Sun-centred System

From primary school upwards, we are taught that the Sun is at the centre of our solar system. This is the 'true' picture. In the Western world at least, people have widely held this belief for less than 400 years. The Ptolemaic view and its earlier versions were the dominant picture for 2000 years, perhaps more. If you are looking for a significant event in history that symbolises the dawn of modern science, then the publication by Nicolaus Copernicus (1473-1543) of *De Revolutionibus Orbium Cœlestium*, finished by about 1530 but not printed until 1543, is it. The book was published at the end of Copernicus' life. The elements of Copernicus' theory were:

- Sun centred planets.
- Planets move around circles at uniform speed - he too had to introduce epicycles because planets, as we now know, don't move uniformly around the Sun. From a modern perspective, this was not much more than a mathematical transformation of the Ptolemaic description to a new centre, with some simplification, but conceptually it was a huge innovation.
- Stars on a distant celestial sphere. He had no concept of celestial space but knew the stars were an immense distance away even compared with the (unknown) distance to the Sun.

The Ptolemaic model was a model of the Universe at large. Likewise the Copernican model.

His ideas went against the authoritative teaching of both Catholic and Protestant church, particularly as it came to be defined in the decades after his death. Martin Luther, who was born 10 years after Copernicus, denounced him as *an arrogant fool who taught in defiance of the scriptures*. Luther wrote that believing the words of the Bible even though they were incomprehensible was preferable to the wickedness of believing what one understood. Such an attitude rather stops rational discussion in its tracks. Copernicus wasn’t arrogant and wasn’t a fool. He was a devout church official, a Canon of Frombork (then Frauenburg) cathedral in NE Poland for most of his working life. From 1491 - 1495 he had attended Krakow University, one of Europe’s best, where astronomy was a significant part of the curriculum. He followed that by 4 years at Bolognia University studying post-graduate law and 2 years at Padua University studying medicine. A Doctor of Law and trained medic, he was no fool.

Copernicus was no amateur astronomer either, trying his hand at a subject beyond his reach. In 1514 he had been invited to Rome to help revise the conspicuously ailing church calendar. The calendar was underpinned by astronomy. Fast days and feast days were defined in the year, which was set effectively by the Sun; Easter and related events also involved the Moon. The calendar had clearly got out-of-step with the equinoxes and solstices. People were eating meat on days that should have been fast days. Whatever next? Copernicus actually declined the invitation to participate in the revision of the calendar, saying that he did not yet have sufficiently accurate data. For various reasons the attempted calendar reform was postponed yet again, not to happen until 1582 when the Gregorian calendar was instituted by papal decree. This is the civil calendar now used world-wide.

I’m tempted to set the scene by saying that Copernicus lived in changing times for European culture. During his lifetime, Columbus discovered America, Vasco da Gama showed that one could sail from Europe to India and Magellan, another Portuguese, was the first to circumnavigate the world. If anyone doubted that the world was round, Magellan provided the proof that we live on a globe. In the arts, Leonardo da Vinci, Botticelli, Michelangelo and others highlighted the Italian Renaissance; Machiavelli wrote how to acquire power and the Borgias demonstrated how to keep it. Martin Luther, John Calvin and John Knox amongst others promoted the Reformation that changed the lives of aristocracy, burghers and peasants in many European countries. Henry the Eighth's dissolution of the monasteries and other religious centres in England, Wales and Ireland is one example of the Reformation's consequences that happened during Copernicus's lifetime, albeit late in his life. As with many revolutions, there came a strong reaction from those who did not want the changes or indeed the new knowledge. These were violent times and what one believed, thought or said could invoke violent reaction. In case all the above seems parochially Western European, I'll add that Arabic scholars say that their astronomers 'discovered' that the Earth spins on its axis and orbits the Sun, centuries before Copernicus. They may have done but their discoveries did not spark the revolution that lead to modern astronomy. Copernicus's ideas did.

Copernicus's *De Revolutionibus Orbium Cœlestium* was dedicated to Pope Paul III, ironically the very Pope who set up the "Congregation for the Doctrine of the Faith" that would supervise the Inquisitions. The Inquisition will come into our story in the next chapter. Copernicus sat on drafts of his own manuscript for over 30 years, not wanting to publish what he feared would not be accepted. Curiously enough, it was the through the intercession of Lutheran friends that Copernicus finally published, although as remarked above Martin Luther was no Copernican supporter. One of the publishing supervisors inserted an editorial of his own that introduced the book's content as **a hypothesis**, a model, one that had greater aesthetic simplicity and better predictive power than the Ptolemaic model. Copernicus's friends were incensed by this because Copernicus himself believed he had uncovered the truth, not just a mathematical artefact. Indeed, what is special about *De Revolutionibus* is that it does not simply spell out a new abstract idea. Copernicus had spent over 30 years collecting planetary observations to test his theory against observation. As it turned out, he did not live to see the controversy it stirred up. Copernicus had a stroke in early 1543 and barely lived long enough to see a copy of his work in print.

[Remember that the Ptolemaic ideas are a mathematical model of the planetary motions. Do the planets 'really' go around in all those epicycles? People had queried this. Alphonso X, 13th century patron of the definitive tables of planetary positions that were in use for some four centuries, is said to have commented that "*if the Deity had consulted him on the creation of the world, he would have given him good advice*", namely not to make the thing so complicated. Rheticus, the Lutheran supporter of Copernicus who actually got Copernicus's manuscript published, said that just as a clockmaker needs no superfluous wheels in his clock train, so God would not require superfluous circles to create planetary orbits. Einstein put a similar thought in more modern language: "*When I am judging a theory*", he said, "*I ask myself whether, if I were God, I would have arranged the world in such a way*". So Copernicus's tract was presented as a model which similarly, the editorial suggested, was not saying that the planets really did go around the Sun, merely that a mathematical model with the Sun near the centre enabled planetary positions to be calculated more easily and accurately. The descriptive word of the age for this was 'a theoric'. Theorics were concepts that enabled you to work things out but weren't what actually happened. In a way a map was a theoric that enabled you to find your way from A to B but of course the route was not a track on a piece of paper. Copernicus's contemporaries understood theorics. Rheticus's felt his introduction was necessary because Copernicus believed his ideas were reality and not a theoric: the Earth actually did orbit the Sun. That was the potential heresy that threatened to have his book consigned to the flames.

Copernicus didn't just introduce the Sun as the centre of planetary motion and the Universe, he also had the world spinning on its axis in space. How many people before Copernicus must have wondered why 1000 stars, the Sun and the planets all seem to move across the vault of the sky at much the same rate? If people had been free to think about it, many would have concluded that the most likely explanation was that the Earth and atmosphere were turning once a day and the stars, Sun and planets didn't move much. However, people weren't free to think about it because 'how things were' was dictated by authority, not simply the authority of those in power at the time but an authoritative view solidified by many centuries of repetition. Many aspects of daily life were conducted under the totalitarian principle "If it's not compulsory, it's forbidden'.].

A Further Digression on Copernicus

The cloak of presenting the ideas as a model wore thin quite quickly and it didn't take long before theologians found statements in the Bible that appeared to contradict the Copernican viewpoint. Put another way, the Copernican viewpoint was seen as contrary to biblical truth, and hence heresy. Heresy was punishable by death, indeed unpleasant death. The Inquisition, sanctioned by the very Pope to whom Copernicus dedicated his book, put *De Revolutionibus* on the Index of Forbidden Books.

Away from the theologians, it's hard to imagine the impact of Copernicus' new idea on people of his age. The Earth-centred perspective was embodied in everyone's view of their surroundings and is apparently in accord with the perception of our senses.

The scene: a wayside tavern on the road between Frauenburg and Gdansk. It's late afternoon on a warm summer evening in 1542. Marek arrives in the courtyard from Frauenburg, spying his friend Wojcek already slaking his thirst.

"Hail Marek, well met". "Hail Wojcek. I'll join you until sunset. A flagon of the landlord's best, wench.

Listen to this, Wojcek. I was talking the other day with Father Nic - the old canon at Frauenburg Cathedral - he's not looking well, you know. He confided in me something he hasn't told anyone outside the precinct before, and I'm not surprised. Wait 'til you hear it. He's full of his explanation of why the stars go around the sky, those pin-pricks of light in the night that help us steer a true course across the Baltic. You know what he thinks, Wojcek? He thinks the stars stand still and it's the whole world that turns. The whole world! The black forest that stretches from here to Marienburg and is so dark you can't see a boar at 10 paces in it, the great marsh where Stanisław lost his life last year, the landlord's meadows here with his 2-score bullocks, and the road to far-off Gdansk and beyond, are all turning round, at a hundred leagues per hour. Can you believe it? Well, they are all turning according to Father Nic, and so are we as we sit here. Do you feel a little giddy just thinking about it, Wojcek? Don't answer that! Does it make sense? Father Nic's convinced. He says he's uncovered a great truth and he's put it in a manuscript that he's going to have printed. I fear for him. Hasn't he read what the ancient sage Ptolemy said? You know, the philosopher with the silent P, more than can be said for your friend over there, Wojcek. Ptolemy wrote that if the Earth moved, there would be a great wind upon it. And there isn't, is there? Well, not normally. I really fear for father Nic, Wojcek. He shouldn't say these things. If it gets out, we'll soon all have to pray for him. He's not well, you know, he's not well. You've been stunned into silence, Wojcek. Let's talk of something else." ….and Marek, who hadn't spoken to a soul all day, left the topic for more mundane matters.

To the man in the tavern, the man in the street and the man in the field it must have seemed nonsense and the Church in particular, whom he looked to for spiritual, moral and scholarly guidance, told him it was nonsense. I'm making an issue of this because it's relevant to us all to appreciate that many ideas we teach as 'obvious' have had to struggle for survival. As scientists, or future scientists, we're all motivated by the thought that we'll find out in future for ourselves how some aspect of nature really works. We tend to assume that when we've cracked our problem, gained the insight and revealed new knowledge that everyone will agree with us, thank us and hopefully continue to employ us. History's lesson is different.

Marek was right to fear for Father Nic. As it happened, fate took over and Copernicus died as *De Revolutionibus* was coming off the press. Some 60 years later the idea was still bitterly opposed by the Catholic Church, to the extent that the philosopher Giordano Bruno was publicly burnt at the stake in Rome for heresy, largely for propagating Copernicus's heliocentric view of the Universe. Copernicus, the good Catholic, would have wept had he been alive.

I'll add that Copernicus was right to believe that a Sun-centred Universe was not just an alternative model for an Earth-centred universe, embodying simply a change in viewpoint. A cosmic body orbiting the Earth will never collide with the Earth. In contrast, two cosmic bodies orbiting the Sun can have orbits that intersect. If the two bodies arrive at the intersection point at the same time there will be a collision. The solar system is peppered with collision craters. You can even find some on Earth. The possibility of future collisions with the Earth is a genuine threat to humanity. The two scenarios are fundamentally different but arguments such as this were centuries in the future as far as Copernicus was concerned.

Tycho Brahe

The crucial test between two completely different models of 'the solar system' is observation. The key observer of the planets in the 16^{th} century was born just after Copernicus died - Tycho Brahe (1546-1601) an aristocratic Dane who became deeply involved in observational astronomy and, with liberal financial support from the Danish King Frederick II, had an observatory built on one of Denmark's many islands. He equipped the observatory with the largest and most accurate observing instruments. Impressive among them was a 2-metre radius mural quadrant (a large vertical protractor of 90°), of his own design, calibrated to 10" of arc. Tycho Brahe spent years in painstaking astronomical observation, recording the positions of stars and planets to an accuracy of better than a tenth of a degree, often to no worse than 1′ arc. He had no telescope. That instrument had not yet been invented.

Why did kings and courts support such astronomical work? It was an age of mysticism and horoscopes - the stars and planets were thought to govern the actions of kings, the fates of nations and the lives of ordinary folk. The underlying premise was that events of man were linked to positions of the "stars" by which was mainly meant the planets. In one sense, planets had replaced ancient Gods in popular mythology. How did Kings know where the planets were in the sky? They employed astrologers. The better the astrologer, the more accurate would be the advice on the likely outcome of actions taken by the King, such as the military campaign he was preparing, the diplomacy he was working on or the daughter he wanted to marry off most advantageously. The best astrologers took the greatest care to know as precisely as they could exactly where the planets were in the sky. If, compared with your neighbouring King's astrologer, your court astrologer had a better idea of the actual position of the planets in the sky, as opposed to their supposed positions, not only ‘now’ but at proposed dates in the future. then your nation’s actions would have a better chance of success. When astrology conveys power, you want the most powerful astrologer. Tycho was a highly-educated nobleman-scholar of wide-ranging interests but part of the reason he was supported by Frederick II was for the solid foundation his observational astronomy and his wide-ranging knowledge gave to astrology. He did not supply astrological predictions to the King or Court on a daily basis but on particular occasions, and for some time he provided annual astrological calendars.

Tycho of course realised that his observations gave him the data to thoroughly explore the accuracy of any model of planetary motion. He invented his own ‘Tychonic system’ that he felt was in best accord with his own observations, of comets in particular. In his system, the planets and comets went around the Sun but the Sun and Moon went around the Earth. Tycho’s writings also highlighted another feature of the Ptolemaic system that was believed in pre-Copernican times, namely that the Ptolemaic planets moved on crystalline spheres that were transparent and solid. Both Copernicus and Tycho Brahe cried in so many words that the Emperor had no clothes (to use another Dane’s tale). The crystalline spheres didn’t actually exist but were only imaginary concepts. This too didn’t go down well with religious authority that had nailed its flag to centuries of acceptance of the Ptolemaic interpretation of planetary and stellar motions. On the whole, though, Tycho Brahe is remembered for the effort he put in to designing, building and using astronomical instruments superior to those of his contemporaries and the legacy of accurate observations he made with them.

On Tycho

Tycho Brahe was a man of strong personality and independent thought. He was one of the 5 sons of a powerful nobleman, Otte Brahe. Legend has it that when Tycho was in his mid-teens, his uncle, who had actually brought up the lad, paid for a tutor to teach him law and sent him to Leipzig in 1562 (aged 16). At that age Brahe cared little for studying law and devoted just so much time to it as would save appearances (how many of you are doing that to at least one course?) and while his tutor slept, he busied himself on clear nights observing the planets and stars. Through these surreptitious observations and allegedly with no other apparatus than a very small globe and a pair of compasses he succeeded as early as 1563 in detecting serious errors in the Alphonsine tables used by astrologers that predicted the positions of the planets. It may not be a verifiable story but it’s a good story.

What is certainly true is that Tycho had a passion for learning and sought not power, the usual quarry of those born into the influential aristocracy, but scholarship. In 1565 he returned to Denmark to lead the life of a nobleman’s son but it is said he soon became disenchanted with the ignorance and arrogance of some of his fellow noblemen. He returned to Germany, Switzerland and Italy to pursue his own interests and to act as a roving emissary for Fredrick II. At Wittenberg in Germany, a small university town made famous as Martin Luther’s base, he lost part of his nose in a duel with another Danish nobleman. The dual seems to have been the product of drunken bravado rather than feudal honour. His opponent’s sword came within an inch of depriving the world of the best observational astronomer of the century. Brahe commissioned an artificial nose for himself, made of gold, silver and wax which fitted well and which he wore for the rest of his life.

He returned home after 2 years and was lucky enough to discover a brilliant supernova in Cassiopeia in 1572. This made his name, or rather the publication of his description of it made his name. The old cosmology considered that the ever-changing world of the Earth was a different place from the astral world of stars, which were all purity and eternity made out of a single element, the aether. The immutability of the heavens is embedded in the cosmology of the Bible. You may remember the very first chapter of Genesis "God… made the stars also. And God set them in the firmament of the heaven, to give light upon the earth". The "firmament" is the word for something fixed and unchanging. Brahe's observation of the supernova - the *Nova Stella* in the Latin of the times - destroyed the immutability of the heavens and indicated that they too changed, only on a different timescale. [A second *nova stella* was observed in 1604 but no more were seen by naked eye until 1987. Brahe was lucky]. In 1573 he married a commoner, Kirsten Jørgensdatter the daughter of the local pastor, which his fellow noblemen felt was even more undignified than being addicted to astronomy.

[Those reading these notes might like to read a little of Tycho's own account, originally written in Latin. The translation is based on that in volume III of Alexander von Humbolt's work 'Cosmos', published in 1851. *When I returned to the Danish islands, after travelling in Germany, I remained a while with my uncle, Steno Bille, at the pleasantly situated former convent of Herrevad, where I was in the habit of quitting my chemical laboratory only in the evening. On coming forth into the open air, and raising my eyes as usual to the well-known heavenly vault, I saw, with indescribable astonishment, near the zenith in Cassiopeia, a radiant fixed star of a magnitude never before seen. In the excitement I thought I could not trust my senses. In order to convince myself that it was no illusion, and to collect the testimony of others, I called my workmen from the laboratory, and asked all the country people who were passing by, whether they saw the new suddenly outshining bright star as I did.* You can just picture the excitement of the moment and get an inkling of Tycho's sense of wonderment.

New stars had appeared in the sky before this time, albeit not very often, and disappeared. What made this appearance special was that the observer was to realise its significance. Tycho immediately thought of comets as star-like objects that appeared, moved through the heavens for a period of a month or two and faded. He had never yet seen a comet but he continued his account: *I found this new star without any tail, not surrounded by any nebulous appearance, and perfectly similar in all respects to all other fixed stars, but sparkling more brightly than those of 1st magnitude. It exceeded in brilliance Sirius, α Lyrae and Jupiter, and could be paralleled by the brightness only of Venus when she is nearest the Earth… . When the atmosphere was clear, men gifted with keen sight could distinguish the new star in the day-time, and even at noon. At night, when the sky has been so far covered that all other stars were veiled, it has been repeatedly seen through clouds of moderate density. Distances from other neighbouring stars in Cassiopeia, which I measured with great care throughout the whole of the following year, convinced me of its perfect immobility. In December of 1572 the light of the star began to diminish; it soon became equal to Jupiter and in January 1573 it was less bright than that planet.* Tycho describes how it gradually faded over the following year and disappeared from view in March 1574, seventeen months after he had seen it first.

Tycho speculated that what he had seen was the result of a star condensing out of nebulous matter in the Milky Way. We now know that he was right that stars are born in a process of condensation but what Tycho saw was a 'Type Ia supernova' in modern language, a star that exploded for reasons now understood. The remnant debris of this explosion is clearly visible with modern technology. The sting in the tail of this story is that Tycho's star was 7500 LY distant and yet at its peak it was visible during the day. If one of our nearby stars becomes a supernova, it will produce light rivalling the Sun and it will bathe us in a great deal of more damaging radiation. We can still very clearly image the remnant of Tycho's star at X-ray wavelengths, over 400 years after the event. Fortunately, modern astronomical knowledge tells us that there are no candidates for the supernova explosion of a nearby star so you can sleep well at night. In this respect, the Earth is lucky. Supernovae are wonders you want to see only a very great distance away. I'll return to Tycho's story.]

King Frederick II, who had recognised the exceptional scholarly ability of Tycho, by now one of the high-ranking aristocrats in Denmark, offered him the small island of Hven (approximately pronounced 'veen') and ensured he had enough income to finance his observatory, which he built in idiosyncratic style and called Uraniborg ("fortress of the heavens"). Uraniborg and surrounding buildings (Stjerneborg "fortress of the stars") became a centre for astronomy, medicinal chemistry and the arts. There Tycho spent 20 years in dedicated observation and promotion of astronomy, helped by assistants. One of his part-time assistants was his youngest sister, Sophie Brahe, who had been taught chemistry and taught herself astronomy. Tycho Brahe produced by far the best star catalogue of the times, he demonstrated convincingly that comets, which had been thought as changeable phenomena to be earthbound, really belonged to the astral world. He provided additional observational evidence for the Copernican model of the heavens by determining that Mars was closer to the Earth at times than the Sun, which it isn't in the Ptolemaic model. He was the first to make proper corrections for the distortion in the observed position of stars as they approach the horizon, caused by atmospheric refraction.

A modern estimate is that the money spent by Brahe from his own estates and from the King's subsidy amounted to 1% of the GDP of Denmark. In those days, the Danish realm stretched from Greenland, Iceland and the Faeroes in the North, via Norway to Gotland in the East and Schleswig-Holtstein in the South. 1% is a higher proportion of GDP than the US spent on NASA in its heyday. Brahe and Uraniborg became international celebrities. James VI of Scotland visited him just after his own marriage to Frederick II's daughter Princess Anne. That royal marriage was undoubtedly blessed by Tycho's astrological analysis of the couple's fortunes. James was impressed by the facilities, the learning and the hospitality he found on Hven. I can add two historic local connections. The ambassador from Scotland who was sent to Denmark to smooth the marriage arrangements was the 5th Earl Marischal, the founder of Marischal College. He made a very good impression in Denmark. The ship that conveyed Anne of Denmark and the newly married James VI back to Scotland in 1590 was the *St Nicholas*, from the city of Aberdeen.

In the introduction to his paperback book "On Tycho's Island" John Robert Christianson describes Tycho Brahe as s*cientist, natural philosopher, technical expert and poet; connoisseur of music, courtly grace, and the fine arts; and one of the most innovative organizers known to history*. He brought to astronomy an independence of thought, passion for his vocation and technical excellence. These qualities are all archetypical of those who have contributed to change in science.

Johannes Kepler

Tycho employed assistants to reduce his raw observations to useful facts and to interpret them in terms of the current models of the Universe. Johannes Kepler was one of his last assistants.

In 1597 Brahe had been driven out of Hven and indeed Denmark by the rise to power under a new King of jealous reactionaries who appeared ignorant and uninterested in his achievements. For posterity, this blot on Danish history serves to emphasise how far ahead of socially acceptable ideas Tycho Brahe's concepts and practice at Uraniborg had been. After two years, Tycho found sanctuary in Prague at the invitation of The Holy Roman Emperor, Rudolf II. In 1600 Johannes Kepler (1571-1630) was employed as mathematical assistant by Brahe in his new home in Prague.

[Kepler was another extraordinary personality in the history of science. To find out more about Kepler and his times (and Copernicus and Galileo, who came before him and after him) I recommend reading Arthur Koestler's "*The Sleepwalkers*"].

Kepler's work on Tycho's data is one of the great stories in science. Near the very end of Tycho's life in 1601 he asked Kepler to prepare a table of future planetary positions, to be known as the *Rudolphine Tables* after his new benefactor. Kepler felt he couldn't do this until the tables at least fitted Tycho's meticulous observations. He worked for 4 years trying to fit Tycho's observations by varying epicycles in Copernican models and in Tycho's own hybrid models of the heavens. Mars was the planet that seemed most in error and Kepler had earlier specifically been assigned Mars by Tycho. After 4 years, during which Tycho Brahe died, Kepler reduced the gap between his predications and Tycho's observations to 1/8°. 1/8° degree is pretty small - say the width of my finger seen from near the rear of the lecture hall. Kepler knew how painstaking Tycho had been and 1/8° was still greater than the error in Tycho's measurements. Kepler knew this. Tycho's data should not have been wrong by more than 1/10° degree, and they were usually much better. Besides, the model of the heavens that came as close as 1/8° with all its epicycles was cumbersome. Kepler scrapped 4 years work, essentially because 1/8° was greater than 1/10°. It was the action of someone totally dedicated to his work of trying to unravel the truth of what was going on. Kepler had taken over the post of court mathematician and astrologer to Rudolph II. (It's an interesting aside that in spite of his title of 'Holy Roman Emperor', Rudoph II was more of a humanist than a strong believer in either Catholicism or Protestantism. He employed Kepler out of recognition of his talent, notwithstanding Kepler's religious persuasion as a protestant).

Kepler began to look at the possibility of planets travelling along oval curves. This was a radical departure from the world view of philosophers and theologists. To stop thinking about spheres and perfect circles, shapes unquestioningly associated with the perfection of the heavens, was an act of detachment that took both courage and genius. It was also a step into greater mathematical difficulty. We all know, for example, that the area of a circle of radius r is πr^2 and its circumference is $2\pi r$ but what is the area and circumference of an ellipse? After years more work, convincingly described by Arthur Koestler, Kepler gradually cracked the problem in stages, and announced over a period of years to an astonished Europe his three laws of planetary motion. The Rudolphine Tables were finally published by Kepler in 1627. We left Kepler in Prague but by 1627 Rudolph II had been dead some 15 years and Kepler had spent the time since then not in Prague but in Linz in Austria.

The Copernican scheme, with its many epicycles, was not conspicuously better than its predecessor as a conceptual tool. Throw away 30 or so epicycles and replace them by 3 laws and now you have conspicuous progress.

Digression

Kepler’s laws have a symbolic value, ushering in the modern era in which science attempts to describe nature with mathematical precision and produce all-encompassing laws - laws of nature, not of mankind.

Very little science from 400 years ago is used directly today. Most early discoveries have been superseded by more quantitative work, more accurate work or more detailed work. Kepler’s Laws, though, have turned out to be more accurate than Kepler could have expected from the quality of data he had available and are still a good description to this day.

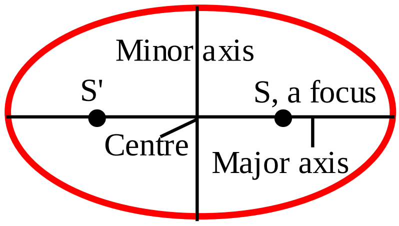
Kepler's laws apply to all planetary systems and even binary stars.

The Laws

1) Planets travel in ellipses around the sun, which is at one focus of the ellipse.

An ellipse is familiar as the shape of a circle seen in perspective. Ellipses come in different *eccentricities*, denoted e. $e = 0$ for a circle, the two foci are coincident at the centre. e almost 1 gives a very long thin ellipse.

To specify an ellipse, only two constants need to be found, e.g. a and b in the diagram, or a and e. The eccentricity e measures how far the focus is from the centre, namely the ratio CS/a.



e is the eccentricity

a is half the length of the major axis

b is half the length of the minor axis

$$CS = ae$$

$$b^2 = a^2(1-e^2)$$

When Newton discovered the law of gravitation, ellipses were found to be a mathematical consequence of the gravitational force decreasing with the square of the distance from the Sun.

2) As a planet moves around its orbit, the area it sweeps out in space in a given time is constant. So what? This is an odd but precise way of saying the closer the planet is to the Sun the faster it covers a given stretch of orbit. This law is important because it tells us how motion around an ellipse is different from the uniform motion in a circle. It is a significant part of the explanation of why the solar day varies in length throughout the year. When Newtonian mechanics was developed, this law was found to be a consequence of the law of conservation of angular momentum. This principle governs the behaviour of everyday objects as well as planets.

3) The third law, which was published 9 years after the first two, tells us about the ratio of orbital times for different planets. The orbital time is called the *period* of the planet. It is basically the planet’s year. Kepler said (in Latin):

"The square of the period (P) of the planet is proportional to the cube of its average distance from the Sun (a)"

$$P^2 = \text{constant} \times a^3$$

For the Earth, a = 1 AU and P = 1 year. Hence, in these units the constant is 1.

i.e. (period in years)^2 = (distance in AU)^3

Hence for Mars, given P = 1.88 years, $1.88^2 = a^3$ and therefore a = 1.52 AU, which is indeed the case [see table 2.2]

Kepler produced his third law from an analysis of the data he had. As far as his contemporaries were concerned it came 'out-of-the-blue'. It worked. However, so you're not left thinking that this was a piece of magic, let me add a few more words on why it works. If you see what's behind it, it is easier to remember. For simplicity, just think about circular planetary orbits of radius r. These at least show what's happening.

Two factors make a planet further from the Sun complete its orbit of the Sun in a longer time.

1) The more distant planet has a longer path to take in a year. Ignoring the orbital eccentricity for the moment, the path is just the circumference of its circular orbit, which increases as r.
2) Secondly, because gravity is weaker further from the Sun, the more distant planet travels more slowly along its orbit. Its period from this effect will be proportional to $1/v$, where v is its speed of travel. From the mechanics of a particle travelling in a circle that many will have met, the acceleration, *acc,* of the particle is related to its speed v and its orbital radius r by $acc = v^2/r$. Now gravity provides the acceleration of the planet and hence from the law of gravity that I'll come to in the next chapter $acc \propto 1/r^2$. Combining these last two facts gives $v^2 = acc \times r \propto 1/r$. Hence, finally, the increase in period from the slower travelling speed of the planet $\propto 1/v \propto r^{1/2}$.

Putting these two effects together, the length of a planetary year $P \propto r \times r^{1/2} = r^{3/2}$. With r taking the role of a, this is just Kepler's 3rd law since $P \propto a^{3/2}$ is the same as $P^2 \propto a^3$.

Kepler could not have given the previous argument. It uses physics that came after his time. Kepler stood at the dawn of modern science. He was steeped in mystic numerology and astrology. He derived his laws empirically and objectively. They worked better than anything else at the time and he felt, we feel, that he contributed to a new view of the heavens. His Rudolphine Tables of 1627, with Brahe's portrait prominent on the title page, were a huge advance over the existing Alphonsine tables. Yet Kepler didn't contribute deep understanding or get to the reason why the planets behaved as they did. That understanding came with Galileo and Newton.

JSR