Astronomy is one of the oldest sciences, and one which has repeatedly led to fundamental changes in our view of the world. This book covers the history of our study of the cosmos from prehistory through to a survey of modern astronomy and astrophysics, itself sure to be of interest to future historians of twentieth-century astronomy!

It does not attempt to cover everything in depth, but deliberately concentrates on the important themes and topics. These include the Copernican revolution, which led to the challenge of ancient authorities in many areas, not just astronomy, and seventeenth- and eighteenth-century stellar astronomy, at the time subordinated to the study of the solar system, but the source of many important concepts in modern astronomy.

Based on the widely acclaimed *Cambridge Illustrated History of Astronomy*, this book is beautifully illustrated throughout, and follows a similar structure and style. However, it is focused to meet the needs of final year undergraduates or beginning postgraduates. This is an essential text for students of the history of science and for students of astronomy who require a historical background to their studies.

Michael Hoskin taught the history of astronomy at Cambridge University for thirty years, and is editor of *The Journal for the History of Astronomy*.

The Cambridge concise history of astronomy

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Edited by
Michael Hoskin

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Preface

University teachers believe that in order to learn a subject, you have first to teach it. The thread running through this book is the history of astronomy as I learned it in three decades of lecturing to Cambridge undergraduates.

All teachers eventually convince themselves that they have seen the wood for the trees. I am no exception, and so I have elected to discuss at length, sometimes at considerable length, those few issues I believe to be of fundamental importance. To make room, questions that other historians might consider important, as well as innumerable lesser topics, are mentioned in passing, if at all.

We concentrate on the development, in the Near East and Europe, of the science of astronomy as the whole world knows it today. Other traditions, such as astronomy in China, and the sophisticated astronomies developed in the New World before the arrival of the *conquistadores*, occupy the attentions of respected historians of astronomy; but here they are described only briefly.

Readers sometimes come to the history of astronomy expecting the discussion to focus on 'who first got it right'. In the present work these expectations will be fulfilled very imperfectly, and this for two reasons.

First, 'getting it right' assumes that science is an onward and uninterrupted accumulation of truth, with theory approximating ever closer to reality. At the factual level, there is something in this. It is difficult to imagine that the claim, dating from Antiquity, that the Earth is roughly spherical will ever be abandoned, or that we shall one day discover that Venus is in fact closer to the Sun than is Mercury. But at a deeper, theoretical level, the development of science is immensely more complex. What has been termed 'normal science' often consists in the gradual clarification and elaboration of what is at first confused, with contributions from many hands. But there are sometimes dramatic and disturbing developments. A century after Isaac Newton's death it was generally believed that he alone of the whole human race had been privileged to announce the fundamental truths of the physical universe – that this announcement had been made once, in 1687, and that the feat could never be repeated. But this complacent view was destroyed by Einstein's root-and-branch reform of the most fundamental Newtonian concepts of space, time, gravitation, and so forth. Yet it would be a poor historian who declared Newton simply to have been 'wrong' and his work therefore unworthy of attention.

Second, today's historians of astronomy see it their duty not to award medals to past astronomers whose opinions coincided with those of their modern counterparts, but to take their readers on an exciting journey. This journey introduces them to lands that are conceptually foreign – to past cultures, that sought as we do to make sense of the heavens, but did so by asking questions often very different from those that we take for granted, and who looked for answers strange to our way of thinking. Historians invite their readers to venture with them into these alien ideas, leaving behind modern assumptions as to the nature and purpose of astronomy, and putting much of our modern knowledge of the heavens onto 'hold'.

For example, Plato's contemporaries observed that the heavens were rotating night after night with constant speed. They saw that there were myriads of 'fixed' stars which, while sharing in this rotation, preserved their positions relative to each other without change; but they also saw, moving among the fixed stars in puzzling fashion, seven 'wanderers' or 'planets': the Sun, the Moon, Mercury and so forth. If, therefore, we are to understand astronomy in the nineteen centuries between Plato and Copernicus, we must put on one side the modern concept of 'planet', and accept the Sun and the Moon as planets. More important still, we must put on one side what we nowadays think of as the job of astronomers, for we are studying cultures in which their job was to contrive, for each of the seven wanderers, a geometrical model from which accurate tables of its future positions could be calculated.

This meant that for nearly two millennia, astronomy was applied geometry. The culmination of this Greek program came with the publication in 1543 of Copernicus's *De revolutionibus*, in which the otherwise-conservative author found himself compelled to make the Earth into a planet in orbit about the Sun. In the early decades of the seventeenth century, Kepler explored the physical implications of this claim – the *forces* at work in the solar system – and he thereby transformed astronomy, moving it from kinematics to dynamics. Not surprisingly, the new concepts developed by Kepler, Galileo, Descartes and their contemporaries were at first vague and confused, and clarification came only in 1687, with the publication of Newton's *Principia*, in which the author claimed that the law of gravitational attraction was the key to understanding the physical universe.

The test of this claim was whether or not the law, when applied to the dauntingly complex solar system, could account for the observed motions of the planets and their satellites, and of the comets. During the eighteenth century and beyond this question occupied the attentions of a tiny band of mathematicians of outstanding genius; and how to deal with their work is a problem for the historian of astronomy. But while their conclusions were of the keenest interest to astronomers, they were not themselves astronomers but mathematicians working in the service of astronomy, and so we can disregard the details of their calculations with a clear conscience.

These 'celestial mechanicians', like their ancient and medieval precursors, were preoccupied with the solar system. The stars were still little more than an unchanging – and therefore uninteresting – backdrop to the movements of the planets, and there was little to be done about them beyond the cataloguing of their positions and brightnesses. Even as late as 1833, the leading authority on the stars and nebulae, John Herschel, published *A Treatise on Astronomy* in which he dealt with these bodies in a single chapter. With rare exceptions, his contemporaries, professionals and amateurs alike, were preoccupied with just one star – namely the Sun – and its satellites.

But since then the balance has tilted sharply in the opposite direction, and today's historian sees that the pioneering eighteenth- and nineteenth-century investigations into stars, nebulae, and 'the construction of the heavens' were to have a profound influence on future astronomical thinking. This book therefore gives more space to early explorations beyond the confines of the solar system than would have seemed proper to astronomers alive at the time.

One issue recurs throughout our account of astronomy in recent centuries: distances. The observer sees the celestial bodies as spread out on the surface of the heavenly sphere; the evidence, that is, is two-dimensional. To theorize about the three-dimensional universe, observers must investigate the third co-ordinate, that of distance.

The story of this investigation is an exciting one, for the successful measurement of the distances of unimaginably remote objects is one of the astonishing achievements of astronomy – even the nearest stars are so far away that their light takes years to reach us. But this remoteness of celestial bodies brings an unexpected bonus, for we see them, not as they are now, but as they were when their light set out on its journey through space. This enables the astronomer to do the seemingly impossible, and look back in time. The more distant the object, the further back in time its light takes us; and today the distances studied are sometimes so great that the objects involved are cited in evidence, for and against cosmological theories of how the universe appeared in its infancy.

When does history end and science begin? Historians are themselves too close to contemporary astronomy to be able to offer a considered perspective. But although it is too soon to see 'Astronomy Today' with historical eyes, astronomy has clearly been transformed in recent decades, and the changes are too dramatic and too exciting for the historian simply to ignore. We therefore end our historical journey by looking around us, at how things stand today in the quest we share with our ancestors both ancient and modern: to understand the universe in which we find ourselves.

The present text is based on that of *The Cambridge Illustrated History of Astronomy*. But whereas the *Illustrated History* was intended for 'the general reader' with a minimal grasp of mathematics and physics, the present text includes certain materials more suitable for those who have studied these subjects at school.

1

Astronomy before history

Clive Ruggles and Michael Hoskin

Most historians of astronomy spend their days reading documents and books in libraries and archives. A few devote themselves to the study of the hardware – astrolabes, telescopes, and so forth – to be found in museums and the older observatories. But long before the invention of writing or the construction of observing instruments, the sky was a cultural resource among peoples throughout the world. Seafarers navigated by the stars; agricultural communities used the stars to help determine when to plant their crops; ideological systems linked the celestial bodies to objects, events and cycles of activity in both the terrestrial and the divine worlds; and we cannot exclude the possibility that some prehistoric and protohistoric peoples possessed a genuinely predictive science of astronomy that might have allowed them, for example, to forecast eclipses.

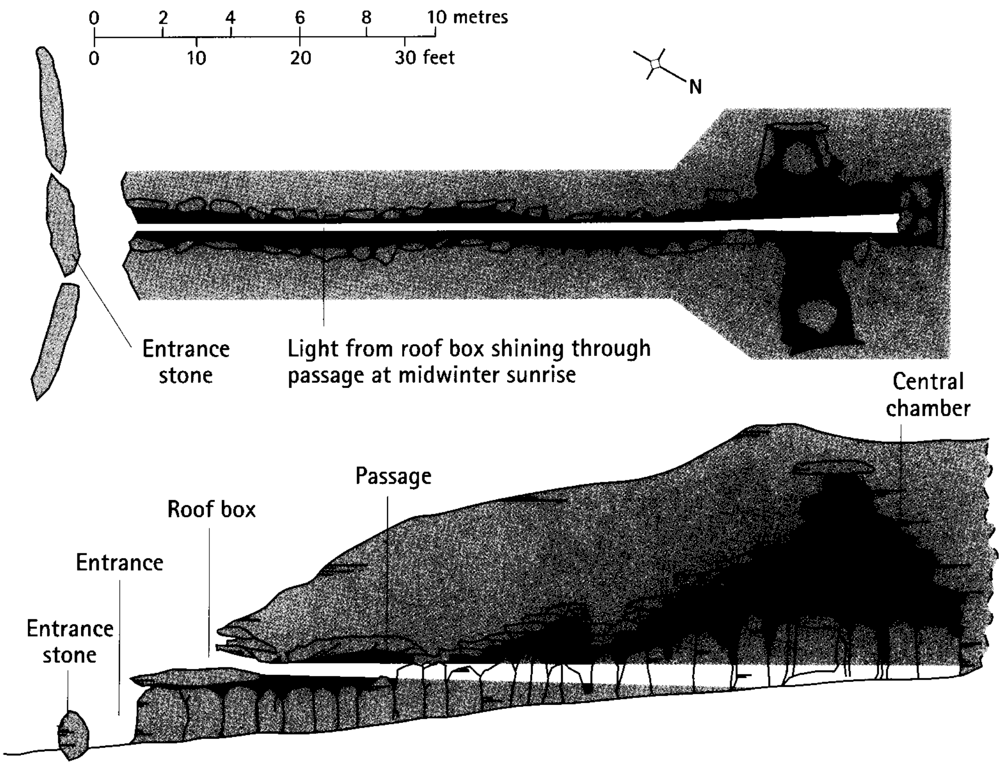
This *History* will concentrate on the emergence of the science of astronomy as we know it today. The historical record shows this development to have taken place in the Near East and, more particularly, in Europe. We therefore begin by asking if anything is known of how prehistoric Europeans viewed the sky, and whether there is any evidence of predictive astronomy. Because it is all too easy for us to fall into the trap of imposing our Western thought-patterns and preconceptions onto the archaeological remains, we also look, by way of comparison, at members of two other groups who viewed or view the sky with minds untouched by Western ideas: the peoples who lived in America before the Spanish conquest, and peoples living today who pursue their traditional ways of life in relative isolation from the rest of mankind.

The celestial phenomena in the two regions most intensively investigated by students of prehistoric and protohistoric astronomy – northwest Europe and the American tropics – are very different. In the tropics the Sun and the other celestial bodies rise and set almost vertically, and for people living there the two times in the year when the Sun passes directly overhead often have special significance. At the higher European latitudes the celestial bodies rise and set along a slanting path and culminate in the south. Around midsummer the days are long, but thereafter the Sun's rising and setting points move steadily further south and the days get shorter and colder: a pattern that threatened disaster, unless the Sun could be persuaded to turn back. Although modern 'Druids' gather at Stonehenge at the midsummer sunrise, the monument's orientation in the opposite direction, towards the midwinter sunset, may well have held powerful symbolism for its builders.

The sky as a cultural resource in prehistoric Europe

Europeans living today enjoy at best the flimsiest of links with the prehistoric peoples who occupied the region. Some links may nevertheless exist. It has been maintained that in Bronze Age Britain a calendar was in use whereby the year was divided into four by the solstices and equinoxes, and each of these four into two and then into two again, giving in all sixteen 'months' of from twenty-two to twenty-four days each; and it may be that vestiges of an eight-fold division of the year survived into Celtic times and hence into the Middle Ages, where they were represented by the feasts of Martinmas, Candlemas, May Day and Lammas in addition to the four Christianized solstices and equinoxes.

Again, legends associated with the huge passage tomb at Newgrange in County Meath, Ireland, built around 3000 BC, make the omniscient god Dagda (or his son) dwell in the monument. Dagda's cauldron was the vault of the sky, and a connection with much earlier practices may be indicated by the modern discovery that the winter sunrise penetrated the furthest recesses of the tomb. From an entrance on the southeastern side, a 62-foot passage leads to a central chamber 20 feet high, from which three side chambers open out. Some time after construction, when the bones of many bodies had been placed in the tomb, the entrance was blocked by a large stone. Yet although the living were excluded, the light of the midwinter Sun continued to enter via an otherwise-inexplicable 'roof-box', a slit constructed above the entrance. For some two weeks either side of the winter solstice, the Sun, on rising, shone down the length of the entrance passage and illuminated the central chamber – as it still does. That this should happen by chance, and that the 'roof-box' has some other explanation, is so unlikely that there is little doubt that Newgrange was



Newgrange, diagrammed from above (top) and in cross-section (below), showing the path of the Sun's rays at midwinter sunrise. The tumulus covering the tomb is some 250 feet across and over 30 feet high.

deliberately constructed to face sunrise at the winter solstice. But we must note that the sunlight was intended to fall upon the bones of the dead, not be seen by the living, and that even a living occupant of the central chamber would have learned only a very approximate date for the solstice.

Even when no such direct links with the past exist, it may be possible to identify with some confidence examples of prehistoric monuments whose construction reflected a concern for the heavens. In the Alentejo region of Portugal, for example, to the east of Lisbon, there are numerous neolithic tombs. Each tomb has an axis of symmetry and an entrance lying on this axis, and so there is a well-defined direction in which the tomb may be said to 'face'. There are scores of these tombs, scattered over a very wide area, yet the directions in which they face all fall within the narrow range of an octant or so – a uniformity that cannot have occurred by chance.

How could the uniformity have been achieved? The terrain is flat, and there is no mountain (for example) that the builders could have used to determine the alignment of the axis as they laid out a new tomb. Nor did these neolithic peoples possess the compass. It seems, therefore, that the custom they were following must have involved the heavens, for only the heavens would have appeared the same from all places throughout this large region.

The orientation of such a tomb is something we can measure, and it is a matter of fact; the high degree of uniformity among the orientations of these tombs is likewise a matter of fact; and the involvement of the heavens in their layout is at least highly likely. On the other hand, we cannot interrogate the builders and they left us no written records, so we have to speculate on the meaning that the orientation of a tomb might have conveyed to its constructors and their contemporaries. Can the range of orientations shed any light on this?

It so happens that each tomb faced sunrise at some time of the year. The south-easterly limit of the tomb orientations coincided with the south-easterly limit of sunrise, at the winter solstice, but most tombs faced sunrise in the late autumn and early spring. The autumn is indeed a likely time of year for beginning the construction of a tomb, for then there would have been less work to be done in the fields and with the animals but the weather was still favourable. We know from historical records that many churches in England were laid out to face sunrise on the day construction began, and that one can calculate possible calendar dates for the beginning of construction from measurement of the orientation of the axis. It seems we can do the same for the Alentejo tombs, and so gain new insights into the annual rhythm of life in neolithic times.

We meet another example of the likely involvement of astronomy in the orientations of prehistoric monuments, in the *taula* sanctuaries on the Spanish Mediterranean island of Menorca, where a Bronze Age culture was at its height around 1000 BC. Such a sanctuary consisted of a walled precinct in the centre of which was the taula, a flat vertical slab of stone set into the ground, with a horizontal stone on top. The front face of the taula looked out through the entrance, nearly always in a southerly direction. Significantly, taulas were invariably located so that worshippers within had a perfect view of the horizon. Why was this important, when today there is nothing of interest to be seen away to the south?

We can find the probable answer by calculating backwards the effect of the wobble ('precession') of the Earth's axis caused by the pull of the Sun and Moon on the non-spherical Earth, which over the centuries alters the stars to be seen from any given location. We find that in Menorca in

1000 BC the Southern Cross was visible: it rose well to the south, being followed shortly by the bright star Beta Centauri, and then by Alpha Centauri, the second brightest star to be seen from the island. This prominent star grouping has been (and is) of great importance in many cultures, and not only in navigation. If, as seems probable, it was associated with the rituals in the taula sanctuaries, we learn something of the religion of the prehistoric people of Menorca; and it may well be that they had links with Egypt, where constellations were routinely identified with deities.

The involvement of the heavens in prehistoric ritual in Europe therefore seems well established. But was there also a quasi-scientific astronomy of precise observation, perhaps even leading to the prediction of astronomical events? In Britain the suggestion that megalithic monuments, now known to have been built in the third and early second millennia BC, incorporated alignments chosen for astronomical reasons goes back to the eighteenth century, while at the beginning of the twentieth century an astronomer of the calibre of Sir Norman Lockyer could write: 'For my own part I consider that the view that our ancient monuments were built to observe and to mark the rising and setting places of the heavenly bodies is now fully established.'

The subject came to popular attention in the 1960s with the publication of a book on Stonehenge in which the author – himself an astronomer – claimed that in addition to the well-known phenomenon of the midsummer Sun rising over the Heel Stone, a great many other astronomical alignments were built into the configuration of the monument. He showed that, given regular observations extending over many years, it was technically possible to use elements of Stonehenge to keep track of the solar calendar, to study the more complex cycles of the Moon, and even to predict eclipses. And this, the author insisted, had indeed been one of its purposes.

If Stonehenge had been one among many similar monuments, these other monuments could have been examined to see if they displayed the same features. Unfortunately Stonehenge is without parallel anywhere in the world – it was an object of wonder even in Antiquity. Its explanation is further complicated by the fact that it was constructed, modified, and reconstructed, over a period of some two millennia. Moreover, the stones we see today may not be exactly in the position they occupied when first erected; and when erected, they may not have been exactly in the position the builders intended. As we cannot interrogate the builders, and as they left no written records of their intentions, we are forced to fall back on probability: we must ask ourselves how likely it is that an arrangement of the stones, that to our eyes is of astronomical significance, has occurred by design rather than by chance. That is, the study of Stonehenge involves us in statistics – and for statistical investigation a unique monument is unsatisfactory.

The least contentious statement that can be made about Stonehenge is that the general orientation of the axis of the monument at various stages in its development was towards sunrise at the summer solstice in one direction, and towards sunset at the winter solstice in the other, and that this may well have been deliberate. A precision equivalent to, at best, two or three solar diameters is involved: the popular notion that the Heel Stone defined the direction of solstitial sunrise more precisely is quite unsupportable, because the supposed observing position (the centre of the monument) cannot be defined precisely enough, while the Heel Stone is too near to provide an accurate foresight and the horizon behind it is featureless.

Most students of Stonehenge have identified certain features at the site and tried to invent a theory to 'explain' them. Even when this is done impartially there are grave dangers in imposing astronomical (and geometrical) frameworks onto what is a very limited sample of the features at this much-altered site – those that today are superficially obvious, those that happen to have been excavated (while large areas of the site are still unexplored), and so on. For example, the Heel Stone is now known to have had a companion, long since destroyed, whose existence was discovered during rescue operations in 1979.

Some of the most famous astronomical theories regarding Stonehenge depend upon statistical arguments that the number of astronomical alignments between pairs of points selected are of possible significance. These arguments fall down on many different grounds: lack of prior justification for the points chosen, and archaeological doubts about some of those that were chosen; numerical flaws in the probability calculation; and, perhaps most importantly, the non-independence of data (for example, except in hilly regions, a line that roughly points towards midsummer sunrise in one direction will automatically point towards midwinter sunset in the other). When these errors are taken into account, no evidence whatsoever remains for preferred astronomical orientations of this sort.

One writer has pointed out that the 56 Aubrey Holes (named after their seventeenth-century discoverer, John

Aubrey) could have been used as an eclipse predictor, if markers were moved around from hole to hole. The problem here is that while this undoubtedly represents a way in which a modern astronomer could use a structure at Stonehenge to predict eclipses, there is ample archaeological evidence to suggest that the prehistoric users of Stonehenge did no such thing. There are in fact dozens of circular enclosures and so-called henge monuments (monuments that resemble the first phases of Stonehenge, before it acquired its distinctive structures of Bluestones and Sarsens) where rings of postholes or ritual pits inside a ditch have been found, and in these the holes vary in number from under twenty to over 100.

On the other hand, in the region around Stonehenge there appears to have been a shift from lunar to solar symbolism as development progressed from the Neolithic into the Bronze Age. This is reflected in the directions in which the burial cairns from each period are aligned, and also in the apparent shift in the axis of Stonehenge from lunar alignment in the earlier phases to solar alignment in the later. A group of post-holes situated in the northeastern 'entrance' – a gap in the ditch between the Aubrey circle and the Heel Stone – may represent evidence that the original construction of the axis was oriented on an extreme rising position of the Moon, though this interpretation remains controversial.

In short, there is good reason to think that the construction of Stonehenge and related monuments embodied astronomical symbolism, but we have as yet no convincing evidence that what we might think of as scientific astronomy was practised there.

While Stonehenge was attracting popular attention (and controversy) in the 1960s, Alexander Thom (1894–1985), a retired Oxford professor of engineering, was quietly continuing the mammoth task he had set himself, of surveying to professional standards the many hundreds of stone rings and other megalithic monuments that survive in Britain, Ireland and northern France. Thom was a collector of facts, and most collectors of facts shy away from speculation. Not so Thom. He maintained, not only that these megalithic monuments were constructed according to complex geometrical designs and laid out using carefully-determined units of measurement (one of which he termed 'the megalithic yard'), but that the prehistoric builders had anticipated an idea later proposed by Galileo and had precisely located their monuments in order to facilitate astronomical observations of great accuracy.

In 1632, in his *Dialogue on the Two Great World Systems*, Galileo has one of his characters relate how he found himself making an accurate determination of the summer solstice, with an instrument provided by Nature free of charge:

> From a country home of mine near Florence I plainly observed the Sun's arrival at, and departure from, the summer solstice, while one evening at the time of its setting it vanished behind the top of a rock on the mountains of Pietrapana, about 60 miles away, leaving uncovered a small streak of filament of itself towards the north, whose breadth was not the hundredth part of its diameter. And the following evening, at the similar setting, it showed another such part of it, but noticeably smaller, a necessary argument that it had begun to recede from the tropic.

Thom believed that the constructors of the megalithic monuments he was studying had anticipated Galileo by three millennia or more. Some standing stones, he maintained, were astronomical backsights; their locations had been carefully selected so that, for example, the Sun at a solstice, or the Moon at one of its extremes, might be glimpsed setting behind a distant mountain, very much as Galileo describes. Priests with knowledge of the dates of these significant solar and lunar events, Thom suggested, might even have been able to predict eclipses and thus reinforce their privileged status in the community.

Not surprisingly, Thom became the centre of controversy: such prehistoric sophistication, especially among the inhabitants of regions remote from the supposed cradle of civilization in the eastern Mediterranean, appeared incredible to many archaeologists. To assess the plausibility of Thom's claims it was necessary to decide whether Thom had focused attention on a particular feature of the skyline as seen from the given site because he already knew it lay in a direction of astronomical interest. Objectors argued that if the skyline contained numerous mountain peaks, one of which was in the direction of (say) the winter solstice, then the alignment of this particular peak with the solstice may well have been accidental.

Thom's sites have since been re-examined under procedures carefully designed to ensure objectivity. The controversy continues, but the re-examination has greatly reduced the plausibility of his claims to have demonstrated the existence in prehistoric Britain of a science of predictive astronomy.

How does the debate now stand? A particularly interesting example of Thom's sites is Ballochroy in the Kintyre peninsula in Scotland. Here there is a row of three standing stones, two of which are thin slabs oriented across the alignment of the row. A few yards away is a rectangular burial cist; this is aligned with the stones, and its longer sides are oriented in the same direction.

Around the solstices, the Sun's rising and setting positions are changing almost imperceptibly: thus in the week before or the week after a solstice, the Sun's rising and setting positions at this latitude alter by only one-third of its diameter. This makes determination of the actual solstices difficult, and the solstices are basic to a knowledge of the annual cycle of the Sun. Thom, however, believed that at Ballochroy the prehistoric erectors of the stones had overcome this problem by the location they had contrived for the stones – one from which the Sun was to be seen at the winter solstice setting behind Cara Island which is on the horizon 7 miles away, and at the summer behind Corra Bheinn, a mountain more than 19 miles distant. Even though the Sun is then altering its setting position from one night to the next by only a few arc minutes, this change becomes apparent to the observer within a very few days of the actual solstice, because of the sensitivity of the vast measuring instrument that Nature has provided. According to Thom, the direction of midwinter sunset was indicated by the alignment of the stones, and that of midsummer sunset by the flat faces of the central stone.

One problem with testing such a theory arises from our ignorance of when, to within several centuries, the stones were erected. Although the directions of solstitial sunrise and sunset at a given location alter only slightly from one millennium to the next, this is enough to make an important difference when we are observing with instruments tens of miles in length. At a site with distant mountains in roughly the right direction, it may well be possible to find a date for the site when it would have had the exceptional characteristics that Thom's theory requires. As to the 'indications' supposedly built into the stones themselves, these are of the kind that tend to be identified by the investigator after he has already convinced himself of the astronomical purpose of the site. It is then that he is likely (in this example) to focus attention on the middle slab (which points roughly in the 'right' direction) rather than on the northernmost (which does not), and to specify the 'intended' alignment of the stones themselves, to a precision quite unjustified for a despoiled (and originally longer) row of three closely-placed, large and irregular stones, two of which are slabs set across the axis. At Ballochroy there is the additional difficulty that the cist would have been covered by a cairn in prehistoric times, and this cairn would have obscured the view towards the midwinter sunset; indeed, the cairn is still to be seen in a seventeenth-century sketch of the site. All in all, then, while there is no doubt that what we may term Thom's Galilean method was feasible in prehistoric Europe (as elsewhere), the claims of this Scottish engineer to have discovered a prehistoric science of predictive astronomy at present merit the peculiarly Scottish verdict of *not proven*.

In conclusion we note that we must avoid a false dichotomy between ritual or folk practice on the one hand and high-level predictive astronomy on the other. Hesiod's description of an early Greek farmer's use of a constellation's heliacal rising (its reappearance at dawn after some weeks of absence lost in the glare of the Sun) to tell the season favourable to planting, is an example of prediction at a low level, and similar predictions are used by farmers in parts of Europe to this day. And since Galileian-type precision observations could have been recorded adequately by backsights consisting simply of poles inserted in the ground, then if stone monuments were indeed erected as backsights, they must also have served another and presumably ritualistic purpose.

Early astronomy in the Americas

The student of prehistoric Europe has virtually no written or oral evidence to guide him, and the monuments he studies are usually modest structures. The complex societies that developed in the American tropics have left a much richer legacy. Many of the buildings that have survived are of great sophistication; investigators have the opportunity to question living descendants; and we possess written records of various kinds – stone inscriptions and other meaningful carvings, documents such as the handful of Mayan bark books known as codices, and detailed accounts from the first Spaniards to come into contact with these cultures.

A strange aspect of Inca society that flourished in Peru at the time of the conquest (in the middle decades of the sixteenth century) has been revealed largely through the study of accounts written by Spanish settlers shortly thereafter. This is the system of *ceques*, conceptual straight lines radiating out from the Coricancha or Temple of the Sun, the central religious monument in the Inca capital of Cuzco. There were 41 ceque lines, along which sacred monuments were located and which served to divide society into different groups. Some ceque lines were oriented astronomically, for example on the rising position of the Sun on the day when it could be seen directly overhead (that is, in the zenith), while others were oriented upon sacred mountains on the horizon; still others were related to water flow and irrigation. Thus we see that such systems of radial lines related spatial divisions on the ground to the divisions in society, to geographical features, and to astronomical events. Astronomy was merely one component of a highly complex system covering many different aspects of society.

Such systems were also present, albeit in less complex forms, in other Inca cities. Indeed, the concept of radiality seems have existed in the Andes even earlier, in pre-Inca times, when systems of straight lines, radiating out from features such as hill tops and cairns, were given physical expression on desert pampas. The most famous such pampa is that at Nazca, in the coastal region of Peru, where there are several dozen 'line centres' with radiating lines constructed by brushing aside the thin layer of brown surface stones to reveal the bright yellow sandy soil beneath. Weather conditions in this region are so stable that these lines have survived to the present day.

Many of the radiating lines join one line centre to another; many are perfectly straight and run for several miles. It appears that they were sacred pathways, and that many factors may have influenced their orientation, just as was the case in the later ceques. Astronomy was one such factor; the direction of water flow was another. While the Nazca lines do not, as has been suggested, represent 'the largest astronomy book in the world', there is little doubt that astronomical symbolism, including alignments on the rising and setting Sun on significant days such as those of its passage through the zenith, features in the construction and use of the lines.

The significance of the Sun's zenith passage is easy to understand. At any given place in the tropics, the Sun spends part of the year to the north, and the rest of the year to the south; but at noon on the day when the Sun passes from north to south, or vice versa, the Sun stands directly overhead. Not surprisingly, zenith passages were also a focus of interest in Mesoamerica, many hundreds of miles to the north. The two days when this occurred could be pinpointed in a simple but very spectacular fashion by the use of so-called 'zenith tubes': when the Sun was directly overhead, its light shone down the tube onto the floor below.

One of the most extraordinary civilizations known to history was the classic Mayan, which flourished in parts of what are now southern Mexico, Guatemala and Belize. The Maya wrote in hieroglyphics, and although nearly all of their bark books were destroyed in the mid-sixteenth century by the invading Spaniards, a handful survived, including two that appear to be detailed astronomical (or rather, astrological) almanacs.

The Maya were obsessed with the passage of time, records of which were inscribed on every form of structure. They used three separate counts of days. The first was a year of 365 days, formed of eighteen months of twenty days each plus an (unlucky) additional period of five days. The second was a year of 360 days or *tun*, used in the calculation of very long periods of time. The third and

The 150-foot image of a spider seen in this aerial view is one of the famous stylistic depictions of animals and birds that occupy a small corner of the Nazca pampa. Much more extensive, however, are trapezoids, rectangles, spirals, and long straight lines, both narrow and wide, some of which can also be seen in the picture. The various features, some obliterating earlier ones, may well span several centuries. Some lines are astronomically aligned, but astronomy is only a small part of the symbolism that brought ritualistic order to an otherwise empty and infertile part of the landscape. Reproduced with kind permission, South American Pictures.

most significant was a sacred almanac of 260 days. Each day of the almanac had a compound name, formed of one of the numbers one to thirteen (which were taken in sequence) and one of twenty names (also taken in sequence).

The day 1 Ahau belonged to Venus, and it was on this day that the cycle of revolutions of Venus had to begin and end. As viewed from Earth, Venus appears to have a cycle (its 'synodical revolution') of fractionally under 584 days, and sixty-five times 584 days equals 146 sacred almanacs of 260 days each. Accordingly, the Venus table in the bark book known as the Dresden Codex covers sixty-five synodical revolutions. However, since the period of 584 days is roughly two hours too long, an adjustment was needed, and this had to be one that somehow preserved 1 Ahau as the beginning date of the Venus cycle. After the sixty-first revolution, the error was between four and five days, the revolution ending on the day 5 Kan which, as luck would have it, was four days after 1 Ahau. The Maya therefore took the opportunity to subtract four days at this point, so that next cycle began again at 1 Ahau. Even this correction left a residual error, and the Codex reveals how further corrections of a similar form were made when the opportunity offered. The final sequence was accurate to some two hours in 481 years.

The obsession with Venus was motivated by astrology: its dawn reappearance after the period of invisibility while it passed between the Earth and the Sun was a time of great peril, and the tables would give forewarning of this and so allow ceremonies to take place that might succeed in warding off the threatened evil. There is no evidence that the Maya took the least interest in other Venus events that, to our geometrical outlook, are of equal if not greater importance.

Immediately following the Venus table in the Dresden Codex is a table that occupies eight pages. It covers some 11,960 days, which equals forty-six sacred almanacs of 260 days. Early in the present century it was noticed that the numbers of days separating the pictures on the pages are familiar to astronomers as intervals between solar eclipses, and it emerged that one function of the table was to give forewarning of these perilous events. The Maya did not possess the knowledge needed to determine whether a solar eclipse would actually be visible from their territory, but no doubt those that were not seen had been averted by the ceremonies prompted by the table.

The table consists principally of totals of 177 (or 178) days, which is the period occupied by six lunar-phase months, with occasional 148-day (five-month) periods. Eclipses take place only when Earth, Sun and Moon are (roughly) in line; seen from Earth, the paths of the Sun and Moon cross every 173.31 days, and a solar eclipse can occur only within a few days of this event. Mayan records must have shown that eclipses took place only during 'danger periods' that occurred every six months (177 days), but the four-day error required the occasional substitution of an interval of five months. The table makes 405 months equal to 11,958 days, which would imply a length of the month only eight minutes short of the modern value.

The table also provides the required calendar pattern involving the 260-day almanac, which in this case had to commence with the day 12 Lamat. The pattern depends upon a remarkable coincidence: three of these natural intervals of 173.31 days equal two of the Mayan 260-day almanacs to within a couple of hours. Occasional adjustments were made for this error, in a way similar to the treatment of Venus intervals.

It must be emphasised that we have been able to give no more than a taste of the tortuous complexities of Mayan calendrics. This unparalleled obsession with the interrelationship of time-intervals, some of them man-made and others supplied by Nature, would be well-nigh inconceivable if we did not possess the written record. But given this obsession, it would not be surprising to find that their buildings incorporated astronomical alignments. The investigator, however, once again faces the problem that each of the complex structures is unique in form, and it is difficult in any given instance to prove that the alignment is intentional rather than accidental. A good example is the Governor's Palace at the great Mayan city of Uxmal in Yucatan (Mexico). This vast building has a different orientation from other buildings on the site, and faces towards what seemed a bump on the horizon but proved to be a huge pyramid some 3 miles to the southeast. Measurements showed that the alignment pointed to the southernmost rising point of Venus, and the suggestion that this was the motivation for the orientation of the Palace found support in the Venus glyphs that are carved on the building. Many similar astronomical alignments have been proposed, and – given what we know of the Maya mentality – it would be surprising if all of them have come about by chance.

The sky as a cultural resource today

The Maya are an example of a highly sophisticated civilization whose interests in astronomy were alien to our own: we shall go astray if we impose our own thought patterns on those outside the European tradition.

The same lesson is taught us with equal force by living societies that are close to nature. In Africa an example of a people whose calendric preoccupations are very different from ours is provided by the present-day Mursi of southwest Ethiopia. They depend for their subsistence on rain cultivation, flood cultivation, and herding, and the timing of their annual migrations from one region to another is crucial. Yet they have no 'scientific' calendar such as we might expect. Their year consists of thirteen months, and so is eighteen days longer than the solar year. But their calendar keeps in step with the seasonal year, not by the occasional omission of a month, but by a process of institutionalized disagreement with continuous adjustment. The balance between divergent opinions as to what stage of the year has been reached is influenced by discussion of seasonal markers such as the appearance of birds, the flowering of plants, and horizon observations of the Sun, *all* of which are seen as inexact. However, one crucial event – the annual flooding of the River Omo – is monitored outside the calendar by the last sunset appearance for some weeks of four stars in Centaurus and the Southern Cross. Thus to our eyes it would seem that in this one instance where precision in timing is vital, the Mursi do in fact use a precise rather than a haphazard method of determining the time of year. But the Mursi do not see it in this way. To them, there is a direct association between these stars and the River Omo and certain flowers and plants: the successive disappearance of the stars in the morning sky is correlated with terrestrial events such as the flooding of the river and the flowering of the plants.

Such direct associations between the celestial and the terrestrial are common among native societies. The Barasana people of the Columbian Amazon, for example, perceive a 'Caterpillar Jaguar' constellation which is the father of caterpillars on Earth: as the constellation rises higher and higher in the sky at dusk, so terrestrial caterpillars increase in numbers. To us this is the result of the coincidence whereby the constellation happens to be in the eastern sky at dusk at the time of year when the caterpillars pupate and come down from the trees on which they feed; but to the Barasana this is cause and effect.

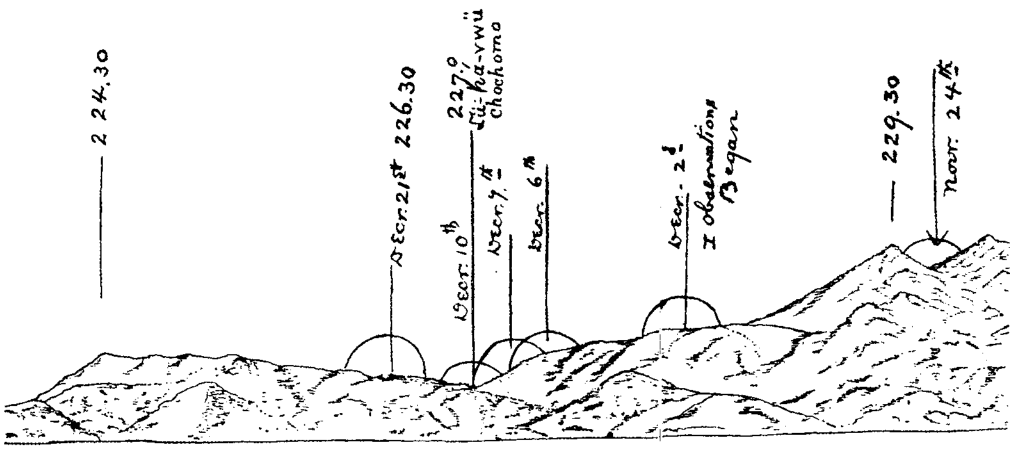
To the people of the remote Andean village of Misminay, the association between earth and sky is stronger still. The Milky Way is regarded as a celestial river which is a reflection of the terrestrial Vilcanota river, and the two are perceived as parts of an integrated system that serves to circulate water through the terrestrial and celestial spheres. The Milky Way is directly overhead the village twice in every twenty-four hours, and it chances that the directions it then makes are at right angles to each other. This results in a conceptual quartering of the sky, which is reflected on the ground in the very layout of the village itself: radiating out from the central building (now a Catholic church) are four paths, together with irrigation channels, that divide the village into four quarters. For the villagers of Misminay, observations of the various celestial bodies are an integral part of their agricultural and pastoral activities and festivals. Some aspects of the system of practice and beliefs found here and in neighbouring villages can be traced back at least as far as Inca times.

Past traditions of the native Americans can sometimes be recovered, for their descendants are with us and can be questioned, and aspects of their practices still survive. A particular study has been made of the Hopi of Arizona. Their cardinal directions are not our north/south/east/west, but the directions to the points on the skyline where the Sun rises and sets at the solstices. The beginning of their winter solstice ceremony (Soyal) is decided by the Sun Chief and the Soyal Chief, who together observe the Sun from their village as it sets in a distant notch in the San Francisco peaks 80 miles away. Soyal lasts for nine days, and begins four days after the chiefs have made satisfactory observations. Calculations show that the Sun sets in the notch between one and two weeks before the solstice, so that the solstice occurs after the ceremonies are well under way. It is interesting that even when the notch in the skyline is so very distant, it has proved desirable to observe the Sun some time prior to the actual solstice, when it is still moving perceptibly from one day to the next.

The remaining chapters of this book will be devoted to the developments in the Near East and Europe that led to the science of astronomy as the whole world knows it today. They will rely mainly on written evidence, supplemented by what can be learned from the instruments that are preserved in museums and observatories.

Written evidence survives in quantity only from the last centuries before Christ. In the present chapter we have seen something of cultures that antedated those of Babylon, Egypt and Greece, cultures that flourished in Europe in the second, third and even fourth millennia BC. Our attempt to infer what was in the minds of such prehistoric builders has been based mainly on what is left of the stones they used in their monuments. By looking at modern peoples whose cultures have been little affected by Western ideas – and by seeing something of American cultures that preceded the Spanish conquest – it has become evident that our preoccupations in studying the sky are by no means the only ones, and that our attempts to interpret these silent stones are fraught with danger.

As we now turn to the historical records, and read what our predecessors actually wrote, we are on safer ground. But the temptation to impose onto these writings our attitudes, our interests, and our factual knowledge of astronomy, is all the more insidious. It must be remembered that history of astronomy is a journey back in time to cultures alien to our modern thinking, and that, like good anthropologists, we must try to see the world through the eyes and minds of those cultures. What gives the history of astronomy its special interest, is the fact that its object of investigation – the sky that prehistoric, ancient and medieval cultures sought to understand – is the same sky that modern astronomers explore.



A Hopi horizon calendar, sketched by the anthropologist Alexander M. Stephen who lived among the Hopi in the 1890s. It shows a Sun priest's observations for the purpose of timing midwinter ceremonies. The Sun's setting in the notch that it reached on 10 December (between peaks of the San Francisco range near Flagstaff, Arizona) was the signal to begin in four days the nine-day celebration of the winter solstice. The solstice occurs on or about 22 December. From A. M. Stephen, *Hopi Journal*, Part II, Map 4, 1936, by permission of the Syndics of Cambridge University Library.