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Excerpt
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1

Watchers of the skies

Astronomy is probably the oldest of all the sciences. It differs from virtually all other science disciplines in that it is not possible to carry out experimental tests in the laboratory. Instead, astronomers can only observe what they see in the Universe and see whether observations fit the theories that have been put forward. Before we start our journey through the Universe in Chapter 2, I would like to share with you a little of the history of astronomy, looking at some of the astronomers who have, in the past, made great contributions to our knowledge.

Galileo Galilei's proof of the Copernican theory of the Solar System

One of the first triumphs of observational astronomy was Galileo's series of observations of Venus, which showed that the Sun, not the Earth, was the centre of the Solar System so proving that the Copernican rather than the Ptolemaic model was correct. He had made observations of Jupiter that showed four moons – now called the Galilean moons – weaving their way around it. This showed him that not all objects orbited the Earth.

In the Ptolemaic model of the Solar System (which is far more subtle than is often acknowledged) the planets move round circular 'epicycles' whose centres move around the Earth in larger circles called deferents. This can account for the 'retrograde' motion of planets such as Mars and Jupiter when they appear to move backwards in the sky. It also models the motion of Mercury and Venus. In their case, the deferents, and hence the centres of their epicycles, move round the Earth at the same rate as the Sun. The two planets thus move round in circular orbits whose centres lie on the line joining the Earth and the Sun, being

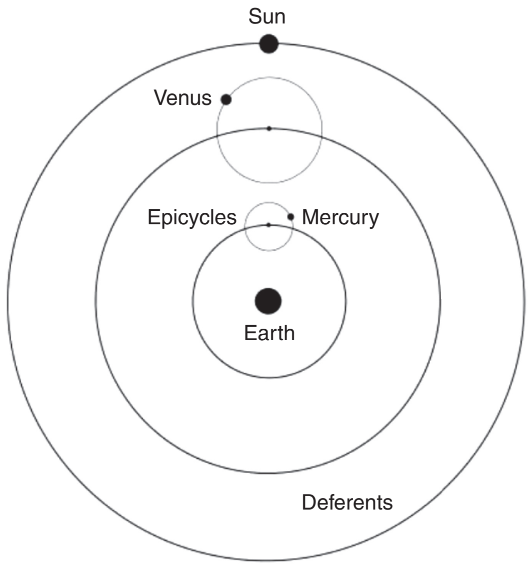

Figure 1.1 The centre points of the epicycles for Mercury and Venus move round the Earth with the same angular speed as the Sun.

seen either before dawn or after sunset. Note that, as Mercury stays closer to the Sun than Venus, its deferent and epicycle are closer than that of Venus – in the Ptolemaic model Mercury is the closest planet to the Earth!

As seen in Figure 1.1, in the Ptolemaic model Venus lies between the Earth and the Sun, hence it must always be lit from behind so could only show crescent phases whilst its angular size would not greatly alter. In contrast, in the Copernican model Venus orbits the Sun. When on the near side of the Sun it would show crescent phases, whilst on its far side, but still visible, it would show almost full phases. As its distance from us would change significantly, its angular size (the angle subtended by the planet as seen from the Earth) would likewise show a large change.

Figure 1.2 shows a set of drawings of Venus made by Galileo when using his simple refracting telescope. They are shown in parallel with a set of modern photographs which illustrate that not only did Galileo show the phases he also correctly drew the changing angular size. These drawings showed precisely what the Copernican model predicts – almost full phases when Venus is on the far side of the Sun and hence has a small angular size coupled with thin crescents having a significantly larger angular size when it is closest to the Earth.

So Galileo's observations, made with the simplest possible astronomical instrument, were able to show which of the two competing models of the

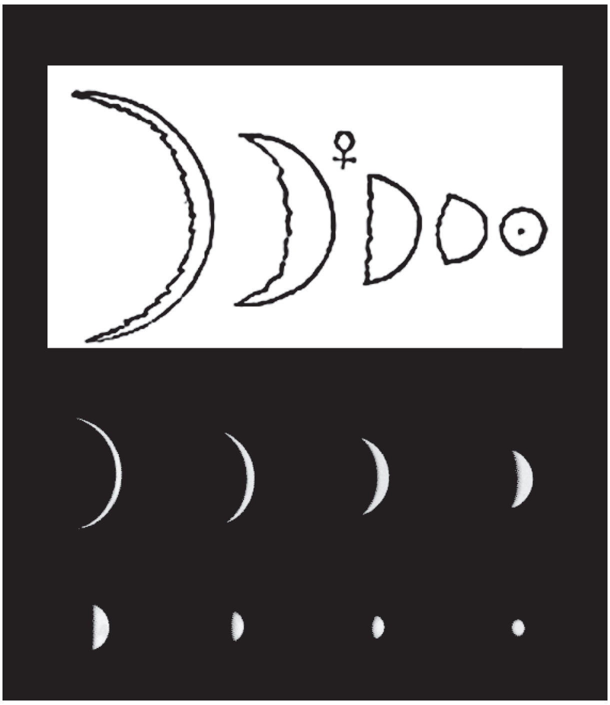

Figure 1.2 Galileo's drawings of Venus (top) compared to photographs taken from Earth (below).

Solar System was correct. In just the same way, but using vastly more sophisticated instruments, astronomers have been able to choose between competing theories of the Universe – a story that will be told later.

The celestial sphere

Looking up at the heavens on a clear night we can imagine that the stars are located on the inside of a sphere, called the celestial sphere, whose centre is the centre of the Earth.

As an aid to remembering the stars in the night sky, the ancient astronomers grouped them into constellations representing men such as Orion, the Hunter, women such as Cassiopeia, mother of Andromeda, animals and birds such as Taurus, the Bull, and Cygnus, the Swan, and inanimate objects such as Lyra, the Lyre. There is no real significance in these stellar groupings – stars are essentially seen in random locations in the sky – though some patterns of bright stars, such as the stars of the 'Plough' (or 'Big Dipper') in Ursa Major, the Great Bear, result from their birth together in a single cloud of dust and gas.

A second major observational triumph

We are now in a position to describe the observations that led to a further major improvement in our understanding of the Solar System.

In 1572, Tycho Brahe, a young Danish nobleman whose passion was astronomy, observed a supernova (a very bright new star) in the constellation of Cassiopeia. His published observations of the 'new star' shattered the widely held belief that the heavens were immutable, and he became a highly respected astronomer.

He realised that in order to show when further changes in the heavens might take place it was vital to have a first-class catalogue of the visible stars. Four years later, Tycho was given the Island of Hven by the King of Denmark and money to build a castle, which he called Uraniborg, named after Urania, the Greek goddess of the heavens. Within its grounds he built a semi-underground observatory called Stjerneborg. For a period of 20 years his team of observers made positional measurements of the stars and, of critical importance, the planets.

Figure 1.3 shows his observatory and indicates how his measurements were made. An observer sighted a star (or planet) through a small window on a south-facing wall. Two things were measured. Firstly an assistant noted the time of transit as the star crossed the meridian. The meridian is the half-circle that runs across the sky through the zenith between the north and south poles and intersects the horizon due south. Secondly, by using a giant quadrant equipped with vernier scales the observer was able to measure the elevation (angular height above the horizon) of the star at the moment of transit. The assistant is standing beside the clock at the lower right of the figure to measure the time at which the star transits and the scribe seated at a table at the lower left would then note the elevation of the star and time of transit in the log book. He could thus determine the position of the star on the celestial sphere.

Not only had Tycho produced a star catalogue 10 times more precise than any previous astronomer – the errors of the 777 star positions never exceeded 4 arcminutes (one arcminute is one sixtieth of a degree) – he had charted the movement of the planets during the 20-year period of his observations. It was these planetary observations that led to the second major triumph of observational astronomy in the sixteenth and seventeenth centuries: Kepler's three laws of planetary motion.

When King Frederik II died in 1588, Tycho lost his patron. The final observation at Hven was made in 1596 before Tycho left Denmark. After a year travelling around Europe he was offered the post of Imperial Mathematician to Rudolf II, the Holy Roman Emperor, and was installed in the castle of Benátky. It was

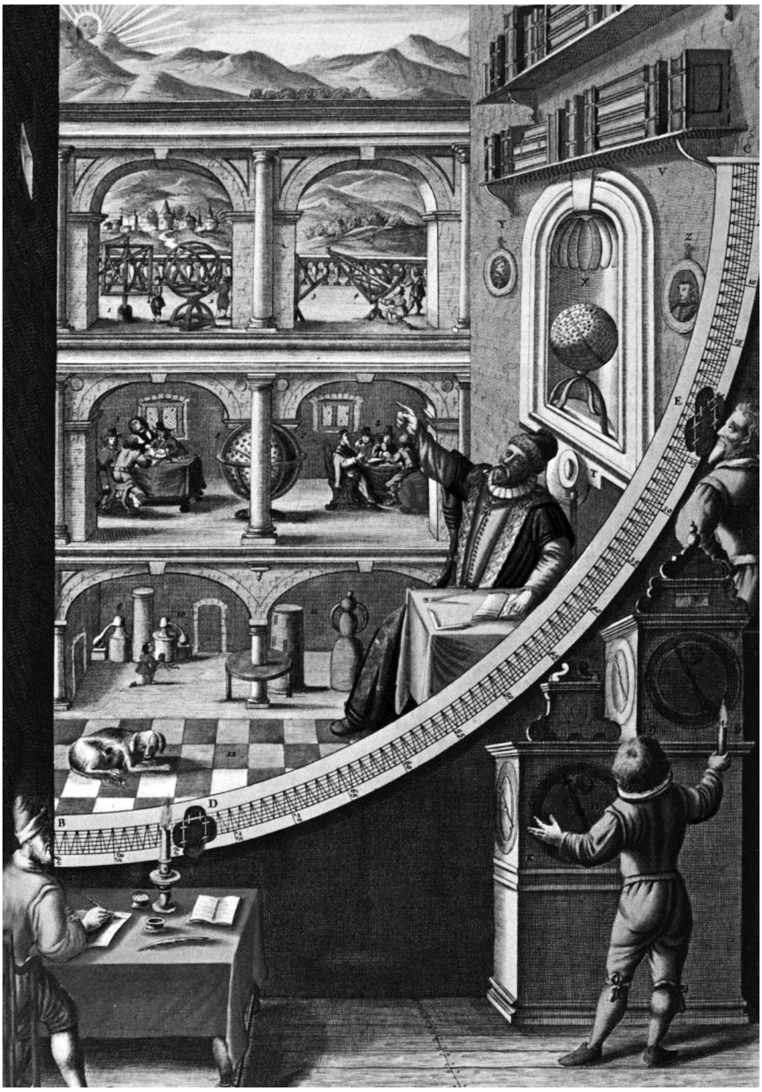

Figure 1.3 A quadrant used by Tycho Brahe to measure the elevation of a star or planet as it crosses the meridian (due south).

here that a young mathematician, Johannes Kepler, came to work with him. Tycho gave him the task of solving the orbit of the planet Mars. Kepler thought that it would take him a few months. In fact it took him several years!

There was a fundamental problem. The observations of Mars had been made from the Earth – which was itself in orbit around the Sun. Unless one knew the precise orbit of the Earth one could not find the parameters of the Martian orbit. In what has been described as a stroke of genius, Kepler realised that every

687 days (the orbital period of Mars) Mars would return to exactly the same location in the Solar System, so observations of the Earth from Mars made on a set of dates separated by 687 days could, in principle, be used to solve for the orbit of the Earth. (As could, of course, observations made on those days of Mars from the Earth.) Having solved for the Earth's orbit, Kepler was then able to deduce the orbital parameters of Mars.

The laws of planetary motion

From the invaluable database of planetary positions provided by Tycho, Kepler was able to draw up his three empirical laws of planetary motion. The word 'empirical' indicates that these laws were not based on any deeper theory but accurately described the observed motion of the planets. The first two were published in 1609 and the third in 1618.

The first law states:

> **Planets move in elliptical orbits around the Sun, with the Sun positioned at one focus of the ellipse.**

The second law states:

> **The radius vector – that is, the imaginary line joining the centre of the planet to the centre of the Sun – sweeps out equal areas in equal times.**

This implies that the planets, in an elliptical orbit, move faster when closest to the Sun – as they near the Sun they lose potential energy and, as the total energy must be constant, increase their kinetic energy, and so move faster.

The third law relates the period of the planet's orbit, T, with a, the semi-major axis of its orbit, and states:

> **The square of the planet's period, T, is proportional to the cube of the semi-major axis of its orbit, a. (For a circular orbit, the semi-major axis is the radius.)**

A highly significant result of the third law is that it enabled astronomers to make a very accurate map of the Solar System. The relative positions of the planets could be plotted precisely *but the map had no scale*. It was like having a very good map of a country but not knowing, for example, how many centimetres on the map related to kilometres on the ground. A way to solve this problem would be to make an accurate measurement of *one* reasonably large distance across the area covered by the map. This would then give the scale, and thus the distance between any other two points on the map could be found.

Isaac Newton and his Universal Law of Gravitation

Isaac Newton was born in the manor house of Woolsthorpe, near Grantham, in 1642, the same year in which Galileo died. His father, also called Isaac Newton, had died before his birth and his mother, Hannah, married the minister of a nearby church when Isaac was two years old. Isaac was left in the care of his grandmother and effectively treated as an orphan. He attended the Free Grammar School in Grantham and took up lodgings there. He showed little promise in academic work and his school reports described him as 'idle' and 'inattentive'. His mother later took Isaac away from school to manage her property and land, but he soon showed that he had little talent and no interest in managing an estate.

An uncle persuaded his mother that Isaac should prepare for entering university and so, in 1660, he was allowed to return to the Free Grammar School in Grantham to complete his school education. He lodged with the school's headmaster, who gave Isaac private tuition, and he was able to enter Trinity College, Cambridge, in 1661 as a somewhat more mature student than most of his contemporaries. He received his bachelor's degree in April 1665 but then had to return home when the university was closed as a result of the plague. It was there, in a period of two years and whilst he was still under 25, that his genius became apparent.

There is a story (which is probably apocryphal) that Newton was sitting under the apple tree in the garden of Woolsthorpe Manor. He might well have been able to see the first or last quarter Moon in the sky. It is said that an apple dropped on his head (or thudded to the ground beside him) and this made him wonder why the Moon did not fall towards the Earth as well.

Newton's moment of genius was to realise that it *was* falling towards the Earth! He was aware of Galileo's work relating to the trajectories of projectiles, and in 1686 he considered what would happen if one fired a cannon ball horizontally from the top of a high mountain where air resistance could be ignored. The cannon ball would follow a parabolic path to the ground. As the cannon ball was fired with greater and greater velocity it would land further and further away from the mountain. As the landing point becomes further away the curvature of the Earth must be considered. In a popular work published in the 1680s called *A Treatise of the System of the World* he included the diagram shown in Figure 1.4. The mountain is impossibly high in order for it to reach above the Earth's atmosphere. But this is a thought experiment, not a real one! One can see from this that if the velocity is sufficiently high the cannon ball would never land – it would be in an orbit around the Earth! (To be brutally accurate it would hit the back of the cannon after one orbit, but we will ignore that.)

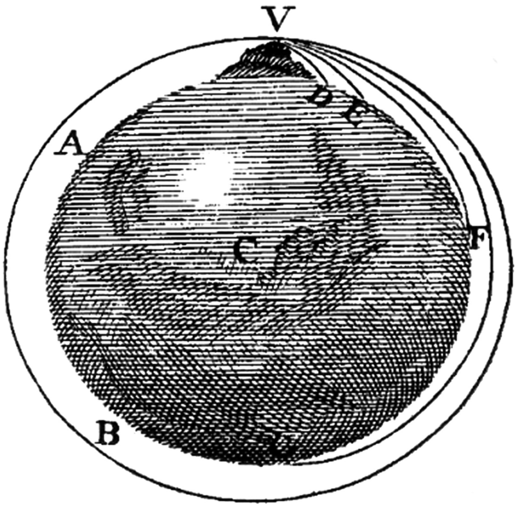

Figure 1.4 Newton's thought experiment using a cannon ball.

Newton applied the same logic to the motion of the Moon, realising that, if the gravitational attraction between the Earth and the Moon caused it to fall by just the right amount, it too would remain in orbit around the Earth. He knew enough about the Moon to be able to calculate the value of the acceleration of gravity at the distance of the Moon. For this he needed to know the radius of the Moon's orbit, assumed to be circular, about the centre of the Earth and also the period of its orbit around the Earth. Newton used a value of the radius of the Moon's orbit of 384,000 kilometres and a period of 27.32 days or 2.36×10^6 seconds and showed that the value of g (the acceleration due to gravity) at the distance of the Moon was 1/3,606 that at the surface of the Earth.

Newton also knew that the radius of the Earth was 6,400 km so that the Moon, at a distance of 384,000 km, was precisely 60 times further away from the centre of the Earth than the Earth's surface. So the value of g at the distance of the Moon had fallen almost precisely by the ratio of the distance from the centre of the Earth squared!

This led Newton to his famous inverse square law: the force of gravitational attraction between two bodies decreases with increasing distance between them as *the inverse of the square of that distance*.

But Newton had a problem. He felt that he could not publish his law until he could prove that the gravitational pull exerted by a spherical body was precisely the same as if all the mass were concentrated at its centre. This can only be proved by calculus, and it took Newton a while to develop the ideas of calculus, which he called 'fluxions'. It was only then that he felt confident to publish his law.

Newton realised that the force of gravity must also be directly proportional to the object's mass. Also, based on his third law, he knew that when the Earth exerts its gravitational force on an object, such as the Moon, that object must exert an equal and opposite force on the Earth. He thus reasoned that, due to this symmetry, the magnitude of the force of gravity must be proportional to both the masses.

His law thus stated that the force, *F*, between two bodies is directly proportional to the product of their masses and inversely proportional to the distance between their centres. The force is then equal to the product of these two factors multiplied by a constant called *G*, the constant of gravitation.

Newton derived a value of *G* by estimating the mass of the Earth, assuming it had an average density of 5,400 kg/m^3. He suspected that the Earth got denser with depth and simply doubled the value of 2,700 kg/m^3 that is measured at the surface of the Earth. (This was a pretty good – and very lucky – estimate as it is actually 5,520 kg/m^3!) The value that he obtained for *G* was 6.76×10^{-11} N m^2 kg^{-2}. Due to his lucky estimate of the mean density of the Earth, this was a very good result – the now accepted value of *G* being 6.67×10^{-11} N m^2 kg^{-2}.

His law was called the 'Universal Law of Gravitation', but why Universal? Using his second law (force = mass × acceleration) and his Law of Gravitation, Newton was able to deduce Kepler's third law of planetary motion. This deduction showed him that his law was valid throughout the whole of the then known Solar System. To him that was Universal!

Charles Messier: a great observer

Messier, a French astronomer, who made his observations from the Hôtel de Cluny in Paris, observed all types of astronomical phenomena such as occultations, transits and eclipses, but his great love was discovering and observing comets. His 13 comet discoveries brought him great fame and he was made a fellow of the Royal Society and elected to the French Academy of Sciences.

Whilst scanning the heavens in August 1758 when searching for new comets, Messier came across a faint nebulosity in the constellation of Taurus, the Bull. Thinking first that this might be a comet, he observed it on following nights and soon realised that it was not a comet as it did not move across the sky. To prevent both himself, and others, wasting observing time in the future he decided to produce a catalogue of nebulous objects that might be first thought to be comets. This object in Taurus thus became the first object in his catalogue: M1. It is the remnant of a supernova that was observed in 1054 and is now known as the Crab Nebula, as a nineteenth-century astronomer, the Third Earl of Rosse, having observed it with his great 72-inch Newtonian, thought that it resembled a horseshoe crab. The task of compiling his catalogue did not begin in earnest until 1764, and within seven months a further 38 entries has been added, such as the globular cluster in Hercules, M13, the Dumbbell Planetary Nebula, M27, and the Andromeda Galaxy, M31.

The first of Messier's catalogues, listing 45 objects, was published in 1774 and his final list of 103 objects was published in 1781. Since then the list has grown to 110 objects as astronomers and historians found evidence of another seven deep-sky objects that had been observed either by Messier or his assistant Pierre Méchain not long after the final list had been published. His list has bequeathed a wonderful resource for amateur astronomers as it contains many of the most beautiful celestial objects that can be seen in a small telescope: covering every type of object from open and globular clusters, diffuse and planetary nebulae to many of the brightest galaxies that can be observed from northern mid-latitudes. Because Messier had discovered them with relatively small refractors (albeit without the light pollution that many of us now suffer) these objects can be observed visually with virtually all amateur telescopes and are among the most attractive deep-sky objects in the heavens.

Edmond Halley and the measurement of the astronomical unit

Edmond Halley is best known for the comet that bears his name and whose story is covered in Chapter 7, but he also had an insight that enabled the distance of the Earth from the Sun (one astronomical unit – 1 AU) to be determined.

In the case of the Solar System, the obvious measurement to make is the distance between the Earth and either of the two planets nearest to it, Venus or Mars. Once this is known, Kepler's third law can be used to calculate the distance of the Earth from the Sun. In 1678 Halley realised that if the transit of a planet across the surface of the Sun could be observed from two widely spaced locations on the Earth, the slight difference observed in the passage across the Sun from the two locations would, in principle, enable its distance to be found by the method of parallax. The problem is that the widest separation possible on the Earth, its diameter of 12,756 km, is small compared to the distances of the planets and thus the angular difference that has to be measured is very small and prone to errors.

There was a major effort to observe the two transits of Venus in the 1700s. In 1761, the most successful observations were made by two surveyors, Jeremiah Dixon and Charles Mason, at the Cape of Good Hope. (They are best known for