PART 1
GENERAL ASTRONOMY

Cambridge University Press
978-0-521-89994-9 - Encyclopedia of the History of Astronomy and Astrophysics
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Excerpt
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ANCIENT ASTRONOMY OVERVIEW

Pre-telescopic astronomy is considered in this survey article in four broad geographical areas based on cultural contacts, regional developments and astronomical traditions. This article is then followed by individual, more detailed articles as indicated in the text.

Africa, Europe, Middle East and India

Not only have the earliest human remains been found in Africa, but so has the earliest physical evidence of astronomical activity. This appears to be a lunar calendar found on an Ishango bone which has been dated at about 23,000 to 18,000 BC (see *Sub-Saharan Africa*). The earliest megalithic structure that appears to be of astronomical significance is that at Nabta Playa, also in Africa, which has been dated to around 5000 to 4000 BC (see *Megalithic astronomy*). The earliest parts of Stonehenge in England, on the other hand, are at least 1,000 years younger, as is the passage tomb at Newgrange in Ireland.

There are thousands of megaliths all over the world, some of which have astronomical significance, built by civilisations of widely different cultures. These civilisations had no contact with one another, as far as we know. But that is not true of ancient Egypt, which was later linked to Babylon and Greece. In these three civilisations we have written records to assist our understanding, which are missing for the early megalithic builders.

The Egyptians had studied the sky since before 3000 BC for both religious and practical reasons (see *Egyptian astronomy*). Their most important gods were the Sun god, Ra, and Nut, the goddess of the sky, who was depicted stretched across the sky as the Milky Way. The heliacal rising of Sirius (Sothis) was also important to the Egyptians, as they used it to predict the annual Nile floods.

The earliest known Egyptian calendar, which was used for both religious and agricultural purposes, consisted of 12 months of 29 or 30 days divided into three 4-month seasons of 'inundation', or flooding of the Nile, 'growth' and 'harvest'. An extra month was added every two or three years in Lower Egypt to ensure that the festival of the birth of Ra occurred in the last month of the year. The same was done in Upper Egypt to ensure that the festival of the heliacal rising of Sothis was in the last month. When Upper and Lower Egypt were unified in about 3000 BC the Upper Egyptian scheme was used.

Astrology was the main driver behind early Babylonian astronomy of the Hammurabi dynasty of about 1895 to 1595 BC, particularly that connected with the visibility of the Moon and planets (see *Babylonian astronomy*). This required the priests to carefully observe the motions of these bodies across the sky, so they could be analysed and predictions made of their future positions. Over the centuries, the Babylonians developed many techniques for these predictions, in the process producing highly accurate estimates of the synodic and sidereal periods of the Sun, Moon and planets. Those of Jupiter, for example, in the second century BC, were accurate to within 0.01%.

The Babylonians saw the sky in two dimensions, whereas the Greeks, who were philosophers, saw it in three (see *Greek astronomy*). They wanted to understand the structure of the universe and explain why the celestial objects moved in the way they did. Thales of Miletus was apparently the first to do this in the sixth century BC, and he is thought by some ancient sources to have discovered the cause of eclipses. A little later, the Pythagoreans hypothesised that the universe consisted of a spherical, non-spinning Earth surrounded by a series of concentric, crystalline spheres that carried the Sun, Moon, planets and stars.

In the fifth century BC, Hicetas of Syracuse suggested that the Earth spun on its axis, but this idea was generally rejected. About two hundred years later Aristarchus of Samos suggested that the Sun, not the Earth, was at the centre of the universe, but this idea was also generally ignored until Copernicus resurrected it about 1,700 years later.

Many of the later Greeks, including Hipparchus and Ptolemy, lived in Egypt, where Eratosthenes measured the diameter of the Earth to a few percent of its correct value in the third century BC. In the next century, Hipparchus estimated the rate of precession of the equinoxes and produced the most accurate star catalogue to date. Three hundred years later, Ptolemy wrote his *Almagest*, which included his star catalogue, and *Planetary Hypotheses*, in which he proposed a geocentric model of the universe based on epicycles and equants. Its largest deficiency was probably that it predicted that the Moon's apparent diameter, as seen from Earth, would vary by a factor of two, which it clearly did not do.

It is unclear how much Babylonian work was known to the Greeks. But the victory of Alexander the Great over the Persian empire in 331 BC certainly improved communications between Greece and Babylon for a while, until the Seleucid empire collapsed in the following century. In the case of India, however, there had been some contact between India and Babylon prior to Darius I's conquest of north-west India in 515 BC, but this conquest naturally produced a greater influx of Babylonian ideas into India (see *Indian astronomy*). So in the fifth century BC, for example, Indian astronomy was a mixture of indigenous astronomy, which involved the sky being divided up into 27 lunar mansions, and methods for predicting the movement of celestial bodies which clearly came from the Babylonians.

In 326 BC, Alexander the Great brought Greek influence to India when he conquered the north-west of the country. Over the next few centuries, Indians translated various Greek and Babylonian works into Sanskrit. Then, in about 425 AD, Indian astronomers devised a new model of the solar system that eliminated Ptolemy's equant. A little later Aryabhata wrote a book, later called the *Aryabhatiya*, in which he recognised that the apparent rotation of the heavens was caused by the Earth rotating on its axis. He produced an accurate estimate of the size of the Earth, and determined the length of the sidereal year to within just 4 minutes.

The prophet Muhammad was born in about 570. Over the next 150 years the Islamic empire expanded to include Spain in the west, and north-west India in the east (see *Islamic astronomy*). The caliph Al Mansūr decided in 762 to move his capital to Baghdad. He then started a major attempt to obtain copies of as many astronomical texts as possible and have them translated into Arabic. This resulted in many Indian and Greek texts being translated. As a result, early Islamic astronomy was a mixture of indigenous work, together with Indian, Persian and Greek astronomy.

In the tenth century, Abd al-Rahman al-Sūfī produced the first significant revision of Ptolemy's star catalogue, followed a little later by Ibn al-Zarqāllu, working in Spain, who produced the *Toledo Planetary Tables*. At about this time a number of Arab astronomers started questioning whether the Earth really was at the centre of the universe, and also expressed a strong dislike of Ptolemy's equant. Then, in the fourteenth century, Ibn al-Shātir succeeded in getting rid of Ptolemy's equant. Interestingly, the movement of the Sun in al-Shātir's geocentric universe was similar to that of the Earth in Copernicus' heliocentric universe.

Unfortunately most ancient Greek astronomical texts disappeared from Europe after the fall of the Roman empire in the fifth century, and it wasn't until the eleventh century that copies began to arrive back in Europe through Islamic Spain (see *European astronomy in the Middle Ages*). The route by which these Arab translations reached Europe was severed in the thirteenth century with the overthrow of the Moors in Spain.

Aristotle's philosophy was taught in European universities in the Middle Ages. That, and the constraints placed on astronomy by the teachings of the Christian Church, had a profound effect on the development of the subject. But some thinkers attacked various of Aristotle's teachings. For example, in the fourteenth century, Thomas Bradwardine attacked the Aristotelian idea that the universe was finite in size, and Jean Buridan dismissed Aristotle's idea that the planets were in motion only because they were each subjected to a continuous force. Instead, Buridan suggested that the planets had been set in motion at their creation and were still moving as they were subject to no resistance.

In 1543, Copernicus published *De Revolutionibus Orbium Caelestium* in which he described his heliocentric theory of the universe. His idea of a spinning Earth in a heliocentric universe was not new, having been proposed by Aristarchus in the third century BC. But the time was now ripe in a Renaissance that was eager for new ideas. Copernicus' theory was based on circular motion and, like Ptolemy's theory, depended on epicycles, although he had deleted the equant. But Copernicus had broken with the Aristotelian concept of a non-spinning Earth at the center of the universe. Then in 1577 Tycho Brahe disproved another of Aristotle's ideas. Aristotle had believed that comets were in the Earth's atmosphere, but Tycho was unable to measure any clear parallax for the comet of 1577. So it could not have been in the atmosphere, and must have been appreciably further away than the Moon.

China and Japan

A rock carving on a cliff at Jiangjumya, which depicts the Milky Way, shows that Chinese astronomy dates back to at least 2000 BC (see *Chinese astronomy*). Oracle bone fragments from An Yang show that by 1400 BC the Chinese had adopted a lunisolar calendar, which consisted of 12 months of alternately 29 and 30 days. Every now and again the Chinese added an intercalary month to keep the lunar and solar years in step. By the late sixth century BC, they realised that the phases of the Moon recur on the same day of the solar year every 19 years. A similar discovery had been made in the West at about the same time. But it was not to be formalised, by Meton of Athens, for another hundred years.

The Chinese had divided the sky into 28 lunar mansions from at least the sixth century BC, whilst the Indians seem to have adopted this concept a little later. The origin of the lunar mansions idea is obscure, however, with many conflicting theories ascribing it to China, India, Mesopotamia, Persia or Egypt.

The Chinese were keen to observe and record any unusual celestial events, and they have left us with the longest unbroken set of astronomical records in the world, dating back to about the sixth century BC. These included extensive records of solar eclipses, comets and new stars. By the first century BC the Chinese understood the real cause of eclipses, and by the third century AD Yang Wei was able to predict the timing of total solar eclipses.

Astronomy was gradually introduced into Japan from China, via Korea, in the sixth century AD, and by the end of the next century the Japanese had adopted the Chinese calendar (see *Japanese astronomy*). Excavation of seventh and eighth century Japanese tombs have revealed ceilings with star charts divided into the 28 lunar mansions. In one case the ceiling showed both the ecliptic and the celestial equator. Both the Japanese and Chinese recorded the new star or supernova of 1054. Thereafter, astronomy gradually stagnated in Japan until the arrival of Jesuit missionaries in the sixteenth century.

The American Continent

The pre-conquest peoples of South America did not develop a written language, and so their history is difficult to interpret (see *South America and the Incas*). The earliest known astronomical alignments in the Americas are at a temple at Buena Vista, near Lima, Peru, which had alignments to both the summer and winter solstices. The temple dates from about 2200 BC. A more complex set of alignments of thirteen towers was found in 2007 at Chankillo, Peru, dating to about 300 BC. Fifteen hundred years later, the Inca built similar structures as part of their horizon-based solar calendar. They, like many other civilisations, also linked the visibility of the Pleiades to their agricultural calendar.

Unlike the Incas, whose known culture seems to have dated from about 1200 AD, the Mayan civilization of Central America dates back a further fifteen hundred years (see *Mayan astronomy*). Also, unlike the Incas, the Maya had developed a written language. This showed that their astronomy had much in common with that of Babylon even earlier still. Both were interested in analysing observations to produce numerically-based predictions of the movements of celestial objects.

For a long time the Maya had two calendars running in parallel: a religious calendar of 260 days and a solar calendar of 365 days, consisting of eighteen months of twenty days, plus five 'nameless days'. As $52 \times 365 = 73 \times 260$, the two calendars repeated after exactly 52 solar years in what was called the 'calendar round'.

Venus had a very important position in Mayan religious observance, as it was seen as a companion to the Sun. Human beings were sacrificed on Venus' first appearance after superior conjunction, and wars were often started based on the Mayan Venus calendar. The Maya recognised that Venus made its heliacal rising almost exactly on the same date in the solar calendar at eight year intervals. In the thirteenth century Dresden codex, the extensive Mayan Venus table made predictions accurate to within one day at the end of 481 years.

It is not clear which civilisation built Teotihuaćan, near Mexico City, which is a large pyramid complex probably built between about 200 BC and 100 AD (see *Central Mexico and the Aztecs*). By the time of the Spanish invasion in the sixteenth century, however, the area had been settled by the Aztecs who continued with the practice, also carried out by the pyramids' builders, of human sacrifices to Venus at its heliacal rising. The Aztec calendars were virtually identical to the 260 day and 365 day Mayan calendars. Every 52 years the Aztecs held a ceremony, called the 'Binding of the Years', when their own 260 and 365 day calendars became temporarily in step.

Evidence of any astronomical activity in North America before the arrival of the Europeans is very sparse (see *North America*). Some of the indigenous Indian tribes, like the Hopi people, used horizon-based solar calendars. In addition, some of the petroglyphs (carvings) and pictographs (paintings) at Chaco Canyon, New Mexico also appear to have astronomical significance, although their exact nature is disputed.

The Pacific Basin

The astronomical culture of the Australian Aborigines (see *Australian Aborigines*) goes back thousands of years. Like indigenous cultures all over the world, these Aborigines used the movement of the Sun and the risings and settings of various stars to regulate their agricultural calendar. But, unusually, they were often more interested in the colours and patterns of the stars than in their intensities. They were particularly interested in the Milky Way, which they called the Emu in the Sky, and recognised planets, comets and meteors. One aboriginal tribe noticed the link between the tides and the phases of the Moon, and another realised that a total solar eclipse was caused by the Moon passing in front of the Sun – but, in the latter case, this was interpreted mythologically.

The Polynesians progressively colonised their small Pacific Islands from about 1500 BC to 400 AD, navigating by the stars over vast distances (see *Polynesian and Maori astronomy*). They moved on to New Zealand later. The Polynesian and Maori people, like many other ancient civilisations, observed comets and meteors, and the Hawaiians had names for the celestial paths followed by the Sun at the solstices. Interestingly, the Polynesians called the Sun Ra, like the Egyptians, which seems a remarkable coincidence, as there is no evidence of any contacts between the two cultures.

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ANCIENT (PRE-TELESCOPIC) INSTRUMENTS

Armillary sphere

The armillary sphere was a development of the equinoctial armilla, which consisted of a single ring fixed in the plane of the equator, which was used to determine the arrival of the equinoxes. To this was added a ring fixed in the plane of the meridian to make a solstitial armilla to measure solar altitudes. In its final form, the full armillary sphere had numerous rings, including those representing the tropics, polar circles, and the ecliptic. In the observational armillary the number of rings was kept to a minimum, and some of the rings were partial with sights and angular markings, whereas in the demonstration armillary, which was used for teaching, the rings were complete. Usually a ball representing the Earth or, later, the Sun was placed at its centre, the first instrument being called a Ptolemaic armillary and the second a Copernican.

It is thought that Eratosthenes (c. 276–195 BC) used a solstitial armilla for measuring the obliquity of the ecliptic, and that Hipparchus (c. 185–120 BC) probably used an armillary sphere of four rings. Ptolemy (c. 100–170 AD) produced an astrolabon, which was a form of armillary, to determine the location of celestial bodies in ecliptic coordinates. Observational devices were used at the Marāgha observatory in Persia in the thirteenth century, and at Samarkand in the fifteenth century. In Europe, Bernhard Walther (1430–1504) undertook numerous measurements of the latitude and longitude of the planets using an armillary. Tycho Brahe (1546–1601) made a 1.2 m diameter zodiacal armillary for measuring latitude and longitude in ecliptic coordinates. He later made a number of equatorial armillaries, which could be larger as they had fewer rings, for measuring right ascensions and declinations. His largest such device was 2.7 m in diameter.

The Chinese also developed the armillary sphere, or *hun yi* ('celestial sphere instrument'). In 52 BC Geng Shouchang introduced the first permanently fixed equatorial ring, and in 84 AD Fu An and Zia Kui added an ecliptic ring. A water-driven armillary sphere was apparently built by Zhang Heng in 132 AD. Another, much larger armillary sphere was built at Kaifeng by Su Song in 1088, linked to a large, water-driven, public mechanical clock, which allowed the observer to track celestial objects across the sky. Then in 1270 Guo Shoujing produced an equatorially-mounted armillary ring, or *jian yi* ('simplified instrument'), which rotated about an axis pointing to the celestial pole. The detailed arrangement was a forerunner of what is now called the 'English Mounting' used for some astronomical telescopes.

There are various mentions of armillary spheres in historical writings, but some of the descriptions are unclear, so it is not absolutely clear that they are describing an armillary. Ptolemy mentioned armillaries in his *Almagest* of about 150 AD. In the eighth century the Islamic astronomer al-Fazārī wrote a treatise on the armillary sphere, which he called *dhāt al-halaq* ('instrument with rings').

Astrolabe

There are a number of types of astrolabe, of which the plane or planispheric astrolabe was by far the most common amongst astronomers. It was a flat, circular wooden or brass instrument, suspended by a ring. On one side was a moveable sighting bar which was used to measure the altitude of celestial objects. On the other side was a stereographic projection of both the heavens and the altazimuth coordinates for a particular latitude. It was used, amongst other things, to determine the rising and setting times of the Sun and stars, and to determine the time during daylight or at night. It could also be used as an analogue computer to solve mathematical problems.

The astrolabe appears to have been invented by the Greeks. Apollonius of Perga (c. 265–190 BC) and Hipparchus (c. 185–120 BC) undertook significant work on mathematical projections, and Hipparchus may well have made the first instrument, but the evidence is circumstantial.

Theon of Alexandria (c. 335–400) wrote a treatise on the astrolabe that is now lost. It appears to have been the basis of John Philoponus (also called Joannes Grammaticus) of Alexandria's treatise of the sixth century, and that of Severus Sebokht of Syria in the following century. The astrolabe was developed by the Islamic Arabs who used it for astronomical and astrological purposes, as well as to schedule morning prayers. According to Ibn al-Nadīm in the tenth century, the first person to build an astrolabe in the Islamic world was al-Fazārī in the eighth century. Al-Battânî (or Albategnius) (c. 855–929) certainly used one at ar-Raqqah in Syria at the end of the ninth century. The earliest surviving astrolabe is dated 927/8.

Astrolabes came to Europe via Islamic Spain in the tenth century. There Ibn al-Zarqāllu (or Azarquiel) (c. 1029–1087) made a major improvement in their design when he produced a universal astrolabe, called a saphea, that could be used at different latitudes. It was further developed by Ibn al-Sarrāj of Aleppo in Syria when he made an even more universal instrument in the early fourteenth century. This device, which was far more sophisticated than any of the later European

Renaissance instruments, was to be the high point of Islamic astrolabe making.

The astrolabe was not common in Europe until the thirteenth and fourteenth centuries, when it was also used as an educational tool. In 1391 Geoffrey Chaucer (c. 1343–1400) wrote a treatise on the astrolabe, which was the first technical treatise on any subject to be written in the English language. The astrolabe peaked in popularity in Europe in the fifteenth and sixteenth centuries.

In 1370 Mahendra Sūri translated a Persian text on the astrolabe into Sanskrit. Then in 1393 Parameśvara started a long series of eclipse observations, using an astrolabe, in Southern India. This was the first use of an astrolabe, as far as we know, in the south of the subcontinent. Astrolabes continued to be made in India until the end of the nineteenth century.

Cross-staff

The cross-staff was a simple device for measuring the angle between two celestial objects. It consisted of a sighting pole or staff, with one or more cross-pieces that could be slid along it. It was first mentioned by the French astronomer Rabbi Levi ben Gerson in 1328, who used it to measure the altitude and separation of the stars and planets, and the diameter of the Sun and Moon.

Quadrant

There were several types of quadrant, including a sine quadrant, which was used to solve trigonometrical problems; an horary quadrant, for measuring the time of day with the Sun; a geometric quadrant; and a mural quadrant. In the geometric or 'old' quadrant, the celestial object was viewed along one edge of the metal quadrant, and a plumb bob hanging over a calibrated scale measured its altitude. In the mural quadrant, the measuring scale was fixed to a wall, and the celestial object viewed from the scale through the centre of the quadrant. There was also a 'new' or astrolabe/almucantor quadrant, described by Jacob ben Mahir in the thirteenth century, which was a mixture of a quadrant and an astrolabe.

The origin of the various quadrant designs is unclear, but they were clearly used by Arab Islamic astronomers. Probably the best known instruments to pre-date the telescopic age were both built by Tycho Brahe. In about 1569 he built a 4.5 metre radius, wooden quadrant near Augsburg that could be rotated in azimuth for measuring altitudes. Then in 1582 he built a 2 metre radius great mural quadrant which was aligned with the meridian and mounted on a wall at his Uraniborg observatory.

Sextant

There were two basic forms of astronomical sextant prior to the invention of the telescope – the mural sextant and framed or frame-based sextant. They were called 'sextant' as they covered an arc of one-sixth of a circle or sixty degrees. The mural version was by far the earliest.

The first known mural sextant was constructed in Rayy, Iran by Abū Mahmūd al-Khujandī in 994. Called the al-Fakhrī sextant, after his patron, it covered a sixty degree arc on a wall, had a radius of 20 metres and was aligned with the meridian. He used it to measure the obliquity of the ecliptic. Ulugh Beg also constructed a Fakhrī sextant at Samarkand in 1420 with a radius of 40 metres, also aligned with the meridian. It was used by a team of astronomers led by Ulugh Beg to produce a star catalogue. They also determined the obliquity of the ecliptic.

Tycho Brahe seems to have invented the frame-based sextant to measure the separation of astronomical objects, because of problems with the cross-staff. He made a number of frame-based sextants, improving their design over time. Basically two observers were used to measure the separation of objects, viewing from the calibrated arc of the sextant through a pointer at the centre of the arc. One person observed along the fixed radius at one object, and the other observed along the movable radius at the other. The angular separation was then read off from the calibrated arc. Tycho's sextants were made of wood and brass and usually mounted on a type of universal joint.

The design of the sextant was radically changed after the invention of the telescope, but these are outside the scope of this article.

Sundial

The gnomon, a simple vertical post, was the first device to enable people to tell the time of day using the Sun. About 3000 BC the Egyptians built obelisks, which were tall, four-sided, tapering stone monuments which enabled them to tell the time by the position and length of their shadows. The obelisks could also be used to tell the solstices from the lengths of their shadow at mid-day. In the *MUL.APIN* of about 1200 BC the Babylonians gave the length of the shadow cast by a vertical rod one cubit (about 45 cm) high at various times of year. Many centuries later, Eratosthenes of Cyrene (c. 276–195 BC) estimated the diameter of the Earth by measuring the different angles of the Sun to the vertical on midsummer's day in Alexandria and Syene (now called Aswan) using a gnomon.

The shadow clock seems to have come into use in Egypt in about 1500 BC. It consisted of a vertical 'T' piece, with the long top of the 'T' horizontal. The 'T' was attached to the end of a long horizontal beam on which the top of the 'T' cast a shadow of varying lengths. This horizontal beam, which was pointed due west (with the 'T' piece at the east end) in the morning and due east in the afternoon, had 5 hourly markings on it.

This enabled the Egyptians to divide the day into 10 'hours', plus one twilight 'hour' at either end. The shadow clock had the advantage over the simple gnomon in that it was portable, although the time measured was only very approximate.

The earliest description of a sundial in approximately its modern arrangement comes from Berossus, a Babylonian priest, in about 290 BC. It is a half-spherical bowl cut out of a block of stone with a small gnomon in the centre and twelve markings to one side of the gnomon to show the hours. A short while afterwards, a sundial, which had been captured from the Samnites, was set up in Rome.

As time progressed different designs of sundials proliferated. Their gnomons were usually either vertical with a horizontal receiving plate, horizontal with a vertical plate, or pointing to the north celestial pole. In the latter case the Sun rotated uniformly around the gnomon, so the hour lines were equally spaced on a plate perpendicular to the gnomon. People also experimented with various shaped receiving plates for the shadow. In about 25 BC Vitruvius, in Book IX of his *De Architectura*, listed many different types of sundials and their inventors, most of them Greek. Fifteen years later the Solarium Augusti, a giant sundial built by the Emperor Augustus, was dedicated to the Sun. It was built in the Campus Martius to commemorate his victory over Egypt in 30 BC, and used a 22 metre high obelisk imported from Heliopolis as the gnomon. Both the obelisk and some of the inscribed marble pavement that had surrounded it still exist, although the obelisk was re-erected in the Piazza di Montecitorio at the end of the eighteenth century.

Apparently the Islamic Caliph Umar ibn 'Abd al-'Azīz (682–720) used a sundial in about 718 to regulate the times of prayers. In about 820 the Islamic mathematician Al-Khwārizmī (780–850), in his treatise on sundials, produced extensive tables showing the polar coordinates of the intersections of the hour lines with the shadows on horizontal sundials for different latitudes. Shortly afterwards Thâbit ibn Qurra (836–901), in his treatise on sundial theory, gave the mathematical theory for constructing sundials in any plane. Eventually most of the major mosques had their own sundials to enable them to time daily prayers. In 1371–2 Ibn al-Shātir (1304–1375) designed a magnificent sundial for the main minaret of the Umayyad Mosque in Damascus that could be used to measure time relative to any of the five daily prayers. It was accidentally broken in the nineteenth century, but fragments of the original and a copy still exist.

Water clock

The water clock was an important tool in the ancient world for timing astronomical phenomena. Our first direct evidence of such a device comes from the inscription in an Egyptian tomb of about 1520 BC, although it was probably used in both Egypt and Babylon before then.

The early Egyptian water clock, which was an outflow type, was used to measure time at night. It was like a stone bucket with sloping sides. Water was poured into the top, and it dripped out via a very small hole near the bottom. The Egyptians divided the night into twelve hours throughout the year, so the hours were shorter in summer than winter. To allow for this, there were a number of vertical scales inside the water clock that denoted the hours of night throughout the year. During daylight, the Egyptians measured time using shadow clocks, although water clocks may also have been used.

Early water clocks in Babylon were also of the outflow type. They were cylindrical in shape and, instead of having internal scales, the hours were determined by the volume of water coming out. In the earliest times their main use seems to have been to measure the length of the three night watches. A measured amount of water was put into the cylinder at the start of the watch, and the watch ended when it was empty. As the nights varied in length over the course of a year, different amounts of water were required. Initially, the amount used was varied only four times a year, but by about 500 BC it was changed every 5 days. Water clocks of similar design were in use in India at about this time. The Greeks started to use water clocks in about 300 BC, and the Romans a little later.

The Chinese used outflow type water clocks known as *lou lou* ('drip vessel') or *ke lou* ('graduated leak') from at least the seventh century BC. In about 200 BC they changed to an inflow clock in which a bowl, with a hole in it, floated in a water container and was timed to sink.

One of the problems with the outflow water clock is that the speed at which the water leaves the container reduces as it gets emptier. To solve this problem the Chinese used a series of header tanks to maintain a constant flow, and measured the amount of water coming out of the clock to measure the time. The Chinese also realised that problems were caused both by evaporation and by the increase in viscosity of water as it got colder. They eventually solved the latter problem by using mercury instead.

Starting in about 250 BC, the Greeks and Romans began to devise water clocks that drove mechanisms of various sorts. These water-driven mechanical clocks displayed the passage of time by ringing bells or moving pointers or dials. In about 132 AD, Zhang Heng used a water clock in China to drive an armillary sphere. This concept was developed over time, and in about 725 Yi Xing invented the escapement mechanism. Then in 1088 Su Song built a 10 m high astronomical clock tower at Kaifeng, then the capital of China, where a water wheel drove two armillary spheres via an escapement mechanism. This was the world's first public mechanically driven clock.

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AUSTRALIAN ABORIGINES

Australia is a vast country which had over 400 different indigenous or aboriginal cultures at the time of the arrival of the first Europeans about 200 years ago. Some of these Aboriginal tribes or peoples became extinct shortly after their first contact with the Europeans, but others survived, and still do so.

The Australian Aborigines have an astronomical culture going back thousands or tens of thousands of years. Most of this has been handed down by word of mouth, although some tribes have left drawings or other artefacts. The Aborigines recognised the planets, comets, meteors, many of the brighter stars and some of the dimmer ones. But they were more interested in star patterns and the colours of stars than their brightness, sometimes ignoring bright stars near much dimmer ones. The Aranda people of Central Australia recognised white, blue, yellow and red stars. Antares was described as *tataka indora*, or very red, whereas stars in the Hyades were described as *tataka* (red) or *tjilkera* (white). Virtually all the Aboriginal people recognised the Milky Way, which was often referred to as the Emu in the Sky, the Coal Sack (the Emu's head) and the Magellanic Clouds.

The Yolngu people of Arnhem Land in the tropical far north described how *Walu*, the Sun-woman, lit a small fire at dawn and decorated herself with red ochre, some of which spilt onto the clouds to produce the red sunrise. She then lit her torch, crossed the sky, and descended to the western horizon, where some of the red ochre spilt onto the clouds to produce the red sunset. She then put out her torch and travelled underground to reappear in the east at dawn. This is typical of Aborigines' astronomy, in which the Aborigines observed an astronomical phenomenon and described it by an imaginative story or myth.

The Yolngu also noticed the link between the Earth's tides and the phases of the Moon. They explained that when the Moon rose at dusk, tides were high and water filled the Moon. But water then ran out of the Moon so that when the Moon was high in the sky at dusk or dawn, the tides fell, leaving the Moon empty. In addition they held a 'Morning Star Ceremony' to celebrate the appearance of Venus in the morning sky. They believed that a rope connected Venus to the Sun, preventing her from moving too far away. The Warlpiri people realised that a total solar eclipse was caused by the Moon passing in front of the Sun. But they interpreted this as the Moon-man making love to the Sun-woman.

Many Aborigines used astronomical phenomena as a guide to the seasons. For example, those people of the tropical far north used the heliacal rising of Arcturus to signal that it was time to harvest the *rakia* or spike-rush plants, which they used to make fish traps and baskets. To the Boorong people of Victoria in the south, the appearance of Arcturus told them that the wood ant larvae were ready to be harvested. The Boorong also linked the appearance of Lyra in March to the Mallee fowl building their nests, and when Lyra disappeared in October they knew that the eggs were ready to be collected. The Pitjantjatjara of the Western Desert linked the appearance of the Pleiades to the season for culling dingo puppies, which were a valuable part of their diet.

A number of Aboriginal artefacts still exist. For example, on the banks of the Murray river, north of Adelaide, there is a site called Ngaut Ngaut which belongs to the Nganguraku people. The rock carving there shows the Sun and Moon and a series of dots and lines, but their significance has not yet been decoded. An analysis of 97 Aboriginal stone alignments in New South Wales has shown that, in the majority of cases, they are aligned either north-south or east-west, indicating that they have been aligned astronomically. There are also a number of stone arrangements, often roughly circular in shape. For example, the 50 m diameter Wurdi Youang stone arrangement in Victoria, built by the Wathaurung people, is approximately egg-shaped. Its major axis is almost exactly east-west, with other of alignments of its stones apparently indicating the solstices.

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BABYLONIAN ASTRONOMY

Babylonian astronomy can usefully be divided into four historical periods: the Old Babylonian, Assyrian, New Babylonian and Late Babylonian periods. The Old Babylonian is generally taken to cover the Hammurabi dynasty of about 1895 to 1595 BC, which ended with the invasion of the Hittites. The Assyrians first captured Babylon in about 1230 BC, but their occupation did not last long. The Assyrian period is taken to last from about 820 BC, when the Assyrians became dominant in

Mesopotamia once more, to 612 BC, when their empire finally collapsed. The New Babylonian period follows that, with the Late Babylonian covering the last three centuries BC.

Old Babylonian period

Omens, some of which were connected with the visibility of the Moon and Venus, were very important to the Babylonians during the Hammurabi dynasty. These Babylonians also developed a calendar based on their astronomical observations. Initially their year consisted of 12 months with a 13 month added, or intercalated, whenever the months seemed to be getting out of step with the agricultural year. The months were started when the new Moon was first seen by the priests.

This early intercalation scheme was very hit and miss, however. For example, a thirteenth month would sometimes be added to two consecutive years, and on one occasion an extra month was added after the sixth month, instead of after the twelfth, which was the norm. At some stage, the intercalation scheme seems to have been improved by observing the heliacal rising of various stars and constellations to decide which year needed a thirteenth month. The rules were spelt out in a later astronomical compendium called *MUL.APIN* of about 1200 BC, copies of which were recovered from the ruins of Assurbanipal's library of the seventh century BC.

The Babylonians of the Hammurabi dynasty made a special study of Venus, which was variously called Nindaranna ('mistress of the heavens') or the star of the goddess Ishtar. They often listed Venus with the Sun and Moon, separate from the other four planets, and they appear to have discovered that it went through phases, like the Moon. Venus' periods of visibility near the western and eastern horizons, and its periods when it could not be seen (as it was too close to the Sun), have been recorded in an Assyrian text that was based on an old Babylonian text of about 1600 BC. The Assyrian text indicates that the Babylonians had correctly identified Venus' synodic period of 584 days.

Assyrian period

The Assyrians, who dominated and later occupied Babylon in the Assyrian period, were very much concerned with the interpretation of omens. The Sun (except for its eclipses) and the stars were of little interest to them, as they were predictable. They were much more interested in the Moon and planets. Red Mars was thought to be an evil star, whereas Jupiter was thought to be a lucky object. The Assyrians observed the colour of the Moon, particularly during eclipses, the intensity of its Earth-shine, its apparent corona or halo, and so on. They were able to predict lunar eclipses to some extent, but were initially surprised when some lunar eclipses were missed because, as they later discovered, some took place in daylight. In addition, they produced rules for the rising and setting of the Moon as a function of phase.

The most important service that the Assyrians of this period gave to astronomy was the library assembled on the orders of Assurbanipal at their capital, Nineveh. It contained copies on clay tablets of the old Babylonian texts supplemented by commentaries and new items. Thirteen thousand fragments from this library, which were discovered in the mid-nineteenth century, are now in the British Museum.

New Babylonian period

In 612 BC the Assyrian empire finally collapsed, and Babylon became the centre of a new empire under Nebuchadnezzar, but in 539 BC it became part of the Persian empire under Cyrus the Great. As time progressed, the Babylonians became less and less interested in interpreting omens and became more interested in trying to detect patterns in planetary and lunar movements, to enable astronomical predictions to be made. Water clocks were used to measure time, and in a text of 523 BC the relative timings of sunrise and sunset, and moonrise and moonset, are recorded to an accuracy of about a minute. The Babylonians measured the positions of the planets relative to the stars, and deduced their synodic periods. So in the case of Jupiter, for example, they observed that its synodic period was 1.09 years, resulting in there being almost exactly 65 of Jupiter's synodic periods in 71 years. The Babylonians also recorded both partial and total lunar eclipses, and observed that the cycle of eclipses repeated itself almost exactly every 223 synodic months, a period now called a 'saros'.

Late Babylonian period

Babylon had been part of the Persian empire for about two hundred years, but in 331 BC it became part of the empire of Alexander the Great. Alexander's conquest resulted in the arrival of the Greek influence in the so-called Seleucid period which lasted until 247 BC. During this period communications between Babylon and Greece naturally improved. But over the following sixty years there was much disruption in the area, and communications between Babylon and Greece became spasmodic once more. Then in 181 BC the Parthians took control, and successfully withstood invasion attempts for almost 300 years. This Parthian domination cut off the Babylonians from the Mediterranean civilisations of Greece, Egypt and Rome, whilst also stifling their local culture. But the priests still continued with their astronomical observations and analysis.

Babylonian priests saw the planets as gods moving in a two dimensional sky, not, like the Greeks, as celestial bodies moving in three dimensional space. Our knowledge of their work in the late Babylonian period is contained in about 300 cuneiform