built five masonry observatories called Jantar Mantar in Jaipur, Delhi, Ujjain, Varanasi, and Mathura. Each contained several great fixed instruments, and apart from the one in Mathura, all of them survive with their instruments fairly well preserved. These instruments include Ram Yantra (a cylindrical structure with an open top and a pillar in its centre to measure the altitude of the sun), the Rashivalaya Yantra (a group of twelve instruments to determine celestial latitude and longitude), the Jai Prakash (a concave hemisphere), the Laghu Samrat Yantra (small sundial), the Samrat Yantra (a huge equinoctial dial), the Chakra Yantra (upright metal circles to find the right ascension and declination of a planet), the Digamsha Yantra (a pillar surrounded by two circular walls), the Kapali Yantra (two sunken hemispheres to determine the position of the sun relative to the planets and the zodiac), and the Narivalaya Yantra (a cylindrical dial). On Jaipur observatory itself, see Case Study 6.1.

What makes Jai Singh II's designs so important is the amalgamation of a long-lasting Islamic-Persian tradition—starting at least with the Maragha Observatory in the mid-13th century and culminating in the Samarqand Observatory in the mid-15th century (see Chapter 10)—with local traditions and personal innovations. Although Jai Singh II became acquainted with contemporary European astronomical knowledge in 1727 through his relationship with a group of Jesuit scholars—they brought to his court a Portuguese astronomer as well as La Hire's astronomical tables—the final design of his observatories remained in the Islamic-Persian tradition of monumental instruments and naked-eye observations. The Jantar Mantar observatories, forming a great network of observational sites, had a supportive role in the production of the *Zīj-i-Muhammad Shāhī,* one of the last comprehensive astronomical tables of classical astronomy.[1]

Prehistoric and Harappan period

The city of **Mohenjo-Daro** (2500 BC) was a cultural and administrative centre, had as its foundation a 12 meter high platform of 400 m × 200 m. The lower city had streets oriented according to the cardinal directions and provided with a network of covered drains. Its houses had bathrooms. The city's wells were so well constructed with tapering bricks that they have not collapsed in 5000 years. The absence of monumental buildings such as palaces and temples makes the Harappan city strikingly different from its counterparts of Mesopotamia and Egypt, suggesting that the polity of the Harappan state was de-centralized and based on a balance between the political, the mercantile, and the religious elites.

Mohenjo-Daro and other sites show slight divergence of 1° to 2° clockwise of the axes from the cardinal directions. It is thought that this might have been due to the orientation of Aldebaran (*Rohinī* in Sanskrit) and the Pleiades (*Krtikkā* in Sanskrit) that rose in the east between 3000 BC and 2000 BC at the spring equinox; the word 'rohinī' literally means rising. Mohenjo-Daro's astronomy used both the motions of the moon and the sun. This is attested by the use of great calendar stones, in the shape of ring, which served to mark the beginning and end of the solar year.

A 3rd-millennium seal from **Rehman Dheri**, showing a pair of scorpions on one side and two antelopes on the other, that suggests knowledge of Vedic themes. It has been suggested that this seal represents the opposition of Orion (Mrigashiras, or antelope head) and Scorpio (Rohini of the southern hemisphere) nakshatras. The arrow near the head of one of the antelopes could represent the decapitation of Orion. It is generally accepted that the myth of Prajapati being killed by Rudra represents the shifting of the beginning of the year away from Orion and it places the astronomical event in the 4th millennium BC.

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[1] Paragraph by Tofigh Heidarzadeh

Neolithic and megalithic sites

Burzahom, Kashmir This Neolithic site is located about 10 km northeast of Srinagar in the Kashmir Valley on a terrace of Late Pleistocene-Holocene deposits. Dated to around 3000–1500 BC, its deep pit dwellings are associated with ground stone axes, bone tools, and gray burnished pottery. A stone slab of 48 cm × 27 cm, obtained from a phase dated to 2125 BC, shows two bright objects in the sky with a hunting scene in the foreground. These have been assumed to be a depiction of a double star system.

Hanamsagar, Karnataka This is a megalithic site with stone alignments pointing to cardinal directions. It is located on a flat area between hills about 6 km north of the Krishna river at latitude 16° 19′ 18″ and longitude 76° 27′ 10″. The stones, which are smooth granite, are arranged in a square of side c. 600 m with 50 rows and 50 columns (for a total of 2500 stones), with a separation between stones of about 12 m. The stones are between 1 and 2.5 m in height with a maximum diameter of 2–3 m. The lines are oriented in cardinal directions. There is a roughly square central structure known as *chakri katti*.

It has been argued that the directions of summer and winter solstice could have been fixed in relation to the outer and the inner squares. The site could also have been used for several other kinds of astronomical observations such as use of shadows to tell the time of the day, and the prediction of months, seasons and passage of the year.

The Plan of the temple

The sacred ground for Vedic ritual is the precursor to the temple. Vedic observances were connected with the circuits of the sun and the moon. The altar ritual was associated with the east-west axis and we can trace its origins to priests who maintained different day counts with respect to the solstices and the equinoxes. Specific days were marked with ritual observances that were done at different times of the day.

For ritual purposes at home, the householder employed three altars that are circular (earth), half-moon-shaped (atmosphere), and square (sky), which resemble the head, the heart, and the body of the Cosmic Man (*Purusha*). In the Agnichayana, the great ritual of the Vedic times that forms a major portion of the narrative of the *Yajurveda*, the atmosphere and the sky altars are built afresh in a great ceremony to the east. This ritual is based upon the Vedic division of the universe into three parts of earth, atmosphere and sky that are assigned numbers 21, 78, and 261, respectively. The numerical mapping is maintained by placement of 21 pebbles around the earth altar, sets of 13 pebbles around each of 6 intermediate (13×6=78) altars, and 261 pebbles around the great new sky altar called the Uttara-vedi, which is built in the shape of a falcon; these numbers add up to 360, which is symbolic representation of the year.

The temple complex at Khajuraho

The town of Khajuraho extends between 79° 54′ 30″ and 79° 56′ 30″ E and between 24° 50′ 20″ and 24° 51′ 40″ N, in Chhatarpur district, in Madhya Pradesh. The temples of Khajuraho were built in the 9th–12th centuries AD by the Chandela kings. Originally there were 84 temples, of which 23 have survived. Of the surviving temples, 6 are associated with Shiva, 8 with Vishnu, and 5 with the goddess.

At the eastern edge of the temple complex are the Dantla hills, with a peak of 390 m at which is located a shrine to Shiva, which is a reference point for the temple entrances. All the temples excepting the Chaturbhuja face the east. The south-eastern edge has the Lavanya hill that is separated from the Dantla hills by the eastward flowing river Khudar. At the foothills of the Lavanya hill at a height of 244m is the shrine of goddess Durga as Mahishasurmardini.

The shrines to Shiva and Durga on the Dantla and Lavanya hills span the polarities of spirit (*Purusha*) and matter (*Prakriti*), which are bridged by the river between the hills. The temples of Khajuraho are popular pilgrimage centres during two spring festivals: Shivaratri that falls on the new moon of Phalguna (February/March), and Holi, which falls on the full moon of Chaitra (March/April). The Lakshmana temple, one of the oldest in the complex, is considered the *axis mundi* of the site. It was built by the king Yashovarman (925–950) as a symbol of the Chandela victory over the Pratiharas and a record of supremacy of their power. This temple is oriented to the sunrise on Holi.

The groups of temples form three overlapping mandalas, with centres at the Lakshmana (Vishnu), the Javeri (Shiva), and the Duladeva (Shiva) temples. Their deviation from true cardinality is believed to be due to the direction of sunrise on the day of consecration. The temple, as a representation of the cosmos and its order, balances the *asuras* (demons) and the *devas* (gods), as well as containing in itself other polarities of existence. The conception of the sanctum is as a mandala.

The planetary deities, the *grahas*, encircle the temple. The temple is envisaged like Mount Meru, the axis of the universe, and the planets move around it.

The Udayagiri observatory

Udayagiri ('hill of [sun]-rise') is one of the principal ancient astronomical observatories of India. It is located at 23° 31′ N latitude on the Tropic of Cancer in Madhya Pradesh, about 50 km from Bhopal, near Vidisha, Besnagar and Sanchi. An ancient site that goes back to at least the second century BC, it was substantially enlarged during the reign of the Gupta Emperor Chandragupta II Vikramaditya (r. 375–414). This site is associated with 20 cave temples that have been cut into rock; 19 of these temples are from the period of Chandragupta's reign.

It appears that the ancient name of Udayagiri was Vishnupadagiri, or the 'hill of the footprint of Vishnu', and the name Udayagiri is after the Paramara ruler Udayaditya (c. 1070–1093). The hill is shaped like a foot. A saddle connects the northern and southern hills, and a passageway is located at the place where the northern hill meets the saddle. The Gupta period additions and embellishments at Udayagiri were concentrated around this passage. Most of the cave temples are located around the passageway.

On the day of summer solstice, there was an alignment of the sun's movement with the passageway. The day mentioned in the dated Chandragupta II Vikramaditya-period inscription in cave 6 has been calculated to be very close to the summer solstice of the year 402 AD. On this day, the shadow of the Iron Pillar of Delhi, which was originally located at the entrance of the passageway, fell in the direction of the reclining Vishnu panel.

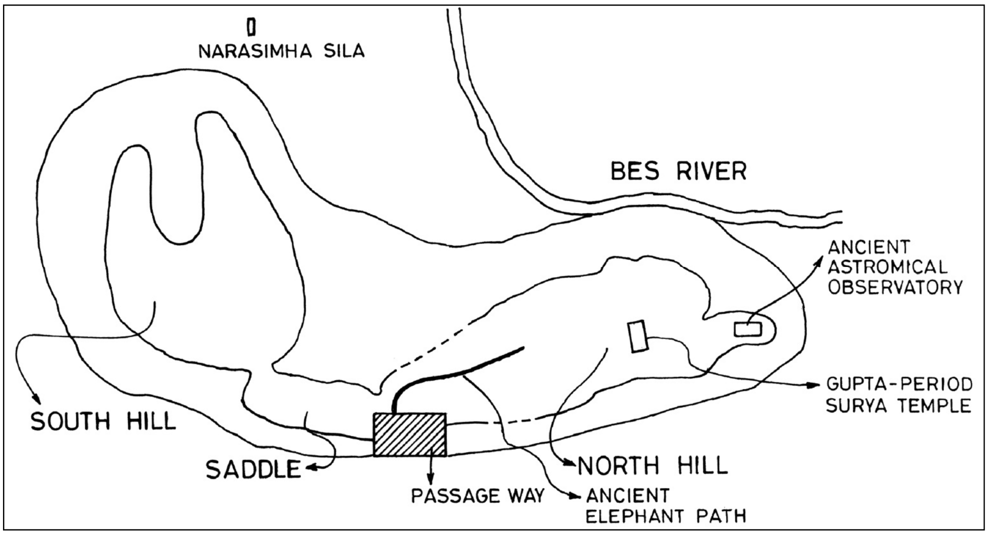

Fig. 6.0.1. The layout of Udayagiri. After R. Balasubramaniam, *Current Science* 95 (2008), 766–770.

On the northern hilltop, there exists a flat platform commanding a majestic view of the sky. Several astronomical marks have been identified at this platform, indicating that this was the site of the ancient astronomical observatory.

Medieval pilgrimage complexes

Medieval pilgrimage centres fulfilled many functions, including that of trade and business. They were important to the *jyotishi* (astrologer) who would make and read the pilgrims' horoscope. The better astrologers were also interested in astronomy and this knowledge was essential for the alignment of temples and palaces.

Every region of India has important pilgrimage centres, some of which are regional and others pan-Indic. The most famous of the pan-Indic centres are associated with Shiva (Varanasi), Krishna (Mathura, Dwarka), Rama (Ayodhya), Vishnu (Tirupati), and the 12-yearly rotation of the Kumbha Mela at Prayag, Haridwar, Ujjain, and Nashik. The question of temple alignments to the cardinal directions or to direction of the sun on major festivals has been studied by scholars at pilgrimage centres such as Chitrakut, Gaya, Madurai, Varanasi, Vindhyachal, and Khajuraho.

The sun temples of Varanasi

Varanasi is an ancient city dating from the beginning of the first millennium BC, whose Vedic name is Kashi (Sanskrit for 'radiance'), a name that continues to be used together with Banaras. Of its many temples, the most important is Kashi Vishvanath Temple, or 'Golden Temple', dedicated to Lord Shiva, the presiding deity of the city. Because of repeated destruction by the sultans and later by Aurangzeb, the current Vishvanath is a relatively modern building. It was built in 1777 by Maharani Ahilyabai of Indore, and its *shikhara* (spire) and ceilings were plated with of gold in 1839, which was a gift from Maharaja Ranjit Singh.

Shiva represents both the axis of the universe as well as that of one's inner being. One of the great festivals celebrated in Varanasi is Shivaratri, which is celebrated on the 13th day of the dark fortnight of the Phalguna month (February-March). On that day, the sun can be seen rising in the east with the new moon just above it, which is represented iconographically by Shiva (as the sun) wearing the moon on his head.

There are several pilgrimage circuits in Varanasi for circumambulating the city. The Panchakroshi circuit has 108 shrines on it, and the four inner circuits have a total of 324 shrines. The city is also known for the circuit of the Aditya shrines. The Adityas are the 7 or 8 celestial gods, although their number is reckoned as 12 in later books. In Puranic India, they are taken to be the deities of the twelve solar months. The Aditya temples were also razed during the centuries of Muslim rule, but have been re-established at the same sites and are now part of the active ritual landscapes.

Several Aditya shrines have been located with the aid of descriptions in the *Kashi Khanda* and pilgrimage guides (Singh and Malville, 1995; Singh, 2009a and 2009b). Six of these lie along one sides of an isosceles triangle with a base of 2.5km. The triangle surrounds the former temple of Madhyameshavara, which was the original centre of Kashi. Pilgrims walking along the triangle are symbolically circumambulating the cosmos.

Sacred cities

There are numerous sacred cities in the Indian sub-continent that were either built to an archetypal master-plan or grew organically by virtue of being connected to a specific celestial deity. Some of the important sacred cities are Varanasi, Vijayanagara, Ayodhya, Mathura, Bhaktapur, Tirupati, Kanchipuram, Dwarka, and Ujjain.

Robert Levy viewed the Indian sacred city as a structured ‘mesocosm’, situated between the microcosm of the individual and the macrocosm of the culturally conceived larger universe. Such a city is constructed of spatial connected mandalas, each of which is sustained by its own culture and performance. The movements of the festival year and rites of passage constitute a ‘civic dance’, which defines the experience of its citizens.

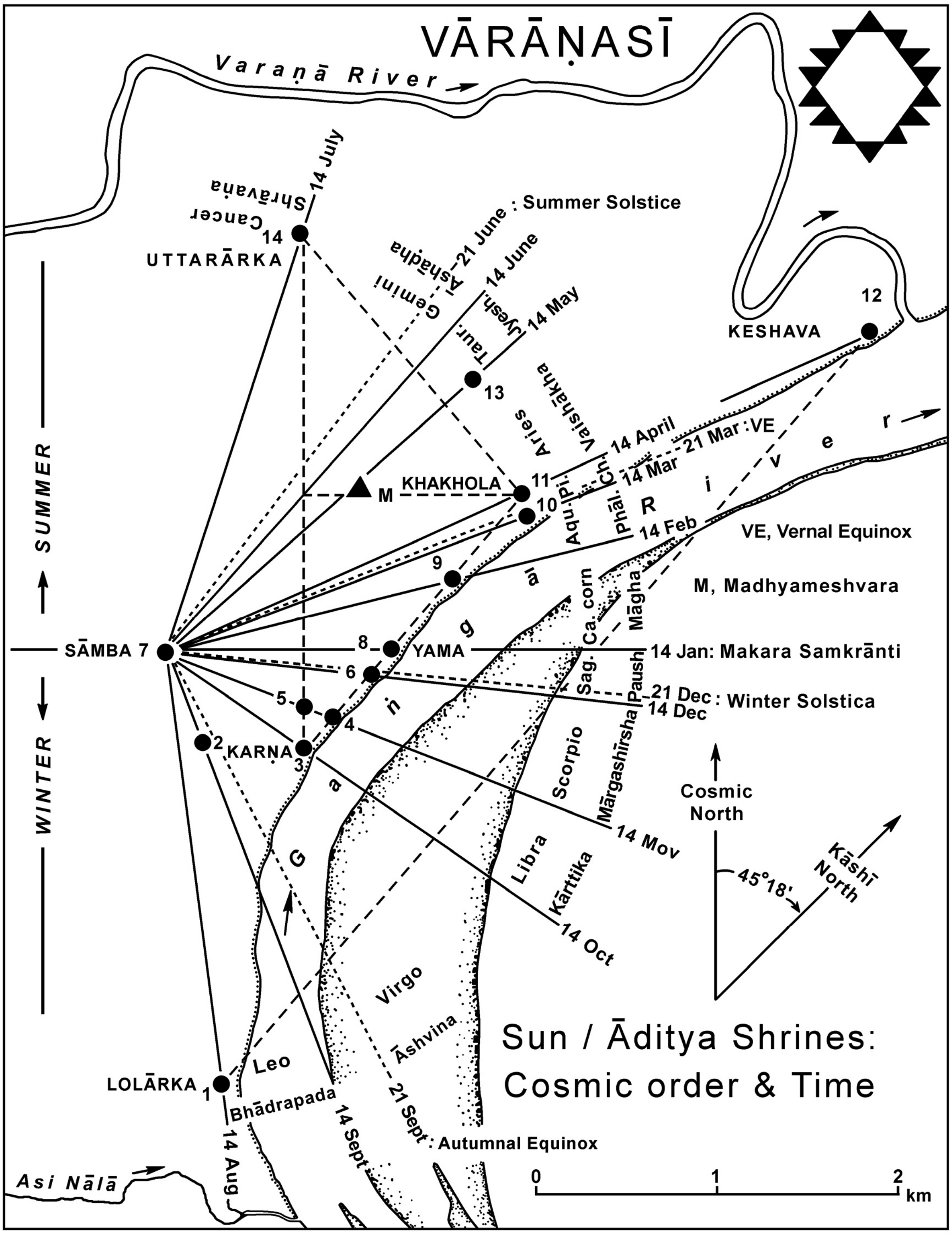

Fig. 6.0.2. Sun shrines at Varanasi: cosmic order and the cyclic orientation of time. After Rana P.B. Singh, *Banaras, Making of India’s Heritage City*, Newcastle: Cambridge Scholars Publishing, 2009.

The life-cycle passages and festivals dedicated to the gods affirm the householders' moral compass, identities and relationships. But there also exist other deities, represented generally by goddesses, who point to the forces of nature outside of moral order. These are brought into the larger order through Tantric invocations and amoral propitiatory offerings. Performances invoking the goddess are the responsibility of the king and the merchants.

Sacrality and royal power at Vijayanagara

The city of Vijayanagara (also known as Hampi) was founded in the 14th century and sacked in 1565. The best-known kings associated with Vijayanagara are Harihara I and II and Bukka Raya I (c. 1336–1404), and Krishnadevaraya and his half-brother Achyutadevaraya (1509–1542). From the mid-14th century to 1565, the city was the capital of the Vijayanagara Empire. According to the Persian ambassador Abdur Razaaq (1442): 'The city of Vijayanagara is such that the pupil of the eye has never seen such a place like it, and the ear of intelligence has never been informed that there existed anything to equal it in the world'.

Hampi had been an important pilgrimage city for centuries owing to its mythical association with the river goddess Pampā and her consort Virupaksha, or Pampāpati. An inscription dated 1163 records a *mahādāna*, a religious offering in the presence of Lord Virupaksha of Hampi by the Kalachuri King Bijjala. The region was part of the kingdom of Kampiladeva until 1326 when the armies of Mohammed Bin Tughlaq defeated the king and imprisoned the two sons of Sangama, Hukka and Bukka. Some years later, the Sultan sent the two as governors of the province. In 1336 they broke free from the Tughlaq allegiance and established the Sangama dynasty with its capital at Vijayanagara.

The destruction of Vijayanagara in 1565 was complete and cruel: in a few days a magnificent and prosperous city was reduced to ruins, its population slaughtered.

Hampi has a strong association with the Ramayana and the names of many sites in the area bear names mentioned in the epic. These include Rishimukha, Malyavanta hill and Matanga hill along with a cave where Sugriva is said to have kept the jewels of Sita. The site of Anegundi is associated with the kingdom of Angad, son of Vali. The Anjaneya Parvata, a hill to the west of Anegundi, is the fabled birthplace of Hanuman.

Each year, in the month of Chaitra (March-April), the marriage of Hampi to Lord Virupaksha (or Shiva) is re-enacted, with the priests of Virupaksha temple devoutly performing every ritual from Phalapūjā (betrothal) to Kalyānotsava (marriage) in the temple.

The Sacred Centre of the city lies south of the Tungabhadra River, and is dominated by the four large complexes of the Virupaksha, Krishna, Tiruvengalanatha (Achyutaraya) and Vitthala temples. The major temples are either close to cardinality, departing by an average of 10´, or are oriented to major features of the sacred landscape.

Further south of the Sacred Centre is the Royal Centre, which is divided into public and private realms. The dividing axis runs north-south and passes almost precisely between the king's 100-column audience hall in the east and the queen's large palace in the west. The Ramachandra temple pierces the axis and connects the private and the public domains. In the homology of the king and the deity, the royalty and divinity of Rama are inseparable.

The Virabhadra temple is on the summit of Matanga hill, which is the centre of the *vāstu-mandala* and the symbolic source of protection that extended outward from it along radial lines. As viewed from a point midway between the audience hall and the queen's palace, the *shikhara* of the Virabhadra lies only 4´ from true north. From the ceremonial gateway in the corridor west of Ramachandra temple, the summit of Matanga hill is just 0.6´ from true north.

The orientations of the major axes of the small temples, shrines, and palaces of the urban core are in marked contrast to these. The smaller structures deviate from cardinality by 17°, suggesting that they were influenced by the position of the rising sun on the morning when it crosses the zenith.

Prospects for the future

Interest in archaeoastronomy and art, as connected to temples and ancient monuments, has blossomed in India as the country's prosperity has increased. This new interest also owes much to the major archaeological discoveries that have been made in the past few decades and to the importance of temple tourism. The interest of the Indian authorities in astronomical heritage is clearly manifested by the 2009 nomination of the Jantar Mantar of Jaipur (see Case Study 6.1) for the World Heritage List, with a reasonable chance of gaining recognition from the Committee. The intention was to make a serial nomination with other Jantar Mantar of Northern India.

The principal authority over significant sites is the Indian Archaeological Survey of India (ASI) and its sister institutions that function at the state level as Departments of Archaeology and Museums. In 1976, the Indian government initiated projects to excavate three great medieval cities: Fatehpur Sikri in Uttar Pradesh, Champaner in Gujarat, and Vijayanagara in Karnataka, which are UNESCO World Heritage sites. The wealth of discoveries made in these cities is strengthening the movement to expose and preserve other sites in the country. Excavation, conservation, and research work can only be expected to increase. In particular, greater attention will be given to the archaeoastronomical aspects of the monuments.

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Case Study 6.1: The Jantar Mantar at Jaipur, India

Michel Cotte

Presentation and analysis of the site

Geographical position: City of Jaipur, State of Rajasthan, India.

Location: Latitude 26º 55′ 27″ N, longitude 75º 49′ 19″ E. Elevation 440m above mean sea level.

General description: The Jantar Mantar of Jaipur is an observatory built in the first half of the 18th century. Today it has 19 main astronomical instruments or groups of instruments. They were generally constructed of brick rubble and plaster, but a few were made of bronze. They were built for naked-eye observations of the celestial bodies and precision was achieved through their monumental dimensions. Generally speaking, they replicated the design of earlier instruments, but the site shows important architectural and instrumental innovations and the size of some of the instruments is among the largest in the world. There are instruments working in each of the three main classical coordinate systems: the horizon-zenith local system, the equatorial system and the ecliptic system. One instrument (Kapala Yantra) is able to work in two systems and to transform coordinates directly from one system to the other. This is one of the most complete and impressive collections in the world of pre-telescopic masonry instruments in functioning condition.

Inventory of the remains: The most significant instruments (yantras) among the collection are:

- Brihat Samrat, probably the largest gnomon-sundial ever built. With a gnomon arm 22.6m high and two lateral quadrants of radius 15.15m, it measures local time to an accuracy of 2 seconds.
- Sasthamsa, which has four large meridian dials inside two high black chambers.
- Jai Prakash, a highly innovative sundial made of two hemispherical bowls that produce an inverse image of the sky and allow the observer to move freely around inside to take readings.
- Great Ram is a rare, and perhaps unique, double-cylinder instrument to record the azimuth of celestial bodies;
- Raj comprises a bronze astrolabe 2.43m in diameter, probably the largest in the world.
- Kapala is able to record the co-ordinates of celestial bodies in both the azimuth-altitude and equatorial systems, and permits a direct visual transformation of the co-ordinates of any point in the sky between the two systems;
- Rasivalaya is a unique group of 12 gnomon-dials to measure the ecliptic co-ordinates of celestial objects, each becoming operative when a different one of the 12 zodiacal constellations straddles the meridian.

History of the site: The Jantar Mantar Observatory was built by Maharaja Sawai Jai Singh II, as a focal point of his new capital, Jaipur, the first and earliest geometrically planned city in India. Jai Singh II was one of several powerful princes rising to power as the influence of the Mughal Empire decreased. In his attempt to become an almost independent ruler of Rajasthan, he started to build a new capital underlining the link between scientific capacities, urban planning and social control. The construction of the observatory site started in the 1720s and was completed in 1738.

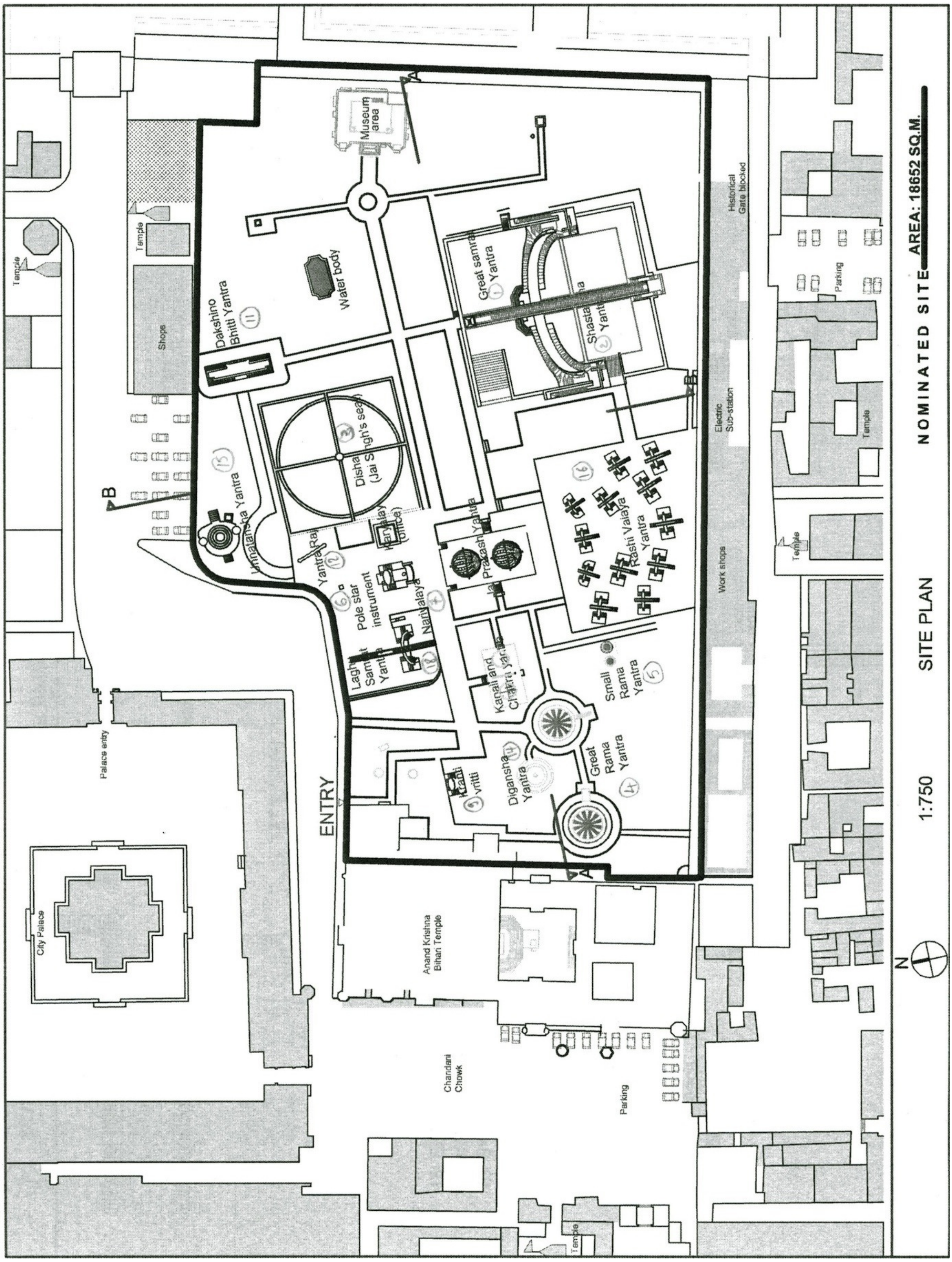

Fig. 6.1.1. Map of Jaipur. © Department of Arts, Literature and Culture, Government of Rajasthan

Fig. 6.1.2. Jaipur: general view. © Department of Arts, Literature and Culture, Government of Rajasthan

Jantar Mantar is the most complete and best-preserved great observatory site built in the Ptolemaic tradition. This tradition developed from Classical Antiquity through to Medieval times, and from the Islamic period through to Persia and China. Jantar Mantar was greatly influenced by earlier great observatories inside central Asia, Persia and China.

The observatory was very active during the life of Jai Singh II, with around 20 permanent astronomers. After his death in 1743, this key landmark in the centre of the capital city of Rajasthan remained in use almost continuously until around 1800. This is evident from the fact that repairs were carried out at least twice during this period. Nevertheless, during the 19th century the site ceased to function permanently as an observatory, being re-opened from time to time between periods of low activity or complete abandonment. Some important restorations occurred at the end of the 19th century, and mainly in 1902, under British rule. This started a new life for the observatory as a monument of Rajasthan. Other campaigns of restoration occurred during the 20th century and the most recent took place in 2006–07.

Cultural and symbolic dimension: The main aims of Jai Singh II's scientific programme were to refine the ancient Islamic zīj tables, to measure the exact hour at Jaipur continuously and to define the calendar precisely. Another aim was to apply the cosmological vision deriving from the Ptolemaic one, based upon astronomical facts, to astrological prediction—both social (e.g. predicting monsoon and crops) and individual (e.g. printing almanacs). This was an important period for the popular adoption into the ancient Hindu tradition of astronomical data coming from Islamic and Persian civilization. The interweaving of science, cosmology-religion and social control has had a great importance in Rajasthan culture since the 18th century, and continues into current times.

Fig. 6.1.3. Jaipur: Brihat Samrat. © Department of Arts, Literature and Culture, Government of Rajasthan

Authenticity and integrity: The main issue here is the number of repairs and sometimes almost complete restorations through the centuries.

In relation to scientific issues and symbolic significance, the integrity of the current property is no less satisfying than that of the original one. Wherever destruction has taken place in order to facilitate restoration, the functional capabilities of the instruments have been safeguarded.

The authenticity of the different instruments is a more complex issue. Most of the scale graduations were originally made of grooves cut in hydraulic lime plaster surfaces, either left open or filled with lead. Just few were made of engraved marble. However, the twentieth-century restorations tended to change this proportion, replacing plaster by marble. During restorations, some staircases were added or modified, new materials were used in rebuilding, and the coating of walls was completely renewed. In some cases it is difficult to know the exact appearance and the detailed structure of the original instrument. It also seems that some Western re-interpretations of the graduated scales took place during the early 20th century.

Documentation and archives: The public offices of the Government of Rajasthan and the Jaipur Library hold important collections of archives and documents. The Department of Archeology and Museum of Rajasthan keep all the works records since 1968.

Present site management

Present use: The site is used for tourism, with more than 700,000 annual visitors in 2006–08. Furthermore, the instruments are in a usable state, and staff or authorized persons are able to perform astronomical observations.

The site is managed by the Department of Archeology and Museum of Rajasthan. The official local staff has around 12 members. Maintenance and survey tasks are subcontracted to private companies, involving around 30 permanent workers on site.

Protection: Jantar Mantar is a public property and is governed by the Archeological Sites and Monuments Act of Rajasthan (1961). It is also protected as a National Monument of Rajasthan (1968).

State of conservation: Following a significant programme of architectural maintenance and restoration that took place in 2006–07, the general state of conservation of the Jantar Mantar seems good. Nevertheless, the metal instruments need some renovation and perhaps some restoration.

Context and environment: The property is set within the historical city of Jaipur, close to the former Royal Palace. It remains close today to the Hawa Mahal Palace and to the City Palace. This buffer zone is both a dense urban landscape and a historical environment of huge importance.

The authorities intend to reshape the landscape around the site for better use in harmony with urban constraints and development: road traffic, car parks, pedestrian access for tourists, etc.

Archaeological/historical/heritage research: For the protection and assessment of the site, the staff produce regular photographic documentation in similar viewing conditions. For science, the main goal is to maintain the instruments through use, by increasing their capacities for current users. For improving the global authenticity-integrity of the site, there is a programme of research and restoration devoted to the historical landscape and natural environment of the monuments.

Main threats or potential threats to the site: The main threats to the site appear to come from:

- the intense and increasing tourist use of the site;
- some water penetration inside the foundations due to rains and to watering during dry seasons; and
- urban pollution.

World Heritage status: The Jantar Mantar of Jaipur is an applicant for the World Heritage List, campaign 2010.

Chapter 7: Mesopotamia and the Middle East

John Steele

The earliest known written sources dealing with astronomy come from the regions of ancient Assyria and Babylonia located in what is now Iraq and its neighbours. These sources are written in the Akkadian language using cuneiform writing on clay tablets. Because clay is a non-perishable material, especially when baked (either intentionally in an oven or in sunlight, or unintentionally in a burning building), several hundred thousand cuneiform tablets have been recovered from archaeological sites in Mesopotamia, and many more are almost certainly still in the ground. Only a small proportion of cuneiform tablets, perhaps around 1%, concern astronomy, but this translates into about 5000 tablets dealing with astronomical observation, prediction, theory and astrology. Of these 5000 tablets, probably between one half and two thirds have been studied and published; work continues on the slow process of publishing the remainder.

Textual evidence indicates that in Mesopotamia the sun, moon, planets, and certain stars and constellations had already been named by the 3rd millennium BC. Also by this time, and quite possibly much earlier, a luni-solar calendar was in use comprising twelve lunar months which began on the evening of first lunar-crescent visibility with intercalations roughly every three years. By the Old Babylonian period (first half of the 2nd millennium BC), the earliest mathematical schemes for modelling changes in celestial phenomena (the length of day and night) had been developed. Also around this time we find the earliest celestial omens based upon the appearance of the moon during an eclipse.

In the 1st millennium BC we find evidence of a large range of astronomical activity in Assyria and Babylonia. This includes: regular and systematic observation; the identification of lunar, solar and planetary periodicities; the development of empirical methods of predicting future astronomical phenomena such as passages of planets by reference stars, lunar and solar eclipses and the dates of first and last visibility and stations of the planets; the development of mathematical methods of calculating lunar and planetary phenomena; the astrological interpretation of celestial events; and the advance prediction of the calendar. Many aspects of Mesopotamian astronomy were transmitted to Greece, India and other cultures, including: the zodiac; the sexagesimal number system; many numerical parameters that underlie the astronomical theories of Ptolemy and other astronomers; whole systems of mathematical astronomy; and, indeed, the very notion that astronomical events can be analysed numerically and predicted.

The astronomical heritage from Mesopotamia is largely in two forms: (i) tangible moveable heritage, namely cuneiform tablets containing astronomical texts; and (ii) intangible heritage, namely the legacy of Mesopotamian astronomy in the astronomy of other cultures. No tangible immovable heritage is known; for example, no buildings have been identified as astronomical observatories or sites, there is little evidence for the use of astronomy in town planning, etc. Given these facts, it is difficult to imagine being able to make a case for heritage status for any ancient Mesopotamian site on astronomical grounds.

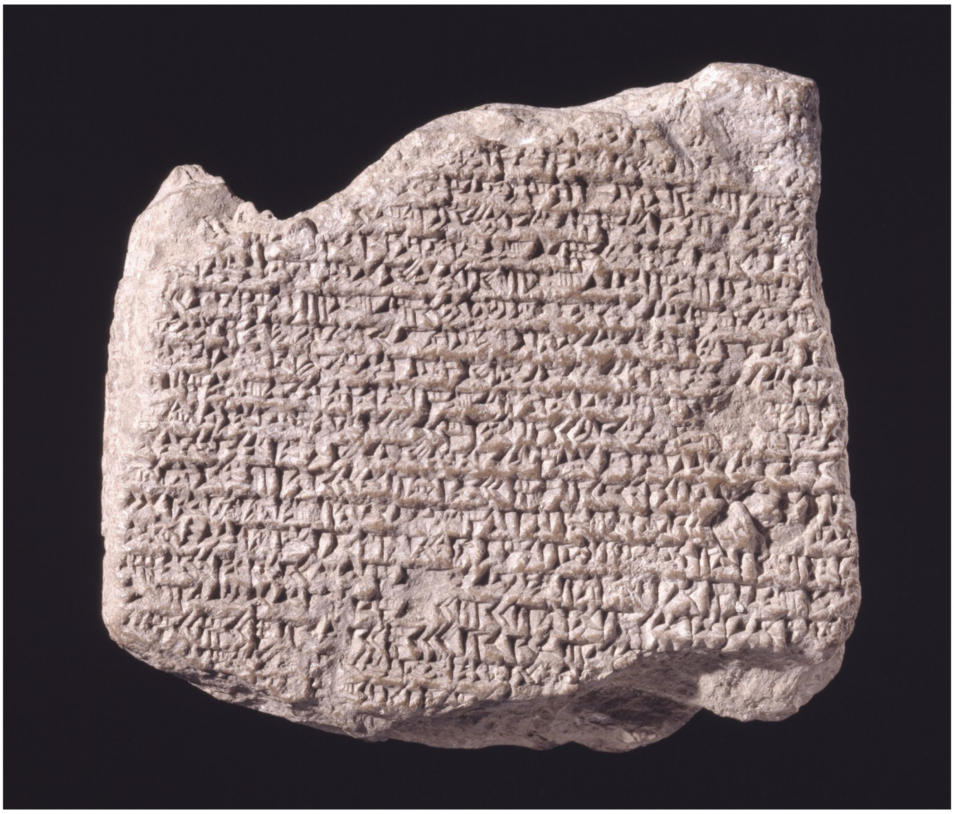

Fig. 7.0.1. An astronomical diary from Babylon containing astronomical records from the last months of year 175 of the Seleucid Era (137–136 BC). Among the observations reported is a detailed account of the total solar eclipse of 15 April 136 BC. BM 45745. © Trustees of the British Museum

Astronomical Cuneiform Tablets from Assyria and Babylonia

Astronomical cuneiform tablets have been recovered from a number of sites throughout Mesopotamia. Almost all preserved tablets date to the Neo-Assyrian (c. 750–600 BC) and Late Babylonian (c. 750 BC – AD 75) periods, although some are clearly copies of earlier works. From Assyria, several hundred astronomical tablets have been recovered from Nineveh, with smaller numbers found at Ashur and Nimrud. From Babylonia, more than four thousand tablets have been recovered from Babylon, a few hundred from Uruk, and a handful from each of Sippar, Nippur and Ur. Outside of Mesopotamia proper, a small number of astronomical cuneiform tablets were found at the Neo-Assyrian city of Sultantepe.

Like most types of cuneiform tablets, astronomical tablets have been recovered in three different ways:

(i) Purchases (19th and early 20th century) by museums of tablets from antiquities dealers. Almost always with purchased collections, no—or at best very little—information concerning provenance is available. Even the assignment of tablets to particular cities is sometimes open to question: usually this assignment is only possible through internal evidence of the text itself and by comparison with other material purchased in the same lot.

(ii) Non-scientific excavations (19th and early 20th century). It is often the case that tablets recovered by early excavations have almost as little provenance information as material from purchased collections.

(iii) Scientific excavations (early 20th century onwards). Beginning with the German excavations of Ashur, Babylon and Uruk, detailed excavation notes indicate the exact find-spots of individual (or sometimes groups of) tablets.

No astronomical tablets are currently known that are in private collections from recent illicit excavations and the illegal antiquities trade.

The various ways that cuneiform tablets have been recovered, and changing laws governing excavated items, have meant that astronomical tablets are now located in at least 17 museums in Europe, the Middle East and the USA. The following table summarises the museums that hold astronomical cuneiform tablets known to the author as of July 2009.

Museum	**Number of Astronomical Tablets**	**Source of Tablets**
Ankara Archaeological Museum	11	Sultantepe
Arkeoloji Müzeleri, Istanbul	c. 150	Uruk
Ashmolean Museum, Oxford	1	Babylon
Birmingham Museum and Art Gallery	4	Babylon
British Museum, London	> 4000	Babylon, Nineveh, Sippar, Ur
Columbia University Library, New York	4	Babylon
Dropsie College, Philadelphia	1	Babylon
Harvard Semitic Museum, Cambridge, Mass.	2	Babylon
Heidelburg	c. 10	Uruk
Iraq Museum, Baghdad	c. 20	Babylon, Uruk, Sippar
Kelsey Museum of Archaeology, Ann Arbor	1	Babylon
Louvre, Paris	c. 15	Uruk, miscellaneous purchased tablets
Metropolitan Museum, New York	11	Babylon
Musée de Rouen	1	Babylon
Oriental Institute, Chicago	27	Uruk
University Museum, Philadelphia	18	Babylon, Nippur
VAM, Berlin	c. 100	Babylon, Uruk, Ashur
Yale Babylonian Collection, New Haven	10	Uruk

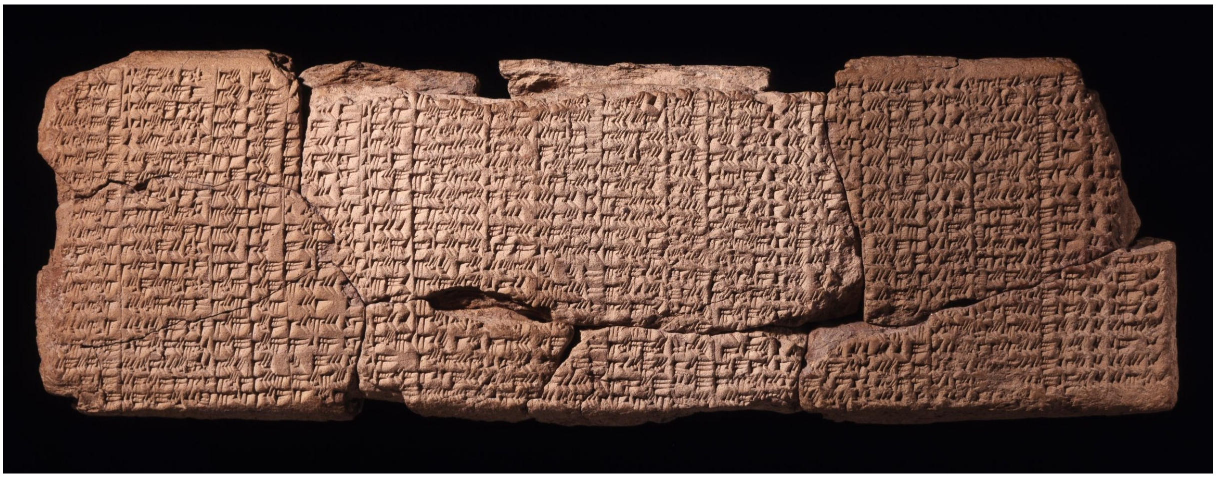

Fig. 7.0.2. A lunar ephemeris from Babylon calculated using ‘System B’. The tablet covers the years 208–210 of the Seleucid Era (104/103 – 102/101 BC). Since this photograph was taken, four small fragments of the tablet have been identified by the author among the holdings of the British Museum and rejoined to this large fragment. The process of identifying and joining tablets is an important part of working with cuneiform astronomical tablets. BM 34580+42690. © Trustees of the British Museum

The wide spread of astronomical cuneiform tablets throughout different museums poses challenges for assessing the astronomical heritage of Mesopotamia. The most extreme example of this is when fragments from an original tablet end up in different museums, making it impossible to study both parts of the text together, or to join the tablets together. Different museums operate different policies with regard to access to their collections. For example, the British Museum operates an open access policy, where anyone can study and publish any tablet. The VAM in Berlin, however, aims to coordinate the publication of their collection so that all material excavated together is published together. Both policies have their advantages and disadvantages: the British Museum's open access policy means that anyone can study any astronomical tablet at any time, but can lead to 'cherry picking', where tablets that are hard to read, badly preserved, or considered uninteresting never get published. The Berlin policy ensures that everything is published, and published in a way that preserves the archaeological context in which the tablets were found, but can lead to long periods of time during which the material is unavailable to scholars. Political circumstances mean that access to the collections of some museums is difficult or even impossible at the present time.

Astronomical Heritage in the Broader Middle East: Qumran

The Dead Sea Scrolls discovered in caves in Qumran include a number of texts dealing with astronomy and the calendar. Prominent among them are fragments of the so-called 'Astronomical chapters' of the Book of Enoch, commentaries on these chapters, and texts concerned with related calendrical and astronomical schemes. Some of this material has clear links with earlier Mesopotamian astronomy and with later Ethiopic astronomy. Publication of all the Dead Sea Scroll texts is underway in the series *Discoveries in the Judaean Desert*.

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Chapter 8: Ancient Egypt

Juan Belmonte

In this chapter we will not deal with the history of mathematical or theoretical astronomy as a natural science, which is hard to trace in ancient Egypt, but rather with the cultural aspects of the discipline. These are the main focus of archaeoastronomy, an interdisciplinary subject in which the powerful tools of spherical and positional astronomy are brought to bear on anthropological and historical questions that could be difficult to address in other contexts: questions such as how people measured time; how they created calendars, sacred or profane; how they orientated sacred structures appropriately according to religious requirements; and how they mapped the sky for suitable guidance, whether for eschatological reasons or for simpler, more prosaic needs.

All such questions are intrinsically related to several important aspects of any culture, whether ancient or modern. Ancient Egypt is no exception and this fact is reflected in its heritage. Setting aside a few outdated commentaries on the development of ancient Egyptian mathematical astronomy, it has become clear in the last decade and a half that sky-watching, and sky-watchers, played a highly significant role in various aspects of the civilization of the pharaohs right through from the proto-dynastic period, when we encounter the first evidence of a lunar calendar probably governed by the Nile regime, to the Ptolemaic and Roman periods, when one of the last masterpieces of Egyptian astronomy, the Zodiac of Dandara (see Case Study 8.3), was created. Thus, for a period of more than 3000 years, Egyptian sky-watchers scrutinized the firmament in a serious attempt to find accurate answers to the questions stated above.

The astronomical/archaeoastronomical context

The ancient Egyptians were keen sky-watchers, as archaeology, epigraphy and history demonstrate. They developed a remarkable time-keeping system that finally produced one of the most sophisticated calendars ever invented by humankind. They completely mapped the skies using a series of evocative constellations, asterisms and individual stars. Their motivations were both prosaic, for example stellar clocks, and highly metaphysical, with the idea of developing a superb and everlasting astral eschatology. They aligned their temples in perfect agreement with the perceived cosmic order, choosing selective patterns of astronomical orientation that differed according to the place, the epoch, and the characteristics of the relevant divinity or divinities. They even invented a ceremony, ‘the stretching of the cord’, to fulfil their expectations. And finally, they may well have selected certain sites within their homeland where cosmic order would be manifested in landscapes reflecting both earthly and celestial aspects of reality.

All this can be easily traced in the material evidence scattered along the Nile Valley and in the nearby oases that has been diligently uncovered from the sands by a legion of dedicated Egyptologists. Essentially, this heritage can be categorised as follows:

1. **Papyri** including astronomical texts or religious writings from which astronomical information can be extracted. The astrological papyri of the Greco-Roman period could also be included here.
2. **Diagonal (decanal) clocks** found among religious items, mainly coffins, dating from the late Old Kingdom onwards. The related 'coffin texts' may also contain relevant information. These items are mostly held in museums away from their original context.
3. The **pyramid texts** of the Old Kingdom, where one finds the earliest stellar references within the context of a complex astral eschatology. The coffin texts of the Middle Kingdom and the various religious books of the New Kingdom and the Late Period (*Am-Duat*, *Book of Day and Night*, *Book of Caverns*, *Book of Gates*, etc.) continue some aspects of this tradition.
4. **Feast calendars** found in religious contexts, either in tombs or temples (sometimes in papyri, but mostly in monumental inscriptions) from the Old Kingdom onwards. Those containing Sothic dates have been critical in establishing ancient Egyptian chronology. Some individual dates found in other documents could also be included in this category.
5. **Astronomical ceilings** of the New Kingdom onwards with more or less sophisticated celestial diagrams. These can include lists of decans, names and representations of constellations and planets, calendars, and stellar clocks.
6. **Astronomically aligned temples** or sacred buildings of different epochs and regions. It has recently been established that a number of astronomical patterns were followed in Egypt. The dominant astronomical targets for orientation were the northern constellation of Meskhetyu; Sirius (Sopdet or Sothis), the brightest star in the Egyptian sky; and the stations of the sun, namely the winter solstice and the spring equinox, or Wepet Renpet (Egyptian New Year's Eve).
7. **Cosmic landscapes**, where the term is taken to mean the location of important sites (of ancient Egypt and beyond) at places where astronomical alignments and the local topography combined so as to reproduce on Earth the cosmic order for which the Egyptians were constantly searching.

The historical and cultural context

Ancient Egyptian history has been divided into great periods or great kingdoms for more than 2000 years and this custom is universal within modern Egyptological studies. However, the ancient Egyptians themselves did not group their rulers according to such criteria. Instead, they seem to have developed the notion of dynasties throughout their history. The exact length and definition of the periods is not agreed. A typical schematic chronology is shown in Table 8.0.1.

Dates before the New Kingdom are approximate and should be treated with caution. Astronomical 'monuments' were erected during all the periods from the early dynasties onwards. (The first evidence of the 'stretching of the cord' ceremony is dated to the 1st Dynasty, according to the Palermo stone.) However, the vast majority of the remains are dated to the three 'kingdoms', particularly the Old and the New, and during the Ptolemaic period. It was during these epochs that the impressive pyramids were built, the pyramids texts written, the best astronomical ceilings created, and the huge astronomically aligned temples erected. A notable exception to this rule is the decanal clocks found in coffins of the 1st Intermediate Period and the Middle Kingdom.

It has been suggested that the astronomical tradition in Egypt started several millennia before the historic period, on the shores of a long-extinct lake at an enigmatic site in the middle of the Western Egyptian Desert: Nabta Playa. In this spot—now deserted, barren and far from any human habitation—a group of cattle-herders erected a number of small monoliths. Some are in long alignments and one set forms a small stone circle or cromlech. Some appear to be astronomically aligned but whether this was intentional, and how the site should be interpreted, is highly controversial.

Late Predynastic	c. 3000 BC
Early Dynastic Period (1st –3rd Dynasties)	2920–2575 BC
1st Dynasty	2929–2800 BC
2nd Dynasty	2800–2650 BC
3rd Dynasty	2650–2575 BC
Old Kingdom (4th – 8th Dynasties)	2575–2134 BC
4th Dynasty	2575–2465 BC
5th Dynasty	2465–2323 BC
6th Dynasty	2323–2150 BC
7th/8th Dynasties	2150–2134 BC
First Intermediate Period (9th – 11th Dynasties)	2134–2040 BC
9th/10th Dynasties	2134–2040 BC
11th Dynasty	2134–2040 BC
Middle Kingdom (11th – 14th Dynasties)	2040–1640 BC
11th Dynasty	2040–1991 BC
12th Dynasty	1991–1783 BC
13th/14th Dynasties	1783–1640 BC
Second Intermediate Period (15th/17th Dynasties)	1640–1532 BC
New Kingdom	1532–1070 BC
18th Dynasty	1550–1319 BC
19th Dynasty	1319–1196 BC
20th Dynasty	1196–1070 BC
Third Intermediate Period	1070–770 BC
21st Dynasty	1070–945 BC
22nd Dynasty	945–712 BC
23rd Dynasty	c. 828–712 BC
24th Dynasty (Sais)	724–712 BC
25th Dynasty (Nubia and Theban area)	770–712 BC
Late Period (25th Dynasty–2nd Persian Period)	712–332 BC
Ptolemaic Period	332–30 BC
Roman Period	30 BC–384 AD

Table 8.0.1. A typical schematic chronology of ancient Egypt.

Ancient Egyptian ‘astronomy’ was intrinsically related to social, economical, political, and religious aspects of the culture. Astronomical ceilings, with their sophisticated celestial diagrams, seem to have been maps or guides to the afterlife but also helped the living to orientate themselves in time and space. Feast calendars, and the civil calendar itself, governed the religious and economic, and consequently the political, life of the country. Stellar clocks were probably developed for timekeeping at night and used in the context of temple administration and cult practices, but they were also offered to the dead kings as guides to the celestial ‘netherworld’. Astronomical orientations in sacred buildings produced impressive and suggestive hierophanies, possibly for practical reasons, but certainly for cult practices related to the display of power.

It is not easy to say how much of the heritage of Egyptian astronomy has reached the present. The civil calendar has certainly left a lasting mark, not only through its direct Coptic descendant but also through its apparent influence on the Gregorian calendar. However, tracing Egyptian influences in other Middle Eastern cultures, the classical world and early Christian astronomical practices is difficult and remains a matter of debate.

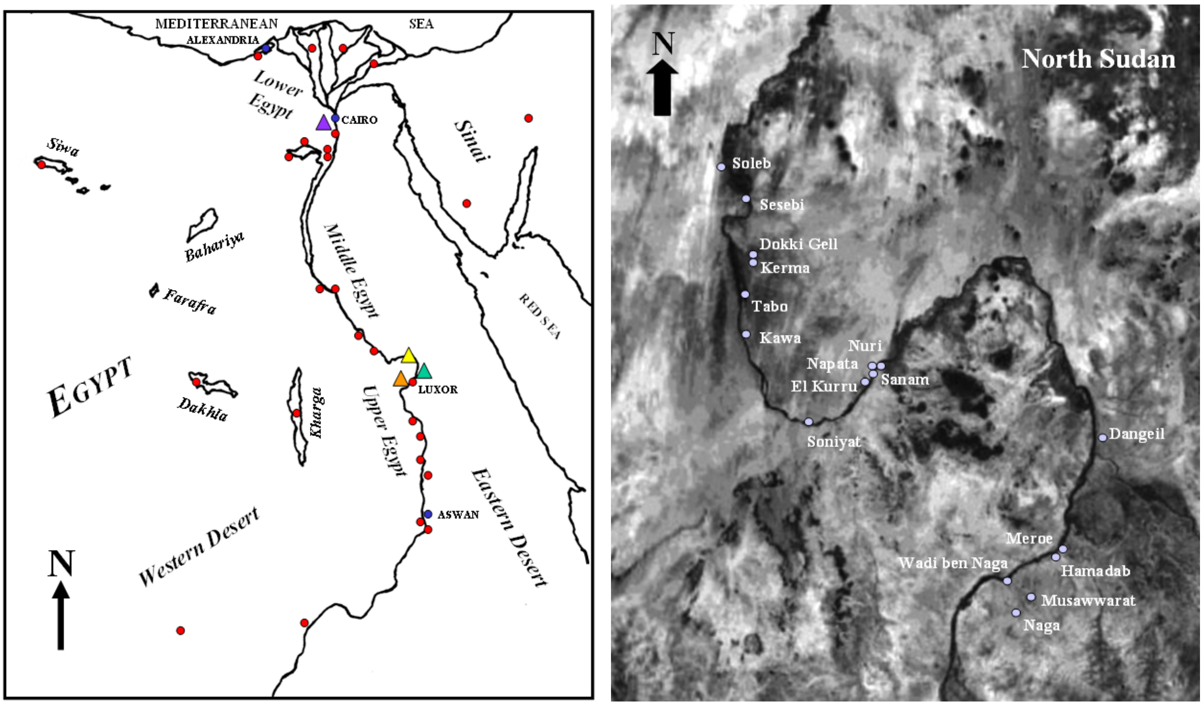

Fig. 8.0.1. Maps of ancient Egypt (left) and Kush (right) showing the relevant sites, including the locations of the Case Studies: Western Thebes (orange triangle), Karnak (green triangle), Dandara (yellow triangle) and Giza (purple triangle) in ancient Egypt and the sector of Napata in ancient Sudan. © Juan Belmonte

Geographical limits

Figure 8.0.1 illustrates the geographical extent of our theme. It includes the entire territory occupied today by the Arab Republic of Egypt, including the valley of the Nile plus the Delta, the Sinai Peninsula, where the impressive temple of Serabit el Khadim is located, the Oases of the Western Desert (Siwa, Bahariya, Farafra, Dakhla and Kharga), isolated complexes in the Eastern and Western desert, and the Mediterranean coast.

The area also extends further south within the present frontiers of Sudan to the area occupied by the ancient Kingdom of Kush, to the south of the Nubian region today inundated by the waters of Lake Nasser (Lake Nubia in Sudan). This area includes monuments of purely Egyptian origin together with those erected over a period of more than ten centuries (roughly from the 7th century BC [Egyptian 25th Dynasty] to the 4th century AD) by the sovereigns of Kush, governing first from the city of Napata and later from the city of Meroe. This area is virtually unexplored from the archaeoastronomical point of view, although some preliminary results suggest that the same trends evident in ancient Egypt are reproduced in Kush with a few intrinsic peculiarities.

There are also a handful of Egyptian monuments scattered outside the frontiers of Egypt. A nice example is the temple of Hathor at Timna, in the Negev Desert, Israel.

Main sites and evidence

A number of monuments in Egypt and Sudan are included in the World Heritage List. Some of these are related to ancient Egyptian civilization, namely (from north to south):

(i) Memphis and its Necropolis—the Pyramid Fields from Giza to Dahshur;
(ii) Ancient Thebes and its Necropolis;
(iii) Nubian Monuments from Abu Simbel to Philae; and
(iv) Gebel Barkal and the sites of the Napatan Region.

The first two of these World Heritage Sites include a large number of different monuments. Group (i) includes the majority of the pyramids of the Old Kingdom plus a handful from the Middle Kingdom, including the famous Giza group, the pyramid of Zoser at Saqqara and the pyramids with texts of the 6th and late 5th Dynasties. It also incorporates the beautifully decorated mastabas of the Old Kingdom, with their lists of festivals, and the scattered ruins of ancient Memphis. Group (ii) covers a large and extremely impressive area that includes the famous temples of Luxor and Karnak, the Valleys of the Kings and the Queens, the Million Year Temples of New Kingdom pharaohs, and several groups of tombs of the nobles. This is one the largest concentrations of archaeological remains anywhere on Earth and astronomical connections are ubiquitous. Group (iii) comprises the marvellous temples of Ramses II at Abu Simbel, famously penetrated by a shaft of sunlight on just two dates in the year, and the temple of Isis at the island of Philae, together with several other temples along the shores of Lake Nasser. All of these temples have been moved from their original location. Group (iv) includes all the monuments built in the area of ancient Napata by the Egyptian pharaohs and their successors in the region, the Kings of Kush. Napata was the first capital city of that kingdom and an important cult and pilgrimage centre for the god Amun at the foot of the mountain Djebel Barkal. The World Heritage Site includes also the famous pyramid fields of El Kurru, Barkal itself, and Nuri.

Table 8.0.2 contains a preliminary list of sites that contain significant astronomical heritage. The list has been prepared following geographical criteria and entries have been classified according to the seven categories defined above. Those sites that fall within one of the four groups above, i.e. are included within an existing World Heritage Site, are shown in italics. The preliminary nature of the list must be emphasized. It is by no means exhaustive, nor is it complete. New monuments or objects may be proposed or identified in the future, as may different and new categories: for example, the scant remains of the ancient *Bibliotheca Alexandrina* and the Serapeum in the same city are not included in any of the suggested categories but must certainly be included in our list.

Preservation and conservation

The Supreme Council of Antiquities of the Arab Republic of Egypt (hereafter SCA) and the Archaeology Service of the Islamic Republic of Sudan (hereafter ASS) are making every effort to keep their monuments in the best possible state of preservation and to safeguard their precious heritage. However, this is not always an easy task considering the huge territory to be covered and the large quantity of monuments needing to be preserved. In many cases these monuments are either completely isolated or else located inside rapidly expanding urban areas. In neither case is protection an easy task.

For example, according to unofficial reports the site of Nabta Playa (see above) has been suffering acts of vandalism in the last few years. As a result, the Egyptian authorities recently decided to move the so-called calendar circle (a standing-stone circle with possible solar alignments) to the gardens of the Nubian Museum in Aswan. While this will protect the stones, it will change the status of the monument and perhaps the attributes of its value, raising questions of authenticity, integrity and conservation management.

However, ancient Egyptian monuments are, in general, well preserved and well protected by dedicated members and inspectors of the SCA. Only a few of the sites listed in Table 8.0.2 can be considered to be in significant danger. The tombs of the Valley of the Kings are one example, since the fluctuations in temperature and humidity caused by the hundreds of daily visitors are starting to cause damage to the impressive decorations. For this reason, some of the splendid celestial diagrams, such as that of King Seti I, are no longer accessible to the general public. The water-table is also a potential problem in a few cases, one being the Osireion in Abydos, where the chamber with the ‘Cosmology of Nut’ painted on its ceiling is occasionally inundated.

Location	Site	Category	Period	Brief description
NILE VALLEY (EGYPT)				
Alexandria	Bibliotheca	Library	Ptolemaic	Scant remains, including possible lecture hall
Alexandria	Serapeum	Sanctuary	Ptolemaic	Foundations and crypts
Buto	Uadjet temple	4 & 6	New Kingdom	In situ Festival List of Thutmose III
Behebit el Haggar	Iseum	6	Ptolemaic	Huge building in ruins
San el Haggar	Ancient Tanis	6 & 7	Late Period	Precinct of the Amun temple
Giza	*Pyramids*	*6 & 7*	*4th Dynasty*	*See Case Study 8.4*
Abu Ghurob	*Solar temples*	*6*	*5th Dynasty*	*Earliest temples dedicated to the Sun*
Saqqara	*Zoser precinct*	*6*	*3rd Dynasty*	*Pyramid, sanctuaries and 'serdab'*
Saqqara	*Pyramids*	*3, 6 & 7*	*5th & 6th Dynasties*	*Pyramid texts in burial chambers*
Saqqara	*Noble tombs*	*4*	*Old Kingdom*	*Festival lists. Calendar dates.*
Dashur & Meidun	Pyramids of …	6	4th Dynasty	Earliest true pyramids built by King Snefru
El-Fayoum	Seila pyramid	6	4th Dynasty	Earliest building cardinally oriented
El-Fayoum	Various sites	6	Ptolemaic/Roman	Temples oriented to New Year's Eve
El-Fayoum	Qsar Qarum	6	Ptolemaic	Solar hierophany at Sobek temple
Hermopolis Area	Various sites	6 & 7	Various epochs	Lunar God city. Lunar alignments?
Tell el Amarna	Atun temples	6 & 7	18th Dynasty	Solar temples with cosmic landscape
Athribis	Ancient site	5 (6?)	Ptolemaic	Zodiacs. Stretching-of-the-cord images
Abydos	Umm el Qab	6	Early dynastic	Earliest astronomically aligned structures
Abydos	Temples	4, 5 & 6	New Kingdom	Cosmology of Nut; List of the Kings
Dandara	Hathor temple	4, 5, 6 & 7	Ptolemaic/Roman	See Case Study 8.3
Luxor (Thebes)	*Karnak temple*	*4, 6 & 7*	*Several periods*	*See Case Study 8.2*
Western Thebes	*Valley of the Kings*	*3 & 5*	*New Kingdom*	*Several celestial diagrams and stellar clocks*
Western Thebes	*Deir el Bahari*	*6 & 7*	*11th & 18th Dynasties*	*Temples of Mentuhotep II and Hatshepsut*
Western Thebes	*Deir el Bahari*	*3 & 5*	*18th Dynasty*	*Senenmut's tomb; see Case Study 8.1*
Western Thebes	*El Assasif*	*3 &5*	*Late period*	*Tombs of Mentuemhat and Padamenope.*
Western Thebes	*Ramesseum*	*4, 5 & 6*	*19th Dynasty*	*Impressive celestial diagram*
Western Thebes	*Medinet Habu*	*4 & 6*	*20th Dynasty*	*Festival calendar; well-preserved temple.*
Esna	Khnum temple	5	Roman	Hypostyle hall with astronomical ceiling
Kom el Ahmar	Hieraconpolis	6	Early dynasties	Earlier-period monuments
Edfu	Horus temple	4 & 6	Ptolemaic	The best preserved temple in Egypt
Aswan	Elephantine	6	Several periods	Legendary origin of the Flooding. Nilometers
Philae Island	*Isis temple*	*6 & 7*	*Ptolemaic*	*Impressive grouping of temples*
Abu Simbel	*Main temple*	*6*	*19th Dynasty*	*Solar-illumination phenomenon*
(SUDAN)				
Kerma	Ancient site	6	Several periods	Earliest astronomical relationships in Sudan
Kawa	Amun temple	6 & 7	25th Dynasty	A possible local twin of Karnak; dais room
Area of Napata	*Barkal & Nuri*	*5, 6 & 7*	*Kingdom of Kush*	*See Case Study 8.5*
Meroe	Ancient site	4, 6 & 7	Kingdom of Kush	Temples and pyramids; 'observatory'
Butana Region	Musawwarat	6 (7?)	Kingdom of Kush	Huge sacred precinct; still to be studied
OASES & DESERTS				
Timna	Hathor temple	6	New Kingdom	Egyptian tradition far away from home
Sinai	Serabit	4, 6 & 7	MK and NK	Temple of Hathor; several steles
Siwa Oasis	Oracle temple	6	Late Period	Temple of Amun
Dakhla Oasis	Deir el Haggar	5	Roman	Latest celestial diagram
Kharga Oasis	Hibis temple	6	Late Period	Peculiar stretching of the cord image
Nabta Playa	Ancient site	6	Early Neolithic	Hypothetical solar and stellar alignments

Table 8.0.2. A preliminary list of ancient Egyptian sites that contain significant astronomical heritage. Those that are included within an existing World Heritage Site are shown in italics. The categories are those listed in the section 'Astronomical/archaeoastronomical context' above.

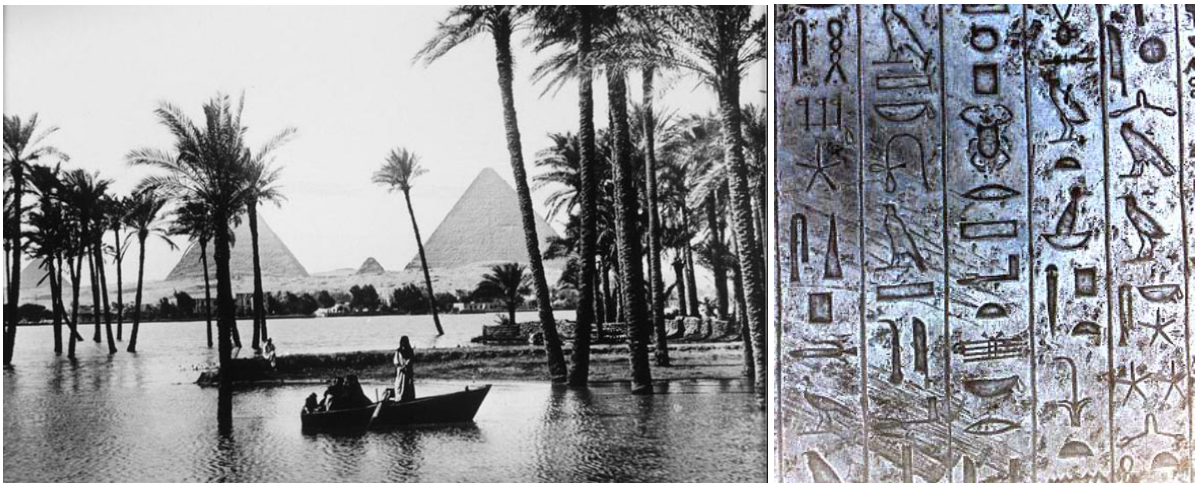

Fig. 8.0.2. The pyramids of Giza at a time of high flooding and the pyramid texts in the burial chamber of King Teti. Astronomy and topography as the nucleus of time keeping and astral eschatology, respectively. Photographs taken in the 1920s by Rudolf Lehnert and Ernst Landrock

On the other hand, the large temples and the pyramid fields are in a relatively good state of preservation considering their age. Sites are frequently fenced, entry is controlled, and even in tiny isolated places such as Serabit el Khadim, in the Sinai Peninsula, there are local guards taking care of the site, even at night (in this particular case, the robbing of stone stelae was frequent in the past). Excavation and conservation work is still carried out in most areas and interesting discoveries are often reported to the media. An example of recent conservation work is the cleaning and accessibility project that has been carried out by a Spanish Mission at the tomb of Senenmut during the last few years. Until now, the magnificent astronomical ceiling of this tomb (see Case Study 8.1) has been only open to a handful of specialists under strict regulations. The idea is to make it accessible to a wider public and even possibly to produce a replica of the tomb that could be visited by the hundreds of tourists who arrive in Deir el-Bahari every day.

An important characteristic of the astronomical heritage of the ancient Egyptian sites is the observation of phenomena such as the heliacal rising of Sirius or sunrise and sunset at particular points in the annual cycle. If modern atmospheric conditions prevent the possibility of actually observing these phenomena today, then they are detrimental to the appreciation of that heritage. For example, the smog created by the huge metropolitan area of Cairo prevents various rising phenomena being observable today from the pyramid fields of the vicinity (see Case Study 8.4), although fortunately other relevant phenomena (mostly settings) remain clearly observable.

Some of the Sudanese sites, such as Kawa and the Meroe ‘observatory’, are covered by sand but the majority are in well-protected areas where the ASS, in collaboration with international teams, continues to carry out excavations and conservation work. At present, the relevant archaeological sites in Sudan attract a much smaller number of visitors than is generally the case in Egypt. This in itself affords a degree of protection and the immediate threats to these monuments are insignificant. However, this situation could change in the next few years depending on the political and social situation in the country.

Perceived value of the sites

Tourism provides one of the most important sources of income for the Egyptian economy. Thousands of Egyptians are in employment that is either directly or indirectly related to tourism. Obviously, the civilization of the pharaohs is one of the main attractions of the country and the preservation and conservation, as well as the suitable exploitation, of the ancient sites is a necessity for the Egyptian authorities as well as a challenge for most of the population. Unlike many other Islamic societies (the other notable exceptions being Turkey and Tunisia), Egyptians are generally proud of their glorious ancient pre-Islamic past, although this feeling does not always correlate with economic motivation. This sense of pride is still stronger within the Coptic minority who consider themselves to be the true direct descendents of the ancient Egyptians.

It is pleasant to visit the Giza plateau in the low season, but all the more so outside the tourist season and during the academic term-time, when the site is still full of young Egyptian student visitors who show an evident sense of admiration and pride in their forefathers when it is explained to them that these huge monuments were aligned nearly perfectly to the cardinal points and that this could only have been achieved by watching the skies. An astonishing ambience is generated in the temple of Abu Simbel in late February and late October, on the dates when the sun penetrates into the deep sanctuary of the temple to illuminate the figures of the king and the solar divinities, Amun and Re-Horahkty, leaving in darkness the image of Ptah, god of the underworld. Ambassadors, high-ranking officials and Egyptian TV channels are among the elect few allowed to view the phenomenon at close range.

The Egyptian people and authorities are fully aware of the astronomical aspects of their ancient heritage where they relate to well-known phenomena and well-established evidence. However, many of the other sites listed in Table 8.0.2 are still ignored by the vast majority of the people and indeed by the local authorities, including the majority of the members of the SCA (on the positive side, the visitor may still be virtually alone, for example, observing sunrise at the winter solstice along the main axis of the temple of Karnak). In Sudan, the local pre-Islamic astronomical heritage is still largely unknown except for a selected group of interested scholars. All this could well change once the places concerned, and their related astronomical phenomena, become more widely known amongst the local communities (in both countries).

Fig. 8.0.3. Sunrise hierophanies at the sanctuaries of the temples of Abu Simbel (left) and Qsar Qarum (right), produced at the beginning of the Going Forth and Draught seasons of the civil calendar, and the winter solstice, respectively. Photographs © Juan Belmonte

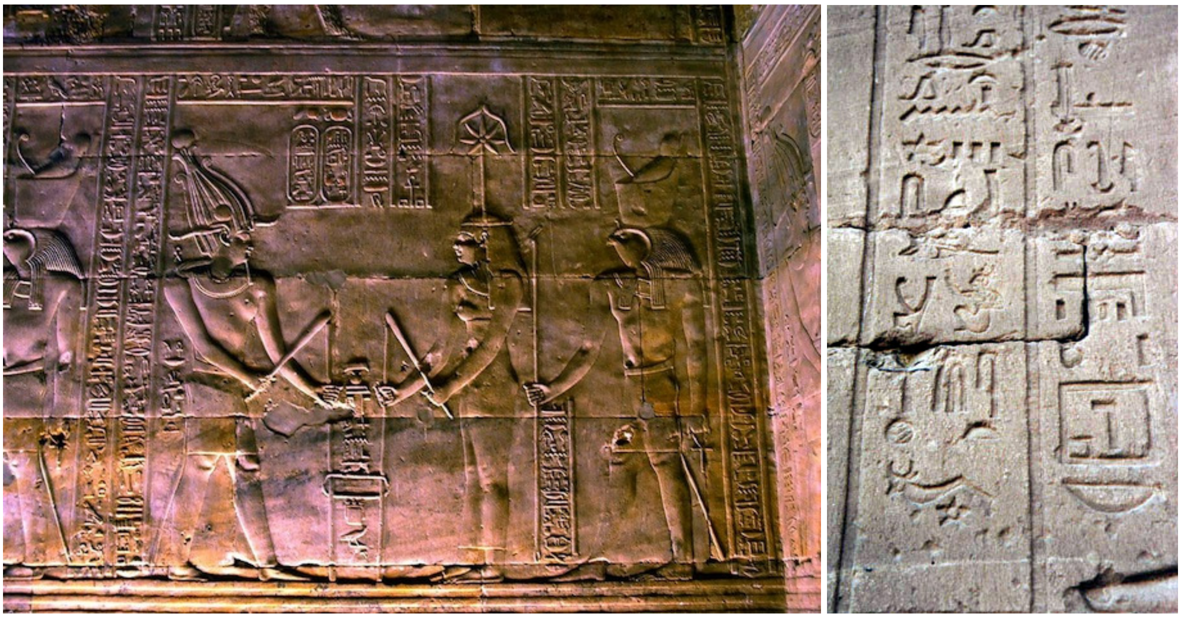

Fig. 8.0.4. The ‘stretching of the cord ceremony’, as beautifully represented in the walls of the temple of Horus in Edfu and the related texts of the temple of Dandara mentioning the orientation of sacred buildings to the constellation of Meskhetyu, the Egyptian equivalent of Ursa Major. Photographs © Juan Belmonte

Fig. 8.0.5. Celestial diagrams of ancient Egypt showing cosmic texts and constellations or stellar clocks in the astronomical ceilings of the Million Year Temple of Ramses II in Western Thebes and the Valley of the King tomb of Ramses IX, respectively. Photographs © Juan Belmonte

Links with other zones

Historically, the Valley of the Nile, where the river approaches the Mediterranean, was one of the best-protected regions of the world. It was isolated and difficult to reach, being completely surrounded by extensive deserts. Yet ancient Egypt was invaded many times, both by people coming across the deserts and from the other shores of the Mediterranean. These included the Heka Khasut, Sea People, Libyans, people of Kush, Assyrians, Persians, Greeks and Romans. On the other hand, ancient Egypt was also an imperialist nation sending out its armies (and spreading its cultural and religious traditions) far away from its own frontiers to places such as ancient Syria and Sudan (especially in the Middle and New Kingdoms), Libya, and even across the sea to ancient Anatolia, Cyprus and the Aegean (during the Ptolemaic Dynasty).

It is clear that we should expect links with all these neighbouring regions, both in general and regarding traditions and practices relating to astronomy. However, these hypothetical links—and particularly the astronomically related ones—remain largely unexplored, and the extent to which the classical world owes a debt to the ancient Egyptian tradition is still a matter of strong controversy. It is clear that our 365-day year and 24-hour day have Egyptian roots but the extent to which many other sorts of astronomical observation or knowledge could have migrated out from the Valley of the Nile remains the source of much discussion.

That said, some of the astronomically related sites found in ancient Greece, Anatolia, the Levant, Mediterranean Africa and even Mesopotamia and Rome almost certainly bear the mark of Egyptian influence. Conversely the *Biblioteca Alexandrina*, and even possibly such items as the Dandara Zodiac (see Case Study 8.3), cannot be understood without considering the influence of other civilizations upon the Egyptian world.

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Fig. 8.0.6. Two fine examples, at Elephantine (left) and Edfu (right), of the so-called feast calendars of the ancient Egyptians, which contain a great deal of astronomical information. The Elephantine calendar shows an example of the rare Sothic dates, which have proved extremely useful in fixing the ancient chronology of the Middle East. Photographs © Juan Belmonte

Case Study 8.1: The Tomb of Senenmut at Western Thebes, Egypt

Presentation and analysis of the site

Geographical position: At the site known as Deir el-Bahari, municipality of Luxor (West Bank), province of Qena, Egypt. It is site TT353 within the Theban necropolis.

Location: Latitude 25º 44´ 10˝ N, longitude 32º 36´ 45˝ E. Elevation 105m above mean sea level (Alexandria).

General description: The tomb itself was never finished and consists of a long descending corridor leading to a pair of successive chambers. Of these, the first, Chamber A, is extensively decorated with paintings and high reliefs.

*Inventory of the remains***:** The four walls are decorated with religious texts, including archaic versions of the pyramid texts where, for example, the 'imperishable stars' are mentioned among other ancient Egyptian star groupings. However, the most important component of the chamber is the astronomical ceiling containing the oldest version of an Egyptian celestial diagram ever discovered. The diagram is divided into two sections, a northern and a southern one. The former includes the earliest known mention of the 12 months of the Egyptian civil calendar and representations of the northern constellations, including Meskhetyu. The southern section includes a putative list of decans and a list of the Egyptian versions of the planets visible with the naked eye, apart from Mars, which is surprisingly absent. It has been argued that the diagram could be a monumental version of a papyrus scheme prepared for the construction of a clepsydra.

History of the site: Senenmut, Queen Hatshepsut's (c. 1470 BC) architect and chancellor, was a powerful man in his time. He was permitted to build this tomb very close to the Million Year temple of his mistress, the queen pharaoh, a rare privilege for a person of non-royal blood. After the death of the queen he was forgotten, and TT353 was never completed. This circumstance may have contributed to the excellent state of preservation of the paintings and inscriptions.

Cultural and symbolic dimension: The main importance of the site is the presence of the earliest known celestial diagram. This apparently reflects a mixture of two different astronomical traditions, which can be traced in later astronomical ceilings.

Authenticity and integrity: The site has recently been prepared for visitors but the decorations have not been altered.

Generalities: There have been several attempts to interpret Senenmut's astronomical ceiling (and a few of the texts in the chamber) with varying degrees of success. Similar 'documents' can be found in the astronomical ceilings of the tomb of Seti I at the Valley of the Kings and the Ramesseum, among others.

Present site management

Present use: The tomb is currently closed to the public. It is only accessible to a handful of specialists with special permits from the Supreme Council of Antiquities of the Arab Republic of Egypt (SCA)

Protection: The site belongs to the SCA and is protected by strict Egyptian laws and regulations relating to archaeological sites and remains. Additionally, it is in a specially protected area, since Thebes is already on the WHL. The tomb is fenced.

State of conservation: The astronomical ceiling and other decorations are in an almost perfect state of preservation. While there are a few traces of damage due to humidity, the problem is not nearly as severe as in the (almost contemporary) tombs of the Valley of the Kings. During the last few years a Spanish Mission has being undertaking cleaning work with the aim of making the tomb accessible to a wider, interested public.

Fig. 8.1.1. Funerary texts mentioning the ‘imperishable stars’. Photograph © Juan Belmonte

Context and environment: The tomb is located at the bottom of the cliffs of Deir el-Bahari, in a dry, dusty environment close to the main entrance to the temple of Queen Hatshepsut.

Archaeological/historical/heritage research: There have been several interpretations of the astronomical ceiling of Senenmut, but no definitive interpretation of the diagram exists at the present time.

Main threats or potential threats to the site: The site is quite dry and, where the decorations are painted or chiselled, the rock is a good quality limestone, so no major threats are evident. Visitors’ breath poses a potential threat in the future, as does new and more powerful illumination.

Management: It is proposed that, as part of its final duties, the Spanish Mission should construct a replica of Chamber A. This will be built close to the entrance of the tomb but at a higher level accessible to the vast majority of the visitors of Deir el-Bahari temple. The replica may include an interpretation centre.

Fig. 8.1.2. The celestial diagram in the astronomical ceiling of the tomb of Senenmut also includes a list of the decanal stars (left) and the earliest representation of the planets (right), with the notable exception of Mars. Photographs © Juan Belmonte

Case Study 8.2: The Temple of Amun at Karnak, Egypt

Presentation and analysis of the site

Geographical position: The temple of Karnak is located in the northern sector of the city of Luxor, province of Qena, Egypt.

Location: Latitude 25º 43´ 5˝ N, longitude 32º 36´ 45˝ E. Elevation 80m above mean sea level.

General description: The site is a huge complex comprising no fewer than ten temples, surrounded by a huge temenos wall. The largest and most conspicuous of the temples is that of the god Amun-Re, the most important divinity of the ancient Egyptians from the 12th Dynasty to the Ptolemaic Period and even later.

*Inventory of the remains***:** The most important temples in relation to astronomy are the temple of Amun itself, the temple of Ra-Horakhty, the temple of Amun-who-hear-the-Prayers, the High-room of the Sun and the temples of Khonsu and Ptah, with their pylons, obelisks, courts, halls and inner chambers. The site includes an open-air museum containing the reconstructed White Chapel of Senuseret I and Red Chapel of Hatshepsut (not on their original sites), as well as some isolated fragments of festival lists dating to earliest periods of the temple. The wall decoration of temples and chapels includes many representations of the stretching of the cord ceremony.

History of the site: The first archaeological remains on the site of Karnak are dated to the 11th Dynasty (reign of Intef II, c. 2050 BC). The first temple was erected by Senuseret I a few decades later and the sanctuary was successively enlarged by several kings from the New Kingdom onwards. The site was sacked by the Assyrians during the reign of Taharqa but further constructions were added during the Late and Ptolemaic Periods.

Cultural and symbolic dimension: Since the earliest construction by Senuseret I, if not before, the temple was aligned upon winter solstice sunrise. Initially, it may also have been deliberately aligned upon sunrise on New Year's Eve, which coincided with the solstice at the beginning of the Middle Kingdom. The fact that the temple enclosure is located at the only place where the solstitial line is perpendicular to the course of the river suggests that the location was deliberately selected, and that the cosmic symbolism extended to the landscape as a whole. When new temples and chapels were added, these followed the same axis and kept the original orientation, producing hierophanies that reinforced this symbolism, as did various wall texts and decorations.

Authenticity and integrity: In common with many Egyptian sites, Karnak has undergone extensive reconstruction and restoration. However, none of this has altered the cosmic symbolism connected with the orientation and location of the original temple and the successive additions, except for the Red and White Chapels, which have been removed from their original contexts.

Generalities: The documentation about the temple of Karnak is very extensive. Much has been written about its cosmic symbolism.

Fig. 8.2.1. Left: Winter solstice sunrise at Karnak, showing the alignment hierophany as it appears today and the precision of the original alignment in c. 2000 BC, when the winter solstice sun rose about one solar diameter further to the right. **Right:** A feast calendar discovered at the temple of Karnak, one of the other significant astronomical connections apart from the temple alignments. Photographs © Juan Belmonte

Present site management

Present use: Karnak is one of the most important tourist attractions in Egypt, already recognised on the World Heritage List as part of the ensemble of 'Ancient Thebes with its Necropolis', listed in 1979 under criteria (i), (iii) and (iv). Hundreds of people visit the site every day and attend the light and sound spectacle offered on site every night. Most of the complex is accessible. The SCA authorities have permitted small New Age groups to hold ceremonies in some of the smaller and more isolated shrines of the complex, such as the temple of Ptah.

Protection: The SCA own and administer the site in the name of the Egyptian government. The whole enclosure of Karnak is fenced and protected by various Egyptian security agencies. There is now a large buffer zone in the surroundings with a huge plaza between the temple and the Nile.

State of conservation: Karnak is well preserved. The SCA continually undertakes excavations and restoration work in different parts of the huge enclosure.

Context and environment: The temple of Karnak was the nucleus of the ancient city of Thebes for many generations. When Thebes was the capital of the country, Karnak was its apex. It is located in the flood plain and its gigantic walls were also effective as protection against the rising waters. The present environment has changed little (although the centre of the new city of Luxor is farther south) and the view is still spectacular from the sanctuary looking west across the river to the Theban hills.

Archaeological/historical/heritage research: Egyptian and European missions continue to carry out excavations and restoration work at Karnak, and there is no prospect of an end to such work. Heritage research at the site is mandatory since it forms part of the larger grouping of Ancient Thebes monuments within the existing World Heritage Site. On the other hand, the astronomical alignment of the site is recognised by just a small group of specialists and in this sense the situation is very different from other Egyptian sites such as Abu Simbel.

Main threats or potential threats to the site: The water table is the main problem at Karnak, in common with several other Egyptian sites. The foundations of some sectors of the temple, such as the Great Hypostyle Hall, have had to be reinforced with injections of concrete and the accumulation of salts in the stones in the walls may adversely affect the decorations and inscriptions. The Egyptian authorities are well aware of the problem and are working to counteract the potential threats.

Management: Karnak follows the general management plan of the World Heritage Site of 'Ancient Thebes with its Necropolis'. It is already a major attraction for mass tourism, without the need of additional outreach or propaganda. Conferences and seminars are regularly held in Luxor where professional scholars of all over the world present their latest discoveries.

Case Study 8.3: The Temple of Hathor at Dandara, Egypt

Presentation and analysis of the site

Geographical position: The enclosure of the temple of Dandara is located in the province of Qena, Egypt, close to the city of Qena (capital of the province), in the west bank across the river from the city centre.

Location: Latitude 26º 9´ 55˝ N, longitude 32º 39´ 23˝ E. Elevation 75m above mean sea level.

General description: The Dandara complex is one of the best-preserved temple enclosures in Egypt. Its huge temenos wall contains two monumental gates enclosing the main temple dedicated to the goddess Hathor, the small temple of Isis, two mammisi and a ruined Coptic church.

*Inventory of the remains***:** Two of the buildings at Dandara are important in relation to astronomy: the temple of Isis, orientated (presumably deliberately) upon the rising position of Sopdet (Sirius), one of the celestial manifestations of Isis, and the temple of Hathor. This fact that the latter is oriented astronomically is established by the various stretching-of-the-cord ceremonies and related texts engraved on its walls. The decorations also include various feast calendars, the famous circular Zodiac in the ceiling of a small chapel (a replica, the original now being in the Louvre Museum in Paris) and a second Zodiac on the ceiling of the hypostyle hall.

History of the site: The temple at Dandara includes the remains of constructions by Old, Middle and New Kingdom pharaohs. For example, the temple of Isis shows evidence of early foundations with slightly different orientations. However, most of what is seen today is the work of the Ptolemaic rulers and the first Roman emperors. The circular Zodiac apparently dates to the reign of Ptolemy XII or perhaps to that of his daughter Cleopatra VII (c. 50 BC) while the astronomical decorations on the ceiling of the hypostyle hall were apparently created during the reign of Tiberius or even later.

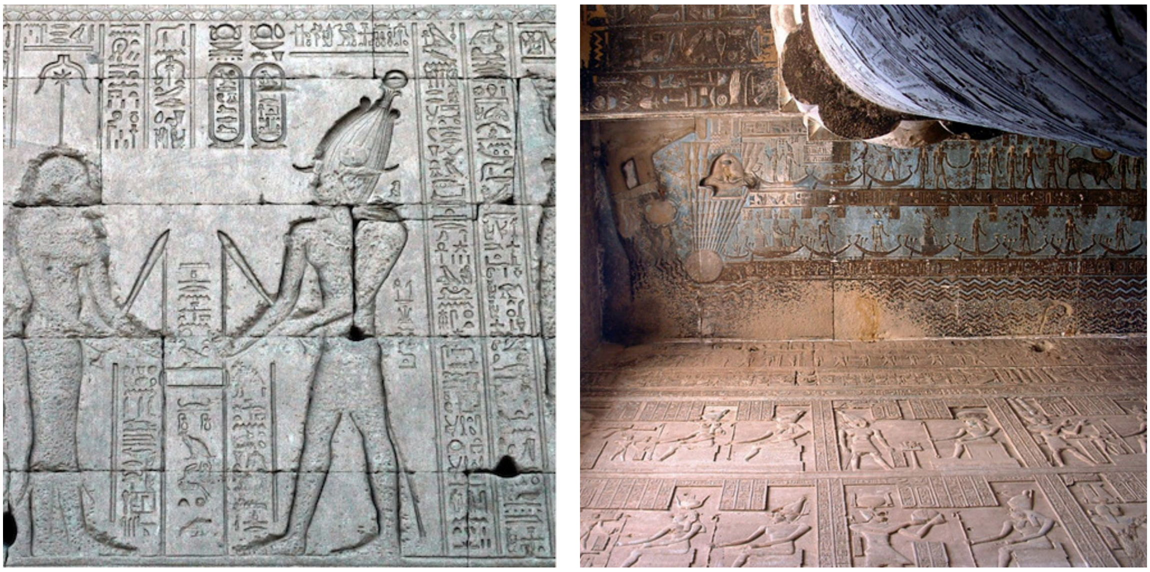

Fig. 8.3.1. Left: Alignments at the temple of Hathor enclosure at Dandara relating to important stars and asterisms in ancient Egyptian skies are reflected in the 'stretching of the cord' texts inscribed on the temple walls. **Right:** The astronomical ceiling of the hypostyle hall. Photographs © Juan Belmonte

Cultural and symbolic dimension: The Zodiacs represent an important astronomical feature of the temple of Dandara. Recent studies suggest that they were maps of the heavens showing stars, asterisms and constellations belonging to the different astronomical traditions existing in Ptolemaic Egypt. The monumental temple of Hathor is orientated to the rising of Meskhetyu (Ursa Major) in the north-east but its axis is also perpendicular to the course of Nile. This suggests that, as at Karnak (see Case Study 8.2) the location of Dandara was carefully selected to combine astronomical and topographic orientations reinforcing the cosmic symbolism of the whole landscape. In the Ptolemaic period there was a close connection between the temples of Dandara and Edfu, and a divine pilgrimage took place between the two sacred precincts.

Authenticity and integrity: The temple of Hathor is beautifully preserved, as are the buildings at Dandara in general. Nearly everything in the temple is original and in situ, with the major exception of the circular Zodiac, which was moved to France in the 19th century; in its place is a good-quality replica.

Generalities: The vast majority of the temple inscriptions, and detailed maps of the different structures, are available in the publications of the Institut français d'archéologie orientale (IFAO). Despite the alarming quantity of highly speculative interpretations (many published on the internet), only a handful of serious works have dealt with the astronomical aspects of the temples.

Present site management

Present use: The temple of Dandara is not on the major tourist routes, but there are daily excursions from Luxor which combine a visit to Abydos and Dandara.

Protection: The SCA own and administer the site. The whole enclosure of Dandara is fenced off and protected. It is surrounded by a buffer zone in the form of a park but the urban expansion of Quena could reach the outskirts of the temple.

State of conservation: The temple of Dandara, along with the temple of Horus in Edfu, is the best preserved of all ancient Egyptian temples. The decorations on the walls, including the astronomical texts and calendars, are well preserved, and all survive in situ apart from the circular Zodiac (which is excellently preserved in Paris) and some of the divine images which were looted in the Christian and early Islamic periods. The celestial diagram on the ceiling of the hypostyle hall, including the second Zodiac, has been recently restored to recreate its original livid colours.

Context and environment: The Dandara complex is located close to the River Nile in its western flood plain. Little remains of the other temples or the village that would have surrounded the sacred enclosure in ancient times.

Archaeological/historical/heritage research: The Institut Français d'Archéologie Orientale (IFAO) has been conducting excavations, restoration, and documentation work at Dandara for several decades. The astronomical context of Dandara is relatively well understood, unlike other similar Egyptian temples.

Main threats or potential threats to the site: The temples on site are well protected and the structure of the buildings is robust; hence there are no immediate direct threats to the site. However, while the temple and surrounding park are currently located within agricultural fields, the expanding city of Qena and its network of roads and streets are slowly approaching the area of the temple. The local landscape may change dramatically in the next few years and this question will need specific attention.

Management: There is little activity at the site apart from the restoration teams (when present) and the site seems to have had no special management plan up until now.

Case Study 8.4: The pyramids of Giza and related buildings, Egypt

Presentation and analysis of the site

Geographical position: The pyramids of Giza are located on a limestone plateau by the edge of irrigated lands at the apex of the delta of the River Nile, in the province of Giza, Egypt.

Location: Latitude 29º 58´ 40˝ N, longitude 31º 8´ 5˝ E. Elevation 60m above mean sea level.

General description: The Giza plateau is a necropolis containing the tombs of several kings and queens of the fourth Dynasty and their families. It was also considered a sacred site and a sanctuary, and cult practices were performed there for dozens of generations, especially in the Sphinx area and in the temple of Isis, Lady of the Pyramids.

Inventory of the remains: The World Heritage Site comprises the large pyramids of three kings of the fourth Dynasty; their related valley temples, upper temples, and causeways; the Sphinx and its temples; and the necropolis of the royal family and the nobles laid out to a Hippodamian (grid) plan. These tombs include texts with festival lists.

History of the site: The plateau of Giza was selected by Khufu (Keops in ancient sources) (c. 2550 BC), second pharaoh of the fourth Dynasty, as his resting place. His burial enclosure included a large pyramid, a large family necropolis and possibly the Sphinx. This part of the necropolis was completed by his son Khafre, who added several monuments and completed the second pyramid. Menkaure, Khafre's son, constructed the third pyramid and associated monuments at a later date. The entire period of construction lasted for some 80 years. The last major monumental construction on the Giza plateau was the step pyramid of Queen Khentkaus, forebear of the kings of the fifth Dynasty.

Cultural and symbolic dimension: The three main Giza pyramids are orientated to the cardinal directions with extraordinary precision. For such huge monuments, this could only have been achieved by astronomical observation, possibly of 'imperishable stars' such as Meskhetyu (Ursa Major) revolving around the north celestial pole. The design of the pyramid of Khufu also includes a series of symbolic alignments in the ventilation channels emanating from two chambers in the interior of the pyramid. As a consequence of the general cardinal grid of the necropolis, the Sphinx, a personification of the god Horus at the horizon (at least from the New Kingdom onwards), faces the equinoctial rising sun. The general pattern of the necropolis also encapsulates a series of additional topographic and astronomical alignments that create a cosmic landscape, reflecting ancient Egyptian world-view.

Authenticity and integrity: Excavated during the 19th and 20th centuries, the monuments have not been extensively reconstructed and the site is remarkably pristine considering that it is 4500 years old. However, on-site conservation work is essential, and this sometimes brings surprises, such as the recent discovery of Khufu's satellite pyramid.

Generalities: The academic literature concerning the pyramids of Giza is very large, but there is also a huge 'fringe' literature and non-specialists do not always find it easy to distinguish between the two.

Present site management

Present use: The Giza pyramids represent one of the most important tourist attractions in the world. As the only surviving example of the Seven Wonders of antiquity, million of people visit the site every year. It has been recognised on the World Heritage List since 1979, under criteria (i), (iii) and (vi), as part of 'Memphis and its Necropolis—the Pyramid Fields from Giza to Dahshur' (World Heritage Site no. 86). The presence of such a huge number of visitors and a range of tourist pursuits alters the former perception of authenticity and creates persistent management problems. The SCA, and the Egyptian authorities in general, are making efforts to restore the site to a more pristine ambience.

Protection: The SCA own and administer the site in the name of the Egyptian government. Tourist police have a strong presence for security reasons. As a consequence of Giza being inscribed on the World Heritage List, the Egyptian government give it the highest protection level. The buffer zone is the desert itself and the whole precinct is now fenced to protect the site from the rapid expansion of Cairo urban area which has already reached the foot of the plateau on the eastern and northern sides.

State of conservation: Considering the age of the Giza monuments, they are well preserved. The SCA continually monitor their state of conservation as a specific action of the management plan for a World Heritage Site. A long spell of restoration work at the Sphinx has now been completed, with excellent results. Excavations are under way in the area of the worker's village and its related cemetery.

Context and environment: The Giza necropolis forms part of the huge necropolis of Memphis, the capital of Egypt during the Old Kingdom. The field extends from Abu Rowash, the site of the pyramid of King Djedefre, eldest son of Khufu, to Meidum, where Khufu's father Snefru built one of his pyramids. Several dozen pyramids and their related monuments were built in

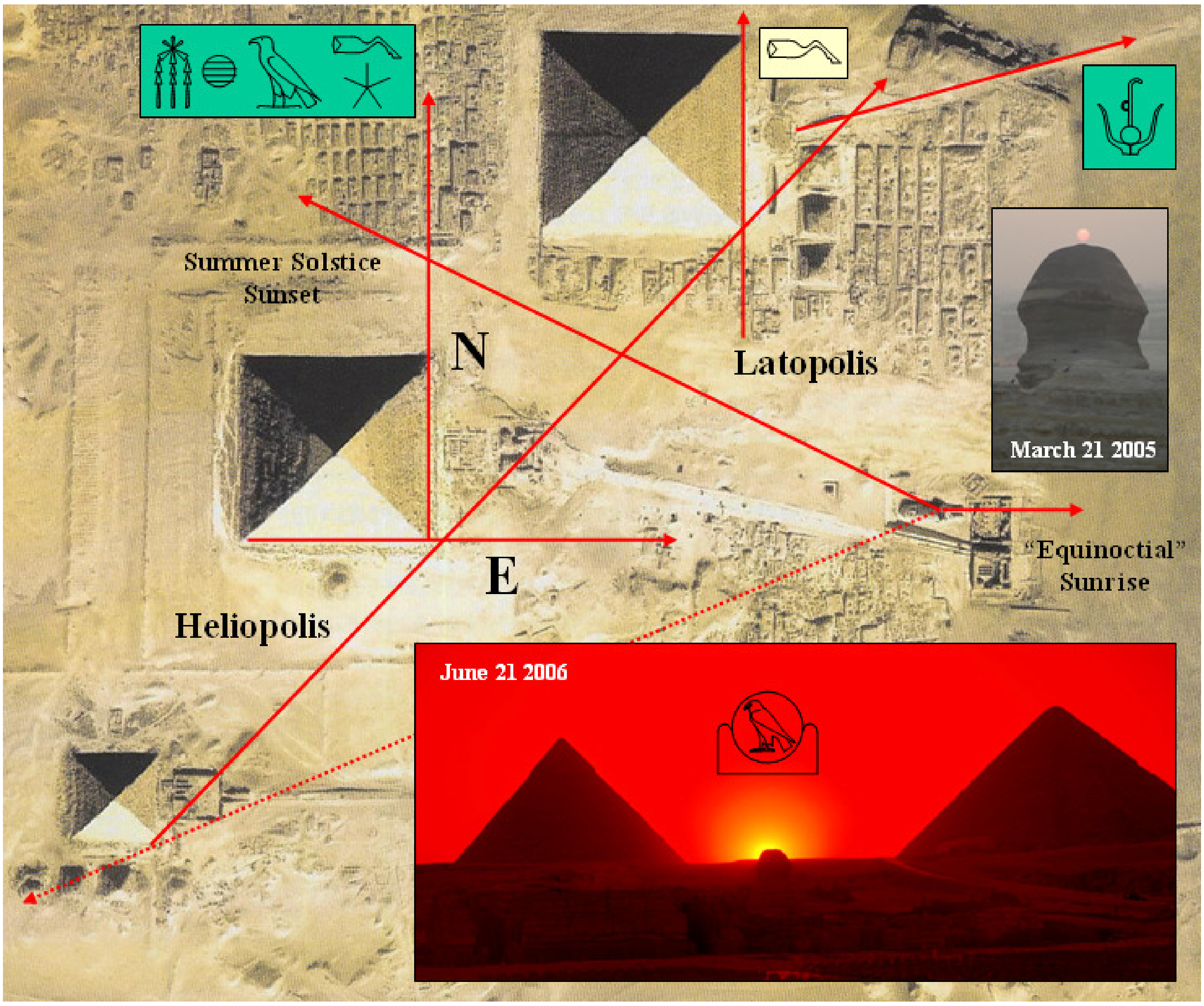

Fig. 8.4.1. Schematic diagram showing various astronomical and topographic relationships between the different monuments erected in the Giza Plateau, in particular the Sphinx and the pyramids, and certain elements of the celestial and terrestrial 'geography'. Graphic © Juan Belmonte

the desert plateaux overlooking the cultivated land on the west bank of the Nile Valley. The pyramids of the third and fourth Dynasties are mute. However, the architecturally unimpressive pyramids of the sixth and late fifth Dynasties contain, among the decorations in their burial chambers, the astronomically related Pyramid Texts.

Archaeological/historical/heritage research: The site continues to provide an extremely productive focus for archaeological research. New discoveries are often presented to the public and published in selective journals. However, several questions, including the precise date of the monuments, remain a matter of debate. Many issues relating to astronomy remain hotly debated. Heritage research on site is mandatory as the Giza monuments and necropolis form part of an existing World Heritage Site.

Main threats or potential threats to the site: The main immediate threat to the site is the millions of visitors that it sustains every year. Some protective measures have been taken: for example, the burial chambers of the kings are closed on a rotating basis in order better to preserve them from the effects of excess humidity. The largest potential threat to the site is the expansion of the metropolitan area of Cairo, which now encloses the Giza Plateau on the eastern, northern and western sides.

Management: The Giza pyramids are managed by the SCA in the context of the global management plan for World Heritage Site no. 86. However, the interpretation of the site could be improved.

Case Study 8.5: Napata, Sudan

including the temples of Djebel Barkal and the Nuri necropolis

Presentation and analysis of the site

Geographical position: The site of Napata is located close to the city of Merowe in the Northern Province of Sudan whose capital in Dongola. (This is distinct from the historical city of Meroe, in the Butana region.)

Location: Latitude 18º 32´ 5˝ N, longitude 31º 50´ 4˝ E. Elevation 260m above mean sea level.

General description: The area is dominated by the mountain of Djebel Barkal, the 'Pure Mountain' of ancient sources, located on the western bank of the Nile. This is surrounded by temples and pyramid fields. The necropolis of Nuri, on the other hand, is located on the east bank.

*Inventory of the remains***:** No fewer than seven temples and several palaces were built by the Nile at the foot of the Pure Mountain. Two small fields of pyramids are located nearby, while the older necropolis of El Kurru is found some kilometres downstream. The temple of Amun at Sanam is located on the east bank opposite Djebel Barkal. The cemetery of Nuri contains no fewer than 20 royal pyramids.

History of the site: The earliest shrines at Napata were built during the 18th Dynasty. The Nubian kings of the 25th Dynasty (c. 700 BC) selected it as their capital, and were buried at El Kurru (with the exception of Taharqa who inaugurated the burial site of Nuri). Napata remained the capital of the Kingdom of Kush for several generations afterwards. The royal cemetery remained at Nuri for a few centuries after the capital had been moved to Meroe by Aspelta (i.e. until c. 300 BC), and the temple of Amun at Napata remained a royal pilgrimage destination until the end of the kingdom six centuries later.

Cultural and symbolic dimension: Napata was the cult centre of Amun, Lord of the Pure Mountain, a hypostasis of the god Amun of Karnak. The temple was built at the foot of the mountain and nearly perpendicular to the Nile. On the opposite bank, at Sanam, Taharqa built another temple for Amun, orientated to sunset at Wepet Renpet (new year) during his reign. Taharqa himself inaugurated the cemetery at Nuri, at a selected spot possibly connected with the Pure Mountain by its intrinsic astronomical alignment. The Nuri pyramids themselves were orientated so that the diagonals of their bases aligned closely with the cardinal directions. One of the late pyramids at the Barkal field contains a celestial diagram with Egyptian typology.

Authenticity and integrity: The foundations of most of the temples are preserved at Djebel Barkal. The temple of Amun has been partially excavated and partially restored during the past decade. The pyramids of Nuri were excavated in the 19th century; since then little preservation, restoration or excavation work has been carried out on site.

Generalities: Until recently, a US Archaeological Mission has been conducting work at Djebel Barkal, producing accurate maps of the area and 3-D reconstructions of the temple enclosure. However, there is no modern map of the Nuri necropolis, nor any documentation apart from the earliest excavation reports.

Present site management

Present use: The remains of Napata are one of the attractions that the Sudanese authorities are trying to exploit in order to bring cultural tourism to the country. The region is rapidly developing.

Protection: The site of Napata is under the control of the Archaeology Division of the Sudanese Ministry of Culture. This department controls access to the sites, which is strictly regulated, and on-site archaeological excavations. For decades, the main protection for the sites has been their relative isolation in an undeveloped and sparsely populated area of Sudan. The Napata region is now inscribed on the World Heritage List as 'Gebel Barkal and the Sites of the Napatan Region' (World Heritage Site no. 1073, 2003) under criteria (i), (ii), (iii) and (iv), so the Sudanese government is giving it the highest level of protection.

Fig. 8.5.1. The temple of Amun at the Pure Mountain in Napata, the nucleus of a large sacred area integrating topographic and astronomical alignments. Photograph © Juan Belmonte

Fig. 8.5.2. An area of the Napata region showing the location of the pyramid cemetery of Nuri and of the sacred mountain of Djebel Barkal, on opposite sides of the course of the Nile. The diagram also shows the view of Djebel Barkal from the base of Taharqa's pyramid (top-left) and a close-up satellite image of the Nuri pyramid field (bottom-right). Graphic © Juan Belmonte

State of conservation: The sites are relatively well preserved. They are fenced and the local population, being very proud of their ancestors, take special care of their monuments. However, most of the movable objects (statues and stelae) have been moved to the National Museum in Khartoum.

Context and environment: The Napata region was the most sacred area of the Kingdom of Kush for several centuries. As the capital city, the main sanctuary of the national god and the necropolis of kings and queens, it enjoyed a very special status. Completely surrounded by deserts in every direction, the Valley of the Nile, flowing in this area from north-east to south-west, was the artery giving life to the region.

Archaeological/historical/heritage research: Heritage research at the site should be mandatory as part of the inclusion of the Napata monuments and necropolis within an existing World Heritage Site.

Main threats or potential threats to the site: The isolation of the site has ensured its preservation for centuries. However, five years ago the Sudanese government began to construct a very large dam a few kilometres to the north of Merowe, and close to Nuri, which is complete at the time of writing. The resulting reservoir will inundate hundreds of hectares of Nile Valley upstream from Nuri, including dozens of minor archaeological sites, but should also bring new wealth to the region, which could have positive consequences.

Management: The site follows the general management plan for World Heritage Site no. 1073. It has strong potential for tourism development and outreach, as the Sudanese cultural authorities recognise. The fact this everything must be built from virtually nothing presents a good opportunity to follow modern best practice.

Chapter 9: The Classical World

Efthymios Nicolaidis, Giulio Magli and Clive Ruggles

What we identify here as the 'classical world' is better defined culturally than geographically. Chronologically, it spans the Greek and Italic societies of the Iron Age (8th to 4th century BC) and the Hellenistic and Roman civilizations, finishing with the end of the Roman empire. In geographical extent it comprises today's Greece and Italy, together with the Greek colonies and Roman settlements extending through almost all the other Mediterranean countries.

The origins of astronomy and astronomical thought in this area can certainly be traced back to the Bronze Age. This is evident, for instance, from astronomical references in Homer's and Hesiod's works, and from the analysis of the archaic Roman (so-called Numan) calendar dating from at least the mid 6th century BC. Influences from the Middle East and Egypt probably occurred in very ancient times, but the true merging of the cultures eventually occurred in the Hellenistic era.

Ancient Greek astronomy: an overview

The extraordinary development of mathematical astronomy in ancient Greece resulted from the efforts of the Classical philosophers to demonstrate the regularity of the motions of the heavenly bodies, which, in Hellenistic times (after 323 BC, following the conquests of Alexander the Great), fused with a Babylonian prepossession with predicting those motions as accurately as possible. The Classical Greek philosophers regarded their astronomy as the 'scientific' pursuit of truth, to be distinguished absolutely from the 'common' use of astronomy, for example by farmers and administrators in keeping calendars.

Ancient Greek mathematical astronomy *by Efthymios Nicolaidis*

Ancient Greek mathematical astronomy can be defined as the astronomy of epicycles. This system of describing celestial movements, which survived until the 17th century, is an invention of the 3rd century BC. The Greek astronomers of that time who arrived at this explanation of the planetary movements already had the benefit of three centuries of observations and mathematical theories.

Little is known about the mathematical astronomy of the Presocratics. Thales of Miletus (7th–6th century BC) is considered to be the first Greek astronomer. He predicted solar eclipses by studying their periodic recurrences, but with significant errors. Anaximander (6th century BC) identified what we now know as the obliquity of the ecliptic. Pythagoras (6th–5th century BC) established the correct order of the planets within the geocentric system (Earth, Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn), while Aristotle later placed the Sun between the Moon and Mercury. A little more is known about Meton, a contemporary of Socrates, who defined the 19-year solar-lunar cycle by observing from the hill of the Pnyx in about 432 BC.

The observational data (especially those concerning retrograde planetary motions and Sun and Moon anomalies) were important enough in Plato's time for him to pose the problem of 'saving the phenomena' (how to explain the observations while interpreting the celestial bodies' motions in terms of circular orbits with uniform speed). According to Simplicius (6th century AD), it was Eudoxus (4th century BC) who managed this, producing a system composed of concentric spheres. The combination of two spheres rotating with constant velocity can effectively represent the retrograde planetary motions. For the motion of the Sun, Eudoxus employed three spheres (one to account for an observation now known to have been mistaken), and another three for the Moon.

In fact, Eudoxus' system only partially saved the phenomena: in particular it did not take into account the variations in the distance of the heavenly bodies (the variation in the apparent diameter of the Sun or in the brilliance of the planets). This problem was recognised during the 3rd century BC. The heliocentric system proposed by Aristarchus of Samos (4th–3rd century BC) was an adequate response to that problem but, probably for philosophical reasons, was not pursued by the main Greek astronomers. According to a later source, Theon of Smyrna (2nd century AD), a system was proposed during the 3rd century BC similar to that envisaged nineteen centuries later by Tycho Brahe. In this system the two inner planets, Mercury and Venus, orbit the Sun, while the latter orbits the earth, the centre of the universe. This system explained the motions of Mercury and Venus far better than that of Eudoxus, and it is highly probable that it was the origin of the astronomy of epicycles. Indeed, if the orbit of the Sun is replaced by the deferent cycle of Mercury and Venus, one reaches the solution attributed to Apollonius of Perge (born c. 244 BC).

In an effort to respond to the solar anomaly, while respecting the principle of circular uniform motion, 3rd-century Greek astronomers proposed the 'eccentric' solution: the Sun travels on an eccentric circle (centred on a point that does not correspond to the earth's centre). This system presented two difficulties: it was not symmetrical and it was contradictory to Aristotelian physics, which could not accept a motion around an imaginary point. It was probably Apollonius who resolved the problem of symmetry, by demonstrating that an eccentric circle was equivalent to an epicycle travelling around a concentric (deferent) circle. (The 'Aristotelian' problem was never resolved.) This epicycle-plus-deferent solution came to characterise all astronomical systems up until the beginning of the 17th century, when Kepler formulated his first planetary law, that of elliptical orbits.

Between them, Apollonius and Hipparchus (who was observing at Rhodes in c. 128 BC) developed a complete epicycle-plus-deferent astronomical theory. By suitably combining the radii and the motions (clockwise or anticlockwise), they could reproduce the retrograde motion of the planets (but not the fact that the 'loops' produced by this motion were asymmetrical) and represent to a reasonable approximation the motions of the Sun and Moon.

By reversing the 'methodological' approach of astronomy, Hipparchus played a decisive role in the development of Greek astronomy. According to the available information, which comes mainly from Ptolemy, Hipparchus was the first to prioritise the collection of observations in order to determine the empirical laws governing the motions of the celestial bodies. Having done so, he modelled these in terms of circular uniform movements, determining the radii of the deferents and the planetary epicycles accordingly.

Hipparchus also produced a successful theory for the motion of the Sun, determining its eccentricity and thus resolving the principal anomaly, that of the inequality of the length of the seasons. It was probably while working on the theory of the Sun that he made his main discovery, that of the precession of the equinoxes. By comparing historical observations, Hipparchus noticed that, in its annual movement, it took the Sun a little more time to reach the same zodiacal point than it did to reach the celestial equator: the sidereal year was therefore different from the solar year. This phenomenon, actually due to the slow rotation of the axis of the earth, was interpreted by Hipparchus as a very slow shift in the sphere of the stars, from west to east, of about 1 degree per century (the true value is 1° 23´ 30˝).

The apex of Greek astronomy was the magisterial work of Claudius Ptolemy. His *Great Mathematical Syntaxis of Astronomy*, also known as the *Almagest*, completed between AD 142 and 146, included all the astronomical phenomena known at that time. This book constituted a unique advance in the history of science: it was to be the main reference for all astronomers until the work of Tycho Brahe and Kepler, almost 1500 years later. Indeed, all Greek, Islamic, or Roman planetary astronomy up until the time of Kepler can be characterized as Ptolemaic.

Ptolemy continued and concluded Hipparchus' work. His method was similar: to collect as many observations as possible; to highlight the anomalies in the planetary motions; to find the empirical laws governing these anomalies; to combine various circular uniform movements in order to 'save the phenomena'; to choose the best of the different solutions, determining the radii and the positions of the circles and the angular speeds; and to compute the planetary tables. If subsequent observations accorded with the computed predictions, then this would confirm the theory.

According to Ptolemy, the main celestial movements were (a) the diurnal motion of the sky from east to west and (b) all other motions, which mainly took place from west to east and close to the ecliptic. Whenever Ptolemy could choose from several possible solutions, he preferred the simplest. Thus he adopted Hipparchus' model for the Sun, but favoured the eccentric rather than the deferent-plus-epicycle. For all the other heavenly bodies he presented his own solution, which in the case of Venus, Mars, Jupiter, and Saturn involved the famous 'equant' (a name that was assigned during the Middle Ages). His idea was that the centre of the epicycle does not move with a uniform motion but instead the circular uniform motion is 'transferred' to a point of another circle (the equant). As a consequence, the phenomena were saved (the planets travel faster at their perigee and more slowly at their apogee), but this represented a serious departure from Aristotelian physics and from the principle of uniform circular motion posed by Ptolemy himself. The system was also extremely complicated: Ptolemy even added circles to move the level of the epicycle from that of the deferent!

Ptolemy presented his cosmological speculations (the mechanisms responsible for all the motions of the heavenly bodies) in his book *Planetary Hypotheses*. This work was the precursor of Islamic astronomical theories on the mechanisms of the celestial spheres (see Chapter 10). Another of Ptolemy's astronomical works, the *Handy Tables*, a revised version of the *Almagest*, remained in use throughout the Middle Ages.

The main Greek commentator on Ptolemy was Theon of Alexandria (4th century AD). His commentary on the *Almagest* and two commentaries on the *Handy Tables* were the last important works of ancient Greek astronomy. In the 6th century, John Philoponus wrote the first known Treatise on the Astrolabe (c. 520–550), based on an unknown source. The first Byzantine astronomer of any note is considered to be Stephanus of Alexandria. He wrote a Commentary on the *Handy Tables* (c. 610–620) inspired by the Small Commentary of Theon, a work designed for students unable to do multiplication and division.

Heritage relating to Greek mathematical astronomy *by Clive Ruggles*

While the development of Greek mathematical astronomy forms a crucial part of the history of modern scientific astronomy, there is very little immovable heritage directly relating to it. No direct evidence remains of the observations carried out by these astronomers: even in the case of Ptolemy, nothing is known about his 'observatory'. On the other hand, some observational places are known, such as Pnyx, the place where Meton observed (see Case Study 9.1).

An exceptional portable item relating to the heritage of Greek mathematical astronomy does exist, however. This is the Antikythera mechanism, discovered in a Roman shipwreck in 1901. It is a bronze mechanical device containing at least 30 gearwheels, probably hand-driven, that calculated and displayed a range of astronomical cycles. These included the phase cycle of the moon, the passage of the sun and moon through the zodiac, the 19-year (235-lunation) Metonic Cycle, the 223-lunation Saros eclipse cycle, and also, probably, a number of

Fig. 9.0.1. The front of the main surviving fragment of the Antikythera Mechanism. This contains 27 gears: the large gear with four spokes at the front is the Mean Sun Wheel. Photograph © Antikythera Mechanism Research Project (http://www.antikythera-mechanism.gr)

planetary cycles. The gears that determined the position of the moon included a remarkable pin-and-slot device that modelled, according to Hipparchus' theory, the irregularities of the moon's motion across the sky due to the ellipticity of its orbit around the earth. Special symbols helped to predict lunar and solar eclipses. There was even a dial that modelled the four-year cycle of the Olympiad. The Antikythera mechanism is thought to have been constructed in the later 2nd century BC. It was originally housed in a wood-framed case, and its two doors appear to have been inscribed with instructions for its use, implying that it was probably intended for personal use by a non-expert traveller. It is unlikely to have been unique.

Other forms of astronomy in ancient Greece *by Clive Ruggles*

The use of stars as seasonal indicators had been known to Greek farmers since at least the 8th century BC, as is evident from the writings of Hesiod. A farmer and poet, his *Works and Days* (recorded three centuries later) contains a series of astronomical signs, such as the first pre-dawn appearance (heliacal rise) of various stars, and activities to be triggered by them. It is both an accumulation of folk knowledge and a kind of farmers' almanac. By the 5th century BC, the development of peg-hole star calendars known as *parapegmata* had begun to play a critical role in regulating the various civic lunar calendars operating, until then largely or completely independently, in different cities.

Astronomy also played a crucial role in Greek religion and cult practices. Watching the sky for signs of divine intervention was common in Greece, an example being the 4th-century-BC custom of the Pythais sacred pilgrimage from Athens to Delphi, which only proceeded if the Pythaistai group saw the correct omens (in this case, lightning flashes) during prescribed days and nights beforehand. Many Greek religious festivals were performed in open spaces, and at night. Various historical sources attest to the importance of the sky as an integral part of the cult experience, as well as to its importance in determining the correct timing of various rites (both the date and the time of day/night).

The practice of constructing large stone temples dates from the 7th century BC, and the ancient Greeks clearly derived both inspiration and technological expertise from ancient Egypt (see Chapter 8). It is not surprising, therefore, to find some evidence of apparently deliberate cardinal and solstitial orientation. However, claims that the predominantly easterly orientation of Greek temples has to do almost exclusively with the sunrise have been thoroughly refuted.

Fig. 9.0.2. The Erechtheion, Athens. Photograph © D.S. Levine, Creative Commons Licence.

Greek religious practices were highly localised, with many different deities and cults: prior to the development of temples these were performed in the open air, and it is likely that the placement and design (including the orientation) of any given temple was strongly influenced by the cult practices with which it was associated.

Evidence is gradually accumulating of temple orientations that deliberately reflected the celestial associations of the gods to whom they were dedicated, so that these associations could be displayed and reinforced during the cult performances held there. Example include the oracle of Apollo in Delphi (connected with the constellation Delphinus), the sanctuary of Artemis Orthia in Sparta (connected with the Pleiades), and the Erechtheion on the north side of the Acropolis in Athens (connected with the constellation Draco). In all three cases, there appears to have been a connection between the timing of certain rites and a stellar event visible above the horizon in the direction towards which the relevant temple was oriented. In each case, the connection between the deity and the star or constellation concerned is confirmed by several strands of evidence: mythology, and in particular the foundation myth of the cult concerned; historical accounts of the timing of the festival; the archaeoastronomical evidence of the temple orientations; and associated archaeological artefacts.

Astronomy in the Italic and Roman world *by Giulio Magli*

The Italic world in the Iron Age comprised a variety of peoples and cultures, with an active network of cultural and trading exchange operating within the Mediterranean area. The Romans were simply one of these Italic peoples. Their expansion and conquest began in the early 4th century BC.

By this time a religion had already developed of which several aspects were intimately connected with the sky. On the basis of the archaeological records and the few available written sources (such as the *Tavole Eugubine)* it is reasonable to conclude that, despite the cultural differences, the main features of this religion were common to all the Italic peoples, although Roman historians only directly refer them to the Etruscans. In this religion, a fundamental connection between humans and gods was provided by the *aruspexes,* priests learned in the so-called *Disciplina*, who exerted the art of reading the will of the gods in the flight of the birds and in the liver of sacrificed sheep, for instance at the foundation of new towns. The sacred workplace of these priests was the *auguraculum,* a square (or rectangular) structure usually deprived of walls and disposed in a prominent position with respect to the landscape and the town. The *Disciplina* is known to us essentially through the writings of Roman authors such as Cicero, but the tradition of *auguracula* is very old, since this kind of building is already documented in the 6th century BC. A fundamental duty of the aruspexes was to reaffirm the cosmic order, and consisted of the individuation of a terrestrial image of the heavens (*templum*) in which the gods were 'ordered' and 'oriented' in 8 (or 16) radial directions starting from due north. As a consequence, these buildings tend to be oriented in the cardinal or inter-cardinal directions.

Other vestiges of Italic religious beliefs relating to the sky can be found in the spectacular *acropoli* of several towns, especially within an area centred upon the *Latium Vetus* (essentially today's Lazio, with its regional capital Rome) and extending through the whole western side of central Italy from Umbria to Campania. Here, impressive polygonal stonework was used to construct imposing buildings aligned upon the cardinal or intercardinal points (e.g. Alatri [see Case Study 9.2] and Ferentino) and/or to the summer solstice sunrise or sunset (such as again Alatri and Norba). An interest in the rising and setting of bright stars, especially those of Gemini, is also well attested.

Almost all Etruscan towns were redeveloped by the Romans, but traces of the foundation rituals and the corresponding division of the 'cosmos' can still be seen in Misa (today's Marzabotto), which was destroyed by Celts before the arrival of the Romans, as well as in the spectacular 'funerary towns' (necropoleis) such as Cerveteri, where the tumuli are mostly oriented towards the north-west.

The Romanisation of the Italic peoples was a gradual process, and it is likely that the orientation of Roman towns inherited beliefs and practices from the existing tradition. However, the role of astronomy in imperial Roman monuments and temples is still far from clear. A key example is the problem of the role of astronomy in the Campus Martius project, the huge flat field near a bend of the Tiber that was conceived by Agrippa as a 'sacred place' devoted to the glorification of the emperor Augustus. The Augustus mausoleum towards the north, a sundial using an Egyptian obelisk (found today in the nearby Piazza Montecitorio) as a gnomon in the 'centre', the Ara Pacis towards the east and the Pantheon towards the south were all fundamental elements in the organization of this space. The complex appears to have embodied a deliberate hierophany, in that the shadow of the obelisk pointed towards the entrance of the Ara Pacis at the equinoxes. However, whether this was specifically planned to highlight Augustus's birthday (implying that the huge sundial played a fundamental role in representing Augustus' central place in the new 'cosmic order'), or just reflected a simpler seasonal relationship, or indeed whether it was intentional at all, is much debated and remains unresolved. On the other hand, there is no doubt that the most representative of the Campus Martius monuments, the Pantheon, which we see today as it was reconstructed by Hadrian around AD 120, is a monument that is strongly connected with the annual and daily cycles of the sun (see Case Study 9.3).

Astronomical heritage within Italy

The sites of interest, or at least those that have been sufficiently well studied, are concentrated in Central Italy. In alphabetical order, the principal Italic/early Roman sites are Alatri, Circei, Ferentino, Norba, and Sant'Erasmo di Cesi, and the principal Etruscan sites are Banditaccia Necropolis (Cerveteri) and Misa. Research on astronomy in Imperial Rome is mainly focused on the Pantheon (together with the whole area of Augustus' Campus Martius) and the Domus Aurea. All of these sites are well preserved, enclosed in protected areas or in living towns, and open to the public.

There is also movable heritage with a strong astronomical interest. A good example is the statue called the Farnese Atlas. Residing today in the National Museum in Naples, it is a masterpiece of early Imperial times representing the god Atlas carrying the celestial sphere. This sphere contains the most complete representation of the constellations coming from the Roman period that is known. Attempts have even been made to reconstruct the original data for this sky map back as far as Hipparcus' 'lost map'.

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Case Study 9.1: The Pnyx, Athens, Greece

Michael Wright

Presentation and analysis of the site

Geographical position: Roughly 300m west of the Acropolis, Athens, Greece.

Location: Latitude 37° 58′ 18″ N, longitude 23° 43′ 10″ E. Elevation 97m above mean sea level.

General description: The Pnyx is an elevated area within ancient (Classical) Athens. Until late in the Classical period it was the usual place of assembly for political meetings, and for this reason its principal significance is usually held to be its association with the development of democracy. Its significance to the history of astronomy is due to the erection there by the astronomer Meton of an instrument named the *heliotropion*, whose name suggests that it was connected with observations of the solstice. It is likely that the observations themselves made use of a natural horizon foresight on nearby Mount Lykabettos. These observations helped Meton identify his famous calendrical cycle, based on the fact that 19 solar (tropical) years are very close indeed to (i.e. within about 2 hours of) 235 lunar (synodic) months.

Inventory of the remains: The place where Meton observed is an almost flat area that was enhanced and enlarged artificially, and occasionally remodelled, explicitly for this purpose.

There is no trace of the *heliotropion* and we do not know what form it took. However, identifying when the solstice occurs using only a self-contained instrument would have been very difficult, because the sun's declination changes extremely slowly close to the solstice. It is likely, therefore, that such observations made use of distant markers, effectively magnifying the scale of the 'instrument'. The view from the observing site on the Pnyx does in fact contain a natural marker in the form of Mount Lykabettos, a hill some 3km away rising to an elevation of about 300m. This northern flank of this hill presents an angular profile interrupting the skyline at the point where the midsummer sunrise occurred. One portion of this profile is steeper than the path of the rising Sun, raising the possibility that there was a particular spot from which the very edge of the sun was seen to 'flash' only on, or very close to, the day of the solstice. Ongoing investigations are ongoing to see if such a spot exists within the area now regarded as the Pnyx. In that case it is possible that the *heliotropion* was simply a marker post or column, forming a backsight and marking the observing spot.

History of the site: According to historical sources, Meton made observations of the summer solstice here in 432 BC. The site was reused for astronomical observations from 1890, when the National Observatory of Athens' 40cm Gautier equatorial refractor dome was constructed here.

Cultural and symbolic dimension: Observations of the summer solstice had a local civic significance, in that the year of the Athenian civil calendar began at the first New Moon following the solstice.

Authenticity and integrity: No trace remains of the instrument used by Meton, nor of any contemporary building or structure. However, the natural horizon formed by Mount Lykabettos, which may well have been vital to Meton's observations, is unaltered.

Documentation and archives: The fact that Meton placed his *heliotropion* on the Pnyx is mentioned in a commentary on the comedy *The Birds* by Aristophanes. In the play, Meton is held up to ridicule and must therefore have been a well-known figure when it was written, in 414 BC. An inscription from Miletus, Ptolemy (*Almagest* 3.1), and Diodorus Siculus (*Library of History* 12.36.1–2) all record Meton's observation of the summer solstice in 432 BC. Diodorus Siculus tells us that Meton instituted his well-known calendrical cycle, according to which 19 years contain 235 synodic months, from that event.

Present site management

Present use: The site is open to the public. There is provision for official supervision during the day, and visitors usually enter the site along a built path and through a gate; but no fee is charged and it appears that the gate is not shut at night. In fact, one can walk past the end of the fence that partly separates the archaeological site from the surrounding area where there are larger shrubs and trees. Residents of the surrounding neighbourhoods walk freely over the whole area for recreation.

Context and environment: The Pnyx itself is largely cleared of vegetation other than grass and small shrubs. Since its former use depended on the area being cleared, the present general appearance of the area is presumably similar to that which it had in antiquity.

Archaeological/historical/heritage research: Several historical sources affirm the use of this place by Meton for solstitial observations. There is also good archaeological evidence to demonstrate the artificial shaping of the area for Meton's observations.

Management: In common with all significant Greek archaeological sites, the Pnyx is the property of the state. The flat area where Meton observed has been exposed and is presented to visitors using discreet labelling.

Case Study 9.2: The Acropolis of Alatri, Italy

Guilio Magli

Presentation and analysis of the site

Geographical position: Town of Alatri, Frosinone Province, Lazio Region, Italy.

Location: Latitude 41° 43´ 35˝N, longitude 13° 20´ 32˝E. Elevation 490m above mean sea level.

General description: Alatri is one of several towns in the ancient Latium Vetus—a wide area in central Italy broadly enclosed by the coast and the Apennines between Rome and Terracina—whose walls and buildings were constructed using the 'polygonal' technique, in which enormous stone blocks are cut in irregular shapes and perfectly fitted together without mortar. Alatri was built around a small hill and the acropolis (citadel) was placed on the hill, forming a sort of huge 'geometric castle' dominating the centre of the town.

Inventory of the remains: The acropolis has two entrances, a major gate (Porta Maggiore) with a 24-tonne lintel measuring 5 × 2 × 1.5m and a postern gate (Porta Minore) on the opposite side. There are no inscriptions: the only mark left by the builders is a symbol on the lintel of the postern gate composed of three phalli arranged so as to form a T-shaped (or cross-shaped) image. On the opposite side of the building, at ground level, are three huge niches (c. 2m high and 1m wide); they have no structural function and appear to have held statues.

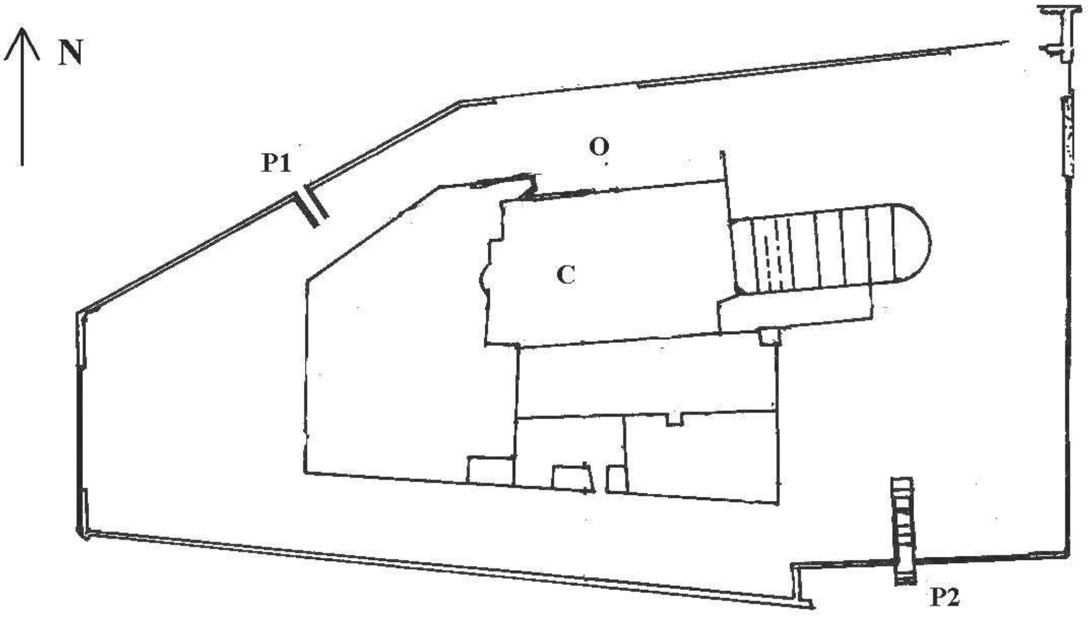

Fig. 9.2.1. Schematic map of Alatri acropolis. P1– Postern gate; P2– Main gate; C– Cathedral; O– Natural fissure in the rocks that might have been used as the foundation deposit of the town. After Magli (2006), fig. 2.

Fig. 9.2.2. The acropolis of Alatri: the north-west front with the postern gate. Photograph © Guilio Magli.

Alatri cathedral stands within the acropolis. The lower courses of stone in its walls belong to an earlier building, possibly a temple, constructed using the polygonal technique. The northern wall contains a huge block measuring 2.5 × 2 × 1m, which was cut with nine corners and then joined to other eight blocks. Just behind this stone there is a natural fissure in the rocks, which might have been the foundation deposit (i.e., a pit, or a natural crevasse, where ritual objects and/or vegetables were buried at the act of the foundation of a town). This point is marked '*O*' in Fig 9.2.1.

History of the site: In Italy, all polygonal walls are attributed to the Romans, and generally thought to date to the time of the Roman *republica* (5th–3rd century BC), although for most of these constructions no reliable stratigraphy is available, and they may be somewhat (up to a few centuries) older. Inside the earthwork supporting the wall in the area of the three niches, the substructure of an archaic building (6th–5th century BC), possibly a temple, has been unearthed. Another temple probably stood where Alatri Cathedral was later constructed, the catedral being constructed upon the surviving lower walls of this second temple.

Cultural and symbolic dimension: Alatri is the most spectacular example of the use of geometry and astronomy in planning during Early Roman times. The point *O* is the basis for a number of geometrical relationships incorporated in the architectural plan: for example, the gates of the city on opposite sides of the acropolis are equidistant from *O*. The main astronomical alignment is from *O* to the north-eastern corner of the acropolis, which coincides with the rising sun at the summer solstice. Astronomical symbolism also appears to have been incorporated in the orientation and distinctive shape of the building. Its east and west walls are oriented cardinally (north–south), while it has been argued that other alignments indicate the bright southern stars of the Southern Cross and Centaurus. Its distinctive shape, which is by no means constrained by the morphology of the hill, reflects that of the constellation of Gemini.

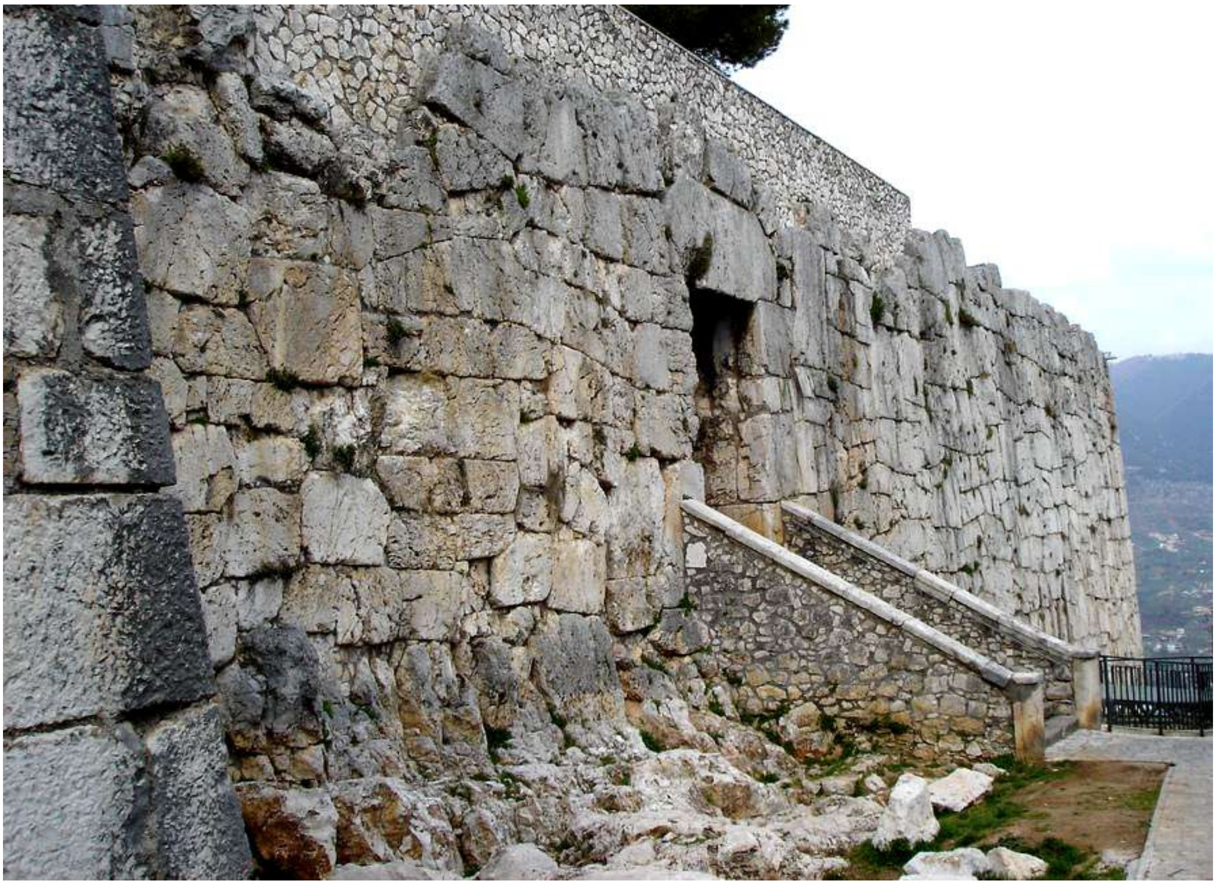

Fig. 9.2.3. The acropolis of Alatri: The south side with the main gate (the staircase is a 19th-century addition). Photograph © Guilio Magli.

Comparative Analysis: Not only in Alatri, but in many other towns of central Italy such as Circei, Ferentino, Norba and Segni, the size of the stone blocks and the ingenuity in the construction of polygonal masonry reach the same magnificence, and give the same impression of power and pride, as characterize the world-famous Mycenaean towns of Tiryns and Mycenae, constructed around the 13th century BC, the so-called pyramid of Helleniko, and the masterpieces of early classic Greek architecture such as the terrace of the Temple of Apollo at Delphi, dated to the second half of the 6th century BC.

Authenticity and integrity: The citadel walls are virtually intact, still rising up to 15m high. The shape and orientation of the building, which are crucial for the astronomical interpretation, are unchanged. However, if the three wall-niches originally held statues, these have been long lost.

Present site management

Present use: The site is used as a monument and park. It is open to the public, free of charge.

State of conservation: The state of preservation of the walls is excellent: the joints between the blocks are so perfect that it is impossible to insert even a single sheet of paper between two of them. The builders' symbol was damaged in antiquity (probably as a pagan symbol) but is still clearly visible.

Context and environment: The city lies on a hill standing at the centre of the (relatively untouched) Liri valley, with other hills around the horizon.

Archaeological/historical/heritage research: The impressive polygonal walls of central Italy were first investigated by 19th-century 'romantic' archaeologists such as Ferdinand Gregorovius, later by Theodor Mommsen, and subsequently by Giuseppe Lugli. The idea that the layout of Alatri was planned on the basis of geometrical and astronomical alignments was first put forward by the local historian Giuseppe Capone in 1982. His results were confirmed and extended by subsequent investigations.

Main threats or potential threats to the site: A continual problem for the dry, polygonal masonry is the growth of tree roots inside the earthwork that stands behind the walls. Today the city authority seems to have this problem under good control, although more funding is needed. Unfortunately an attempt at restoration was made in the 1970s, in which cement was injected in some sectors; this has caused a series of problems because the masonry cannot oscillate and the area is one of high seismic activity. However, it seems to be impossible to restore the pre-restoration situation, so the monument is (for the first time in millennia) at some risk from earthquakes.

Management: The site is owned by Alatri city administration.

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Case Study 9.3: The Pantheon, Rome, Italy

Guilio Magli

Presentation and analysis of the site

Geographical position: Piazza della Rotonda, Rome, Italy.

Location: Latitude 41° 53´ 55˝ N, longitude 12° 28´ 37˝ E. Elevation 15m above mean sea level.

General description: The Pantheon is the one of best-preserved buildings of the Roman period in Rome and shares with the Coliseum the title of most famous.

Inventory of the remains: The Pantheon as preserved today is composed of a rectangular *pronaos* (portico) with three lines of granite columns fronting a circular building. The latter is designed as a huge hemispherical dome (43.3m in diameter) built over a cylinder of the same diameter and as high as the radius. There is a circular opening (oculus) 8.3m wide in the top of the cupola. The wall in the interior is divided into sixteen regularly spaced sectors: the northernmost contains the entrance door while the rest contain niches and columned recesses in alternation.

Fig. 9.3.1. Sunlight entering the Pantheon through the oculus. Photograph © Giulio Magli.

The oculus provides the only source of natural light for the building, since direct sunlight can never enter through the north-facing entrance. As a consequence, the interior gives the visitor a strange impression of coldness and dark, except on sunny days when one's attention is drawn to the huge beam of sunlight entering through the oculus.

History of the site: The Pantheon was built by Agrippa around 27 BC under Augustus's rule, but its present form is due to Hadrian, c. AD 128.

Cultural and symbolic dimension: The Pantheon has exerted a tremendous influence on architecture since the Renaissance; however—apart from a brief mention by Pliny and one by Cassius Dio, writing some 70 years after Hadrian, who makes a cryptic statement about the monument being the temple of all the gods—no written source tells us why the Pantheon was built or how it was used. However, there exists convincing evidence that this monument was strongly connected with the solar cycle during the course of the year, and that at least one of its main functions (if not its main purpose) was to associate the sun with the power of Rome and to reinforce the emperor's divine right to rule.

The monument acts like a giant sundial with a dark interior, a type well known in the Roman world. During the winter months the beam illuminates only the vaulted dome. However, at noon on the equinoxes it just touches the base of the dome. After the spring equinox it starts descending and on the days around Apr 21 (as well as the symmetric ones in late August) the beam of sunlight fully illuminates the entrance at noon, creating a spectacular hierophany. Closer to the summer solstice, the beam passes across the floor during the middle of the day, although it never reaches the centre.

Fig. 9.3.2. The main hierophany occurring in the Pantheon on April 21, when the beam of sunlight illuminates the entrance fully at noon. Photograph © Giulio Magli.

The spring equinox was connected with the apotheosis of the emperor, while Apr 21 was the traditional date of the foundation of Rome as stated, for example, by Ovid. (In Hadrian's times the differences between the Julian Date in use and the 'correct' Gregorian date was still minimal.) By entering 'with the sun' during celebrations on this day, the emperor would succeed in 'placing Rome among the Gods'. In this and other ways, it is likely that the Pantheon encapsulated Hadrian's ideas about the relationship between Roman religion and power.

Authenticity and integrity: The architectural alignments giving rise to the solar phenomena in the Pantheon are unaltered since the time of Hadrian's reconstruction. The shift in the sun's position owing to the change in the obliquity of the ecliptic since that time is almost negligible.

Present site management

Present use: The site is open to the public, free of charge.

Protection: The Pantheon is on the World Heritage List as part of the "Historic Centre of Rome" World Heritage Site (no. 91).

State of conservation: Very good.

Archaeological/historical/heritage research: There is a substantial literature relating to the Pantheon. See the selective bibliography and references therein for research relating to astronomy.

Main threats or potential threats to the site: No threats known.

Management: The monument is the property of the Italian State. It is entrusted to the 'Soprintendenza per i beni architettonici e paesaggistici' of the Roman administration authority, which is responsible for its maintenance.

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Chapter 10: Islamic Astronomy

Tofigh Heidarzadeh

In the time interval between Ptolemy (2nd century AD) and Copernicus (16th century), the major developments in observational and theoretical astronomy took place from North Africa to Central Asia—during late Antiquity, and then in pre-Islamic and finally Islamic societies. The main advances happened between the 9th and the mid-15th centuries. During this period, Muslim scholars familiarized themselves with Indo-Persian astronomical traditions, mastered Ptolemaic planetary models, improved computational and observational techniques, established large-scale observatories, devised accurate observational instruments and, finally, developed several non-Ptolemaic planetary models to make the observed motions of planets more compatible with Aristotelian cosmology.

The introduction of Hellenistic astronomy

Our knowledge about the extent of peoples' familiarity with astronomy in the Arabian Peninsula in pre-Islamic times is limited. However, it is known that they were familiar with the sun's journey through the zodiacal signs, and that they adopted a lunar calendar, defined lunar mansions by identifying certain fixed stars and asterisms, and used the rising and setting times of certain specific stars to predict seasonal and meteorological phenomena.

The rapid expansion of the Islamic territories from the mid-7th century onwards put Muslims in contact with Persians and Byzantines who had a long tradition in astronomy. However, Muslims' acquaintance with 'foreign' sciences, including astronomy, really began in the late 8th century when the first translations of Greek, Syriac and Persian works into Arabic became available in the court of the ʿAbbasid caliph, al-Mansūr, in the newly built capital city of Baghdad. The establishment of the House of Wisdom, an institute for research and translation, in the early 9th century in Baghdad led to the start of the great project of translating scientific and philosophical books from the Greek, Hellenistic, Persian, and Indian traditions.

Before long, thanks to the translation of works such as the Persian *Zīj-i Shahriyār* (translated into Arabic as *Zīj al-Shāh*), the *Sindhind* (Indian astronomical tables in Sanskrit), Ptolemy's *Mathematikē Sýntaxis* (*Mathematical Treatise,* commonly called *Almagest*, based on the Latin form of its Arabic title, *Kitab al-Majistī, The Great Book)*, and other mathematical works from the Greek and Hellenistic traditions, Muslims became familiar with planetary models and mathematical astronomy. However, it was Ptolemaic astronomy that finally became dominant among Muslim astronomers, although preparing zījs based on the Indo-Persian tradition also continued. During the 8th and 9th centuries, Ptolemy's *Almagest* was translated at least five times into Arabic, and his other works—most importantly the *Planetary Hypothesis*—also became known to astronomers practising in the Islamic territories. When the main texts became available, several commentaries, critical revisions, and summaries also appeared. Some of these discussed the difficulties and inconsistencies found in the original texts, while others helped to make them comprehensible to students.

Muslims' first introduction to computational astronomy was through the zījs. A zīj is a combination of tables consisting of observational data about the motion and position of the planets, sun, moon, and certain fixed stars, and the coordinates of the points of intersection of major circles in the celestial sphere, which enabled astronomers and astrologers to make their astronomical calculations and predictions. The term is derived from the Middle Persian word *zīk* or *zīg*, meaning cord.

The first zījs produced in the Islamic period were based on the Indo-Persian tradition: *Zīj al-Arkand* was written in Arabic in the year 735 based on Indian tables; *Zīj-i Shahriyār* was translated from Pahlavi in the final years of the 8th century (Muslim astronomers knew it in the Pahlavi original long before its translation); and *Zīj al-Sindhind* was translated from Sanskrit in the 770s by al-Fazārī and Yaʿqūb ibn Tāriq, the court scholars of the Abbasid caliph al-Mansūr. However, in the first half of the 9th century al-Khwārizmī, a Persian mathematician and astronomer who lived in Baghdad, compiled a zīj, which is the first extant original Islamic astronomical table. Although elements from the previously translated tables are used in this zīj, Ptolemaic elements were also introduced. The zīj was written under the patronage of caliph al-Ma'mūn, during whose reign (813–33) Ptolemy's *Almagest* was twice translated into Arabic.

Mixing parameters from the Indian-Iranian and Ptolemaic tables, as was done in al-Khwārizmī's zīj and other similar tables, would have created disparities both in practical and predictive astronomy. On the other hand, more than six centuries had elapsed since the time of Ptolemy, during which period the parameters of positional astronomy had altered anyway, so the early Islamic observational astronomers' struggle with the observational discrepancies was inevitable anyway. The earliest efforts at observational astronomy included attempts to build instruments based on information from Ptolemy and other sources, and to measure some of the basic parameters of positional astronomy such as the obliquity of the ecliptic, the length of the solar year and the length of a degree of latitude, as well as certain lunar parameters. Muslim astronomers also performed observations to fix local coordinates in order to determine the *qibla*—the sacred direction of Mecca—towards which Muslims face when praying. Through these observational programs, astronomers were able to correct errors found in the ancient observations, and to obtain updated values for astronomical parameters. This helped them avoid using contradictory parameters from different sources.

During al-Ma'mūn's reign, other observational programs started in Baghdad and Damascus. New parameters were calculated for the solar, lunar, and planetary motions; the obliquity of the ecliptic was measured; and observations took place to determine the positions of stars. Astronomers also performed geodesic measurements to determine the size of the earth by measuring the length of a degree of latitude (in order to provide a new map of the world), and fixed local coordinates by simultaneous observations of a lunar eclipse from Baghdad and Mecca, in order to determine the *qibla* in Baghdad. The outcome of these diverse observations was (directly or indirectly) influential in providing new zījs, among them *al-Zīj al-Mumtahan* and the zīj of Habash al-Hāsib. In these tables, not only were new values used for astronomical parameters; new computational techniques were also employed, as one can see from the use of new spherical trigonometry in the zīj of Habash al-Hāsib. In addition, the comparison of the results of these observations with those from the Hellenistic period led to important corrections to the existing kinematic models. For instance, it was established that, contra Ptolemy and Hipparchus, the position of the solar apogee with respect to the vernal equinox was not fixed.

This observational tradition persisted after al-Ma'mūn. Among the astronomers of the second half of the 9th century was Thābit ibn Qurra (836–901), a polymath and the editor of an Arabic translation of Ptolemy's *Almagest*. Thābit was a Sābian from Harran (now in southern Turkey). Sābians were the followers of an ancient religious order who worshipped the heavenly bodies. Thābit carefully observed the motions of the sun and the moon, measured the length of the sidereal year, determined the solar apogee and eccentricity, and wrote the *Book on the Solar Year*, *On the Visibility of the New Moon*, and a book concerning

Fig. 10.0.1. A page from al-Sūfī's star catalogue: the constellation Sagittarius as seen on a celestial globe. From ʿAbd al-Rahmān al-Sūfī (Azophi) (964), *Book of Fixed Stars*. Creative Commons Licence

the apparent motion of the moon based on Ptolemy's lunar theory. Thābit also concluded that the precession of the equinoxes was not linear, but rather that it was oscillating periodically. He explained this theory of the trepidation of the equinoxes in his treatise *On the Motion of the Eighth Sphere*. Thābit proposed that the poles of the eighth sphere were moving on small circles whose centres held the poles of a ninth sphere.

A contemporary of Thābit, the astronomer al-Battānī or Albategnius in its Latinized form (*c*. 850–929), observing from a city located on the north bank of the Euphrates, calculated a new figure for the obliquity of the ecliptic (23° 35′ instead of Ptolemy's 23° 51′ 20″), found an accurate value for the eccentricity of the sun (0.017326 instead of Ptolemy's 0.0175), observed the planetary motions carefully, and improved the observed values for the moon's mean motion in longitude. In his zīj (known as *al- zīj al-Sābi'ī*) al-Battānī not only used improved values for most of the planetary parameters, but also employed new formulae in spherical trigonometry. In addition, he introduced revised or new types of observational instruments, such as a new sundial, an armillary, and a mural quadrant. Al-Battānī, for the first time in the history of astronomy, talked about the possibility of solar annular eclipses, which he deduced from the variations in the apparent sizes of the moon and the sun.

By the beginning of the 11th century, attempts to perform accurate observations, hand in hand with the development of new methods in mathematical astronomy, became a characteristic feature of Islamic astronomy: the astronomers concerned include ʿAbd al-Rahmān al-Sūfī (903–86), Abū'l Wafā al-Būzjānī (d. c. 997), Ibn Yūnus (d. 1009), and Abū Rayhān al-Bīrūnī (973–1048). The Persian al-Sūfī, in his *Book of Fixed Stars* (964)—which was the first complete survey of the night sky since Ptolemy—provided an accurate star catalogue with corrections to the positional data and magnitudes in Ptolemy's star list. He also described a number of nebulous objects which we now categorize as galaxies and star clusters. Abū'l Wafā, another Persian astronomer and mathematician, worked mostly on mathematical astronomy and made significant developments in spherical astronomy. By introducing new methods, Abū'l Wafā made the solution of problems involving oblique spherical triangles simpler and more accurate than using Ptolemy's methods, which were based on the Theorem of Menelaus. Ibn Yūnus, observing in Cairo, prepared an excellent zīj (called the *Hakīmī Zīj*) which differed from other extant zījs by exhibiting the author's knowledge of his predecessors' observations and his awareness of observational errors and computational precision. His tables for timekeeping were still being used in Cairo in the 19th century. The multi-disciplinary scholar al-Bīrūnī not only introduced a sophisticated spherical trigonometry to solve astronomical and geodesic problems, but also attempted to re-measure some of the astronomical parameters and local coordinates.

Meticulous observations such as these became an integral part of astronomy in the Muslim world throughout the following centuries. However, this was not the main contribution of Islamic astronomy. Major developments also occurred in the fields of theoretical and mathematical astronomy. Some of these developments were triggered by practical needs relating to astronomical and geodesic problems in Islamic rituals, while others were theoretical and philosophical in nature. In both aspects, astronomers in the Islamic territories made significant progress in the history of astronomy.

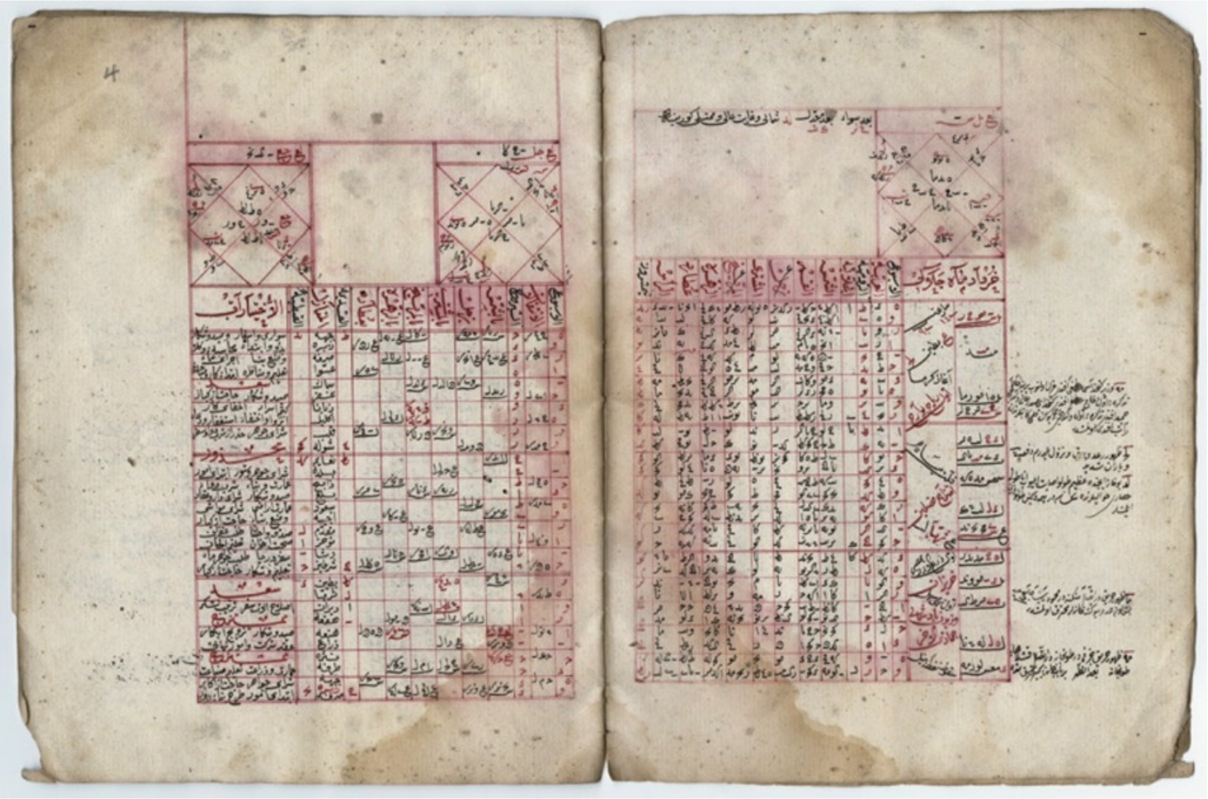

Fig. 10.0.2. Zīj Gurgani [*Zīj-i Jurjānī* = Gurgani Astronomical Tables]. 1193 H/1779**.** *Beinecke Rare Book & Manuscript Library.* (Public domain)

Practical astronomy

The astronomical and geodesic issues relating to Islamic rituals can be discussed under three headings: problems related to timekeeping; the determination of the sacred direction (*qibla*); and the regulation of the lunar calendar. The exact times of the five daily prayers are based on the position of the sun in the sky: the times of the daylight prayers are determined by the length of shadows, while the times of prayers when the sun is not above the local horizon are established on the basis of twilight phenomena. The morning prayer begins at dawn and ends before sunrise; the noon prayer starts at noon, after the sun crosses the local meridian and the shadow of a vertical object reaches its minimum; the next prayer starts in the afternoon, when the length of the shadow of any object is equal to the sum of its midday minimum shadow and the length of the object casting the shadow; the next prayer starts after the afternoon prayer and ends before sunset; and the final prayer starts when the afterglow disappears and should end before midnight. Although it is not difficult to estimate these prayer times empirically, to determine them accurately one needs to acquire a good knowledge of the local coordinate system and the day-to-day changes in the apparent position of the sun in the sky.

During the first thirteen years of the rise of Islam, Muslims faced Jerusalem while praying. However, seventeen months after the Hijra—the migration of the prophet Muhammad from Mecca to Medina—the orientation of prayers (*qibla*) changed so as to be towards the *Kaaba* in Mecca. Since Mecca is located south of Medina, finding the *qibla* in Medina was not difficult. However, once the Islamic territories expanded, finding the right *qibla* became a challenging problem in spherical geometry. The problem was to find the direction of the great circle passing through two points on the globe. Over the centuries, Muslim astronomers and mathematicians developed methods to solve this problem based on spherical trigonometry, and produced tables and even sophisticated instruments to find the orientation of Mecca from different locations.

The regulation of the lunar calendar was one of the most important and at the same time one of the most difficult problems for Muslim astronomers. In Islamic sacred law, the lunar month starts with the first sighting of the new crescent moon. Depending on the time that has elapsed since new moon, this first crescent can be very tricky to observe, owing to the short time it stays above the horizon and its faint glow compared to the brightness of the western horizon after sunset. Therefore, one needs to know exactly when and where to look to find the first crescent. Traditionally, observers were sent to locations with an open horizon to report on the visibility of the moon. If they failed to see it, they would need to repeat their observations the next evening. If the horizon was cloudy, fixed number of days had to be assumed for the month in question. These uncertainties, especially for the holy month of Ramadan, were problematic. Early Muslim astronomers, based on Indian sources, developed procedures to define the visibility of the new crescent by calculating the relative distances of the sun and the moon and working out the difference in their setting times. However, in the centuries that followed they developed more complex procedures, taking into account also the angular separation of the sun and the moon and the apparent velocity of the moon, and provided complicated tables to determine the visibility.

Observatories

In order to obtain accurate celestial data for both astronomical and astrological purposes, continuous observational programs were a necessity. While some data can be obtained in a relatively short time with portable instruments, most of the data needed in positional astronomy require long-term observations. As a result, the establishment of observatories became an integral part of astronomical programmes in the Islamic period. According to available sources, the first observatories in Islam were established in Baghdad and Damascus under the patronage of the Abbasid caliph al-Ma’mūn in the early 9th century. These observatories, which have not survived, were mainly established so as to update the values of astronomical and geodesic parameters in order to compile new zījs, to prepare accurate tables for timekeeping and calendar regulation, and to produce new star maps.

Some scholars made observations independently of al-Ma'mūn's observatories, using their own private observational stations. For example, al-Battānī observed for many years in Raqqa (in northern Syria); the Banū Mūsā brothers observed for about thirty years from their own properties in Baghdad and the nearby city of Samarra; the Banū Amājūr family, including the father, two sons, and a freed slave, observed over a long period and made their own zījs; and Sharf al-Dawla built an observatory in the garden of his palace in Baghdad.

From the mid-10th to the mid-13th century, observatories or observational stations were built all over the Islamic territories, with various observational instruments and to perform different astronomical programs. In the 950s al-Sūfī conducted observations in Rayy (near Tehran) and Shiraz; in the late 10th century Abū'l Wafā al-Būzjānī observed from Baghdad, and observed a lunar eclipse simultaneously with al-Bīrūnī while the latter was in Khwarizm (in modern Turkmenistan); in 994 al-Khujandī measured the obliquity of the ecliptic in Rayy using a sextant about 20m in radius; in the 970s Ibn Yūnus started an extended observational program in Cairo which he explains in his zīj; in the late 10th century and the first two decades of the 11th century al-Bīrūnī conducted observations for more than thirty years in Khurasan (eastern Iran); in the late 11th century 'Umar al- Khayyām used an observatory in Isfahan, Iran, for about 18 years where he prepared a zīj and supervised the calendar reform project for the Seljuk ruler, Malik Shāh; and finally Sā'id al-Andalusī and Ibn al-Zarqāllu undertook a long-term observational program in Spain in the 11th century.

However, two observatories in the Islamic period occupy a special place in the history of astronomy: the Maragha Observatory, built in 1259 in northern Iran under the patronage of Hūlāgū (a grandson of the Mongol conqueror Genghis Khan); and the Samarqand Observatory, founded by Ulugh Beg (a grandson of Tamerlane) in 1424. The scale of the observational instruments in these two observatories, the importance of their observational programmes, their institutional setting, and the number of affiliated astronomers and mathematicians, combine to make these two institutions unique in the history of medieval astronomy. (See Case Studies 10.1 and 10.2.)

The Samarqand observatory, which was based upon ideas from the Maragha Observatory, in turn became a model for an observatory built by Taqī al-Dīn in Istanbul in 1575 and a group of observatories in north India in the 1720s (see Case Study 6.1). After the fall of Ulugh Beg's dynasty in the 1450s, a number of scholars in Ulugh Beg's circle emigrated to the newly born Ottoman Empire, where they strongly influenced scientific developments. Taqī al-Dīn, the court astronomer of Sultan Murad III (reign 1574–95), established an observatory in Istanbul, something the Turkish Sultans had dreamed of ever since they conquered Constantinople in 1453. About fifteen astronomers helped to build and use the instruments, whose purpose was to produce a new *zīj*. However, after two years the great comet of 1577 appeared, which Taqī al-Dīn interpreted as a sign that the Turkish army would be victorious against Persia. Although the Persian army was defeated in the war, the Turkish troops also suffered heavy losses. In the same year several dignitaries died within short intervals, and there was also a plague. Referring to these unpredicted horrifying events, the Sultan believed that the comet appeared because of the establishment of the observatory and that it would go away if its cause (the observatory) were removed. As a result, the observatory was demolished at once, before Taqī al-Dīn was able to finalize his *zīj*.

The Jantar Mantar observatories built by Jai Singh in northern India between 1724 and 1734 (see Chapter 6), although built after the invention of the telescope, continued the Islamic-Persian tradition of monumental observatory building and were greatly inspired by the Samarqand Observatory.

Theoretical Astronomy

In addition to observational and computational astronomy, Muslim astronomers had a special interest in creating a clear picture of the universe in its physical sense. It was generally accepted that the earth was located at the centre of the universe, with all celestial bodies moving uniformly around it. Aristotle had argued that the celestial region consisted of a series of concentric spheres (or ‘orbs’) with the earth at the centre. Each of the planets, for example, moved at a constant rate around one of these orbs. However, observational data did not support this picture: all celestial bodies from the sun and the moon to the planets and stars manifested different short-term or secular non-uniform motions. To explain these observations, non-concentric models of planetary motions had been developed in the 3rd and 2nd centuries BC, culminating in Ptolemy’s model of the planetary motions. This preserved the concentric orbs but included other eccentric orbs and epicycles embedded in each orb. According to Ptolemy, the uniform motion of a planet or the centre of an epicycle occurred around a point called the *equant* which did not coincide with the earth. With this innovation, the observations and the mathematical models of the planetary motions became compatible, but the physical structure of the universe became unclear. The problem was simple: given that the eccentric orbs, epicycles and equant were only mathematical devices to make the planetary motions calculable, what was the true physical configuration of the celestial spheres? Even Ptolemy was not explicit in his treatment of the universe: in the *Almagest* he merely describes the motions and models mathematically, while in his *Planetary Hypothesis* he talks about the configuration of the spheres without referring to problematic premises that underlie his mathematical models.

Critiques of Ptolemy started to appear soon after Muslim astronomers became familiar with the Ptolemaic system. Doubts concerning either Ptolemy’s observational data or his description of the cosmos became common in Islam. The main challenge was to create a configuration (*hay’a*) of the universe that satisfied both observational and physical principles. The main goal, in other words, was to develop models involving uniform motions around the centre of the universe—the earth—that were compatible with observations.

Solving this problem occupied the minds of several Muslim astronomers, among them Ibn al-Haytham, Ibn-Sīnā’s student Abū ‘Ubeyd Jūzjānī, Ibn Rūshd, and Ibn Bājja. However, it was Nasīr al-Dīn al-Tūsī who developed a revolutionary solution to eliminate the equant. Tūsī introduced an arrangement in which the circular motions of two spheres produced a linear motion displacing a point (for example the centre of

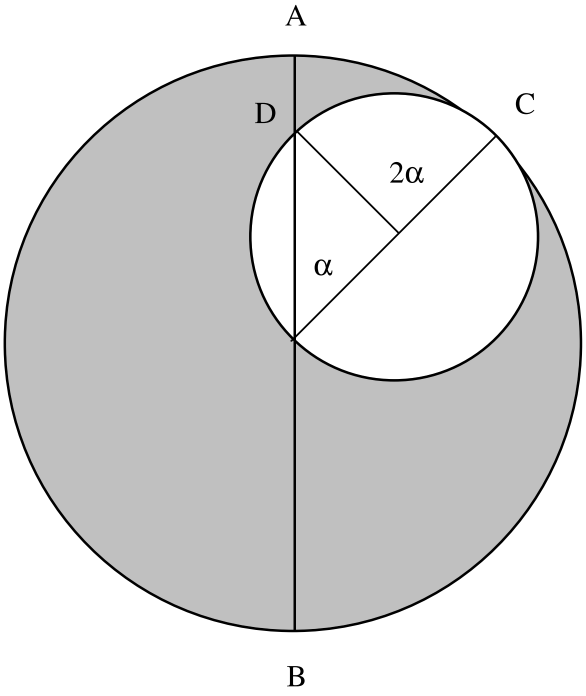

Fig. 10.0.3. Tūsī’s couple. Imagine two spheres internally tangent at one point (*C*), the diameter of the small sphere being equal to half of the other. If the small sphere uniformly moves twice (2α) as fast as the big sphere but in the opposite direction, the common point *D* will move back and forth along *AB*. In other words, the uniform circular motions of the two spheres create a linear motion. By choosing a Tūsī’s couple with the right dimensions and speeds of the two revolving spheres, and attaching it to a given sphere, one can produce the observed non-uniform motion of a particular planet around the central earth, even though the motion of the revolving spheres is uniform. Therefore, both observation and physical principles are preserved. © Tofigh Heidarzadeh.

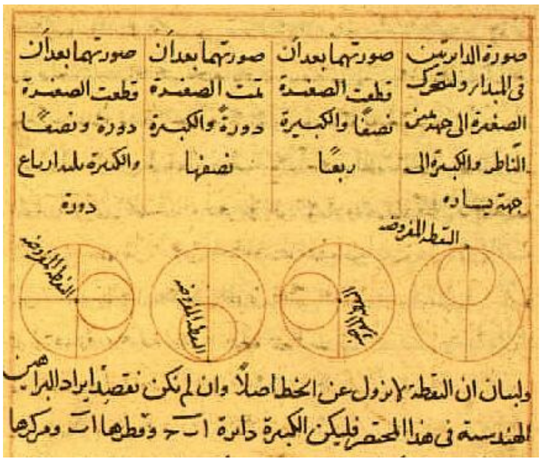

Fig. 10.0.4. Tūsī's diagram of the couple, showing the oscillation of a given point along the diameter of the big circle. After *Tūsī couple from Vat*. Arabic ms 319, commons. wikimedia.org. CreativeCommons Licence

an epicycle) closer to or further from a central point. This arrangement (called Tūsī's couple), which was able to produce non-uniform motions from concentric uniform motions, was a key concept in the development of non-Ptolemaic models. Tūsī's contemporaries Mu'ayyad al- Dīn al-'Urdī and Qutb al-Dīn Shīrazī also developed innovative non-Ptolemaic models, and the tradition continued with further models produced by Alī Al-Qūshjī (of Samarqand Observatory) and Ibn al-Shātir (1304–75), the timekeeper of the Umayyad Mosque in Damascus.

Copernicus repeatedly used concepts developed by Tūsī and his followers and colleagues. In *De revolutionibus* he employed Tūsī's couple to create the variation in the obliquity of the ecliptic and to produce an oscillation in the orbital planes of planets. In the *Commentariolus* Copernicus uses al-'Urdī' and Ibn al-Shātir's models to develop his own models for planetary longitude. Copernicus's model for the lunar motions is almost the same as the model proposed by Ibn al-Shātir. Copernicus probably became aware of Muslim non-Ptolemaic models, especially those developed by Tūsī and his followers, when he was studying in Italy, where there was easier access to Arabic texts.

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Case Study 10.1: The Maragheh Observatory, Iran

Presentation and analysis of the site

Geographical position: Maragha, North-west Iran

Location: Latitude 37° 23′ 46″ N, longitude 46° 12′ 33″ E. Elevation 1560m above mean sea level.

General description: The Maragha Observatory has a unique place in the history of medieval astronomy. It represents a new wave of scientific activities in the Islamic world in the mid 13th century, it had a key role in the development of some sophisticated pre-Copernican non-Ptolemaic systems for explaining the planetary motions, and it was the model for several observatories that were built in Persia, Transoxiana, and Asia Minor up to the 17th century. As an influential institution that was not devoted solely to astronomy, the Maragha Observatory revived advanced scientific studies during what is normally considered the period when science declined in Islam. Ideas initiating from the Maragha School impacted well beyond the Islamic territories and influenced the astronomical revolution of the 16th century.

*Inventory of the remains***:** The central structure, which is assumed to be the main building of the observatory, is circular. Its diameter is 22m and the base of its enclosing wall is 80 cm thick. A 1.5m-wide entrance opens into a 3.1m-wide corridor that marks the meridian line and contains the remains of the mural quadrant, of which 5.5m has survived. On each side of the central corridor are 6 rooms, the pair at each end being smaller than the rest. Outside the main building towards the south, south-east and north-east are five circular constructions. These were the places where the smaller observational instruments were once mounted. There is also a separate building, with an area of 330m^2, which is assumed to be the library of the observatory. In addition, archaeologists have discovered a unit where the metal parts of the instruments were cast and assembled.

History of the site: The construction of the Maragha Observatory commenced in 1259 under the patronage of Genghis Khan's grandson Hūlāgū. Its director was Nasīr al-Dīn Tūsī (1201–1274), an eminent Persian mathematician, astronomer and philosopher whose reputation spread as far as China and whom Hūlāgū had appointed as one of his advisors. The observatory was in fact a scientific institute, with a main building for the observational equipment, some

Fig. 10.1.1. An aerial view of the observatory site. After Parviz Vardjavand, *Kavosh-e Rasadkhaneh-e Maragha*. Tehran: Amirkabir Publications, 1987.

Fig. 10.1.2. The observatory site before excavation (top) and after the first stage of excavation. After Parviz Vardjavand, *Kavosh-e Rasadkhaneh-e Maragha*. Tehran: Amirkabir Publications, 1987.

auxiliary buildings, and accommodation quarters. In the observatory, there was a library which is said to have contained about 400,000 volumes. A team of astronomers, most of whom were invited from different parts of the Islamic world, were responsible for the design and construction of the astronomical instruments, as well as for conducting observations and performing calculations.

According to a text written by Mu'ayyad al- Dīn al-'Urdī (d. 1266), one of the chief astronomers and instrument designers of the observatory, its astronomical equipment included a mural quadrant with a radius of about 40m, a solstitial armilla, an azimuth ring, a parallactic ruler (triquetrum), and an armillary sphere with a radius of about 160cm.

After the death of Nasīr al-Dīn Tūsī in 1274, the Maragha observatory was supervised by his son and remained active until the end of the 13th century. However, following the death of Hūlāgū in 1265 and his son Abāqā in 1282, it lost its powerful patrons and had become inactive by the beginning of the 14th century. Despite this, we have reports that Ghāzān Khān, who reigned from 1295 to 1304, visited the Maragha Observatory several times, probably using it as a model for his own observatory in Tabriz (which has not survived).

Cultural and symbolic dimension: Maragha observatory is the place where Tūsī, with the cooperation of a number of renowned astronomers, mathematicians, and instrument makers, compiled one of the most important Islamic astronomical tables, the *Īlkhānī Zīj*, completing this work in 1272. The astronomers at Maragha also carried out complicated programmes in observational and computational astronomy to update the Ptolemaic parameters.

In addition, the Maragha Observatory represents a turning point in the development of alternatives to Ptolemy's planetary models that were compatible with Aristotelian cosmological principles. These elaborate models, together with further innovations developed at the Samarqand

Observatory and later at Damascus, found their way to Europe and formed a critical part of the mathematical tools that enabled Copernicus to create the heliocentric model of the universe.

Authenticity and integrity: The location of the observatory is essentially an archaeological site with visible material remains and ruins of ancient constructions.

Present site management

Present use: Apart from a few star parties and occasional visits to the site by scholars, there is little activity at the site.

Protection: Since the Islamic Revolution in Iran (1978), the nearby Tabriz University has been responsible for the management and protection of the Maragha site.

State of conservation: In recent years a dome-shaped shelter has been constructed above the remnants to preserve them from further destruction.

Context and environment: The observatory is located at the top of a hill to the west of Maragha.

Archaeological / historical / heritage research: The site of the observatory was excavated in the 1970s by an Iranian archaeological team supervised by P. Vardjavand. They recovered the remnants of 16 original constructional units: some are located at the central observatory building, while others are assumed to be auxiliary structures. There have not been any further investigations since this time.

Management, interpretation & outreach: There is no indication of a general plan for the future of the site.

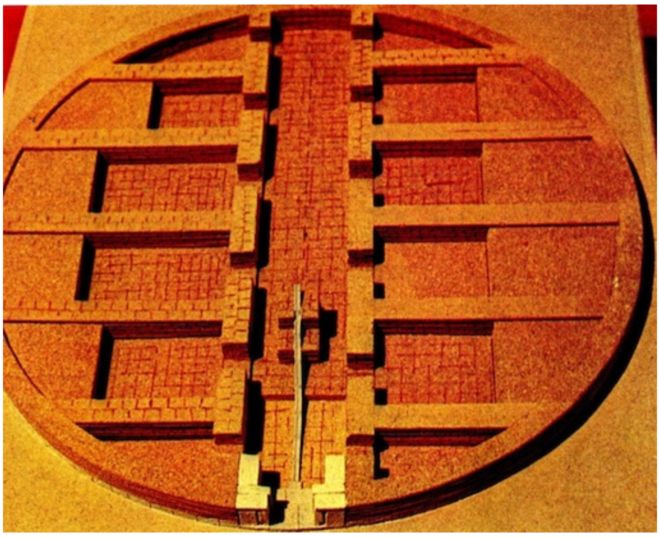

Fig. 10.1.3. Model replica of the observatory site. After Parviz Vardjavand, *Kavosh-e Rasadkhaneh-e Maragha.* Tehran: Amirkabir Publications, 1987**.**

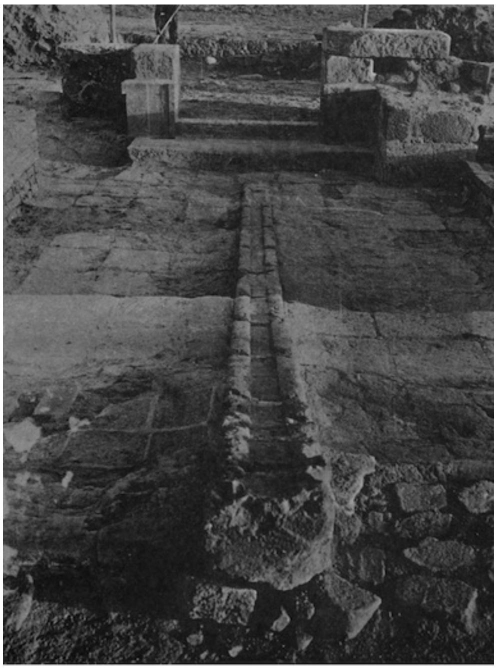

Fig. 10.1.4. Top: The remnants of the mural quadrant, the observatory's main instrument. **Bottom:** Auxiliary observational sites close to the main building of the observatory. After Parviz Vardjavand, *Kavosh-e Rasadkhaneh-e Maragha.* Tehran: Amirkabir Publications, 1987**.**

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Case Study 10.2: Ulugh Beg’s Observatory, Uzbekistan

Presentation and analysis of the site

Geographical position: City of Samarkand, Uzbekistan.

Location: Latitude 39° 40′ 29″N, longitude 67° 0′ 20″E. Elevation 705m above mean sea level.

General description: The site comprises the remains of a meridian arc that originally formed part of the 15th-century observatory of Ulugh Beg. This colossal quadrant, its white marble slabs containing incised Arabic symbols and numerals, was constructing by cutting its lower part out of living rock while its upper part was supported by a brick structure 40m high.

History of the site: Ulugh Beg, the ruler of Transoxiana from 1409 to 1449, had been interested in astronomy from childhood and had visited the remains of Maragha Observatory in his younger years. In 1420 he established a school in his capital city Samarqand, where mathematical sciences were taught, and after four years he established his own observatory, one of the largest in the pre-modern era.

The observatory was a large round building with three stories, decorated with glazed tiles, majolica and mosaic. Its main instrument was a huge sextant with a radius of 40m, embedded in a trench about two metres wide, dug into a hill in the plane of the meridian. This method of construction made the instrument completely stable and reduced the errors arising from the minor displacements common in movable observational tools. At the same time, the enormous size of the sextant made its graduation very accurate. On the arc of the sextant, divisions of 70.2 cm represented one degree, while marks separated by 11.7 mm corresponded to one minute and marks only 1mm apart represented five seconds.

Following the demise of Ulugh Beg the observatory was reduced to ruins. Its remains, primarily the sextant, were discovered in 1908.

Cultural and symbolic dimension: The main purpose of the observatory was to produce a zīj, and the *Sultānī Zīj* or the *Zīj-i Ulugh Beg* was duly compiled in 1438–39. This became one of the most widespread zījs: it was copied more than a hundred times, translated into Arabic and Turkish, and parts of it were translated into Latin and published in Oxford and London in the mid 17th century.

An important aspect of the *Sultānī Zīj* is its updated values for astronomical parameters and new computational procedures. Samarqand astronomers attempted to calculate the trigonometric tables from scratch and derived new values for essential parameters. The basis of the trigonometric tables of the *Sultānī Zīj* is the very accurate calculation of the sine of 1°, which Ulugh Beg Ghiyāth al-Dīn Jamshid al-Kāshī, the senior astronomer of the observatory, calculated using new procedures to sixteen decimal places. His work the *Key to Arithmetic* is one of the best treatises written about arithmetic in the Middle Ages.

Fig. 10.2.1. Ulugh Beg's Observatory, Samarkand, Uzbekistan. Photograph © OUR PLACE THE WORLD HERITAGE COLLECTION (www.ourplaceworldheritage.com).

Under the patronage of Ulugh Beg, Samarqand became an ideal place to study science at an advanced level, and attracted many students from all over the Islamic territories, even including the farthest western regions. As a result of these scholarly exchanges, the influence of Samarqand Observatory, which was itself a continuation of the Maragha School tradition, spread through a vast area from Tranoxiana to the Ottoman Empire. The social and political turbulence that followed the fall of Ulugh Beg and continued until the establishment of the Safavid dynasty in Persia in the early 1500s triggered a massive emigration of scholars from the eastern parts of the Islamic territories into the Ottoman Empire. Among them were several astronomers and mathematicians who were either working at the Samarqand Observatory or else trained by Samarqand scholars; and their influence upon the development of science in the Ottoman Empire was considerable.

Authenticity and integrity: The three-storey building has been destroyed and all that has been preserved is a part of the huge sextant.

Documentation and archives: Al-Kāshī, in his treatise on astronomical instruments, describes some of the instruments used in the Samarqand Observatory. Another treatise, written by ʻAbd al-Mumʻim al-ʻĀmili almost a century after the observatory had been reduced to ruins, also gives valuable information about the instruments.

Present site management

Protection and conservation: Ulugh Beg's observatory forms part of the World Heritage Site 'Samarkand—Crossroads of Cultures' (no. 603), inscribed in 2001 under criteria (i), (ii) and (iv). As one of the major monuments of the property, it is afforded Uzbekistan's highest level of cultural protection and conservation. For more details see ICOMOS (2001).

Context and environment: The monument is situated in the north-eastern outskirts of the city of Samarkand at the foot of Chupan-ata mountain.

Fig. 10.2.2. Ulugh Beg and his observatory on a 1987 Soviet postage stamp. After North 2008, fig. 88.

Archaeological/historical/heritage research: The remains of a number of other astronomical instruments were found during excavation work in the 1960s.

Main threats or potential threats to the sites: See ICOMOS (2001).

Management, interpretation and outreach: The global management of the observatory is organised as part of the general management plan of World Heritage Site no. 603. There is a museum at the site, presenting information about astronomical instruments relating to the Timurid epoch.

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Chapter 11: Medieval Astronomy in Europe

Stephen McCluskey

It would be helpful to begin to spell out the geographic, chronological, and cultural limits of medieval European astronomy by distinguishing it from three other astronomical traditions with which it is related:

- the Classical World (ancient Greece; Hellenistic period; Rome) (see Chapter 9);
- Arabic and Islamic Astronomy (see Chapter 10); and
- astronomy from the Renaissance to the mid-twentieth century (see Chapter 12).

All of these boundaries are somewhat problematic. Medieval astronomy benefited from the heritage of both the Classical and Islamic worlds and contributed significantly to the astronomy of the Renaissance. Furthermore, some of the important traditions of Islamic astronomy were developed in parts of medieval Europe, most notably the astronomy of *al Andalus* (Islamic Spain and Portugal).

Turning to a positive definition, we can define the astronomy of medieval Europe as those astronomical practices that took place in Europe from the fall of the Western Roman Empire in the late 5th century to the Renaissance. From the perspective of art history, the Renaissance began in the 13th century in Italy, but from the perspective of the history of science the medieval traditions of astronomical study continued to flourish through the 14th and 15th centuries and only ended with the publication of Copernicus's *De revolutionibus* in 1543. Culturally and linguistically, this discussion is restricted to the astronomies of the Latin[1] tradition of Europe, as well as those that were expressed in various indigenous languages.

Chronologically, the Middle Ages are conventionally divided into an Early Medieval and a Later Medieval period. A chief marker of this division is the re-emergence of urban society in the 12th century, which was accompanied by several changes that transformed medieval astronomy. The first was the movement of astronomical study from monasteries and cathedrals to the emerging universities. Accompanying the rise of the universities was the change of the content of astronomical study, since both astronomy and geometry took on a renewed quantitative aspect founded on the study of ancient texts. The rise of urban life saw the development of learned and skilled professions, including architects who applied this astronomical knowledge in their work.

In the past two decades, the picture of astronomy in medieval Europe has undergone fundamental changes. Until recently, it had been customary to skip from the Greek and Roman astronomy of late antiquity to its recovery in the 12th century through Arabic intermediaries. In popular histories of astronomy, the Early Middle Ages was dismissed as a dark, thousand-year interlude between the fall of Rome and the Renaissance. Recent studies have displayed the extent and variety of early medieval astronomical study. Its primary emphasis was more on the interpretation and elaboration of received texts than on observations of celestial phenomena. It is only in the later Middle Ages, with the recovery of Ptolemaic texts, that astronomy was transformed to integrate quantitative observations with quantitative predictions using trigonometrically computed tables derived from geometrical models.

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[1] A separate study would be possible of astronomical sites in the medieval Greek world.

It is useful to consider six distinct, yet interacting, astronomical traditions in the European Middle Ages: the arithmetical tradition of computus, concerned with determining the date of Easter in the context of the Julian calendar; the practical tradition within monastic communities of determining times of prayer by observing the stars and the Sun; the ancient Roman tradition of astronomy as one of the mathematical disciplines within the seven liberal arts; the ancient Greek tradition of predictive mathematical astronomy stemming from the work of Ptolemy; a practical concern with the annual motion of the Sun along the horizon for various purposes including the orientation of churches; and finally, the various techniques of astrological prognostication.

Medieval Astronomical Traditions

	Computus	**Timekeeping**	**Roman liberal arts**	**Ptolemaic astronomy**	**Solar horizon astronomy**	**Astrology**
Period of significant activity	Entire Middle Ages	Entire Middle Ages	Before c. 1200	After c. 1100	Entire Middle Ages	After c. 900
Method	Predictive	Observational	Descriptive	Predictive	Observational	Predictive
Astronomical artefacts employed	None?	Structures and apertures; sundials, nocturnals, astrolabes, quadrants	None?	Astrolabes, quadrants, etc.	Oriented churches	Astrolabes, quadrants, etc.
Astronomical memorials	Zodiacs	Sundials, clocks	Zodiacs		Oriented churches; light interactions	Zodiacs
Principal bodies considered	Moon and Sun	Sun and stars	7 planets and stars	7 planets & stars	Sun	7 planets and stars
Types of phenomenon	Discrete	Continuous	Continuous	Continuous	Discrete	Various
Considered in terms	Quantitative temporal	Temporal and spatial	Qualitative spatial	Quantitative spatial	Spatial and temporal	Various

Computus was a practical astronomy, concerned with reconciling the periods of the Sun and Moon—in other words "the science of the numbering and division of time".[2] Specifically, computus addressed the practical problem of establishing a reliable and uniform method for computing the date of Easter and the other moveable feasts in the Christian calendar. Its astronomy was bookish, relying on received values of astronomical periods such as the 19-year luni-solar cycle and the 365¼ day Julian (solar) year; observational instruments were not used to question computistical practice until late in the 11th century. A source of physical artefacts is found, however, in the computists' discussions of the Sun's orderly motion through the twelve signs of the zodiac. Aspects of the zodiac were presented in religious calendars and appeared as iconography in various works of art, including paintings and sculpture adorning buildings.

Timekeeping provided the earliest locus of medieval astronomical observations. When he sent a sundial to the Burgundian king, Gundobad, Cassiodorus described knowledge of the correct time as the thing that separates man from the beasts. Near the end of the 6th century Bishop Gregory of Tours described in his *De cursu stellarum* how the celestial order could be used to regulate monastic prayer at night. Through the 13th century a variety of texts presented

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[2] Grosseteste, Robert (1926). *Compotus ... factus ad correctionem communis kalendarii nostri*. In Robert Steele, ed., *Opera Hactenus inedita Rogeri Baconi*, fasc. VI. Oxford: Clarendon Press. p. 213.

similar techniques for observing particular stars in relation either to the local horizon or to conveniently located structures.

In the 9th century, we begin to see different kinds of portable instruments being used to regulate nocturnal prayer. The earliest *horologium* was the star clock described in the early 9th century by Pacificus of Verona, which determined the time by observing a bright star (Polaris) rotating around the faint star that was then the pole star. Around the year 1000 we see the astrolabe recommended as an instrument to regulate times of prayer.

During the day, prayer could be regulated by the more permanent structure of the sundial. The 7th-century Escomb dial marks the times of the monastic prayers of Terce, Sext, and Nones while the more elaborate dial of the 7th-century Bewcastle Cross marks the twelve hours from sunrise to sunset. The earliest clocks appear in monasteries and these mechanical models of the regular motion of the heavens would come to supplant sundials on medieval churches, incorporating greater astronomical and calendrical detail by the later Middle Ages and Renaissance.

Fig. 11.0.1. Sundial on Bewcastle Cross (late 7th century). Photograph by Tom Middlemass, © Univ. of Durham Corpus of Anglo-Saxon Stone Sculpture, Vol. 2, Image 99.

Fig. 11.0.2. Vertical sundial, church of St Gregory, Kirkdale, York (1055 × 1065). Photograph by Tom Middlemass, © Univ. of Durham Corpus of Anglo-Saxon Stone Sculpture, Vol. 4, Image 568. The inscription reads:

Orm Gamal's son
bought Saint Gregory's minster
when it was utterly ruined
and collapsed and he

had it built anew from the ground
to Christ and to Saint Gregory,
in the days of King Edward,
and in the days of Earl Tosti

This is the day's sun-marker
at every hour
and Hawarð made me
and Brand the priest.

The liberal arts presented the general medieval cosmological picture through the study of ancient texts dealing with the four mathematical arts of the quadrivium: astronomy and geometry, music and arithmetic. This kind of astronomy employed the continuous figures of geometry to provide a qualitative understanding of the structure and motions of the heavens. The motions of the Sun and Moon were commonly described in relation to the zodiac, but neither observations nor computations formed a part of this tradition.

The Ptolemaic tradition, enhanced by Arabic improvements, brought a new concern with quantitative observations and computations to Western European astronomy in the 11th and 12th centuries. Astronomical specialists designed and employed instruments for both observations and calculations. This new astronomy found a home in the new universities of the 13th century, where it was taught and studied.

Solar horizon astronomy reflects the ancient recognition, expressed by Isidore of Seville (early 7th century AD), that the sun "will set in a different place tomorrow, and that it had in a different place yesterday.... When it rises, [it] holds a path through the south. Afterward, it goes to the west and plunges itself into the Ocean."[3] Isidore also maintained that the ancients built temples so that "whoever would take counsel or pray would look to the equinoctial east (*orientem spectabant aequinoctialem*)".[4] This tradition of turning east to pray was frequently elaborated by Christian writers and the astronomical principle was incorporated into the construction of many medieval churches.

In the last century, many surveys of medieval churches have been undertaken, although few of them have been published in detail and no large-scale surveys have been analysed with anything like the statistical rigour that has become routine in archaeoastronomical investigations. These surveys report mixed results; some claim to find orientations towards sunrise on the feast of the church's patron saint, while others deny such patronal orientations. In general, they indicate a tendency to build churches so that the congregation would face the rising Sun at some ritually or calendrically significant time of the year. A recent systematic survey of a carefully selected set of medieval English village churches has shown that the equinoctial direction, as defined by the astronomical principles of medieval calendars and computus, plays a significant role in the orientation of these churches.

Astrology used as its astronomical basis the calculation of the positions of the stars and the seven classical planets for any chosen date or time. Until very recently, the scholarly consensus maintained that before the reception of Ptolemaic astronomy in the 11th and 12th centuries, Europeans lacked the astronomical and mathematical techniques needed to support horoscopic astrology. Recent examinations of previously neglected texts, however, have demonstrated that they provide the necessary techniques. These include a method to compute the sign of the zodiac that was rising on the horizon at a chosen date and time and several methods to compute 'positions' of the planets which, while bearing no relation to astronomical reality, do provide sufficient data for astrological prognostication.

Situating astronomies in medieval Europe

These astronomical traditions flourished at different times. The computistical tradition was concerned with the astronomical basis of the ecclesiastical calendar and endured throughout the Middle Ages; in fact the question of the date of Easter underlay the Gregorian calendrical reform of 1582. The practical monastic tradition of keeping time by watching the stars is

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[3] Isidore of Seville (2006). *The Etymologies of Isidore of Seville*, trans. Stephen A. Barney, W. J. Lewis, J. A. Beach and Oliver Berghof. Cambridge: Cambridge University Press. p. 102.

[4] Isidore of Seville (1962 [1911]). *Etymologiarum sive originum*, ed. W. M. Lindsay. Oxford: Clarendon Press. xv.4.7; cf. Isidore of Seville (2006) [see above], p. 309.

mentioned in the earliest Western monastic rules of the 5th century, and continued into the 13th century. By that time, however, observing instruments and mechanical clocks (both of which incorporated a geometrical picture of the cosmos) had made their way into the timekeeping tradition. The classic texts of the liberal arts tradition were written from the 4th through to the 7th centuries, and gathered glosses and commentaries from the 9th century to the 13th centuries. Beginning in the 12th century, however, they began to be supplanted by texts reflecting the mathematical astronomy of the Ptolemaic tradition. The astronomical orientation of religious structures was called for as early as Vitruvius (1st century BC) and Isidore of Seville (early 7th century AD); this concern continues through to William Durandus and William of St. Cloud (both late 13th century). However, determining when these astronomical principles were actually being followed in the construction of churches requires systematic measurements of the orientations of well defined groups of churches. Astrology, as already discussed, was clearly practiced as early as the 10th century.

The practitioners of these traditions were not members of an astronomical profession, unless we count as astronomers those masters who taught astronomy in the universities from the 13th century until the Renaissance. Astronomical knowledge was developed, preserved, and transmitted as part of a broader intellectual enterprise, overlapping with the theoretical study of natural philosophy, with the practical studies related to the maintenance of the religious calendar, and with those practical activities related to keeping the time of day for religious and civil purposes.

There is little evidence that medieval Europeans made quantitative measurements of celestial phenomena before the 11th century. Most Early Medieval astronomical observations for which we have written records were simple naked-eye observations that qualitatively described fundamental astronomical phenomena: the phases of the Moon, the occurrence of a solar or lunar eclipse, or the periodic appearances of a planet. It is only in the second millennium that quantitative measurements began to emerge in the Latin West, chiefly measurements of the elevation of the Sun and stars using the astrolabe and the various forms of the astronomical quadrant. These instruments reflected and contributed to the incorporation of quantitative geometrical concepts into medieval astronomy.

As regards the material heritage of astronomy in the European Middle Ages, the absence of professional astronomers and the limited role of observations raise several problems. Since medieval astronomy was not institutionalised as a profession, there were few, if any, astronomical observatories in the sense of sites purposefully designed to house instruments for astronomical observation and to preserve the records of those observations. In this period, the few instruments that exist were not the corporate property of scientific institutions but were, as far as we can tell, used either by the assigned timekeepers at religious institutions or owned by individuals who had a special interest in astronomy.

In approaching the material record of medieval astronomies, it is also important to recognise that most historical research into medieval science has focused on texts and their authors; we know more about them than about the places where medieval astronomy was practiced. In some cases, it is not even clear where an author was when he discussed a particular astronomical topic. This makes the designation of some astronomically significant sites somewhat problematic. Similarly, records of astronomical observations, teaching, and theory are not located at specifically astronomical institutions, but are intermingled with other documents in libraries and archives. Although there were no specially designed observatories, occasionally some structures were used for astronomical observations because of incidental characteristics of their design that facilitated such observations.

Astronomy in churches. Churches are among the most abundant medieval sites in all of Europe; every village had one and many of them survive to the present. For example, a recent study noted that there are more 18,000 churches in Britain, some 12,000 occupying sites established before the 13th century. By the 11th century, the construction of standardised village churches had reached a level that "groups of masons could provide 'off the peg' onecell and two-cell churches".[5] Churches do not form a single category but range from simple village churches to elaborate monastic and cathedral churches. Many of them embodied astronomical principles in a variety of ways: some were oriented astronomically; some used the changing light of sunbeams throughout the day and the year for timekeeping or symbolism; many incorporated formal timekeepers, from sundials to clocks, in their structure; and some were decorated with astronomical iconography or symbolism.

The astronomical orientations of many European medieval churches, ranging from great cathedrals to simple village churches, most of which were built after the year 1000, have been measured in varying detail. Although there have been many surveys of the orientation of individual churches—especially of major churches that are noteworthy for artistic or historical reasons—more significant from an archaeoastronomical perspective are systematic surveys of groups of contemporary churches in a single geographical region.[6]

A second class of astronomical interaction with churches involves the controlled use of sunlight within the church to illuminate selected portions of the interior at specific times of the day and of the year. The 13th-century Parisian astronomer, William of St Cloud, discussed how sunbeams, crossing the church from a southern window, could be used to mark midday and other times of day. He asserted that this was the intention of the builders, since they commonly placed an image of a cockerel—the traditional sign of calling monks to prayer—as a weather vane ('weathercock') to show the direction of the winds. A number of recent Italian studies have uncovered cases where paintings or statues of a saint were illuminated by a beam of sunlight on the saint's feast day (for an example see Case Study 11.2). A related concern with interactions of light and church structure is found in a more secular kind of astronomical interaction fashioned during the Italian Renaissance. Astronomically inclined clerics, concerned with the problems of the ecclesiastical calendar, the time of prayer, and other astronomical questions, introduced small apertures in the southern walls of their churches that projected the image of the sun onto permanent meridian lines (*meridiane*) marked or inset on the floor. With these they could determine the exact day of the equinoxes, the time of noon, and even measure the changing diameter of the Sun.

In the latter case, we have documentary evidence where the priests who installed these *meridiane* tell us of their astronomical purpose; more commonly we lack such documentation and thus face the standard archaeoastronomical problem of determining whether the astronomical properties of a structure are intentional. Two approaches that use only the archaeological evidence of the standing structure have been used to try to determine the intended astronomical significance of churches, either in the sense of their axial orientation or of the interaction of their structure with solar rays. From an archaeoastronomical perspective the sounder approach is to consider a geographically, chronologically, and stylistically well-defined group of churches to determine whether, as a group, they tend to share certain astronomical characteristics. But such a study of groups raises difficulties if we want to identify specific examples of individual churches displaying a particular astronomical characteristic. Since the characteristic was identified by a statistical study, although the ensemble of sites may display a particular astronomical characteristic to an extent more than one would expect by chance, individual members of the group may totally lack that characteristic. Conversely, if we were to select from the group only those churches that do display a characteristic, we would give the false impression that the astronomical characteristic under consideration is much more widespread than it actually is.

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[5] Blair, John (2005). *The Church in Anglo-Saxon Society*. Oxford: Oxford University Press. p. 414.

[6] These studies are too numerous to mention here, but for a brief discussion with bibliography see McCluskey, Stephen C. (2004), "Astronomy, time, and churches in the Early Middle Ages", in Marie-Therese Zenner, ed., *Villard's Legacy: Studies in Medieval Technology, Science and Art in Memory of Jean Gimpel* (Aldershot: Ashgate), 197–210, pp. 208–210.

The second approach found in the literature is to identify the astronomical characteristics of churches by studying an individual church to determine its precise astronomical orientation or the interactions of solar rays with other architectural elements. Often these studies are done as part of a broader investigation of an otherwise significant site. In this case, the astronomical associations can be incorporated as an element of a wider heritage approach in the case of a structure that is considered significant for other, non-astronomical, reasons. However, in many cases the astronomical characteristics of churches may only be adequately demonstrated by producing documentary evidence or by considering a regional group of related buildings of the same period that share those same characteristics.

Timekeepers of various kinds. A common theme in the Middle Ages was the use of astronomy for the reckoning of time, first for religious and later for civil purposes. Timekeepers ranging from sundials to ornate astronomical clocks were often incorporated as a semi-permanent feature of churches and other religious or civic structures. The Cathedral of Chartres, for example, incorporates two astronomical clocks and an ornate sculptural sundial. An elaborate example of such timekeepers is found in Strasbourg Cathedral, which includes numerous sundials and a sequence of elaborate astronomical clocks built in the 13th, 16th, and 19th centuries (see Case Study 11.3). All three clocks incorporated various principles drawn from medieval astronomical traditions, displaying the motions of the Sun and Moon, and in the later clocks the planets, as well as various calendrical and computistical parameters related to the fixed and movable religious feasts. Both of these cathedrals are on the World Heritage List, but these astronomical concepts are not mentioned in the nomination. Such astronomical elements should be incorporated as part of the significance of structures presently on the list and in future nominations.

Fig. 11.0.3. Sundial at Chartres Cathedral. Photograph © C.H. McCluskey

Structures embodying astronomical iconography or symbolism. A common theme in medieval artistic depictions, both in manuscript illustrations and in architectural decoration, is the movement of the Sun through the zodiac and its relation to human activities. Colum Hourihane (see bibliography) has provided an extensive catalogue of the appearance of these symbols in astronomical texts, in religious calendars, and as stained glass, paintings and sculpture decorating churches. The 12th-century sculptural decoration of the arches over the west facade of Chartres Cathedral, for example, depicts the signs of the zodiac and the related labours of the month. The same pattern is evident in the late 13th-century sculptures at the bases of the niches on the west façade of Strasbourg Cathedral and on the Baptistery of the Cathedral of Parma (see Case Studies 11.2 and 11.3). To the extent that the decorations of medieval churches were created as textbooks for the illiterate, these sculptures reflect an attempt to disseminate a general understanding of the relation of human activities to the cosmos.

Centres of learning and patronage. Perhaps the most historically significant, although less immediately apparent, category of medieval astronomical sites are those that housed various centres of learning where astronomy was developed, studied and taught. This includes monasteries, which housed the monastic schools of the early Middle Ages; cathedrals, homes to the cathedral schools; and their successor, the medieval universities, where the new Greco-Arabic astronomy was assimilated and transformed. Astronomy was not only a concern of these formal educational institutions; it was also a topic of discussion at many courts, as rulers played the Platonic (or Solomonic) role of the philosopher king. Among those are the courts of Theodoric the Ostrogoth at Ravenna, of the Visigothic King Sisebut at Toledo, and of the Emperor Charlemagne and his successors at Aachen.

Important examples of such centres are the monastery of Wearmouth–Jarrow at the time of Bede (see Case Study 11.1); the scholarly network centred on the Carolingian court in the 9th century; and the University of Paris in the 13th and 14th centuries. The Monkwearmouth and Jarrow Monastic Sites are on the United Kingdom's tentative list; the Carolingian cathedral at Aachen (Germany) was inscribed on the World Heritage List in 1978 under criteria (i), (ii), (iv) and (vi).

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Case Study 11.1: Monkwearmouth–Jarrow, United Kingdom

Presentation and analysis of the site

Geographical position: City of Sunderland (Monkwearmouth) and South Tyneside Metropolitan Borough (Jarrow), North Tyne and Wear, England, United Kingdom.

Location: Monkwearmouth: Latitude 54º 54´ 48˝ N, longitude 1º 22´ 29˝ W. Elevation 50m above mean sea level. Jarrow: Latitude 54º 58´ 49˝ N, longitude 1º 28´ 20˝ W. Elevation 75m above mean sea level.

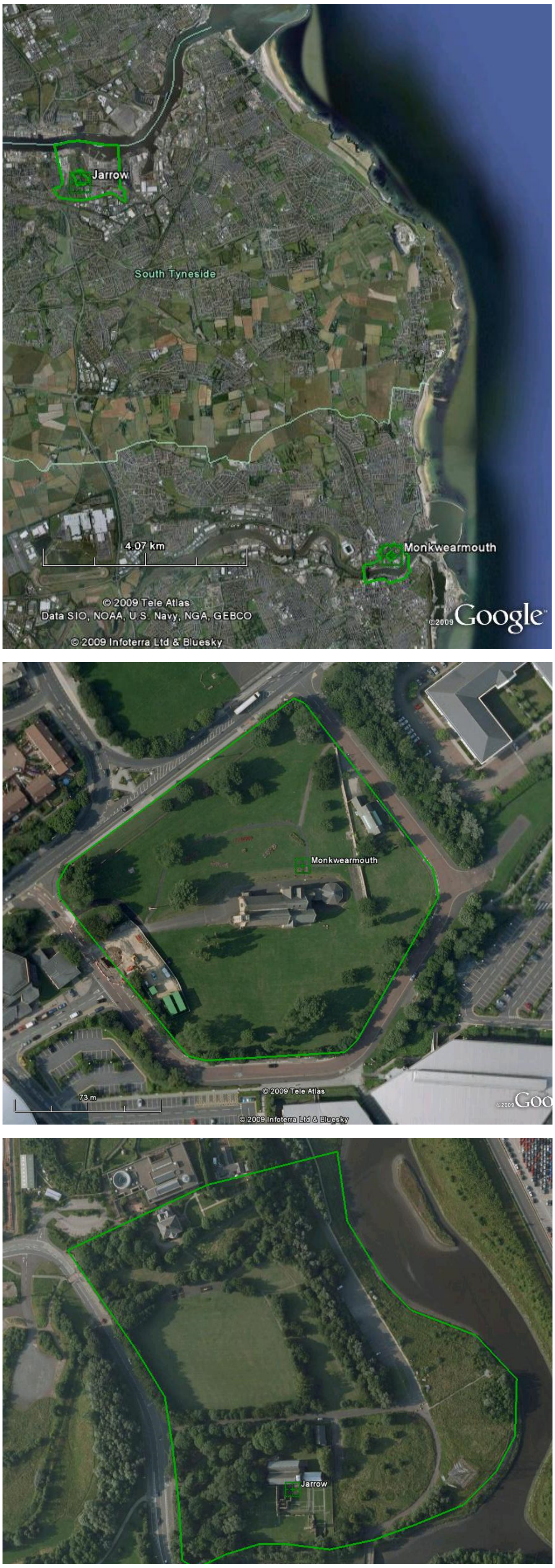
General description: The twin monastery of St Peter (Monkwearmouth) and St Paul (Jarrow) lies near the mouths of the rivers Wear and Tyne.

Inventory of the remains: The relevant portions include the Anglo-Saxon monastery and Medieval Priory Scheduled Monument and St Peter's Church at Monkwearmouth and St Paul's Church and Churchyard and the St Paul's Monastery and Village of Jarrow Scheduled Monuments at Jarrow.

History of the site: The twin monastery was established in the seventh century by Benedict Biscop and by the early eighth century was an internationally renowned centre of learning with one of the most important libraries and scriptoria of its time.

Cultural and symbolic dimension: The significance of this site for the development of astronomy relates to the scholarly activity of the monk, Bede of Jarrow (c. 673–735), who entered the monastery at the age of seven and remained there for the rest of his life. As the proposed statement of value from the draft site nomination says:

> "Bede's exceptional abilities ... flourished in this environment. His prolific output ... on a great variety of ... subjects, including theology, astronomy, science, music and language ... still inspire active international scholarship, as they have done for more than thirteen centuries."



Bede wrote his works on astronomical computus between AD 703 and 731. His writings focused on integrating the astronomical and liturgical concepts of time, by means of numbers, in order to compute a correct religious calendar. These works were rapidly carried throughout Europe and provided a significant intellectual element of the Carolingian Renaissance. His *On the Reckoning of Time* became the principal text for early medieval astronomical study and continued to be taught and copied from the eighth to the fifteenth centuries.

Authenticity and integrity: The physical site contains elements of the original seventh-century monastic structure, and the plan of the site follows the plan of the original seventh-century monastic settlement. From the astronomical perspective, the associated computistical and scientific works of the Venerable Bede are of even greater significance.

Present site management

Present use: The Churches of St Peter (Monkwearmouth) and St Paul (Jarrow) are operating churches, currently owned in trust by their respective incumbent rectors and managed by their respective Parochial Parish Councils.

Protection: St Paul's Monastery at Jarrow, the Village of Jarrow, and Monkwearmouth Anglo-Saxon Monastery and Medieval Priory are designated as Scheduled Monuments. St Peter's Church at Monkwearmouth, St

Fig. 11.1.1. The World Heritage Property proposed by the State Party: Monkwearmouth–Jarrow: overview (top), Monkwearmouth (centre) and Jarrow (bottom). © Document from *Wearmouth-Jarrow Candidate World Heritage Site*, 2010, based on Google.

Fig. 11.1.2. Top: St Peter's Church, Monkwearmouth. Photograph © R.J. McNaughton, Creative Commons Licence. **Bottom:** St Paul's Monastery, Jarrow. Photograph © Ken Crosby; Creative Commons Licence

Paul's Church at Jarrow, and the ruins of the Jarrow Medieval Monastic Site are Grade I Listed Sites. Additional elements of the site have further statutory protection. Protection of St Peter's Church and St Paul's Church is effected by the Church of England through its own internal controls that require a license, called a 'faculty' for all alterations to the fabric, ornaments or furniture of churches.

State of conservation: The state of conservation of both churches is monitored by the Church of England and that of St Paul's monastic site by English Heritage. Both are generally good.

Context and environment: The two monastic sites are in an area of controlled urban growth; their historical importance guides the planning of this development.

Main threats or potential threats to the site: These are pressures from urban development, and hazardous industrial operations in the vicinity.

Management: The Churches of St Peter and St Paul both maintain outreach and interpretation programs based on the archaeological and historical discoveries. English Heritage currently conducts an ongoing interpretation programme at the monastic site of St Paul, Jarrow; arrangements are being made for an interpretation program at the monastic site of St Peter, Monkwearmouth.

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Case Study 11.2: The Baptistery of Parma, Italy

Manuela Incerti

Presentation and analysis of the site

Geographical position: Parma, Emilia Romagna, Italy

Location: Latitude 44º 48´ 10˝N, longitude 10º 19´ 50˝E. Elevation 62m above mean sea level.

General description: The Baptistery of Parma is a religious building in Parma, located adjacent to the Cathedral. It is one of the most important medieval monuments in Europe.

Inventory of the remains: The main axis (from the baptismal font to the altar) points to the rising sun on the feast of the Purification of the Blessed Virgin Mary (Feb 2). The patron saints of the Baptistery are the Virgin Mary and St John the Baptist, and the episode of the Purification is also displayed in the inner lunettes. Other alignments indicate sunrise and sunset on the equinoxes and solstices.

The solstitial direction (very close to the feast of St John the Baptist, Jun 24) is indicated by numerous elements found in the fifteenth sector: the bas-relief of St John the Baptist, the beginning of the Cycle of the months, the unexpected appearance of St John the Evangelist in the sector reserved for the Prophets, and the unique cross with leaves in the starry sky.

It is likely that the placement of the statues of the months and of Antelami's zodiac were influenced by astronomical considerations. The annual cycle starts with summer solstice sunrise. The statue of spring is aligned with the equinoctial axis, although it is not positioned between the appropriate statues of the month. The anomalous position of spring (between Gemini and Cancer) can thus be explained on archaeo-astronomical principles.

On the feast of St John the Baptist (Jun 24) many light effects occur. The main baptismal font is struck by a ray of sunlight, while other events involve the smaller baptismal font and the altar.

On the fifth level of the cupola, a ray of light strikes the painting of the Baptism of Jesus in the River Jordan during the Easter period, beginning on Mar 25 and ending around Apr 10. This corresponds to the early church's practice of only celebrating baptismal rites on a few days: Easter and Pentecost (movable fests), and the nearly-solstitial feasts of St John the Baptist, Epiphany and Christmas.

Fig. 11.2.1. The Baptistery of Parma. Photograph © Philip Schäfer, Creative Commons Licence

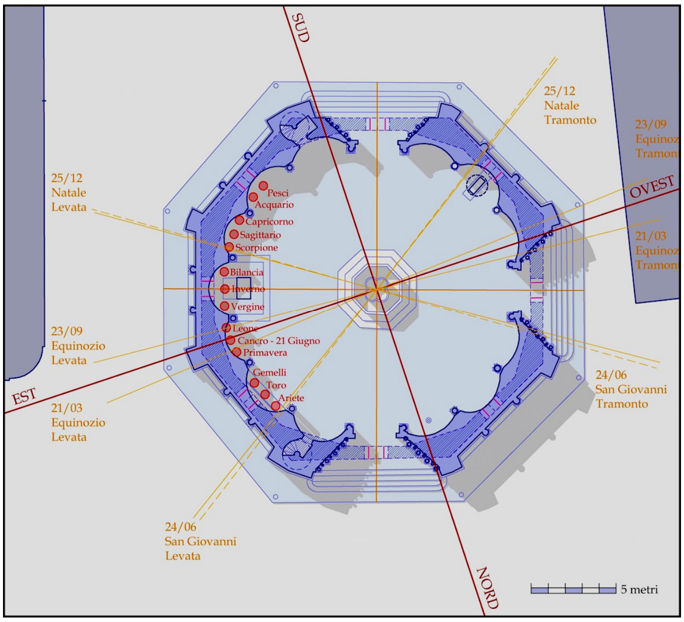

Fig. 11.2.2. Ground plan of the Baptistery of Parma. Note the positions of solstitial and equinoctial sunrise and sunset, and the internal depictions of the zodiac and the seasons. After Incerti (2001)

History of the site: The Cathedral was built in 1046 and rebuilt after an earthquake in 1117; the Baptistery was begun in 1196 under the direction of Benedetto Antelami, and completed in 1270.

Cultural and symbolic dimension: There are three different design aspects of the relationship between medieval architecture and the heavens that have influenced the history of humanity. The first is the alignment of buildings towards visible points on the horizon on certain days of the astronomical calendar or of the liturgical year, governed by the rising or setting of the sun, the moon, the planets, or the stars. The second is the three-dimensional relationship between the ground plan and the building elevations that can produce spectacular and impressive light effects (hierophanies) on certain days of the year. The third is decorative elements such as wall paintings, frescoes or statues, sometimes added long after the date of construction, carefully placed so as to catch a ray of light on a specific day. The Baptistery of Parma encapsulates examples of all three elements.

Authenticity and integrity: The baptistery meets the criteria of authenticity both as regards its medieval structure and the architectural conception, sculpture, and building materials.

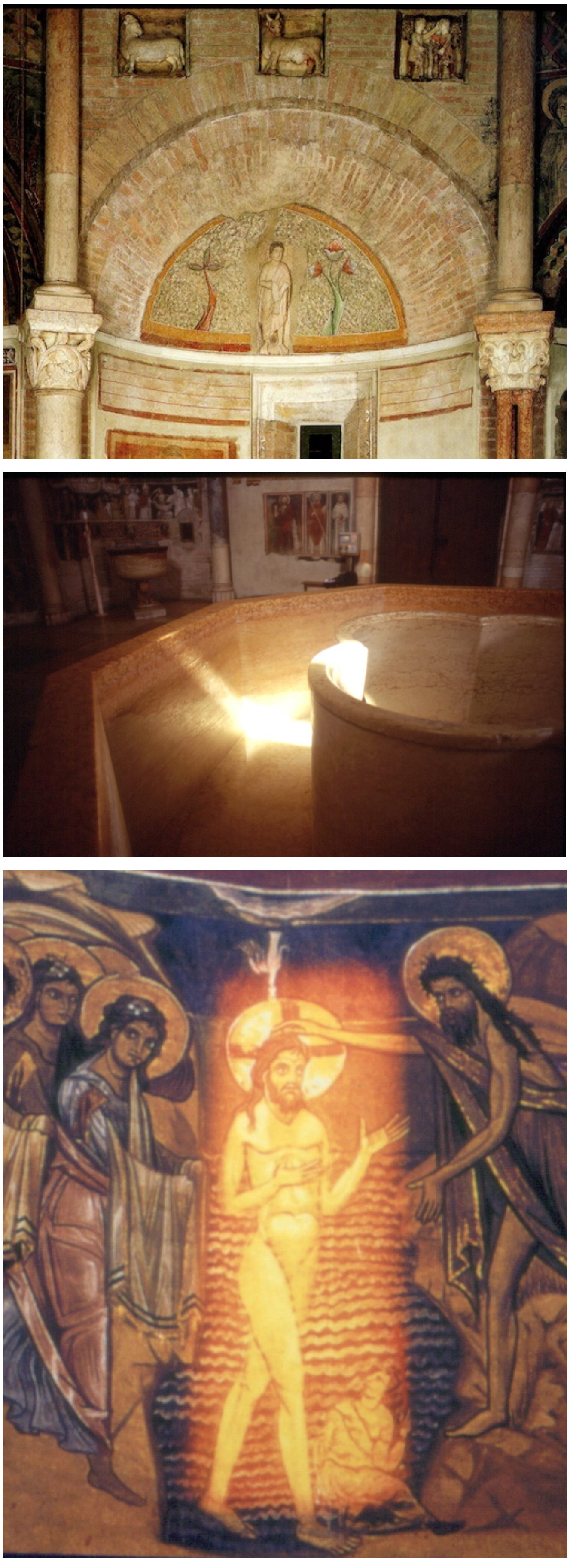

Fig. 11.2.3. Top: Part of the Zodiac: Aries, Taurus and Gemini. **Middle:** Sunlight falling on the Large Baptismal Font on the Feast of St John the Baptist. **Bottom:** Sunlight falling on the Baptism of Christ close to the equinoxes. Photographs © Manuela Incerti

Present site management

Present use: The baptistery is a church building, the property of the Diocese of Parma.

Protection: The site falls under the protection of national and municipal legislation concerning cultural heritage, respectively Decree n. 42/2004 (Codice per i beni culturali ed il paesaggio) and the Town Planning – Municipal Plan of Operation, which guarantees the conservation of its historic and artistic features.

State of conservation: The building is well preserved. The most recent restoration works were undertaken in 1988–92 (interior paintings and exterior marble) under the direction of the Ministero Beni Culturali (MIBAC).

Context and environment: The Baptistery is in the historic centre of the City of Parma, which is also a centre of tourism.

Management, interpretation and outreach: The building is open daily to tourists.

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Case Study 11.3: Strasbourg Cathedral, France, and Astronomical Time

Presentation and analysis of the site

Geographical position: City of Strasbourg, Département du Bas-Rhin, Alsace region, France.

Location: Latitude 48º 34´ 55˝ N, longitude 7º 45´ 5˝ E. Elevation 150m above mean sea level.

General description: The Cathedral of Notre Dame, constructed from the 11th to the 14th centuries, forms the core of this site. Several original timekeepers which have been removed from the cathedral are now in Strasbourg's Museum of Decorative Arts and Musée de l'Œuvre Notre-Dame. The Cathedral forms part of the World Heritage property 'Strasbourg–Grande Île' inscribed on the List in 1988 under criteria (i), (ii) and (iv).

Inventory of the remains related to astronomy:

Location	***Description***
Sundials	
Niche in buttress of south transept; original in Musée de l'Œuvre Notre-Dame	Statue of youth with a sundial (1225 × 1235)
Gable of south transept	Three vertical sundials, Conrad Dasypodius (1572)
Exterior wall of the Treasury	Vertical sundial (1488?)
Exterior buttress of the Treasury	Vertical sundial (15th century)
South transept above clock; original in Musée de l'Œuvre Notre-Dame	Relief of astrologer with a sundial (c. 1490)
Inside door of south transept	Meridian line (1838–42)
Tower's four sides at platform level	Four vertical dials (16th century)
Tower's south side at platform level	Meridian with triangular stylus and single vertical noon line (16th century)
Tower	Statue of man holding sundial-like shield with concentric circles (late 15th century)
Clocks	
South transept, above entrance	External clock shows hour of day and day of week (and corresponding planet)
Formerly opposite the present clock in the South Transept; cock-automaton in Museum of Decorative Arts	First astronomical clock (1352–4)
Formerly in the location of the present clock in the south transept; mechanism now in Museum of Decorative Arts	Second astronomical clock (1571–4), Conrad Dasypodius
In the south transept	Third astronomical clock (1838–42), Jean-Baptiste Schwilgué
Zodiac	
West front, right portal, niches in bases of statues	Zodiac and occupations of the months (late 13th-early 14th centuries)

History of the site: With the construction of the west front, the cathedral obtained its earliest known display of astronomical time—one that the cathedral shares with many other large churches—the carved reliefs depicting the signs of the zodiac and the labours of the months in the bases of the statues flanking the right portal (Fig. 11.3.1).

The most widely known of these astronomical displays of are the cathedral's elaborate astronomical clocks. The 14th-century clock included a calendar, a mechanically driven stereographic projection showing the movement of the stars, and pointers showing the positions of the Sun and Moon. Atop the clock was an automaton of a cockerel, which crowed at noon, flapping its wings.

The 16th-century clock added to these elements a rotating celestial sphere on which were depicted all 1020 stars of Ptolemy's star catalogue together with figures of 48 constellations, a disc showing the ecclesiastical calendar for 100 years, and depictions of all eclipses over an interval of 32 years. A stereographic projection of the stars, Sun and Moon, like the one in the original clock, was enhanced with additional pointers showing the positions of all the visible planets and the 'Dragon', or lunar node, which served to explain eclipses (Fig. 11.3.2a). Elements of the case and display were incorporated into the current clock. Although the clock reflected the geocentric model of astronomy, its decoration included a portrait of Nicolas Copernicus.

The 19th-century clock reflected Copernican astronomical concepts. The geocentric stereographic projection of the Sun, Moon, and planets was replaced by a heliocentric model of the visible planets, plus the Earth and Moon, in the solar system (Fig. 11.3.2b). It displayed both uniform civil time and the apparent time indicated by the daily motions of the Sun. The stellar globe now portrayed more than 5000 stars, extending down to faint sixth magnitude ones. In addition, the clock incorporated a perpetual calendar, computing the 'solar' cycle of 28 years, the lunar cycle of 19 years, the date of Easter, and other calendrical parameters traditionally found in ecclesiastical computus.

The concern with time that we see in the cathedral's clocks also appears in its fourteen sundials, which date from the 13th to the 18th centuries. The oldest sundial, dated between 1225 and 1235, marks seven times of prayer in the course of the day, beginning at dawn and continuing until sunset. The 15th century saw the addition of three more sundials, dividing the day into twelve hours from sunrise to sunset (Fig. 11.3.2c). In the 16th century, five dials were installed at the platform level of the tower and three mathematical dials, designed by the builder of the second clock, were installed on the gable of the south transept (Fig. 11.3.2d). The builder of the 19th-century clock, Jean-Baptiste Schwilgué, installed a vertical meridian line inside the entrance to the south transept (Fig. 11.3.3), marking local apparent noon to regulate the clock.

Fig. 11.3.1. Occupations of the months and signs of the zodiac, west façade, right portal—May, Gemini; June, Cancer; July, Leo; August, Virgo. Photograph © Ad Meskens, Creative Commons Licence

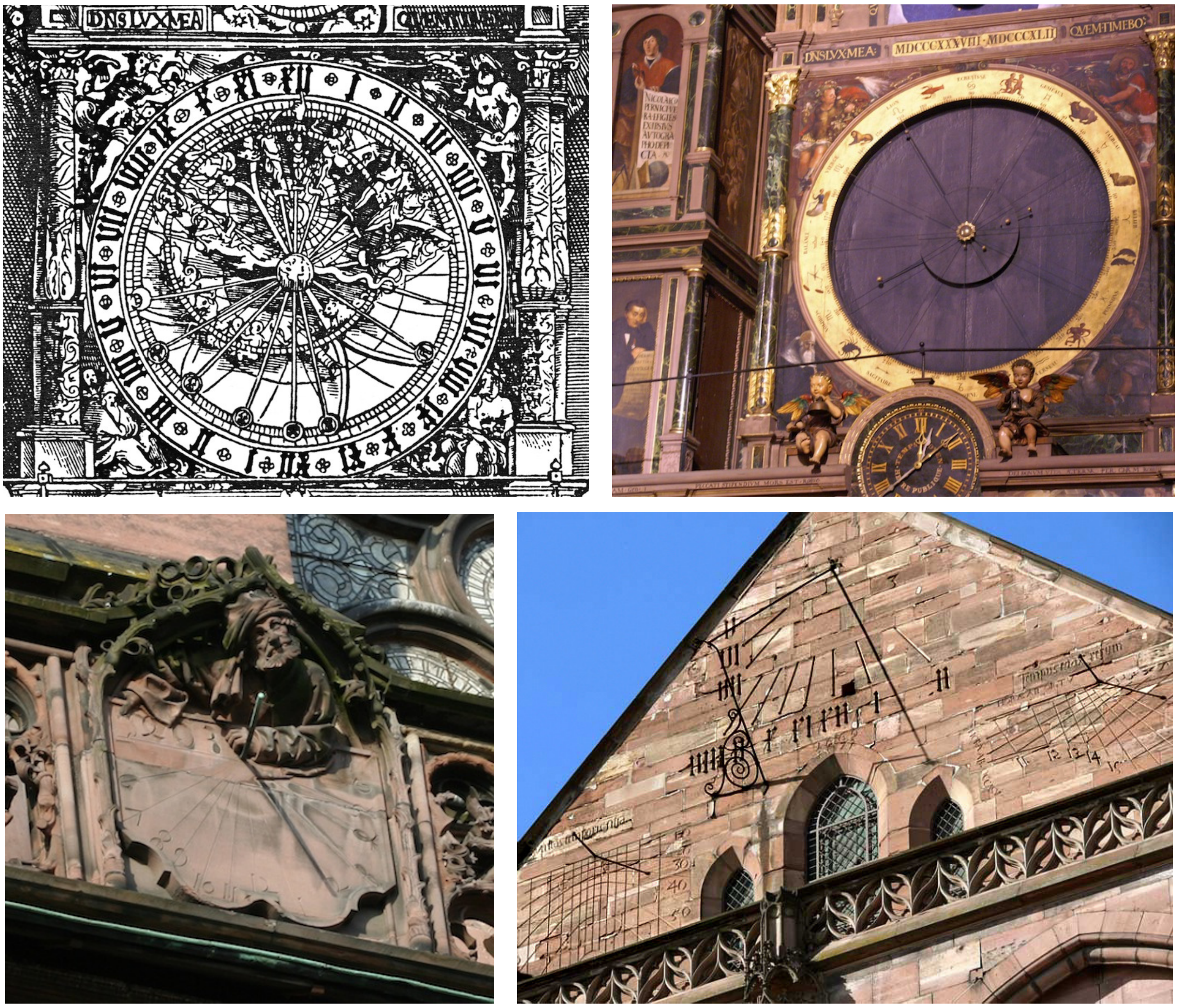

Fig. 11.3.2. Top left (a): Astrolabe planetary dial of the second astronomical clock. Detail from Woodcut by Tobias Stimmer (1574). **Top right (b):** Heliocentric planetary dial of the third astronomical clock. Photograph © Didier B (Sam67fr), Creative Commons Licence. **Bottom left (c):** Astrologer with a sundial, south portal. Photograph © Coyau, Creative Commons Licence. **Bottom right (d):** Three sundials on south gable: altitude/azimuth dial (left), vertical sundial (centre), and dial reading hours from sunrise and sunset (right). Photograph © Jean-Marie Poncelet, Creative Commons Licence.

Cultural and symbolic dimension: The display of astronomical time was central to the cultural uses of astronomy in medieval Europe. Strasbourg cathedral, which was the 'principal element of the nomination' for the World Heritage Site Strasbourg–Grande Île, embodies these astronomical concepts in three ways. Symbolically, the cathedral's sculptures bind the zodiac to the labours of the months; at a more direct practical level the cathedral displays astronomical time in numerous sundials; and—perhaps most famously—there is the historical sequence of its three great astronomical clocks.

Notwithstanding this, the description of the attributes of value of the property—both in the 'justification of value' from the State Party and in the ICOMOS evaluation—takes a classical heritage approach, elucidating this exceptional Gothic church in terms of the history of art, the history of structural design, the history of urban construction, and the history of medieval Christianity, but does not elaborate at all on the astronomical features of the place.

Authenticity and integrity: The Cathedral clocks have undergone successive transformations through the centuries; the present 19th-century clock is a development in the tradition of the 14th-century original. Much of the cathedral's statuary, including two of the sundials, have been replaced by copies; the originals are preserved in the Musée de l'Œuvre Notre-Dame.

Present site management

Present use: The cathedral is a place of worship and also a centre of tourism.

Protection: The Cathedral was designated a *Monument Historique* in 1862 and has been part of a World Heritage Site since 1988.

State of conservation: The astronomical elements of the cathedral are involved in the general conservation management plan of the building. The present state of conservation of these elements is good.

Context and environment: The Cathedral is located in a historical, urban environment.

Main threats or potential threats to the sites: Pressures of development and tourism.

Management, interpretation and outreach: The Cathedral provides tours of its major sites, including the clocks and the platform at the tower where some of the more important sundials are located. The Museums have an active program of interpretation of their collections.

Fig. 11.3.3. Schwilligué's meridian line (detail), inside entrance, south transept. Photograph © Jean-Marie Poncelet, Creative Commons Licence

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Chapter 12: Astronomy from the Renaissance to the mid-twentieth century

Michel Cotte, Danielle Fauque and Clive Ruggles

The period from the European Renaissance to the middle of the 20th century was an extremely rich one for the history of astronomy. The heliocentric paradigm of Copernicus (mid 16th century) followed by the techno-scientific revolution of Galileo's refracting telescope (1609) initiated a tremendous movement for revival and progress in astronomical observations and theoretical understanding of the sky that favoured the construction and development of many new observatories with successive generations of completely new instruments. In the late 19th century, astronomical observations were strongly transformed by the methods of astrophysics following the discovery of the wave nature of light and emission spectra from heated materials.

The astronomical heritage of the four centuries in question is huge, mainly and firstly in European countries and later in others parts of the world. It involves several different categories of heritage simultaneously: moveable instruments, fixed instruments, observatories, and records of original observational data.

The sheer size of this topic presents us with a problem in the context of this Thematic Study, since it must aim to achieve balance over a very wide range of themes without letting any one of them dominate. This problem would have been impossible to resolve but for the timely publication of a separate volume wholly dedicated to the theme *Astronomical Observatories: From Classical Astronomy to Modern Astrophysics*, edited by Gudrun Wolfschmidt (Berlin, 2009: ICOMOS, Monuments and Sites XVIII). The volume represents the proceedings of an international symposium on "Cultural Heritage: Astronomical Observatories (around 1900)" organized by ICOMOS Germany together with the University of Hamburg in October 2008 and contains 40 articles on classical observatories and their heritage. Instead of duplicating this effort by trying to present a complete overview of the theme of astronomy from the Renaissance to the mid-twentieth century, we refer the reader to the Hamburg symposium publication and simply offer here a brief chronological survey whose length is consistent with the other chapters.

Similarly, the five case studies have been chosen as far as possible to complement rather than to reproduce the information available in the Hamburg book. They are: the Royal Observatory, Greenwich, UK; the Royal Observatory, Cape of Good Hope, South Africa; the Observatory of Paris–Meudon, France; the Mount Wilson Observatory, California, USA; and the Einstein Tower in Potsdam, Germany. Greenwich and Cape Town are featured in the Hamburg volume but included here in the interests of balance, Greenwich because it is part of a World Heritage Site and exemplifies several important issues, and Cape Town Observatory because of its special significance due to its position both in the South Hemisphere and in Africa.

Sometimes, the heritage approach in modern and contemporary astronomy focuses strongly on a given instrument. Historically, this was often the essential reason for the creation of the observatory itself, so that a remarkable instrument is considered the core part of the place, giving it all its value. The scientific requirements and the technical capacities at a given moment come together to create a high-performance instrument: in scientific/technological terms this, rather than its architectural context, is the real work of genius. We have addressed this issue in Introduction and Conclusion of the Thematic Study, and discuss there the difficulties in keeping in strict accordance with the application of the World Heritage Convention. To do that we must consider a site, in the sense of a whole property; in other words, the instrument cannot be separated from its direct surroundings or from its material environment considered as a totality. The accordance between an instrument and a site (fixed tangible heritage) and between an instrument and its scientific uses and results (intangible heritage) are essential issues if the aim is to develop a definition of a property with a view to a viable nomination.

* * *

Researched and written around 1530, *De revolutionibus orbium cœlestium,* the reference book by Nicolaus Copernicus (1473–1543), was published in the year of his death. Within the history of cosmogony and European thought, this book carried an outstanding change of paradigm. The Ptolemaic description of a geocentric world (2nd century AD) was replaced by a heliocentric system that conserved circular orbits and uniform motions.

During the second half of the 16th century, the positions of celestial objects were determined by the naked eye, using classical instruments inspired both by the European medieval and the Arabic-Islamic traditions (see Chapters 10 and 11). In Europe, the most important astronomical project was the construction of the Uraniborg observatory complex. Funded by the king of Denmark, it was built on a small island by the astronomer Tycho Brahe (1546–1601) between 1576 and 1580. Equipped by large new instruments, it permitted Tycho and his group of astronomers to work over a long period to establish new astronomical tables for more than 1000 stars. These tables were later published by Johann Kepler (in 1627). Tycho also improved the quality of the measurements, reaching a precision of less than one arc minute, and permitting the accurate prediction of celestial events.

An important social event of the period linked with astronomy and cosmology was the reform of the calendar adopted by the Catholic Church in 1582 under the rule of Pope Gregory XIII. The difficulties in changing the cosmological paradigm during the late Renaissance are illustrated by Tycho Brahe's ambivalent attitude in trying to keep the Earth at the centre of the universe, with the planets circulating around the Sun and the Sun around the Earth. Giordano Bruno's (1548–1600) concept of the infinite universe illustrates the general flowering of ideas in science and cosmology during the Humanist period and also the difficulties hindering their social and cultural recognition.

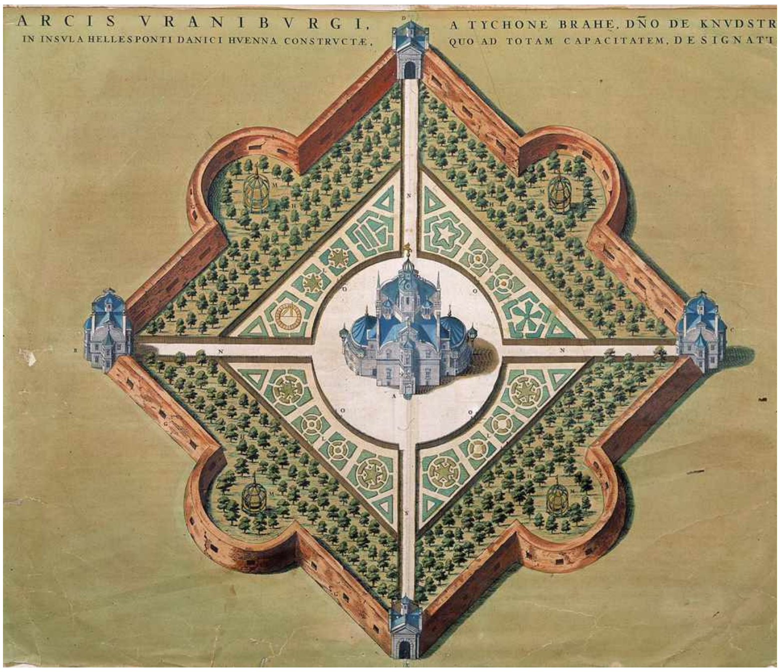

Fig. 12.0.1. "Uraniborg", in Tycho Brahe, *Astronomiae instauratae mechanica* (1598). It was demolished during the 17th century. Wikimedia Commons (Public domain)

Johannes Kepler (1571–1630) continued Tycho Brahe's work, using the results to support Copernicus's propositions concerning the celestial movements by means of his famous three laws: that planetary orbits are elliptical, that the line from the Sun to a planet sweeps out equal areas in equal times, and that a simple formula links the period of revolution to the dimensions of the orbit. Kepler launched the 'modern scientific revolution' by formulating extremely simple mathematical laws that have universal consequences. However, Kepler remained a man of his time, publishing popular almanacs and compiling horoscopes and astrological prognoses for his clients.

Copernicus's heliocentric system took time to be fully recognised as a completely new description of the sky: Galileo Galilei's (1564–1642) famous controversy with the Catholic Church lasted from the 1610s until his death. In the process of reaching his own certitude in support of the Copernican model, Galileo radically changed the capacities of astronomical observations by the use of the refracting telescope—two convex lenses mounted in a tube that magnified the field of vision. From 1609 onwards, astronomical knowledge was suddenly transformed, as telescopes started to reveal a multitude of celestial objects that no human being had ever seen before. One of Galileo's earliest and most significant discoveries was the existence of Jupiter's four (largest) moons, showing that the Earth was not unique among the planets in having a moon and hence supporting the Copernican model. Another was the discovery of mountains on the Moon, demonstrating its materiality and its similarities with the Earth.

A new epoch began in the middle of the 17th century following the development of reliable and efficient refracting telescopes. Scientists and craftsmen improved their know-how and built better instruments, for example adding angular measurement systems to the telescope. Such devices leaded to numerous new discoveries: for example in the 1650s Christiaan Huygens (1629–1695) discovered Saturn's rings and its moon Titan and made the first known sketch of the Orion nebula. They also offered improvements in transoceanic navigation since astronomical observations could be used to determine one's position at sea. This period was characterised by observation programmes and the exchange of information through networks of European scientists. The powerful kingdoms of the time chose to construct major observatories, using the latest technological improvements to create new instruments, and funding professional astronomers recruited from all over Europe. In 1641, Johannes Hevelius (1611–1687) founded an observatory at Danzig (Gdańsk) equipped with a large telescope. The Paris Observatory was founded in 1667 by Louis XIV, with a range of astronomers centred at first around Jean Picard (1620–1682) and then around Jean-Dominique Cassini (1625–1712), who became the first director. The Royal Observatory at Greenwich (see Case Study 12.1) was commissioned by the English king Charles II in 1675 and directed by the 'Astronomers Royal' John Flamsteed (1646–1719) followed by Edmund Halley (1656–1742).

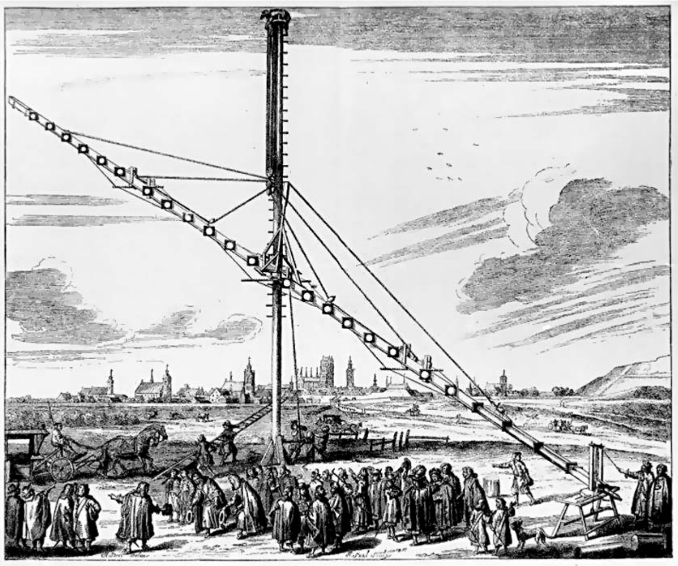

Fig. 12.0.2. The 140ft telescope of Johannes Hevelius (from *Machina coelestis*, 1673). Wikimedia Commons (Public domain)

The availability of all this new equipment and the increasing number of astronomers led to many crucial discoveries, and generated a completely new view and understanding of the sky. Specific events such as the appearance of Halley's comet (1680–84) engaged a wide public and offered many opportunities for discussion among the elite in salons. Astronomers published revised catalogues of stars and updated ephemerides.

With his *Principia* (1687), Isaac Newton (1643–1727) produced the greatest theoretical achievement of the 17th century, unifying celestial science and terrestrial physics. The concept of universal gravitation and the three laws of motion formed the basis of a complete and coherent mathematical model underlying what became known as 'celestial mechanics'.

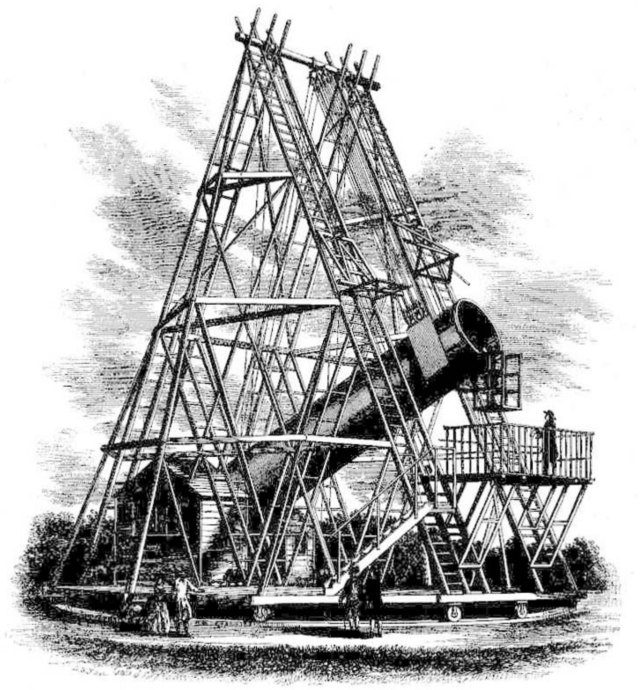

Fig. 12.0.3. William Herschel's 40ft reflector, completed in 1789. (Public domain)

This period also marked the appearance of new associated fields of experimental discovery such as the determination of the finite speed of light in 1676 by Ole Christensen Rømer (1644–1710), while at the Paris Observatory. An apparent variation in the position of stars observed at the end of the 17th century gave hope of determining their parallax (the annual variation in their position caused by the earth's motion around the sun), and hence their distance. Instead, it led James Bradley (1693–1762) to discover the aberration effect (1727), which is a consequence of the finite speed of light, and confirmed Rømer's theory. Bradley also discovered the nutation of the Earth's axis in 1738.

Improvements in instruments and theory brought about many further developments in the astronomical sciences during the 18th century. New accurate instruments were invented, such as Rømer's meridian telescope (1704) equipped with micrometers, and Pierre Bouguer's heliometer (1748). Techniques of fabricating parabolic bronze mirrors were improved, so that reflecting telescopes became viable, while in 1758 John Dollond (1706–1761) discovered a way to largely eliminate the chromatic aberration of lenses in refractors. By the end of the century, these improved instruments had led to the completion of a number of substantial catalogues and ephemeredes. Thus:

- in 1764, Jérôme Lalande (1732–1807) published his *Traité d'Astronomie*, a compendium of astronomical knowledge of the time, in the rational and pedagogic manner of the Enlightenment;
- in 1771, Charles Messier (1730–1817) published his catalogue of celestial bodies outside the solar system;
- in 1776, the first edition appeared of the *Berliner Astronomisches Jahrbuch*, an annual ephemeris and astronomical periodical that continued until 1960; and
- in 1801, Jérôme Lalande (1732–1807) published the *Histoire Céleste Française*, which contained a catalogue of over 47,000 stars.

William Herschel (1738–1822), who discovered Uranus in 1781, started a family dynasty of astronomers. His high-precision instruments marked the beginning of a new generation of great reflecting telescopes.

During the 18th century a number of scientific expeditions were organised in order to determinate the size and true shape of the Earth. The measurement of the Paris meridian from one end of France to the other, a project begun by Picard, was pursued by J.-D. Cassini and his son Jacques. Expeditions to Peru and Lapland, coordinated by the *Académie des Sciences* in Paris in the mid-1730s and involving numerous astronomers and other scientists, established that the Earth was flattened at the poles. The transits of Venus (across the solar disc) in 1761 and 1769 led to the organization of scientific expeditions involving international cooperation and the coordination of observations in different parts of the World, the main aim being to obtain a more accurate measurement of the distance of the sun and hence to 'scale' the solar system.

Another important question deriving from the new astronomical possibilities arose at the beginning of the 18th century: could longitude be determined by astronomical observations at sea and/or by time measurements using accurate and sustainable maritime clocks? Solutions were mainly developed in England and France. Octants usable for navigation started to be produced in the early 1730s, portable sextants followed in the 1750s, and an improved reflecting circle (essentially an octant extended to a full circle) was invented by Jean-Charles Borda in 1787. The last aspect of the solution of the quest for longitude at sea was the production of tables of lunar motions in 1752 by the German astronomer Tobias Mayer (1723–1762).

* * *

The construction of new observatories continued and even accelerated in the 19th century, creating not only a sizeable international network in Europe but also, and for the first time, a significant scattering of modern observatories all around the world. Between 1830 and 1840, the classical architecture of the dome observatory arose, producing a specific and popular landmark that is easily recognizable. It still remains today emblematic of astronomy and astronomers. Of the many such constructions of that period, the Pulkovo Observatory in St Petersburg, Russia, constructed by order of the Tsar Nicolas I and opened in 1839 under the directorship of Friedrich Georg Wilhelm Struve (see Case Study 14.1), was probably one of the most typical and the most complete. The Harvard College Observatory in the USA, founded in 1839, and the Royal Observatory at the Cape of Good Hope in South Africa (see Case Study 12.2) are good examples of permanent sites constructed outside Europe.

Fig. 12.0.4. Pulkovo Observatory. Photograph © Vladimir Ivanov; Creative Commons licence

At the same time, the efficiency of the instruments continued to increase in various ways: in terms of the quality of the metal, the mechanical capabilities of the builders, the workmanship of the lens-makers and the precision of the mirror polishing. For example, the availability of achromatic homogeneous glass allowed larger objective lenses to be built, so that large refracting telescopes could be constructed for the first time; and equatorial supports and mechanical drives allowed the telescope to follow stars in the sky, thus permitting an extended survey of a single field with the precision of observation being limited only by external factors such as diffraction and air turbulence. One effect of all these improvements was that pride of place in the observatory now went to the refracting telescope. Another was that smaller objects were now visible, so that, for example, many 'double stars' (binaries) could now be resolved. The theoretical capacities of astronomers of this period are illustrated by Carl Friedrich Gauss (1777–1855) successfully predicting in 1801 the sky position of the asteroid (now dwarf planet) Ceres by calculation; and later in 1846 by the discovery of Neptune by Urbain Le Verrier (1811–1877) using calculations based on perturbations in the position of Uranus.

The middle of the 19th century is characterised by large systematic surveys of the sky. International projects were producing large catalogues and maps, listing an increasing number of celestial objects, together with their position, magnitude, and other details. The New General Catalogue (NGC), produced in 1880, listed 7840 'non-stellar objects'—star clusters and nebulae, many of which we now know to be other galaxies. It was the beginning of a deeper understanding of the Universe.

* * *

In the late 19th century, the use of spectroscopy and photography triggered a fundamental shift in emphasis from mapping the skies to understanding the physical processes going on in space. The origins of astronomical spectroscopy go back to the mid-1810s, with Joseph Fraunhofer's (1787–1826) observation of dark spectral lines in the solar spectrum, but its implications for astronomy were only followed up seriously in the 1850s and 1860s, and in 1868 Pierre Janssen (1824–1907) and Norman Lockyer (1836–1920) discovered a new element, helium, in the Sun. Spectra rapidly led to an understanding of the chemical structure not only of the sun but of other stars.

Janssen was a pioneer in astrophotography, taking early photographs of the sun and introducing technical innovations that enabled large numbers of photographs to be taken in quick succession. From the 1870s onwards, new photographic emulsions and improved accuracy of movement in equatorial drives enabled magnificent photographs to be taken, and this led to the creation in 1885 of a global international programme for mapping the sky, the *Carte du Ciel*.

The new field of astrophysics connected astronomy to physics and chemistry, and led to the creation of specific communities of practitioners in the 1860s and 1870s such as the Italian Society of Spectroscopists. Two complementary improvements permitted spectrometry to become standard practice in systematic studies of the sky: the replacement of glass prisms by high-density diffraction gratings and the use of fine-grain photography to record the spectra. Specific centres for astronomical spectroscopy were set up during the 1870s at Greenwich, Potsdam (see also Case Study 12.5) and Meudon (see Case Study 12.3), close to the great scientific cities of the time. Programmes were initiated to catalogue stellar spectra and to work towards a better understanding of stellar structure.

By the end of the 19th century the Universe was understood to be a complex and dispersed ensemble of galaxies of different types containing an incredible number of stars, their interdependent movements following the laws of celestial mechanics and their light providing information on their chemical structure and temperature. Successful methodologies had been developed for systematic astronomical studies involving worldwide networks of observatories and the international community of astronomers.

Nonetheless, instrumental performance remained limited at the turn of 20th century by the size of the telescopes and by physical limits such as air turbulence and diffraction. Furthermore, artificial lighting and urban fogs were detrimental both to direct observation and spectrometry. Added to this, astrophysicists began to realise the importance of the new information that could be obtained by observing radiation outside the visible range. The problem was that such radiation was badly affected by the Earth's atmosphere, especially at low levels. The solution was to displace some observatories to new, more isolated locations and to construct new ones in mountain sites with high-quality, stable atmospheric conditions.

Two new observatories that overcame these dual limitations—the dimensions of the reflectors and air perturbation—were built during the first half of the 20th century in the USA, under the conception of George Ellery Hale (1868–1938). The Mount Wilson Observatory, on which construction started in 1904, was built in California at an elevation of 1740m. It was equipped with a high-quality 1.5m reflector in 1908, and with a 2.5m reflector in 1917 (see also Case Study 12.4). A technical innovation invented by Bernhard Schmidt (1879–1935) in 1930 corrected the problem of off-axis aberrations that restricted the field of view of large telescopes, thus facilitating surveys covering large areas of the sky. The Hale observatory that opened in 1936 on Mount Palomar, also in California, contained a 46cm Schmidt telescope. The 200in (5.08m) reflector known as the Hale telescope, which was installed in 1948, remained the largest aperture optical telescope in the world until 1976.

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Case Study 12.1: The Royal Observatory, Greenwich, United Kingdom

Rebekah Higgitt

Presentation and analysis of the site

Geographical position: London Borough of Greenwich, England, United Kingdom.

Location: Latitude 51° 28′ 38″ N, longitude 0° 0′ 0″. Elevation 46m above mean sea level.

General description: The Royal Observatory, Greenwich (ROG) was built in 1675–76 and was a working observatory until the 1950s. The site was handed over to the National Maritime Museum (NMM) piecemeal and opened to the public. It now contains displays on the history of the ROG, finding longitude at sea and time-determination, modern astronomy galleries and a planetarium. Objects include 18th- and 19th-century instruments used at the ROG, such as the Airy Transit Circle, which defines the Prime Meridian of the world.

The Observatory forms part of the property 'Maritime Greenwich' already inscribed on the World Heritage List in 1997 under criteria (i), (ii), (iv) and (vi).

Brief inventory:

Buildings: Flamsteed House (1675, extended 18th–20th centuries); Meridian Building (1740, extended 19th century); Great Equatorial Building (1857); Altazimuth Pavilion (1899); South Building (1891–99).

Fixed instruments:

Mural: Halley's Quadrant (1725), Bradley's Quadrant (1750), 6ft Mural Circle (1810).

Transit: Halley's 5ft (1721), Bradley's 8ft (1750), Troughton 10ft (1816), Airy Transit Circle (1850).

Zenith: Bradley's 12.5ft (1727), Pond's 9.5ft (1812).

Equatorial: 28in refractor (1893), Newbegin refractor (c. 1888), Dallmeyer photoheliograph (c.1873).

Moveable instruments:

Regulators: Tompion (1675), Graham (c. 1750), Earnshaw (c. 1790), Hardy (c. 1825), Shepherd (1852).

Other items from the NMM collection, a proportion relating to the work of the ROG and its successor, the Royal Greenwich Observatory (RGO).

History of the observatory: The ROG was founded by Charles II in 1675 to produce astronomical data that would aid navigation. Successive Astronomers Royal contributed to this project with a programme of meridian observation, leading to a successful solution with the publication of the *Nautical Almanac* from 1767. Work expanded in the 19th century to include magnetic and meteorological observation, photography, spectroscopy and time-signals. In the 20th century work was moved away from Greenwich: magnetic work moved initially to Abinger, Surrey, and the whole institution to Herstmonceux, Sussex, after World War II. The institution moved to Cambridge in 1990 and was closed in 1998.

Fig. 12.1.1. Aerial view of the site, 2007. Photograph © National Maritime Museum.

Cultural and symbolic dimension of the site: The ROG site is of fundamental importance to the history of astronomy, its work and reputation for accuracy being influential throughout the world. It is one of the earliest government-funded scientific institutions and survived for more than three centuries. The choice of the Greenwich meridian as the Prime Meridian reflects this history as well as Britain's international standing in the 19th century. Greenwich is widely viewed in the British tradition as the 'centre of the world' and the 'home of time'. It also contributes strongly to the universal exceptional value of the whole Maritime Greenwich property, which 'symbolizes English artistic and scientific endeavour in the 17th and 18th centuries'.

Authenticity and integrity: Buildings were often altered over the institution's working history and after 1950 many instruments and some buildings were removed. As a museum, renovations provided visitor and staff facilities and buildings were 'restored' to earlier forms, resulting in the removal of some 19th- and 20th-century heritage. Some instruments were altered when in use and others, kept as relics, were stripped of parts.

Documentation and archives: The RGO archives are kept at Cambridge University Library. Images of the Observatory and other materials are in the collections of the NMM and elsewhere.

Fig. 12.1.2. Top: The Meridian Building in the 1930s, before the 1960s reconstruction work. **Middle:** The Meridian Building and the Great Equatorial Building, 2009. **Bottom**: The South Building, 2009. Photographs © National Maritime Museum

Present site management

Present use: The site is part of the NMM and attracts over a million visitors annually: these are international, domestic and local, including many school parties.

Protection: The site is part of the NMM and within a Conservation Area. Flamsteed House is a Grade I and the South Building a Grade II Listed Building. It benefits from the highest degree of protection for World Heritage sites in the United Kingdom, where specific protection legislation will be in place soon for this category of heritage sites.

Fig. 12.1.3. Flamsteed House, 2009. Photograph © National Maritime Museum

State of conservation: The buildings are in good repair, safeguarding the authenticity of the architecture and structures. Maintenance is carried out regularly according to the general management plan of the World Heritage property.

Context and environment: The ROG is set within a Royal Park and the Maritime Greenwich World Heritage Site, which provide fitting environmental, architectural and intellectual context.

Archaeological/historical/heritage research: Work on the fabric is documented by the Museum and collections are catalogued to MLA standards and beyond. The history of the instruments, site and institution has been and continues to be the focus of scholarly study.

Main threats or potential threats to the sites: There are threats from the number of visitors and from water penetration. There is potential negative impact from the use of Greenwich Park for the 2012 Olympics.

Management, interpretation and outreach: The site is, in effect, divided: Flamsteed House and the Meridian Buildings provide historical displays and the Meridian Line, while the South Building and planetarium focus on public engagement with modern astronomy. There is little historical interpretation of the later buildings and work in areas other than meridian astronomy and timekeeping. The management plan of the World Heritage ensemble requires specific and respectful use of the property in general, and of the buildings bearing the attributes of the heritage value in peculiar.

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Case Study 12.2: The Royal Observatory, Cape of Good Hope, Republic of South Africa

Ian Glass

Presentation and analysis of the site

Geographical position: Observatory district, Cape Town, Western Cape Province, Republic of South Africa.

Location (Airy Transit Circle): Latitude 33º 56´ 03.5˝ S, longitude 18º 28´ 39.0 E˝. Elevation 15m above mean sea level.

General description: The Royal Observatory, Cape of Good Hope is the original name for the headquarters of the present-day South African Astronomical Observatory (SAAO). Its 9ha property occupies a small hill about 5km east of central Cape Town, within the Two Rivers Urban Park. Founded in 1820, the property remains in use for professional astronomy today. If an application in progress to the South African National Heritage Agency is approved, it will be the first South African cultural property designated for its scientific research history.

*Brief inventory***:** The buildings on the site include:

- The **Main Building** of the Observatory, completed in 1828, a neo-classical structure designed by the naval architect John Rennie (1761–1821). It was built with walls of plastered-over uncut stone; teak floors, door, window frames and shutters; and impressive Doric pillars constructed of brick with wooden cladding.
- The **Photoheliograph Building**, completed in 1848, distinctive in having a pre-fabricated wooden dome that rotates on cannon balls.
- The **McClean Building**, completed in 1896. Designed by the famous architect Herbert Baker, this building combines elements of Dutch and British colonial architecture. It features a hydraulically operated rising floor. Originally, a hydraulic motor was also used to rotate the dome.

Many of the other buildings on the site have their origins in the nineteenth century.

The McClean Building still houses the McClean (or Victoria) telescope, manufactured by Howard Grubb of Dublin in 1897. Most of the other nineteenth-century telescopes are still in place including a photoheliograph similar to one designed by de la Rue (1878), a Grubb 6-inch telescope (1882), and a 13-inch Grubb Astrographic telescope (1889) used for the Carte du Ciel project. The Gill Transit Circle (1905) also remains in its original position, as does an 18-inch telescope manufactured by Cox, Hargreaves and Thompson in 1955.

The surviving moveable artefacts include a repeating transit used by the first astronomer before the completion of the Main Building; a speculum mirror by W Herschel (1811); a time signal pistol (1833); nine highly precise ‘regulator’ pendulum clocks; six chronometers by various nineteenth-century manufacturers; a Ross lens used by Sir David Gill for his epoch-making photography of the Great Comet of 1882; a large Dallmeyer portrait lens used for the Cape Photographic Durchmusterung (the first photographic sky survey); the eyepiece and lens of the Airy Transit Circle (installed in 1854); and a Victorian Standard Weights and Measures Box (the contents of which are said to be in a storeroom of the Iziko South African Museum in Cape Town).

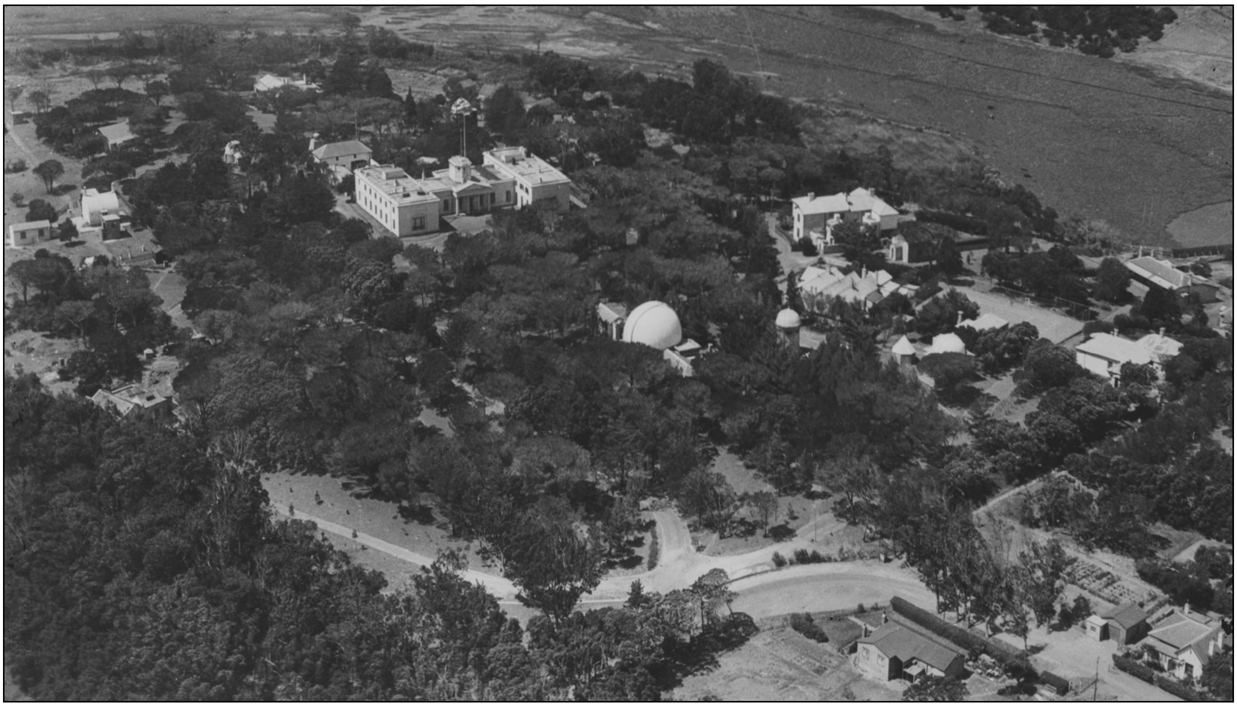

Fig. 12.2.1. The Royal Observatory in the early twentieth Century. Photograph © SAAO.

History of the observatory: The Royal Observatory was founded a few years after the Cape became a British colony, in order to determine accurate star positions and provide a reliable time service to aid maritime navigation. The chosen location was within clear view of the City's harbour, Table Bay, so that visual time signals could be seen by visiting ships.

The Main Building, commenced in 1825 and completed in 1828, originally housed a mural circle and a transit telescope. By 1855, these had been replaced by a transit circle designed by Airy. Several other buildings and instruments were constructed in the nineteenth century, including a magnetic observatory (1841) comprising several buildings, none of which survives today.

During the regime of Sir David Gill, Her Majesty's Astronomer during the years 1879–1907, activity on the site reached its zenith. This period saw the construction of the Astrographic dome (1888), the Heliometer dome (1888), the McClean dome (1896) and the Gill Transit Circle (1905).

The last instrument within the Main Building, the Airy Transit Circle, was removed in 1950. In 1972, the best telescopes were moved to Sutherland because the city's skies had become too bright. However, the construction of new instruments continues to be carried out in the modern Technical Building, which accommodates special rooms and laboratories for numerically controlled machining, vacuum coating, metrology, electroplating etc.

Cultural and symbolic dimension of the site: The Royal Observatory was the first major scientific institution to be erected on the continent of Africa. It is also the first permanent Observatory to have been constructed in the southern hemisphere. For much of the nineteenth century it occupied an important position in the Cape Colonial hierarchy, His or Her Majesty's Astronomer being called upon to give advice and to serve on the boards of cultural and educational institutions.

Over the years, the Observatory became the repository of standard weights and measures as well as setting the standard of time. Its noonday cannon is still fired to this day. The centre of the Airy Transit Circle in the Main Building became the point of reference for all geographical positions in South Africa.

Fig. 12.2.2. The McClean Building (dome and laboratory). Photograph © Ian Glass.

Several important scientific advances were made at the Observatory, including the first successful measurements of the distance of a star (Alpha Centauri, by Thomas Henderson in 1832–3); the first use of photography to make a systematic sky survey (by David Gill in 1885–90); and the determination (again by David Gill, in 1913) of the distance between the earth and the sun, the basic unit of length in solar system astronomy, regarded as the best available for some 45 years.

Authenticity and integrity: The present appearance of the site remains very much as it was left behind by Sir David Gill in 1907. Many of the buildings on the site are original structures, and the extant buildings still contain many of the instruments used over the Observatory's history. The Main Building has been modified only marginally; the original teak floors, doors, window frames and shutters still remain. Most of the nineteenth-century telescopes are still in place and a number remain more or less in working order. The hydraulic rising floor mechanism of the McClean dome is still operational and makes use of its original 3-cylinder hydraulic pump. The McClean laboratory still exists, with its original cupboards, benches and fittings. Gill's transit circle is also complete, as is the 18-inch telescope of 1955.

Nonetheless, the Royal Observatory, as a living institution, has evolved continuously since its foundation. Many buildings, fittings and instruments have come and gone, or been altered, to meet the changing requirements of science and to take advantage of advancing technology. Some of the old instruments have recently been restored.

Documentation and archives: All phases of the existence of the Royal Observatory are well documented. Large amounts of material exist in the following archives: the Hydrographic Office of the Royal Navy (UK); the Royal Greenwich Observatory Archives (now in Cambridge University Library); the South African Government Archives; and, of course, the SAAO

Archives, which are kept on the Royal Observatory site. Rennie's original designs for the Royal Observatory, dated 1 March 1821, are located today in the Public Record Office (UK).

Present site management

Present use: The property is owned at present by the National Research Foundation (NRF), the umbrella agency of which the SAAO and a number of other scientific institutes form part. The site is now the Headquarters of the Southern African Astronomical Observatory and the Southern African Large Telescope Foundation. It is used exclusively for astronomical purposes.

At the present time, the central part of the Main Building houses the National Library for Astronomy, one of the most comprehensive astronomical libraries in the world. The rooms in the wings, which were originally used as residences, are now mostly offices for the astronomers.

Protection: The property is central to the Two Rivers Urban Park, a conservation area established by the City of Cape Town. It is bordered to the East and North by wetlands. As such, it is protected from encroachment.

State of conservation: Most of the buildings are regularly maintained but some of those not in use for current astronomical projects require restoration. In particular, the Gill Reversible Transit Circle building of iron and steel is in poor condition. The archives and retired instruments are generally well protected from environmental damage.

Context and environment: The site is no longer dark and rural. Beyond the boundaries of the Two Rivers Urban Park, it is surrounded by freeways, major roads, and office buildings. However, the property is one of the last remaining places close to the city centre where the original ecology of the area is preserved. The Two Rivers Urban Park is a wetland area that supports a wide range of bird and animal life as well as a variety of flowering bulbous plants. The Observatory marks the northern limit of the Western Leopard Toad (*Bufo Pantherinus*), an endangered species, and is the only remaining habitat of the rare iris *Moraea Aristata*. An 'Observatory Baseline Information Study' has been commissioned to further analyse the natural and urban environment of the site and better characterise its unique properties, with a view to preserving them.

Fig. 12.2.3. The central room of the library, Main Building. Photograph © Ian Glass

Archaeological/historical/heritage research: The Royal Observatory is well documented historically in books by Sir David Gill and Brian Warner and by many articles in books and journals. There is ongoing historical research by various interested parties. An independent 'Friends of the Observatory' group was recently formed, aiming particularly to restore the old instruments and domes to working order.

Main threats or potential threats to the sites: The main threat to the Royal Observatory site lies in the ever-increasing pressure on open urban land from real-estate developers. Some degree of protection derives from the fact that the Royal Observatory is a limited-area site partly flanked by preserved wetlands that are unsuitable for development.

Management, interpretation and outreach: The McClean telescope is used on open nights for public viewing and, very occasionally, for special occultation events, while the adjoining astrophysical laboratory is preserved as a museum. It also contains a selection of the smaller antique instruments no longer in use.

For many decades there has been a public outreach programme. Open nights are held at least once a month, when members of the public are given free of charge a tour of the Observatory, a lecture on an astronomical topic and the opportunity to view the sky through a telescope. In addition, many school and other groups tour the establishment during the daytime.

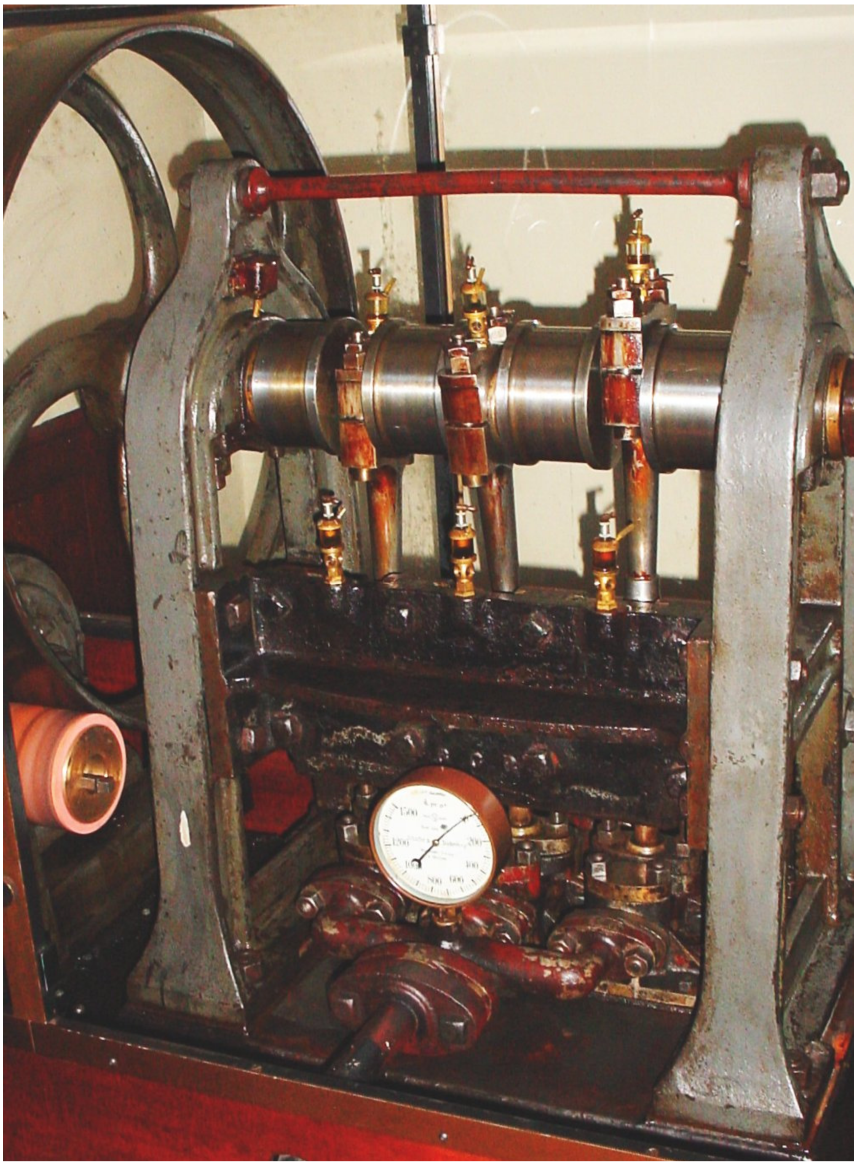

Fig. 12.2.4. The three-cylinder hydraulic pump (1896) that provides power for the rising floor in the McClean dome. Photograph © Ian Glass

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Case Study 12.3: Meudon Observatory, France

Stéphane Le Gars

Presentation and analysis of the site

Geographical position: 61 Avenue de l'Observatoire, 75014 Paris, France.

Location: Latitude 48° 48′ 18″N, longitude 2° 13′ 52″E. Elevation 160m above mean sea level.

General description: Meudon is one of a number of new observatories built in Europe in the 1870s that integrated telescope and laboratory facilities in order to carry out astronomical spectroscopy and address the big questions of the new discipline of astrophysics—the nature of the physical structure and the chemical composition of the stars.

Brief inventory: The buildings on the site include:

- The **Grande Coupole**, 18.5m in diameter, completed in 1895. It houses the Grande Lunette, a double refractor with an 83cm lens for visual observation and a 62cm one for photography. This instrument remains today the third largest refractor in the world after those at Lick (put into service in 1888, with a diameter of 91cm) and Yerkes (1897 and 1.02m) observatories in the USA.
- Two **7.5m cupolas**, one containing a 1m reflector with 3m focal distance, suitable for the study of the planets, the Moon, or comets, whose constructions was also completed in 1895.
- A laboratory situated in the outbuildings, containing two spectroheliographs installed in 1897 and 1906 by Henri Deslandres (Janssen's successor as observatory director). These are constantly improved and still used.

Other important equipment at the observatory includes a large siderostat built in 1908 (put into service in 1910); a coelostat built by Georges Prin in 1909; an equatorial table put into service in 1931 and now used with a 60cm reflector for educational purposes; a Lyot monochromatic heliograph (1953); a solar tower built in 1969; and a high-resolution 10m vacuum ultra-violet (VUV) spectrograph put into service in 1972.

History of the observatory: "L'observatoire d'astronomie physique de Paris" was officially created on 6 September 1875, thanks to a decree signed by the president of the French republic. The same decree appointed the physicist and astronomer Jules Janssen to be its director. Janssen had worked since 1860 applying spectral analysis to the study of the stars, and helped to create a new discipline: physical astronomy, today called astrophysics. This new field of knowledge represented a break from the traditional practice of astronomy: while celestial mechanics and positional astronomy continued to prevail in the Paris Observatory, at Meudon Janssen promoted the introduction of methods from physics and chemistry—spectroscopy, photography, and photometry—as an integral part of the work of the observatory.

For Janssen, the choice of site was dictated by reasons both scientific and political: it had to be close to Paris, but also sufficiently isolated "to escape the vibrations of the earth and the illumination of the atmosphere in the capital"[1]. It also had to be set in a reasonably clear spot

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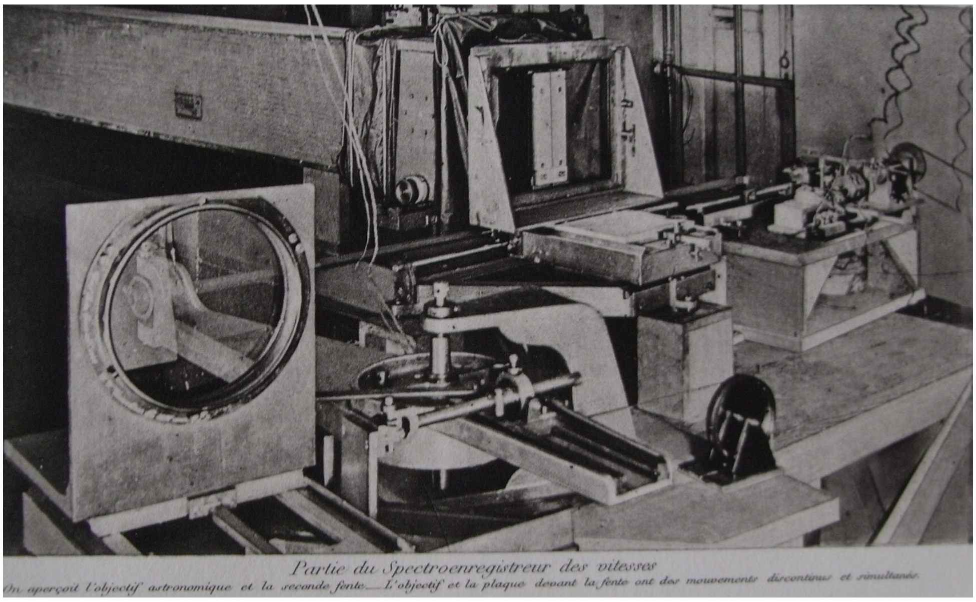
[1] Janssen Jules, « Rapport au Ministre », 05/1874, AN F17 3745.

(especially to the south and to the east), such as a slight eminence surrounded by meadows. The chosen property was a dilapidated castle, Château Neuf, at Meudon. Janssen received a large budget to renovate and fit out the place for its new function. A law passed in 1879 formally allocated the Meudon property to the new observatory and over the next three years the process began of transforming the castle and buying instruments.

Since 1926 the Meudon observatory has been attached to the Paris Observatory.

Cultural and symbolic dimension of the site: Meudon was the first observatory in France of a new type: a place where physics met astronomy, and where the laboratory entered into the observatory. The spectroscopic analyses undertaken in the outlying buildings and the photographs obtained with Janssen's instruments permitted the astronomers at Meudon to draw important conclusions about the physical structure and chemical nature of the Sun, which was the main focus of research at this site. However, important work on the planets has also been carried out in Meudon: for example, it is thanks to the Grande Lunette that the controversy about Martian canals was finally brought to an end in 1909.

Fig. 12.3.1. Meudon observatory in 2001, prior to renovation. Photographs © Stéphane Le Gars.



Partie du Spectroenregistreur des vitesses

On aperçoit l'objectif astronomique et la seconde fente — L'objectif et la plaque devant la fente ont des mouvements discontinus et simultanés.

Fig. 12.3.2. The Meudon spectrophotometer around 1910. From *Annales de l'Observatoire d'Astronomie Physique de Paris,* Tome 4, Paris 1910.

Present site management

Present use: Meudon is currently one of the three sites of the Paris Observatory, the others being the historical (17th-century) Observatory of Paris itself and the radio-astronomy station at Nançay (Cher) founded in 1953.

Protection: The Château Neuf is scheduled as historical monument by a law passed on 12 April 1972.

State of conservation: A general renovation of the Meudon buildings was undertaken in 2001, respecting the scientific designation of the site and the original architecture and its decoration, and following the law for the protection of historical monuments in France.

Context and environment: The Château Neuf is itself a French heritage monument. The Duchess of Etampes, a favourite of François I, received the original Meudon Castle in 1527. New buildings were constructed during the 16th century, and at the end of the 17th century it acquired gardens designed by the architect Le Nôtre. In 1695, the castle was purchased by Louis XIV for the use of his son, the Grand Dauphin, and it was at this time that new outbuildings (those in which the astronomers work today) and the Château Neuf, the present building of the Grande Coupole, were constructed. After a period of decline under Louis XV and Louis XVI, Napoleon called for the restoration of the Château Neuf, but it was burned down during the war of 1870 and was in danger of disappearing completely. Astronomy is to be thanked for this not having happened.

Management, interpretation and outreach: As part of the Paris Observatory, Meudon is under the guardianship of the Ministry of Youth, Public Education and Research. The administration of scientific matters is the responsibility of the president, board of directors and scientific council of the Paris Observatory. The administration of the buildings is carried out by the president of the Paris Observatory and the Division Immobilière et Logistique (DIL).

Case Study 12.4: Mount Wilson Observatory, USA

Gudrun Wolfschmidt and Clive Ruggles

Presentation and analysis of the site

Geographical position: Mount Wilson, Los Angeles County, State of California, USA.

Location (150ft solar tower): Latitude 34° 13´ 28˝ N, longitude 118° 3´ 31 W˝. Elevation 1740m above mean sea level.

General description: The Mount Wilson Observatory, founded in 1904, is one of a number of observatories built around the turn of the 20th century at mountain locations chosen for the quality of the astronomical seeing. It is one of three great observatories conceived by George Ellery Hale (1868–1938), a pre-eminent figure in the development of the best possible equipment for advancing solar and stellar astrophysics.

Fig. 12.4.1. Aerial view of the Mount Wilson Observatory: In the lower-left are the 150ft and 60ft solar tower telescopes; in front is the horizontal Snow solar telescope. The domes of the 60-in and the 100-in Hooker telescope are visible behind. Photograph © Norm Vargas (http://www.mwoa.org/).

Brief inventory: The instruments at Mount Wilson include:

- The horizontal 'Snow telescope', built in 1903 by George W. Ritchey (1864–1945) and moved here in 1904.
- The 60 ft solar tower telescope (1904; the dome was not installed until 1914).
- The 150ft solar tower telescope (1910).
- The 60-inch (1.5m) silver-on-glass-mirror reflector, made by George W. Ritchey (1908).
- The Hooker 100-inch (2.5 m) equatorial reflector, also made Ritchey (1917).

History of the observatory: Hale, who was director of the Yerkes Observatory at Williams Bay, Wisconsin from 1895 until 1905, obtained a grant to found the Mount Wilson observatory from the Carnegie Institution of Washington (CIW). The mountain site provided near-ideal conditions for the world's largest telescope, the 60-inch reflector, which went into service in December 1908. The even larger 100-inch reflector went into service in 1917.

Meanwhile, in 1904, the Snow telescope for solar observations was moved to Mount Wilson Observatory. It was not hugely successful, however, because the horizontal solar telescope was affected by air-currents from the warmed-up soil. For this reason, Hale had the idea of building a tower telescope, and the 60 ft solar tower telescope was duly constructed. In 1908 the larger 150 ft tower was built with the help of the Carnegie Foundation.

Further technological progress was made in many areas during the following decades, examples being the photomultiplier tube and the development of the modern magnetograph (using fibre-optics) in order to improve the solar images.

Fig. 12.4.2. The Hooker Telescope (2.5m) used by Edwin Hubble for the discovery of the expansion of the Universe. Photograph © Andrew Dunn, Wikimedia Commons. Creative Commons Licence.

In 1984, the CIW was considering closing the Mount Wilson Observatory, but in 1985 it accepted the wishes of the Division of Astronomy and Astrophysics at the University of California at Los Angeles (UCLA) to use the towers for research in solar seismology, supported by the *Mount Wilson Observatory Association* (MWOA).

Cultural and symbolic dimension of the site: The importance of reflectors is directly connected to the rise of astrophysics. The new silvered-glass reflecting telescopes were essential for spectroscopy and photography because they had no chromatic aberration. The two glass reflectors at Mount Wilson (the 60-inch reflector and the Hooker telescope) represent the triumph of such reflectors at the beginning of the 20th century. The Hooker telescope remained the largest telescope in the world until 1949.

Mount Wilson saw the realisation by Harlow Shapley (1885–1972) that our solar system is not at or near the centre of our own galaxy (the Milky Way), arguably a 20th-century equivalent to the ‘Copernican revolution’); the realisation by Edwin Hubble (1889–1953) that globular clusters and spiral nebulae were in fact other galaxies outside the Milky Way; and the distance measurements, also by Hubble, that allowed him to present a linear distance-redshift relation which revealed that the Universe is expanding.

Mount Wilson was also of key importance in the development of solar astronomy. The solar tower, a special new architecture, was invented here, as were various new instruments for studying the solar atmosphere. Using the 60ft tower, Hale discovered in 1908 that sunspots have strong magnetic fields, several thousand times stronger than the Earth’s.

Present site management

Present use: The observatory remains an active scientific institution, with both towers still being used for solar research.

Management, interpretation and outreach: Since 1986, Mount Wilson Observatory has been operated under an agreement with the CIW by the Mount Wilson Institute (MWI), a non-profit corporation whose mission focuses on scientific research, historic preservation, astronomical education and public outreach.

The Friends of Mount Wilson Observatory (FOMWO) offer visits of the observatory to the public. Visitors are given the opportunity to view the Universe through the 60-inch telescope, the largest telescope in the world available exclusively to the public.

Case Study 12.5: The Einstein Tower, Potsdam, Germany

Gudrun Wolfschmidt and Michel Cotte

Presentation and analysis of the site

Geographical position: Telegrafenberg 1, 14473 Potsdam, Germany.

Location: Latitude 52° 22´ 44˝ N, longitude 13° 3´ 50 E˝. Elevation 87m above mean sea level.

General description: The Einstein Tower, designed by the Berlin architect Erich Mendelsohn (1857–1953) and built in the early 1920s, is both an astrophysical observatory and a masterpiece of the history of modern architecture in Germany.

Brief inventory:

- The **tower** itself is 20m high. It was constructed between 1920 and 1922, but owing to a lack of modern construction materials after World War I, the tower had to be built with bricks instead of reinforced concrete. As a protection against the wind and heating, a wooden structure was added on the inside of the tower, and this supports the objective lens.
- The **instrumentation** was installed in 1924. The dome is 4.5 m in diameter and contained the two 85 cm-coelostat mirrors. The lens of 60 cm aperture and 14.50 m focal length produced a solar image 14 cm in diameter. The company Zeiss of Jena was responsible for the instrumentation.
- The **cellar** contained a room at constant temperature. Here, two high-resolution spectrographs produced solar spectra from red to violet with a length of 12 m. In 1925, a physical-spectrographic laboratory was constructed. This contained a spectral furnace as a comparison light source, an apparatus to produce an electric arc, a photoelectric Registration photometer, an electromagnet and an apparatus for the investigation of the hyperfine structure of emission lines. The instrumentation reached the highest technological standards found anywhere at the time.

History of the observatory: By the beginning of the 20th century, the USA had attained a strong position in the development of astronomy. In Germany, by comparison: there was too much emphasis on classical astronomy instead of modern astrophysics and solar physics; the astronomical instruments in most observatories were not up to date; the climatic conditions and seeing quality were no match for those in California; and there was no possibility of the levels of private financial sponsorship that could be sought in the USA. Yet there was a strong political will to promote science after World War I—the slogan ‘Science as substitute for political power’ was introduced—and in 1920 the “Notgemeinschaft der Deutschen Wissenschaft” (NDW) was founded, so that German science flourished in the 1920s despite the political and economic conditions.

The impulse for financing a German solar observatory arose from the spectacular result of the English eclipse expedition in October 1919, which confirmed Einstein’s general theory of relativity. Other attempts to do so having been unsuccessful, the idea was to measure the red shift of spectral lines in the gravitational field of the Sun with a new kind of solar telescope. In fact, this attempt failed too, because the effect on the redshift due to relativity is swamped by other, stronger effects present in the Sun; however, as a consequence of studying all these other effects, the Einstein Tower became the most important solar observatory in the world in the 1920s.

It was renamed in 1933, in the context of the political developments of the Nazi era, becoming the *Institute for Solar Physics*, but its significance only started to decline as new solar observatories started to be constructed in other countries in the late 1930s. In 1950 Harald von Klüber (1901–1978) succeeded in measuring the general magnetic field of the Sun using photographic methods in the Einstein tower.

Cultural and symbolic dimension of the site: Erwin Finlay-Freundlich (1885–1964), astronomer and architect, gave advice about the instrumentation and Mendelsohn, who was a personal friend of Freundlich's, was assigned the task of designing the tower. Mendelsohn became fascinated by Einstein's world of thought and this inspired him to produce novel architectural ideas. He was looking for new architectural forms of expression, which he wanted to achieve with modern materials such as steel and reinforced concrete, and he even designed the office furniture and fixtures. The resulting building, with its gently bulging shapes, is a perfect synthesis between dynamics and functionality and is widely recognised as one of the best examples of explorations in constructivist and expressionist architecture during the 1920s in Central Europe.

As Freundlich himself opined:

> "The design of the telescope as a tower telescope gave the Einstein Tower its special character and allowed the architect to allocate the building the character of a monu ment due to the epochal significance of the theory of relativity in the development of physics."[1]

The building design is dynamic, using curved lines and window openings to play around with the verticality of the solar instrument, while the horizontal annexes are softly linked with the surrounding ground surface. It is like a monumental coating—a sort of sculptural/architectural dressing—on the machine. The interior of the tower gives the feeling of a putting the scientific devices 'on stage', establishing a deep resonance between modern architecture and cutting-edge science. The Einstein Tower is a remarkable example of osmosis between two very different fields of research—structural design on the one hand and astrophysics on the other. It elegantly expresses human hopes for scientific progress in harmony with the cultural values of society.

Comparative analysis: In the 1920s several further solar towers were built, but they mostly had a 30cm aperture; none surpassed the Einstein Tower. The full list is as follows:

Observatory	Year	Aperture	Focal length	Solar image
Mount Wilson 18m	1907	30cm	18m	5–17cm
Mount Wilson 50m	1912	30cm	46m	5–43cm
Utrecht	1922	25cm	13m	7–17cm
Potsdam	1922–24	60cm	15m	14–25cm
Arcetri	1926	30cm	18m	17cm
Pasadena	1926	30cm	5.5m	5–42cm
Tokyo	1928	45cm	15m	14–25cm
Canberra, Australia	1924–50	30cm	13m	12cm

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[1] Finlay-Freundlich, Erwin, "Wie es dazu kam, daß ich den Einstein-Turm errichtete", *Physikalische Blätter* 25 (1969), 538–541, p. 541.

Fig. 12.5.1. The Einstein Tower (1924) is an astrophysical observatory and also a masterpiece of the history of German architecture designed by Erich Mendelsohn (1857-1953). Photograph © R. Arlt.

In terms of architecture, the 19th century and modern period had produced observatories that were neo-classical monuments, frequently repeating the same shape and decorative patterns as civil palaces. The only specific feature of the observatory remained the ‘dome’, conceived generally as an associated device for the telescope. In term of design, the dome was frequently a pure hemisphere or something close to it, clearly separated from the vertical walls of annexes. At the Einstein Tower, the dome is completely integrated into the whole structure, and its curves are also present and repeated in the overall shape of the monument.

The Einstein Tower is arguably a rare, and perhaps unique, example of a real creative effort in observatory design, directly related to a new structural style, by a major architect of the time. It brilliantly brings together different sources of creativity and innovation.

Present site management

Present use: The Einstein Tower is still active as a solar observatory.

Protection: The building is under monument protection.

State of conservation: The tower has been restored many times during past decades; a very careful restoration (costing three million euros) was carried out between 1997 and 1999, financed jointly by a private grant and the Astrophysical Institute Potsdam.

Context and environment: The tower is located in the *Wissenschaftspark Albert Einstein*.

Management: The Einstein Tower belongs to the Astrophysical Institute Potsdam.

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Chapter 13: The Development of Radio Astronomy

Richard Wielebinski and Tom Wilson

Radio astronomy has been a very instrument-driven science. The great discoveries of radio astronomy often happened soon after a new radio telescope was put into operation. Many of these discoveries have been serendipitous but contributed to the rapid progress in modern astronomy. Thus the question of what has happened to the historic instruments is a very relevant topic. In this article we sketch the history of the discoveries in radio astronomy and investigate the status of the heritage instruments that were involved in these discoveries.

The first detection of comic radio waves was made in 1932 by Karl Jansky, a physicist working for the Bell Telephone Laboratories in the USA. The detection was made in the frequency range around ~20 MHz (15m wavelength), where commercial telephone communications were carried out. Jansky was studying the causes of disturbances to radio telephone communications. The observations were made with a rotating ‘Bruce array’ that allowed the direction of the disturbances to be pinpointed. Jansky found that in addition to natural causes of disturbances such as thunderstorms, a hiss-type disturbance was changing with sidereal time, and he correctly identified this to be due the radio emission of the Milky Way. The next serious astronomical investigation of the radio emission was made by Grote Reber in 1944 (see Fig. 13.0.1) who surveyed the sky at ~160 MHz with a paraboloid reflector. The first maps of the radio Milky Way that were presented showed that the most intense radio emission came from a region some 30° away from what was the accepted position of the Galactic Centre, a spectacular radio astronomy discovery.

The development of radio astronomy followed the first steps taken by Jansky and Reber. At the outset, dipoles (known and used by Heinrich Hertz in the 1880s) made into arrays were generally used. These were suitable for observations at metre wavelengths. The paraboloid reflector radio telescope, first used by Grote Reber, became the mainstay of radio astronomy. Such reflectors were general-purpose instruments and could be constructed to operate at short centimetre and millimetre wavelengths, to which radio astronomy moved in later years. Neither of the historical instruments of Jansky and Reber exists on its original site. Jansky’s original antenna was at the Holmdel New Jersey field station of the Bell Telephone Laboratories. A replica of this antenna can be seen at the entrance of the National Radio Astronomy Observatory in Green Bank, West Virginia, USA. Nearby stands the antenna used by Grote Reber on his private land at Wheaton, Illinois. This antenna was transferred to Green Bank but its wooden sections required considerable refurbishment.

Technological developments during the Second World War brought about a huge improvement in radio reception methods. New antennas and sensitive receivers were developed, albeit not for radio astronomy. A report about the detection of solar radio waves was published by J.S. Hey in 1946. Hey and his colleagues also observed fluctuations in the cosmic radiation and correctly interpreted them as being due to discrete radio sources. These new discoveries, added to the diffuse emission from the Milky Way that had already been observed by Jansky and Reber, laid the basis for radio astronomy. After the Second World War, trained radar experts quickly adapted their equipment to study cosmic radio emissions.

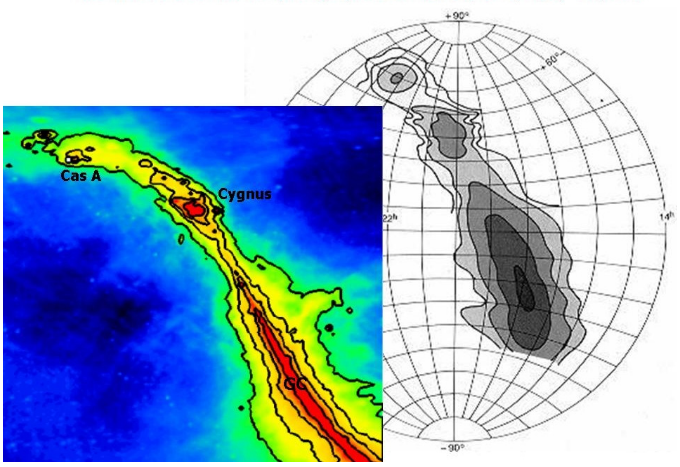


Fig. 13.0.1. Right: The first radio map of the Milky Way at 160 MHz. After G. Reber, *ApJ* 100 (1944), 279. **Left:** a recent 1400 MHz map of the same region by W. Reich. © Max Planck Institut für Radioastronomie

The discovery of discrete radio sources led to the need for ever-greater angular resolution and to the construction of more sensitive radio telescopes. The first optical identifications of radio sources, made by J.G. Bolton and others in 1948, showed that these were some of the most unusual cosmic objects with angular structure. The next step that was needed was to map the structures of these objects.

The existence of line emission at radio wavelengths had already been predicted by Henk van de Hulst in 1944, and the discovery of the hyperfine line of neutral hydrogen, HI, from the Milky Way at 21cm wavelength was made by H.I. Ewen and E.M. Purcell in 1951. They used a horn antenna placed on a building of the Lyman Laboratory at Harvard University. This original horn antenna is also on display in Green Bank. Shortly after the initial discovery of the HI line, confirmatory measurements were made at the Leiden Observatory and the CSIRO Radiophysics Division in Sydney. In the following years these groups mapped the entire Galaxy in this spectral line, giving us information about the spiral structure of the Milky Way. Further discussion about possible radio line emissions led to the construction of powerful spectrometers that eventually brought about the rapid development of radio spectroscopy.

In 1945, military-disposals equipment became available for peaceful purposes. One of the most important disposal items in facilitating the rapid start of radio astronomy in Europe was the 7.5m-diameter ‘Würzburg Riese’ paraboloid antenna used in the German radar system. Numerous Würzburg dishes were transferred to various European observatories in the United Kingdom, the Netherlands, France, Sweden and Czechoslovakia where they were used in early radio-astronomy discoveries. Several of these dishes have now found their way into museums. Most of the Würzburg dishes required considerable maintenance work before their transfer to museums, since corrosion was active in the metallic sections. They can be seen in Deutsches Museum, München, at Douvres la Delvarne, France, Waaldorp, Netherlands, and the Imperial War Museum at Duxford, U.K. The last active use of Würzburg dishes was in Ondřejov, Czech Republic, for solar research.

In the USA many military laboratories became involved in radio astronomy research. The Naval Research Laboratory in Washington DC has a long record of radio-astronomy research. A 50ft dish on top of a building was used for early observations at high radio frequencies (up to 10 GHz, the first cm-wavelength observations). The thermal emission of planets, the free-free HII emission in the Milky Way and the polarization of the Crab Nebula were all discovered in the 1950s by the group using the 50ft dish. This radio telescope is still present and can be seen when landing at the Ronald Regan airport in Washington DC. Another important early instrument, which was used in the discovery of the first molecular emission (the OH line) in 1963, was the 84ft parabolic antenna of the Millstone Hill Observatory of the Lincoln Laboratory. This instrument is also still in use. One of the most unusual single radio telescopes, still standing on its original site, is the 20ft-aperture horn-reflector antenna used by Arno Penzias and Robert Wilson in 1964 in the discovery of the 2.7°K cosmic microwave background (CMB), for which they received the Nobel Prize in 1978. This telescope stands on the grounds of the former Bell Telephone Laboratories in Holmdel, New Jersey. The present owners are the Alcatel-Lucent company.

Single dishes could map the smooth extended emission of the Milky Way but did not have the angular resolution to locate the positions and determine the structure of discrete radio sources. The need for higher angular resolution to study the discrete radio sources led to the introduction of radio interferometry. Martin Ryle's group in Cambridge had been using interferometers from the very beginning in 1946. In addition to long-wavelength interferometers, two Würzburg dishes were used as an interferometer to make accurate positional determinations of radio sources and permit subsequent optical identification. Other antenna configurations used in the early days of radio astronomy in Cambridge were cylindrical paraboloid and corner reflectors placed on an east-west line. These antennas were structurally very simple and have not completely survived. In Australia a cliff interferometer was used first for solar research by J.L. Pawsey and colleagues in 1946; they also related interferometer measurements to imaging. Two years later J.G. Bolton and colleagues presented the first optical identifications of radio sources. The quest to improve the angular resolution led to the construction in 1953 of a grating interferometer with 32 small dishes for solar research. Radio telescopes of this type were built in Japan, Canada, the Soviet Union and India. Also in 1953, B.Y. Mills and A. Little in Australia invented an antenna system that became known as Mills Cross. This instrument synthesised a pencil in both Right Ascension and Declination, so that accurate positions could be determined and good maps made of the diffuse emission. None of the early antennas in Australia exist in full on the original sites. Mills Cross antennas were constructed in Italy, the Soviet Union, and most recently at Molonglo in Australia. All these antennas are still in use. The sites within the city of Sydney were taken over for building construction or reverted to public reserves. The Fleurs field station, which hosted the Chriss-Cross and the Mills Cross, was transferred from CSIRO to the University of Sydney. However, radio astronomy was also abandoned at this site and some of the instruments were transferred to the Australia Telescope National Facility headquarters in Epping. Most of the early antennas—many of which, built for low radio frequencies, used wood as construction material—have not survived. The early paraboloid dishes were also of a very light construction and were not maintained. Some antennas were ultimately moved to other locations.

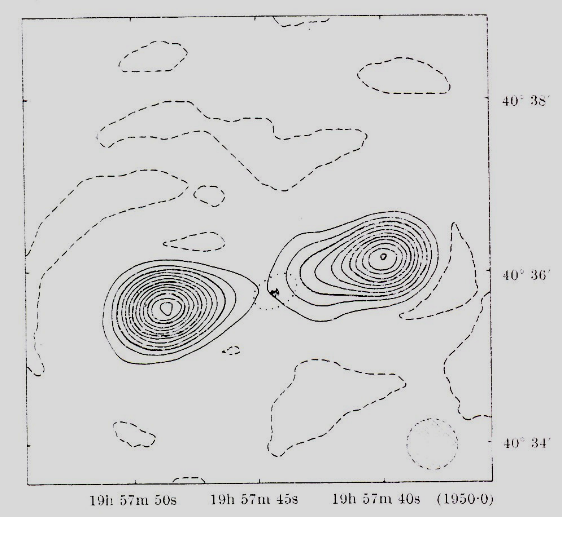
The beginnings of radio astronomy as 'big science' led to the foundation of new observatories and to the financing of new radio telescopes. Paraboloid telescopes of the ~25m-diameter class were constructed in numerous observatories including Dwingeloo, Netherlands (1955), Stockert, Germany (1956) and Pushino, Soviet Union (1959). The National Radio Astronomy Observatory, founded in the USA, began operations with the Tatel 85ft (26m) radio telescope in 1958. At the same time the construction of a 140ft-precision telescope begun in Green Bank (completed in 1965). This telescope is still standing on the original site, part of the NRAO organisation. While the construction of the 140ft dish experienced delays, a 300ft transit dish was built in Green Bank in 1962. This dish collapsed owing to metal fatigue failure in 1988. The Stockert and Dwingeloo telescopes are still standing on their original sites, protected by foundations that support historical objects. (The Stockert antenna is examined more closely in Case Study 13.1.) The construction of what was then the world's largest reflector, a 250ft (74m) radio telescope, was completed at Jodrell Bank, UK, in 1957. This radio telescope has been refurbished several times, and is still actively used in research, having been renamed the 'Lovell Telescope'. Single-dish antennas were used in the 1960s to measure linear polarization and the radio Zeeman effect, advances that led to the beginning of research in cosmic magnetic fields.

The construction the Giant Pulkovo Radio Telescope—a section of a reflector corresponding to an aperture of 130m × 25m, designed to operate in the centimetre and long millimetre wavelength range—was completed in 1956 in the Soviet Union. This telescope is still used for solar research. Experimenting with new types of antenna, J.D. Kraus designed a large reflector-director system. The first such radio telescope, later named the 'Big Ear' when used for the search of signals from extraterrestrial civilizations (SETI), was constructed for the Ohio State University. This type of radio telescope, which combines low cost with a large collecting area, was copied in several other observatories. The Kraus telescope became operational in 1960 but had to make way for real estate development and a golf course in 1998. A large decametre radio telescope of the reflector-director type at the Nançay Observatory, France, which was completed in 1965, is still operating today. The 64m Parkes radio telescope became operational in 1962. Owing to its position in the southern hemisphere it was a major contributor to many studies of the Milky Way. The Parkes radio telescope is still a fully operational instrument. The largest reflector, a spherically shaped, non-steerable 1000ft-diameter reflector, was built in 1963 at Arecibo, Puerto Rico. This instrument was used initially for ionospheric work and planetary radar but later the research was shifted to radio astronomy. The large collecting area of this instrument opened up a new dimension in single dish sensitivity. The Arecibo facility is still operational although subject to threats of closure owing to financial problems.

The decade 1960–1970 was marked by the development of the **aperture synthesis** method. A prerequisite of this method was high stability of amplifiers, local oscillators and cables. Computing power was also a necessity since data had to be Fourier transformed in order to produce images. The first practical aperture synthesis system was used by and Martin Ryle and A.C. Neville in Cambridge in 1962. This experiment used sections of the 178 MHz cylindrical paraboloid—some of the structures are still standing at the Lord's Bridge observatory. This development led ultimately to the discovery of **quasars**, the most distant sources in our universe, and allowed the nature of **radio galaxies** to be studied with the higher angular resolution. For their contribution to the development of aperture synthesis, Martin Ryle and Anthony Hewish were awarded the Nobel Prize in 1974.

Additional aperture synthesis telescopes were constructed in the Netherlands, USA, United Kingdom, India, Australia and Canada. Details are given in Table 13.0.1. They have been the driving force in present-day radio astronomy. In addition to radio continuum maps, line observation became feasible. At first, only HI maps were possible, but maps in many molecular lines were produced later. The consequent use of HI data on the rotation of galaxies, in combination with optical line data, led in the 1980s to the realization that galaxies contain considerable **dark matter**.

The scintillation method at lower radio frequencies offered an interesting way to study astrophysical plasmas. Several dedicated instruments were constructed for this purpose. One of the great discoveries, made at the low radio frequency of 85 MHz, was the detection of **pulsars** in 1967. The original antenna that detected pulsars was an array of dipoles on wooden posts constructed in Cambridge in 1962 and hence does not exist any more. The discovery of the **binary pulsar** at Arecibo in 1974 led to a revolution in gravitational physics and was recognised with the Nobel Prize in 1993. Another great discovery in the field of pulsar research was the detection of the first **millisecond pulsar** in 1982. The precise pulsar timing that became possible led to the detection of the first **extrasolar planetary system** in 1992.



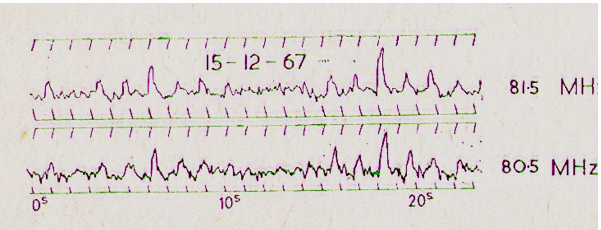


Fig. 13.0.2. Left: An early **aperture synthesis** map of the radio galaxy Cygnus A. After M. Ryle et al., *Nature* 205 (1965), 1259. See Fig. 13.0.4 for comparison. **Above:** The pulsar discovery record. After A. Hewish et al., *Nature* 217 (1968), 709.

Table 13.0.1. Interferometers in operation (2009).

Name	Country	Antennas	Array elements baselines	Operating frequencie
VLA, Soccoro	USA	27 × 25m	36.4 km Y-configuration	74 MHz – 86 GHz
WSRT, Westerbork	Netherlands	14 × 25m	2.8 km East-West	237 MHz – 6 GHz
Cambridge	UK	8 × 13m	4.6 km East-West	2.7 GHz – 15 GHz
ATCA, Narrabri	Australia	7 × 22m	6 km	1.4 GHz – 86 GHz
DRAO, Penticton	Canada	7 × 8.5m	604 m East-West	408 MHz – 1.4 GHz
Pune	India	30 × 45m	25 km irregular	50 MHz – 1.4 GHz
Merlin	UK	25m, 32m, 76m	233 km irregular	150 MHz – 23 GHz
Plateau de Bure	France	6 × 15m	North-South, East-West: 760m max.	90 GHz – 345 GHz
Nobeyama	Japan	6 × 10m	560-m T-base	24 GHz – 90 GHz
Carma	USA	6 × 10.4m, 9 × 6.1m	2.0 km max.	90 GHz – 230 GHz
SMA, Mauna Kea	USA	8 × 6m	500 m	230 GHz – 600 GHz

Table 13.0.2. Large single dishes in operation (2009).

Name	Country	Size	Maximum frequency
Arecibo	Puerto Rico	305m	8 GHz
GBT, Green Bank	USA	110m × 100m	86 GHz
Effelsberg	Germany	100m	86 GHz
Lovell Telescope, Jodrell Bank	UK	76m	8 GHz
Goldstone, Robledo, Tidbinbilla	USA, Spain, Australia	70m	24 GHz
Yevpatoria	Ukraine	70m	6 GHz
Parkes	Australia	64m	43 GHz
Kalyazin, Ussurijsk, Bear Lakes	Russian Federation	64m, 70m, 64m	6 GHz
Miyun	China	50m	8 GHz

Spectroscopy became a major driving force in radio astronomy as a result of the detection of more than 150 molecular species. The beginning of molecular radio spectroscopy was the detection of the OH molecule in 1963, which was followed by the detection of ammonia in 1968 and water and formaldehyde in 1969. It became clear that there was a huge potential for spectroscopic discoveries in the millimetre wavelength range. Millimetre wavelength sources were difficult to measure at first since water vapour (also N_2 and O_2) in the Earth's atmosphere reduces astronomical signals and the early mm-wave receivers had low sensitivities. In the early 1960s, the typical single-dish size was 5m and these were located at sea-level sites. The first impressions were that there was little to be added to the measurements conducted at centimetre wavelengths. This changed as a result of two factors related to instruments. The first was the construction of a 36ft (later rebuilt to 12m) dish at 2500m elevation, started in 1965 at the Kitt Peak site in Arizona. Since water vapour has a scale height of 2000m, this high site and larger collecting area brought about a large improvement in sensitivity. The second factor was the introduction of more sensitive receiver systems. A far-reaching discovery made immediately was that of carbon monoxide (CO) at 115 GHz. This spectral line is widespread and rather intense, so it allowed mapping similar to the mapping done in the 21cm line of atomic hydrogen, HI. In addition, it was later shown that there is a rather simple relation between the abundance of molecular hydrogen and CO, so molecular cloud masses could be determined. The Kitt Peak 12m millimetre telescope is still operational under the auspices of the Steward Observatory of the University of Arizona. Surveys using 1.2m telescopes at 3 mm have allowed the distribution of CO in our galaxy to be determined from data collected in both the northern and southern hemispheres. The 1.2m dish is still operated by the Center of Astrophysics and the University of Chile. The molecular hydrogen distribution is strongly correlated with the distribution of HII regions, and thus with high-mass stars. In addition, CO measurements of nearby molecular clouds showed that stars are associated with these regions, and thus form in molecular clouds. It follows that to understand star formation one must study molecular clouds. In this respect, both the higher line transitions and the various isotopic species are a great help in determining the temperature and the density in these regions.

The next step in the development of radio telescopes was the inauguration of the Westerbork Synthesis Radio Telescope (WSRT) in 1970. This array consisted originally of 12 (now 14) 25m dishes on an east-west line. The Ooty radio telescope, a parabolic cylinder 530m long, was built in India in 1970. This telescope was originally designed for observing lunar occultations of radio sources but became a more general-purpose telescope in later years. It is still actively used in research. The inauguration of the 100m-precision radio telescope in Effelsberg (Germany) took place in 1971. For this telescope a new construction method named ‘homology’ was employed. Homology allows deflections in a structure but ensures that a paraboloid shape is maintained. This meant that high-frequency use of the 100m Effelsberg telescope, up to 86 GHz, was possible. The new radio telescopes allowed considerable progress in our knowledge: giant radio galaxies were discovered (WSRT), magnetic fields in nearby galaxies could be mapped (Effelsberg), and sensitive spectral observations could be made. Thus, for example, weaker atomic hyperfine lines from ionized 3-helium were observed in 1982, and a special facility was built for the detection of deuterium in 2007. In the Soviet Union, the Ratan 600 radio telescope was constructed in the Caucasus region, a 600m circle of reflecting panels that can be used particularly in multi-frequency mode. The Very Large Array (VLA), an array of 27 antennas 25m in diameter on a 27km Y-shaped line of tracks, was constructed near Soccoro, New Mexico and started full operations in 1980. The Giant Metrewave Radio Telescope (GMRT) near Pune, India has been operational since 1999. In addition, interferometers with radio links, rather than cables, became operational (Merlin, UK) giving increased angular resolution, and leading to the discovery of **gravitational lensing** in 1979.

The aperture synthesis method required that all antennas should be connected by cables or radio links. The development of highly stable clocks and of magnetic tape recorders led to the invention of ‘independent oscillator-tape recorder interferometry’. In this method the antennas could be distributed widely over the whole world so that in the end this technology came to be

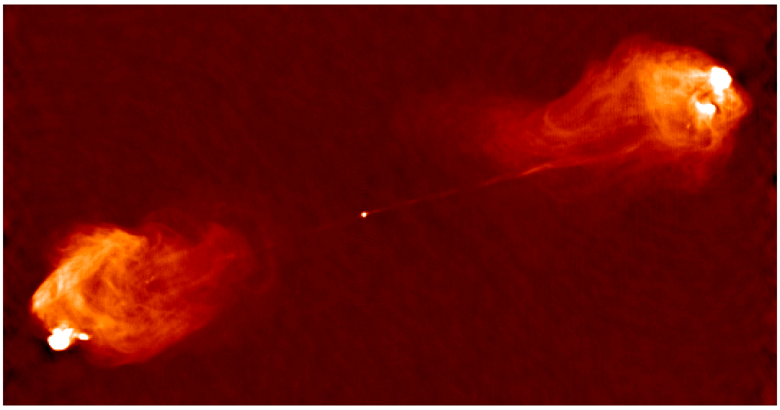


Fig. 13.0.3. A VLA map of Cygnus A. © National Radio Astronomy Observatory

known as 'very-long-baseline interferometry' (VLBI). VLBI was first mooted in the Soviet Union and implemented in 1967 in Canada and the USA. Progress in this area was dependent on better atomic clocks and wider-bandwidth tape recorders. It also required international cooperation and the setting of standards. VLBI networks were set up with the data correlated and processed centrally. The European VLBI network co-opted telescopes in China. A dedicated network in the USA, the Very Long Baseline Array (VLBA), replaced ad-hoc agreements. The VLBA often operate together with radio telescopes in Europe, and in particular with the 100m Effelsberg radio telescope. A separate network grew up in Japan and another one in Australia. The final extension of VLBI occurred when a radio telescope was placed in orbit by the Japanese space agency—this is known as the HALCA project. Numerous dishes in the 25m to 64m class were constructed with the dedicated aim of working in one of the VLBI networks. One of the spectacular discoveries of VLBI was that of the **superluminal motions** made in 1970. For masering spectral lines of OH and water vapour, VLBI provided source sizes and positions. Water masers have been used to estimate the mass of the centre of NGC 4258 and to estimate the Hubble constant, using the Nobeyama 45m radio telescope at first and later VLBI. The extension of VLBI to a wavelength of 1.3 millimetres will inevitably lead to the imaging of the event horizon of the source Sgr A*, the centre of our Galaxy. The centimetre emission from Sgr A* is likely to be optically thick synchrotron emission which becomes optically thin at short wavelengths. Thus images to the edge of the Schwarzschild radius require millimetre VLBI. Sgr A* is thought to be a supermassive black hole, so with millimetre VLBI we can study strong-field general relativistic physics close to home.

Space radio astronomy had its beginnings with the launch of the Ariel III cosmic radio experiment in 1967. In this simple experiment the cosmic noise was to be measured in the frequency range 2 MHz to 4 MHz, a frequency region not normally accessible to ground-based observations owing to the Earth's ionosphere. Later radio satellites concentrated on measurement at higher frequencies. The most prominent satellite in the mid-1980s was the ESA-NASA Infra Red Astronomy Satellite (IRAS) that provided a 1-arc-minute-resolution survey of the sky. The Soviet Union launched the satellite Relikt-1 in 1983 to study the CMB radiation at 37 GHz. Since this radiation peaks at a wavelength of about 1 mm, accurate measurements from the ground are difficult. IRAS was followed by the Infrared Space Observatory (ISO), which was used to study specific sources. With the NASA Cosmic Background Explorer satellite COBE it was shown that the spectrum is indeed black-body. This established that the 2.73 K background is most likely the remnant of the Big Bang, so that alternate theories are highly unlikely. The two principal investigators of COBE, G. Smoot and J. Mather, received the 2006 Nobel Prize. The continuation of COBE was the Wilkinson Microwave Anisotropy Probe (WMAP) satellite, a NASA project that gave excellent results in high-frequency bands from 23 GHz to 94 GHz. PLANCK, a European Space Agency (ESA) satellite, is now at the Lagrangian 2 point and will progress this field of research. The Herschel Satellite Observatory, which was launched together with PLANCK in May 2009, is the most ambitious radio-infrared satellite project yet launched. The Herschel observatory is equipped with a 3.5m-diameter telescope that has three detector systems. The PLANCK satellite will survey the sky in 9 bands, from 30 GHz to 857 GHz, most of them with polarization data. Satellites use cooled detector systems and hence have a finite lifetime. They become space debris once their useful life comes to an end, usually owing to a lack of coolant. Hence we have no durable and authentic heritage satellites in space. Some pre-engineering models or copies do find their way into museums.

The development of millimetre-wavelength astronomy in the 1970s progressed with the construction of 14m- to 20m-diameter telescopes in radomes, but then progressed further with the construction of millimetre and sub-millimetre observatories at high and dry sites. The Institute for Radio Astronomy in the Millimetre Wavelengths (IRAM), a French-German-Spanish organization with headquarters in Grenoble, operates a 30m telescope at the 2850m-high Pico Veleta site in Spain and a millimetre interferometer on the 2552m-high Plateau de

Bure in France. The Caltech Sub-millimeter Observatory (CSO) built a 10m dish and a UK-Dutch-Canadian consortium built the 15m James Clerk Maxwell Telescope (JCMT) on the 4200m-high Mauna Kea site in Hawaii. The 15m Swedish-ESO Sub-millimetre Telescope (SEST) was erected at ESO's La Silla site in Chile. The National Astronomy Observatory of Japan constructed a 45m telescope and a millimetre interferometer in Nobeyama. The 10m Heinrich-Hertz-Telescope on a 3200m-high site at Mount Graham, Arizona, became operational in 1998. At Green Bank, as a result of the collapse of the 300ft transit telescope in 1988, a replacement was constructed, named the Robert C. Byrd Green Bank Telescope. The GBT, a 100m × 110m offset paraboloid reflector, became operational in 2000. In the quest for even better sites the 12m dish for the APEX sub-millimetre telescope was constructed on the 5105m-high Chajnantor plateau in Chile. In addition, the Japanese 10m telescope project ASTE became operational on a high site in Chile. A sub-millimetre interferometer (SMA) came into operation on Mauna Kea. Nearing completion is the Large Millimetre Telescope (LMT) on a 4600m-high site in Mexico. At the best sites, measurements can be made from ground-based telescopes up to a frequency of 1.3 THz, a wavelength of λ ~300µ. At the very best sites on Earth, it may be possible to extend measurements to somewhat higher frequencies. One of the sites now being extensively tested is Dome C in Antarctica. An intermediate between ground-based observatories and satellites is the airborne observatory SOFIA (Stratospheric Observatory for Infra-Red Astronomy). SOFIA is a US-German project that uses a 747 aircraft. It has a 2.5m telescope with an optical quality. It should begin science operation in 2010.

Until recently, ground-based radio astronomy relied on national incentives or the cooperation of a small number of individual nations. Examples of smaller cooperations are IRAM (France-Germany-Spain) and the JCMT (UK-Netherlands-Canada). The first global project that has brought together Europe, North America and East Asia is the ALMA millimetre project on the Chanjantor site in Chile. ALMA will have at least 66 antennas of 12m diameter and some of 7m diameter, making it the largest such facility on Earth. At low radio frequencies the goal is to build a Square Kilometre Array (SKA). The SKA will be preceded by smaller pathfinder projects such as the Low-Frequency-Array (LOFAR) in Europe, the Allen Telescope Array in the USA, the Australia-SKA-Precursor (ASKAP) in Australia and the Karoo Array Telescope (KAT) project in South Africa. In China, radio astronomers have now embarked on the construction of a 500m spherical radio telescope in the Karst region of Guizhou province. This can be thought of as a larger version of the 1000ft (305m) Arecibo design.

The history of radio astronomy has been marked by startling discoveries. From the first measurements, it was clear that radio and optical astronomy produced very different views of the sky: from this beginning came the discovery of synchrotron radiation, then quasars, pulsars, molecules and molecular clouds, the CMB gravitational lenses, and so on. The implications of these discoveries are still in the process of gestation. From the CMB, it is clear that our universe began about 13.7 billion years ago in an explosive process. From the newest WMAP results, it appears that baryons make up only 4% of the matter in the universe, with the rest being Dark Matter and Dark Energy. In addition to studies related to fundamental aspects of physics, we hope to learn from studies of star formation how our solar system was formed and perhaps how life on earth began. The early radio telescopes that made these discoveries possible are now heading for 'heritage instrument' status. However, it is surprising to see how many of these old instruments are still in full operational mode. It will require considerable determination to secure the necessary funds to preserve old radio telescopes.

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Case Study 13.1: The Stockert Radio Telescope, Germany

Richard Wielebinski

Presentation and analysis of the site

Geographical position: Stockert mountain, D-53902 Bad Münstereifel, Nordrhein-Westfalen, Germany

Location: Latitude 50º 34´ 10˝N, longitude 6º 43´ 19˝E. Elevation 435m above mean sea level.

General description: The 33,000m^2 property holds the 25m radio telescope together with 10m millimetre radio telescope, a laboratory/workshop building, a residence for observers and a house for the site manager.

*Inventory of the remains***:** The 25m radio telescope stands on a pyramidal base, with technical rooms spread through several stories. All the electrical supply rooms are in the basement of the pyramid. The upper floors host the control room, receiver controls, computers, etc.

When the telescope was inaugurated in 1956, it had a mast supporting a dipole-reflector feed (1 in Fig. 13.1.1). In 1968 the dipole feed was replaced by a four-leg support system that permitted either prime focus or secondary focus operation. The low noise receivers (LNRs) were normally placed in the cabin behind the elevation drive (5). The azimuth drive (6) operated through a gear that allowed full rotation. This required a complex system of brush contacts (10) between the LNRs and the back-end electronics.

History of the site: The 25m Stockert radio telescope was used for astronomical research from its inauguration in 1956 until its closure in 1995. Between 1956 and 1966 it was run by the Bonn University Astronomy Department. In 1966 the Max-Planck-Institut für Radioastronomie was founded in Bonn and took over operations at the Stockert site. In 1978, however, after the 100m Effelsberg radio telescope had been completed, the operation of the Stockert site reverted to Bonn University.

Bonn University sold the Stockert site to an investor in 1995, and in that same year a foundation called the 'Förderverein Astropeiler Stockert e.v.' was set up with the aim of restoring the 25m radio telescope. This group of active supporters started to press for the status of a 'historical monument' for the radio telescope, and this was achieved in 1999. In 2005 the Nordrhein-Westfalen-Stiftung (http://www.nrw-stiftung.de/) purchased the site from the former investor and allocated funds for a massive refurbishing of the instrument, thus promising a secure future.

Cultural and symbolic dimension: Observations with the Stockert radio telescope were made at 21 and 11 cm wavelength. Several extended surveys were made of both the radio continuum and the HI line. Pulsar observations were also carried out with the Stockert telescope.

Authenticity and integrity: In order to maintain the structure of the telescope, rusted sections have been replaced and the whole instrument has been painted. Virtually every system of the telescope needed new electronics: the drive system and the astronomical control system as well as the receivers have been renewed. Many of the old electronic racks are still standing: they will be preserved as historical background.

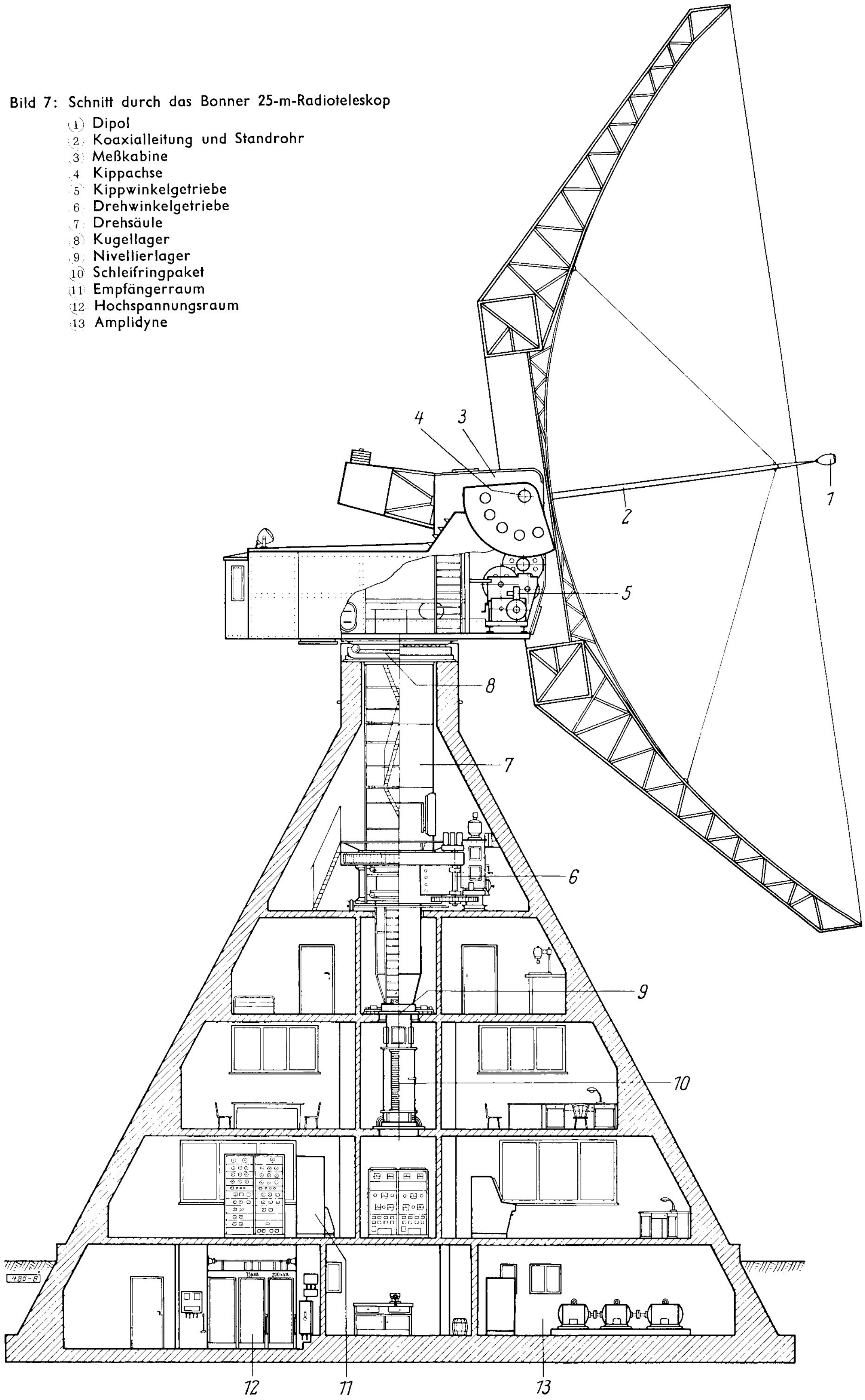

Fig. 13.1.1. The original technical drawing of the 25m Stockert telescope. After Mezger (1958).

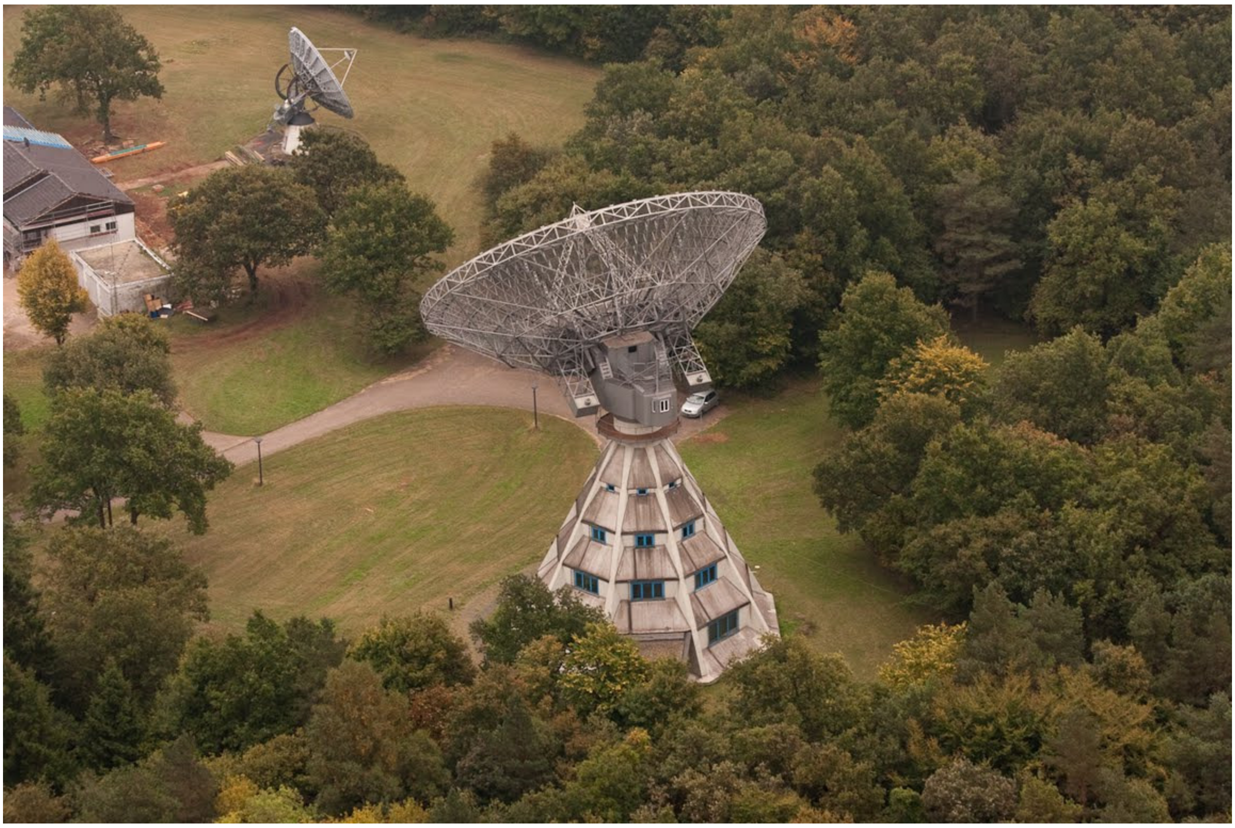

Fig. 13.1.2. A recent aerial photograph of the Stockert site. © Robert Spieß, Essen.

Present site management

Present use: The site is closed at present.

Protection: Since 1999 the Stockert radio telescope has had the status of a 'historical monument'.

Management, interpretation and outreach: The further use of the Stockert telescope has been entrusted to the Förderverein. Their aim is to modernise the observational possibilities, to make the instrument available to amateurs, and to support schools in technical education as well as to preserve the historical instrument for posterity.

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Chapter 14: Applied Astronomy in Modern Times

Michel Cotte

The development of astronomical knowledge in modern times has forged strong connections with technology and led to the development of a variety of new applications of that knowledge. At the same time, many of the social uses of astronomy are, essentially, unaltered since ancient times: these include the establishment of calendars; aiding human navigation across deserts, large plains and the seas; and time measurement.

Recognizing the positions of the stars has benefited navigators within many different human societies. In early modern times, instruments for measuring the positions of stars, such as astrolabes and quadrants, were used in simplified form together with ephemerides in order to determine the latitude and to help identify maritime routes. Within Europe, the development of particular types of quadrant with improved accuracy provided a crucial step in oceanic navigation, culminating in the invention of the sextant, which permitted accurate measurements of the altitude of the sun, moon and stars.

The question of time measurement linked with astronomy, having already progressed from the gnomon to medieval celestial clocks, underwent a series of developments during the modern period. For example, the problem of determining longitude during long transoceanic expeditions during the 18th century required both improvements in astronomical instruments for navigation and reliable mechanical clocks. During the 19th century, observatories providing time measurement became directly linked with specific organisations that needed 'astronomical time' on a continuous basis, such as clockmakers and staff at railway stations who needed to coordinate the management of train timetables. Applied astronomy could provide permanent knowledge of the precise time and guarantee the synchronization of clocks separated by large distances.

The measurement of the Earth and the definition of metric units of measurement were also important questions that were addressed using astronomy. The triangulation method for the measurement of meridians was implemented by the abbot Jean Picard (1620–1682) during the second half of the 17th century. It was continually used thereafter, with successive refinements in precision, to determine the exact size and shape of the Earth. One such determination, made by Friedrich Georg Wilhelm Struve in the mid-19th century, is important in having left a unique material legacy (the 'Struve arc') that remains today (see Case Study 14.1), unlike many others that are mainly known through historical accounts.

Based upon an increasingly copious amount of technology coupled with a series of major scientific discoveries during the modern and contemporary periods, astronomy has gone on to deliver an extraordinary level of fundamental support for the 'conquest of space' that has taken place in the second half of the 20th century (see Chapter 15).

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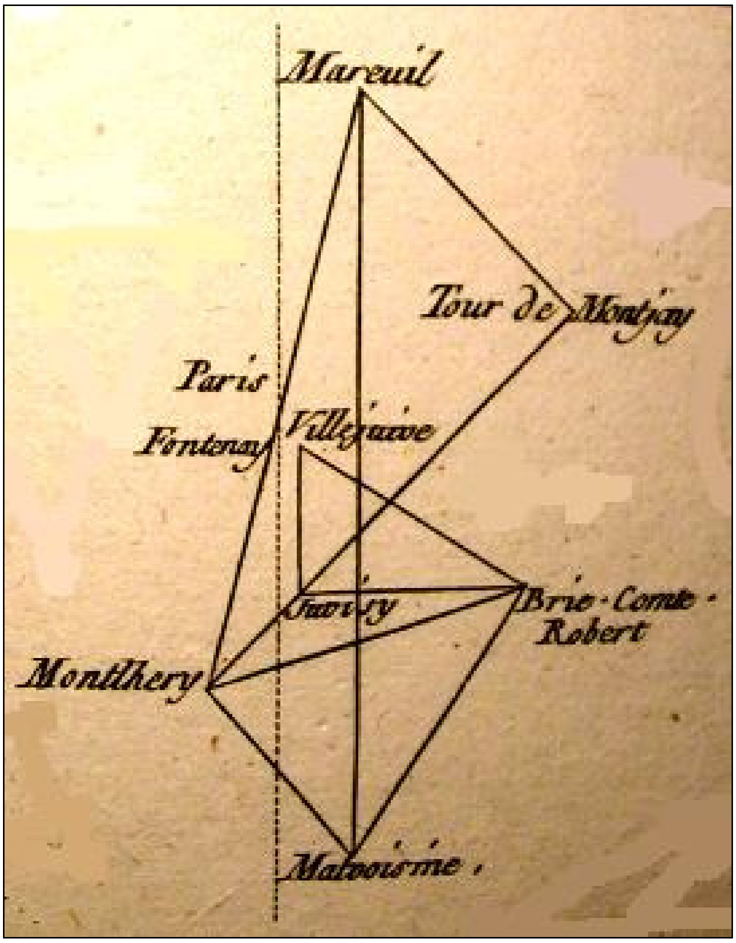

Fig. 14.0.1. The triangulation method was implemented and used practically by Jean Picard for measuring one arc degree of the 'méridien de Paris' during the 1670s. It was used throughout the 18th and 19th centuries for the determination of different meridian lines all over the world and to determine the exact shape and size of the Earth. After Jean Picard, *Le Traité du Nivellement*, Paris 1684. Photo from Wikimedia commons (Public domain).

Case Study 14.1: The Struve Geodetic Arc

Belarus, Estonia, Finland, Latvia, Lithuania, Republic of Moldova, Norway, Russian Federation, Sweden, and Ukraine

Presentation and analysis of the site

Geographical position: Thirty-four different locations in the nominating states.

Location: Latitude 45º 19´ 54˝ N to 70º 40´ 12˝ N, longitude 22º 44´ 45˝ E to 28º 55´ 41˝ E. Elevation up to c. 250m above mean sea level. A full list of the 34 locations is available in the nomination file (see bibliography).

General description: The Struve Geodetic Arc World Heritage Site, a serial inscription made in 2005 under criteria (ii), (iii) and (vi), comprises a string of 34 surviving nodes of a 265-point triangulation network set up between 1816 and 1851 by the astronomer Friedrich Georg Wilhelm Struve (1793–1864) and his colleagues in order to determine the precise size and shape of the Earth. It runs through ten modern countries from the north coast of Norway down to the Black Sea.

*Inventory of the remains***:** Of the 34 listed nodes, 4 lie in Norway, 4 in Sweden, 6 in Finland, 1 in Russia, 3 in Estonia, 2 in Latvia, 3 in Lithuania, 5 in Belarus, 1 in Moldova and 4 in Ukraine. A full description of each can be found in the nomination file. The various nodes are marked in different ways, which can be broadly classified as follows:

- a small hole drilled in the rock surface, sometimes filled with lead;
- a cross-shaped engraved mark on the rock surface;
- a solid stone or brick with a marker set in it;
- a mound of stones (cairn), with a central stone or brick, marked by a drilled hole;
- a single brick; and
- a specially constructed ‘monument’ to commemorate the point and the arc.

History of the site: A decision was reached in 1815 to establish agreed international boundaries in Europe and this required accurate mapping. Following the defeat of Napoleon, accurate mapping was also a priority for the new European rulers who did not trust the peace to be long lasting. It was in this context that the Russian Tsar Alexander I provided Struve with the resources to establish a new long geodetic arc. Struve was working at Dorpat (Tartu) University in what is now Estonia, and decided to establish a triangulation arc following a line of longitude (meridian) passing through the university’s observatory. Several decades later, a 2800km-long arc was finally established by connecting and extending earlier, shorter arcs. It stretched from Fuglenaes near Hammerfest in the far north to Staro-Nekrasowka, near Ismail, on the shore of the Black Sea.

Cultural and symbolic dimension: Determining the size and shape of the Earth had been a key problem for natural philosophers since ancient Greek times. Eratosthenes’ method, developed in the 3rd century BC, used length measurements and angles determined by observations of stars, but was very inaccurate. Only in the 17th century did accurate measurements become feasible, using the newly developed technique of triangulation. By this method, only much shorter lines had to be measured accurately, while the long distances were determined using a chain of connected triangles (a ‘triangulation arc’).

Fig. 14.1.1. The northernmost node of the Struve arc, marked by a memorial obelisk, at Fuglenaes, Norway. Photograph by F. Bandarin. © UNESCO World Heritage Centre.

During the 18th century, early arcs were constructed in France, Peru, Lapland, Italy, South Africa and Austria, but all of them had shortcomings. Struve's arc was the longest such arc when it was created, and remained so for over a century (its length was only eventually exceeded by an arc completed in 1954). It was also the most accurate, producing measurements correct to 4 mm in 1 km. It brought about the development of new and more accurate measuring equipment, and assisted indirectly in promoting the standard metric system. It was the first meridian measurement device crossing the borders of several countries and formed the basis for mapping not only of those countries that it traversed but also of central Eastern Europe in general.

Struve's arc is not only a key example of the broader application of astronomy in modern times; it also represents an important step in the development of the earth sciences and in the use of state-of-the-art technologies.

Authenticity and integrity: All 34 nodes are in their original location; some are in remote areas that are unchanged since the arc was created.

Present site management

Protection: All 34 nodes are legally protected, in most cases by two laws—one protecting geodetic points and the other for the protection of cultural heritage.

State of conservation: The cultural-historical importance of some of the nodes was recognized long ago and many of them came under the protection of the cultural heritage legislation of the relevant countries. As recognized monuments, the relevant laws have been applied, including those relating to conservation.

The present state of conservation of the 34 nodes on the World Heritage List seems good. Many of them still form part of their national geodetic grid, and are permanently maintained. Most of them still have their original plaques. Some have been reinstalled, but in the exact original position.

Main threats or potential threats to the sites: The only potential risk is from increased numbers of visitors, which is possible following the World Heritage inscription. Managing such risk is one of the considerations of a coordinating body that has been created by the ten countries.

Management, interpretation and outreach: Each of the nominating countries has their own regime to manage the heritage. At the same time, the ten countries have set up a joint 'management mechanism', in the form of a coordinating committee, to coordinate the management of the nominated sites.

Many of the nominated 'sites' are points or other shapes in the rock, with very small area around them. Most of them still form part of the relevant national geodetic system and therefore could potentially be used—in other words, they retain a practical importance. Therefore they are managed by national geodetic services and controlled by national cultural heritage institutions.

The existing management and legal protection were two of the criteria used by the State Parties to choose the 34 nodes for nomination from the many more that were originally in the Struve Arc and may survive.

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Chapter 15: Space Heritage

The term ‘Space heritage’ can have several connotations, of which the commonest perceived could be summarised as:

(1) heritage related to the process of carrying out science in space;

(2) heritage related to manned space flight/exploration; and

(3) human cultural heritage that remains off the surface of ‘planet Earth’.

Although inextricably linked in the public perception, (1) and (2) are largely separate. (1) represents the heritage directly associated with the development of space sciences in a broader sense, while (2) represents the heritage of the technology developed in order to make space exploration (including manned space flight) possible.

Space heritage in sense (3) could arise as a by-product of any human activity in space, and could include both material vestiges on other worlds (e.g. scientific and other equipment left on the moon or Mars; the first footprints on the moon), or material left in space (e.g. orbiting satellites; deep-space probes).

What follows is divided into two parts. The first is a tentative taxonomy of fixed sites and facilities pertaining specifically to space astronomy and/or generally to space science, with illustrative examples mostly from the USA. It focuses on places such as launch facilities, design and test facilities, and tracking sites that have historical meaning and value in relation to space heritage using definition (1). The second is a broader discussion of the heritage of space exploration, including space instruments and the spacecraft themselves.

The heritage of space science and space astronomy *by David DeVorkin*

In this section we propose a tentative taxonomy of fixed sites and facilities pertaining specifically to space astronomy and/or generally to space science. The major items in the taxonomy are illustrated by examples that might provide useful case studies, but no effort has been made to check to see if they are suitable (e.g. in a state desirable for preservation or restoration) or even still existant. Rather, they are listed here as illustrative of the sorts of site bearing a significant technical relationship to the history of the project, event, or achievement. In other words, this is a ‘blue-sky’ list that is intended purely to stimulate further discussion and investigation; it should neither be considered complete nor representative of any collective opinion and has no proven value related to the World Heritage List. The examples are limited to the USA and Canada but could certainly be extended to other countries.

‘Space science heritage sites’ could be geographical landmarks where instrument packages were conceived and built, tested, launched, controlled, analysed, or somehow employed in the generation of new knowledge about space and the things in space. They could also be sites where capabilities in space flight pertaining to the sciences were conceived, built, tested, etc. Facilities may also be found within these sites, or separate from any designated site. These are structures and environments where the instruments and systems were created, tested, etc. These could be rooms or chambers with or without *in situ* apparatus unique to the history of the instrument, mission or event. Instruments are best understood in context of the environments that produced them or employed them. We have not considered archival records, or instruments best preserved in museums or for which *in situ* preservation is no longer possible.

Our taxonomy will emphasize those sites or facilities that were uniquely suited to the design, construction and use of instrumentation that flew in space. Laboratories, launch sites and commercial industrial sites whose remit was more generic have not been considered unless they supported a wide range of activities over many years or somehow participated in an unusually important event, mission or discovery.

There is virtually no overlap with Harry Butowsky's 1989 report for the National Park Service aiming to "identify the sites, structures, buildings and objects significant in the history of the sciences of astronomy and astrophysics in the United States"[1] because the sites considered here are under 50 years old. Nonetheless, it is useful to bear in mind the NPS's criteria for demonstrating historical, cultural and architectural significance on a national level, which state that a candidate site should be

(A) "…associated with events that have made a significant contribution to the broad patterns of our history; or

(B) … associated with the lives of significant persons in or past; or

(C) … embody the distinctive characteristics of a type, period, or method of construction, or that represent the work of a master, or that possess high artistic values, or that represent a significant and distinguishable entity whose components may lack individual distinction; or

(D) … have yielded, or may be likely to yield, information important in history or prehistory."[2]

The NPS is concerned with commemorating, validating and illuminating historical events, lives of note, and objects of construction or manufacture within their original environments. It is also concerned with land use and national identity. An entity of the Department of the Interior, it promotes programmes in public recreation and education, with preservation at its core.

The suggested taxonomy reflects these criteria. "Significant contributions to the broad patterns of our history" might well include the launch pads that symbolised the space race between nations, or the place where the first dedicated astronomical X-ray satellite was conceived and constructed. Criterion B identifying significant persons of the past should naturally include people like James Van Allen, the leader of the team that instrumented the first successful American satellites that ultimately revealed a whole new portion of the Earth's outermost atmospheric and magnetospheric regions. Criterion C covers the identification and preservation of laboratories where distinctive practices were developed within distinctive architectural space that led to successful space missions. These can range from vacuum chambers and Faraday cages to deep tanks of water that simulate zero gravity. Criterion D is less obvious or relevant given the huge amount of documentation available for this period in other forms.

No effort has been made to identify extraterrestrial sites of importance in the history of space astronomy. However, one site does comes particularly to mind: the landing site for Apollo 16, where in 1972 astronauts set up the first astronomical observatory on another celestial body—George Carruthers' Moon Camera.

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[1] Butowsky, H.A. (1989). *Astronomy and Astrophysics: National Historic Landmark Theme Study* (Washington DC: Department of the Interior, National Park Service). The quote is from p. 11.

[2] National Register Bulletin, *How to Apply the National Register Criteria for Evaluation*. http://www.cr.nps.gov/nr/publications/bulletins/nrb15/nrb15_2.htm.

The taxonomy

Launch facilities that engaged in space science missions

Examples:

Holloman Air Force Base	Balloon and rocket launch facilities, tracking facilities
Fort Churchill (Manitoba)	Balloon and rocket launch facilities, tracking facilities. See *http://www.mhs.mb.ca/docs/mb_history/44/exploringnorthernskies.shtml*
Wallops Island	NACA/NASA facility
Stratobowl	Scientific balloon launches from the 1930s
Palestine	Balloon launches starting in the 1950s, especially the ‘Skyhook’ series and ‘Stratoscope’ series.

Suggested Case Study:

White Sands Missile Range (formerly Proving Grounds), White Sands, New Mexico.	What still exists from the period 1945–1951 when the first ultraviolet solar spectra were obtained from a rocket and the cosmic ray plateau was detected? The first Aerobee sounding rockets were also launched here: Aerobees were the most successful scientific sounding rockets in history. See *http://www.las-cruces.org/public-services/museums/history_exhibit/Images/warRockets/warRocketWSMR.html* and *http://www.wsmr.army.mil/wsmr.asp*, particularly White Sands Missile Range Launch Complex 33 (National Historic Landmark) (*http://www.wsmr.army.mil/wsmr.asp?pg=y&page=560*) and *http://www.wsmr.army.mil/wsmr.asp?pg=y&page=552*

General Resource:

Roger D. Launius and Andrew K. Johnston (2009), *Smithsonian Atlas of Space Exploration* (Harper-Collins, Bunker Hill Publishing). Part three, “Gateways to Space”, describes mission-control centres and launch facilities including those in the USA, such as Cape Canaveral, Vandenberg and Wallops, as well as the major Russian facility at Bayconour, the European Space Agency facility at Kourou, and others in Israel, Japan and China. A world listing of active, projected and abandoned sites is included.

Conceptual design, construction and testing sites

Examples:

Applied Physics Laboratory	Original campus in Silver Spring, MD - what still exists of the two structures? Present campus located in Columbia, MD has facilities that date from the 1960s. See *http://www.jhuapl.edu/aboutapl/heritage/aplgrowth/default.asp*
Goddard Space Flight Center	High-bay test facilities, control rooms, vacuum facilities; clean rooms
Jet Propulsion Laboratory	Instrument laboratories, test facilities, the Arroyo Seco static test site.
Ames Research Center	Wind tunnels, long path-length spectroscopy facilities
Johnson Space Flight Center	Lunar receiving laboratory, astronaut training facilities
Applied Science and Engineering (Cambridge, MA)	
Naval Research Laboratory (Washington, DC)	

Campus sites for design and construction and analysis

Examples:

University of Iowa	Van Allen
University of Colorado	Pointing controls
University of Michigan	Early space science centre
University of Wisconsin	Early space astronomy centre
Princeton	Ballooning, OAO, HST

Tracking sites

Satellite-tracking sites for ranging and other geodetic interests

Sites for the Baker-Nunn satellite-tracking network (in the USA: Florida and Arizona)

Goldstone-type sites that received telemetered scientific data

Resource:

Shirley Thomas (1963), *Satellite Tracking Facilities: Their History and Operation* (New York: Holt, Rinehart and Winston).

Specific offices/laboratories

Examples:

James Van Allen's office and laboratory at the University of Iowa	*http://www.lib.uiowa.edu/spec-coll/Bai/halas.htm*
Herbert Friedman's laboratory or remnants thereof	Of special interest would be the preservation of George Carruthers' laboratory that still contains an original 'filling station' where Friedman's team prepared their halogen-filled proportional counters. See *http://siarchives.si.edu/research/videohistory_catalog9539.html*
Richard Tousey's NRL office and laboratory facilities	… especially if any of his early V-2 era and Aerobee-era systems are still extant. Extensive oral histories have been conducted with Tousey and his staff members.
Vacuum test chambers	… developed and maintained by NRL dating from the 1950s and 1960s, especially one where Vanguard 1 (TV-3) was assembled and tested. See *http://siarchives.si.edu/research/videohistory_catalog9539.html*
Special Faraday Cage instrument assembly and testing room at NRL	Dates from the 1950s. See *http://siarchives.si.edu/research/videohistory_catalog9539.html*
Laboratories on the University of Wisconsin campus	… where the payload for OAO II were designed and constructed and tested.
IUE control room at the Goddard Space Flight Center	Building 21 (original control systems have been removed but room still exists?). See *http://siarchives.si.edu/research/videohistory_catalog9543.html*

Locales critical to the design and development of the first two generations of the Wide Field Planetary Camera (Caltech, JPL, Princeton).

Laboratories and facilities responsible for the construction of Riccardo Giacconi's original Aerobee X-ray payload that confirmed that non-solar discrete sources of X-ray energy existed (American Science and Engineering, Cambridge).

HST Spacecraft Control Facility, Goddard Space Flight Center.

High-bay test facilities at NASA centres, specifically those utilised to train astronauts for HST repair missions.

The Lunar Receiving Laboratory, Johnson Space Flight Center, Huntsville, Alabama. See *http://www.lpi.usra.edu/lunar/documents/lunarReceivingLabCr2004_208938.pdf*

Lockheed Sunnyvale vertical test chamber for HST

Ball Brother Research Corporation	The development and refinement of stabilised satellites, sounding rockets and balloon packages. Many of the first-, second- and third-generation scientific satellites were the product of this company.

Space Telescope Science Institute on the Johns Hopkins campus, Baltimore, MD

Pad facility known as 'launch complex 18A' at Cape Canaveral for failed attempt to launch Vanguard 1, December 6, 1957.

Pad facility and blockhouse at Cape Canaveral known as 'Launch Complex #26' for successful launch of Explorer 1, 31 January 1958. See *http://www.patrick.af.mil/news/story.asp?id=123083696*

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Space achievements as world heritage *by Mikhail Marov*

Since the middle of the 20th century, great breakthroughs in astronomy have occurred owing to the beginning of space exploration. This milestone in the development of human civilization has tremendously enriched and expedited astronomy as well as science in general. All wavelengths have effectively become available from gamma rays through to the far infrared and microwaves: this has allowed us to penetrate deep into space and to observe extraordinary natural phenomena occurring because of matter transformations accompanying the release of huge amounts of energy. Space vehicles have approached other planets and their satellites and even landed on their surfaces; as a result we have opened up new worlds beside us in the Solar System and discovered diverse processes of physics and chemistry responsible for their nature, formation and evolution. Planetary exploration has also advanced different branches of the earth sciences.

Modern astronomy not only attempts to understand what caused the observed large-scale structure of the universe and its overall composition involving dark matter and dark energy; it also touches upon numerous philosophical questions relating to the place and role of humans in space, in particular how we came to exist on this world and our fate in the future. Basic ideas at the frontiers of contemporary physics and cosmology deal with the possible existence of a multitude of multidimensional parallel universes (the ‘multiverse’), a sort of ‘spatio-temporal-foam’ that continually forms and decays in different regions and different times as the result of quantum oscillations in the vacuum and may experience collisions, the origin of our universe being the result of one such collision. A huge range of challenging ideas and new visions such as these have only come about as a result of space exploration and robust space technologies.

In sum, space astronomy has had a huge impact upon our knowledge of our own space neighbourhood as well as the universe as a whole. It is clear that the heritage of space astronomy—heritage relating to historically important achievements in space science and technology—forms a vital segment of global astronomical heritage in general.

If space heritage is to have universal value then it must have a true international significance in terms of humankind’s relationships with the sky. The historical context is human progress from naked-eye astronomy to ever more powerful and capable instruments and eventually to contemporary astronomical facilities and networks. In view of this, we first consider astronomical spacecraft, space-born instruments, and planetary space missions that produce close-up views of other worlds.

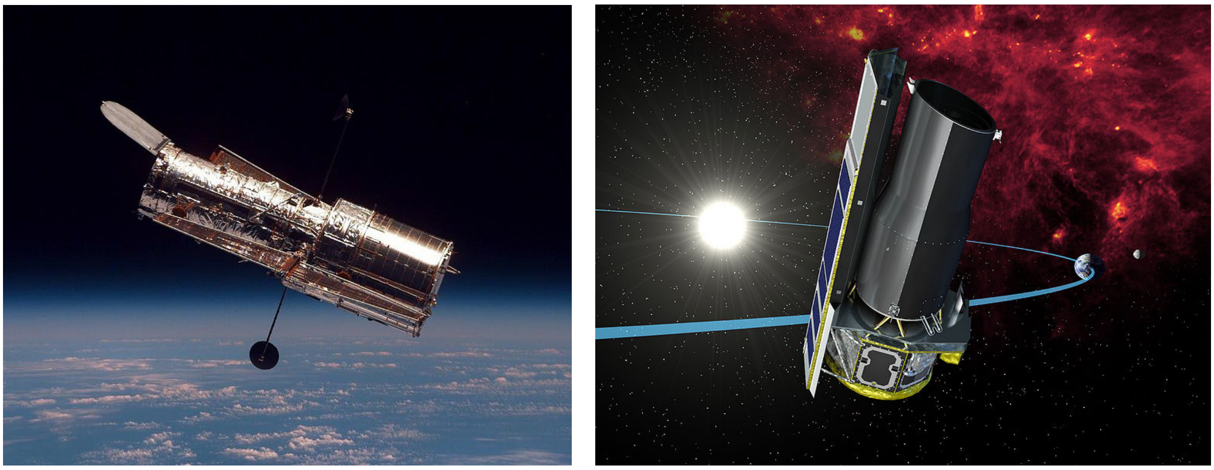

Fig. 15.0.1. Left: The Hubble Space Telescope. **Right:** The Spitzer infra-red space telescope. Images from NASA (Public domain)

Spacecraft and scientific instruments in space

Space scientific instruments. Several instruments on board space vehicles have proved of enormous significance to astronomy. They include the Hubble Space Telescope, which has observed deep space in great detail; the Chandra spacecraft (X-ray Observatory), which has contributed significantly in high-energy astrophysics; the Wilkinson Microwave Anisotropy Probe (WMAP); the Spitzer infrared space telescope; the ESA satellite Planck; and the Kepler space telescope, for the discovery of extra-solar Earth-like planets.

These spacecraft have been equipped with very capable telescopes and detectors to make observations in the different wavelengths, and have produced extremely valuable information about various space objects and the processes involved. For example, since 1990 the Hubble Space Telescope has given us hundreds of thousands of images of galaxies, nebulae, and stars at different stages of their evolution, and opened to our eyes the very depths of the cosmos. Even more importantly, these and other observations and the results derived from them have advanced astrophysics through the development of coherent theories concerning the structure of stars, galaxies, clusters of galaxies, and other objects. They have also allowed us to address some of the most challenging problems concerning the origin and evolution of the universe itself, thus advancing both cosmogony and cosmology. Basically, observations from space have opened a new era in astronomy and brought about very significant progress in the field.

Space vehicles for lunar and planetary exploration. Another important aspect of space heritage is spacecraft important in the exploration of our Solar System. Many planetary missions undertaken since the very early 1960s have made us better acquainted with our close neighbours in space; these missions can be regarded as the first steps towards humankind's expansion throughout the whole Solar System. The Moon was the cornerstone along this path, demonstrating the capabilities of both space science and space technology. The *Apollo* and *Luna* missions returned lunar soil samples—unique samples of extraterrestrial origin. These provided extremely important information about the Earth-Moon system and the very early stages of Solar System evolution, particularly during the first half-billion years of the Earth's history: such information has been erased on the Earth by active geological processes.

Space vehicles also given us an opportunity to view other planets at close range, together with their moons and rings, and also some small bodies—asteroids and comets. The information obtained has dramatically increased our knowledge about the diversity of the natural mechanisms operating in the various worlds and, through comparative analysis, has also significantly contributed to our understanding of our own planet. The planets Venus and

Mars are the two most important 'other worlds' in this regard, since they provide two very different extreme models of how Earth's evolution might have progressed.

There are many fine examples of space vehicles used for lunar and planetary exploration that deserve to be commemorated as a significant part of our space heritage even where there is no possibility that they could be retrieved and preserved on Earth and they remain typically 'moveable heritage'. These include *Luna 3*, the first to fly past the Moon and transmit photographs of its far side; *Luna 9*, the automatic spacecraft that performed the first soft landing on the Moon's surface; the *Eagle* module that performed the first manned landing on the Moon with astronauts Neil Armstrong and Edwin ('Buzz') Aldrin in the framework of the

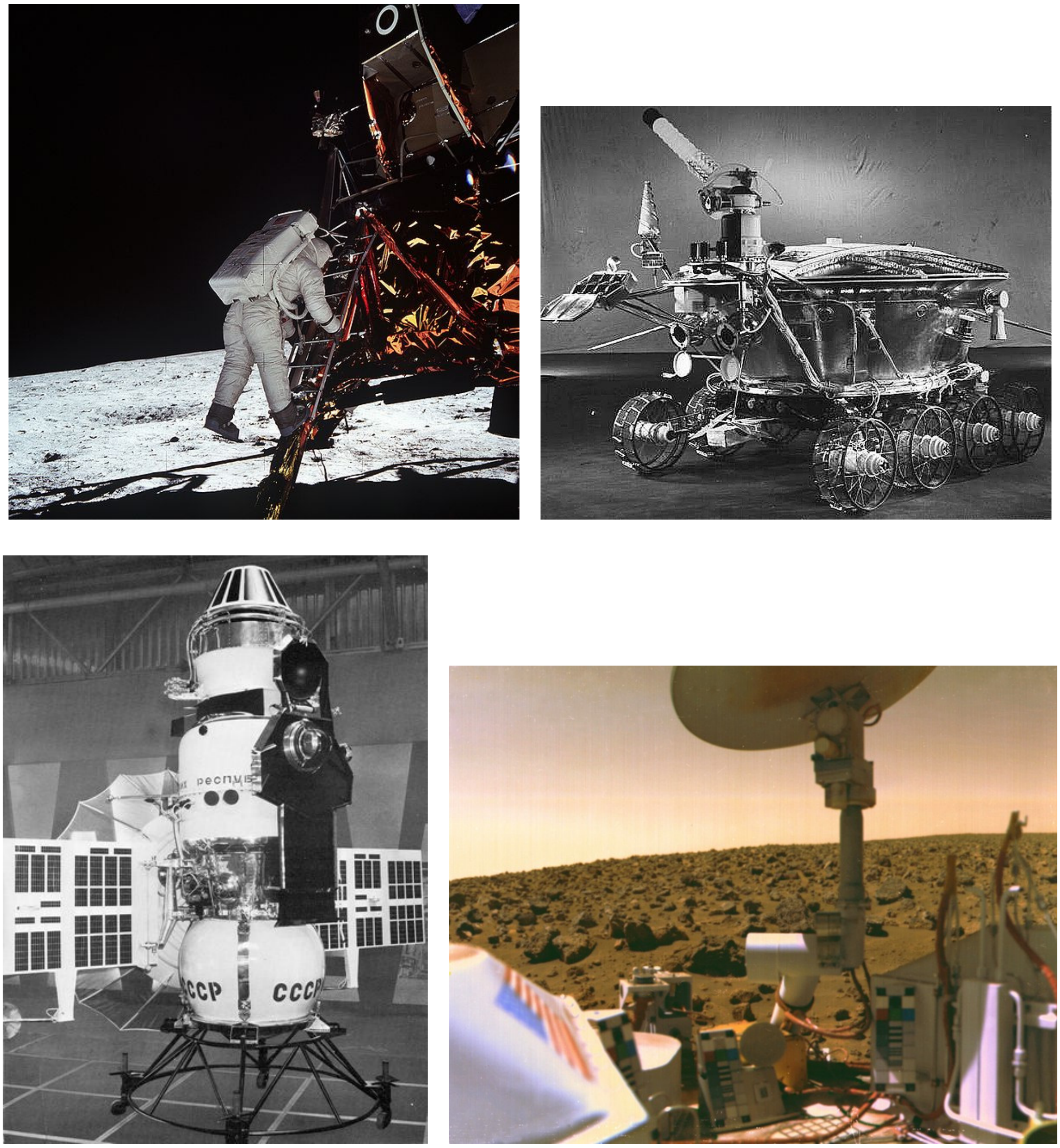

Fig. 15.0.2. Top left: Edwin Aldrin descending from *Eagle*, about to become the second man on the moon. Photograph by Neil Armstrong. **Top right:** Lunokhod 1, the first Moon rover. **Bottom left:** Venera 4, Venus descent module. **Bottom right:** 'Self-portrait' taken by Mars lander Viking 2. Photographs from NASA (Public domain)

Apollo programme; *Luna 16*, the first automatic probe to land on the Moon and return a soil sample to Earth, and *Lunokhod 1*, the first Moon rover; *Viking 1* and *Viking 2*, the first spacecraft to land on the surface of Mars and operate successfully; *Venera 4*, parachuted into Venus' atmosphere, the first space vehicle to make *in situ* measurements of the planet's temperature, pressure, and composition; *Voyagers 1 & 2*, which performed the first close-up study of the outer planets, their satellites and rings; *Vega* and *Giotto*, which performed 'fly-by's of Halley comet; *Galileo*, the first probe to enter Jupiter's atmosphere; and *Huygens*, which made the first landing on Saturn's moon Titan as part of the *Cassini-Huygens* mission. All these and others—the list could be substantially extended—are astronomical vehicles that have given us hugely valuable information about outer space in general and specifically about the other bodies in our Solar System.

Other aspects of space heritage

The heritage of space exploration extends beyond the space vehicles that have advanced astronomy and our knowledge about the space environment. It also includes the heritage relating to numerous key technological breakthroughs and elements of space infrastructure. This must undoubtedly include the first satellite *Sputnik*, Yuri Gagarin's first orbital flight capsule *Vostok*, Yuri Gagarin's and Neil Armstrong's space suits, many components of the historic *Apollo* programme, and the first orbital stations (*Salyut*, *Skylab*, and *MIR*), which paved the road to the International Space Station (ISS).

Special attention should be given to Cosmodromes and Deep Space Networks. These were important parts of the overall space infrastructure that ensured the successful launches of spacecraft and provided tracking and operation control, thus making possible all the historically important steps in space exploration. Obvious examples are Bayconour Space Centre, Cape Canaveral Space Center, and Kourou launch site. Launch pads are a complex ensemble of buildings, infrastructures, facilities, technical innovation and applied science, aimed at preparing the way for controlled space flights. Their heritage is complex in terms of attributes of value: they provide evidence of various activities in science, technology and civil engineering; they produce moveable and unmoveable legacies; and they give rise to tangible and intangible heritage. They should probably be understood as part of a 'presence-in-space system' at a given time, which would imply the inclusion of the remains of space vessels, satellites, and their scientific instruments.

A rather different, but undoubtedly important, aspect of the heritage of human achievements in space is that relating to the great pioneers in this area—people such as Konstantin Tsiolkovsky, Hermann Oberth, Robert Goddard, Yuri Kondratyuk, Serge Korolev, and Verner von Braun. Consider, for example, the case of Konstantin Tsiolkovsky (1857–1935), a Russian space-flight pioneer, scientist and general visionary. His works contain in embryo numerous techno-scientific attainments in space exploration and in the development of engineering facilities to help solve many complicated technological problems. His pioneering paper "Free Space" was written in 1883, where he put forward for the first time his ideas concerning conditions in outer space in the absence of gravity, the principles of reactive motion, and the possibility of controlling and stabilising a body in motion in space. Believing that the conquest of space was a goal not only attainable but attainable in the not-too-distant future, he made a detailed study of the life-support conditions necessary for manned flight, investigated changes in the physiological functions of the human body under weightless conditions, and suggested setting up centrifugal facilities to examine the effects of high acceleration on living organisms. Tsiolkovsky is widely regarded as the scientist who paved the way for space science and exploration. The intangible aspect of Tsiolkovsky's heritage is his impressive vision of the prospects of mankind for conquering space; the tangible aspects would include historical manuscripts with his space foundation and published works.

Concerning the first samples of lunar soil delivered to Earth by the *Apollo* and *Luna* missions, the main bulk of these samples is currently preserved in the Johnson Space Flight Center, Houston, USA, and in the Vernadsky Institute, Moscow, Russia. Minor pieces are distributed among various scientific laboratories and universities over the world. These samples represent the accomplishments of humankind in a very direct sense and form a very significant part of the heritage of space exploration. A similar remark would apply to any samples of extraterrestrial origin brought to Earth by future space missions.

Concluding remarks

In the last half-century, space astronomy and lunar and planetary missions have progressed our knowledge of the Solar System and of the Universe as a whole, broadening human horizons tremendously. There can be no doubt that the space-borne instruments, vehicles and earthbound infrastructure and facilities that have brought this about form a highly significant segment of our astronomical heritage. Of those that survive, the physical circumstance of where they finish up—back on the Earth, on another body in the Solar System, or permanently in space—seems irrelevant to their value in science or technology heritage terms. Meanwhile, the tangible immovable heritage (in the sense of the World Heritage Convention) relating to space exploration—sites, places, and 'monuments' on the Earth such as development sites, launch sites, and tracking sites—generally relates rather more indirectly to the actual science performed in space and more to the technological infrastructure supporting it.

The challenge is to find a consistent approach to these and the other aspects of the legacy of human activity of various types in space. The two different approaches presented in this chapter serve to illustrate the depth and complexity of this challenge and the possibility of different approaches and points of focus. Obviously, we have to think more deeply about what is undoubtedly a growing field of human legacy; this is important both for heritage professionals and for historians of astronomy, science and technology. It raises new questions, some of which can seem a little strange from a terrestrial 'reference-frame' (see the concluding chapter). We probably have to develop a systemic approach to the complexity of such heritage, taking account of the many different issues it raises and the diverse attributes of value. On the other hand, the experience gained by trying to apply the World Heritage convention to what could be a very distinctive type of cultural and natural property would certainly help to build cooperation in recognising and preserving heritage relating to human activity in space.

Chapter 16: ‘Windows to the Universe’:
Starlight, Dark Sky Areas, and Observatory Sites

Cipriano Marín, Richard Wainscoat and Eduardo Fayos-Solá

The sky, our common and universal heritage, is an integral part of the environment perceived by humanity[1]. Starting from this general idea, the Declaration in Defence of the Night Sky and the Right to Starlight, adopted in 2007, states that “an unpolluted night sky that allows the enjoyment and contemplation of the firmament should be considered an inalienable right of humankind equivalent to all other environmental, social, and cultural rights”[2].

Many different factors, but most notably the continued increase in light pollution, are turning this resource—virtually unchanged throughout the history of humankind—into an extremely scarce asset. An essential element of our civilisation and culture is rapidly becoming lost, and this loss is affecting most countries on Earth (see Fig. 16.0.1). Under these conditions, certain places whose sky is still dark, and whose scientific cultural or environmental values depend on starlight, should be recognized and preserved as points of reference to a common heritage in danger.

An eroding nightscape

The importance of preserving places with pristine dark skies not only has repercussions for astronomical observations. It is of vital importance in many different ways. The light of the stars and other heavenly bodies has always enriched the spectacle of terrestrial nature as well as the human habitat, creating reference landscapes traditionally perceived by people as an integral part of their natural and cultural heritage. Starry skies have been one of the most powerful driving forces related to landscape throughout the ages, but in recent times, all over the world, they have been losing their power. The nocturnal ‘skyscape’ or ‘starscape’, in spite of its diversity and magnificence, remains the most hidden aspect of the current concept of cultural and natural landscape.

Nightscapes can be very diverse. They include starry landscapes related to rural areas, urban oases, and ‘geoparks’, as well as natural areas or sites associated with tangible and intangible astronomical heritage. All cultures throughout history have identified the most privileged sites for the observation of the firmament. Each of these places has its own vista of starlight handed down through the generations. These sites and settings should be preserved to prevent them losing their meaning.

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[1] Explanatory Note concerning the Proclamation of 2009 as the International Year of Astronomy (33rd session of the UNESCO General Conference).

[2] The Declaration was adopted on the occasion of the Starlight Conference held in La Palma in 2007. It was promoted by (among others) UNESCO, the IAU, the UN–World Tourism Organisation (UNWTO) and the Instituto de Astrofísica de Canarias (IAC), with the support of several International Programmes and Conventions, such as the World Heritage Convention (WHC), the Convention on Biological Diversity (CBD), the Ramsar Convention and the Convention on Migratory Species (CMS), the MaB Programme, and the European Landscape Convention.

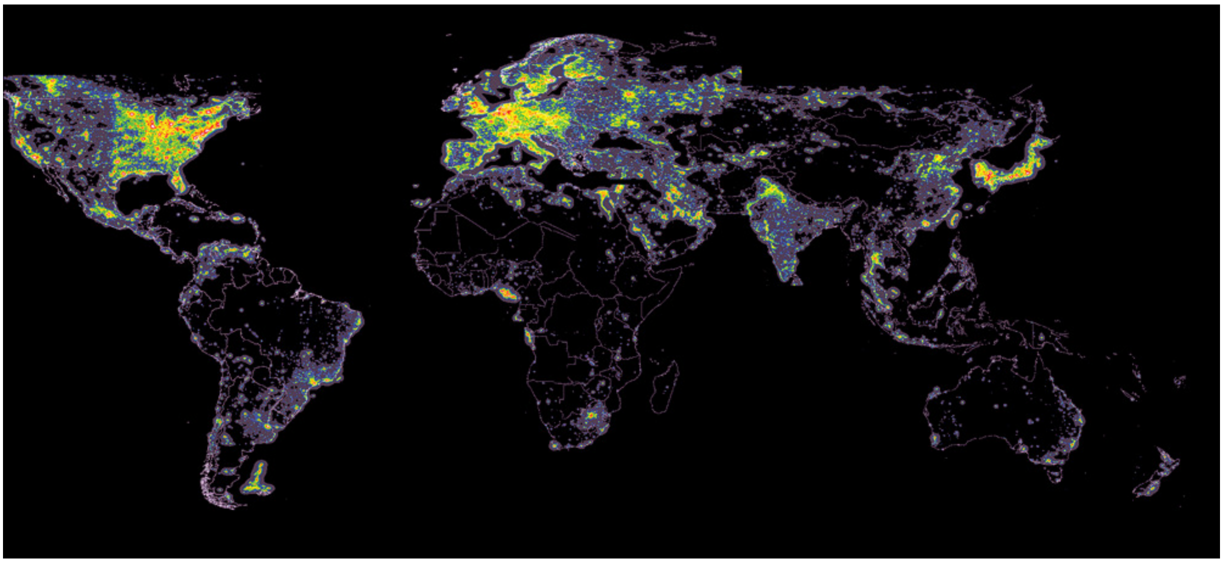

Fig. 16.0.1. The World Atlas of Artificial Night Sky Brightness, by P. Cinzano, F. Falchi (University of Padova) and C. D. Elvidge (NOAA National Geophysical Data Center, Boulder). © Royal Astronomical Society. Reproduced from the *Monthly Notices of the Royal Astronomical Society* [328 (2001), 689–707] by permission of Blackwell Science.

Examining starry night landscapes soon leads to the recognition that it is imperative to protect dark skies in order to preserve essential parts of our common heritage. In fact, there are several reasons to protect the natural night sky:

The preservation of starscapes related to geology. Some geological landscapes are at their most impressive in combination with the nocturnal sky. Sites like Cerro Ventarrones in the Atacama (Chile), the natural bridges at Arches National Park and the Alabama Hills (USA), Mount Norikura (Japan), Arkaroola Wilderness Sanctuary (Australia) and Pic du Midi (France), provide just some examples of how geological landscapes blend with starlight, creating emblematic natural spaces at night.

Commemorative integrity, or the authenticity of historic sites, monuments and cultural-ritual skyscapes. The quality of the night sky can often affect the integrity of the tangible cultural heritage of astronomy. Starry-sky settings are inherent to the perception of cultural landscapes relating to the view of the firmament, and the degradation of this element at sites such as Rapa Nui (Chile) and Montaña de Tindaya (Spain) would result in the decontextualisation of the protected heritage itself. A similar consideration applies to prehistoric monument ensembles associated with the vision of the firmament, such as Zorats Karer (Armenia) and Stonehenge (UK; see Case Study 2.1). The loss of integrity that has already taken place is even more evident at historical observatories such as Cheomseongdae (Korea; see Case Study 5.4) and Jantar Mantar (India; see Case Study 6.1), as well as at more recent ones, such as Armagh (UK) and Mount Wilson (USA; see Case Study 12.4).

The preservation of cultural traditions, both modern indigenous and classical, that relate to the night sky. The relentless increase in light pollution causes the disappearance of starry skies, not only physically but also culturally. This can result in the irrevocable loss of intangible heritage—legends, folk tales, children's stories, old pilgrimage routes, and traditional festivals relating to the night sky—across the globe. This situation suggests that this dimension could be considered for inter-convention recognition, in particular with the Convention for the Safeguarding of the Intangible Cultural Heritage.

Ecological integrity of natural environments. The experience accumulated in protected dark-sky areas such as Torrance Barrens (Canada), Galloway Forest Park (UK) and Hortobágy National Park (Hungary), in emblematic places for nature conservation such as Doñana (Spain) and the East Alpine Starlight Reserve (Austria), and exceptional landscape areas like the MacKenzie Basin (New Zealand), forces us to consider very seriously the importance of night-sky quality for conserving nature and the remarkable values that certain places have with regard to the night. Darkness and natural lighting at night are indispensable for the healthy functioning of a range of species and ecosystems. We tend to forget that life goes on for 24 hours a day and that ecosystems have adapted themselves to the natural rhythms of the moon and stars in the course of millions of years of evolution. As over half of the creatures living on this planet are nocturnal, any degradation in the quality of the sky, by day or by night, is having a profound effect on their behaviour and on the equilibrium of the biosphere.

For reasons related to the conservation of nature, and in recognition of the other benefits of dark skies, the Dark Skies Advisory Group of the IUCN's Cities and Protected Areas Task Force supports the inclusion of night sky protection and appreciation in world heritage considerations, either as one of the outstanding universal values of a heritage site, or as part of a new class of protected area.[3,4] In this context, and in view of the different approaches to this issue, it is worth recalling the appeal made by the Starlight Declaration (2007):

> "The Conference requests the five Conventions in the Biodiversity Liaison Group to examine the outcomes of its deliberations and, if appropriate, take to their governing bodies a combined view of the role of the conventions in helping increase protection for the night sky, understanding that this action will have positive effects on landscape conservation and the wise use of biodiversity".

Appreciation of the integrity, character and beauty of urban and rural landscapes. Nowadays it is unthinkable that minds such as Vincent van Gogh would create works of art such as 'Starry Night'. The loss of the dark sky is not only affecting cities, because the adverse effects of light pollution can extend for hundreds of kilometres. The European Landscape Convention, as well as initiatives such as the Campaign to Protect Rural England (CPRE)[5], have now started to address this issue.

When speaking of the possibility of preserving pristine dark skies, we are not only referring to locations far away from cities and bright areas, remarkable natural landscapes at night, and unique settings related to astronomical activity in human culture. There are also areas near cities, towns and villages whose value in relation to natural or cultural heritage cannot be considered exceptional, and whose sharpness parameters do not meet the required standards for astronomical observation, but which do, nonetheless, offer excellent opportunities for education in astronomy and the possibility of enjoying (relatively) dark skies. In areas such as Großmugl Starlight Oasis (Austria) (see Case Study 16.2), Monfrague National Park (Spain) and the various public observatories in the Coquimbo Region of Chile (see Case Study 16.3), the dark night sky provides a critical element in the natural outdoor experience in relatively accessible places. Here, people can still have easy access to a type of heritage at risk: starlight.

Certain sites combine several different qualities and exceptional values in the same place: they are multifunctional windows to the universe. This is the case at Lake Tekapo–Aoraki–Mount Cook (see Case Study 16.1). This region has outstanding natural landscapes of

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[3] Welch, D., Trzyna, T. and Lopoukhine, N.. Prologue by the IUCN's Dark Skies Advisory Group (DSAG) to the Report of the 'Starlight Reserves and World Heritage' Expert Meeting, March 2009.

[4] Note [MC & CR]: This support for the inclusion of night sky protection and appreciation in world heritage considerations is not necessarily shared by ICOMOS.

[5] With the support of British Astronomical Association's Campaign for Dark Skies (CfDS).

exceptional scenic beauty, enhanced by a starry sky setting. Both the quality and the clarity of the night sky are very high, which has led to the establishment of an observatory and to significant stargazing tourism. It also is a place of significance for the Maori, who visited the area for generations for food gathering and to observe the regular 'night visitors'—the constellations. Another example is Onk Jamel (camel neck) in southern Tunisia, a landscape of great dunes under the stars historically crossed by caravans, which includes exceptional troglodyte settlements. Places such as this, where multiple natural and cultural values converge, deserve special attention when considering the preservation of the dark night sky.

The World Heritage Convention refers to science in Articles 1 and 2. More specifically, in Article 2 it establishes that the following shall be considered as natural heritage: "natural sites or precisely delineated natural areas of outstanding universal value from the point of view of science, conservation or natural beauty". Nevertheless, as in other Conventions, the most emblematic dark sky areas and their associated scientific, cultural or natural heritage, are not taken into account as an indivisible whole, regardless of how exceptional they are. In terms of heritage identification to date, the day is considered immutable, while night is ephemeral.

Where the Earth meets the universe

The scientific aspect of a starry night is an essential part of the legacy of the sky. The ability of the planet's astronomical sites and observatories to detect and interpret data from outside the world we live in should be considered as a resource of extraordinary value for the progress of knowledge, as it has been throughout history. Dark skies are still the windows to our knowledge of the greater universe.

Historically, ground-based observatories have provided the vast majority of our knowledge of outer space. However, present-day technical and scientific requirements restrict suitable areas to very specific and limited locations offering good conditions for the development of astronomy, and of optical and infrared astronomy in particular. There are only a few places on the planet where we find this unique combination of environmental and natural circumstances: well-conserved spaces with very little alteration to natural starlight.

The quality of astronomical observation is influenced in many ways by the Earth's atmosphere. Although these effects can be eliminated by launching telescopes into space, space astronomy is extremely expensive, very large telescopes cannot be launched into space, and servicing and maintaining space telescopes is difficult or impossible.

The identification of windows on the Earth for the observation of the universe is a task where several limiting factors come into play (Table 16.0.1). Most of them affect the sharpness of images, something that is of paramount importance in astronomical observation. Blurry images cause confusion, and nearby stars cannot be resolved from each other. Faint stars take much longer to detect if the images are blurry.[6]

At mid-latitudes, the wind direction in the upper atmosphere is from west to east. This arises from Earth's rotation and the Coriolis force. As a result, the air arriving at the west coast of a continent or isolated island flows in a non-turbulent manner. It is in such places that we obtain the sites that have the best image quality, since they lack turbulence caused by phenomena such as the mixing of cooler and warmer air that causes blurring of stellar images.

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[6] With a good detector, the signal-to-noise ratio is: Signal-to-noise = $N^* / \mathrm{sqrt}\,(N^* + npix(Ns))$, where N^* is the number of photons from the star, *npix* is the number of pixels containing the star and sky, and *Ns* is the number of photons per pixel from the sky. Sharp images reduce *npix*, and therefore allow observations to be acquired more quickly. An elevated sky background from artificial light makes astronomical observations more difficult and slower.

Table 16.0.1. **ATMOSPHERIC FACTORS AFFECTING ASTRONOMICAL OBSERVATION**
Turbulence in the atmosphere air blurs images of stars and other objects — turbulence causes mixing of cooler and warmer air, and the turbulent air acts like a lens, blurring images of astronomical objects.
Weather (e.g., clouds, rain) prevents observations some of the time.
Water vapour and carbon dioxide absorb infrared light at some wavelengths, making the atmosphere opaque.
Air molecules and aerosols scatter artificial light, making the sky bright.
Molecules and atoms high in the atmosphere absorb sunlight during the day and re-emit it at night, creating a dim glow from the atmosphere at night.

Observatories must be located at sites with good weather. Tropical rain forests and temperate rain forests are clearly not good locations for observatories. In general, trees are not consistent with good observatory sites. The equatorial region has (meteorological) convergence and hence a lot of rainfall. Latitudes close to 60 degrees are also regions of convergence, and are poor locations for observatories. However, latitudes close to 30 degrees (north or south) are regions of subsidence (dry air) and are good locations for observatories.

Wind is also an important consideration. High altitudes have strong winds while mid altitudes have gentler winds. Low altitudes have more air pollution, and there is a low moist marine layer in coastal locations. Lower altitudes also have more atmospheric turbulence, because there is more air to look through. A temperature inversion often traps the moisture and air pollution at lower altitudes.

The dominant west-to-east airflow means that mountains on the west coast of continents, or isolated islands with moderately high mountains, are ideal locations for observatories. The mountains allow the observatory to be located above the turbulent lower atmosphere. In addition, clouds at lower altitudes can blanket artificial light sources, reducing light pollution.

Observatory sites must also be accessible. They cannot be too high, since higher altitudes are very difficult to work at. Antarctica is an excellent site for astronomy, but is not easily accessible, and the northern sky cannot be seen from there. Observatory sites should also be geo logically stable. High-seismicity zones, active volcanoes and glaciers must therefore be avoided.

Collisions of Pacific and American plates have created mountain ranges along the west coast of North and South America. At mid-latitudes, these mountains are in California, Baja California, and northern Chile. The mountains in California are located too close to major light sources, and are no longer good observatory sites. Instead, several areas in Northern Chile and Baja California (Mexico) have excellent qualities and feature appropriate locations for observatories. Other continents, such as Australia, do not have suitable mountains on the west coast.

Volcanic hotspots have created the Hawaiian and Canary Islands. These isolated islands each have excellent observatory sites, most notably Mauna Kea Observatory in Hawaii, and Teide and Roque de los Muchachos Observatory in the Canary Islands. The South Island of New Zealand has suitable high mountains along its west coast, but is located further south in the ‘Roaring Forties’ zone, so that weather conditions along this coast are not optimal, although on the east side of the mountains there is a protected high-country plateau, the Mackenzie Basin, which is moderately good for optical astronomy. Observatory sites in South Africa (SAAO Site), Arizona and Texas are also good, but not as good as the Chilean, Hawaiian and Canary Island sites, because they are located further from the coast.

The above-mentioned sites are characterised by extraordinarily good sky-quality parameters that determine exceptional windows to the Universe. These are:

- Useful Time (of clear sky).
- Sky background (darkness)
- Atmospheric Extinction (transparency). [The term 'extinction' means the loss of light in the atmosphere from a directly transmitted beam. Two different mechanisms contribute to extinction: absorption and scattering.]
- Seeing (for sharp images). [Astronomical 'seeing' refers to the blurring and twinkling of astronomical objects such as stars caused by turbulence in the Earth's atmosphere.]

Having identified the best locations for astronomical observation throughout the planet, it is critically important to try to conserve and protect them. It is essential to include sites in each hemisphere, since northern sites cannot see parts of the southern sky and southern sites cannot see parts of the northern sky. In addition, there are natural and man-made threats to the observatory sites that make it essential to protect several of them in each hemisphere. These threats include volcanic eruptions, major earthquakes, mining and atmospheric pollution as well as light pollution. For these reasons it is critical not to concentrate exclusively on the most outstanding observatories in isolation, but to develop a collective vision of an ensemble of windows open to the universe, needing to be kept open and protected appropriately.

These exceptional sites, including their natural components, can be considered as 'landscapes of science and knowledge'. It is no surprise that the world's largest contemporary observatories are located in these places: Keck I and II, Subaru, and Gemini North in Hawaii; Gran Telescopio Canarias in La Palma; Very Large Telescope 1,2,3 and 4, Magellan 1 and 2 and Gemini South in Chile; the Giant Binocular Telescope and Multiple Mirror Telescope in Arizona; the South African Large Telescope in South Africa; and the Hobby Eberly Telescope in Texas.

These are true scientific monuments, and we recall that Article 1 of the Convention defines cultural heritage as monuments and groups of buildings that "are of outstanding universal value from the […] scientific point of view". At the same time the locations of these observatories are all, to a greater or lesser extent, important historically in the context of indigenous cultures and their astronomy. Case Studies 16.3–16.5 (northern Chile, Hawaii, and the Canary Islands) present prominent examples in more detail.

Fig. 16.0.2. A selection of remarkable observing sites. Based on "The process of selection of exceptional observing sites", by Richard Wainscoat; elaboration on CIA's *Physical Map of the World*, 2004.

The management of dark sky sites

The effective preservation of dark areas requires the establishment of appropriate criteria for their management, especially with regard to the mitigation or elimination of light pollution. It is important to identify and establish ‘umbral’ zones, together with ‘penumbral’ zones around them, depending on the level of impact on the type(s) of value to be preserved in the dark sky area concerned. Different approaches might be needed, in other words, depending upon whether the aim is to preserve clear skies for astronomical observations, the scenic context of cultural sites related to astronomy, dark skies for wildlife conservation, natural areas or nightscapes, or any combination of these. According to the function of each site, the requirement level will be higher or lower. The zoning systems proposed to date are similar, in terms of night-sky quality, to those established in areas such as biosphere reserves or other protected entities.

The Starlight Reserve concept, developed in cooperation with the ‘Astronomy and World Heritage’ Thematic Initiative, establishes a zoning scheme of this type, consisting of a core zone, a buffer zone and an external zone. A set of requirements and general recommendations on total exclusion or the intelligent use of artificial lighting has been specified for each area, and these have been compiled into a Guide.[7] This guide has been proposed and developed as a general reference document for World Heritage Sites and in particular for those related to astronomy. Similar considerations are found in the application criteria developed for International Dark Sky Parks and Reserves by the International Dark Sky Association (IDA) (http://www.darksky.org/).

The dark sky should also be considered as an additional criterion for existing World Heritage Sites. This does not just include those having astronomy-related values, but any cultural landscapes and natural areas sensitive to alterations to the natural lighting. Furthermore, reducing light pollution at cultural sites connected with astronomy can be considered, at the very least, an exercise in coordination that helps to safeguard the integrity of the site.

With regard to legal issues, it should be noted that some of the most important areas for astronomical observation were also important in pioneering the development of regulations and laws to ensure the adequate protection of sky quality. The first attempts to regulate light pollution were made in the USA (for example, at Arizona), but the first national law that explicitly protects the sky for astronomical observation is the 1988 ‘Ley del Cielo’ (‘Sky Law’) that protects the Canary Islands’ observatories. Chile subsequently developed its ‘Norma Lumínica’ and Hawaii an ordinance for the Mauna Kea Observatory. Lake Tekapo is also governed by an ordinance: this dates from 1981 and is a pioneer of its type. These issues are dealt more in depth within the case studies.

These pioneering initiatives have provided an example that has been copied progressively in the last decade, spreading out to other areas, and from protected sites to cities. More than 200 initiatives have commenced in the last decade, culminating in advanced laws and regulations on intelligent lighting, such as the most recent law against light pollution passed in the Lombardy Region (Italy). Some of these legal instruments have been designed to face simultaneously the dual challenges of protecting the quality of the night sky and supporting energy-saving intelligent lighting systems—both fighting against climate change and recovering starry skies.

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[7] This Guide was finalised at the International Workshop and Expert Meeting on ‘Starlight Reserves and World Heritage: scientific, cultural and environmental values’, held in Fuerteventura in March 2009. The Starlight Reserve Guidelines were prepared with the participation of over 100 international experts and developed in cooperation with the World Heritage Centre and organizations such as the International Astronomical Union (IAU), the IAC (Instituto de Astrofísica de Canarias), UN–World Tourism Organization, the International Commission on Illumination (CIE) and the MaB Programme, with inputs from IDA (International Dark Sky Association) representatives.

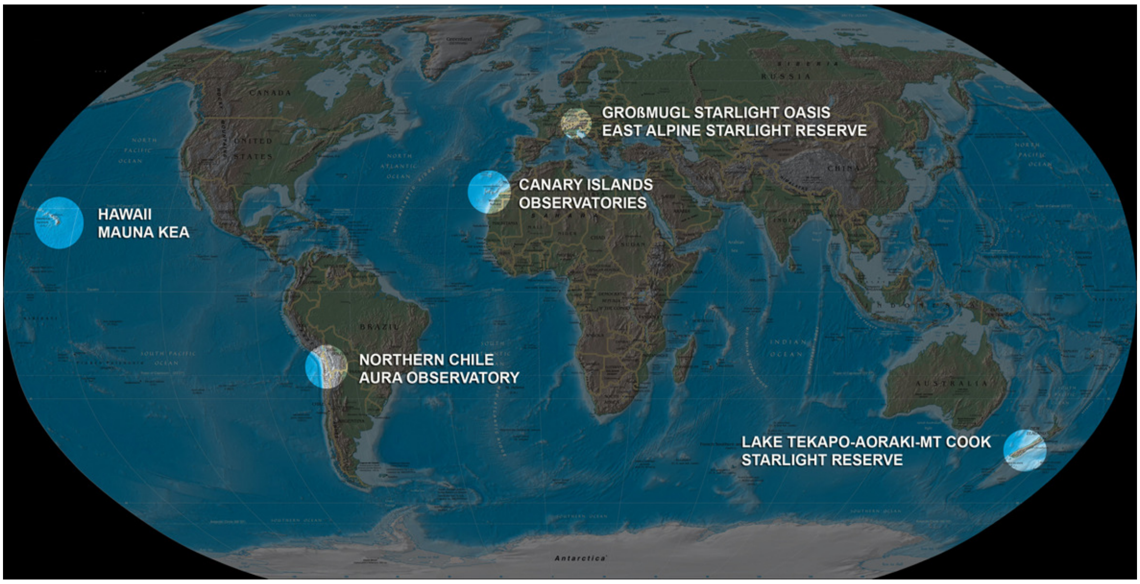

Fig. 16.0.3. The case studies. Elaboration on CIA's *Physical Map of the World*, 2004.

The fragile light of stars can become an engine for sustainable development in local communities. 'Star tourism' opens up new possibilities for responsible tourist destinations, offering such diverse activities as watching starry skies, aurorae and eclipses; visits to astronomical observatories; sailing holidays featuring navigation by the stars; following pilgrimage routes; discovering the nature of the night; or experiencing a desert under the stars. All of these have the potential to become viable, sustainable sources of income and employment, and are already beginning to do so in an increasing number of areas around the world.

Starlight tourism also makes it possible for the first time to bring science and tourism together. Star destinations can be defined as visitable places characterised by their excellent potential for the contemplation of starry skies, and this encourages the development of tourist-educational activities based on this resource. Star tourism not only allows science to be recognised as a tourist product but also, at the same time, develops new working methods in tourism, through science-based standards and procedures. This has been already done in cooperation with UN-WTO for the development of the Starlight certification. This innovation also shows that an appropriate blend of science and tourism can contribute to the global acceptance of the 'green economy' and the 'global sustainable village'.

Starlight destinations are diverse, including observatory sites, landscapes relating to the cultural heritage of astronomy, and natural dark-sky areas of outstanding beauty. The Alpine Starlight Reserve case shows us how night skies are already well embedded in National Park programmes including night hiking and the observation of nocturnal species. Many such programmes rely on the natural night-time environment, integrating astronomical observation and additional night resources. The development of this type of tourism is also important in reducing tension between modern astronomy and indigenous concerns: astronomy becomes a driving force of development in local communities. In the case of Italy's Amalfi Coast, the first customers and recipients in this new era of tourism are the local communities, who avoid the creation of segregated resorts and instead share the enjoyment of a common heritage.

The heritage of science continues to be insufficiently recognized, something that was stressed as recently as 2008 at a UNESCO International Expert Meeting on Science and Technology held in London. A part of the necessary recognition, at least in the astronomical field, may come from a new concept of tourism. In addition, the starry sky can highlight the strong link between tangible and intangible heritage.

Case Study 16.1: Lake Tekapo – Aoraki – Mount Cook Starlight Reserve, New Zealand

Margaret Austin and John Hearnshaw

Presentation and analysis of the site

Geographical position: Central South Island of New Zealand in an area bounded by the main range of the Southern Alps in the west and the Two Thumb Range in the east, including a large part of the Mackenzie Basin and also Mount Cook National Park in the province of Canterbury. Villages include Tekapo, Mount Cook and Twizel.

Location: Latitude 44º 00.5´ S, longitude 170º 28.7´ E (Tekapo Village). Elevation from 710m above mean sea level (Lake Tekapo) to 3750m above mean sea level (Mount Cook).

General description: The core area is Mount John University Observatory (elevation 1032m) on the south-western shore of Lake Tekapo. Tekapo Village (population about 400) is 3 km from the summit of Mount John in a direct line. Twizel and Mount Cook Village are 40 km and 50 km from the summit respectively, neither being visible from Mount John.

*Inventory of the remains***:** The Mount John University Observatory houses four research telescopes of apertures 1.8, 1.0, 0.6 and 0.6m respectively.

History of the site: The Mount John site was surveyed in the early 1960s using NSF funds from the University of Pennsylvania. The observatory was founded in 1965 as a joint astronomical research station of the Universities of Canterbury and Pennsylvania. The partnership continued for a decade.

Cultural and symbolic dimension: The Mount John site is the principal astronomical observatory in New Zealand and the world’s southernmost observatory (other than instruments in the Antarctic). It is an excellent site for observing the Magellanic Clouds and the centre of the Galaxy.

The Tekapo and Aoraki/Mount Cook regions have outstanding landscapes of exceptional scenic beauty, including mountains, glaciers, lakes and rivers. The flora and fauna are also exceptional, a number being protected or endangered.

Light pollution is very low and atmospheric transparency is excellent. For a thousand years Maori visited the area to gather food and to observe the regular ‘night visitors’ in the sky.

Documentation and archives: Information on Mount John can be obtained from the website http://www.phys.canterbury.ac.nz/research/mt_john/index.shtml.

Present site management

Present use: The main astronomical research activities undertaken at the Mt John observatory are high-resolution spectroscopy and studies of variable stars, microlensing and near-Earth asteroids. The site is also used for geophysical and atmospheric research. A 45cm telescope on Mt John and a 40cm telescope at Cowan’s Hill near Tekapo are used for public outreach.

Fig. 16.1.1. Top: Mount John University Observatory from the air. **Bottom:** The 'AstroCafe' and its environment. Photographs © Fraser Gunn, courtesy of Mt John Earth and Sky Telescope, New Zealand

Tourist access to Mount John and other dark sky sites in the region is excellent and encouraged, both for recreation and 'astro-tourism'. The area attracts some 30,000 day-time tourists and 10,000 night-time skywatching tourists annually.

Protection: Light pollution is controlled through a lighting ordinance covering a large region of up to 50 km around Mount John (Section 11 of the Mackenzie District Plan—see link below). This lighting ordinance includes the village but not the Aoraki/Mount Cook National Park, where the New Zealand National Parks Act 1980 (see link below) provides the only existing protection. An extension of the zone protected by the lighting ordinance is currently being mooted, which would include the National Park.

State of conservation: The scientific buildings on Mount John are maintained by the University of Canterbury to the highest standards commensurate with those of a world-class scientific establishment. Three university staff members are permanently resident on site or in the nearby Tekapo Village. Further maintenance personnel make regular visits to Mount John to ensure building maintenance and health and safety issues are addressed.

As major tourist attractions since 2005, the 'AstroCafe' and 45cm telescope on Mount John are required to be maintained to the high standards suitable for an important tourist destination.

Context and environment: The environment in the Mackenzie Basin is mainly highland tussock (crown lease land), the remainder being used for sheep runs or recreation. Aoraki/Mount Cook National Park adjoins the basin and comprises steep mountain valleys, high peaks, glaciers and some native forests. Three large lakes formed in the last ice age dominate the region: Tekapo, Pukaki and Ohau.

The Mount John site itself is one of the driest and sunniest locations in New Zealand, with over 2200 hours of sunshine and only 575mm of rainfall annually.

Fig. 16.1.2. The MOA telescope at Mount John and the Milky Way. Photograph © Fraser Gunn, courtesy of Mount John Earth and Sky Telescope, New Zealand

Main threats or potential threats to the site: The enforcement of the lighting ordinance needs to be maintained with vigilance. Over one million tourists annually pass through Tekapo en route to other destinations, and many stay overnight. As tourism develops, the careful protection of the environment in the village is essential. Fortunately, the Mackenzie District Council is committed to sustainable development that protects the environment, including the night sky.

The Mount John site is a mixed site for scientific research, educational tourism and recreation. So far this has been a successful venture, but it needs to be carefully controlled and monitored.

Management: The environment in the Mackenzie Basin is mainly crown lease land, the remainder being privately owned.

The Mackenzie District Council is the branch of local government with jurisdiction over the Mackenzie Basin and Aoraki/Mount Cook. The Council's District Plan is part of the Resource Management Act 1991 and includes a lighting ordinance, first enacted in 1981—see http://www.mackenzie.govt.nz/Site/Internal/Environmental/Districtplan.aspx.

The Aoraki/Mount Cook National Park (http://www.doc.govt.nz/parks-and-recreation/national-parks/aoraki-mount-cook/) is controlled and managed by the New Zealand Department of Conservation under the authority of the National Parks Act 1980 (http://www.legislation.govt.nz/act/public/1980/0066/latest/DLM36963.html).

The University of Canterbury leases the 3 ha. summit of Mount John from the crown (New Zealand government). Earth and Sky Ltd (http://www.newzealandsky.com/) have an agreement with the University of Canterbury to run educational astro-tourism at Mount John. This activity is a required condition of the Mount John lease.

Case Study 16.2: Eastern Alpine Starlight Reserve and Großmugl Starlight Oasis, Austria

Günther Wuchterl

Presentation and analysis of the site

Geographical position: East Alpine Starlight Reserve: numerous communities, provinces of Lower Austria, Upper Austria, Styria and Carinthia, Austria. Großmugl Starlight Oasis: community of Großmugl, province of Lower Austria, Austria.

Location: East Alpine Starlight Reserve: Latitude 46° 52´ to 47° 58´ N, longitude 13° 35´ to 14° 55´ E. Elevation generally between c. 1000m and 1500m above mean sea level. Großmugl Starlight Oasis (core zone): Latitude 48° 29´ 20˝ N, longitude 16° 13´ 20˝ E. Elevation 250m above mean sea level.

General description: Within the Eastern Alps WSW of Vienna is an elliptical area, about 200 × 100km in size, where the high surrounding mountains provide sufficient shielding from light pollution that the dark night skies are of near perfect natural quality. A separate, much smaller area to the north of Vienna provides a dark-sky 'oasis' that is easily accessible of millions of city dwellers.

Fig. 16.2.1. The constellation Orion is almost overwhelmed by the light from the countless stars in the pristine skies above the Gesäuse National Park in the East Alpine Starlight Reserve. Photograph © M. Reithofer.

Inventory of the remains: The East Alpine Starlight Reserve is an area of about 20,000 km^2, located about 150km to the west of Vienna where the Alps reach a height of 3000m. At the heart of this area, the dark night sky is of an exceptional quality. This is because low lighting in the surrounding communities together with the mountain topography provide an 80km-wide shield against central European light-pollution and city-light ‘domes’. The high elevation also reduces light scattering and extinction of starlight.

The Großmugl Starlight Oasis is a small area of 1.3 km^2 within the lower hills at the very eastern end of the Alps, about 30km north of Vienna. While the skies here are not pristine they are dark enough to provide a clear view of the Milky Way and thousands of individual stars (with a dependable visual limiting magnitude of 6). This is because the hills cover the sky-glow from nearby Vienna. Within the Oasis, a viewing spot near the largest bronze-age tumulus in central Europe offers a 360° unobstructed horizon, 250m above sea level. Taken together with the nature reserve *Leiser Berge*, the Starlight Oasis covers 300 km^2.

Cultural and symbolic dimension: It is extraordinary that an area with a near-natural dark night sky should exist within the heart of Europe, a continent that is so brightly lit. Furthermore, the proximity of the East Alpine Starlight Reserve to population centres, including the cities of Vienna, Salzburg, Linz and Graz, as well as to a major north-south route across the continent, provides millions of people with easy access to an area where they can view a near pristine dark night sky. This is an almost unique natural resource.

The Großmugl Starlight Oasis provides a smaller but still exceptional dark-sky resource that is even closer to the City of Vienna—it is only 33km from St Stephen’s Cathedral in the city centre—and hence within easy reach of 70% of the Austrian population.

Fig. 16.2.2. The view north-eastwards at midnight towards the south-western end of the Gesäuse National Park in the East Alpine Starlight Reserve. The setting moon illuminates the Admonter Kalbling, 2196m, in the background. Photograph © Thomas Posch.

Present site management

Present use: The night skies in the East Alpine Starlight Reserve area are already well embedded in National Park programs including night hiking and observation of nocturnal species, many of them endemic and reliant oupn the natural nighttime environment. The area also includes the world's largest monastic library, at Admont, and the Eisenerz Iron Road world heritage initiative.

The Großmugl Starlight Oasis is used by local schools and universities in their courses, as well as for recreational and amateur astronomy. The Starlight Oasis provides optimal conditions for viewing the dark night sky, with moderate temperatures and sufficient oxygen (being at a low enough elevation) that visual perception is not impaired.

Protection: The bronze-age tumulus in Großmugl is protected by federal law as a historic monument. It is surrounded by a circular no-building zone, 0.65km in radius, regulated by the community. A 10km buffer zone has been proposed, which would include an existing nature protection area, the *Leiser Berge*.

The Starlight Oasis is fully supported by the community of 300 households in Großmugl itself, where there are fewer than 100 streetlights. By-laws to protect the night sky have been passed by the city council, making reference to the Starlight Reserve.

Context and environment: The naked-eye sky quality in the East Alpine Starlight Reserve area is indistinguishable from the best sites in the world. Measurements at elevations of 800m to 1800m give a sky brightness of 21.6 (for the Milky Way) to 21.8 mag/arcsec^2 (for the Galactic pole). Light-levels of near 1mlx are indistinguishable from the world's best astronomical sites. With the mountains shielding most of the natural airglow, valley light levels drop below 100 µlx, producing pure starlight. Atmospheric inversion frequently provides viewing conditions above cloud-covered valleys that are similar to these obtained in western-continental deserts and trade-wind volcanic islands.

Management: The East Alpine Starlight Reserve area contains the *Kalkalpen* and *Gesäuse* National Parks (both IUCN category II), the *Dürrenstein* wilderness area (IUCN Ib) and more than 10 nature reserves. The Conservation areas and National Parks are managed by the respective administrative bodies.

The bronze-age tumulus area is protected by the federal agency for historic monuments (Bundesdenkmalamt) and managed by the town and community of Großmugl.

Case Study 16.3: AURA Observatory, Chile

Malcolm Smith

Presentation and analysis of the site

Geographical position: Approximately 80km east of La Serena, Coquimbo Region, Chile.

Location: Cerro Tololo: Latitude 30º 10.2´ S, longitude 70º 48.4´ W. Elevation 2240m above mean sea level. Cerro Pachón: Latitude 30º 14.4´ S, longitude 70º 44.1´ W. Elevation 2700m above mean sea level.

General description: The AURA (Association of Universities for Research in Astronomy) Observatory in Chile comprises two mountain-top groups of telescopes: Cerro Tololo and Cerro Pachón. Cerro Tololo is the site of the first of the various major, international observatories that are now operating in Chile. Following this lead, and attracted by the pristine night skies, the world's astronomers have made northern Chile the primary centre for major astronomy research observatories in the southern hemisphere. The wide-field, 4m, Blanco telescope was the largest optical telescope in the southern hemisphere during the period 1975–1997. Clear, dark skies over the Blanco telescope were crucial to its selection by the two groups who used it to make the initial discovery of the acceleration of the Universe.

Inventory: Main telescopes: 4m Blanco; 8m Gemini South; 4.2m SOAR; and 8.2m Large Synoptic Survey Telescope (LSST) under development. There are also other, smaller telescopes. This site was recently selected for the LSST after an international, competitive survey. This telescope will provide deep images of the whole sky every 3–4 nights.

History of the site: The observatory has been in operation on this site for nearly 50 years.

Cultural and symbolic dimension: The AURA Observatory in Chile forms a part, located in the southern hemisphere, of a single set of sites in the world with exceptional conditions for observing the Universe. These sites, including their natural and cultural components, are exceptional 'windows of science and knowledge'.

Present site management

Present use: The observatory is the site of the telescopes listed above.

Regarding interpretation and outreach, the observatory has formed a 200+ schools network and support organization in collaboration with the Municipality of La Serena and the local University. The Coquimbo Region has an extensive astro-tourism development initiative.

Seven public and private observatories have opened in the Region in response to the demand from networks of schools and from tourists.

Protection: The zone around the site has been declared 'of Scientific Interest' by the Chilean Government, which protects it against incursion by mining interests. Any mining activity within this area, including prospection work, would require the written permission of the President of the Republic of Chile. The buffer zone is protected from mining operations via a formal program of constant monitoring of requests for mining activity.

The Region of Coquimbo is one of three Regions in northern Chile where artificial lighting is governed by the requirements of Supreme Decree 686/98 (the 'norma luminica', signed by the President of the Republic of Chile). This protects against light pollution.

On the property, AURA voluntarily complies with and exceeds all environmental protection requirements of the Chilean government.

State of conservation: The buildings and telescopes are well maintained, consistent with the operation of a major research facility.

A National Office for the Protection of the Quality of the Skies of Northern Chile (OPCC) has the mission to carry out public education and to assist the government in the protection of this natural heritage. Under supervision of the Superintendent's Office of Electricity and Fuel (SEC) and local municipalities, about 2/3 of all street lights in the three, key, 'astronomical' Regions of Northern Chile have now been modified or replaced in order to comply with the requirements of the 'norma luminica'. The broad-band, artificial sky background is, even in the worst directions, still within 10–15 degrees of the horizon, and does not yet interfere with any observatory operations.

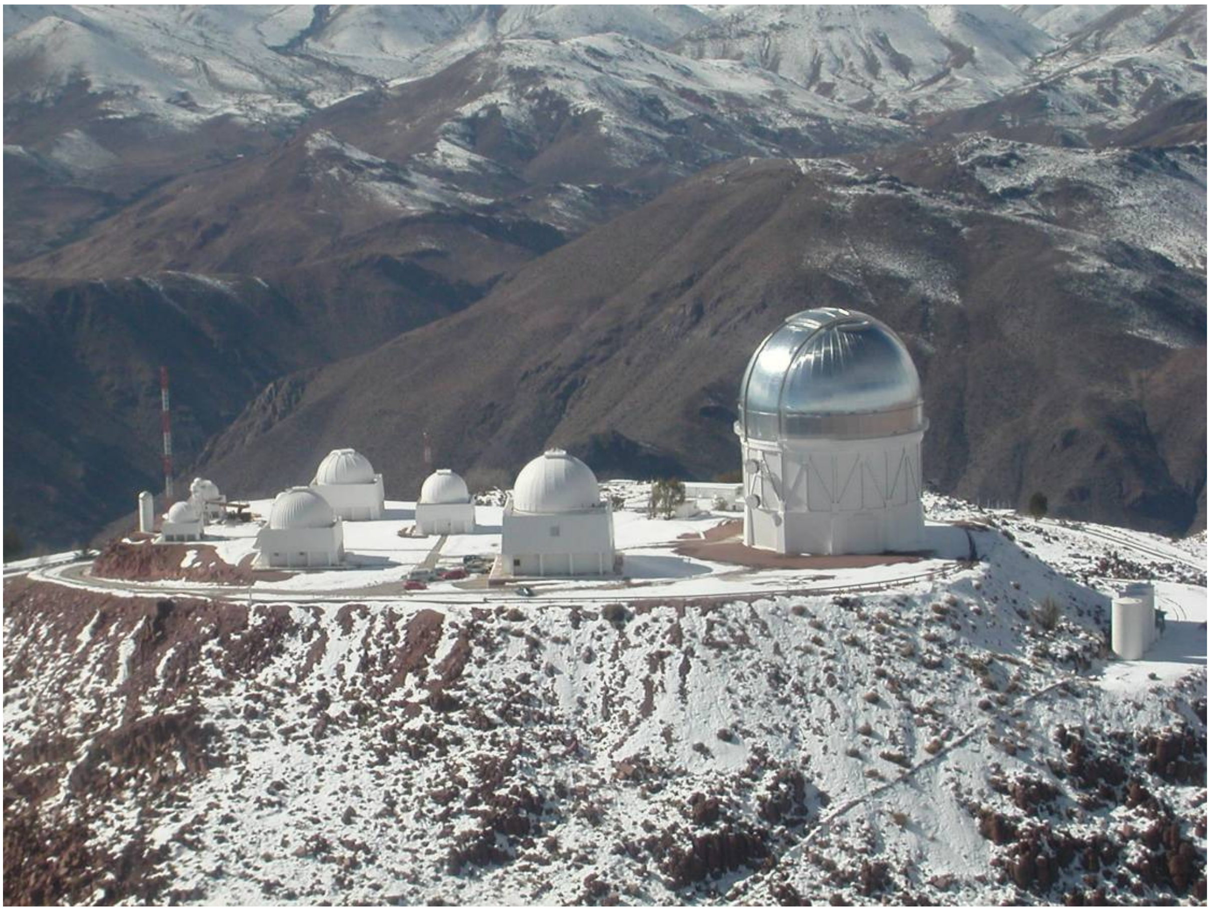

Fig. 16.3.1. Cerro Tololo. © David Walker, Creative Commons Licence

Fig. 16.3.2. Cerro Tololo at night. Photograph © Arturo Gómez and José Velásquez / CTIO

Context and environment: ‘Astrotourism’ has arisen because of the contrast between the polluted skies of Europe, Japan and the USA and the unparalleled, naked-eye view of the night sky over the Andes, the Pacific Ocean and the deserts of northern Chile. Recognizing this natural and cultural heritage, the motto of the Coquimbo Region of Chile is now “Coquimbo—the Star Region”.

Archaeological/historical/heritage research: The Diaguita and Molle cultures in the immediately surrounding area are extinct. There are two examples of rock art (not necessarily connected with astronomy) on Cerro Pachón. A statistical study of Molle sites might reveal further astronomically relevant information.

Main threats or potential threats to the site: The main threat is light pollution: this is the most threatened of the major observatory sites in Chile. The other significant threat is mining.

Management: The entire 34,491ha (344.9km^2) site is owned by AURA, the Association of Universities for Research in Astronomy. AURA is recognized by the Chilean Government as an accredited International Organization, with a variety of diplomatic privileges. The stakeholders are the 40 international member institutions of AURA Inc.

Case Study 16.4: Mauna Kea Observatory, Hawaii, USA

Richard Wainscoat

Presentation and analysis of the site

Geographical position: Summit of Mauna Kea on the Island of Hawaii, Hawaiian Islands, USA. It is located about 300 km from Honolulu, which lies on the island of Oahu.

Location: Latitude 19º 49´ N, longitude 155º 28´ W. Elevation 4100m above mean sea level.

General description: Mauna Kea (‘White Mountain’) is a dormant volcano on the island of Hawaii, the largest and southernmost of the Hawaiian Islands. The highest point in the Pacific Basin, and the highest island-mountain in the world, Mauna Kea rises 9750 m from the ocean floor to an altitude of 4205 m above sea level, which places its summit above 40 percent of the Earth’s atmosphere. The broad volcanic landscape of the summit area is made up of cinder cones on a lava plateau.

Mauna Kea is unique as an astronomical observing site. The atmosphere above the mountain is extremely dry—which is important in measuring infrared and sub-millimetre radiation from celestial sources—and cloud-free, so that the proportion of clear nights is among the highest in the world. The smooth shape of the isolated mountain, along with its high altitude, produces astronomical image quality that is among the best of any location on Earth. The atmospheric pressure at the summit is approximately 600 mb.

Inventory: Telescopes: Keck I and II, Subaru, Gemini North, IRTF, UKIRT, CFHT, JCMT, CSO, SMA, UH 2.2m and 0.9m, VLBA.

History of the site: The first large telescope on Mauna Kea, the 2.2m, demonstrated the remarkably stable and dry atmosphere above the observatory, and led to the development of a series of larger telescopes, many of which are owned and operated by international countries or partnerships. Mauna Kea was recently selected as the site for the Thirty Meter Telescope.

Cultural and symbolic dimension: The Mauna Kea Observatory forms part of a single set of sites in the world with exceptional conditions for observing the Universe. These sites, including their natural and cultural components, are exceptional ‘windows of science and knowledge’.

Present site management

Present use: The observatory is the site of the telescopes listed above.

The Mauna Kea Visitor Center is open 365 days per year, and offers summit tours on weekends and evening stargazing. The annual visitor count exceeds 250,000. Astronomers and staff from the Mauna Kea Observatories are also engaged in extensive outreach activities across the island of Hawaii, and elsewhere in the Hawaiian Islands.

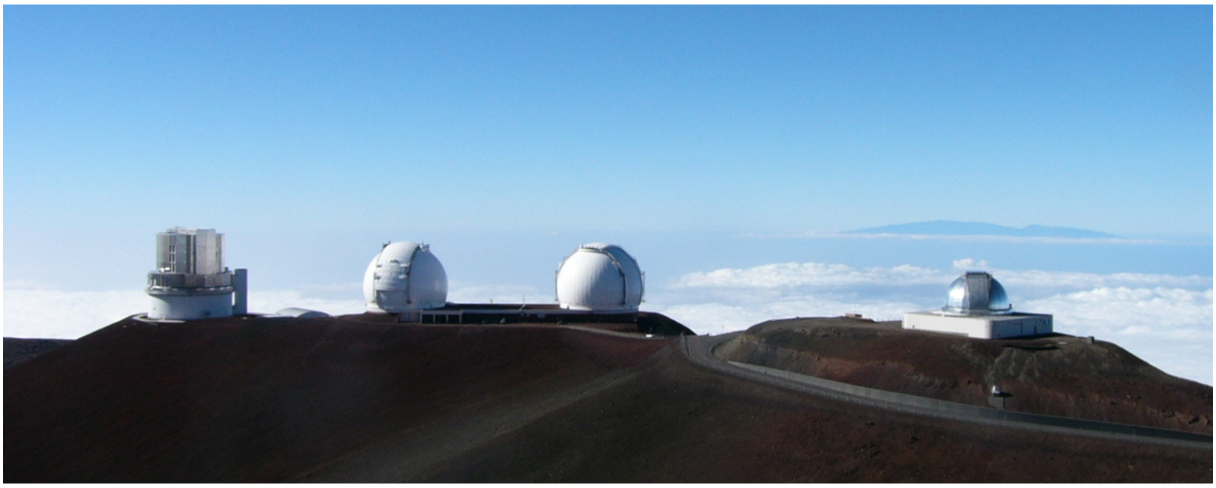

Fig. 16.4.1. View of Mauna Kea observatory showing the Subaru, Keck I and II, and IRTF telescopes. Photograph © Sasquatch at Wikimedia Commons, Creative Commons Licence.

Protection: The zone around the observatory is called the "Mauna Kea Science Reserve" and has strict controls on usage. A subset of this reserve is designated for astronomical usage. A pie-shaped sector of the zone around the observatory is preserved as the "Mauna Kea Ice Age Reserve". A lighting ordinance for the island of Hawaii has been established to limit artificial light and its damaging effects on the observatories.

A large area around the science reserve is preservation land owned by the state of Hawaii. Few people live within 25 km of the summit.

State of conservation: The observatory has been in operation for 40 years. The buildings and telescopes are well maintained, consistent with the operation of a major research facility.

The lighting ordinance has been in place for 20 years, and has provided good protection for the night sky. However, there are many lights on the island that do not conform to the ordinance, either because they were installed prior to it, or have been installed in violation. Better enforcement is expected in the future. The present level of light pollution does not compromise research.

An ongoing eruption of nearby Kilauea volcano is producing copious amount of volcanic gases and haze. These gases are nearly always trapped at lower altitudes by a temperature inversion, and do not affect the astronomy.

Context and environment: The summit region is sacred to the native Hawaiians. The summit area is a spectacular natural landscape composed of multiple cinder cones, a high altitude lake, and glacial moraine field.

Archaeological/historical/heritage research: An ancient adze quarry is located to the south of a summit, with very hard rocks formed during the last ice age from lava being cooled by a glacier; the hard rocks were used as tools by pre-European-contact Hawaiians. Numerous archaeological monuments are located around the summit region.

Main threats or potential threats to the site: The main threat is light pollution from the nearby urban areas. Population growth is occurring mostly on the western (dry/clear) side of the island, leading to increasing artificial light.

Management: The Mauna Kea Science Reserve and Ice Age Reserve are owned by the State of Hawaii. A large area around these reserves is also owned by the State of Hawaii.

The summit area is managed by the Office of Mauna Kea Management of the University of Hawaii. Rangers patrol the summit area for conservation purposes and to assist visitors with problems. The larger conservation area surrounding the summit is managed by the Department of Land and Natural Resources of the State of Hawaii.

Each of the telescopes has a sublease from the University of Hawaii. The University of Hawaii has leased the Mauna Kea Science Reserve from the State of Hawaii. The lease expires in 2031.

Case Study 16.5: Canarian Observatories, Spain

Casiana Muñoz-Tuñón and Juan Carlos Pérez Arencibia

Presentation and analysis of the site

Geographical position: ORM: on the edge of the Caldera de Taburiente National Park, island of La Palma, Canary Islands, Spain. OT: close to the Teide National Park, island of Tenerife, Canary Islands, Spain.

Location: ORM: Latitude 28º 46´ N, longitude 17º 53´ W. Elevation 2396m above mean sea level. OT: Latitude 28º 18´ N, longitude 16º 30´ W. Elevation 2390m above mean sea level.

General description: The two observatories of the Instituto de Astrofísica de Canarias (IAC)—the Roque de los Muchachos Observatory (ORM) on the island of La Palma and the Teide Observatory (OT) on the island of Tenerife —constitute an ‘astronomy reserve’ that has been made available to the international community. The Canary Islands’ sky quality for astronomical observation has long been recognised worldwide. They are near to the equator yet out of the reach of tropical storms. The whole of the Northern Celestial Hemisphere and part of the Southern can be observed from them. The observatories are located 2400 m above sea level, above the temperature-inversion layer produced by the trade winds. This ensures that the installations are always above the so-called ‘sea of clouds’, where the atmosphere, stabilised by the ocean, is clean and turbulence-free.

*Inventory***:** The two observatories currently house telescopes and other instruments belonging to 60 scientific institutions from 19 different countries, together with the scientific and technological resources of the IAC’s Instituto de Astrofísica at La Laguna (Tenerife) and Centro de Astrofísica en La Palma (CALP) at Breña Baja (La Palma). The main telescopes are:

ORM: 10.4m Gran Telescopio CANARIAS (GTC), 4.2m William Herschel Telescope (WHT), 3.5m Telescopio Nazionale GALILEO, 2.56m Nordic Optical Telescope (NOT), 2.5m Isaac Newton Telescope (INT), 2m Liverpool Telescope, 1.2m MERCATOR, 0.45m Dutch Open Telescope (DOT), 1m Solar Telescope (SST), MAGIC I and II (which detect very-high-energy gamma rays), SuperWASP-North (robotic observatory).

OT: 1.55m CARLOS SÁNCHEZ, 1m OGS, 0.8m IAC-80, 0.5m MONS, 0.4m OTA, 1.5 GREGOR (Solar), 0.9m THEMIS (Solar), 0.7m VTT (Solar), 0.3m Bradford Robotic Telescope, 1.2m Robotic telescopes STELLA.

History of the site: As far back as 1856, the Astronomer Royal for Scotland, Charles Piazzi Smyth, conducted astronomical experiments on the mountain summits of the island of Tenerife.

Fig. 16.5.1. The Gran Telescopio Canarias (GTC). Photograph © Pablo Bonet

Cultural and symbolic dimension: The ensemble of observatories on the Canary Islands has played an important role in astronomy, being the place where, for example, the optical counterpart of a Gamma Ray Burst was first observed, the first unequivocal evidence for a stellar-sized black hole in the Galaxy was obtained (something that had been sought for decades), and the first brown dwarf was discovered. The GTC, at present the largest optical and infrared telescope in the world, will 'see' the farthest and faintest objects in our Universe, and will help provide answers to many questions about how the known universe was created.

The Canarian observatories form part of a single set of sites in the world with exceptional conditions for observing the Universe. These sites, including their natural and cultural components, are exceptional 'windows of science and knowledge'.

The Teide mountain is world-renowned for its contribution to science in modern times, especially in the field of geology and the study of the atmosphere. The Teide National Park was inscribed on the World Heritage List in 2007 under natural criteria (vii) and (viii). Its connection with science is evident: "…the area is a major centre for international research with a long history of influence on geology and geomorphology especially through the work of von Humboldt, von Buch and Lyell, which has made Mount Teide a significant site in the history of volcanology". Pioneering atmospheric observations were also carried out in this area. Within this context, it seems logical to consider a possible application of cultural criteria in the light of its astronomical values and significance.

Present site management

Present use: The observatory is the site of the telescopes listed above.

Both observatories have, for decades, carried out intensive activity in the dissemination and interpretation of astronomy. Over 30,000 tourists every year visit the Teide National Park at night to see the stars. The ORM receives about 5000 visitors annually. La Palma is now firmly established as a starlight tourist destination.

Protection: The whole area where each observatory is located enjoys a high level of protection. Each of the observatories is located within a European Special Area for Conservation, and lies at the edge of a National Park (see also below).

The astronomical quality of the Canary Islands' observatories is guaranteed under a specific national 'Sky Law' ('Ley del Cielo'—Law 31/1988) approved in 1988.

Relying upon this regulatory development, a high-sensibility 'core area' has been established around the ORM, extending 9 km in each direction. The rest of the island of La Palma (25 km around the Observatory) is considered a high-protection buffer zone, while the external zone is the area visible from La Palma, 100–160 km around the Observatory, which includes to the island of Tenerife. The protection also covers radio and atmospheric pollution (prohibiting emission sources above 1500m elevation), and air traffic.

State of conservation: The sky protection law has been in place for 22 years, and has provided good protection for the night sky, especially on the island of de La Palma. The IAC, long aware of the importance of promoting initiatives to protect the ORM and OT, created a Sky Quality Group in the late 1980s and a technical office for sky protection (OTPC) in 1992 to provide advice on the application of the Sky Law. The level of protection has been increasing in recent years, overcoming the initial reluctance of the local population. Better enforcement is expected in the future. The present level of light pollution does not compromise research, maintaining the high level of excellence of the sky quality parameters.

Context and environment: Both observatories are located within areas of the utmost value from an environmental point of view, with exceptional natural scenery. The ORM is located within the core zone of the La Palma Biosphere Reserve and within the buffer zone of the Caldera de Taburiente National Park. The OT is located on a mountain covered in volcanic cinder close to the Teide National Park, with a spectacular view of the Teide stratovolcano itself.

Archaeological/historical/heritage research: Close to the Roque de los Muchachos is the prehistoric cult area of 'Llano de Las Lajitas', part of the astronomical legacy of the Awara, the ancient inhabitants of the island of La Palma.

Main threats or potential threats to the site: The main threat is light pollution, in common with all of the main observation sites in the world.

Management: Both observatory areas are municipality-owned and administrated by the IAC. The IAC is constituted administratively as a Public Consortium, created by statute in 1982, with involvement from the Spanish Government, the Government of the Canary Islands, the University of La Laguna and Spain's Science Research Council (CSIC).

Fig. 16.5.2. The Teide Observatory (OT). Tenerife, Canary Is. © Instituto de Astrofísica de Canarias

Conclusion

Astronomical Heritage in the Context of the UNESCO World Heritage Convention: Developing a Professional and Rational Approach

Michel Cotte and Clive Ruggles

General remarks

One of the declared objectives of UNESCO's Astronomy and World Heritage Initiative is to promote nominations to the World Heritage List that recognize and celebrate achievements in science. A number of different fields of human scientific endeavour might provide a satisfactory framework for exploring issues, developing methodologies, and attempting to identify principles that apply to science heritage in general. Astronomical heritage, however, has the advantage of being universal, in the sense that every human culture has a sky and 'astronomy', which we take, broadly, to mean the cultural interpretation and use of what is perceived in the heavens. In this sense, astronomy is present in all cultural contexts, from ancient to modern, and whatever their geographical location.

What are the best ways to support and encourage the inscription of the most outstanding examples of astronomical heritage onto a globally balanced World Heritage List? A prerequisite is to develop and establish a professional and rational approach to the identification, protection and promotion of the world's most valuable astronomical heritage.

But we also need to work within the context of the World Heritage Convention as it is applied today, developing specific approaches appropriate to properties with clear significance and value in relation to science. This imposes a framework that can be summarised by the diagram in Fig. 17.1.

In the discussion that follows, an 'astronomical heritage site' is taken to be a cultural property with part (but not necessarily all) of its cultural or natural value arising because of its relationship to astronomy. As is clear from the figure, even where astronomy accounts for all of the perceived attributes of the value (as elaborated in the dossier), it is necessary to consider a range of wider cultural (or natural) issues—the broader context—when proposing a statement of outstanding universal value (OUV).

The discussion is organised into three main parts: (1) general trends and issues arising from the Thematic Study; (2) evaluating an astronomical heritage site; and (3) creating a credible dossier. A selection of the preceding thematic essays and case studies, which deliberately include a mix of sites ranging from the world-famous to the (as yet) almost unknown, will be used to illustrate the main points made.

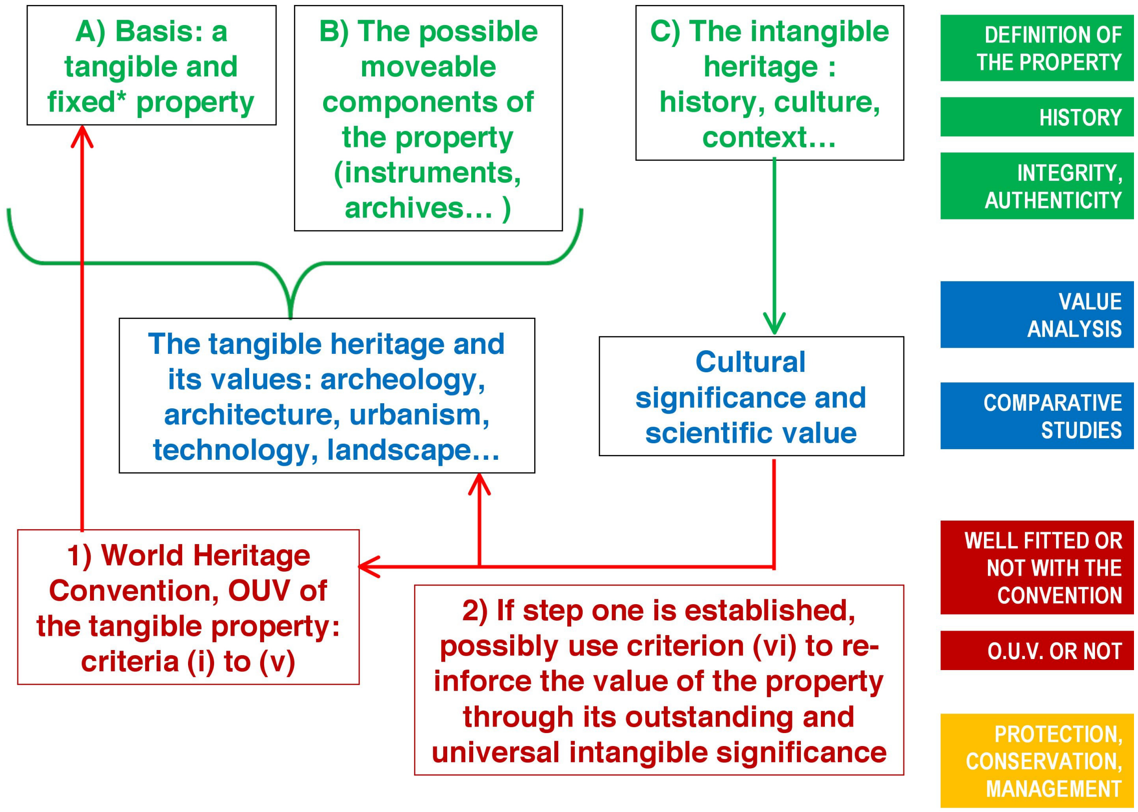

Fig. 17.1. Framework appropriate to properties with clear significance and value in relation to science. *Note that we use the term ‘fixed’ rather than ‘immovable’, since some heritage that falls under the Convention (e.g. a stone circle) is not strictly ‘immovable’ but is merely understood not to have moved (yet) from its original position.

General trends and issues[1]

There is no doubt that some level of interest in celestial objects and events is a feature of nearly all, if not all, human societies throughout the ages. For most of those in the past, the sky formed a prominent and immutable part of the observed world, its repeated cycles helping to regulate human activity as people strove to make sense of their world and keep their actions in harmony with the cosmos as they perceived it. In some cases this was simply in order to maintain seasonal subsistence cycles; in others it helped support dominant ideologies and complex social hierarchies. It is this quest for knowledge and understanding—‘science’ in its broadest sense—that most clearly links people with an active interest in the skies right through from the earliest skywatchers to modern astronomers and cosmologists. Astronomy really is a fundamental attribute of humankind, a vital facet of human culture common to every chronological period, geographical situation, and type of human society.

On the other hand, the diversity of human practices associated with observing the skies, and the variety of manifestations of astronomy in human culture, present some substantial challenges in carrying out comparative assessments of the associated heritage. One of the

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[1] See also Clive Ruggles, “Astronomy and world heritage”, pp. 6–15, and Michel Cotte, “Astronomical and archaeoastronomical heritage: a shared thematic study for improved understanding”, pp. 81–83, in *World Heritage* no. 54 (2009), published by UNESCO, Paris.

main difficulties arises because—as the various themed essays and cases studies show very clearly—different types of heritage (as defined in the Introduction) frequently overlap. Compounded with this, the different kinds of evidence available provide different types and levels of insight into the original practices. Contrast, for example, the limitations that apply in the case of prehistoric societies, where the evidence is purely archaeological, and the relative richness and directness of the historical accounts and records that are often available in later periods. In both cases, interpretations must be based on sound theoretical principles, whether anthropological or historical, and secure methodologies. However, the firm insights that archaeological evidence can provide may often seem paltry in comparison with historical cases, with much remaining hypothetical and controversial. It must be borne in mind that such insights, although limited, may be matchless.

Astronomy in context

Beyond its manifestation as modern ‘rational’ science (and arguably in that case also), practices related to astronomy are inextricably linked to broader assemblages of cultural activities. It follows that the material heritage of astronomy in the form of artefacts and constructions will often be deeply integrated within material heritage of a broader nature and significance. The Viña del Cerro site in Chile (Case Study 3.4), for example, provides an excellent example of astronomy in a broader, integrated context of resource exploitation, sacred places, calendar and landscape. This implies in turn that we should not focus exclusively (or even, possibly, most of the time) upon ‘astronomical heritage sites’ *per se* but upon sites exhibiting an important set of valuable attributes, astronomy being just one component among others.[2]

Several sites of this nature are already on the World Heritage List, including Stonehenge (Case Study 2.1), the pyramids of Giza (Case Study 8.4), Ulugh Beg’s observatory in Samarkand (Case Study 10.2), and the Royal Observatory, Greenwich (Case Study 12.1), and a challenge in these cases is to progress to a fuller recognition of their astronomical value. Where astronomy was not identified as a component of OUV, encouragement should be given for a re-nomination that acknowledges the astronomical value, and in the meantime this could at least be acknowledged at national level and included in the scope of Management Systems.

Ulugh Beg’s observatory is an example of the mutual reinforcement of value coming from different cultural fields—urban, social and political history, history of architecture and decoration, cultural practices in the arts, etc.—in Central Asia during Ulugh Beg’s time. The immediate urban surroundings of the Jantar Mantar in Jaipur (Case study 6.1) provide a similar example where overlapping aspects of value are gathered together in one property; similarly, the Dengfeng Observatory (Case Study 5.2) forms part of a large site including a range of 13 temples, towers, a monastery, and gardens.

Astronomy can take many forms but it is never alone: it is always a part of a larger ensemble of attributes that characterise a human society in context. Consequently, when considering the value of a property relating to astronomy, each issue should be studied taking full account of the mutual links and correlations between astronomy and other components of human culture in a given society in a given historical period. This is clearly relevant to anyone considering nominating a property relating to astronomy for inscription onto the List but it is also evident that analysis of the role of astronomy in society through the heritage already inscribed remains relatively poor and is sometimes completely absent. A real challenge exists to ‘re-read’ and possibly ‘re-evaluate’ many inscribed sites following the Convention rules.

The heritage of astronomy is often linked to complex systems of representation. For example, astronomical observations are frequently motivated by a need to predict the future (for various reasons including prognostication, predicting recurrent phenomena, or ‘testing’

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[2] An excellent example in this regard is the Einstein Tower in Potsdam (Case Study 12.5), which combines outstanding scientific and architectural qualities.

hypotheses in modern 'rational' context), and this leads to the development and use of a variety of forms of symbolic notation. As a result, attempting to interpret the heritage involves examining the diverse relationships that exist between human beings and the sky as manifested through the use of artefacts and representations. These not only include notations and drawings but also architectural constructions that 'symbolise' the skies in various ways: terrestrial material manifestations of the human cognisance of the universe that can be seen as a concretisation of the human relationship with the heavens. We must also be concerned with protocols and methods of observation, together with a full range of beliefs and modes of behaviour (i.e. magic as well as science, astrology as well as astronomy in the modern rational sense, and religious faiths as well as beliefs in physical laws).

This discussion raises once again the issue of the meaning of the term 'science', both as simple terminology and as a more complex epistemological question. In the introduction we presented, effectively, a straightforward dichotomy between modern 'rational' methods of enquiry (narrow definition of science) and any attempt to comprehend the nature of the perceived life-world by imposing some sort of cognitive structure upon it (wide definition). However, at a more subtle level the question of what constitutes 'pure science' in astronomy remains extremely open and dependent upon context. It is certainly allied to the question of predicting the future and it is also linked with cosmology (in the anthropological sense) and with religion and ideology. The general question of what constitutes 'pure' science or 'pure' astronomy is probably not relevant in itself, except in so far as it helps to define modes of connection between astronomical beliefs and practice and their social and cultural context and hence leads to more efficient ways of understanding the value of heritage sites with a relationship to astronomy.

An important category of astronomical heritage relates to the application of astronomical techniques and technology to other sciences. Thus the Struve arc (Case Study 14.1) represents astronomy as technology applied to earth science. Space science, in the sense of science carried out in space, may include astronomy but the associated fixed heritage is purely technological (Chapter 15 and see below).

Categories of cultural heritage

Several of the thematic essays demonstrate how the various categories of astronomical heritage defined in the introduction—'tangible immoveable', 'tangible moveable', and 'intangible'—relate to one another in different contexts. Although the World Heritage Convention focuses on tangible immoveable heritage (valued through intangible evidence), in our global Thematic Study we have a duty to present immovable as well as moveable, and intangible as well as tangible, since the essential evidence for certain types of early astronomy is almost exclusively in these other forms. Our knowledge of astronomy in ancient Mesopotamia, for example, comes exclusively from moveable cuneiform tablets, together with its intangible legacy in the astronomy of other cultures (Chapter 7).

In other cases, different forms of heritage may tend to relate to different aspects of the astronomy. The classic example of this is ancient Greece (Chapter 9), where the historical documents relate mainly to the development of mathematical astronomy by an elite of scholars, while much of the material astronomical heritage (e.g. the configuration of ancient temples) relates to astronomy in the service of religion practiced by the people at large. Since the first of these forms a crucial part of the history of modern scientific astronomy, the archaeoastronomical evidence is largely ignored by historians of astronomy. However, it is no less important from a cultural astronomy (anthropological) perspective. Indeed, while a classical heritage approach focused on the fixed heritage could redress the balance, it might well overemphasize the latter.

Islamic astronomy (Chapter 10) presents another balance between the availability and state of conservation of tangible fixed evidence and other forms of heritage relating to crucial developments in astronomy. Based on the available historical sources, we can create quite an accurate account of several aspects of the development of astronomy in the Islamic world during the 12th to 16th centuries, and we know that it provided a vital link between ancient Greek astronomy and the subsequent development of scientific astronomy in renaissance Europe and in Mogul India. However, despite the huge importance of the Islamic observatories in the development of mathematical and observational astronomy during this period, none has survived intact. In other words, the fixed heritage that not only bears witness to but fundamentally underpinned these developments has largely disappeared. In this context, the partial survival of two major observatories (Maragha and Samarqand) that demonstrably played a very significant role in these developments is all the more fortunate. This must surely influence our assessment of their very high value as astronomical heritage, an importance that could come into play, for example, when facing authenticity and integrity concerns.

The balance between the various categories of legacy is an important consideration in considering the value of the tangible immoveable heritage and raises a variety of issues. For example, in the case of Palaeolithic mobile art on moveable artefacts—objects that may provide some of the earliest insights into human perceptions and uses of the skies (Case Studies 1.1–1.3):

- Does their existence strengthen the value of their place of discovery, even if they are now removed from it in museum collections?
- Should we focus at all on the place of discovery, when what is important from the astronomical heritage point of view is the object itself?
- Is the authenticity of the object more to do with the reliability of the archaeological context it came from than with its own ‘genuineness’ (e.g. lack of damage/restoration)?

Jumping from one end of the timescale to the other, space heritage (see Chapter 15) throws the issue of ‘fixed’ versus ‘moveable’ heritage into sharp focus. A ‘fixed’ location on the moon, such as Neil Armstrong’s landing site or first footprint, is a moving point relative to any location on the earth; while a geostationary satellite which, to some degree of approximation, is stationary relative to any location on the earth, would not seriously be considered a ‘fixed’ object. Clearly, relativity of movement seems a poor criterion for heritage evaluation in these cases (albeit an excellent illustration for a major concept of modern physics). The only reasonable conclusion is that the dichotomy between ‘fixed’ and ‘moveable’ makes little sense as a classificatory criterion in astronomical heritage in particular, or in science or technology heritage in general.

Tangible and intangible heritage relating to astronomy

The ‘core’ heritage of astronomy as ‘science’ in either the broad or narrow sense—in other words, ideas, knowledge and understanding—is intangible. The essay on the historical development of radio astronomy (Chapter 13) gives an excellent example of the ways in which the tangible and intangible are inextricably interwoven in a modern context, and all of the preceding essays address this issue at some level.

The issue is also highly pertinent in the case of indigenous uses of astronomy (Chapter 4), with the example from Aboriginal Australia (Case Study 4.3) demonstrating the links that can exist in a modern context. A rather different example is provided in Chapter 4, which concerns an Ethiopian indigenous calendar of huge importance from the point of view of the anthropology of astronomy since it undermines a number of assumptions people tend to make about the ‘inevitable’ ways in which calendars developed in the past. However, but also raises an important question for the Convention. Surviving calendrical practices may be preservable as part of a living ‘cultural landscape’ such as the Cliff of Bandiagara (Land of the Dogons) World Heritage Site in Mali—but is this the appropriate way to try to sustain and protect intangible astronomical heritage of this nature?[3]

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[3] Part of the traditional ‘Mursi country’ is in fact listed as part of the ‘Lower Valley of the Omo’ World Heritage Site in Ethiopia, inscribed for its palaeontological and prehistoric sites.

Despite their importance in the development of sciences and arts, the goal of the Convention is not to celebrate the achievements of individuals. Hence, as at Monkwearmouth (Case Study 11.1), the fact that a place is associated with a great person and/or their discoveries does not constitute value by itself, although it can clearly strengthen other aspects of the value.

Space heritage

Space heritage (Chapter 15) is not really heritage of astronomy but actually of science in general and of technology. Nonetheless, it is important in this study in that it raises novel questions concerning the heritage approach.

The term 'space heritage' is widely misinterpreted as the heritage of space travel, but it is really the heritage of space science, or more truly space 'techno-science'—a set of technological applications that support a variety of scientific endeavours carried out in space, of which astronomy (research) is just one. The activity of space science leaves no tangible science heritage sites on the territory of State Parties, since by definition it takes place either on other heavenly bodies (e.g. the Moon or Mars) or in space itself. Examples of the sorts of issue this raises are:

- *Ownership*. Once a satellite goes into orbit and becomes operational, does it become international property? (This invokes international law about space; there are clear parallels with maritime law.)
- *Conservation*. In the case of a dossier concerning such heritage, would a 'no conservation' policy and a Management System that endeavours 'to observe only' be acceptable? After all, there is unlikely to be any other viable option.
- *Duration of the heritage*. This is not necessarily indefinite: for example, orbiting objects in space must eventually fall back to earth.

Cultural and natural heritage relating to astronomy

The Pnyx (Case Study 9.1) is a place significant for the history of astronomy because historical records attest that it was the place from which the Greek astronomer Meton made observations of the solstice in the 5th century BC that led to his discovery of the calendrical cycle now known as the 'Metonic cycle'. There are no tangible remains, fixed or moveable, bearing direct witness to Meton's observations. However, Meton's observations may well have made use of the visible horizon (formed by a hill 3km away). In this sense, the natural landscape formed part of the 'instrument' and so directly forms part of the astronomical significance of the place (although recognising this as World Heritage could be problematic).

The same is true of the many prehistoric and historical constructions aligned, for example, on the horizon rising or setting positions of the sun (e.g. Case Studies 2.1, 2.2), the appropriate horizon point being marked in some cases by a natural feature such as a distant hill-slope or mountain summit (e.g. Case Study 4.2). It would be misleading to view most of these constructions as observing 'instruments', since that was not their main function, but it is true to say that the alignment—the feature that 'connects' the human monument to the sky and contributes to (or in some cases, constitutes the totality of our knowledge of) its significance in relation to astronomy—links the human construct and the surrounding natural landscape—doing so in an even more specific way when a horizon 'foresight' completes the alignment. It follows that the natural landscape, and in some cases specific features within it, must in a very real sense be considered as contributing to the value of the monument, implying, for example, that Management Systems would need to address to question of keeping the natural landscape intact and the sightline unobstructed. At the same time, natural sites used for astronomical purposes (both in the present and in the past, where there is clear evidence to support the assertion) could fall into the 'cultural landscape' sub-category.

A related issue is the removal of a monument, even for its own protection, as at Abu Simbel or, potentially, at Nabta Playa (see Chapter 8). If the monument contains connections with the surrounding landscape, such as alignments, then its removal may have stronger implications than simply eliminating its eligibility for inscription as immovable heritage, since such connections will be destroyed, thus also removing an important (and perhaps the only) aspect of its value as astronomical heritage and thus destroying its integrity.

Human constructions incorporating astronomical alignments are also, of course, ‘connected’ in a cognitive sense to the astronomical body in question: this connection was periodically ‘revealed’—reaffirmed visually—when the sun, star, etc actually rose or set in the alignment. Light-and-shadow ‘hierophanies’ (e.g. Case Studies 9.3, 11.2) represent another case where a direct connection between a human construction and a celestial body is periodically ‘made physical’. It is also true that in a more general sense all astronomical heritage sites have a connection to the very sky to which they related.

The visibility of the sky

Given that an important aspect of the heritage of many ancient and historical sites is the observation of certain naked-eye astronomical phenomena, the possibility of actually observing those phenomena today is a relevant consideration in valuing and preserving that heritage. For example, various rising phenomena of importance at the pyramids of Giza (Case Study 8.4) cannot be seen today owing to the Cairo smog (see Chapter 8), which is detrimental to the appreciation of that aspect of their significance. Since many sites relate to night-time observations, a consideration of considerable importance in this respect is the visibility of the dark night sky.

In terms of the application of the Convention, it is difficult to see how the criteria for assessing tangible cultural heritage could be extended to the sort of *negative* definition of a property (the absence of artificial light) that would characterise a ‘Starlight Reserve’ or ‘Dark Sky Park’ (Case Studies 16.1 and 16.2). Instead, we must consider this issue in terms of natural value: a dark sky is an aspect of the quality of the environment of a cultural site.

That said, in terms of scientific value (and cultural value in general) connected with the history of astronomy, it is quite valid to recognise the absence of light as a prerequisite for the satisfactory observation of the night sky.

While clearly of huge importance for astronomical observations, the darkness of the night sky is only one condition among others such as atmospheric turbulence and weather (see Table 16.0.1). The ‘classical’ solution to this ensemble of terrestrial problems was in effect to remove the observatory as far as possible away from them—at first by adding domes (which, incidentally, protect from rain as well as light), then to move the observatories away from cities, then up mountains, and then finally into space (see Chapter 15). The whole set of constraints/conditions that define an exceptional place for observation (see Chapter 16) itself forms an important part of the *cultural* value of the place in relation to a major observatory, particularly if that observatory plays a major role in the history of science.

The cultural value of the dark night sky extends well beyond historical and modern scientific astronomy—through its role in social history, its myths, its symbolic representations (with complex and multiple layers of meaning) and so on—across all human communities and throughout the ages. This reinforces the idea that the strong cultural significance of the dark night sky is extremely general among human societies, but also that its value in relation to a particular, well-defined cultural property can only be established with reference to a set of other remarkable attributes forming the global value (and, potentially, the OUV) of the property.

The dark sky may not always be part of the intrinsic (cultural) value of a cultural property related to astronomy but, where it is still present, it is certainly part of the intrinsic natural value of the place in question. Preserving or improving the dark sky is certainly a relevant protection/management issue in many cases. As a broader issue it rests seductively in the context of present-day ecological sensibilities.

Evaluating an astronomical heritage site

In the opening chapter we introduced a global methodology for establishing the components of a property and their significance in relation to astronomy.

In order to implement this methodology in practice it is essential to recognise an astronomical heritage site as a 'monument of science', and hence as an integrated system. This means that fundamental links are understood to exist between the following different classes of heritage:

(A) fixed heritage (monuments, sites, fixed instruments, palaeography, etc);

(B) moveable heritage (portable artefacts and instruments, archives, satellites etc); and

(C) intangible heritage (knowledge, theories, social and cultural beliefs, etc).

As a consequence, the creation of an inventory taking a global approach must take into account not only the material evidence of the property (A) but also (in relation to B and C) knowledge, outputs, applications in society, etc.

The value of fixed heritage (A), which is within the scope of the convention, together with moveable heritage (B), is critically dependent upon intangible knowledge (C). The material evidence may be modest in itself (although substantial enough to clearly demonstrate the ideas with which it is associated) but may have exceptional value as a result of the context of ideas that derives from people's understanding of the sky and celestial events. In other words, (A) derives its meaning in the light of (C), and is intrinsically linked to (C).

In order to identify our most exceptional astronomical heritage, it is important to recognise the continual interchange between the 'tangible' and 'intangible' categories, which is part of the fundamental paradigm that constitutes the scientific process in general.

We must also recognise that the history and heritage of science is inextricably linked to the history and heritage of technology. This implies that it will be at best unproductive, and at worst counterproductive, to try to classify and evaluate the heritage of science in isolation from the heritage of technology. Both dimensions certainly exist within astronomical heritage, which provides a paradigmatic example among the heritage of both science and technology. Indeed, the only tangible immovable heritage relating to space science (Chapter 15) is the technology heritage of launch sites and associated ground-based laboratories.

Integrity must be understood as the completeness of a monument of science. The question, in determining the integrity of a site and the material evidence relating to the attributes that establish its value, is whether we have enough material and intangible information to give us a comprehensive view of the property and of its historical functions.

Authenticity. The question of authenticity raises particular issues in the context of science heritage, as we have seen in the introductory chapter. Change, improvement and innovation are positive attributes of science and technology in general, and of astronomy in particular, and so are likely to add to, not detract from, the value of the associated heritage. The 1994 Nara conference on authenticity (see *Operational Guidelines*, annex 4) underlines the need for a comprehensive approach, considering the property first in its global cultural context and second in relation to a detailed description of its attributes. The scientific use of a property gives rise to a specific form of the definition of authenticity and this necessitates a careful study of each component of the value of the site, in terms of its use and associations as well as its form.

The authenticity of a 'fact' is also linked to the credibility of the 'fact' and its interpretation. In other words, it is linked to the degree to which the 'fact' has been proven according to current standards in the discipline concerned—e.g. history, archaeology or archaeoastronomy.

Serial approach. A serial approach may be appropriate but it is not an obligation. Each State Party is free to choose its own approach towards its astronomical and archaeo astronomical heritage. A serial approach would need to highlight the various similarities and complementarities that exist between the different sites within the ensemble, as well as highlighting the different qualities that attest to the significance and value of the ensemble as a whole. On the other hand, a single outstanding example may provide a better demonstration of value, and potentially of Outstanding Universal Value (OUV) in the sense of the application of the Convention to inscribe a given property on the World Heritage List.

Credibility. The credibility of dossiers is crucial for the future of the implementation of the Astronomy and World Heritage Initiative within the framework of the World Heritage Convention. It is important not only for the World Heritage Committee but also for the scientific community in general. For this reason, we devote the main part of this concluding discussion to the topic of how to create a credible dossier for an astronomical heritage site.

Creating a credible dossier

A number of issues must be addressed in the dossier that is required for every property that is nominated for inscription to the World Heritage List. It must include:

1. a definition of the property, inventory, and definition of the buffer zone;
2. its history and its position in a global context;
3. its authenticity and integrity;
4. a comparative study with similar places in the region but also with any in other countries and, beyond that, in other epochs;
5. a value analysis;
6. protection, conservation and management; and
7. legal protection in the buffer zone.

In this section we will briefly discuss some specific issues that arise in preparing the dossier for an astronomical heritage site. For the general issues dealing with the preparation of the dossier we recommended the reader to refer to the official documents of the Convention, and in particular *The Operational Guidelines for the Implementation of the World Heritage Convention* (http://whc.unesco.org/en/guidelines/), especially annex 8. Documentation addressing specific questions can be found on the World Heritage website and on the ICOMOS website: e.g. *What is OUV? Defining the Outstanding Universal Value of Cultural World Heritage Properties* (http://www.international.icomos.org/publications/monuments_and_sites/16).

What follows is not meant to be a blueprint for a ‘good dossier’, but merely a first approach presenting some examples illustrating questions of methodology, the comparative study, the global survey of a period, and so on. The demonstration of Outstanding Universal Value (OUV) is a crucial objective of the dossier, and the value of the property can really only be demonstrated in relation to the global cultural and historical context.[4].

A ‘bad dossier’ will lead to misunderstandings and certainly fail to demonstrate OUV. Typical shortcomings in existing dossiers suggest that the main failings might be:

- weaknesses in defining the property, demonstrating the importance of the astron omical evidence, and/or showing how the astronomical significance is conveyed by the material evidence;
- weakness in the comparative study (inadequate comparisons with other potential sites);
- a flagrant overestimation of the local or regional significance of the property’s attributes and/or the overemphasis of particular functions;
- an insufficient understanding of the cultural–historical context, and/or overly superficial historical studies; and
- overly controversial interpretation of the site, artefacts, etc.

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[4] In some cases the comparisons need not be global but can be within a geo-cultural region.

Definition of the property, inventory, and definition of the buffer zone

Strictly speaking, 'moveable' objects as opposed to 'immovable' heritage are not covered by the Convention, as indicated into the Introduction. However they may well form an integral part of a 'monument of science'. Examples not only include observatories containing moving instruments such as modern telescopes; the observatory itself may have fixed walls but a moving dome or rising floor, as for example the McClean Building at the Royal Observatory, Cape of Good Hope (Case Study 12.2), or may have both fixed and moveable instruments integral to the design, as in the case of a radio-astronomy interferometer (see Chapter 13) comprising a fixed dish and one or more that are moveable, for example along rails. This parallels a known situation with regard to technology heritage already inscribed on the World Heritage List, examples being the Semmering Railway, Austria, the three Indian mountain railways, and the Albula-Bernina Swiss line. In all these cases the line itself (track and infrastructure) together with the stations have been recognised as of Outstanding Universal Value but the inscription does not include the rolling stock, because it is moveable. On the other hand, moveable parts of 'machines' inscribed on the World Heritage List are entirely part of the property, examples being the Transporter Bridge of Vizcaya (Spain), the locks in the Canal du Midi (France) and Rideau Canal (Canada) and the hydraulic lifts of the Canal du Centre (Belgium). Here, 'immoveable' and 'moveable' must be understood in their classic juridical sense.

From a science or technology heritage point of view, then, it is clearly essential to extend the inventory to include moveable portions where they form an integral part of the 'monument of science'. It is perhaps necessary to reemphasize that these parts perform actions, need to be maintained, and need to be replaced from time to time. Such an approach has already proved productive in technology heritage.

The example of space heritage clearly shows that there exist certain types of astronomical endeavour for which it is impossible to recognise science heritage sites on the list: only technology heritage sites. In many other cases, the heritage of the science is inseparable from the heritage of the technology, and it is natural to deal with both together in the application of the Convention.

Where features in the natural landscape form an integral part of alignments preserved in architecture, the most productive approach may be to consider two different concepts: cultural landscape heritage that should be included as part of the property, and landscape preservation that forms part of the protection of the setting. The existence of such alignments, and hence the desirability of maintaining the visible landscape in certain directions, could certainly influence the definition of a buffer zone. The definition of the setting is also of critical importance at dark-sky sites, where one needs to ensure the maintenance of the dark sky in the core area (see Chapter 16).

Serial nominations Serial nominations relate to groups of discrete sites that demonstrate outstanding universal value as a group. Within astronomical heritage sites this can arise in three distinct ways:

- where the group represents the material heritage relating to a single, integrated concept;
- where the sites in the group are linked thematically; and
- where the evidence of universal value can only be obtained by considering the group as a whole.

The 34 nodes of the Struve arc (Case Study 14.1) clearly form a group of the first type. The arc itself is a single, integrated concept. The Iberian seven-stone antas (Case Study 2.2) form a group of the third type. Each of the antas in the group was evidently built according to strict prevailing protocols, but *we* need the group as a whole in order to recognise the existence of a specific practice of astronomical orientation and hence to appreciate its significance and demonstrate its value. In this case, the definition of the property also deals clearly with the integrity concept.

A thematically linked group could relate, for example, to architectural typology, types of instrument, types of science or the nature of discoveries. Thematic linkage perhaps holds the widest potential but it also presents the greatest challenges in creating a consistent and valuable (in the sense of OUV) group while avoiding producing what is essentially no more than a catalogue of sites. To take just one example, Strasbourg Cathedral (Case Study 11.3)—which provides another starting point for reflection about astronomical heritage within existing World Heritage Sites—introduces a broader thematic context (medieval astronomical clocks) that might conceivably form the basis of a serial heritage approach, drawing out important new types of value. For this to be successful, though, each member of the group (each clock) would have to contribute effectively and significantly to OUV.

Whether OUV is best demonstrated for any particular theme through a single nomination or a serial nomination, where both possibilities are viable from the scientific point of view, requires careful consideration. Serial nomination may be more globally representative of a particular development or concept, but each element of the series must bear a significant part of the OUV by itself and so the 'weakest link' might bring it down. On the other hand, a single nomination may 'cast a shadow' on other future nominations, since its acceptance (through a comparative analysis) would imply that the one site concerned adequately characterises the OUV of the development or concept in question, and so the others are not needed.

Compromises may be possible. Serial nomination is not the only way of making connections between different sites: other options include twinning and networking between sites already on the List, on the basis of informal agreement. This has proved a successful approach in the case of Biosphere Reserves, linked through UNESCO's Man and the Biosphere Programme.

Credibility as an authenticity issue

The various themed essays and case studies raise a range of matters relating to authenticity and integrity and serve to demonstrate the complexity of the issues involved. To take just one example, the circular Zodiac, the most significant astronomical artefact in the temple of Hathor at Dandara, Egypt (see Case Study 8.3) was removed to the Louvre in Paris, where it is well preserved, and its exact original position is marked by a good-quality replica. The issues of scientific information in context, materiality of the evidence, and position of the evidence, would all be relevant to the question of authenticity in this case.

As we have already noted, the authenticity of a 'fact' is linked to its credibility, as judged by current standards in the relevant academic discipline. The issue of credibility is especially critical where the basic evidence comes from archaeoastronomy, a relatively new and in itself strongly interdisciplinary field of endeavour, where issues of theory and method are still hotly debated. Before accepting the intentionality and putative meaning(s) of astronomical alignments at archaeological, and particularly prehistoric, sites—however self-evident they might appear to the modern eye, or however stunning the associated visual hierophany—it is essential to consider the broader cultural context, balanced where possible with appropriate statistical confirmation. Chapters 2 and 3, and several of the themed essays contained within them, illustrate this point in different ways.

Nowhere are the difficulties clearer than in the oldest evidence of all, presented in chapter 1. Evidence of this type is complex. It is also inherently subjective—there are many stars in the sky and many drawings upon which one might seek to impose an astronomical interpretation—so evidence of this type and has to be weighed up with great care as well as paying sufficient attention to the cultural context.

It is helpful to identify four broad categories of archaeoastronomical credibility, examples of each of which can be found at existing World Heritage sites:

(1) *Generally accepted*. Examples include the alignment of the Neolithic passage grave at Newgrange in Ireland upon the rising sun at midwinter, and the solstitial alignment of Stonehenge in the UK (Case Study 2.1). Nonetheless, while the intentionality of these

alignments is largely undisputed, the interpretation of their purpose(s) and meaning(s) rightly continues to be debated.

(2) *Debated among specialists*. Example: the interpretation of the circular Caracol at Chichen Itza in Mexico as an observatory for watching the risings and settings of the sun, planets and stars. Archaeoastronomers continue to debate this interpretation. Despite the uncertainties, the building is widely referred to as 'the Observatory'.

(3) *Unproven*. Example: the 'equinox hierophany' at the Kukulcan pyramid, again at Chichen Itza. This phenomenon attracts many thousands of visitors each year, but there is no convincing historical or contextual evidence to support the conjecture that it was actually deliberate and intentional. Despite this, it is widely cited as the principal astronomical connection of the site.

(4) *Completely refuted*. Example: the interpretation of four rock-painted symbols at Chaco Canyon, USA as a depiction of the 1054 supernova. Cultural evidence strongly suggests that the symbols marked a sun-watching station for native priests. Yet the 'supernova' remains signposted at the site.

It is not unusual for the number of serious scholarly archaeoastronomical interpretations to be relatively small while the number of highly speculative interpretations available, both in popular publications and on the internet, is much larger—the pyramids of Giza (Case Study 8.4) are a good example. This not only has a serious affect upon public perceptions, but can also start to affect 'official' perceptions, as has occurred for example at Chichen Itza, where the Management Plan is reportedly being revised to take account of the equinox hierophany at Kukulcan.

Another factor that can sway public, and even official, opinion is the perception of certain ancient sites as demonstrating the intellectual achievements of ancestors and hence feeding modern nationalist agendas. A notorious example is the site of Odry, Poland (Case Study 2.3), used for Nazi propaganda during the 1930s. A sense of national pride or political expediency can sometimes be implicit in claims that, for example, a site is 'the oldest observatory' in a given region. The irony is that such attitudes are founded upon a mistaken belief in a single 'path of progress' towards modern science, something that actually places a negative value on other cultural perspectives and practices.

It may well be that a global programme should be developed with a view to helping State Parties identify those archaeological, and particularly prehistoric, sites that might be most credible as nominations to the World Heritage List on the basis of the archaeoastronomical evidence of their association with astronomy.

Ways forward

Many of the issues raised in this Thematic Study will, of course, need to be developed more deeply. In practice, some of this work will inevitably fall upon the writers of potential property nomination dossiers as part of their preparatory work of identification and study. To conclude this summary we wish only to underline a few additional points.

A key issue in the evaluation of a given property is whether its value (in the context of the World Heritage Convention) is local, national, or global. Astronomy, as we have discussed, is just one component among a range of attributes that might define the value of a site. In some cases it may be sufficient to consider the astronomical heritage in the context of the architectural heritage, with the astronomical devices being viewed as only one of a range of architectural attributes defining the value of the monument. The preceding discussion suggests, however, that it will more often be necessary to consider, in a comprehensive and consistent way, the various manifestations of astronomy that are embedded among a broader range of attributes with more complex interrelationships.

The new Intangible Convention adopted by UNESCO in 2003[5] may also provide a way forward. It aims to protect oral traditions and expressions, performing arts, social practices,

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[5] UNESCO (2003). *Convention for the Safeguarding of the Intangible Cultural Heritage*. http://unesdoc.unesco.org/images/0013/001325/132540e.pdf.

rituals and festive events, knowledge and practices concerning nature and the universe, and traditional craftsmanship. To date, it has been mainly been applied to traditions such as pilgrimage and to collective practices concretised by local skills, such as traditional cooking and crafts. The inclusion of knowledge and practices concerning nature and the universe implies that it could and should be extended to scientific behaviours and methodologies.

This suggests in turn that the possibility should be explored of promoting inter-convention nominations for science heritage in general and astronomical heritage in particular.

We have already mentioned the possibility of updating the Management Systems of existing World Heritage Sites that may now be recognised as having astronomical value. For example, the new Management Plan for Stonehenge and Avebury recognises that Stonehenge's astronomical associations form an important aspect of the monument's overall significance, even though this was not part of the reason for its inscription. This leads to the recognition of the importance of maintaining as dark as possible a night sky, and of encouraging night tourism in relation to the site. This type of consideration may be appropriate in many cases.

Conclusion

Astronomy represents a rich and significant aspect of cultural and natural heritage. Recognising this permits us to identify and to clarify astronomical value in the context of the World Heritage Convention and raises serious possibilities of inscribing new properties on to the World Heritage List as well as re-evaluating properties already on the List.[6]

However, it also offers a profound new vision. It raises valuable new heritage concepts, combines different categories of cultural heritage in previously unrecognised and unexplored ways, and highlights hitherto unrecognised types of linkage between cultural and natural heritage. This has important implications for the more effective implementation of the Convention and for helping State Parties create credible nomination dossiers.

We believe that the principal aspects of the vision arising from this Thematic Study are applicable more broadly to science heritage in general, and indeed also to technology heritage (which in many cases has helped us to gain a better understanding of astronomical heritage). In drawing attention to the various issues and challenges in the context of astronomical heritage, it is to be hoped that the broader implications will also be thoroughly pursued. If so, this will be to the lasting benefit of the whole of science and technology heritage.

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[6] The recognition of new types of OUV at these properties can only be achieved through re-nomination.