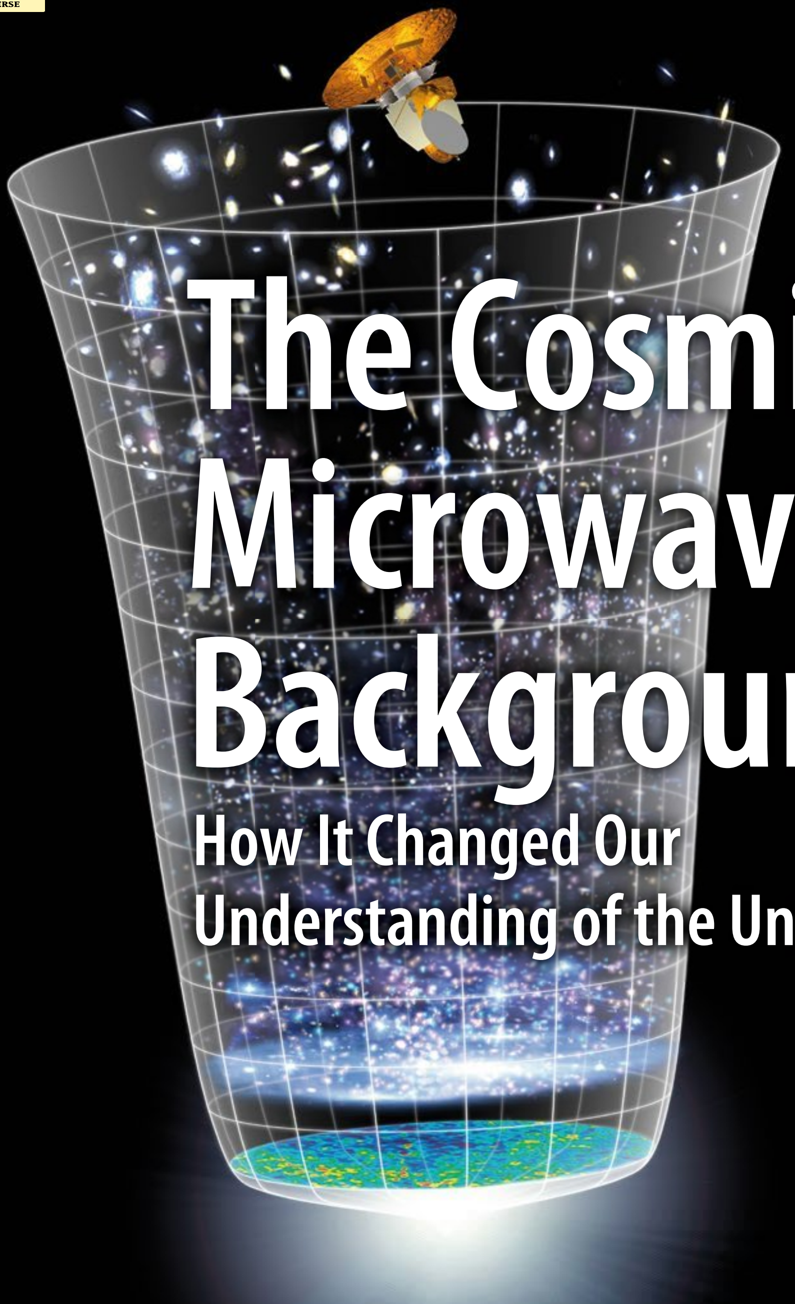
Astronomers' Universe

Rhodri Evans

The Cosmic Microwave Background

How It Changed Our Understanding of the Universe



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Cover illustration: The Orion Nebula, the closest of over 100 known huge gas and dust clouds located in our Milky Way Galaxy, appears to be a very busy "newborn nursery" where many new solar systems are being built. This photograph courtesy of NASA/ESA/Luca Ricci shows a collection of six such new planetary systems, some of which may in the far distant future, provide a home for life. Credit: NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA), the Hubble Space Telescope Orion Treasury Project Team and L. Ricci (ESO)

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For my parents Colin and Audrie; my sister Jill, my wife Maggie and my children Meirin, Siân-Azilis and Esyllt. Thank you.

Preface

On Sunday the 16th of March this year, just a few weeks ago from my writing this, rumours started circulating on social media that there would be a *major* announcement from cosmologists at Harvard University the following day. By the following morning it was clear that the announcement was going to be coming from the team conducting an experiment at the South Pole using a telescope called BICEP2. When the press conference arrived the physics and cosmology communities almost went into a meltdown. The BICEP2 team announced that they had found the best evidence yet for something called "cosmic inflation", which happened when the Universe was 0.000000000000000000000000000000000001 of a second old.

Although this result is currently hotly disputed, if correct, it is a spectacular evidence that we understand the physics of the Universe as far back as this unimaginably small fraction of time after it came into existence. However, since the March 2014 announcement by the BICEP2 team, a huge amount of debate has ensued in the cosmology community as to whether their result is real or not. The arguments in this debate will be discussed in more detail in the book.

"*Cosmology*" is the subject of understanding the beginning, evolution and nature of the Universe. It is a subject which has always fascinated humanity, and every civilisation has its own cosmology. Whether it is the "*Genesis story*" common to Judaism, Christianity and Islam; the Hindu's belief that Lord Brahma created the Universe, Lord Vishnu maintains it, and Lord Shiva will destroy it; or the complex "*dream time*" origin stories of the Australian Aboriginals, as a species we have always tried to understand the Universe, and from where it and we ourselves have come. It seems to be a basic human need in all of us. It is also a subject which has fascinated me ever since I was 12 and saw a BBC Horizon programme called "*The Key to the Universe*".

In this book I present scientists' current favourite cosmology, the "*hot big bang theory*". This theory postulates that our Universe began some 13.7 billion years ago when time and space were created in an unimaginably dense "fireball"—the big bang. Since that moment of creation, space has been expanding and evolving. The stars, galaxies, elements and life in our Universe have all developed from this.

This book traces the history of our understanding of the Universe, from the early ideas of the Greeks through to the latest findings announced in the last few weeks which probe the conditions in the very earliest moments of our Universe's existence. After laying down the evidence that our Earth is not the centre of the Universe as the Greeks had thought, but rather orbiting the Sun on the outskirts of an average galaxy, I show how we now know that our Milky Way is just one of billions of galaxies, and that the Universe is expanding. I present the story of the 1931 prediction of the big bang, and the 1948 prediction of a relic radiation from the early Universe which we call the "*cosmic microwave background radiation*".

This radiation was finally discovered in 1964, and since then advances in both theory and observations (such as the BICEP2 experiment mentioned above) now allow us to argue that we understand the physics of the Universe back to the briefest fraction of a second after it started (we are still not quite sure about the time before that!).

What a remarkable journey we have made; barely 100 years ago we did not know how stars got their energy, whether our Milky Way was the entire Universe, or from where the elements which make up our very fabric had come. We now believe we know all of these things. Yet there is still so much that we don't understand. Understanding the details of the structure of the Universe has led us to the remarkable and exciting finding that ordinary matter may only make up about 5 % of the Universe; with the rest being made up of about 20 % of "dark matter" and about 75 % of "dark energy". At this present time, we have no idea what dark matter and dark energy are, just that it seems they exist.

My aim is that this book should be of interest to all those people who want to learn more about where our Universe has come from, and how we have gone from the ignorance of the past to the understanding we have today. I have tried to make the story as engaging as possible, science is a human activity and I have attempted to give a flavour of some of the people who have played key parts in advancing our knowledge of the Universe. I have also tried to explain any necessary physics at a level which I hope will be understandable to a non-scientist; any lack of understanding by you the reader is due to my own inadequacies in doing a proper job in my explanations.

We stand at a remarkable moment in *cosmology*. In the last 30 years separate lines of evidence have come together to give us a consistent picture of the origin, composition and structure of the Universe. However, there are also many unanswered mysteries including dark matter, dark energy and whether our Universe is just part of a "*multiverse*". There is, however, a caveat; as my ex-Ph.D. supervisor and "science mentor" Professor Mike Disney always reminds me, there has never been a time in history when people didn't think that they had the correct cosmology. Maybe our current cosmology is as incorrect as our ancestors'. Only time will tell.

Wales, UK Rhodri Evans
April 2014

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Chapter 1
At the Centre of Creation?

Early models of the Universe by Greeks such as Ptolemy placed the Earth at the centre of the heavens. In the sixteenth century, Copernicus suggested that the Sun and not the Earth was at the centre of creation, and Galileo found observational evidence for this in the 1609–1611 period. Kepler worked out that the planets orbit the Sun in ellipses and not circles, and later in the seventeenth century, Newton wrote down the laws of gravity and mechanics which shaped our understanding of Physics for the next 250 years. Using a method suggested by Halley, in 1761 and 1769 we measured the distance from the Earth to the Sun, and by 1838 we had measured the distance to one of the nearest stars. In 1814 Fraunhofer learnt that stars have dark lines in their spectra, and this could be used to measure how quickly they are moving towards or away from us, and by the 1910s Henrietta Leavitt had discovered a way to measure vast distances using a particular type of star called a Cepheid variable.

1.1 Ptolemy's Universe

To even the casual observer, the daily motion of the Sun from East to West across the sky is very obvious. A little more observations over a few weeks and one will notice the changing phases of the Moon, with each full Moon spaced by about 30 days. Beyond this, more detailed observations of the night-time sky can reveal that different stars appear at different times of the year. For example, the easily recognisable stars that form the constellation Orion can be seen in the autumn and winter skies, but not in the summer. Conversely, the stars Vega, Deneb and Altair which form the summer triangle cannot be seen in the winter skies.

Even more detailed observations will show that not all the stars behave the same way. There are five star-like objects which appear to wander amongst their fellow stars. These are the five naked eye planets, Mercury, Venus, Mars, Jupiter and

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Saturn. The Greek name ‘planet’ actually means ‘wandering star’. In any model of the Universe, these observations need to be explained.

The model which has been believed for most of the last 2,000 years is one that is chiefly attributed to the Greek astronomer Claudius Ptolemy [1], who lived in the second century BC in Alexandria. In his model, the Earth was placed at the centre, with the Moon, Sun, planets and stars all orbiting it at different rates.

A model is, of course, only successful if it can match the observations. Although the planets appear to normally wander through the background stars in an easterly direction from night to night and month to month, sometimes they appear to reverse direction. The planet which shows this brief westerly motion against the background stars most markedly is Mars. This phenomenon, called ‘retrograde motion’, could not be explained with the simple model shown above. Ptolemy had to introduce the idea of ‘epicycles’, which were superimposed on the planet’s motion along its deferent (the circles shown in Fig. 1.1). By adjusting the size of a planet’s epicycle,

Fig. 1.1 Ptolemy’s model of the Universe placed the Earth at the centre, with the Sun, Moon, planets and stars all moving about it. This drawing is taken from Peter Aplan *“Cosmographia”* (1524)

Ptolemy was able to get excellent agreement between the positions of celestial objects as predicted by his model and what was observed.

Ptolemy's incorrect 'geocentric' (Earth-centred) model was not overthrown until the early 1600s. The Polish astronomer Nicholas Copernicus is most often credited with suggesting that the Sun and not the Earth lay at the centre of the Universe. However, he was not the first. Even before Ptolemy, another Greek astronomer, Aristarchus of Samos, working in the third century BC proposed that the Sun and not the Earth was at the centre of the Universe. But Ptolemy's model was preferred, mainly because it fitted in well with the philosophical world-view developed by Plato and Aristotle.

1.2 Copernicus' Revolution

The person who is most credited with suggesting the heliocentric (Sun-centred) Universe is Nicholas Copernicus. Copernicus had trained as a church cleric, and through the help of his uncle who was Bishop of Ermland, he held a position as a canon at the cathedral in Frauenburg in modern-day Poland. Copernicus had studied law and medicine in Italy, so his main duties as a canon were to act as physician and secretary to his uncle. His duties were not particularly demanding, allowing him to indulge in his real passion, astronomy.

In 1514, Copernicus wrote a 20 page pamphlet *Commentariolus* [2] ('Little Commentary') which laid out his belief about the Earth's place in the Universe. Although it was not formally published, he circulated it amongst a few people, and in it he laid out some of the most radical ideas that anyone had made. He stated that the heavenly bodies do not contain a common centre and that the Earth does not lie at the centre of the Universe. Rather, he said, the Sun lay near the centre of the Universe, and the distance from the Earth to the Sun was tiny compared to the distances to the stars. He also stated that the apparent motion of the Sun and stars across the sky from East to West was due to the Earth's rotation, and that the change in the position of the Sun from season to season was due to our motion around it. Finally, he stated that the apparent retrograde motion of some of the planets was due to seeing their motion from a moving Earth.

He was correct in each one of these statements, something to which very few astronomers of his age would have agreed, but which most would do by the end of the sixteenth century. Around the time that Copernicus wrote this pamphlet, his uncle died, and Copernicus moved to Frauenberg Castle where he set up his own observatory. He spent the rest of his life reworking Commentariolus into a much more learned and complete piece of work. With his religious training as a canon, Copernicus was fully aware how his arguments flew in the face of hundreds of years of Church teaching, and so was reluctant to share his work with anyone for fear of persecution.

However, in 1539 a young German man by the name of Georg Joachim von Lauchen, but known as Rheticus, travelled from Wittenberg to meet Copernicus.

Rheticus spent 3 years at Frauenberg Castle with Copernicus, reading his manuscript and giving him feedback and reassurance on its contents. By 1541, Rheticus had received permission from Copernicus to take the manuscript to a printing house in Nuremberg for publication. At last, in the spring of 1543, *De revolutionibus orbium caelestium* [3] ('On the Revolutions of Heavenly Spheres') was published. But, in late 1542 Copernicus had suffered a cerebral haemorrhage, and had spent the intervening months in bed struggling to stay alive. Copies of his book reached him just as he was losing his battle, and upon seeing his life's work finally in print his life slipped away. His friend Canon Giese wrote a letter to Rheticus saying

> For many days he had been deprived of his memory and mental vigour; he only saw his completed book at the last moment, on the day he died.

Copernicus' model placed the Sun at the centre of the Universe, with the Earth, Moon, planets and stars orbiting the Sun in perfectly circular orbits (see Fig. 1.2). Mercury and Venus were placed inside of Earth's orbit, the Moon orbiting the Earth as Earth orbited the Sun, and Mars, Jupiter and Saturn orbited outside of Earth's orbit. Finally, the last sphere in this cosmic Russian doll was the sphere of the 'fixed stars'.

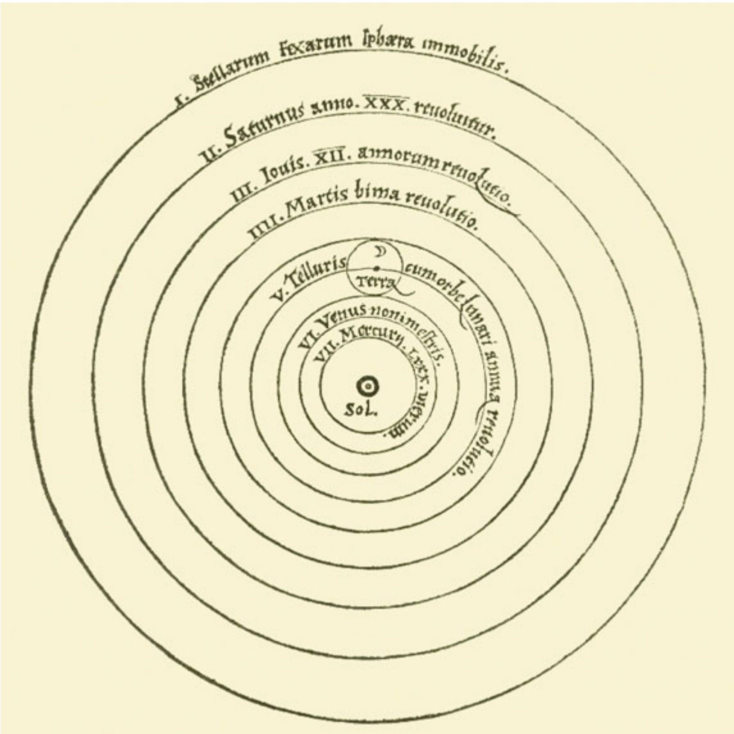

Fig. 1.2 Copernicus' model of the Universe placed the Sun and not the Earth at the centre (image from Copernicus' *De revolutionibus orbium coelestium* (1543))

Much like Aristarchus before him, Copernicus' Heliocentric model was quickly dismissed as it was found to be less accurate than Ptolemy's. In some ways it was not surprising that Ptolemy's model was so successful; over the centuries the size and speed of the planets' motions along their deferents, and the size of the epicycles, had been refined to agree with observations. It had become a very successful model in accurately predicting the positions of the planets, but it had also become highly complex in order to achieve this accuracy. Copernicus' model could not have been more different, it was elegant in its simplicity. It simply had the Sun at the geometric centre of a series of perfect spheres, with the other celestial bodies and the Earth moving within these spheres.

1.3 The Man with the Metal Nose

The most able observational astronomer of the late 1500s was also its most colourful, Tycho Brahe. Born into Danish nobility in 1546, at the tender age of twenty he got involved in a duel with his cousin Manderup Parsberg and had the bridge of his nose sliced off. From this point on, Brahe glued a false metal nose in its place, but by carefully blending gold and silver and copper the colour actually matched his skin tone and most people were unaware of the prosthetic.

But, although eccentric, Brahe is best known for the accuracy of his astronomical observations. His reputation led to King Frederick II of Denmark giving him his own island, Hven, 10 km off the Danish coast near Copenhagen, and paid for Brahe to build an observatory there. Brahe named his observatory *Uraniborg*, which means 'Castle of the Heavens', and one could argue that it was the most expensive observatory ever built as it used up more than 5 % of Denmark's gross national product!

The Observatory was lavishly furnished with a printing press, a library, accommodation for the servants who would help Brahe with his observations, and observing towers equipped with the best instruments of the day. Remember, this is before the invention of the telescope; but the sextants, quadrants and other naked-eye observing tools were of a better accuracy and quality than any that had been used before.

With these facilities at his disposal, Brahe produced the most accurate stellar and planetary positions ever seen. He would typically measure the position of celestial objects to an accuracy of 1/30th of a degree (for comparison, the full Moon is 1/2 of a degree across). This was about five times better than anyone had previously obtained. As Brahe's fame spread, a steady stream of important people came to Uraniborg to visit him. In addition to wishing to see the impressive observatory and its eccentric director, they were probably also drawn by the wild parties that Brahe threw there (Fig 1.3).

His observations found disagreement with the Ptolemaic model. Brahe had a copy of Copernicus' De revolutionibus in his library and we know that he was sympathetic to Copernicus' writings. But, rather than adopt them whole heartedly,

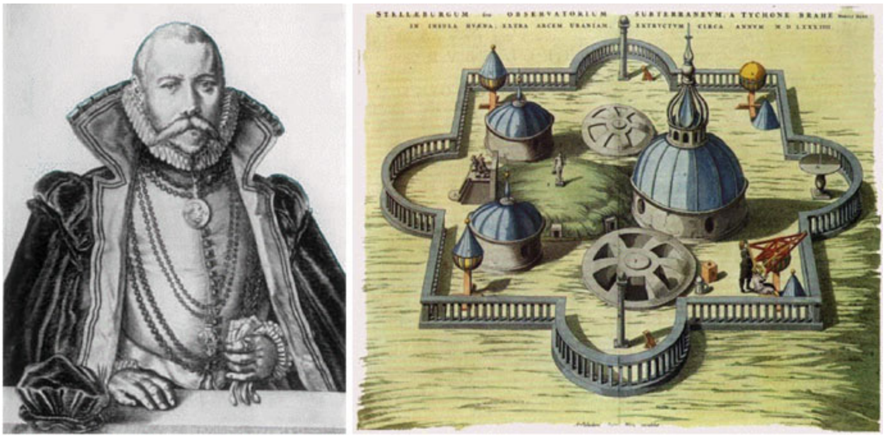

Fig. 1.3 One of the most celebrated astronomers of the sixteenth century, Danishman Tycho Brahe lost his nose in a duel when he was 20. He established a lavish observatory called Uraniborg on the island of Hven near Copenhagen (image of Uraniborg taken from Brahe's *Astronomiae instauratae mechanica* (1598))

Brahe developed his own hybrid model in which all the planets orbited the Sun, but the Sun and the other planets then orbited the Earth (see Fig. 1.4). This model was published in 1588 in *De mundi aetherei recentioribus phaenomenis* [4] ('Concerning the New Phenomena in the Ethereal World'). Unfortunately for Brahe, in this same year his patron King Frederick died after a session of excessive drinking, and his successor King Christian IV was not prepared to continue to fund Tycho's observatory or his lavish lifestyle.

Tycho left Denmark with his family, servants and all the astronomical equipment he could transport and made his way to Prague, where Emperor Rudolph II gave him the position of Imperial Mathematician and gave him money to establish a new observatory in Benatky Castle. This move proved to be fortuitous for Brahe, as it was in Benatky Castle that he met a 29 year old called Johannes Kepler. Kepler came to visit Brahe in January 1600, and started working with the master immediately. They made an ideal team, as Brahe was the diligent observer, whereas Kepler was a diligent mathematician.

Kepler's arrival was just in the nick of time. By October 1601 Brahe was dead, from a bladder or kidney infection after attending a banquet in Prague. We shall never know, but it is possible that his excessive drinking was a contributing factor, but what we do know is that on his deathbed he was preoccupied with his legacy, repeatedly saying 'May I not have lived in vain'. Luckily for him, it is due to what Kepler did with Brahe's observations that Brahe's name has lived on.

Kepler had shown an early interest in mathematics and astronomy. Born into a poor family in Weil der Stadt in what is now southern Germany in 1571, he had a very hard upbringing in a family that suffered constant upheavals due to war, religious strife, a father who was a mercenary and disappeared when Kepler was

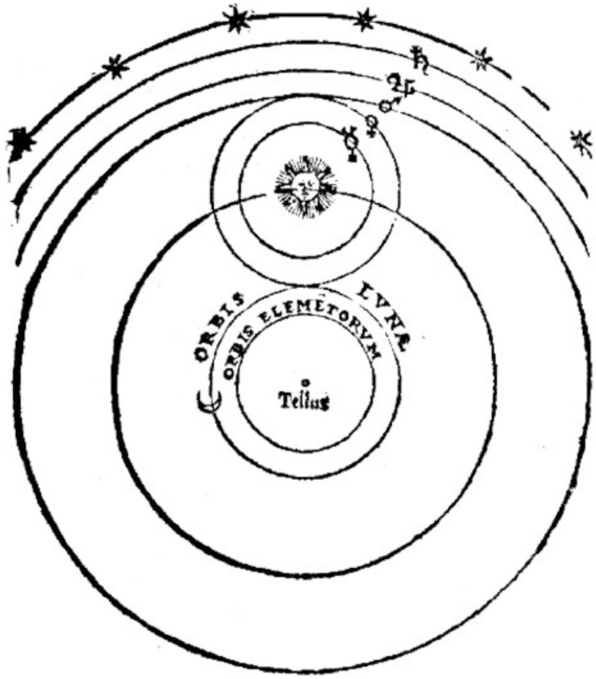

Fig. 1.4 Brahe's hybrid model kept the Earth at the centre of the Universe, with the Sun and other planets orbiting it, but with Mercury and Venus also orbiting the Sun (image from a drawing by Valentin Naboth in *Primae de coelo et terra institutiones* (1573))

only 5 years old; and a mother who was sent away after being accused of witchcraft. But, Kepler found solace in his studies. At only six he observed the great comet of 1577, and at the age of nine he observed a Lunar eclipse. By the age of twenty five he had taught himself enough astronomy to write *Mysterium Cosmographicum* [5] ('Cosmic Mysteries'), which defended Copernicus' De revolutionibus. He was convinced of the correctness of the Sun-centred model, and was determined to find what in Copernicus' model made it less accurate than Ptolemy's geocentric model.

Although Brahe's death was clearly unfortunate for Brahe, really it was the break Kepler needed. Because of Kepler's humble background compared to Brahe's own noble one, it is unlikely that Brahe would have ever properly collaborated with Kepler or treated as anything like an equal. But with Brahe gone, Kepler inherited all of his observing notes, and set about trying to find a model of the Universe that would fit them (Fig. 1.5).

Kepler thought he would have the problem solved in a week or two. In fact, it took him 8 years! His calculations filled nine hundred pages, but in one of the most supreme examples of single minded perseverance, he eventually did produce a model which fitted the observations. One cannot over emphasise what an arduous and difficult task this was, but why did it take him so long?

Fig. 1.5 Johannes Kepler discovered that the planets orbit the Sun in ellipses and not circles (image from a 1610 oil painting of Kepler)

The solution Kepler eventually found required him to abandon one of his most cherished beliefs—that the planets moved about the Sun in perfect circles. For years Kepler stuck to this idea, but he could not get good agreement with Brahe's observations. Eventually, Kepler was able to show that the planets did not move in circles but in ellipses. He also showed that they changed their speed as they orbited the Sun, and that the Sun was not at the centre of the ellipses that the planets followed. Each one of these three findings flew in the face of not just what Copernicus had proposed in his Heliocentric model, but even in the face of Ptolemy's Earth-centred model. In Ptolemy's model the celestial bodies moved in perfect circles at a constant speed along each deferent with the Earth at the geometric centre of these concentric circles.

Whereas most people are familiar with circles, ellipses are a little less familiar, so let me cover the basics necessary to understand what Kepler had discovered. As you may recall from your school days, to draw a circle you can wrap a loop of string with a pencil around a drawing pin, stick the drawing pin into a piece of card, and keeping the loop of string tight you move the pencil around the pin. An ellipse can be produced in essentially the same way, the only difference is that instead of wrapping the loop of string around one drawing pin, you wrap it around two of them. The long axis of an ellipse is called the *major axis*, the short axis is the *minor axis*. Half of the length of the major axis is referred to as the *semi-major axis*.

A circle is, in fact, a special case of an ellipse when the two foci are in the same place. The further apart the foci are, the more elongated (elliptical) the ellipse becomes (see Fig. 1.7). This can be quantified as the ratio of the minor axis b to that of the major axis a. However, just to be perverse, mathematicians prefer to talk of the *eccentricity*, denoted by the letter e, which is defined as $e = (1 - b/a)$. If $e = 0$ we have a circle (as the minor axis and the major axis have the same length). If $e = 1$ we would have a straight line, as the minor axis b would have zero length.

Kepler published his findings about the orbit of Mars in 1609 in a book entitled *Astronomia Nova* [6]. In this book he stated two principles of planetary motion, namely

1. That the planets orbit the Sun in ellipses, with the Sun at one of the foci of the ellipse.
2. That the speed of a planet changes in its orbit, sweeping out equal areas in equal times.

Figure 1.6 shows the first of these principles, but what about the second principle? Although it sounds rather complicated, it is in fact not too difficult when one sees a diagram of what it means (see Fig. 1.8). The shaded areas labelled A in Fig. 1.8 all have the same area, but as you can see the distance the planet moves in a time t differs in the three places. To put this another way, when the planet is closer to the Sun (near *perihelion*), it will travel faster, and when it is farthest from the Sun (at *aphelion*) it will travel the slowest. These two principles are now known as Kepler's first and second law of planetary motion.

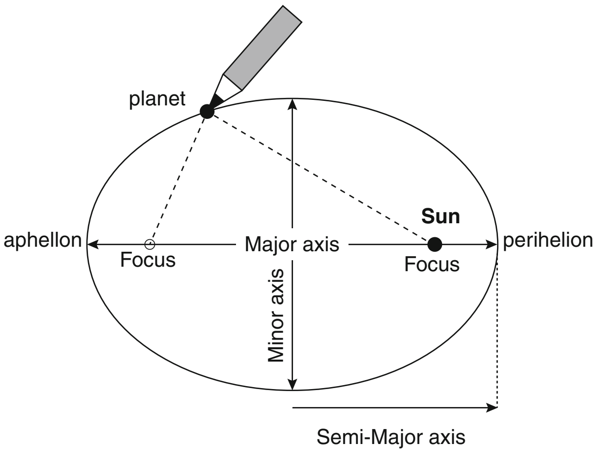

Fig. 1.6 Kepler's 1st law states that the planets orbit the Sun with the Sun lying at one focus of the ellipse

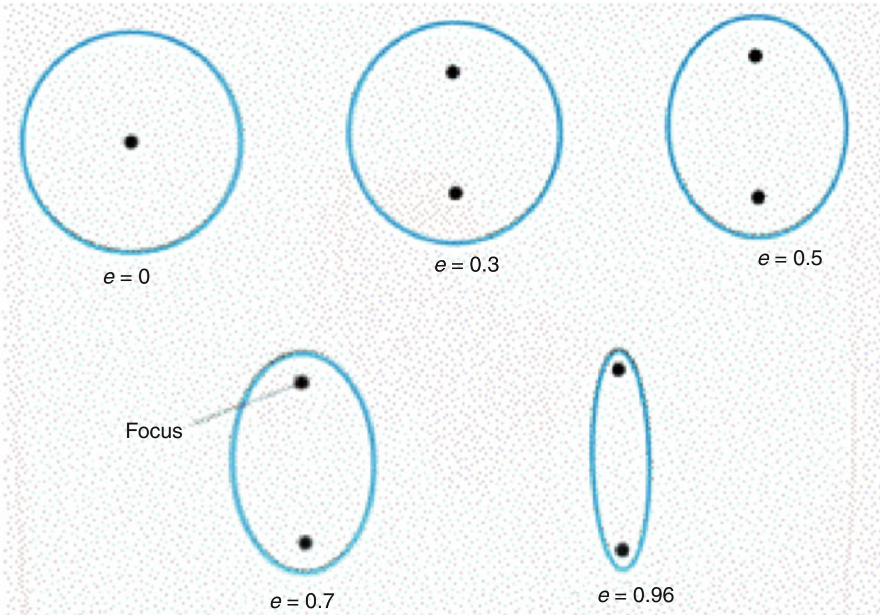

Fig. 1.7 The eccentricity *e* of an ellipse is a measure of how elongated it is compared to a circle

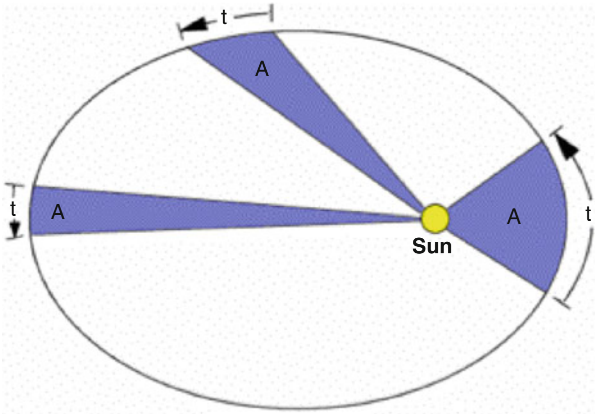

Fig. 1.8 Kepler's second law states that the three *shaded areas* are all the same, meaning that the planet travels quicker when it is near the Sun and slower when it is further from the Sun

Kepler then continued working for another 10 years on various projects. One with which he became obsessed was an idea called 'the music of the spheres', a mistaken belief that the motions of the planets produced musical tones. This was based on an idea Pythagoras had, but Kepler took the idea much further, spending far too much time on such a crazy idea. He also wrote one of the first works of science fiction, a story called *Somnium* [7] ('The Dream') in which a group of adventurers travel to the Moon.

In 1619 Kepler published a third principle of planetary motion in *Harmonices Mundi* ('The Harmony of the World') [8], which we now call his third law. This stated that the square of the orbital period of a planet is proportional to the cube of the semi-major axis of its orbit. This sounds very complicated, but what it basically means is that the more distant planets actually move more slowly than the planets nearer the Sun, in addition to having to travel further in their path. This law actually came out of his work on the music of the spheres, but is the only useful thing to come from that work.

Kepler was also busy compiling data for what became known as the *Rudolphine* Tables [9], which were finally published in 1627, although Kepler had them ready by 1623. The 4 year delay was due to legal wranglings with Brahe's heirs over using his observations. The volume consisted of a star catalogue and tables publishing the positions of the planets many years into the future. The catalogue contained the position of 1,006 stars measured by Brahe, and directions and tables for calculating the positions of the planets. The tables had a level of accuracy never seen before, and amongst other things predicted a transit of Venus in 1631 and a transit of Mercury in the same year.

1.4 Dancing Moons and Crescent Planets

Whilst Kepler was publishing his *Astronomia Nova*, an Italian by the name of Galileo Galilei was exploring the sky using the newly invented telescope. Born in Pisa in 1564, Galileo had started training in medicine, but in 1581 whilst bored sitting in the Cathedral in Pisa listening to a sermon, Galileo was looking at the chandeliers hanging from the ceiling which were moving back and forth due to gusts of wind. He noticed that how long a chandelier took to swing back and forth (its *period*) did not seem to depend on the size (*amplitude*) of the swing. This single observation, and his investigation of it, changed the course of his life.

He persuaded his father to allow him to abandon his medical studies and was allowed to switch to studying mathematics and 'natural philosophy' (as physics was known at the time). In 1589 he was appointed to the Chair of Mathematics at Pisa University, and in 1592 he moved to the University of Padua where he taught geometry, mechanics and astronomy. In 1609, Galileo heard about the invention of an optical instrument that allowed distant objects to appear larger—what we now call a telescope. We don't know who invented the telescope, but in 1608 Dutchman Hans Lippershey tried to patent the idea in the Netherlands. Galileo heard about descriptions of this instrument, and in 1609 set about building his own. The result was a small 2.5 cm aperture telescope with a magnification of about three times (Fig. 1.9).

Galileo quickly set about observing the Moon with his newly fashioned instrument. In late 1609 he made sketches of the Moon, and noticed that its surface was irregular. Looking at the dividing line between the light and dark parts of the Moon, the *terminator,* he correctly deduced that the irregular appearance of this line when