# Gresham College Main logo

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**How the Earth Moves**

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# history

There are many simple observations anyone can make with the unaided eye and enough patience: day turns into night turns into day in an endless cycle; the Sun and the Moon follow a set path across the sky from East to West; the Moon changes not only in its position against the stars from one night to the next, but also in its phase. During the night we can observe that the positions of the stars relative to one another remain fixed in an unchanging tapestry; however, this pattern moves across the sky from east to west in a slow but continuous motion; and from one night to the next the same stars rise a few minutes earlier than the previous night. This daily four-minute shift of which stars are rising leads to a cumulative effect over a few months that means which stars are visible at any time of night depends on the season, and it takes a full year for the sky to look the exactly the same at the same time again.

These predictable patterns of behaviour enabled ancient cultures to develop an agricultural calendar, where the first appearance of certain stars in the sky could mark the appropriate time to either sow or harvest a crop. Archaeological records have shown that civilisations tracked key changes in the behaviour of celestial bodies through the year, as reflected in some of the alignments of old stones, or the way sunlight would fall across markings. They could predict important changes.

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Thousands of stars are detectable to the unaided eye, and the importance of being able to reference certain markers in the night sky means that all ancient civilisations grouped stars into recognisable patterns known as *constellations.* These commonly trace out creatures or characters from myths and legends (sometimes using what must be a very active imagination!). Today our stellar atlases divide the sky into distinct regions – some small, some large – so that every star is mapped to one of 88 constellations which are based on, but refined and revised from, the work of the astronomers of ancient Greece. Chinese astrologers mapped the stars into different constellations, and today we retain many of the Arabic names for the more prominent stars.

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The first successful attempt to chart the heavens was a catalogue of stars created by Hipparchus of Nicaea in the second century BCE, which included 850 stars mapped to a precision of about a degree (twice the angular size of a full Moon), and grouped into 100 constellations. Hipparchus was also responsible for introducing our current system of describing stellar brightnesses in terms of *magnitudes*, as mentioned in a previous lecture (*The lives of stars*).

# A Geocentric Universe

Astronomical observations were recorded as far back as 1000 BCE during the Babylonian era. These marked the appearance and motions of celestial bodies, but ancient civilisations had no idea how far away the stars and the planets really were.

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We know now that a constellation pattern is only formed by a random line-of-sight grouping of stars – in reality the stars are widely separated in their distance away from Earth, and only appear to be close as they lie in the same direction when viewed from our vantage point. However, that wasn’t clear to most ancient civilisation, who (quite reasonably) believed that all the stars were located at the same distance from the Earth. Many came up with the idea of the *celestial sphere -* though it was most obviously promoted by the early Greek philosopher Plato (4th century BCE) - where stars were points of light embedded on the inside of an immense spherical shell surrounding Earth. It seemed natural to interpret the observations of the motions of the night sky most simply as the rotation of this celestial sphere around the Earth from East to West at a constant speed. In addition, the movement of the Sun and the Moon could also be due to their revolution around the Earth. These assumptions underpinned the work of the scholars in both ancient Greece and China. Thus the first working models of the Universe put the Earth at its very centre. This was successful in accounting for the fundamental observations of motions of the Sun, the Moon and the stars… the exception was the behaviour of the bright planets (the ‘wandering’ stars).

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Five planets are obvious to the unaided eye: Mercury, Venus, Mars, Jupiter and Saturn. Like the stars, the Moon and the Sun, they are all observed to rise in the East and set in the West each day. Like the Sun and the Moon, over days, weeks and months, they move against the backdrop of the stars fixed in the constellations, and are also confined to following the same narrow path across the sky. But where the Sun and Moon move at a constant speed and direction relative to the celestial sphere, the planets move much more slowly, and sometimes display a more complex behaviour. Direct (or *prograde*)motionis when the planet moves the same way as the Sun and the Moon, eastwards across the stars. But sometimes they are seen to stop this relative motion and then reverse direction to move westwards in a *retrograde* motion for a short while, before resuming their previous path. This traces a loop against the celestial sphere. Another observation is that unlike other celestial objects, the planets vary in their brightness, growing brighter and dimmer over periods of months; the retrograde motion of Mars, Jupiter and Saturn always happens when the planet appears at its brightest. The explanation of this retrograde motion would remain a serious challenge to models of the Universe for many centuries to come!

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The early Greeks designed geometric models to describe and predict the motions of all the celestial bodies, incorporating the ‘perfect’ symmetry of circles and spheres. They already knew the Earth was a sphere from observations of the shape of its shadow during a lunar eclipse, or the way that boat sails disappeared below the horizon at large distances. The most successful of the Greek models for the Solar System was that devised by Ptolemy, an astronomer working during the second century AD at Alexandria (by then part of the Roman Empire) who had inherited Hipparchus’ catalogue of the night sky.

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Ptolemy attempted to refine the arrangement of the Sun, Moon and planets to account for the retrograde motions observed. He retained the Earth at the centre of the system, with the Sun, Moon, planets and fixed stars still revolving around it on circular tracks at constant velocity; all the circles were flattened in a plane and rotating in the same sense. However he added the modification that each planet was carried on a small rotating *epicycle*, the centre of which followed a second larger rotating circular track known as the *deferent.* A range of motion could then be produced by varying how rapidly the epicycle rotated relative to the motion along the deferent. Although the Earth remained motionless, it was shifted slightly so that it was no longer exactly at the centre of the deferent motion, but off to one side in the *eccentric;* and while the deferent rotated in a uniform manner around the Earth, this was relative to an off-centre point known as the *equant.* With these changes Ptolemy could successfully produce not only an explanation for the backwards retrograde motion, but the changes in the distances of planets from the Sun tallied with retrograde motion occurring when they were nearer, and thus brighter. He could predict the positions and paths of the Sun, the Moon and all the planets with much better accuracy than before. His findings were published in a series of volumes known as the *Almagest*, and this successful model of the Universe persisted for centuries. Further refinements and modification were added only when observations didn’t quite agree with the model, and eventually it would lose much of the appeal of the original scheme’s elegance and simplicity.

# The Heliocentric Universe

While the Dark Ages endured in Europe, the tradition of astronomy and astrometry continued to flourish in the Arabic world and in Asia, improving the instruments and equipment used to measure the position of cosmic bodies. The more precise measurements led to better compilations and catalogues of the night sky. A radical overhaul of our understanding of the relative position of cosmic bodies, however, had to await the European Renaissance; when the news of discoveries and inventions from other lands - including the re-discovery of Ptolemy’s original texts - provided a catalyst refreshing scientific enquiry.

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It was the Polish scholar Nicolaus Copernicus (1473-1543) who suggested a much simpler description of the relationships between planetary bodies could be obtained if one placed the Sun at the centre of the Universe. This model could explain the motion of the planets – and particularly the retrograde motion – in a more natural way than the Ptolemaic system. Copernicus reached this conclusion by applying logical reasoning to the observations of how certain planets appeared in particular parts of the sky, and how fast they moved across the sky to work out the correct order of the planets out from the Sun. Mercury and Venus are always seen near the Sun in the sky, no further than 28° and 47° E or W of the Sun respectively. This implied they must then always lie physically close to the Sun, and so should have orbits located inside that of the Earth. When one of these planets was seen in the evening twilight at its maximum elongation to the West, it would draw steadily closer to the sunset with time until it disappeared from view for a while, only to re-emerge in the morning to the East before sunrise. Copernicus’ re-interpretation successfully predicted that Mercury and Venus should show phases like the Moon. The Ptolemaic model implied that we’d only ever see a small part of the fully sunlit side of the planet, whereas the heliocentric model permits us to observe the full range of phase from Earth depending on where they are in their orbit. This was confirmed when Galileo observed the phases of Venus through a telescope in the early 17th century. Similarly, Copernicus’ model also predicted that the two *inferior* planets are the only ones that can pass in front of the disc of the sun; and indeed the first transit of Venus was observed by Jeremiah Horrocks in 1639.

The fact that the other three planets known at the time could travel round to lie exactly opposite the Sun on the sky, high above the horizon at midnight, meant that the Earth must sometimes lie between the Sun and these planets. Thus the orbits of Mars, Jupiter and Saturn (the *superior* planets) must be larger than the Earth’s. This could then also resolve the problem of retrograde motion: the more distant a planet is from the Sun, the more slowly it will move in its orbit, enabling a faster-moving Earth to overtake the slower-moving outer planets. From our viewpoint they will appear to shift against the celestial sphere in a backward direction at *opposition* (when the planet closest to Earth and at its brightest). Since the orbits of all the planets are not in exactly the same flat plane, loops in the retrograde motion will occur. Copernicus was still restricted by the assumption that the planetary motions had to follow a perfect circular path. Although he provided a natural explanation for retrograde motion, he still had to use epicycles and the eccentric to account for slight variations in the speed of planets around their orbit, which slightly detracted from the original simplicity of this new model. Fearing the reaction of the Catholic Church, who had declared as doctrine that the Earth occupied the centre of the Universe, Copernicus delayed the publication of his model until 1543, the year of his death.

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Unfortunately, the predictions of planetary motion in the Copernican model weren’t much better than those from the Ptolemaic model, which led to some resistance to it being accepted as correct. The largest difference between the two models is that in the Ptolemaic system Earth is stationary, whereas in the Copernican it is always moving. For many scientists of the time, the concept of the Earth underneath us moving seemed to defy common sense - not only should the seas and air be ripped away by the great speed, but anything thrown upwards should fall slightly to the west of its expected landing position, because of the eastward motion of the Earth underneath during the flight. None of this motion was detectable. We know now that we don’t feel any of this motion as it stays constant – one is only aware of motion if undergoing acceleration or deceleration that produces a change in speed.

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In November 1572 – about 30 years after Copernicus’ death – a brilliantly bright new star appeared in the constellation of Cassiopeia, lasting almost 18 months before it faded completely from view. This was a supernova, marking the violent demise of a very massive star, but at the time it wasn’t evident that this sudden transitory event was even a star at all. One way to test whether it was a star was to see if it was as distant as the others. This was attempted by the young Danish astronomer Tycho Brahe (1546 – 1601), using the method of *parallax*. Parallax is the apparent displacement of an object against a background between two observing locations – the smaller this shift, the further away the object must be. The ancient Greeks were already aware that the Moon would appear in slightly different locations relative to the stars when viewed from different locations on the Earth, and used this effect to accurately estimate its distance from Earth. However, the lack of any parallax between the stars demonstrated that they were immensely far away compared to the size of the Earth. Tycho’s observations looking for parallax of the new star using simultaneous observations from different locations on Earth proved it was as distant as the other stars, and thus part of the celestial sphere. He also undertook parallax measurements of a great comet that appeared five years later, showing that it must lie beyond the Moon, and that for the first time, comets were part of the realm of the heavens rather than occurring within Earth’s atmosphere.

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One problem of acceptance for Copernicus’ heliocentric Universe, however, was that it predicted an annual parallax in the stars that was not observed. If the Earth moved round the Sun, observations of the same star six months apart would be taken from a much longer baseline than could be afforded just around the surface of the Earth. Thus stars should be slightly displaced when viewed from different locations in Earth’s orbit around the Sun, ie at different times of year. While Copernicus was aware of this deficiency of his model, he extended the argument of the Greeks: that the stars were too distant for parallax to be observed, located at scales far greater than the size of the Earth’s orbit. However, the lack of any detectable annual stellar parallax left some scientists sceptical of the Copernican model.

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Tycho Brahe in particular undertook meticulous observations of stars and planets specifically to test the Copernican idea. His instruments were the most precise and cutting-edge available at the time, enabling measurement of the position of an object in the heavens to within 1/8 the angular diameter of the full Moon. We know now that the parallax due to the Earth’s motion about the Sun is far too small for him to have been able to measure, particularly for observations made without the use of a telescope, but this is because we know the stars to be at vastly greater distances than was supposed then. Unable to find evidence for the motion of the Earth around the Sun, Brahe concluded that the heliocentric model was false. However, the data that he had collected proved an important legacy for his new assistant, Johannes Kepler (1571-1630), who inherited the detailed records of observations accumulated over many years,

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Kepler was more favourably disposed towards a heliocentric interpretation than his erstwhile employer, and he analysed Brahe’s data to try and bring the observations into agreement with the Copernican model. Kepler’s major breakthrough was to reject the archaic requirement for heavenly objects to follow ‘perfect’ circular paths. Instead, if he allowed the planets to move in ellipses he could discard all the introduced deferents, epicycles and eccentrics to realise a much more elegant solution that precisely matched Brahe’s observations. Kepler’s work on planetary motion came to the conclusion that each planet follows an elliptical orbit with the Sun at one of the foci (with nothing at the other focus). These ellipses need only be a slightly more squashed than a circle in shape. As it moves around in its orbit, the distance between a planet and the Sun will vary. Kepler’s second breakthrough was to realise that the speed of the planets could also vary in its orbit – that a planet moves most rapidly when it is nearest the sun, and most slowly when it is furthest. Finally he deduced a relationship between the dimensions of a planet’s orbit and the time it takes to go once round the sun: the larger a planet’s orbit, the longer it takes to complete.

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More evidence supporting the heliocentric interpretation came with the first use of the telescope for astronomical observations by the Italian scientist Galileo Galilei (1564-1642), providing the first new astronomical data for centuries. He observed that Venus displayed phases and changes in its apparent size that correlated with its angular distance from the Sun, confirming Copernicus prediction. He also discovered four Jovian moons, whose orbits around Jupiter obeyed Kepler’s laws of planetary motion, and whose existence demonstrated that there could be other centres of motion than the Earth. He published these observations (and many others) in a pamphlet called *Sidereus Nuncius* (‘the Starry Messenger’) in 1610, a short scientific treatise designed to be accessible to an educated public. Only 24 pages in length, it was not written in formal Latin, and lacked the details of formulae, calculations and tables of data more normally included in publications at the time. Galileo’s promotion of the heliocentric model was in contradiction to beliefs of the Catholic Church, and he was forced to publicly withdraw his support for the Copernican model by 1616. A later attempt to further support a heliocentric Universe through a drama written for a cast three characters caused him to be summoned before the Inquisition. He was again forced to renounce the idea that the Earth moved, his play was banned, and he was placed under house arrest for the remainder of his life.

While the work of Kepler and Galileo supported the inference that the Sun lay at the centre of the Universe, it was not until Newton developed his laws of motion and his theory of gravity that it could be explained exactly *why* the planets moved in these patterns. At this point the Copernican model became much more widely accepted and adopted.

# rotation of the Earth

The Copernican model did not just demand that the Earth revolved around the Sun, but in order to obtain the steady change of constellations through the night sky the Earth must also rotate on its axis. Day and night are then provided not by the Sun’s motion around the Earth, but by the Earth continuously turning into and then out of sunlight. This view of the sky from a rotating platform also accounts for other fundamental observations without the need for a celestial firmament also in rotation about the Sun. If we now accept that the stars are distant and fixed, and not rotating, then the slow change of which stars are overhead at any time from one night to the next happens as a natural consequence of Earth’s orbit around the Sun, as its night-time side is gradually turned towards different parts of the sky.

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The rotation of the Earth can be demonstrated by a device known as the *Foucault pendulum*. This is a pendulum on a very long string that is free to swing through any plane in the vertical direction. The plane of the swing appears to rotate relative to the Earth, as the oscillation remains fixed while the Earth rotates underneath it. The amount of swing observed depends on latitude: the plane of the pendulum swing undergoes a full clockwise rotation once a day at the North Pole (and one anti-clockwise at the South Pole); at the equator the plane of the oscillation is fixed relative to the Earth, and at other latitudes the rate of swing lies in between these extremes.

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Today we still reference the idea of a celestial sphere, but it is used an imaginary concept to define and provide a reference frame for the stars in positional astronomy rather thought of as a physical reality. We project the directions of the Earth’s rotational axis out into infinite space and the points where they intersect the celestial sphere are known as the north and south *celestial poles.* The line that forms a projection the Earth’s equator out into space is the *celestial equator*  and it provides an imaginary division of the sky into northern and southern hemispheres.

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Stars close to the celestial poles will not rise and set during a night, but always stay above the horizon; in the Northern hemisphere we know these as the *circumpolar* constellations such as *Ursa Major* or *Cassiopeia,* each lying to either side of the Pole Star, *Polaris,* which is located less than 1° away from the north celestial pole. An observer at the North or South Pole on Earth sees every star as circumpolar, moving horizontally around the sky, parallel to the horizon; an observer at the equator is tilted by 90° relative to one at one of the Poles and so they thus see all the stars rise straight up, moving perpendicularly to the horizon and there are no circumpolar stars. Other observers will see the stars rise and set at an angle to the horizon, the size of this angle is dependent on their latitude.

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During the Earth’s yearly orbit, the position of the Sun, as viewed from Earth, will gradually shift against the background stars. Because there are 365 ¼ days in a year and 360° in a circle, the Sun’s location shifts at a rate of about 1° a day from West to East in the opposite direction to the apparent motion of the celestial sphere. The Sun is thus observed to move through different constellations during the year: currently it’s in the constellation of Pisces and by the end of the month it will be in Aries. The twelve constellations that lie along its path form the *zodiac* (since the boundaries between constellations were finally defined, the constellation of Ophiuchus which lies between Scorpius and Sagittarius is also technically part of the zodiac). Because the Solar System is in the form of a flat plane, the motions of the planets and the Moon are also confined to this relatively narrow track across the sky, a circular path around the sky known as the *ecliptic.* The ecliptic is *not* the same as the celestial equator; the two are inclined to one another 23.5°, the same as the tilt between the Earth’s rotational axis and the plane of the Solar System. The ecliptic and the celestial equator intersect at two points exactly opposite to each other on the celestial sphere, known as the equinoxes.

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The simplest frame of reference against which to define the position of a star in the sky would be to use its altitude and azimuth (*ie* the angular height above, and direction around, the horizon). But this system is subjective, as it depends on where you are located on the Earth’s surface, and the positions of the stars relative to your horizon will be constantly changing because of the Earth’s rotation. Given also that the stars rise approximately four minutes earlier on each successive night, even when viewed from the same location at a specified time, ‘alt-az’ coordinates change from day to day. Instead astronomers use an absolute co-ordinate system that is independent to Earth’s motion. This is similar in principle to the latitude-longitude system of coordinates on the surface of the Earth, but it is marked on the celestial sphere. The *declination* is the angular distance of a star to the north or south of the celestial equator, as measured along a circle passing through both celestial poles; this is equivalent to the idea of latitude. Longitude is similarly represented by *right ascension,* the angular distance to a star as measured from the position of the vernal equinox (the first of the points where the celestial equator and the ecliptic intersect).

However, even this system of co-ordinates is not immune to long-term change in the way the Earth moves. Both the direction and the tilt of the Earth’s rotational axis changes very slowly under the influence of the combined gravitational pull exerted by the Sun and the Moon and the way they continuously change location relative to each other.

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Due to the centrifugal force of its rotation, Earth is not a perfect sphere, but is wider by about 40 km at its equator than at its poles. The gravity of the Moon and the Sun exert a pull on this equatorial bulge, trying to turn Earth’s axis so it is perpendicular to the plane of the ecliptic. However, because the Earth is spinning, the net effect is instead to pull the axis of rotation around to create a *precession*, analogous to the behaviour of a spinning top. The axis remains tilted at 23.5° to the perpendicular, but the direction it points in gets pulled around to sweep out a circular cone. The north and south celestial poles thus change their position relative to the stars, each tracing a full circle against the sky every 25,770 years. Currently the north celestial pole lies to within a degree of the star Polaris, but in 12,000 years’ time the Pole star will be the bright star Vega. The early Greek astronomer Hipparchus was the first person to detect the effects of precession, when he noticed discrepancies between the positions of stars in his catalogue with the measurements from the Babylonians three centuries earlier. Precession also causes the Earth’s equatorial plane to change in orientation; and as this plane defines the location of the celestial equator on the sky, the celestial equator must also precess, leading to each equinox shifting slightly westward along the ecliptic with time. This *precession of the equinoxes* means that all RA-Dec co-ordinates have to be referred to a certain epoch, and it must be taken into account when interpreting historical observations.

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A further effect of the gravitational pull of the Sun and Moon on the Earth's equatorial bulge produces a slight nodding motion in the angle of the Earth’s tilt known as *nutation,* with a dominant period of 18.6 years. Although this was discovered in 1728 by the British astronomer James Bradley (more of whom we shall hear in a moment), it was not explained until 20 years later. Nutation also changes the location of markers defined by the Earth’s tilt, such as circles of latitude. There are also other smaller periodical nutation’s that must be taken into account, and full understanding of these has to take into account the internal structure and properties of the Earth itself. Currently the Earth is tilted at 23.44 degrees, roughly halfway between its extreme values of 22.1° and 24.5°. The axial tilt is decreasing and will reach its minimum value around the year 11,800. The north and south poles of the Earth also migrate across its surface, producing a change in location of around 9m over a period of 433 days. This is another nutation produced in a spinning non-spherical body, and it combines with a further annual component to produce a total polar motion that varies with a period of about 7 years.

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The Earth moves around the Sun in an elliptical path; but the exact shape of this ellipse varies between being very nearly circular and mildly eccentric (where eccentricity measures of the departure of an ellipse from circularity) with cycles lasting 100,000 and 410,000 years. This variation in orbital shape is mainly due to the gravitational pull of the giant planets Jupiter and Saturn. The long (semi-major) axis of the ellipse does not vary (the change is in the shorter, semi-minor axis), and as this (by Kepler's laws of planetary motion) is what determines the period of a planet’s orbit, the length of the year is unaffected.

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The elliptical orbit of the Earth around the Sun also rotates gradually over time, and precesses in space - again, primarily as a result of the gravitational effect of Jupiter and Saturn. Finally, the inclination of Earth's orbit wobbles up and down due to a precession of the whole ecliptic plane with a cycle having a period of about 70,000 years.

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All these changes in the way that the Earth moves – the nutation and precession of its rotational axis, the precession, rotation, and variation in eccentricity of its orbit around the Sun – can affect the climate on the very longest timescales, as each can alter the amount and direction of Solar energy reaching the Earth. For example: when the orbit is at its most elliptical, the amount of solar radiation at perihelion (nearest point to the Sun) will be about 23% more than at aphelion (the furthest point); changes in the axial tilt mean that at times the summers receive more radiative Solar energy, and winters less; and which hemisphere is pointed towards the Sun at its closest point will have more extreme seasons than the other. The Serbian astronomer Milutin Milankovitch computed the meshing of all these orbital variations and suggested that occasional the effects of the cycles can combine to produce long-term dramatic fluctuations to the Earth’s climate, such as ice ages. Indeed, deep-sea sediment cores suggest that ice ages have occurred at specific stages of orbital variation of the Earth.

# The aberration of light

During the 17th century the idea of an orbiting and rotating Earth became increasingly popular, but the final predicted consequence of this motion - that of the annual parallax of the stars that must occur if the Earth orbits the Sun - still eluded observers. Astronomers persisted to try and detect it; not only would it prove the motion of the Earth around the Sun, but it would enable them to finally determine a distance to the stars.

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Robert Hooke (1635-1703) – a former Gresham Professor of Geometry – attempted to measure the annual parallax of the star γ Draconis in 1669. This particular star was chosen because it passed overhead in London, and thus the effects of atmospheric refraction (which could displace the image of a star slightly) on the observations would be minimised. The star was bright enough to see through a telescope during the daytime, and there was the expectation that a brighter star would be also be more likely to be nearer, thus displaying a larger annual parallax than those that were further. Hooke built a zenith telescope into his Gresham College apartments. This was a refracting telescope; the observer had to lie under the eyepiece on the ground floor and look up through holes cut into both the upper floor and the roof, and through an objective poking out from the top of the building. Hooke attempted to measure the angle between the zenith and γ Draconis as it crossed exactly overhead, hoping to pick up annual parallax as a variation in this angle of separation over the period of a year. He published his results in 1674, claiming to detect annual parallax, but only from four observations. His claim was greeted with some scepticism at the time, and indeed now we know that the annual parallax of γ Draconis is far too small for him to have observed with this apparatus.

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Attempts to detect annual parallax proved unsuccessful until it was first observed in 1838 – but the failure to detect the annual stellar parallax led to another discovery of a new and unexpected phenomenon, which instead provided the first direct evidence for the Earth’s motionthrough space round the Sun.

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James Bradley (1693-1762, later to be appointed the third Astronomer Royal) re-attempted Hooke’s observations with a better telescope enabling very precise observations − a zenith telescope with a 24-inch objective, funded by a rich supporter and amateur astronomer, Samuel Molyneux. He failed to measure the annual parallax of γ Draconis, and this placed the star at a minimum of 400,000 times more distant from the Sun than the Earth, very much more distant than had been previously estimated.

However, he discovered that γ Draconis *did* show an annual pattern of displacement – just not in the way reported by Hooke or expected from the Earth’s motion round the Sun. It was three months out of phase, with the maximum variation from the expect position occurring in March and September rather than as expected in December and June.  To try and understand the meaning of this measurement Bradley commissioned a new shorter, but better zenith telescope, with a wider field of view to allow him to check more star positions than just that of γ Draconis. He found that every star seemed to show the same strange displacement in its position, all three months off from the predicted effect. The story is that he only understood what he had discovered whilst sailing on the Thames in 1728, when he was watching the behaviour of a small flag at the masthead. Every time the boat changed its course, the wind direction shown by the flag also appeared to change. He conferred with the crew, who reported that the flag’s behaviour didn’t reflect a true change in wind direction, but it was affected by the motion of the boat in its course. Bradley realised that his observations – made from the viewpoint of a telescope located on a moving Earth – would necessarily be subject to the same effect.  He had discovered the *aberration* of starlight.

Light from a star takes a tiny, but still finite, time to travel the length of a telescope tube; during that short time the tube moves slightly because of the motion of the Earth, so to properly receive the light the telescope must not be aimed directly at the star, but tilted slightly toward the direction of the Earth’s (and thus the telescope’s) motion. As the Earth changes direction along its orbital around the Sun, the direction of the displacement of the star’s light due to aberration will change (the exact pattern of apparent movement depending on the location of the star in the sky). But unlike parallax, the angular displacement to aberration does not depend on the distance to a star. It turns out that it would not be possible for Bradley (or Hooke) to have measured parallax without first having taken into account the aberration, as it is a stronger effect which completely dominates the measurements.

Yet Bradley had proven for the first time that the Earth moves around the Sun, and not only that, but how fast. The size of the aberration is directly related to the ratio between the speed of the Earth and the speed of light. Bradley’s observations implied that the orbital velocity of Earth is about 1/10,000 the speed of light, and indeed the Earth travels round the Sun at about 30 km/s. The fact that Bradley compiled observations over a period of many years also enabled him to establish the nodding of the Earth’s axis known as nutation, which created a small change in all stellar positions over the years.

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The first reliable observation of annual parallax was made by the German astronomer Friedrich Bessel in 1838, and the amount of parallax detected was far less than Bradley would have been capable of measuring. It helps that the annual parallax was detected in the motion of the star 61 Cygni, which at 10 light-years distant is much closer to Earth than γ Draconis, and would thus show a larger parallax. Bessel’s strategy was to measure relative motions of two stars close together in the sky but greatly separated in true distance; these would show the same displacement due to aberration, but very different amounts of annual parallax. By the late **1830s parallax measurements had not clearly demonstrated the motion of the Earth round the Sun, but established the distances to a handful of stars for the first time. In turn,** knowledge of true astronomical distances allowed astronomers to calibrate their observations, enabling comparison of the intrinsic physical properties of stars (such as their luminosity and size). Once **photography became employed in astronomical observation, it allowed a much more efficient compilation of stellar positions and distances; and by** the early 20th Century, all-sky surveys had produced 3-dimensional mapping over 2000 stars in the sky.

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To establish whether or not an object is moving, a reference frame needs to be established. In addition, by the end of the 19th Century, there was great debate about the nature of light itself. Newton had already expressed the view that light is a particle, but the English scientist Thomas Young had experimentally established that light behaved as a wave. By the early 1860’s the Scottish physicist James Clerk Maxwell (1831-1879) had successfully encapsulated the behaviour of electric and magnetic fields into his eponymous four equations, and in turn predicted that light consisted of *modulations of the same medium which is the cause of the electric and magnetic phenomena.* The question was, if light was a wave, what was the medium it propagated through? After all, water waves travel through water, sound waves travel through air, light waves should travel *through* something – and this medium should fill space, all the way out to the stars. To fulfil this need, the existence of the *aether* was hypothesized to pervade interplanetary, and interstellar, space. Maxwell’s discovery that electro-magnetic waves (which included light) all travel at the same speed suggested a way of experimentally detecting Earth’s absolute motion through this aether, by measuring the speed of light from earth’s (moving) frame of reference and comparing to the theoretical value.

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In 1887 the two American scientists Albert Michelson (1852-1931) and Edward Morley (1838 – 1923) devised a way of detecting the wind expected to result from Earth’s passage through the stationary aether, as it constantly shifted in its orbit around the Sun, and spun on its axis. They recorded the return speed of light in different directions at a variety of different times; but even though the Earth was known to move at a speed of 30 km/s, the experimental results implied that the Earth had a zero velocity through the aether. Many subsequence experiments made with an increased precision also returned null results – the speed of light was unchanged, regardless of the velocity of the laboratory on Earth relative to the source of light. The null result was only understood after Albert Einstein’s had devised his theory of special relativity in 1905 and in particular, his realisation that light always travels at an absolute rather than a relative speed, independent of the state of motion of the emitting body. There is no aether.

# All the motions of the Earth

So in summary, not only is the surface of the Earth spinning on its axis at speeds of up to 1600 km/hr (0.4 km/s) at the equator, (although this speed decreases as you move away to the north or south), but the whole planet is hurtling round the Sun at 107 million km/hr (30 km/s). But the Sun itself is not stationary!

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The Sun is one of a hundred thousand million stars that are in orbit around the centre of the Milky Way, and as it moves it will drag its retinue of planets along with it. Stars in the galaxy will have both systematic (rotational) motion around the centre, along with more random local movements. [As we’ve taken most of the talk to understand how the Earth is moving, appreciate there’s another lecture at least disentangling the kinematics of the contents of the Milky Way…] If all the stars are moving, then what do we define what the stars are moving with respect to? (ie what is ‘at rest’ that we can compare to?) We define a *local standard of rest* (LSR)that applies to just our immediate neighbourhood, obtained from the average motion of all the stars nearby; this local standard of rest is orbiting around the centre of the Milky Way at around 220 km/s. The Sun is then moving *through* and relative to this whole neighbourhood at about 19 km/s in the direction towards the bright star Vega – not only is it moving a little faster than the LSR, but it’s also a little towards the galactic centre, and slightly northward out of the galactic plane. Our LSR is orbiting the Milky Way once every 225 million years, meaning that we have only completed twenty orbits of the Galaxy since the Sun and the Earth first formed.

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The Galaxy is not only spinning, but also speeding on its own journey through the Universe. Direct evidence of this motion is seen in the Doppler shifts that dominate the signal in the cosmic microwave background (see my lecture *Echoes of the Big Bang*): the radiation in the Earth’s direction of motion appears blueshifted (and hence hotter), while radiation on the opposite side of the sky is red shifted (and colder). The level of these shifts implies that we (and the rest of the Local Group of galaxies) are moving at about 370 km/s relative to this primordial radiation, a motion caused by the gravitational attraction of nearby clusters and superclusters of galaxies pulling us around.

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Nowadays we routinely measure the parallaxes of very distant stars; many of these displacements are too tiny to be measured by Earth-bound telescopes because the atmosphere shifts and distorts the signal. Today measurements are made by telescopes on satellites in space. For example, in the 1990s *Hipparcos* (HIgh Precision PARallax COllecting Satellite ) precisely measured the positions of almost 120,000 stars through the parallax method.

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The very latest in astrometrical measurement comes with the launch of the European *Gaia* spacecraft in December 2013, which will – over the next five years – observe parallax displacements with a precision a hundred times better than achieved by *Hipparcos. Gaia* will systematically survey the sky, mapping the position, parallax and proper motion of one billion stars (which still constitute only about one per cent of the Galaxy's stellar population!). The precision of the observations will enable *Gaia* to determine distances to stars out to 30 000 light-years away – and a hundred times farther than was possible previously. A full three-dimensional stellar map will be created, and combined with observations about the real (*ie* not those due to the Earth’s motion) motions astronomers will be able to study the dynamical history and evolution of the Milky Way. The observations will also characterise the physical properties (mass, luminosity, age) of the stars surveyed to produce a census of the Milky Way's stellar population.

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*Gaia* will also observe and record precise positions of thousands of extra-galactic objects, such as very distant quasars. These are at such immense distances that their images do not exhibit any angular displacement at all due to parallax, and thus can be used to establish a new Universe-wide standard of rest, against which the motions of not just the Earth, but all the stars in the Galaxy can be compared.

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