Babylon to Voyager and Beyond

A History of Planetary Astronomy

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1.1 Early astronomy

It is easy to ignore the skies these days when many of us live in light-polluted cities, rushing around without time to think, but things were very different for our distant ancestors. In those days, before the rise of the great civilisations of Babylon and Greece, for example, primitive peoples needed to know when to plant and harvest their crops, when to move their animals to winter pasture, and so on. They regulated their working and sleeping patterns according to the times of the rising and setting of the sun, and understood the regular cycle of the moon, but working out the seasons was more difficult. In the absence of any other information, they used their own experience, but this could sometimes prove unreliable, so a more structured guide to the seasons would be useful.

It was easy to measure a day or a lunar month, its so-called synodic period from one new moon to another, but how could a year and its seasons be determined? Some civilisations used midsummer's day as a baseline, when they knew that the noon-day sun was at its maximum altitude,[1] and worked out the seasons from that. Others used standing stones or stone circles, like Stonehenge, to measure the position of the rising or setting sun against the horizon on midsummer and midwinter's day. Yet others determined the seasons from the rising or setting of certain stars. The Egyptians, for example, knew when they were developing their calendar in about 3000 BC that the annual Nile floods occurred when Sirius, the brightest star in the sky,

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[1] This is not so in equatorial regions, of course, where the seasons alternate between dry and rainy periods, rather than between the winter, spring, summer or autumn of higher latitudes.

became visible for the first time in the morning twilight just before dawn. On the other hand the Australian aborigines linked the start of spring to the visibility of the Pleiades star cluster in the evening sky. So the ancient civilisations became familiar with the movements of the sun, moon and stars in the heavens.

As time passed, more advanced civilisations started to use the sun and stars for navigation, which required a knowledge of their position in the sky with some accuracy. Other people began to ask not just where the sun, moon and stars were at a particular time of day or night, but what caused their movements through the heavens. The planets that were known to the ancients, that is Mercury, Venus, Mars, Jupiter and Saturn, were seen to move in the sky in a peculiar way which seemed to have a meaning. Total solar eclipses and comets were also observed from time to time, spreading alarm and despondency through many populations. So early astronomy became inextricably linked with religion and superstition.

Religion placed a different requirement on astronomy compared with agriculture, however. The start of the various seasons did not need to be known exactly for agricultural purposes, but religious observances demanded a precise calendar so that their rituals could be planned in advance. The problem is that there is not an integral number of days in a lunar month, nor is there an integral number of lunar months in a year, which complicated matters greatly.

One lunar (synodic) month, from new moon to new moon, is now known to be, on average, 29.53059 days, and one solar or tropical year,[2] as it is known, is 365.24220 days. So, one solar year is 12.3683 lunar months, or about 11 days longer than 12 lunar months. In fact, over 19 years there are almost exactly 235 lunar months, which is 7 months more than if there had been just 12 months in each of the 19 years. So, provided 7 extra, so-called 'intercalary' months are added over 19 years, the lunar phase on the first day of the year is almost exactly the same as it was 19 years previously. Such a discovery of this so-called 'Metonic cycle'[3] was made only gradually, by the empirical approach of adding an extra month, as required, to a year of 12 lunar months to correct for the observed agricultural seasons. Eventually the

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[2] A year based on the seasons.

[3] This cycle was named after Meton, a Greek astronomer, who lived about 460–400 BC, and who was originally thought to have discovered it. The discovery was made more gradually, however, as mentioned above, but Meton was the first person to propose that it be adopted as the basis for a calendar.

Egyptian,[4] Babylonian and Jewish calendars were structured to have 12 years of 12 months and 7 years of 13 months in each 19 year period.

1.2 The Babylonians

The Babylonians of about 2000 BC, who lived in southern Mesopotamia,[5] had had to observe the western horizon to detect the new moon, and hence to officially start a new month. In the process they not only deduced its 29.5 day cycle, but also clearly observed Venus (called Nindaranna), which is often very bright in the west after sunset and in the east before sunrise. Venus' periods of visibility near the western and eastern horizons, and its periods when it could not be seen (because it is too close to the sun), have been clearly recorded in a text from Ashurbanipal's library of the seventh century BC, which was based on a text of about 1600 BC.[6]

The Assyrians, who came from northern Mesopotamia, became the most powerful force in Mesopotamia in about 800 BC, conquering Babylon and adopting a large part of their culture.[7] They studied the sky as a source of omens, however, rather than to improve their calendar, linking the planets to their gods like talismans. Mercury was linked to Nabu, Venus to Ishtar, Mars to Nergal, Jupiter to Marduk and Saturn to Ninib. Nabu was the god of wisdom, Ishtar the goddess of love, Nergal the god of war and the underworld, Marduk the god of Babylon and the chief god, and Ninib a solar deity responsible for the seasons.

Now that the positions of the planets in the sky were linked to omens, their movements were more closely studied by the Assyrians, as was that of the moon, in order to predict lunar eclipses which were considered to be of special significance. A record of previous omens, used by the priests to interpret new celestial alignments and positions, was contained in a collection of seventy tablets called the 'Enuma Anu Enlil', which dated back to the pre-conquest era of about 1400 BC.

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[4] The Egyptians ran two calendars in parallel. The one described above was the astronomical calendar, but there was also an administrative calendar with a year of exactly 365 days, which was $^1/_4$ day shorter than in the astronomical calendar!

[5] Mesopotamia was the region of the Middle East which was based on the Tigris and Euphrates rivers. It is approximately equivalent to modern Iraq.

[6] These observations relate to the reign of King Ammisaduqa of Babylon who is variously thought to have reigned about 1702–1682 BC, 1646–1626 BC, or 1582–1562 BC, depending on whose chronology is used.

[7] The Assyrians first captured Babylon in 1234 BC but the occupation did not last long.

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 messages from the gods, as seen by planetary alignments and lunar eclipses, and became more interested in trying to see 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 in the sky relative to the stars, and deduced their synodic periods. So in the case of Jupiter, for example, they observed that the turning point in its movement amongst the stars was reached every 1.09 years, that is its synodic period, 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'. We now know that the reason for this is that eclipses can only take place when the sun–earth–moon line lies approximately along the line of nodes, which is where the inclined orbit of the moon intercepts the orbit of the earth around the sun. This line of nodes is not fixed in space, however, as it regresses (i.e. precesses backwards), allowing an alignment of the sun–earth–moon line every 223 synodic months.

Babylon was 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. The Parthians then took control of the area, and successfully withstood invasion attempts by Rome, in particular, over the next three centuries. Fortunately, during all these changes the priests continued with their astronomical observations and analysis.

The late Babylonian period

Our knowledge of astronomy in the late Babylonian period, covering the last three centuries BC, is contained in about 300 cuneiform tablets excavated from Babylon at the end of the nineteenth century, and from Uruk in southern Mesopotamia in the early twentieth century.

The Babylonian astronomers produced numerous extensive tables containing intricate calculations of the movements of the sun, moon and planets through the heavens. By now their positions were measured in ecliptical longitude and latitude coordinates.[8] The longitudes were recorded in one of twelve zodiacal signs, each of which covered 30° longitude, with their subdivisions being recorded in the sexagesimal notation based on units of sixty. So $28^\circ\ 10'\ 39\frac{2}{3}''$ or $28^\circ.177685$ in our decimal system, based on powers of ten, becomes $28^\circ,10,39,40$ in the Babylonian system, based on powers of sixty.

Two systems were used in these cuneiform tablets to predict the movements of the sun and moon. So the first visibility of the crescent moon could be predicted every month, thus enabling the new month to be officially started.

The first analysis system was given in the earliest cuneiform fragments, dated about 170 BC. In these it was assumed that the sun moved along the ecliptic at 30° per synodic month for 194° of the ecliptic, and at $\frac{15}{16} \times 30^\circ$ per month for the remaining 166°. This implied that there are 12.36889 or $12\frac{83}{225}$ synodic months in a sidereal year (of 360°), or that there are 2783 synodic months in 225 sidereal years. Assuming a mean synodic month deduced by the Babylonians of 29.530594 days (29d 12h 44m $3\frac{1}{3}$s, see later), gave a sidereal year of 365.260637 days or 365d 6h 15m 19s, which is only just over six minutes too long compared with the value known today.

The second analysis system was found in cuneiform tablets dating from about 130 BC. It assumed that the sun's velocity per synodic month varied linearly, in a zig-zag fashion, from $30^\circ\ 1'\ 59''$ to $28^\circ\ 10'\ 39\frac{2}{3}''$ and back again, changing at the rate of $0^\circ\ 18'$ per synodic month. This gave an average velocity of $29^\circ\ 6'\ 19\frac{1}{3}''$ per synodic month, compared with the currently accepted value of $29^\circ\ 6'\ 20\frac{1}{5}''$, which is remarkably close. Given the average solar velocity of $29^\circ\ 6'\ 19\frac{1}{3}''$ per synodic month, it would take 12.368851 synodic months to complete a full 360° sidereal year.

At the rate of $0^\circ\ 18'$ per synodic month, however, it would take 12.369136 synodic months for the sun's velocity to go from maximum to minimum and back again, which is higher than the number of synodic months needed to traverse the 360° of a sidereal year. The time for the sun to go from maximum velocity to maximum velocity is now called the anomalistic year. The above estimate is 12;22,08,53,20 synodic months in Babylonian notation,[9] or $12\frac{299}{810}$ synodic months using fractions, implying that there are 10,019 synodic months in 810 anomalistic years. At an average velocity of $29^\circ\ 6'\ 19\frac{1}{3}''$ per synodic month, the sun would move $360^\circ\ 0'\ 29''.8$ along the ecliptic in

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[8] The ecliptic is the plane of the earth's orbit around the sun.

[9] The semicolon separates the full number from numbers less than unity.

an anomalistic year. So the Babylonians appear to have realised that the sun moves slightly more than 360° in going from maximum velocity to maximum velocity, the excess being 29″.8, compared with the presently known value of 11″.6.

The Babylonians, who were fascinated by numbers, saw the heavens in two dimensions, rather than the three dimensions envisaged by the Greeks. They were content to analyse the movements in the sky by arithmetic means, whereas the Greeks tried to explain the movements by recourse to geometrical figures. Although the Babylonians observed that the sun's motion along the ecliptic was not uniform, they did not seem to ask themselves why this was. We now know that this is because the earth's orbit around the sun is elliptical, with the earth moving faster when it is nearer to the sun at perihelion, and slower when it is furthest away at aphelion. As a result, the apparent solar velocity varies sinusoidally between these two extremes, rather than in the zig-zag fashion assumed by the Babylonians. We also now know that the orbit of the earth is not fixed in space, but it is moving such that the perihelion is precessing, thus explaining why the anomalistic year is not the same as the sidereal year.

In the second century BC, the Babylonians concluded that the average synodic month was 29d 12h 44m $3\frac{1}{3}$s or 29.530594 days long. It was also found that it could be as long as 29d 17h 57m $48\frac{1}{3}$s or as short as 29d 7h 30m $18\frac{1}{3}$s. The Babylonians analysed the moon's motion using a zig-zag function, with successive synodic periods, on the linear parts, increasing or decreasing by 1h 30m. This meant that it took 13.9444, $13\frac{17}{18}$ or $\frac{251}{18}$ synodic months for the moon to go from the longest synodic month to the shortest and back again. In this time the moon has orbited the earth $\frac{251}{18} + 1$ times, so $251 + 18 = 269$ anomalistic months is equivalent to 251 synodic months. So the average anomalistic month (from maximum to maximum orbital speed of the moon) was found to be 27.554569 days or 27d 13h 18m $34\frac{3}{4}$s, just 2.7 seconds from the value known today. Incidentally as $\frac{269}{251} \approx \frac{239}{223}$, a saros has almost exactly 223 synodic months or 239 anomalistic months.

As mentioned above, the main objective of these Babylonian analyses, which were mainly decoded in the early twentieth century by the Jesuit priest Jos. Schaumberger, was to predict when the crescent moon would first be visible each month. To do this, astronomers used any known lunar eclipse to provide the initial conditions. The angular separation of the sun and moon could then be calculated, knowing their various orbital velocities as determined above. The day of the year gave the inclination of the ecliptic to the horizon, and a knowledge of the moon's latitude

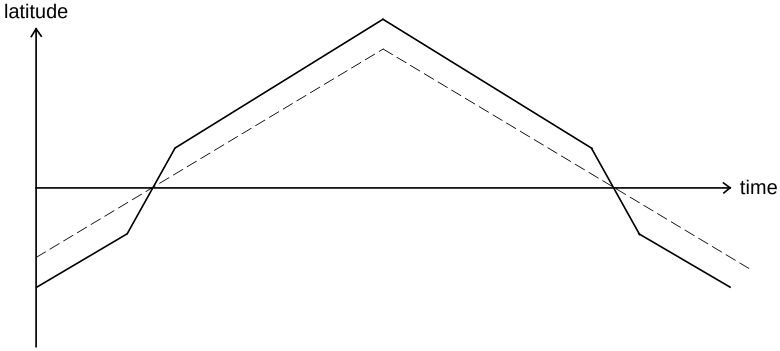

Figure 1.1 Plot of the moon's latitude relative to the ecliptic, versus time, as used by the Babylonians to predict eclipses. The solid line shows the modified zig-zag function used.

relative to the ecliptic then enabled the visibility of the crescent moon to be determined.

The above Babylonian calculations were shown on extensive lunar tables, the most complete of which ran to eighteen columns of numbers, giving values of the various quantities used. These tables were produced not only to predict the visibility of the crescent moon, but also that of lunar eclipses. To do this, astronomers realised that it was vital to get a good estimate of the moon's latitude above or below the ecliptic, which is now known to be due to the moon's orbital plane being inclined at about 5° to the ecliptic. It was recognised by the Babylonians that a straightforward zig-zag function of latitude versus time would not be sufficient, so they used a modified form as shown in Figure 1.1. This enabled them to calculate an index which predicted not only when there would be a full or partial lunar eclipse, but also approximately how long it would last.

A slight diversion is now called for, outlining the movement of the planets as we now know them, before going on to describe the Babylonian observations.

An inferior planet, i.e. Mercury or Venus, that orbits the sun inside the orbit of the earth, has the apparent orbit around the sun as shown schematically in Figure 1.2 relative to a stationary earth. At point A the planet is first seen as a morning 'star', at what is called its heliacal rising. On subsequent days, it appears higher and higher in the sky before dawn until it reaches its greatest western elongation at point B, so-called because it is west of the sun in the sky (although it is seen in the eastern sky). On the following days the planet is seen to be lower and lower in the pre-dawn sky, until it is lost in the bright dawn sky after point C. Some time later at point D the planet

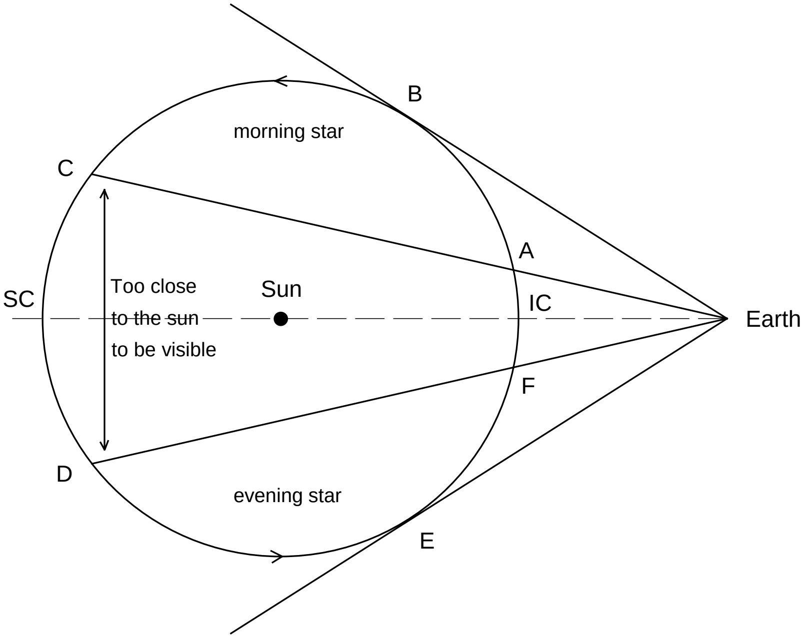

Figure 1.2 A schematic showing the apparent orbit of an inferior planet relative to a stationary earth. (The real figure is not a circle, but the diagram illustrates the principle under discussion in the text.)

first starts to be seen low down in the evening sky just after sunset. Point E is its greatest eastern elongation, and point F is its last visible appearance in the evening sky at the planet's so-called heliacal setting. IC is called the planet's inferior conjunction and SC its superior conjunction. Because the orbits of Mercury, Venus and the earth are elliptical, the greatest elongations from the sun vary from about 18° to 28° for Mercury and from 45° to 47° for Venus.

We turn now to the superior planets that were known to the ancients, that is Mars, Jupiter and Saturn. Unlike the inferior planets, the superior planets can be seen at any time of night, depending on their orbital positions. When they reach their highest point in the sky, crossing the meridian at local midnight, they are 180° away from the sun, and are said to be at opposition. Whereas when they are directly in line with the earth and sun, but behind the sun, they are at conjunction.

The orbits of the superior planets, as seen from the earth, are complex, as their orbits are ellipses inclined to the ecliptic. They orbit the sun in the same direction as the earth with lower angular and linear velocities.

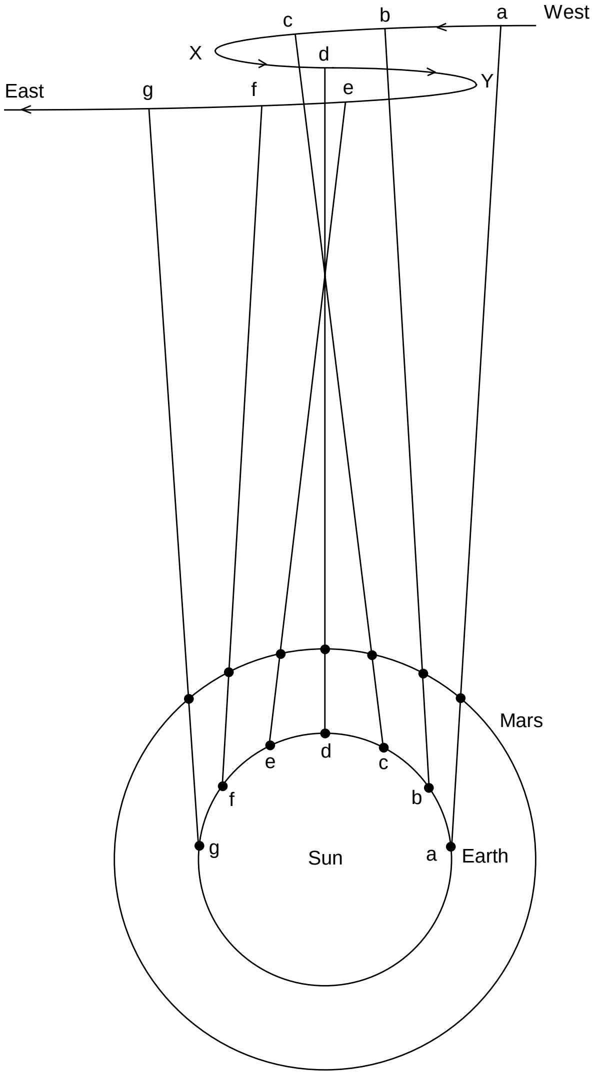

Figure 1.3 Plot to show the apparent movement of Mars against the stars, as seen from a moving Earth. The first and second stationary points are labelled 'X' and 'Y'. Mars is at opposition at point 'd'.

As a result, if the positions of the superior planets are plotted against the stars night after night, they show a general movement to the east (see Figure 1.3).[10] Around opposition, however, they trace out an S-shaped curve, temporarily turning back on themselves at their first stationary

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[10] Although Figure 1.3 is for Mars, the general configuration shown is the same for all the superior planets.

point. At the second stationary point the planets resume their easterly motion.

The Babylonians' planetary tables gave data on the heliacal rising and setting of the planets, and on the first and second stations (stationary points) and oppositions of the superior planets. The data on Jupiter are particularly extensive.

As in the case of the sun and moon above, Babylonian astronomers wished to predict the position of Jupiter in the sky based on their records of its position going back over many years. In their simplest arithmetical 'model' they assumed that Jupiter moved at 30° per synodic period when it is situated between 85° and 240° ecliptic longitude, and at 36° per synodic period over the remainder of the ecliptic. This gave the average movement in a synodic period (called a synodic arc) of $33^\circ\ 8'\ 45''$, with 10.8611 synodic periods in a sidereal period, giving a sidereal period of 11.8611 years and a synodic period of 1.0921 years. These values of Jupiter's sidereal and synodic periods are within 0.01% of those used today.

The Babylonians also used a second, slightly more sophisticated model, assuming that Jupiter moved at 30° per synodic period for 120° of the ecliptic, 36° for 135°, and $33^\circ\ 45'$ for the transition regions of 53° and 52° between these two.

Finally, in a third alternative model they assumed that the movement of Jupiter varied linearly from $28^\circ\ 15'\ 30''$ to $38^\circ\ 2'$ per synodic period and back again, in a zig-zag function over one sidereal period, changing at the rate of $1^\circ\ 48'$ per synodic period. The average movement was still $33^\circ\ 8'\ 45''$, with $10.8611 = 10\frac{31}{36}$ steps or synodic periods per sidereal period, giving a sidereal period of $10\frac{31}{36} + 1 = \frac{427}{36} = 11.8611$ years.

Although these three models produced the same synodic and sidereal periods for Jupiter, they produced positions for the first and second stations of the planet that differed from the observed positions by up to almost 2° over the course of one sidereal period.

The Babylonians also produced similar data for Mercury, giving a synodic period of $\frac{480}{1513} = 0.31725$ years, Mars with a synodic period of $\frac{284}{133} = 2.1353$ years, and Saturn with a synodic period of $\frac{265}{256} = 1.0352$ years. Although these values compare very well with the values known today,[11] the predicted positions of the planets at their stations or heliacal risings or settings were, like those predicted for Jupiter, not all that accurate.

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[11] The errors are all less than 0.01%.

1.3 **The Greeks**

As mentioned previously, the Babylonian astronomical observers were generally priests trying to predict the movement of heavenly objects using arithmetical techniques, whereas the Greeks were philosophers trying to understand the cosmos. There were other differences also. The Babylonian records do not give us the names of their observers, whereas we know the names of the Greek philosophers. Unfortunately, however, the Greeks used less durable materials for recording their work than the clay tablets of the Babylonians, and so most of the early Greek written material is lost, and we have to rely on second or third hand accounts, with the inevitable contradictions and confusion that that creates.

Thales

Aristotle (384–322 BC) considered Thales of Miletus[12] (*c*. 625–547 BC) to be the founder of Greek natural philosophy. He was both a geometrician and philosopher, but he probably undertook no serious astronomical observations of his own, being more interested in theoretical ideas. Thales seems to have been the original absent-minded professor interested in 'higher things', if Plato (*c*. 427–347 BC) is to be believed. He tells the story that Thales was so engrossed in looking at the stars when he was out walking one night that he fell down a well. Or, as Plato explains it in his book *Thaetetus*, because Thales wanted to 'know what went on in the heaven, [he] did not notice what was in front of him, nay, at his very feet'.[13]

Thales hypothesised that the sun and stars were made of water, and that the earth was a flat disc that floated on water which evaporated to produce the air. There are also disputed Greek sources that say that Thales at some stage recognised that the earth was spherical, and understood the true cause of lunar and solar eclipses. Herodotus (*c*. 484–425 BC) claims that Thales predicted the solar eclipse that took place during a battle between the Lydians and the Medes, which is now thought to have taken place on 28th May 585 BC. This story must be treated with caution, however, as Herodotus says that Thales predicted the year of the eclipse, but not its day. This seems

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[12] Miletus was a Greek colony on the west coast of Asia Minor (modern Turkey). It is just south of Ephesus.

[13] Translation by T. L. Heath in his *Greek Astronomy*, Dent, London, 1932, republished by Dover 1991 (afterwards referred to as Heath, *Greek Astronomy*), p. 1.

strange, as if Thales was able to predict solar eclipses, which at that time the Babylonians were not, he must have realised on approximately what days of the year they were possible.

Anaximander

Anaximander (*c.* 610–545 BC), also of Miletus and one of Thales' pupils, thought that the earth was a cylindrical column surrounded by air. Its height was one-third of its breadth, and it floated in space at the centre of an infinite universe. Unlike Thales, however, he thought that, because the earth was at the centre of the universe, it was equidistant from all points on the celestial circumference, and so was naturally at rest, and did not need to be supported by water or anything else.

In Anaximander's scheme, a wheel or ring, with a diameter of 27 or 28 times the earth's diameter, surrounded the earth. This wheel had a hollow rim or tyre filled with fire, in which there was a hole the size of the earth. This hole is what we see as the sun.[14] From time to time this hole is closed, and then we see a total solar eclipse. Likewise, inside this wheel was another wheel, with a diameter 19 times that of the earth, again with a flame-filled tyre. A hole in this was the moon. Inside this was a sphere with a fire-filled surface, which had holes in it to produce points of light that were seen as the stars.

Anaximander proposed that the solar and lunar wheels and the stellar sphere all rotated around the earth at different rates. However, he did not, as far as we know, try to explain how we can see the sun and moon behind the stellar sphere, or why the sun was not eclipsed by the lunar wheel every time the sun crossed behind it. Although his model of the universe looks strange to us,[15] it was important as being the first one that we know that saw the universe as a 'mechanical' system.

We now know that the earth's equatorial plane is inclined at about $23^1/_2{}^\circ$ to the plane of the earth's orbit around the sun (the ecliptic). But the projection of the earth's equatorial plane into space is seen as the celestial equator, so the ecliptic is inclined at about $23^1/_2{}^\circ$ to the celestial equator; this angle

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[14] There is some confusion about the size of the solar wheel, as Hippolytus says that Anaximander thought that it had a diameter of 27 times that of the moon's wheel, rather than 27 or 28 times the earth's diameter.

[15] Anaximander was closer to the mark in proposing that life started in the oceans, with the first animals being like sea urchins. They eventually left the water, adapting their structure to their new land-based environment.

being called the obliquity of the ecliptic. It can be measured in a number of ways, the simplest of which is by measuring the angle that the sun makes to the horizon at local noon on midsummer and midwinter's day, and dividing the difference by two. Such observations were probably first made by the Babylonians, Chinese or Egyptians, but the first Greek known to have made such an observation was either Anaximander or Pythagoras (*c.* 580–500 BC). Anaximander is also thought to have introduced the gnomon (a sundial with a vertical needle) into Greece from Babylon, which not only allowed him to measure the altitude of the sun, but also to find the dates of the equinoxes and solstices and hence deduce the length of the tropical year.

Pythagoras

The name of Pythagoras is well known, so it is surprising that we have none of his original writings. Because of this, we are not sure what to attribute to him and what to attribute to his followers, but undoubtedly the basic philosophy espoused by them was due to him.

Pythagoras was born on Samos, an island off the coast of Asia Minor,[16] not far from Miletus, where Thales, Anaximander and a good many other Greek philosophers lived. A pupil of Anaximander and the mystic Pherekydes, Pythagoras travelled widely and probably visited Egypt and Babylon, like many other Greek scholars of his period. Then in about 530 BC, when he was about fifty, he left Samos for good and settled in Croton,[17] which was a Greek colony in southern Italy. There he set up a religious order and school of philosophers, sometimes known as the Pythagorean Brotherhood, that soon ruled the town and the surrounding area. The Brotherhood led a communal existence, sharing property and spending time in contemplation and reflection. Because of its political power, however, adjacent Greek states felt threatened. As a result, intervention by a Greek called Cylon caused Pythagoras to be banished towards the end of his life to Metapontum, another Greek colony in southern Italy. About sixty years later his school of philosophy was forcibly dispersed, and some of its members killed.

So Pythagoras was not just a mathematician and astronomer, but also a politician and religious leader. He even worked miracles, practised medicine,

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[16] Asia Minor is now basically modern Turkey.

[17] The ancient Greek letter Κ or κ (kappa) is generally replaced by 'c' in proper names and 'k' in other words in English, although some writers replace it by 'k' in all words. So Croton is sometimes written Kroton, and the Ecphantus is sometimes written Ekphantus.

and went around the countryside giving religious sermons. He must have been quite a man.

The Pythagoreans believed in the harmony of nature and the purity of numbers, discovering, amongst other things, the pattern of standing waves on the plucked string of a musical instrument and the note that it produced. They were probably the first to appreciate that the earth is spherical,[18] and that the planets each move in separate orbits, all inclined to the celestial equator. In addition, the Pythagoreans were almost certainly the first Greeks to have realised that Phosphorus and Hesperus, the morning and evening stars, were one and the same astronomical body.

The early Pythagoreans introduced the doctrine of the 'Harmony of the Spheres' in which a non-spinning, spherical earth was surrounded by a series of concentric, crystalline spheres. The moon, sun, individual planets, and stars were each supported by a sphere, which revolved around the earth at different speeds. These spheres were thought to produce a musical sound, known as the 'Music of the Spheres', as they went past each other.

According to Pliny (23–79 AD), the musical notes were determined by the separations of the spheres as follows:

Earth to Moon, a tone
Moon to Mercury, a semitone
Mercury to Venus, a semitone
Venus to Sun, a minor third
Sun to Mars, a tone
Mars to Jupiter, a semitone
Jupiter to Saturn, a semitone
Saturn to the fixed stars, a minor third

This gives the scale, starting with C, of C, D, E flat, E, G, A, B flat, B, and D. A beautiful notion linking, as it does, the beauty of the sky with the magic of numbers and musical harmony.

Philolaus

In the following century the Pythagorean Philolaus (*c*. 450–400 BC) devised a new cosmic model in which the earth was also moving, rather than being

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[18] Very little is one hundred per cent certain about this period of Greek astronomy. Although the Pythagoreans are generally thought to have been the first to have proposed that the earth is spherical, some people attribute this to Parmenides of Elea (*c*. 504–450 BC).

static at the centre of the universe. He appears to have been influenced in his world picture by the fact that the moon always turns its same face to the earth. This led him to suggest that the earth orbits a central fire, called Hestia, once per day, in the earth's equatorial plane. He also suggested that the earth kept its inhabited part permanently facing away from the fire. This meant that the earth would have to rotate on its axis once per day, as it orbited Hestia, which was a revolutionary idea at the time. His model was even more revolutionary, as he proposed that there was also a counter-earth, or antichthon, on a line between the earth and the fire, also orbiting the central fire once per day, to shield the earth from its heat. This counter-earth was proposed, according to Aristotle, as it meant that there would be ten bodies in the universe, namely the earth, moon, sun, five planets, the sphere of fixed stars and the counter-earth; ten being a perfect number to the Pythagoreans.[19]

Outside the orbit of the earth, according to Philolaus, was the moon that was thought to orbit Hestia once every $29^1/_2$ days. Then came the sun, which took one year to complete an orbit, the planets, a sphere carrying the fixed stars, and finally a wall of fiery ether surrounding the universe. The latter, along with the central fire, provided the universe with light and heat. All the orbits, including that of the earth and counter-earth, were circular. The sun was not self-luminous, but was like a crystal ball, reflecting and scattering the light from the central fire and fiery ether, with an orbit inclined to that of the earth, thus explaining the seasons.

There is some confusion between the writers of antiquity when they come to describe the relative positions of the planets and the sun in Philolaus' universe. Some, including Plutarch (46–120 AD), state that Philolaus placed the orbits of Mercury and Venus between those of the moon and sun, whereas others say that he placed all five planets outside of the sun's orbit. He may well have done both, of course, at various times. Whatever is the case, the main point is that the Pythagoreans proposed schemes, including both an earth-centred and a non earth-centred universe, in which all the heavenly bodies were in orbit. This is very different from the relatively crude ideas of Thales, Anaximander and their ilk.

It had been known for a long time that there are more lunar eclipses than solar eclipses seen from a given point on the earth's surface. We now know that this is because the earth's shadow on the moon is larger than the moon's shadow on the earth, because of the relative sizes of these two bodies. This was not understood in fifth century BC Greece, however. Instead

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[19] As ten is the sum of the first four whole numbers.

Philolaus explained the effect by supposing that lunar eclipses are caused by either the earth or counter-earth intercepting the sun's light en route to the moon, thus increasing the number of lunar eclipses, compared with solar eclipses.

Although Philolaus had required the earth to keep the same face to the central fire, as it orbited it once per day, he did not specifically mention that the earth spun on its axis. In fact, Hicetas of Syracuse seems to have been the first person to have done this. Unfortunately, little is known about Hicetas, except that he was a Pythagorean who lived at about the same time as Philolaus, and proposed that the earth spun on its axis at the centre of a geocentric (i.e. earth-centred) universe. It is not clear whether this idea superseded that of Philolaus amongst the Pythagoreans, or whether both existed in parallel. What is clear, however, is that Hicetas' geocentric universe, with a spinning earth, was adopted later in the fourth century BC by Ecphantus the Pythagorean and Heracleides of Pontus.

Heracleides[20] (*c*. 388–315 BC) was born at Heraclea in Pontus, on the Black Sea coast of Asia Minor, but emigrated to Athens where he came under the influence of Plato, Aristotle and the Pythagoreans. Whether he knew Plato and Aristotle is unclear, but he himself was an original thinker, having little time for academic tradition. His greatest contribution to the evolving world picture was in connection with Mercury and Venus, which are always very close to the sun in the sky. This led Heracleides to conclude that these two planets, unlike Mars, Jupiter and Saturn, actually orbited the sun as the sun orbited a spinning earth, all these orbits being circular. Given the misnomer 'The Egyptian System', this structure of the universe became accepted by a large number of people towards the end of the fourth century BC.

Aristarchus

So far in the Pythagorean models of the universe, we have had those centred on a non-spinning or spinning earth and those centred on the central fire, Hestia, whilst Heracleides had proposed that Mercury and Venus orbit the sun as it goes round a spinning earth in a geocentric universe. Aristarchus (*c*. 310–230 BC) was to go one step further, and be the first to propose a sun-centred or heliocentric universe, in which the planets orbit the sun in the (correct) order of Mercury, Venus, Earth, Mars, Jupiter, and Saturn, with the moon orbiting the spinning earth.

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[20] Sometimes latinised as Heraclitus.

Aristarchus, who was one of the last of the Pythagorean school, was born on Samos about 270 years after Pythagoras, and died in Alexandria about eighty years later. He and Archimedes knew each other, and it is from Archimedes that we have a clear statement in his book *The Sand Reckoner* (216 BC) of Aristarchus' cosmology. Archimedes says,[21] 'For he [Aristarchus] supposes that the fixed stars and the sun are immovable, but that the earth is carried round the sun in a circle which is in the middle of the course [i.e. the sun is at the centre of the circle[22]]; but the sphere of the fixed stars, lying with the sun round the same centre, is such a size that the circle, in which he supposes the earth to move, has the same ratio to the distance of the fixed stars as the centre of the sphere has to its surface'. The last half of the sentence is clearly nonsense, as Archimedes observed, as the centre of a sphere has no size. It is clear what Aristarchus meant, however, namely that the sphere of the fixed stars, centred on the sun, is at a very great distance from the sun and earth, as otherwise the effect of parallax would be seen as the earth orbited the sun.

Aristarchus' idea of an orbiting earth is also mentioned in Plutarch's book *On the Face in the Moon*, where he says that Aristarchus[23] 'supposed that the heavens stand still and the earth moves in an oblique circle at the same time as it turns round its axis'. Here Plutarch clearly shows that Aristarchus also believed that the earth spun on its axis.

We have some first-hand knowledge of Aristarchus' work, as we still have a copy of his book *On the Dimensions and Distances of the Sun and Moon*. In this he started with a number of premises, the most important of which is that the moon shines by reflected sunlight. He then used various ingenious measurements which enabled him to deduce the relative sizes and distances of the sun and moon from the earth. For example, he observed the moon at quadrature, when it is exactly half illuminated, and deduced that the sun–earth–moon angle was 87° at that time. This led him to conclude that the sun–earth distance was about 19 times (sec 87°) the moon–earth distance. Although this is over 20 times too small,[24] as the true angle is

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[21] Translation by J. L. E. Dreyer in his *History of the Planetary Systems from Thales to Kepler*, Cambridge University Press, 1906, republished as *A History of Astronomy from Thales to Kepler*, Dover, 1953 (afterwards referred to as Dreyer, *A History of Astronomy from Thales to Kepler*), p. 137.

[22] This interpretation is given in Heath, *Greek Astronomy*, p. 106.

[23] Translation from Dreyer in his *A History of Astronomy from Thales to Kepler*, p. 138.

[24] Because of the difficulty in deciding when the moon is exactly half illuminated.

about 89° 50′, he had proved that the sun is much further away from the earth than is the moon. Since the angular sizes of the sun and moon, as seen from earth, are about the same, this meant that the sun was about 19 times the diameter of the moon, according to his measurements.

Observing the size of the earth's shadow on the moon during a lunar eclipse to be about double the diameter of the moon enabled Aristarchus to estimate that the earth is about $\frac{57}{20}$ times the diameter of the moon, implying that the sun's diameter is about $19 \times \frac{20}{57} = 6\frac{2}{3}$ times larger than that of the earth. Measuring the moon's angular diameter, and knowing that its linear diameter is $\frac{20}{57}$ or 0.35 times[25] that of the earth, enabled Aristarchus to deduce that the moon was about 25 earth diameters away. This is very close to the true value of about 30 earth diameters. So Aristarchus had estimated the size of the earth–moon system reasonably accurately, but his sun was about 20 times too close to the earth and so was about 20 times too small.

Strangely, as far as we know, Seleucus of Seleucia, in Mesopotamia, who lived in the second century BC, was the only person to adopt Aristarchus' ideas of a heliocentric universe, until Copernicus resurrected it about 1,700 years later. To understand why, we have to retrace our steps to Plato in the fourth century BC, to uncover the alternative cosmologies then under consideration.

Plato

Plato (*c*. 427–347 BC) would have had little place in Gradgrind's[26] history of astronomy, were he to have written one, as Plato's contribution to the factual basis of astronomy is very small. However, he was to have a profound effect on the development of ideas regarding the structure of the universe for almost two thousand years. In about 387 BC he founded an Academy in Athens to encourage the systematic pursuit of philosophical and scientific ideas.

A great deal of Plato's work survives consisting of philosophical dialogues in which an idealised Socrates appears. Like Socrates, who was his tutor, Plato had little interest in the reality of nature preferring, instead, to examine the purity of ideas. Nevertheless his books covered a wide range of subjects from physics and mathematics to philosophy and politics, but his most interesting books, from an astronomical viewpoint, are *Timaeus* and the *Republic*.

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[25] The true value is now known to be 0.27 times that of the earth.

[26] Gradgrind was the school teacher in Dickens' *Hard Times* who was only interested in facts, facts and more facts, rather than 'fanciful ideas'.

It is difficult to know how interpret the ideas expounded in Plato's books, as the descriptions given are allegorical and ambiguous. Sometimes he even seems to be deliberately vague, leaving scholars to continue to argue, even to this day, as to what he really meant and thought. That having been said, some of his ideas are clear. For example, in *Timaeus* he says,[27] 'And he gave the universe the figure which is proper and natural . . . Wherefore he turned it, as in a lathe, round and spherical, with its extremities equidistant in all directions from the centre, the figure of all figures most perfect and most like to itself . . . He allotted to it the motion which was proper to its bodily form . . . Wherefore, turning it round in one and the same place upon itself, he made it move with circular rotation . . . 'He then goes on in the *Republic* to describe how the celestial bodies, which are fixed to one of eight concentric wheels, revolve around an axis passing through the earth at their centre. The order, from the earth, he took to be the moon, sun, Venus, Mercury, Mars, Jupiter, Saturn and the stars.[28] The outermost (stellar) circle moved rapidly in one direction, whilst the other celestial bodies moved slowly, relative to the stellar circle, in the opposite direction.

Plato recognised that Venus and Mercury behaved differently to the other planets, and he ascribed the same angular orbital rotation rates to them as to the sun. The moon was given the fastest rotation rate *relative to the stars*, followed in velocity by the sun, Venus and Mercury as a group, with the rates of Mars, Jupiter and Saturn being progressively less. He described the colour and intensity of all these celestial bodies, and stated that the moon shines by reflecting light from the sun. All the planets, plus the moon and sun, are said to be spherical, as that is the perfect shape. Finally, he is thought[29] to have defined the distances from earth of the moon, sun, Venus, Mercury, Mars, etc. as 1, 2, 3, 4, 8, 9 and 27, apparently by using two interlocking geometrical progressions namely, 1, 2, 4, 8 and 1, 3, 9, 27.

Plato's scheme was very crude as it did not explain the oscillations, as seen from the earth, of the inferior planets around the sun, nor the temporary reversal of direction of the superior planets at the stationary points. His lasting legacy was, however, his belief that the detailed movements of the

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[27] Translation by Heath in his *Greek Astronomy*, pp. 49–50.

[28] It is not clear why Plato put Venus, rather than Mercury, after the sun. This could possibly have been because Venus does not move as far away from the sun in the sky as Mercury, or because it is brighter.

[29] This is the generally accepted interpretation of Plato's text, although there are other interpretations.

sun, moon and planets could be described using uniform circular motions, even if he was unable to find a suitable system himself. This idea was to dominate astronomical thinking for almost two thousand years.

Eudoxus

One of Plato's pupils, Eudoxus (*c.* 408–355 BC) made a very bold attempt to solve the problem of defining a model of the universe based on the principle of uniform circular motion. Born in Cnidus in Asia Minor, Eudoxus attended Plato's Academy in Athens for two or three months at the age of twenty-three, and later went to Egypt for sixteen months. He then returned to Asia Minor, setting up his own Academy at Cyzicus. According to Seneca, Eudoxus studied planetary movements in Egypt, although there is no evidence that the Egyptians were experts in this field at that time, but he was probably drawn to observe the planets by their excellent climate. He also became versed in the intricacies of the solar and lunar cycles and their impacts on the calendar, as these had been studied by the Egyptians. Some time later Eudoxus appears to have been the first person to suggest that three 365 day years should be followed by a 366 day year, to keep the calendar in synchronisation with the year's natural length.[30] This was three hundred years before Julius Caesar implemented such a calendar.

According to Diogenes Laertius (*fl.* third century AD), Eudoxus was an expert geometer, astronomer, physician and legislator. He was reputed to have written parts of books V, VI and XII of Euclid's *Elements of Geometry*, but his main claim to fame in astronomy was his cosmological structure based on concentric spheres. This structure was originally explained in Eudoxus' book *On Velocities*, which is now lost. Aristotle (384–322 BC) mentioned the scheme briefly in his book *Metaphysics*, and his pupil Eudemus described it in more detail in the second book of his *History of Astronomy*, but that is now also lost. Sosigenes explained the theory, using Eudemus' book as the source, in yet another lost book, and finally in the sixth century AD Simplicius quoted extensively from Sosigenes in his book[31] that is now used as the main source of the theory.

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[30] In 238 BC King Ptolemy III of Egypt was the first ruler to order that such a system be adopted, following advice from Aristarchus, but resistance to the proposal in Egypt was so great that it was not implemented.

[31] This was Simplicius' commentary on Book II of Aristotle's *De Caelo*.