Theme 4: From the Greeks to the Renaissance: the Earth in Space

4.1 Greek Astronomy

Unlike the Babylonian astronomers, who developed algorithms to fit the astronomical data they recorded but made no attempt to construct a real model of the solar system, the Greeks were inveterate model builders. Some of their models—for example, the Pythagorean idea that the Earth orbits a celestial fire, which is not, as might be expected, the Sun, but instead is some metaphysical body concealed from us by a dark "counter-Earth" which always lies between us and the fire—were neither clearly motivated nor obviously testable. However, others were more recognisably "scientific" in the modern sense: they were motivated by the desire to describe observed phenomena, and were discarded or modified when they failed to provide good descriptions. In this sense, Greek astronomy marks the birth of astronomy as a true scientific discipline.

The challenges to any potential model of the movement of the Sun, Moon and planets are as follows:

- *Neither the Sun nor the Moon moves across the night sky with uniform angular velocity.*
  The Babylonians recognised this, and allowed for the variation in their mathematical descriptions of these quantities. The Greeks wanted a physical picture which would account for the variation.
- *The seasons are not of uniform length.*
  The Greeks defined the seasons in the standard astronomical sense, delimited by equinoxes and solstices, and realised quite early (**Euctemon**, around 430 BC) that these were not all the same length. This is, of course, related to the non-uniform motion of the Sun mentioned above.
- *The planets undergo **retrograde motion**.*
  All the planets spend part of the year moving "backwards" (retrograde) with respect to other motions seen on the night sky. The Babylonians made accurate measurements of the period and nature of the retrograde motion for each planet; the Greeks again wanted a physical model.
- *The planets vary in brightness, and the Moon varies in apparent size, over time.*
  The Greeks had a sophisticated understanding of geometry and were capable of recognising that these changes imply a variation in the distance of the objects in question. However, the development of Greek models of the cosmos clearly show that these variations were not a primary concern of Greek astronomers (Ptolemy's model of the Moon's motion, which is a good fit to the Moon's ecliptic longitude, is obviously wrong about the variation in the Moon's distance, but this does not seem to have caused much concern).

Of these, the retrograde motion of the planets is the most obvious; the others require careful observation and record-keeping, which is less apparent in Greek astronomy than in Babylonian.

The Greek astronomers also lumbered themselves with the requirement that all celestial motions should be circles or combinations of circles. This is clearly a philosophical axiom rather than an empirical constraint, the idea being that the Heavens are perfect and the circle is a perfect curve. (Some of the more advanced Greek constructions, with the Earth at one side of the centre of the circle and another "special point", the equant, on the other side, seem to the modern eye to scream "try an ellipse!"—that none of the Greek astronomers thought of this, despite the fact that Greek geometers were perfectly familiar with conic sections, shows the power of preconceived ideas. In the same way, the visibly mottled surface of the Moon failed to convince them of the imperfection of celestial bodies.)

4.1.1 Early work

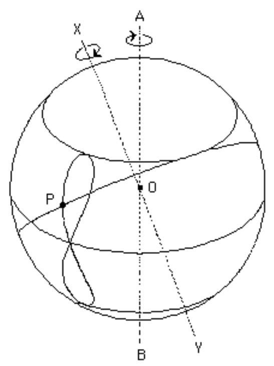

Figure 4.1: spheres of Eudoxus. The figure-8 shape is the hippopede.
From http://www-groups.dcs.st-and.ac.uk/~history/Biographies/Eudoxus.html

The first attempt to combine circular orbits to produce regular retrograde motion seems to have been the **spheres of Eudoxus** (~400–350 BC), see figure 4.1. The construction involved two nested spheres, rotating in opposite directions around slightly offset axes. The poles of the inner sphere are fixed to the outer sphere, so most of the motion cancels out, leaving only a figure-of-eight called a **hippopede** ("horse-fetter", because it looks like a hobble)[1]. If this nest is now placed inside another sphere to provide the overall motion along the ecliptic, you have a model of retrograde motion. (Eudoxus actually used four spheres; the fourth allows the planet's path to deviate from the ecliptic.)

This model does not, in fact, represent the paths of the planets very well. The shape of the hippopede requires the planet to cross the ecliptic four times (once at each end of the 8 and twice in the middle); this is not observed, and it is also impossible to adjust the spheres to give the right proportion of retrograde motion, especially for the outer planets. However, its construction of nested spheres seems to have shaped the thinking of all Greek astronomers thereafter. It is not known whether Eudoxus thought of his spheres as real: he was a very able mathematician and geometer as well as an astronomer, and could easily have thought of them as imaginary "construction lines". However, the extremely influential **Aristotle** (pupil of Plato and teacher of Alexander the Great) certainly did think of them as real, which imposes severe constraints on model construction (real spheres must not intersect one another, whereas imaginary spheres obviously can).

Aristotle's influence on astronomy is generally viewed as negative. He did believe that the Earth is a sphere, and gave cogent arguments in favour of this; however, he was equally convinced that it was at rest and not rotating. As with many other Greek philosophers, his concerns over

[1] If you take a photograph of the Sun at the same time each day and superimpose them, you get a figure-8 shape called the **analemma**. The origin of the analemma is the tilt of the Earth's axis with respect of the ecliptic: it does not look exactly like Eudoxus' hippopede, because the Earth's orbit is elliptical. There is a nice account of the analemma at https://medium.com/starts-with-a-bang/throwback-thursday-the-earths-analemma-590ce068eee2#.ozdgh62s8

rotation and motion were essentially that only objects actually fixed to the Earth's surface would share its motion: anything thrown into the air would come down miles from its starting point, in complete contrast to everyday observation. In addition, his general theory of the four elements earth, water, air and fire required the Earth to be spherical and at rest in the centre of the Universe: he believed that the natural tendency of the element of earth was to fall downwards towards the centre—therefore the Earth must be spherical (the Greeks were aware that a sphere is the shape which minimises distance from the centre), and must be at rest at the central point.

4.1.2 Heraclides and Aristarchos

The "common-sense" arguments for the fixity of the Earth did not convince everyone. **Heraclides** (388–315 BC) is known to have believed that the Earth rotates (his work has not survived, but several later writers refer to this), and may also have thought that Mercury and Venus orbit the Sun.

Aristarchos (~330–230 BC) even proposed that the Sun is at rest and the Earth orbits around it (we know this second-hand, from a brief comment by Archimedes, and therefore do not know what Aristarchos thought about the motion of the other planets). Aristarchos also wrote a book (which *has* survived) on the distance of the Sun compared to the Moon. He argued that the Moon shines by reflected sunlight, and therefore at the precise moment of first or last quarter (when the Moon is exactly half illuminated) the angle Sun-Moon-Earth is a right angle. If you can accurately measure the angle Sun-Earth-Moon, i.e. the Moon's elongation, at that time, you can construct a right-angled triangle, and trigonometry will then give you the distance of the Sun in terms of the Moon's distance.

This calculation is sound in principle, but it is actually extremely difficult to measure the exact moment of first quarter (the terminator isn't sharp enough, and gauging a precise half-circle is difficult), and the numbers Aristarchos plugged into his formula were badly wrong (he thought the Moon's elongation at first quarter was 87°; it's actually more like 89.8°). Hence he concluded that the Sun was about 20 times as far away as the Moon, when he should have concluded that it is about 400 times as far away. Nonetheless, he still deduced that the Sun is considerably larger than the Earth; this may have motivated his belief that the Earth orbits the Sun rather than *vice versa*.

Unfortunately, it is practically impossible to provide observational evidence for a heliocentric cosmos using naked-eye astronomy: indeed, as far as the Greeks were concerned, Aristarchos' theory not only contradicted the everyday experience that the Earth is stationary beneath our feet, it also failed its only observational test. In the Greek mind, the stars were located quite nearby, just beyond the outermost planet (agreed to be Saturn). They would therefore have expected Aristarchos' stars to have measurable parallaxes, which they did not. Aristarchos' only defence was to argue that the stars were extremely distant (this is the context in which Archimedes mentions him). Although this is in fact the correct explanation, it's not surprising that the Greek astronomical community dismissed it as special pleading.

4.1.3 Hipparchos

Hipparchos (worked ~167–126 BC) probably deserves to be remembered as the greatest of the Hellenistic astronomers. In this era Seleucid Babylonia was part of the Greek world, and Hipparchos successfully combined the Babylonian tradition of accurate observations and record-keeping with Greek model-building and geometry. He made observations himself, as well as using Babylonian records, and compiled a star catalogue (it has not survived, but is almost certainly the basis of Ptolemy's). Pliny says the star catalogue was compiled because Hipparchos observed "a new star"—it is not clear whether he saw a nova, a comet, or a variable like Mira which is only visible with the naked eye for part of its cycle, but as a motivation it is curiously reminiscent of Tycho's "new star" (SN 1572), see below. He also estimated the distances of the Sun and Moon, using the geometry of eclipses: his estimate for the Moon (between 59 and 71 Earth radii) is consistent with the modern value, though his solar distance is a severe underestimate.

Hipparchos recognised the distinction between the tropical year (period between successive vernal equinoxes) and the sidereal year (Sun's return to the same position in the stars). By comparing his results with those of earlier astronomers, he discovered the precession of the equinoxes and estimated its rate as "not less than 1° in 100 years" (it's actually about 1.4°; Ptolemy seems to have taken "not less than 1°" as simply 1°, which was the source of considerable later confusion). He verified earlier Greek observations of the inequality of the seasons, improved the measured values, and explained them by a model of the Sun's motion in which the Sun's orbit is not centred on the Earth (this is the original meaning of the word *eccentric*—Hipparchos and Ptolemy regularly use off-centre circles in their systems, but do not use ellipses).

To understand the irregularity of the Moon's motion, Hipparchos resorted to the idea of **epicycles**, see figure 4.2. He does not appear to have invented this idea; Pannekoek says it is "connected with the name of the great mathematician Apollonius of Perga" (who, ironically, worked on the conic sections Hipparchos really needed); but he certainly developed it in the form later perfected by Ptolemy. In the epicycle model, either the planet moves on a small circle whose centre (the **deferent**) moves on a larger circle, or the planet moves in a large circle whose centre (the **eccentric**) moves on a small circle: the two constructions are completely equivalent, as Hipparchos himself showed. In Hipparchos' theory of the Moon, the Moon moves clockwise round the epicycle; the deferent moves anticlockwise round the Earth. Hipparchos knew that the Moon was relatively close to the Earth, and that parallax would introduce shifts in its observed position; he therefore used lunar eclipses as reference points (at a lunar eclipse the Moon is exactly opposite the Sun, and Hipparchos could calculate the Sun's position from his theory of the Sun's motion). The resulting geometry gave good results for new moon and full moon, but—as Ptolemy noted—was not satisfactory at intermediate positions.

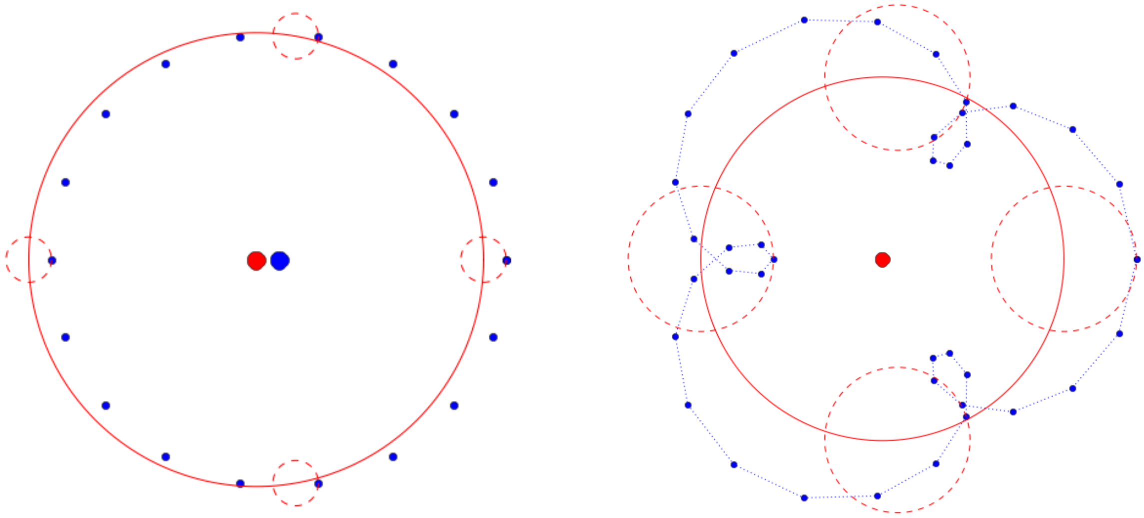

*Figure 4.2: epicycles. Left, an epicycle described with the same period as the deferent, but in the opposite direction, effectively describes an off-centre circle. Hipparchos used this for his lunar theory. Right, an epicycle described in the **same** direction as the deferent, but with a different period, can create retrograde motion, as in Hipparchos' and Ptolemy's planetary models.*

Hipparchos also produced epicyclic models for the orbits of the planets. However, the definitive statement of the epicyclic model of the geocentric cosmos was worked out not by Hipparchos, but by the Alexandrian astronomer **Claudius Ptolemy** (worked 127–150 AD).

Hipparchos' model of the motions of the Sun and Moon, and probably also of the planets, is embodied in a remarkable object recovered in 1901 from a Roman ship wrecked off the Greek coast. The **Antikythera Mechanism** (figure 4.3), dating from around 100 BC, contains gear trains which allow it to act as an orrery, i.e. a working model of the planetary system. Its simulation of lunar motion includes an ingenious pin-and-slot construction that replicates Hipparchos' theory of the Moon's motion; it is suspected from the inscriptions (although the relevant gear trains are now lost) that it also included the motions of the planets.

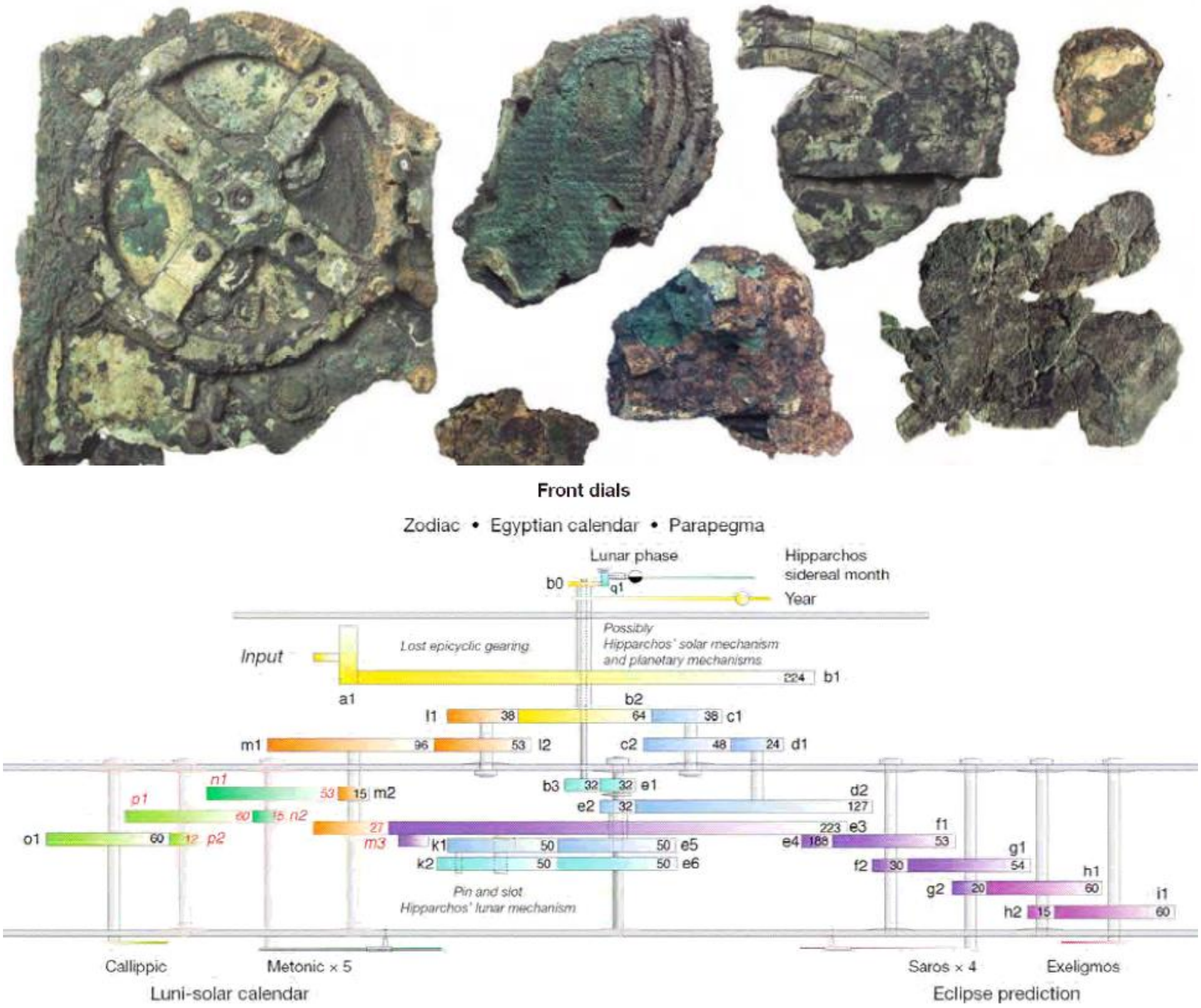

Figure 4.3: the Antikythera mechanism. Top, the largest of the surviving fragments. Bottom, reconstructed gear trains for the lunisolar calendar and eclipse predictor. It is suspected that there were similar gear trains for the planets, but these have not survived.
*Pictures from T Freeth et al., Nature **444** (2006) 587–591.*

The Antikythera mechanism is an astoundingly sophisticated instrument. Nothing remotely similar survives from antiquity, but it is impossible to believe that this was the first such device ever constructed: it shows, as Freeth et al. comment, "great economy and ingenuity of design", which are not features one expects in a first prototype. Bronze is expensive and easily recycled: probably quite a few "Antikythera mechanisms" were melted down for their metal content in the two millennia that elapsed between the construction and recovery of the one we have.

4.1.4 Ptolemy

Ptolemy worked in Alexandria, had a Romanised name (Claudius Ptolemaeus), wrote in Greek, and was most probably an Egyptian Greek (perhaps a descendant of Alexander's army). As the latest and most developed form of the epicycle theory, his work on the subject, the *Mathematical Compendium* (*Mathematike Syntaxis*, known by later Islamic scholars as the *Greatest Compendium*, *Megiste Syntaxis*, and hence—with the addition of the Arabic article *al*—ending up as the *Almagest*) became a classic reference among later astronomers, and has consequently survived in full. He based much of his theory on that of Hipparchos—most of our knowledge of his work comes from Ptolemy's account of it—but refined and improved it.

The basic principles of Ptolemy's epicycle model, as shown in figure 4.4, are as follows:

- For inner planets (Mercury and Venus), the line joining the Earth to the deferent (in the epicycle view) is always parallel to the Sun-Earth line.
- For outer planets (Mars, Jupiter and Saturn), the line joining the Earth to the eccentric (in the eccentric view; or the line joining the deferent to the planet in the epicycle view) is always parallel to the Sun-Earth line.

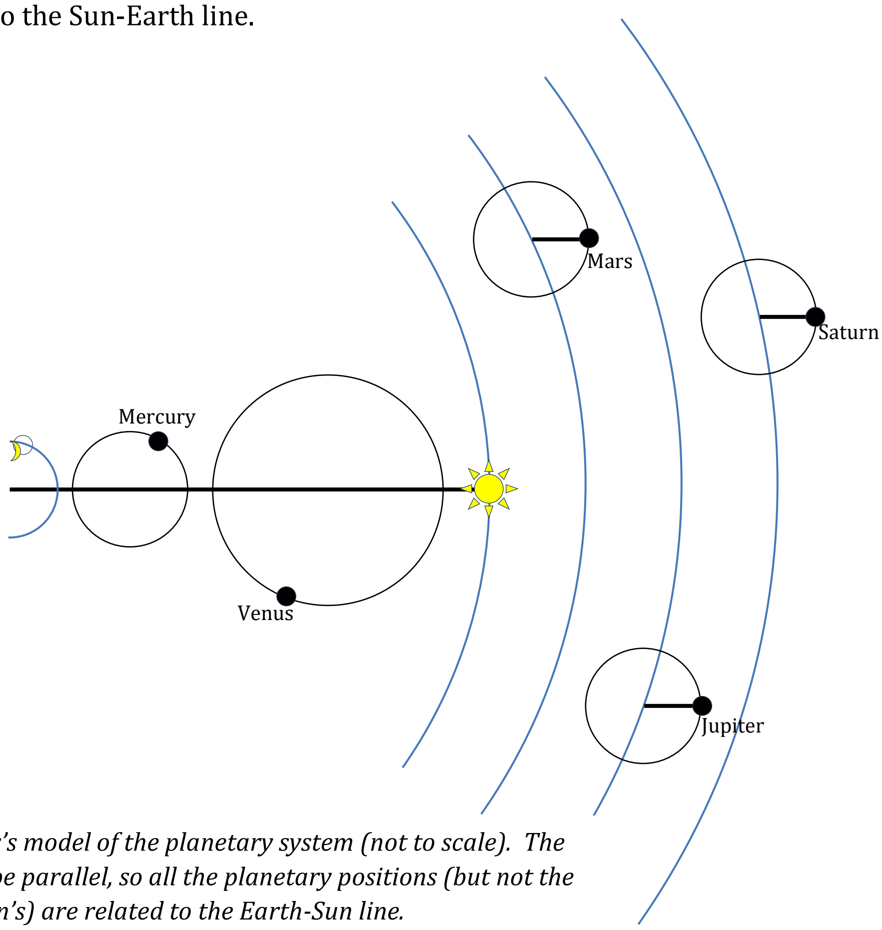

Figure 4.4: Ptolemy's model of the planetary system (not to scale). The thick lines must all be parallel, so all the planetary positions (but not the Moon's) are related to the Earth-Sun line.

With hindsight, as Thurston remarks, it is rather surprising that Ptolemy (or Hipparchos) did not think to equate all these parallel lines: if they had done so, they would have automatically constructed either the Aristarchan/Copernican heliocentric system or the Tychonic system in which the Sun goes round the Earth and everything else goes round the Sun (this is clearly equivalent to the Copernican system with a different reference frame). The latter, in particular, does not violate the Earth-is-at-rest assumption. The likely explanation is that, following Aristotle, they thought of the spheres defining the orbits as real, and therefore unable to intersect (the epicycles are seen as balls rotating inside a pair of nested spheres; although we draw the epicycle as crossing the deferent's orbit, Ptolemy would have drawn an inner and outer circle surrounding the epicycle). It is, of course, also possible that they never drew all the orbits out together, and thus failed to notice the regularity.

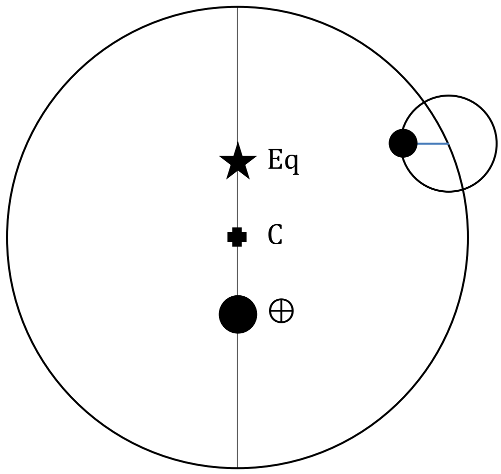

Figure 4.5: Ptolemy's model of a planetary orbit. The Earth is located away from the centre of the orbit, and the equant is equidistant from the Earth on the opposite side.

Ptolemy's real system was more complicated than this, because the planets' behaviour does not have the symmetries this would imply (for example, periods of retrograde motion are not all of equal length). Ptolemy noted that the motion of the planets is not uniform as viewed from the Earth, and is also not uniform as viewed from the centre of its deferent circle. He therefore assumed that the motion *is* uniform as seen from another point, the equant. He assumed that the Earth and the equant were equidistant from the centre of the deferent circle, as shown in figure 4.5 (this is the construction that looks remarkably like the two foci of an ellipse, to us if evidently not to Ptolemy; and indeed the need for this device does derive from the elliptical orbits of the planets). He also had a rather messy construction intended to reproduce the variation in the planets' ecliptic latitudes—the mess is generated by the fact that the planets' orbital planes pass through the Sun, not the Earth as Ptolemy expected. Nevertheless, because the two-circles model is geometrically nearly correct (the planets' motions *are* a combination of two "circles"—their near-circular orbits and the Earth's near-circular orbit), it is not surprising that Ptolemy could get a good fit to planetary motions with this model.

The Moon presented more of a problem, precisely because the two-circles model is *not* a good geometric representation of reality in this case. Ptolemy modified Hipparchos' theory by including both an epicycle and a moving eccentric, to try to improve the fit at half-moons. This does help, but has the unfortunate consequence that the Moon's distance from the Earth varies by nearly a factor of 2 over the course of its orbit. This is clearly wrong—it would imply that the Moon's apparent size would also vary by nearly a factor of 2, which someone would surely have noticed (it does vary, owing to the significant eccentricity of the lunar orbit, but only by about 14%)—and Ptolemy must have known it was wrong. However, the model does give a rather good description of the Moon's ecliptic longitude over the whole of the lunar cycle. Clearly Ptolemy was prepared to overlook the incorrect prediction of the Moon's apparent size because of the correct prediction of the Moon's position.

4.2 Islamic Astronomy

After Ptolemy, little new astronomical work emerged from the later Roman empire. The Romans, somewhat like the Egyptians, were extremely skilful engineers (consider aqueducts, hypocausts, etc.), but not much given to pure science. Greek ideas spread via the trade routes to India, where a system similar to, but independent of, Ptolemy's was developed by Āryabhaṭa around AD 500. However, the most fruitful dispersal of Ptolemaic astronomy was to the Islamic world that developed in the Near East from the 7th century AD.

The Islamic scholars had access to many now lost Greek manuscripts, and also close contact with Indian astronomers and mathematicians. As mentioned earlier, they adopted the efficient decimal place-value numerical system of the Indians (which we, having got it from them, miscall "Arabic" numerals); they also developed the ideas of trigonometry, so that the tables of chord lengths used by Hipparchos and Ptolemy were replaced with modern sines and cosines. They translated Ptolemy's *Syntaxis* and other works into Arabic; some of these would have been entirely lost if it were not for Islamic scholarship.

Despite their respect for Ptolemy's work, Islamic astronomers did not accept it without question. Like many earlier and later astronomers, they felt that the introduction of the equant violated the principle of uniform circular motion (which, by any reasonable argument, it does), and invented various ingenious if misguided schemes to reproduce its effects without introducing non-uniform motion. They also recognised the unsatisfactory nature of Ptolemy's theory of the Moon's motion, and developed a rather better system employing an epicycle on the epicycle instead of an epicycle plus an eccentric.

Many Islamic astronomers were theorists rather than observers—the supernova of 1054, which created the Crab Nebula and was extensively observed by the Chinese, attracted almost no attention in the Islamic astronomical community. Nevertheless, they greatly improved astronomical instrumentation, particularly the astrolabe, and made extremely good measurements of quantities such as the length of the year and the obliquity of the ecliptic. (Part of the improvement was due to longer time baselines, but better instruments also played a role.) They constructed a number of astronomical tables, using Ptolemy's theory but their improved measurements, which spread to the West via Moorish Spain and were widely used.

Although the number of genuinely new ideas introduced into astronomy by the Islamic scholars was rather small—they were much more inventive in mathematics and medicine—the debt owed to them by early modern astronomy is considerable. This can be seen by the number of star names incorporating the Arabic article *al*: Aldebaran, Algol, Altair, Fomalhaut, etc. Perhaps more important in the long run were the advances made by Islamic mathematicians (note the words *al*gebra, *al*gorithm), which allowed calculations on the celestial sphere to be done simply and accurately using "Arabic" numerals and Arabic spherical trigonometry. The conquest of Moorish Spain in the 12th century opened up a huge resource of Islamic astronomical literature, and led to the rebirth of astronomy in Western Europe.

4.3 The Renaissance and the "Copernican Revolution"

After the fall of the Western Roman Empire in the 5th century AD, Western Europe fragmented into many small "barbarian" kingdoms. Although the Roman disdain for non-Roman cultures involves a considerable amount of prejudice, there is no doubt that very few of these new societies were as literate and educated as the preceding Romanised peoples had been, and astronomy along with the other "liberal arts" fell into near disuse (apart from the fairly rudimentary observations needed to calculate the date of Easter, a lunar festival, in a solar calendar). The situation began to settle down after around AD 1000, and astronomy began to revive thanks to contact with the Islamic world through Moorish Spain, and sometimes with what remained of Greek scholarship through Constantinople. Ironically, it was probably the fall of Moorish Spain to the Christian Reconquista that did most to stimulate Western astronomy, by making Arabic manuscripts available (in Latin translation) to students in Western universities. The initial signs of revival are various textbooks for university use, which improve over the course of the 13th century as the Arabic knowledge is assimilated, and improved astronomical tables, in particular the influential **Alfonsine Tables** dedicated to King Alfonso X ("the Wise") of Castile. The astrolabe was introduced from the Islamic world in the 11th century, and other observational instruments such as the quadrant and the cross-staff were invented or improved in the course of the 13th century for use in observational astronomy and, increasingly, navigation.

The 13th century also saw the development of early mechanical clocks: although the surviving descriptions actually date from the early 14th century, the clocks they describe are very sophisticated and must have had simpler predecessors. Since the telling of time was much more directly associated with astronomy then than it is now, many of the early 14th-century clocks are astronomical in nature, showing the phases of the Moon, sunrise and sunset, planetary positions, and so forth.

4.3.1 Regiomontanus

From the point of view of science and education generally, one of the most important inventions of this period was the mid-15th century development of printing with movable type. This allows even complicated and abstruse texts, which would be extremely difficult for a professional scribe to reproduce without error, to be produced in multiple copies at reasonable cost. It transformed the transmission of existing knowledge from a task which could consume the entire life of a trained professional into something which could be accomplished comparatively easily, and allowed new ideas, even unconventional ones which might not have seemed worth copying by hand, to spread quickly through the developing network of universities.

An astronomer who was quick to see the value of printing was Johannes Muller of Konigsberg (1436–1476), known as **Regiomontanus** from the Latin version of his birthplace. He was a student of a Vienna-based astronomer and astrologer, **Georg Purbach**, who had written a textbook explaining the Ptolemaic system for use in universities. Regiomontanus visited Italy in the company of a Greek scholar named Bessarion, collected manuscripts, and settled down in the town of Nuremberg, a centre of the new printing industry. There he organised a printing business, saw Purbach's textbook into print (it was an academic bestseller) and a work of his own, the *Ephemerides*, containing a set of planetary tables for the next 30 years (another bestseller). It is known that he planned to publish a comprehensive set of astronomical and scientific works of the Hellenistic school, including Ptolemy, Euclid and Archimedes, in new Latin translations (a letter of his concerning these plans survives); he also set up an observatory in the house of a patron, Bernhard Walther, from which he and Walther made a series of highly accurate observations of solar and planetary positions, using instruments of his own design.

Had Regiomontanus lived to a ripe old age, the birth of modern astronomy would have been much easier. Unfortunately, when Pope Sixtus IV decided that the Julian calendar had outlived its usefulness and needed serious revision, Regiomontanus was the obvious man for the job. He was summoned to Rome in 1475 and died there a year later, with most of his plans uncompleted. His observing programme was continued by Walther, but his printing business was not taken on, and his intended Latin edition of the Greek scientific texts never appeared.

4.3.2 Copernicus

Fortunately, with the increased political stability of Europe, travel was becoming easier, and the loss of Regiomontanus' textbook printing programme was not as disastrous as it might have been. **Nicolaus Copernicus** (1473–1543), who was born in Poland and initially studied at the University of Cracow, seems to have had no difficulty in going to Italy to study law and medicine at the University of Ferrara (it is sobering to realise he might have had more trouble doing this in the 20th century than he did in the 15th!). Astronomy was taught at Cracow, and Copernicus maintained his interest in the subject in Italy, learning Greek so that he could read the Hellenistic classics, many of which had been brought to Italy by Greek scholars fleeing the fall of

Constantinople in 1453. Although he continued to study law, gaining his doctorate in 1503, he became known as an astronomer, lecturing on the subject in Rome in 1500 (according to an account by his student Rheticus).

He then returned to Poland, where he worked as a cathedral administrator at Frauenburg (nepotism, literally; his uncle was the bishop!) and continued to think about astronomy. Like the Islamic astronomers, he was unhappy with Ptolemy's use of the equant; in his studies of the Greek works he would have been told of the theories of Heraclides and Aristarchus; he had presumably also read Purbach's text, printed by Regiomontanus, in which Purbach said, "It is clear that each of the six planets in its motion shares something with the Sun, and the Sun's motion is, so to speak, the common mirror and measure for their motions."[2] In 1512 he wrote a short paper called the *Commentariolus* ("little commentary"), in which he set out the principles of a heliocentric system. This paper, however, was not formally published but simply sent out to friends and colleagues.

Copernicus' reasons for introducing a heliocentric system are more philosophical than scientific. He argues that the Earth rotates because it is "natural" for it to rotate, and therefore it is also "natural" for objects belonging to the Earth to partake in that motion; this avoids the problems raised by Aristotle and Ptolemy. He also argues that the heavens, being larger than the Earth, are more likely to be stationary, and that being stationary is "nobler" than motion and therefore more appropriate for the heavens than the Earth. These are clearly not arguments from observation. Though more elegant, in the sense that the periods of retrograde motion appear naturally instead of having to be put in by hand for each planet, Copernicus' theory was also not that much less complicated than Ptolemy's: some of the epicycles he removed by putting the Sun at the centre were replaced by epicycles introduced by his removal of the equant. (He could not remove the eccentric: in truth, his system is not quite "heliocentric" but centred on the centre of the Earth's orbit. As Hipparchos had realised over 1500 years before, this is necessary to explain the inequality of the seasons.)

Indeed, Copernicus respected the work of the Hellenistic authorities rather too much. His model was unnecessarily complicated by attempts to reconcile his observations with the results quoted by ancient astronomers, meaning that he treated as variable a number of quantities, e.g. the rate of precession, which really ought to be constants. When he eventually wrote up a full account of his theory, including a series of calculations demonstrating that it could reproduce the observed motions of the planets as well as Ptolemy's could, he consciously took Ptolemy's *Almagest* as a model. Although there is no doubt that he meant his heliocentric cosmology to be taken seriously as a model of the world (not simply as a calculational convenience), he still saw himself as refining and improving the models of the ancients, not really—despite the title of his work—as fomenting revolution in the heavens.

Copernicus does seem to have been conscious that his theory might meet religious opposition—not so much from the Vatican, which at this time was not strongly opposed to the heliocentric model (it was another half century before Galileo pushed the Catholic establishment too far), as from the Protestant authorities, who were more inclined to require the literal truth of the Bible. He delayed the publication of his complete work, the book *De Revolutionibus* ("On the Revolutions"), until the year of his death, 1543, when it was published at Nuremberg by his pupil Rheticus (who had published a brief account of it, the *Narratio Prima*, in 1540). With hindsight, the effect of the publication seems somewhat anticlimactic: the work was appreciated as the basis for more accurate planetary tables (the Prutenic Tables, calculated from Copernicus' re-

[2] The quotation is from Hoskin, pp 88–89. Purbach therefore saw the regularity that Ptolemy seems to have missed.

sults by Reinhold), but its theoretical basis was not generally accepted. (One should note that a foreword had been added to the book by a theologian friend of Copernicus called Osiander, in which it was explicitly stated that the heliocentric idea should be regarded as a convenient fiction for calculation rather than a physical fact. This foreword was not sanctioned by either Copernicus or Rheticus, both of whom took precisely the opposite view.)

4.3.3 Tycho Brahe

In the 15th century, Regiomontanus and Walther had established a new standard of accuracy for observations: Pannekoek says that the mean error of Walther's planetary observations was only 5', and his solar observations were better than this. This tradition was continued in the 16th century by the Danish nobleman **Tyge** (Latinised to "Tycho") **Brahe** (1546–1601). Surprisingly to modern eyes, his interest was founded in astrology: he was a fervent believer in the idea that God created all things for a purpose, and since the stars and planets do not seem to have much of a purpose in timekeeping or illumination, their purpose must be astrology. He was therefore disturbed to discover, when observing a conjunction of Jupiter and Saturn in 1563 (note he was then only 17), that the standard Alfonsine Tables were a month out in the predicted date, and even the new, Copernican, Prutenic Tables were days out. How could reliable astrological predictions be made if the tabulated planetary positions were themselves unreliable? He concluded that better observations, made with better instruments, were necessary, and began to design such instruments; in 1569 he designed a 19-foot quadrant in Augsburg, and a portable sextant for himself. He developed a clever zigzag technique to make accurate small subdivisions of angular scales (the Vernier scale was not invented for another half century).

A key event in Tycho's astronomical life occurred in November 1572: he observed a new star in the constellation Cassiopeia. It was extremely bright—as bright as Venus—and obviously not a previously known object (we now know that it was a supernova). Tycho was aware of Aristotle's assertion that the heavens "above the Moon" did not change: this new object should therefore be lower than the Moon, which meant it would have a measurable diurnal parallax. He checked this by measuring its position relative to the other stars of Cassiopeia over the course of a whole night (the Earth's rotation, rather than its orbit around the Sun (which Tycho did not believe in!), provides the baseline for a diurnal parallax measurement). No parallax was seen: the star was not "sublunary", and Aristotle was wrong. He was sufficiently convinced of his observations to publish a book on the subject, *De Nova Stella*, in 1573 (despite misgivings as to whether book publishing was appropriate for one of noble birth!). Similar observations of a comet which appeared in 1577 produced the same result: comets, too, belonged to the space beyond the Moon.

Tycho built an observatory on the Danish island of Hven and equipped it with state-of-the-art instrumentation: quadrants, sextants and armillae. His measurements of stellar positions were generally correct to within 1' or better—the best ever attained by naked-eye astronomy. His observations of the new star of 1572 had been hampered by the poor quality of existing star catalogues, so the construction of a new and much more accurate catalogue was part of his observing programme. He knew of Copernicus' theories, but was not happy with the idea of a moving Earth, and developed his own hybrid model in which the Earth is fixed, the Sun and Moon orbit the Earth, and the planets orbit the Sun. This explained the fact that the stars had no observable parallax, which seemed implausible in Copernicus' model—Tycho, like other astronomers of his time, could not believe that the stars were as distant as we now know them to be.

One possible test of the different world systems was the search for a measurable parallax of the planets, especially Mars. In Ptolemy's system, Mars is always more distant than the Sun; in Copernicus' and Tycho's systems, Mars at opposition is much closer than the Sun. Because the Sun's distance had been consistently underestimated since antiquity, Tycho believed that, if his system or Copernicus' were correct, he should be able to observe the parallax of Mars at opposition. (In fact, the diurnal parallax of Mars, even at opposition, is only about 20", well below even Tycho's limits for naked-eye observation.) He therefore made extensive observations of Mars around several successive oppositions in the hope of demonstrating the incorrectness of the Ptolemaic model. Although this endeavour was doomed to failure, the resulting set of detailed, accurate observations of Mars provided the data that Johannes Kepler would use to overturn the centuries-old assumption of circular motion in the heavens.

4.3.4 Johannes Kepler

Kepler (1571–1630) was born near Stuttgart and studied at the University of Tubingen, intending to enter the Protestant ministry, but was sidetracked into mathematics when Tubingen was asked to provide a mathematics teacher for the town of Graz. Fortunately, the astronomy professor at Tubingen, Michael Mastlin, covered the Copernican model in detail in his courses, and Kepler was impressed by its elegance. This conviction was cemented when he discovered that he could produce a fairly good fit to the relative orbital radii of the six planets by assuming that their spheres were separated by the five Platonic solids. In 1596 he published a book, *Mysterium Cosmographicum*, detailing this theory. Tycho received a copy of the book, was impressed by it, and invited Kepler to join him at Hven. Kepler initially refused, but religious persecution of Protestants made life in Graz untenable, Tycho moved from uninviting Hven to more sophisticated Prague, and Kepler decided that joining him wasn't such a bad idea. He arrived in Prague in 1600, a few months before Tycho's death, and made a sufficiently good first impression that when Tycho died he was appointed Imperial Mathematician.

Tycho had asked Kepler to preserve his legacy. Kepler did so in spectacular fashion, if not in the way that Tycho, as a non-believer in a heliocentric cosmology, would have wished. Using Tycho's extensive series of observations of Mars, Kepler set out to produce a precise mathematical description of planetary orbits. The eventual report of what Kepler called his "warfare with Mars" was a book called *Astronomia Nova* ("New Astronomy"). The book is most unlike a modern scientific report, in that it covers, in exhaustive detail, every stage of his analysis, blind alleys and all, and therefore gives a clear picture of his thought processes. He began by using Ptolemaic tools, including the despised equant, to fit the orbit. This produced a fit that would have seemed good enough for earlier data—but discrepancies of 8 arc minutes were not, in Kepler's opinion, tenable with Tycho's exceptionally accurate observations. Kepler suspected that his assumptions about the Earth's orbit, based on Ptolemy and Copernicus, were at fault. Detailed analysis showed that, indeed, these assumptions were flawed: Earth, like the other planets, needed a displaced equant point to describe its orbit.

Kepler was enough of a proto-physicist to dislike the idea that the motion of a planet is determined by reference to some arbitrary point in empty space. He felt that, despite appearances, it must in fact be the Sun which determined the varying speed of the planet. After much calculation, he first decided that at aphelion and perihelion the planet's speed was inversely proportional to its distance from the Sun, and later (using an approximation to the not-yet-invented integral calculus) that the area swept out in a given time was constant. This is what we now know as **Kepler's second law**.

Armed with the second law, and a better orbit for the Earth, Kepler went back to the Mars data, only to find that he still had an 8 arc minute discrepancy. He finally concluded that there was no way to interpret the Mars data satisfactorily with a circular orbit: the orbit must be "oval". "Oval" is a vague term, and Kepler did not initially assume an ellipse, for the completely sensible reason that it seemed too obvious—surely, if an ellipse were the correct answer, one of the Greek experts on conic sections would have realised this? However, eventually he realised that the fractional difference between the semi-major and semi-minor axes of Mars' orbit, $(1 - b/a)$, seemed to be equal to half the square of its eccentricity. This is exactly what one expects from a low-eccentricity ellipse (the semi-minor axis of an ellipse is given by $b^2 = a^2(1 - e^2)$, so for small e the binomial expansion gives $b = a(1 - ½\, e^2)$). The orbit really was an ellipse, with the Sun at one focus: this is **Kepler's first law**.

(Note that it is our extreme good fortune that Mars, the best subject for Tycho's attempted parallax measurement, is one of only two naked-eye planets with a significantly eccentric orbit; the other, Mercury, is too close to the Sun for decent naked-eye observations. Had Mars' orbit been as nearly circular as Venus', Kepler would never have had to abandon circular orbits.)

The *Astronomia Nova* was written in 1605 and finally appeared in print in 1609. Kepler subsequently analysed the orbits of Mercury and Venus in terms of ellipses, and in 1618 published an *Epitome of Copernican Astronomy* in which the whole solar system was interpreted in terms of his new ideas. As Tycho had, he also disposed of the varying constants Copernicus had introduced to accommodate the measurements handed down from antiquity (as a dedicated observer, Tycho probably had a clearer idea of the reliability of these measurements than his predecessors did!). The *Epitome* presents the solar system in essentially its modern form, though the absolute scale was still unknown (Kepler did know that the parallax of Mars must be smaller than about 1', because it was not visible in the residuals for his fitted orbit) and there was no explanation of the motion. Kepler also set in train the calculation of new tables of planetary positions based on his new theory: these **Rudolphine Tables** (named for his sponsor, the Holy Roman Emperor Rudolph II) were eventually published in 1627.

Kepler himself never lost the mystic streak that had resulted in his early *Mysterium Cosmographicum*. His book *Harmonice Mundi* ("Harmony of the World") attempts to connect his astronomical work with other fields such as geometry, numerology and music, largely without success. It is, however, remembered for one relation which *has* stood the test of time: his **third** or **harmonic law**, that the cube of the orbital radius of a planet is proportional to the square of its period.

4.4 The birth of modern science: Newton and the *Principia Mathematica*

The 17th century marked a turning point in the history of science. During this period, the first scientific societies and journals were founded, casual observation gave way to controlled experiments, the invention of calculus allowed previously intractable mathematical problems to be addressed, and the whole idea of science as the explanation of empirical observations by means of universal mathematical laws became established. The crowning achievement of 17th century science was Isaac Newton's *Principia Mathematica Philosophiae Naturalis* ("Mathematical Principles of Natural Philosophy"), one of the most influential books in the history of science.

Kepler's three laws of planetary motion are an early example of the 17th-century approach: they condense the principles of planetary motion into three *general laws* which are stated in *mathematical form*. However, Kepler's laws were purely empirical—there was no *explanation* of the physical principles behind them. Kepler recognised the need for this, and attempted to address it, but without success. He did recognise that the key to the problem must be the Sun, but without the general concepts of inertia and force he was unable to make progress.

Inertia is a key concept in classical mechanics. Up to this point, it had seemed self-evident that the natural state of (terrestrial) matter is to be at rest relative to the Earth: if you stop pushing something, it stops moving. This common-sense idea was challenged by **Galileo** in his experiments on inclined planes: he argued that a ball rolling down an inclined plane accelerates, at a rate which decreases as the slope decreases; a ball rolling up an inclined plane decelerates similarly; so a ball rolling on a perfectly level plane should neither accelerate nor decelerate, but continue moving at a constant speed. (He also showed that, if the ball starts at rest, the distance moved is proportional to the square of the elapsed time—in modern notation, $s = \frac{1}{2} at^2$.) These were some of the earliest properly controlled physics experiments; Galileo left detailed descriptions of his equipment, which show the care he took to avoid potential problems such as friction. Histories of science written by scientists (as opposed to historians) tend to agree in regarding Galileo as the first truly modern scientist. However, despite his triumphs with the telescope and his (personally disastrous) popularisation of the Copernican model, Galileo himself did not make great advances in astronomical theory.

René Descartes (1596–1650), in contrast to Galileo, was a theoretician and philosopher rather than an experimentalist. His basic philosophical principle was that matter and space are essentially identical, being differentiated only by their motion: what we perceive as matter is, according to Descartes, a vortex in the matter/space fluid. Because the fluid is all-pervading, it is natural that bodies/vortices should exert forces on one another (though Descartes did not achieve a quantitative understanding of Kepler's laws). Descartes incorporated Galileo's findings—effectively, what we now call "Newton's first law"—into his theory; however, in practice, it would be almost impossible for a body in Descartes' universe to be isolated from external influences. His ideas, set out in his *Principles of Philosophy* of 1644, were extremely influential in the mid-17th century: the young Newton was a Cartesian.

The **Royal Society**, founded in 1660, brought together the many gifted British scientists of the 17th century, and provided a forum for their papers in its *Philosophical Transactions*. The Royal Society had a strong experimental bias, unlike the more philosophical bent of Descartes; **Robert Hooke** (1635–1703) was their Curator of Experiments, charged with devising interesting demonstrations for the edification of the Fellows. Following William Gilbert's description of the Earth as a magnet, the fellows of the Royal Society were inclined, like Kepler, to think of the Sun's influence on the planets as in some way related to magnetism. This did produce the useful idea that the force of attraction should diminish as the distance between the bodies increased: in 1662, Hooke tried to measure the reduction in gravity between ground level and the top of tall buildings such as Westminster Abbey.

Hooke does deserve credit (which Newton, who detested him, was reluctant to give) for suggesting that gravity was an inverse square law, and affected both falling bodies and planetary orbits. However, he did not have the mathematical skill to prove that the inverse square law was correct (he also considered a $1/r$ law), and—typically—he failed to follow up on his initially promising ideas. In fact, combining Kepler's third law with the circular acceleration v^2/r found by Huygens in 1673 makes an inverse square law for planetary orbits seem natural; however, the task of demonstrating that more complicated curves, i.e. Kepler's ellipses, follow from an inverse square law was pushing 17th century mathematics to its limits.

Isaac Newton (1642–1727) is one of *the* great geniuses of science. He became Lucasian Professor of mathematics at Cambridge in 1669, at the age of 27—his mentor, the incumbent professor, resigned in his favour. He was a brilliant mathematician, and invented differential calculus ("the method of fluxions")[3], which provided him with an invaluable tool in studying orbits, and became interested in the problem of gravity at an early age: the story that he was inspired by watching an apple fall in a local orchard seems to have some basis in truth, although the idea that it hit him on the head is a later embellishment. He and Hooke exchanged letters on the subject before falling out.

It is not clear exactly when Newton worked out the relation of elliptical orbits to the inverse square law, but it was certainly before 1684, since he already knew the answer when Halley asked him in that year what orbital shape corresponded to an inverse square law of force. Halley asked him for the proof; Newton promised to supply it, and sent Halley a nine-page draft. In this first draft the attraction was one way—the Sun attracted the planets, but not *vice versa*—but this was quickly remedied in a second draft. The full version of the *Principia* was eventually published, thanks to Halley's diplomacy (everyone seems to have liked Halley, in contrast to both Newton and Hooke) in 1687.

The *Principia* established the concept of momentum ("quantity of motion", in Newton's Latin), the three Laws of Motion, and the Law of Universal Gravitation. Newton demonstrated that motion under an inverse-square force would take the form of a conic section (an ellipse for planets, but perhaps a parabola or hyperbola for comets), and that the force required to keep the Moon in orbit was exactly consistent, under the assumption of an inverse square law, with the acceleration of falling bodies near the Earth's surface. He also discussed the tides, the slightly flattened shape of the Earth, and the resulting precession of the equinoxes. The book was a *tour de force*.

Unfortunately it was also extremely hard to understand: although Newton probably worked out his results using calculus and algebra, he chose to present them in the traditional Greek style of geometrical proofs, which were very difficult to follow. Perhaps because of this, it took some time for Newtonian physics to oust Cartesian vortices. An additional problem was the extreme difficulty of solving Newton's equations for any but the simplest systems (in fact, there are no general analytical solutions to many-body problems in Newtonian gravity); in the 18th century, some very talented mathematicians (e.g. d'Alembert, Euler, Lagrange, Laplace) worked on developing the necessary techniques. Probably the most public triumph of Newtonian theory was engineered by **Edmund Halley**, though he did not live to see it completed. Halley investigated historical records of comets, to see if any could be explained in terms of an elliptical orbit: he found that the comet of 1682 had a retrograde orbit strikingly similar to those of 1531 and 1607, concluded that this was a single comet on a closed elliptical orbit, and predicted its reappearance "about the end of the year 1758, or the beginning of the next." It duly returned, reaching perihelion in March 1759 (Halley's slight error was the result of neglecting the influence of Jupiter on the retreating comet), and has been known as Halley's Comet ever since. Newton's laws reigned for over 200 years, until Einstein published the General Theory of Relativity in 1915, and are still the backbone of most dynamical calculations in astronomy and physics. From 1687 onwards, astronomy and physics are recognisably sciences in the modern sense.

[3] Leibniz invented the technique independently at about the same time. Typically—he really doesn't seem to have been a likeable man—Newton engaged in an acrimonious argument over priority.

4.5 The Solar System after Newton

The success of Newton's laws established the modern picture of the solar system, although its scale was still a matter of dispute, gradually resolved over the coming 250 years with improvements in technology (see next section). However, the 17th century solar system still contained very few ingredients not known since antiquity—only some satellites and Saturn's rings had been added to the tally of Sun, Moon, six planets, and the occasional comet. The first advance on this was made in 1781, when **William Herschel** discovered Uranus. This was a technology-driven accidental discovery: Herschel had the largest telescopes of his day, and nobody was expecting additional planets in the solar system. Indeed, Herschel initially thought he had discovered a comet, and only realised the magnitude of his achievement when orbital calculations demonstrated that the new object (which he tried to call *Sidum Georgium*, for King George III) had a planetary near-circular orbit rather than a cometary ellipse.

Uranus' discovery had the side-effect of apparently verifying a numerological relation between the sizes of planetary orbits known as the **Titius-Bode Law**, proposed by **Johann Titius** in 1766 and publicised by Bode in 1772 (as with many astronomical ideas, it may have been circulating earlier). This rule "predicts" the planetary orbits according to the algorithm $a = 4 + 3{\times}2^n$, where $n = -\infty, 0, 1, \ldots$ (i.e. the sequence goes 4, 7, 10, 16, 30, 52, 100, 196, 388, ...). Measured in tenths of an AU, the true values are 3.87, 7.23, 10.0, 15.2, 52.0, 95.4, 192. This last number is for Uranus, and is close enough to the predicted 196 that astronomers began to look seriously at the "gap" corresponding to 30. Around the turn of the 19th century, a group of European astronomers, calling themselves "the Celestial Police", planned a systematic hunt for the "missing" planet, but were beaten to it by **Giuseppe Piazzi**, who discovered Ceres during a sky survey in 1801. Owing to illness, Piazzi "lost" Ceres after only a month of observations, which made it impossible with the techniques of the day to establish its orbit; fortunately, the brilliant German mathematician **Carl Friedrich Gauss** took an interest in the problem, and was able to use his newly invented method of least squares ("which," says Agnes Clerke, "he had devised though not published"—which was entirely typical of Gauss, who became notorious for not publishing even major discoveries) to fit the orbit and predict Ceres' reappearance in the night sky to within half a degree.

Ceres was followed in rapid succession by Pallas, Juno and Vesta, and the status of these objects as *bona fide* planets became questionable: one object in a "planetary" orbit, however small, had claims to be a true planet, but four in the same region of space seemed less appropriate. Herschel demoted them to "asteroids" (the name, meaning "starlike", refers to their appearance in a telescope, not to their nature); Clerke calls them "minor planets". Both terms entered the astronomical nomenclature, eventually to be superseded in 2006 by the new IAU definitions, which make Ceres and any other asteroids large enough to be approximately spherical "dwarf planets", and the remainder "small solar system bodies". The latter term is too unwieldy for common use: I predict that "asteroid" will remain the standard usage, misleading though it is (asteroids are not "starlike" in any real sense).

Uranus was thus discovered by accident, as was Ceres, but the other early asteroids were discovered as a result of an empirical (or inductive) prediction; Ceres presumably would have been found by the Celestial Police if Piazzi hadn't found it first. The next major solar system discovery was also made following a prediction, but the prediction was of a completely different character.

By the early 19th century, the orbit of Uranus was causing serious concern. Uranus is fairly bright, reaching magnitude 5.5 at opposition, and had been recorded as a fixed star several times before Herschel noticed that it moved. These "pre-discovery" observations should have made it possible to compute the orbit of Uranus with considerable accuracy—but in fact it proved impossible to reconcile them with the post-discovery positions. Ignoring them as inaccurate and fitting only the recent measurements was tried, but within a few years it became apparent that this orbit was also failing to predict Uranus' motion within the observational errors of the time. One possibility seriously entertained was that Newton's law of gravity failed at large distances, but the more popular hypothesis was that an undiscovered outer planet was responsible. This "inverse problem" of locating a perturbing object from its perturbations is much harder than the direct problem of calculating the perturbations from the location and mass of the object, and was at the limits of the mathematical skills of the time. Two people, **John Couch Adams** of Cambridge and **Urbain Jean Joseph Leverrier** of Paris, independently took up the challenge, and both produced positions for the perturbing body. Famously, Adams (who had only just graduated) had great difficulty in persuading the British astronomical establishment to take him seriously, whereas Leverrier, whose reputation in celestial mechanics was established, fairly easily convinced **Johann Galle** of the Berlin Observatory to take a look. Galle promptly discovered Neptune; Challis, who had finally been asked by Airy, the Astronomer Royal, to conduct a search (after Airy had been sent Leverrier's prediction and had found it to be in agreement with Adams'), would have found it earlier, but had for some reason failed to examine the plates on which it was to be found. Considerable acrimony ensued, because this represented the British losing out to the "Continentals"; it is to Adams' credit that he did not participate. Indeed, the controversy has continued to this day: because Adams' predictions were not published at the time, it is difficult to be certain that the material he sent Airy would in fact have led to the discovery of Neptune had it been acted on, and some commentators have accused the British participants in the debacle of unjustly attempting to secure credit for Adams after the fact.

Be that as it may, the discovery of Neptune is clearly different in kind from those of Uranus and the asteroids. As with the asteroids, the discovery arises from a prediction; but the prediction is not a simple numerological guess but a clear consequence of an established physical law: if Newton's laws are assumed to hold, then there must be a planet close to the predicted position[4]. When the planet was duly found, it provided a very strong confirmation of the universal validity of Newton's laws.

The final major discovery in the outer solar system, that of Pluto, is often presented as a companion piece to Neptune's. In the early 20th century it appeared that Uranus' orbit was not fully explained by Neptune, and several astronomers suggested the presence of a ninth planet. One such, the wealthy amateur **Percival Lowell**, not only made the relevant calculations, but built himself a research quality observatory at Flagstaff to pursue this and his other obsession, the Martian "canals". He hired professional astronomers for his observatory: the director, **Vesto Slipher**, would later win renown for measuring the redshifts of nebulae.

Lowell died in 1916, and there was a lengthy legal battle over the money he left to Flagstaff (his widow contested the will). Eventually, the search for the object Lowell had called "Planet X" resumed in 1927, and Slipher hired a young amateur, **Clyde Tombaugh** (1906–1997) to conduct it. Tombaugh conducted a carefully designed, methodical, professional search and found Pluto in February 1930. Pluto, however, is *not* Lowell's Planet X: it is too small and nowhere

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[4] Actually, neither Leverrier nor Adams had a very accurate orbit for Neptune. This is because both used the Titius-Bode law as a starting point for their calculations, and hence assumed Neptune had $a \sim 39$ AU. In fact, the law fails for Neptune, which has $a = 30.1$ AU. Leverrier and Adams wound up with rather eccentric orbits which were approximately correct for Neptune's then-current position, but would have diverged later.

near massive enough to affect the orbit of Uranus. It is now known that the observed discrepancies were actually the result of a slight error in Neptune's mass, corrected after the Voyager flyby. Therefore, the discovery of Pluto is not comparable to that of Neptune: it is more like those of Uranus and Ceres—an accidental discovery made because the observer in question was careful, conscientious and unlikely to overlook an unusual phenomenon. As Louis Pasteur once said, "Fortune favours the prepared mind."

As with Ceres, Pluto was initially accepted as a major planet, but over time it became clear that there were many smaller objects in similar orbits: in fact, Pluto was a member of an outer asteroid belt, called the **Kuiper Belt** after the American astronomer Gerard Kuiper (though it was actually predicted earlier by the Irish astronomer **Kenneth Edgeworth**, and is occasionally referred to as the **Edgeworth-Kuiper** belt in recognition of this). Because the interval between the discovery of Pluto and the recognition of the existence of the Kuiper belt was longer than that between Ceres and the asteroid belt, there was much more resistance to recategorising Pluto than there had been to relabelling Ceres (it may also be relevant that Clyde Tombaugh was liked and respected by the whole astronomical community, and nobody really wanted to deprive him of "his" planet). Eventually, the discovery of **Eris**[5]—a trans-Neptunian object which was actually slightly *more* massive than Pluto—in 2005 brought the issue to a head: if Pluto is a planet, Eris must be one too, and we need to reconsider the status of Ceres (much the largest of the main-belt asteroids). In 2006, the International Astronomical Union considered the matter, and produced a definition of "planet" which excludes members of asteroid belts (a planet must have gravitationally "cleared the neighbourhood around its orbit" of smaller bodies). The new term "dwarf planet" was introduced for those objects which are massive enough to have settled into a near-spherical shape, but not massive enough to gravitationally displace other objects in similar orbits. Currently there are five fully accredited dwarf planets in the solar system—Eris, Pluto, Makemake, Haumea and Ceres, the first four all being trans-Neptunian—but several other known trans-Neptunian objects almost certainly qualify, and the tally will doubtless rise.

4.6 Summary: the solar system in the history of astronomy

For most of its history, astronomy *was* the study of the solar system: from antiquity to the 19th century, the stars were basically landmarks (with a few exceptions such as the Chinese interest in transients, some of which were novae and supernovae outside the solar system), and the interesting phenomena were the moving bodies—the Sun, Moon and planets. In the Western tradition, we start with simple record-keeping, move on to predictive mathematical models with the Babylonians, and then to physical models with the Greeks. The increasing precision of observations led to increasing dissatisfaction with the models, and thence to several qualitative jumps in understanding: the move from geocentric to heliocentric models (attempted at least twice, though only successful in the 16th century, with Copernicus[6]), the abandonment of circular orbits (Kepler), and the successful unification of terrestrial and celestial physics (Newton).

After Newton, the theoretical basis of the model did not change until Einstein's general theory of relativity in 1915, but the solar system continued to dominate research until at least the late

[5] The name Eris was chosen after the resolution of the debate: in August 2006, the body had the provisional designation 2003 UB313 (using a standard convention for newly discovered minor planets). The subsequent choice of Eris deliberately reflects the events its discovery had precipitated: Eris is the Greek goddess of strife and argument.

[6] One could argue that even the Copernican model never gained general acceptance: by the time the heliocentric model became mainstream, it was Kepler's model, not Copernicus', that was the state of the art.

19th century—arguably the early 20th. The replacement of naked-eye observation by telescopes led to the discovery of smaller bodies, such as satellites of the major planets, and later asteroids; the challenge of dealing with Newtonian gravitation for more than two bodies attracted the attention of leading mathematicians such as Euler and Laplace; the determination of the *scale* of the solar system, exemplified by the "solar parallax" (i.e. the accurate measurement of the astronomical unit), continued to be an active topic of research until the radar distances to Venus and Mercury in the 1960s established it to extremely high precision.

The development of spectroscopy in the early 19th century, especially following the establishment of the Kirchhoff-Bunsen laws in 1859, coupled with the development of thermodynamics and kinetic theory and assisted by better telescopes, led to a shifting of emphasis from the solar system first to stars and then to more distant objects. However, the development of space exploration from the late 1950s onwards stimulated solar-system astronomy once again—the planets and minor bodies of the solar system are the only astronomical objects we can physically visit. Since 1995, planetary astronomy, and particularly theories of the formation and evolution of the solar system, has been revolutionised by the discovery of thousands of extrasolar planets: the properties of these planets comprehensively demolished the then-prevalent models of the formation and composition of planetary systems (which had expected that all extrasolar planetary systems would resemble the solar system, with small terrestrial planets close to the star, large gas giants further out, and all planets in nearly circular orbits—none of this turns out to be right). This is an example of a failure of induction: deriving general laws about planetary systems from the single example of our own solar system turned out to be most unsafe, however physically plausible those general laws had seemed to be.