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Beware the tides of March

How the fact that gravitating bodies are extended and not mere points explains many everyday phenomena

There is a tide in the affairs of men, which taken at the flood, leads on to fortune. Omitted, all the voyage of their life is bound in shallows and in miseries

William Shakespeare

Julius Caesar

Time and tide wait for no man

Geoffrey Chaucer

It is a bright and frosty morning in mid-March and a washed-out Moon, close to full, is hanging in the blue sky. We are waiting, expectantly, on the river bank, hundreds of us. There is even a TV crew with a young woman in a red puffa jacket and Burberry scarf talking to camera. Now and then people glance down at their watches, then back downstream. But there is nothing to see except a wide river rolling languorously down to the ocean and a pair of comedy swans, repeatedly up-ending their white bottoms by the opposite bank.

The scene is so tranquil here on the River Severn at Minsterworth in Gloucestershire that it is impossible to believe that anything out of the ordinary is going to happen. Could it be that we have driven to this location in the West of England and parked in this field for absolutely nothing? Could it be that we are all deluded, gullible victims of some ridiculous hoax?

But then we hear it - a faint rumble like distant thunder. The swans, startled, right themselves and look all about. The TV reporter in the red puffa jacket breaks off in mid-sentence and swivels to look downstream. And there, suddenly, we see it, preceded by spray, spurting high into the air at a sharp bend in the river bank: a boiling, churning wall of froth and chocolate brown water spanning the entire 90 metre-width of the river and carrying with it kayakers and wet-suited surfers who have been riding the wave all the way from the Severn estuary (the world record, by the way, held by surfer called Steve Ling, is a 14.9 kilometres). Behold the Severn Bore, an angry, stirred-up metre-high hummock of water, racing at up to 21 kilometres an hour the wrong way up the River Severn.

Just as quickly as it arrives, it has gone, disappearing from view around the next bend in the river, heading for the city of Gloucester where it will be truncated by the city's docks. Most but not all of its human cargo have gone with it. Two surfers, who collided as they threaded their boards back and forth across the wave front, are now bobbing up and down in the gently undulating water of the bore's wake, along with the bemused swans.

The TV crew packs up its equipment into shoulder bags and boxes, while the rest of us head back to our cars. Everyone is laughing, light-headed, exhilarated. No one is in the slightest doubt that what they have just witnessed one of the wonders of the natural world.

Interesting bores

The Severn Bore is one of about 60 bores around the world [1]. The biggest and most terrifying by far is on the Ch'ient'ang'kian River in China. In spring, a monster wave as high as a three-storey house surges upriver faster than most people can run [2]. So great is its roar that it can be heard from 22 kilometres away. Boats must be lifted clear of the river lest they are smashed to matchwood. And every year, despite abundant warnings signs erected by the authorities along the riverbank, some people stand too close and are swept away and drowned.

The necessary conditions for a bore are a river estuary of a very particular shape and a large tidal range. The Severn estuary, where the water rises as much as 15.4 metres between low and high tide, has the second highest tidal range in the world. The fast-rising water is funnelled into a channel which rapidly becomes narrower and shallower. Eventually, the speed of the water flowing upriver exceeds that of the water flowing downriver, and a step in water height, technically known as a "hydraulic jump", is born, and travels rapidly upstream (A similar phenomenon, though static, can be seen in a kitchen sink when water from a tap strikes a basin and spreads out, creating an abrupt change in water height where its speed matches that of the incoming water). Just as a tsunami is imperceptible out at sea but amplified when it enters shallow coastal waters, the Severn Bore is an imperceptible ripple out in the estuary but grows and picks up speed as it is funnelled by the ever-shrinking channel.

The biggest bores occur in spring and autumn. This is because the Severn Bore and its cousins around the world are merely extreme manifestations of the ocean tides, which are at their largest in spring and autumn. Since the tides are the result of the influence of the Moon it follows that so too is the Severn Bore. Remarkably, a super-localised hummock of speeding water, capable of startling swans and delighting surfers and kayakers, owes its existence to an astronomical body 384,000 kilometres away across space.

The Moon appears so small in the sky it can be covered by a thumb held at arm's length. That it should be the orchestrating such a down-to-earth event on a cold March day on the River Severn seems utterly preposterous. No wonder nobody guessed the cause of the Severn Bore. No wonder nobody guessed the cause of the ocean tides. Not for a long, long time.

Baffled by the tides

Nobody knows when the tides were first noticed. But our ancestors left the cradle of Africa in several waves, beginning 1.8 million years ago with *Homo erectus* and finishing 60,000 years ago with modern humans. Very probably, they made their way around the globe by following the shoreline of the oceans, thus avoiding the obstacles of mountains, deserts and forests, and ensuring an ever-present source of food in the adjacent sea. As they padded barefoot along the wet sand, one thing would have been obvious to our not-quite-human ancestors and our fully human ancestors: twice a day, the sea breathes in and out, surging up a sandy beach before slinking back whence it came. From a clifftop or any other place where the coastline is vertical, it would have been clear that this in-and-out motion is actually a consequence of something more fundamental: twice a day, mysteriously, the ocean rises and falls.

Time passed. Immense tracts of time. People invented farming, started to live in cities and began to speculate about the phenomena shaping the world they found themselves in. By a quirk of geography, the ancient civilisations of the West bordered a sea – the Mediterranean - which experiences barely noticeable tides. People remained ignorant of the phenomenon, and this ignorance had severe consequences for Julius Caesar whose invasion of Britain in 55 BC and 54 BC required him to take a Roman fleet outside the Mediterranean:

> It happened that night to be a full Moon, which usually occasions very high tides in that ocean; and that circumstance was unknown to our men. Thus, at the same time, the tide began to fill the ships of war which Caesar had provided to convey over his army, and which he had drawn up on the strand; and the storm began to dash the ships of burden which were riding at anchor against each other. [3]

"Beware the Ides of March", Julius Caesar is warned by a soothsayer before his murder in the play by William Shakespeare. Perhaps if he had been warned "Beware the tides of March", his invasion fleet would have suffered less heavy damage in the Atlantic. Such a warning should actually have been possible. Although knowledge of the tides was not widespread in Roman times, their key characteristics had been known since about 330 BC when the Greek astronomer and explorer Pytheas sailed from the virtually landlocked Mediterranean all the way to Britain. On emerging for the first time into the vast open expanse of the Atlantic Ocean, Pytheas made a fundamental discovery [4]. The tides are biggest at new Moon - when the Moon is completely unlit by the Sun - and at the full Moon - when the Moon is completely lit by the Sun. Bizarelly, the tides appear to be controlled by the Moon.

Actually, the observation that the highest tides occur when the Moon and Sun are arranged in space so that the Moon is either completely lit or completely un-lit by the Sun strongly hints that the Sun also plays a role in the phenomenon, something also realised by Pytheas. The involvement of the Sun is also supported by the fact that the tides are bigger in spring and in autumn, two very particular times in the Earth's annual journey around the Sun.

Knowing the key characteristics of the tides is obviously a very important first step on the road to understanding the cause of the phenomenon. Nevertheless, for almost two millennia after Pytheas, no one came even close to explaining the baffling spectacle.

At the beginning of the 8th-century, however, the Venerable Bede, an English monk and chronicler, noticed that high tide arrives at different times at different ports around the coast of Britain. The implication was that local geography, as well as the influence of the Moon and Sun, plays a role in determining the characteristics of the tides – an observation reinforced by the absence of significant tides in the land-locked Mediterranean and the presence of giant tides in the funnel-shaped estuary of the River Severn.

As for the cause of the tides, Bede, like everyone else, was, well, totally at sea. He speculated that the Moon *blew the ocean inland*. And, when the Moon had *moved a bit* so that the ocean was subjected to weaker breath, it returned whence it had come. "It is as if [the ocean] were dragged forwards against its will by certain exhalations of the Moon", wrote Bede, "and when her power ceases, it is poured back again into his proper measure."

The first attempt at a scientific explanation came from an Arab physician and astronomer in the 13th century. According to Zakariya al-Qazwini, the tides are caused by the Sun and Moon heating the water of the ocean, which causes it to expand outwards from the point of heating. Though eminently plausible, the idea fails to explain why the Moon and not the Sun plays the dominant role. The tides pulled by the Moon are about twice as big as those pulled by the Sun.

In 1609, Johannes Kepler, very likely influenced by William Gilbert's recent discovery of the Earth's magnetic field, proposed that the tides were caused by the magnetic attraction of the Moon and Sun on the oceans. Galileo was a big admirer of Kepler's. However, he was shocked by this "childish" suggestion. The whole idea that astronomical bodies could reach out across empty space and affect the Earth smacked to him of the "occult". Galileo instead suggested that the tides are caused by the combined effect of the Earth rotating on itsaxis and orbiting the Sun, motions which he claimed cause the oceans to slosh back and forth.

The truth is that nobody had the slightest chance of discovering the origin of the tides because nobody had the right mathematical tools to do so.

Nobody, that is, until Isaac Newton. Newton alone created a system of the world, which united the Earth and the heavens in one theoretical framework. Newton alone discovered a universal law of gravity. And, in 1686, as he feverishly explored the consequences of his law of gravity in his emerging masterwork, the *Principia*, he picked up the mathematical tools that he alone in the world possessed and applied them to the tides.

Tides: the lunar connection

In estimating the gravitational force exerted by the Earth on the Moon, Newton had assumed that it is the same as if the entire mass of the Earth is concentrated at a single point at its centre. He had even proved this is so with his new-fangled mathematics of integral calculus. But considering the Earth as a point-like mass is merely a good approximation. The Earth in reality, of course, is an *extended body*. And, because it is an extended body, naturally, there are parts of the planet that are closer to the Moon than others. The closer parts experience a stronger pull from the Moon than the other parts. Such differences in gravity, Newton realised, have important consequences. And those consequences are most significant for the oceans because water, unlike solid rock, is free to move.

Consider the point on the ocean immediately below the Moon. The gravitational pull on the water at the surface, which is closer to the Moon, is stronger than the pull on the water at the seabed, which is further from the Moon. This difference in gravity, Newton realised, causes the surface water to be pulled away from the seabed so that the ocean bulges upwards towards the Moon.

But this is not all.

Consider the ocean at a point on the opposite side of the Earth to the Moon. Here, the gravitational pull of the Moon on the water at the seabed, which is closer to the Moon, is stronger than on the water at the surface, which is further from the Moon. The difference in gravity causes the water at seabed to be pulled away from the surface so, once again, the ocean bulges upwards.

According to Newton's reasoning, then, the Moon creates not one but two bulges in the ocean - one at the point in the ocean closest to the Moon and one in the point in the ocean farthest away from the Moon [5].

The Earth, however, is not static but spins on its axis. This means that the ocean moves through the two bulges every 24 hours. And, from the point of view of someone standing on a beach on the edge of the ocean, the water rises and falls twice every 24 hours. Newton had therefore explained what nobody in history had been able to explain: why there are two tides a day. They are nothing more than a consequence of a universal law of gravity which weakens with distance. But, of course, no one knew of such a law before Newton.

Actually, there is a subtlety here, of which Newton was aware. It is not quite true that the tides at any location repeat every 24 hours. They repeat roughly every 25 hours, something actually noticed by Pytheas in 330 BC.

Picture the Moon again. It does not simply hang static in the sky above a single location on the ocean while the Earth turns beneath it. Instead, it circles the Earth in the same direction as the Earth's rotation, taking 27.3 days to make a complete circuit. This means that a point on the ocean directly beneath the Moon will not be directly beneath the Moon again after 24 hours. In the time the Earth has taken to turn once on its axis, the Moon will have moved on its orbit. For the point on the ocean to be directly below the Moon again the Earth must rotate a farther 1/27.3 of a complete turn, which takes 1/27.3 of 24 hours, or about 53 minutes. Consequently, two tides are experienced not every 24 hours but every 24 hours and 53 minutes. This is just one of many reasons why predicting the precise times of low and high tide at any location on a coast requires detailed tide tables.

The fact that the Moon rises 53 minutes later each day and the tides are delayed by 53 minutes each day is yet more evidence that the tides are principally caused by the Moon.

But why are the tides so small in the Mediterranean? The answer is part geography and part ocean depth. As the Earth rotates, the two tidal bulges move westward through the oceans. But this means they head towards the Mediterranean from the direction of the Indian Ocean. Unfortunately, there is a brick wall standing in the way: the landmass of Middle East. Consequently, no ocean bulge makes it into the eastern Mediterranean.

But what about times when the Moon is directly above the Mediterranean? In this case, the Moon *will* create a bulge in the Sea. However, it will be small. The reason is that the difference in the Moon's gravity experienced by water at the surface of the ocean and at the seabed depends on the depth of the water. If the ocean is shallow, the difference is small, and so too is the tidal bulge; if the ocean is deep, the difference is big, and with it the tidal bulge. The Mediterranean is relatively shallow. In fact, its average depth is 1.5 kilometres compared with the 3.3 kilometres of the Atlantic. Consequently, tides in the Mediterranean are less than half as impressive as in the Atlantic even when the Moon is hanging directly above the Mediterranean.

Confession time. The twin tidal bulges in the oceans, which are often shown as huge in textbooks and popular science books, are actually ridiculously small. In mid-ocean, the Moon's gravity lifts the water by at most a metre – little more than a ten-millionth of the Earth's radius. But, of course, an ocean has a very large area, and a metre-high bulge spread over a very large area accounts for a lot of water. When that water sloshes into the shallows around the land, it is amplified in height in exactly like a tsunami. Though the tides at mid-ocean are unnoticeable, along the shorelines of the ocean they can be more than 10 times as big.

Tides: the solar connection

As Pytheas discovered, however, the tides are not caused by the gravitational pull of the Moon alone but by a combination of the pull of the Moon and the

Sun. The reason these two bodies are responsible is simple. They are the celestial objects with the dominant gravitational pull on the Earth. The Moon is enormously less massive than the Sun but an awful lot closer – and its closeness wins out. This is why the tides pulled by the Moon are twice as big as those pulled by the Sun (From this, it can be deduced that the Moon is twice as dense as the Sun [6]).

The biggest tides occur, not surprisingly, when the effect of the Earth and the Sun reinforce each other. This happens in spring and autumn. It is not easy to visualise. But the key thing is that the Earth spins like a top tipped at 23.5° to the vertical. This means that the Moon's orbit is also tipped [7]. The geometry of the situation means that the only time the Moon and Sun can be perfectly aligned and so pull on the Earth's oceans with maximum force is when the Earth in its orbit is halfway between summer and winter - that is, in spring and autumn.

The perfect alignment also requires the Moon and Sun to be either on the same side of the Earth, so that the Moon is in shadow – a new Moon – or on opposite sides of the Earth, so that the Moon is completely illuminated – a full Moon. This is why the biggest tides – and the biggest Severn bores – occur in spring and autumn around the time there is a full or new Moon in the sky [8].

But the Moon and Sun do not exert a tidal effect only on the oceans; they exert a tidal effect on the whole planet. However, because the rock of the Earth is a more rigid than water, the effect on the planet is far smaller and much harder to spot. Remarkably, though, such an effect was first noticed – though not understood – in antiquity.

Tides in the rock: wells and springs

The tides have many baffling features. They occur, after all, twice every 25 hours not every 24 hours. They vary according to the seasons and according to the phases of the Moon. And they vary according to local geography. But one feature of the tides – first noticed by the Greek philosopher Poseidonios - is arguably more baffling than all the rest.

Poseidonios, who lived between 135 and 51 BC, made observations of the tides in the Atlantic off the coast Spain. He also observed water in wells. And what he noticed was something very peculiar. As the water in the ocean rises, the water in wells falls; and vice versa. Poseidonios' original observations are lost. However, the Greek geographer Strabon, who lived from 63 BC until about 25 AD, reports them in his *Geographika*:

> There is a spring at the [temple of] Heracleium at Gades [Cadiz], with a descent of only a few steps to the water (which is good to drink), and the spring behaves inversely to the flux and reflux of the sea, since it falls at the time of the flood-tides and fills up at the time of the ebb-tides.

What in the world could cause the water in such a localised region as a spring or well to do the exact opposite of what the water in the ocean is doing? There was unlikely to be an answer while the cause of the tides remained a mystery. In fact, incredibly, the puzzle was solved only in 1940 by an American geophysicist called Chaim Leib Pekeris [9].

A tide can be defined as the distortion in the shape of one body caused by the gravitational pull of another body not simply a distortion in the shape of its water. And, in fact, the pull of the Moon causes a tidal bulge in the rock immediately beneath it in exactly the same way that it causes a tidal bulge in the ocean immediately beneath it. The bulge in the rock, however, is a lot smaller on account of rock being a lot more rigid than water. Twice every 25 hours, then, the solid Earth at any location bulges upwards and shrinks back down again, stretching and squeezing the rock.

Now imagine that the rock into which a well is dug is porous so that it contains water. This is not unlikely since the very fact that a well contains water means there must be water in its vicinity. The surrounding rock is therefore like a water-logged sponge. And, like a water-logged sponge, it sucks water out of a well when the rock is stretched and squirts it back into the well when the rock is squeezed.

The rock and ocean are stretched at high tide and squeezed at low tide. Consequently, at high tide, water is sucked out of a well, lowering its water level, and, at low tide, water is squirted back into a well, raising its water level. This is precisely the phenomenon observed by Poseidonios. It took 2000 years but Pekeris finally explained it.

Tides in the rock: the LHC

There is, however, a more contemporary and more high-tech example of the effect of the tides on the solid planet. At CERN, the European laboratory for particle physics, near Geneva, subatomic particles are whirled at dizzying speed around a subterranean racetrack 26.7 kilometres in circumpherence. While cows graze peacefully in fields spanning the border between France and Switzerland, 100 metres or so below them the microscopic building blocks of matter are slammed together in collisions of unimaginable violence. The energy of motion of the incoming particles is converted into the mass-energy of new particles, which are conjured out of the vacuum like rabbits from a hat [10]. As the subatomic shrapnel speeds outwards from the collision point, it is detected by cathedral-sized detectors. It was in such collision debris, for instance, that the Higgs particle, the "quantum" of the Higgs field, responsible for endowing all other subatomic particles with their masses, was discovered in July 2012.

The Higgs was found with the Large Hadron Collider, which whirls beam of protons both ways around the underground ring at 99.9999991 per cent of the speed of light before slamming them into each other [11]. But the LHC occupies the circular tunnel previously used by another particle accelerator: the Large Electron-Positron Collider, which instead smacked together electrons and their antiparticles, positrons. And, it was while using the LEP in 1992, that physicists noticed something peculiar about the energy of the particle beams [12].

More than 3000 electromagnets distributed around the circular LEP tunnel constrained the electrons and positrons, continually bending their trajectories away from the straight-line trajectory their inertia wanted them to take. However, the LEP physicists noticed that, *twice every 25 hours*, the beams were drifted slightly from their path and back again. In order to keep the beams from wandering outside the giant ring, the physicists had to continually compensate for the drift by slowly increasing the energy of the particles, then reducing it again. The necessary change in energy of the beams was tiny – about a hundredth of a per cent.

What could possibly be causing the particle beams to drift periodically from their circular path? After the physicists had scratched their heads for a while, the penny finally dropped. The tides rise and fall *twice every 25 hours*. Incredible as it seemed, the effect observed at the LEP was connected to the tides.

Twice every 25 hours the rock into which the LEP ring was bored bulged upwards. This stretching of the rock caused the LEP to shrink. And twice every 25 hours the crust dropped back down, compressing the rock and expanding the LEP. The crust moved up and down by only 25 centimetres, the height of a hardback book, and this changed the circumpherence of the LEP by at most 1 millimetre [13]. Nevertheless, it was enough to require the energy of the circulating particles to be periodically adjusted by about 0.01 per cent lest they wander from the ring [14]

The effect was of course largest when the Moon was full or when there was a new Moon - times when the Sun and the Moon are aligned and reinforce each other's effect on the Earth. It is hard to imagine a more high-tech manifestation of the effect of the tides on the solid Earth [15].

Moonquakes

But the rocks on the Earth are not alone in experiencing tidal stretching and squeezing. So too do the rocks on the Moon. In fact, the tides the Earth pulls on the Moon are much bigger than the tides the Moon pulls on the Earth because the Earth is about 81 times more massive than the Moon. Naïvely, it might be expected that the tides on the Moon are also 81 times bigger than on the Earth. But, remember, tides are not caused merely by gravity but by differences in gravity. And the Moon is only about a quarter the diameter of the Earth, which means it has only a quarter of the length span over which such a difference in gravity can manifest itself. The tidal stretching of the Moon by the Earth is therefore not 81 times bigger than the tidal stretching of the Earth by the Moon but only a quarter of that figure, or about 20 times [16]. Nevertheless, it is enough to stretch the Moon by about 10 metres.

Most people think the Moon is stone-cold dead, its grey, crater-strewn desolation untouched by the hand of change. However, the tidal stretching and squeezing of the Moon means that the Moon is not quite the inert world of popular imagination. In fact, since well before the invention of the telescope, people have reported seeing strange lights on the Moon at a rate of once every few months. One of the earliest sightings, for instance, was made on 18 June 1178 by five monks at Canterbury Cathedral who reported an explosion on the Moon. The mysterious lights, known as Transient Lunar Phenomena, are one of the greatest mysteries of the Moon.

TLPs that have been observed in the age of the telescope share a number of common features. They are localised, slightly bigger than the resolution limit of the human eye, implying they cover an area of at least 1 square kilometre. They last from a minute to a few hours. They involve a brightening, dimming or even blurring of the lunar surface. And, before they disappear, they sometimes change colour to a ruby red.

For a long time many astronomers believed that TLPs are "in the eye of the beholder" and not a phenomenon intrinsic to the Moon. But, in 2002, Arlin Crotts of Columbia University in New York sifted through the records of 1500 historical sightings. He discovered that most reliable TLPs occur at just six locations on the Moon – half at the 45 kilometre-diameter Aristarchus crater and a quarter at the 100 kilometre Plato crater [17].

The six locations are all places where the lunar crust has been violently fractured, either by relatively recent asteroid or comet impacts - within the last few hundred millions of years - or by the flurry of mega-impacts which occurred 3.8 billion years ago and caused lava to well out of the Moon's interior and form the lunar "seas", or Maria [18].

Seismometers left on the Moon by all but one of the Apollo missions have recorded several hundred "moonquakes", which, not surprisingly, are more common when the tidal effect of the Earth is greatest. Most have been located along the boundaries of the mare basins where the rock is most fractured. Not only that but Apollo 15, Apollo 16 and the Lunar Prospector probe, which orbited the Moon in 1998, all detected occasional bursts of radioactive radon-222 gas on the surface, and these were associated exclusively with the six TLP sites.

Radon-222 is a decay product of uranium, which is distributed throughout the rocks of the Moon's interior. Crotts therefore speculates that TLPs occur when moonquakes cause gas from deep in the lunar interior to vent through fissures and cracks. The gas often builds up pressure before bursting its plug of lunar soil, or "regolith", and exploding into space.

Crotts thinks a mere half a tonne of gas escaping into the vacuum would be enough to puncture the regolith, creating a cloud a few kilometres across that persists for between 5 and 10 minutes. The gas cloud either plunges the surface below into shadow or shines brightly because the dust grains it contains reflect more light when scattered through the vacuum than when clumped together on the surface. It is also possible that friction between the grains separates out negative and positive electrical charge, eventually triggering a "breakdown discharge" like lightning which energises the atoms of the gas, causing then to emit characteristic red light.

According to Crotts' calculations, the periodic tidal stretching and squeezing of the Moon by the Earth's gravity grinds up about 100,000 tonnes of rock a year – a mass equivalent to one aircraft carrier. And, from this, is released about 100 tonnes of gas.

None of this speculation is academic because there are plans for humans to go back to the Moon. Apollo 18, which was cancelled before its launch, was actually scheduled to land at one of the principal TLP sites. If a

TLP happened at a landing site it would be very dangerous for any astronauts. Imagine the scene:

20 July 2025, Aristarchus crater, lunar nearside: NASA's Altair 2 landing craft touched down only hours ago and astronauts are now walking on the Moon again for the first time in more than half a century. Suddenly, a large area of the crater floor begins to convulse and a titanic explosion of gas sends dust fountaining up into the vacuum. Knocked off their feet by the blast, the astronauts look back towards their landing craft. But it is no longer there. It has disappeared in a roiling cloud of silver dust.

If Crotts is right, the Moon is a more dangerous place for humans than anyone suspected. And it is entirely a consequence of Newton's theory of tides.

Since moonquakes can be triggered by tides pulled by the Earth in the Moon's rock, it is natural to wonder whether terrestrial earthquakes are triggered by tides pulled by the Moon in the Earth's rock. It seems, however, that they are not – at least not the big earthquakes. Interestingly, however, the aftershocks of the devastating earthquake which struck Christchurch in New Zealand on 22 February 2011 were found to be correlated with the location of the Moon in the sky [19]. A possible, though currently hand-waving, reason for this may be that the big quake left the rock in an unstable state, ready to move again if nudged by even the slightest force.

Tidal spin-down of the Moon

The tides on the Earth and Moon do more than simply distort the shape of each body, causing the rise and fall of the seas on Earth and moonquakes on the Moon. They have profound consequences for the system of the Earth and Moon as a whole. Once upon a time, for instance, the Moon spun faster than it does today. Its rotation was slowed by the tidal interaction with the Earth.

This is how it happened… When the Moon was spinning faster, the bulge pulled in the Moon by the Earth was dragged around with the rotation of the Moon so that the bulge no longer quite faced the Earth. The Earth's gravity pulled back on this receding bulge and the effect of this was to brake the rotation of the Moon. Eventually, a point was reached when the Moon was spinning so slowly that it was turning only once on its axis during each orbit of the Earth.

This is the case today. One face of the Moon - the lunar nearside - perpetually points towards the Earth while the lunar far side perpetually faces away from the Earth. In fact, the far side of the Moon was seen for the first time only on 7 October 1959 when the Soviet "Luna 3" space probe flew over it [20].

Because of the Moon's "synchronous" rotation, the tidal bulge caused by the pull of the Earth points perpetually towards the Earth. Since the bulge is no longer being dragged around by the Moon's rotation, the Earth's gravity, which formerly pulled back on the receding bulge, braking the Moon's spin, no longer has any effect on the Moon's rotation. In fact, the Moon's rotation has been "locked" in this state ever since the moment the Moon's rotation period first matched its orbital period.

Tidal spin-down of the Earth

But the Moon is not alone in having its rotation slowed by a tidal interaction. The rotation of the Earth is also slowed. The effect is less dramatic than in the case of the Moon because the Earth, being a far heavier flywheel, is more resistant to having its motion changed. But imagine the bulge created in the ocean on the side of the Earth facing the Moon. Because the Earth is spinning quickly, the bulge tends to get ahead of the line joining the Earth to the Moon [21]. The Moon's gravity pulls back on this receding bulge, braking the Earth's rotation.

The unavoidable conclusion is that the Earth must have spun faster in the past. And evidence supports this. It comes from corals. Such marine organisms, most commonly found in tropical seas, secrete calcium carbonate to form a hard skeleton. The daily and seasonal growth of the skeletons creates regular bands in much the same way that the yearly growth of trees creates tree rings. By counting the bands, it is possible to determine how many days there are in a year. The evidence from fossil corals which lived about 350 million years ago is that at the time there were about 385 days in a year. Since the year – the time taken for the Earth to circle the Sun – is unlikely to have been different, it must mean that the day 350 million years ago was less than 23 hours in length [22].

A reduction of just over an hour in the day in 350 million years indicates a relatively modest slowing down of the Earth's spin. But the slowdown is remorseless and ongoing. We know, for instance, that the day today – if that makes sense - is longer than the day of a century ago by about 1.7 milliseconds. In fact, we can be sure that for the past 2500 years the length of the day has been increasing at 1.7 milliseconds per century. The evidence, remarkably, comes from Babylonian clay tablets [23].

Babylonian astrologers used such tablets to record total eclipses of the Sun, when the disc of the Moon slides across the solar disc, plunging the world into darkness in the middle of the day. Most of the tablets were unearthed in the 19th century by peasants looking for bricks and sold to antique collectors in Baghdad, 85 kilometres to the north of the ancient city of Babylon. From there they found their way to the British Museum in London, which boasts an almost complete collection. Many of the clay tablets record the precise times of the total eclipses.

But the timings pose a puzzle.

In 136 BC, for instance, an astrologer recorded that, at 8.45am on the morning of 15 April, Babylon was plunged into darkness when the Moon passed in front of the Sun. There is no reason to doubt the astrologer's account. However, if present-day astronomers use a computer to wind back the movements of the Earth, Moon and Sun, like a movie in reverse, they find something puzzling. The total eclipse of 15 April 136 BC should not have been visible from Babylon. The Earth, Sun and Moon were simply not lined up in such a way to create a total eclipse. In fact, the "zone of totality" should have passed over the island of Mallorca, 48.8 degrees west of Babylon.

A difference of 48.8 degrees amounts one-eighth of a complete rotation of the Earth, or 3.25 hours. It seems, therefore, that, during the total eclipse of 15 April 136 BC, the Earth was one-eighth of a turn to the east of where it should have been. There is only one way to explain this. Over the past millennia, the Earth’s spin must have slowed down. Since 136 BC there have been about a million days, so, even if the day was only a fraction of a second longer back then, all those fractions of a second would have added up to explain the 3.25 hours discrepancy in the timing of the 136 BC total eclipse. In fact, the only way to make sense of the Babylonian eclipse records is if the day in 500 BC was about 1/20 of a second shorter than it is today, and that ever since it has been lengthening by 1.7 milliseconds per century.

It is amazing that marks scratched onto a clay tablet by an ancient civilisation can yield such super-precise astronomical information. The key to the phenomenal accuracy of the techniques is the astronomical coincidence that the Moon and Sun appear the same size in the sky. This leads to an eclipse "track" which is at most 250 kilometres wide, making total eclipses at any given spot on Earth very rare indeed. So if someone in antiquity recorded an eclipse at a particular location, it is not necessary for astronomers today to know a precise date in order to identify it. Knowing the year to with 20 years either way is usually good enough.

There is twist to this story. Subtle changes in the shapes of the orbits of artificial satellites caused by the Earth's tidal bulge imply that tidal breaking of the Earth should in fact be lengthening the day by 2.3 milliseconds per century not 1.7 milliseconds. Something else must be affecting the Earth’s spin. The something else turns out to be connected with the last ice age, which finished about 13,000 years ago.

During the ice age, the tremendous weight of the ice sheets bore down on the Earth, flattening the planet slightly at the poles and making it fatter. At the end of the ice age, however, when the ice began to melt, the land began slowly to rise. This process of "post- glacial rebound" is still going on today. Its effect is to make the Earth more circular and less fat. Consequently, like an ice skater pulling in their arms, the planet spins ever faster. The effect causes a shortening of the day by between 0.5 and 0.6 milliseconds per century, and explains why the day is currently lengthening not by 2.3 milliseconds but by only 1.7 milliseconds per century.

In the long-term, the braking effect of the Moon on the Earth's rotation might be expected to slow it to the point at which one face of the Earth perpetually faces the Moon just as today one face of the Moon perpetually faces the Earth. If this were to happen, the Moon would be invisible from one half of the planet just as the Earth is today invisible from one half of the Moon. Calculations show that such a "locking" of the Earth's rotation will occur when the Earth's spin has slowed so much that it turns on its axis once every 47 present-day days.

It will take more than 10 billion years for the Earth's rotation to slow down this much. By that time, however, the Sun will have run out of hydrogen fuel in its core, swelled into a red giant and either incinerated or swallowed both the Earth and Moon. The truth is therefore that the Earth's rotation will never become locked liked that of the Moon. There is simply not enough time available. Nevertheless, there are systems out in space where this has indeed happened. Stars whirling around each other in close "binaries" are expected to have their rotations tidally locked, with each star perpetually showing its partner the same face. And, closer to home, Pluto and its moon, Charon, are both tidally locked.

The fleeing Moon

The tidal effect of the Moon on the Earth slows the rotation of the Earth, reducing its "angular momentum". There is a fundamental edict of physics known as the "conservation of angular momentum", which says that the angular momentum of an isolated, or "closed", system can never change. So, if the angular momentum of the Earth goes down, the angular momentum of something else must go up to exactly compensate for it. That something else can only be the Moon.

It happens this way… The Moon’s gravity creates two bulges in the ocean - on opposite sides of the Earth – but the one closest to the Moon is the one with the strongest and most significant gravitational pull on the Moon. Recall that this tidal bulge tends to lead the Moon its orbit because the Earth is rotating much faster than the Moon is orbiting the Earth. Its gravity therefore tends to drag the Moon along in its orbit, speeding it up.

Now, recall that the Earth’s gravity at the distance of the Moon is exactly that required to bend the trajectory of a body moving at the Moon’s speed into the closed orbit we see. If the Moon speeds up, therefore, it finds itself travelling too fast for its orbital distance and is effectively flung outwards. Outwards – that is, farther from the Earth - is “up”, and, as we know, when an object such as a ball is thrown upwards, gravity slows it down. So, paradoxically, the Moon, which is speeded up by its tidal interaction with the Earth, ends up moving more slowly in an orbit farther from the Earth. And this does indeed increase its angular momentum, as required [24].

This is not just theoretical. The manned American spacecraft, Apollo 11, 14 and 15, and the unmanned Russian rovers, Lunokhod 1 and 2, all left reflectors on the lunar surface. The fist-sized mirrors, known as "corner-cubes", have the property that they reflect back light in exactly the direction it comes from. It is possible to fire a laser beam at the Moon, bounce it off a corner-cube reflector, and time how long it takes for the beam to return to Earth. Knowing the speed of light, it is a simple matter to deduce the distance of the Moon [25].

The experiments reveal that every year the one-way journey of a laser beam gets longer by 3.8 centimetres [26]. In other words, the Moon is receding from the Earth by a thumb’s length every 12 months. If you live to be 70, the Moon will recede by the length of a family car during your lifetime.

The visibility of total eclipses

The fact that the Moon is moving away from the Earth at 3.8 centimetres a year obviously tells us it was closer in the past. And this has implications for the visibility of total eclipses, arguably the most spectacular of natural phenomena.

As mentioned before, a total eclipse occurs when the Moon passes between the Earth and the Sun, blotting out the solar disc and bringing midnight in the middle of the day. Such an event is possible, however, only because of a cosmic coincidence. Although the Sun is about 400 times bigger than the Moon, it also about 400 times further away. This means the two bodies appear the same size in the sky. This is a very fortunate circumstance for us. Even though there are 170-odd moons in the Solar System, there is not another planetary surface from which such a perfect eclipse can be seen. But we are not simply lucky to be in the right place, we are also lucky to be alive at the right time.

Because the Moon is moving away from the Earth, in the past it appeared bigger and in the future it will appear smaller. It turns out that there were no total eclipse before about 150 million years ago and there will be no more after another 150 million years. Total eclipses have been possible for only a few per cent of the lifespan of the Earth. For most of the reign of the dinosaurs there were no total eclipses.

The fact that the Moon is moving away from the Earth and was closer in the past ties also ties in neatly with an idea about the birth of the Moon.

The planet that stalked the Earth

The Moon is unusually large compared to the Earth - about a quarter of its diameter. All other moons in the Solar System are tiny compared to their parent planets. Granted, Pluto has an even bigger moon relative to its size but, as pointed out earlier, Pluto has not been considered a fully-fledged planet since 2006.

The unusual size of the Moon is a hint that it had an unusual origin. In fact, it is believed that shortly after the birth of the Earth 4.55 billion years ago, the planet was struck by a Mars-mass body. The titanic collision with "Theia" liquefied the exterior of the Earth, splashing mantle material into space to form a ring, not unlike the rings seen today around the gas giant planets of our Solar System. The material of the ring congealed quickly into the Moon - but orbiting about 10 times closer than it does today. Thereafter, the Moon began moving away from the Earth.

The key evidence for this "Big Splash" theory of the Moon's origin came from NASA's Apollo programme, which found that the Moon is made of material suspiciously like the Earth's exterior "mantle". Its rocks are also drier than the driest terrestrial rocks, indicating that intense heat once drove out all their water. The problem has been that, for a Mars-mass object to create the Moon and not shatter the Earth, it must have made a glancing blow at a very low speed. However, bodies orbiting the Sun both inside and outside the Earth's orbit are moving far too fast.

The Big Splash theory can be made to work, however, if Theia actually shared the same orbit as the Earth. This could have happened if it formed from rubble that accumulated at a stable "Lagrange point", either 60° behind or 60° ahead of the Earth in its orbit around the Sun [27]. Today, similar asteroidal rubble can be seen orbiting the Sun 60° behind and 60° ahead of Jupiter, becalmed in a kind of gravitational Sargasso Sea. According to this twist on the Big Splash theory, Theia stalked the Earth for millions of years before being nudged into a catastrophic colliding orbit.

Recall that, while the gravity of a body weakens with the inverse-square of the distance from the body, the tidal force, which is due to differences in gravity, weakens as the inverse-cube of the distance. At the distance from the Earth at which the Moon formed – about 10 times closer than it is today – the tidal force it exerted on the Earth was therefore 10^3 = 1000 times greater than today. The Earth at the time, being still molten from its fiery birth, is unlikely to have had any oceans. But imagine if it had: twice daily the sea would have risen not by metres *but by kilometres*.

But the new-born Moon did not only exert a tidal effect on the Earth, the Earth exerted a tidal effect on the Moon. And that effect too was 1000 times bigger than today. In fact, the tidal braking of the Moon's rotation was so huge that it is probable that its rotation became locked very early on – perhaps within only 10 million years of its violent birth. Since the first microorganisms on Earth appeared much later, probably between 4 and 3.8 billion years ago, no living thing has ever looked up at the night sky and seen the far side of the Moon rotate into view.

The Moon was not always fleeing so fast

An interesting question is: Has the Moon always been receding from the Earth at 3.8 centimetres a year? In 2013, a team led by Matthew Huber of Purdue University in West Lafayette, Indiana, considered the situation 50 million years ago. They fed into a computer model that simulates tides data on ocean depths and the contours of the continents that existed at the time. They concluded that, 50 million years ago, the Moon was receding from the Earth at a slower rate, perhaps only half as fast [28]

The key is the North Atlantic Ocean, which today is wide enough for water to create a large tidal bulge, which can pull on the Moon, causing it to recede relatively quickly. About 50 million years ago, the Atlantic had not grown to its present size so the tidal bulge created by the Moon in the Atlantic was smaller and its effect on the Moon's recession was less marked. At the time, most of the Earth's tidal effect on the Moon in fact came from the Pacific Ocean.

This is yet another illustration of the complexity of the ocean tides. How big they are and how much they brake the Earth's rotation and the speed the recession of the Moon depends on the how easy it is for tidal bulges to move through the oceans. This is in turn depends on the arrangement of the continents, which is continually changing over geological time because of continental drift, more correctly known as "plate tectonics".

It is the long-term unpredictableness of plate tectonics that makes it hard to predict how long it will take for the Earth's spin to slow sufficiently that it perpetually presents one face to the Moon. It is possible to say only that this state, in which the Earth spins on its axis once every 47 present-day days and the Moon has receded to the point that it takes 47 days to orbit the Earth, will be achieved after *more than 10 billion years*. But, of course, as pointed out, this is totally hypothetical since the Sun will have evolved into a monstrous red giant 10,000 times as luminous as it is today and destroyed or at least disrupted the Earth-Moon system.

Tides have a final twist. Every day as the sea surges up beaches around the shorelines of the continents, countless pebbles are tumbled and smashed together. Friction between them generates heat-energy, which his lost forever. In fact, it is this friction which is ultimately responsible for slowing down the rotation of the Earth.

The tidal heating of the Earth is modest. If you wade into the sea, the sand and pebbles are not likely to scorch your feet. However, there is one place in the Solar System, where tidal heating is not modest at all: Jupiter's giant moon, Io, discovered by Galileo in 1609.

Pizza moon

It is 8 March 1979. NASA's Voyager 1 space probe has streaked through the Jupiter system faster than a speeding bullet. It is now heading towards a rendezvous with Saturn in autumn 1980. But, before the probe leaves the gas giant planet forever, the Voyager team orders its camera to point back the way the space probe has come and take a parting shot of Io. Navigation engineer Linda Morabito is the first to see the image after its 640 million kilometre journey back to Mission Control. When she does, her heart misses a beat. Spouting from the tiny crescent moon, silhouetted against the starry backdrop of space, is a phosphorescent plume of gas.

Morabito is the first human in history to see the super-volcanoes of Io. Over the next days, as the Voyager team pore over image-enhanced photos and thermal data, they spot a total of eight gigantic plumes, pumping matter hundreds of kilometres into space. Io turns out to be the most geologically active body in the Solar System, with more than 400 volcanoes. The vents that pepper the orange and yellow and brown of its pizza-like surface are reminiscent of the geysers of Yellowstone Park. In fact, strictly speaking, that is what they are: geysers not volcanoes. Lava from the moon's molten interior, instead of erupting directly, super-heats liquid sulphur dioxide just beneath the surface, converting it into gas which bursts from the vents exactly like the pressurised steam of a terrestrial geyser.

Every year, Io is pumps about 10,000 million tonnes of matter into space. As it falls back in the moon's low gravity, it coats the surface with sulphur just like the deposits around a Yellowstone fumarole. This is the origin of the satellite's pizza-like appearance. The lurid colours are simply the "phases" sulphur exhibits at different temperatures.

Jupiter, a whopping 318 times as massive as the Earth, is obviously the key to understanding Io's super-volcanoes. Io orbits about as far from the giant planet as the Moon is from Earth. But the giant planet's enormous gravity whirls the moon around not in 27 days like the Earth's satellite but in only 1.7 days. That gravity, acting on the tidal bulges of Io, long ago braked Io's rotation so that it orbits today with one face forever locked to its master. If, one day, people get to set foot on that face, what a view they will have, peering through the visors of their spacesuits with Jupiter and its whirling, multi-coloured cloud belts filling almost a quarter of the sky.

Because Io's rotation is "locked", the two bulges pulled in the moon by Jupiter point perpetually towards Jupiter and perpetually away from Jupiter. This means they do not travel through the rock of Io in the way that the tidal bulges on Earth move through the oceans. If such a process occurred on Io, it would stretch and squeeze the rock, over and over again, heating it by internal friction in much the same way that a rubber ball squeezed repeatedly is heated. Since such a process is not happening, however, it would appear there can be no tidal heating of Io by Jupiter.

But there is.

The key to the mystery of Io's heating is two of the other "Galilean" moons that orbit farther out from Jupiter than Io –Europa and Ganymede.

Ganymede is actually the largest moon in the Solar System, bigger even than the innermost planet Mercury. For every four circuits Io makes of Jupiter, Europa completes two and Ganymede one. Because of this, the two satellites line up periodically, reinforcing each other’s tug on Io. The effect is to yank Io, elongating its orbit. So Io swings in close to Jupiter and then flies back out again, repeatedly. And it is this, it turns out, is behind the prodigious heating of Io.

Yes, the tidal bulges of Io perpetually point towards Jupiter an away from Jupiter. However, when Io is at its closest to the giant planet, the tidal bulge is bigger than when Io is at its farthest from Jupiter. Up and down, up and down, the rock is stretched and squeezed. The process is so effective at warming the moon that the body in the Solar System currently generating most heat, pound for pound, is not the Sun [29]. It is Io.

The Jupiter-Io system, however, is not the only one in the Solar System in which a tidal interaction has resulted in two bodies orbiting each other with their rotations locked so that they perpetually show the same face to each other. There is also Pluto and its giant moon Charon.

The mystery of Pluto and Charon

The most notable thing about Charon is that it has half the diameter of Pluto. For a while this made Pluto the planet in the Solar System with the biggest satellite relative to its size. In 2006, however, it was stripped of its planetary status by the International Astronomical Union and demoted to the category of dwarf planet. It had been found to be merely one of the largest bodies in a swathe of tens of thousands of pieces of icy debris orbiting the Sun in the outer reaches of the Solar System.

The “Kuiper Belt” is composed of icy builders’ rubble left over from the birth of the planets, which could never form a planet because it was spread too thinly. It is the outer Solar System’s analogue of the Inner Solar System’s Asteroid Belt - rocky builders’ rubble left over from the formation of the planets, which was prevented from aggregating into a proper world by the gravity of Jupiter. The inner edge of the Kuiper Belt is near Neptune - about 30 times as far from the Sun as the Earth - whereas the outer edge is at about 50 times the Sun-Earth distance. Despite its name, the Kuiper Belt was actually predicted by a former Irish soldier and amateur astronomer called Kenneth Edgeworth in the 1943, and, by rights, should be called Edgeworth-Kuiper Belt.

Pluto fulfils the first two criteria of the IAU's 2006 definition of a planet: it orbits the Sun and is round. However, because it is accompanied by a large number of Kuiper Belt Objects, Pluto does not meet the IAU's third criterion that it should also have cleared its orbit of all other bodies.

On 14 July 2015, NASA's New Horizons sped like an express train through the Pluto-Charon system, skimming just 14,000 kilometres above what had been a planet when the space-probe had been launched a decade earlier but was now a mere dwarf planet. The shock to those back at Mission Control on Earth was that a world they had fully expected to be dead and inert, suspended in the deep-freeze of the outer Solar System, was in fact alive with nitrogen glaciers and mountains of water-ice pushing up towards the thin swirling clouds. Most surprisingly, the pink, heart-shaped region christened "Tombaugh Regio" after the discovered of Pluto, Clyde Tombaugh, was devoid of any craters, indicating that ice had spilled across it relatively recently, erasing any sign of the craters that peppered the rest of Pluto.

Where does the energy to drive all this unexpected activity come from? The interior of the Earth is heated by the radioactivity of uranium, thorium and potassium but such heating is believed to be insufficient to warm the interior of Pluto. And tidal heating by Charon is also ruled out since it is impossible in a system in which a moon is in a circular orbit and its rotation is locked to its parent planet. However, tidal heating is ruled out only if the capture of Charon took place at the birth of the Solar System much like the capture of the Moon by the Earth. If, instead, Charon was captured relatively recently – within the past half a billion years – tidal heating could have occurred as the system gradually approached the locked state we see it in today. Nobody whether this happened. The jury remains out.

Ocean moons

Tidal heating also has implications for the prospects of life – not on Io perhaps, which seems too inhospitable, but on Europa. Europa is tidally heated by the tug of Jupiter, Io and Ganymede. But, instead of being made of rock like Io, Europa is predominantly made of ice. The unavoidable conclusion is that the interior of Europa must have melted. It must contain liquid water.

A body containing liquid spins differently from a solid body. And the evidence from the way Europa spins is that, beneath a surface layer of ice 10 kilometres thick, there lies a 100 kilometre-deep ocean - the biggest ocean in the Solar System.

From afar, Europa looks like a snooker cue ball, its super-smooth surface the largest ice-rink in the Solar System. But from close-up, giant cracks in the ice come into view. The crazy paving-like pattern of the surface is reminiscent of sea ice in the Arctic Ocean, which breaks up in summer, floats about, then re-freezes in winter. This is yet further evidence of the existence of a sub-surface ocean.

A buried ocean, languishing in permanent sunless darkness, might not seem a likely place to find life. However, a key discovery made back on Earth has changed everything in the 1977. Using the submersible "Alvin", the American oceanographer Bob Ballard discovered "hydrothermal vents". Kilometres down on the sea floor, they gush superheated minerals into the ocean and support a thriving ecosystem, all in total darkness. At the bottom of the food chain are bacteria which get their energy not from oxygen but from sulphur compounds. At the top are giant "tube worms" the size of a forearm.

Given the fact that Europa is tidal heated, almost certainly there will be hydrothermal vents on its sea floor. It makes Europa the most likely place to find life in our Solar System. Currently, NASA is planning to send a space probe to the moon. Ideally, of course, a lander should be dropped onto Europa capable of drilling down through 10 kilometres of ice to the ocean. But this is way beyond current technical capabilities. Nevertheless, Jupiter Icy Moon Explorer (JUICE), planned for launch in 2022, may be able to exploit a recent discovery.

In 2013, the Hubble Space Telescope, currently in Earth orbit, detected jets of water spouting 200 kilometre into space from cracks in the Europan ice. They can be coming only from a sub-surface ocean. NASA scientists believe that, if they fly JUICE through these icy plumes and sample them, they may be able to detect Europan microorganisms.

Another moon with fountains spewing ice into space is Saturn's moon, Enceladus. At barely 500 kilometres across, nobody expected such a tiny moon to be active. But tidal stretching appears to have liquefied its interior. Enceladus may contain the smallest ocean in the Solar System. And, like the ocean of Europa, it may also contain life.

The fact that the Jovian and Saturnian moons are heated by the tidal interaction with their parent planets may also have implications for finding life elsewhere in our Galaxy. The reason is that Jupiter and Saturn are outside the "Habitable Zone" of the Sun. A planet in the Habitable Zone of its parent star is close enough to the star that water does not freeze and far enough away that water does not boil. Jupiter and Saturn are so far away from the Sun that water, essential for "life as we know it", should freeze. But, as can be seen in the case of Europa and Enceladus, this has not happened. Gas giant planets, many of which are larger than Jupiter, appear to be common around nearby stars. They might very well be orbited by moons bigger than Io and Europa and kept warm by tidal heating.

Precession of the equinoxes

The tides are not the only way that gravity affects the Earth through it being an extended rather than a point-like object. There is another way: the precession of the equinoxes.

The seasons occur because the spin axis of the Earth is tilted relative to the plane of its orbit around the Sun. Specifically, as already mentioned, the axes is tilted at 23.5 degrees to the vertical, which means the equator is also tilted at 23.5 degrees to the plane of the Earth's orbit. Summer in the northern hemisphere occurs when the northern hemisphere is tipped towards the Sun and winter when it is tipped away. And summer and winter in the southern hemisphere occur when the southern hemisphere is tipped toward and away from the Sun.

Spring and autumn are of course the in-between seasons. However, astronomers like to be a lot more precise than that. They say that spring an autumn occur when the plane of the Earth's orbit – known as the "ecliptic" - crosses the plane of the equator. These times during the Earth's journey around the Sun are known as the spring and autumn equinoxes.

The ecliptic was recognised as special even in antiquity and the stars along it were grouped into 12 constellations, corresponding to the 12 "signs of the Zodiac". In 2000 BC, when the Babylonians created the system, the spring equinox was in the direction of Aries. However, the spring equinox moves through the signs of the Zodiac at about one sign every 2000 years. At the time of Christ, the spring equinox was in the direction of Pisces. Today, the spring equinox is beginning to move into Aquarius – it will officially get there in AD 2600 – which is why people talk of the "coming of the Age of Aquarius."

This peculiar movement of the Zodiac constellations around the night sky is known as the precession of the equinoxes. It is the third of the Earth's motions – after the planet's rotation on its axis and the planet's circling of the Sun – and it is the most mysterious. Its discovery is credited Hipparchus, a Greek who lived and worked on the Mediterranean island of Rhodes and who is often described as "the greatest astronomer of antiquity.

In 129 BC, when Hipparchus was compiling the star catalogue for which made him famous, he noticed an odd thing: the positions of the stars did not match up with the Babylonian measurements. Furthermore, the stars seemed to have shifted their positions in a systematic way. Hipparchus was led to speculate that it was not the stars themselves that had moved but the Earth.

Using Babylonian observations, Hipparchus accurately estimated the speed at which the positions of stars shifted. It seemed that the axis of the Earth changed its orientation in space by about 1 degree every 72 years. This "precession" causes the planet's spin axis – still maintained at 23.5^{o} to the vertical – to rotate about the vertical once every 26,000 years. Because of this motion, the star immediately above the north pole of the Earth's spin axis – the pole star – is not the same one that the Egyptians saw. We see Polaris in the constellation of Ursa Minor, the Little Bear. However, 5000 years ago the Egyptians saw Thuban, a relatively faint star in the constellation Draco the Dragon.

The wobble, or precesssion, of the Earth's spin axis is behind the "precession of the equinoxes". No one had ever guessed at a reason for this motion. Until Newton.

Newton realised that the shape of the Earth is distorted not only by the gravitational pull of the Moon and Sun but by its own rotation. This causes material on the equator to be flying around at 1670 kilometres an hour. The Earth's gravity has difficulty providing the centripetal force necessary to keep stuff moving around at such a tremendous speed. Consequently, it flies outards. In fact, the Earth bulges outwards by about 23 kilometres more than it would if the planet was a perfect sphere.

Newton realised that the gravitational pull of the Sun and the Moon on this "equatorial bulge" causes the spinning Earth to wobble like a top. In fact, the direction in which the spin axis points moves in a circle. From the forces acting on the Earth's equatorial bulge, Newton calculated that this precession would take 26,000 years, precisely as observed.

Newton's law of universal gravity, it turns out, is a gift that keeps on giving. And there is yet more.

In proving the inverse-square law of gravity, Newton assumed that the Sun pulls on each planet as if the Sun and planets are point-like masses. He assumed the Earth pulls on the Moon as if the Earth and Moon are point-like masses. But the Earth and Moon are extended bodies, and this is at the root of new phenomena such as the tides and precession of the equinoxes.

But Newton made another approximation to crank out predictions from his theory of gravity. He assumed that the Sun alone pulls on the Earth, and the Earth alone pulls on the Moon. The breakdown of this assumption can be seen in the case of the tides, where both the Moon *and* the Sun affect the Earth. And this is a general feature of the real world: bodies are pulled on by more than one other body. This not only leads to bodies like planets not moving in exact elliptical orbits but to the possibility of deducing from the perturbed motion of known bodies the existence of *new bodies*.

[1] The word *bore* derives from the Old Norse word *bára*, meaning "wave" or "swell".
[2] The bore can be as much as 7.5 metres high and reach a speed of 27 kilometres an hour.
[3] "Caesar in Britain. Heavy Damage to the Fleet", *History of the Gallic Wars* by Julius Caesar.
[4] "A concise history of the theories of tides, precession-nutation and polar motion (from antiquity to 1950)" by Martin Ekman, 1993; http://www.afhalifax.ca/magazine/wp-content/sciences/vignettes/supernova/nature/marees/histoiremarees.pdf
[5] The tidal force on the ocean farthest from the Moon is slightly smaller than on the ocean nearest the Moon by a factor of about $(60/62)^2 = 0.94$ because the ocean there, rather than being 60 Earth radii from the Moon is 62 Earth radii from the Moon. Consequently, the tildal bulge is slightly smaller.
[6] From the fact that the tides pulled by the Moon are about twice as big as those pulled by the Moon, Newton was able to deduce that the average density of the Moon is about twice that of the Sun. His logic is as follows… The tidal force exerted by a body depends on its mass. Tidal forces are also due to *differences in gravity* so they weaken not according to an inverse-square law but *an inverse-cube law*. The tidal force exerted by a mass *m* at a

distance *r* is, therefore, $\sim m/r^3$. But $m \sim \rho d^3$,where ρ is its average density and *d* is its diameter. *d* is just rθ, where θ is the angle subtended by the body in the sky. Putting all this together implies that the tidal force $\sim \rho\ \theta^3$. But the angular size of the Moon and Sun, by a cosmic coincidence, are almost the same – it is why the Moon can exactly blot out the Sun during a total eclipse. Therefore the Moon and Sun exert a tidal effect *in proportion to their densities* – a surprising result. Since the Moon pulls tides twice as big as the Sun, it follows that it must have twice the average density of the Sun.

[7] The plane of the Moon's orbit is inclined to the Earth's equator, varying between 18.28 - 28.58 degrees of the equatorial plane.

[8] To be precise, maximum bores occur one to three days after new and full moons.

[9] 'Note on Tides in Wells' by Chaim Leib Pekeris (*Travaux de l'Association Internationale de Géodésie*, Paris, vol 16, 1940).

[10] In 1905, Albert Einstein discovered that mass is simply a super-compact form of energy (His formula $E = mc^2$ describes the exact connection, with *c* representing the speed of light). According to the law of conservation of energy, energy cannot be created or destroyed, only converted from one form to another. This means that the energy of motion (kinetic energy) of colliding subatomic particles can be converted into mass-energy of new particles. This, in a nutshell, is how particle colliders such as the one at CERN work.

[11] Technically, the protons have an energy of 7 teraelectonvolts (TeV), giving a total collision energy of 14 TeV. At 99.9999991 per cent of the speed of light, they travel around the CERN ring 11,000 times a second. Their "Lorentz factor", γ, is about 7500, which means they are 7500 more massive than at protons at rest. This is an effect of Einstein's special theory of relativity, which ensures massive bodies become ever more massive and ever harder to push as they approach the speed of light, so that the speed of light is forever unreachable (See chapter 5). Although the LHC protons travel within a mere 3 metres per second of the speed of light – the speed of a

jogger - boosting their velocity by that amount would require an infinite amount of energy.

[12] Every subatomic particle has an antimatter twin with opposite properties such as electric charge and quantum “spin”. The antiparticle of the negatively charged electron is the positively charged positron.

[13] “Effects of terrestrial tides on the LEP beam energy” by L. Arnaudon et al (*CERN SL*/94-07 (BI) https://jwenning.web.cern.ch/jwenning/documents/EnergyCal/tide_slrep.pdf

[14] To keep a body of mass, *m*, moving in a circle of radius, *r*, at a velocity, *v*, requires a centrally directed, “centripetal force”, $F = mv^2/r$ (See chapter 1). If the radius of the ring gets bigger, the force, *F*, exerted by the LEP magnets, which is constant, is too big to keep the particles travelling around the larger circle. Unless v^2, which is related to the energy of the particles, goes up in the same proportion. On the other hand, if the radius of the ring gets smaller, the force, *F*, exerted by the magnets is too small to keep the particles travelling around the smaller circle. Unless the energy of the particles goes down in the same proportion.

[15] The tidal effect on CERN’s accelerator ring is not the only effect that has been observed by the laboratory’s physicists. Every day, at very particular times, the energy of the beams has to be corrected. It took the physicists many months to discover why. Bizarrely, it was the fast TGV train linking Geneva and Paris. As it passed close to the LEP ring, it released a lot of electrical energy into the ground which perturbed the particle beams.

[16] The same logic predicted that the tidal forces on the Mediterranean are less than half those on the Atlantic because the Mediterranean is on average less than half the Atlantic’s depth.

[17] "Transient Lunar Phenomena: Regularity and Reality" by Arlin Crotts (http://xxx.lanl.gov/PS_cache/arxiv/pdf/0706/0706.3947v1.pdf).
"Lunar Outgassing, Transient Phenomena and the Return to the Moon, I: Existing Data" by Arlin Crotts (http://xxx.lanl.gov/PS_cache/arxiv/pdf/0706/0706.3949v1.pdf).

"Lunar Outgassing, Transient Phenomena and the Return to the Moon, II: Predictions of Interaction between Outgassing and Regolith" by Arlin Crotts and Cameron Hummels
(http://xxx.lanl.gov/PS_cache/arxiv/pdf/0706/0706.3952v1.pdf).
"Lunar Outgassing, Transient Phenomena and the Return to the Moon, III: Observational and Experimental Techniques" by Arlin Crotts
(http://xxx.lanl.gov/PS_cache/arxiv/pdf/0706/0706.3954v1.pdf)
26 March 2008
"Does the Moon have a volcanic surprise in store?" by Marcus Chown (*New Scientist*, 26 March 2008)
[18] The creation of the Mare basins is associated with the Late Heavy Bombardment. This is believed to have happened when Jupiter and Saturn, in moving to their present locations, briefly entered a 2:1 resonance in which for every two orbits Jupiter made around the Sun Saturn circled just once. This periodically brought the two planets close together, boosting their gravitational effect on other bodies. Like a child periodically pushed on a swing that gets ever higher, small bodies such as the rocky asteroids were pushed ever more from their orbits, and plunged into the inner Solar System, where they bombarded the inner planets such as the Earth and Moon.
[19] "Correlations between solid tides and worldwide earthquakes MS ≥ 7.0 since 1900" by L. Chen et al (*Natural Hazards & Earth System Science*, vol 12, p 587, 2012).
[20] Actually, because of a wobble caused in the motion of the Moon known as "libration" and the fact we see the Moon from different directions depending where we are on the planet – an effect known as "parallax" - we see about 59 per cent of the lunar surface.
[21] The tidal bulge makes an angle of 3 degrees with the Moon, so there is a 3/360 hours X 24 hours = 12 minutes difference between the time a high tide is expected to arrive and the time it actually arrives.
[22] "Fact or Fiction: The Days (and Nights) Are Getting Longer" by Adam Hadhazy (*Scientific American*, 14 June, 2010).

[23] "In the shadow of the Moon" by Marcus Chown (*New Scientist*, 30 January 1999).

[24] The angular momentum of a point mass, *m*, is defined as its linear momentum, *mv*, multiplied by the distance, *r*, from the centre of rotation. Since the orbital velocity of a body at a distance, *r*, from the Earth is proportional to $1/r^{1/2}$, this means the angular momentum is proportional to $r \times 1/r^{1/2} = r^{1/2}$. Therefore, the angular momentum of the Moon does indeed go up as it recedes from the Earth.

[25] The Lunokhod 2 reflector works occasionally but the one on Lunokhod 1 was lost for almost 40 years. However, recently, the Lunar Reconnaissance Observer probe imaged the landing site. The coordinates were passed to scientists in New Mexico. And, remarkably, they fired a pulse of laser light at the landing site and, on 22 April 2010, were stunned to receive a return burst of 2000 particles of light, or "photons". With four, and possibly five, five corner-cubes now in action it will be possible to observe not only the recession of the Moon but changes in its shape as it is tidally stretched and squeezed by the Earth.

[26] "Lunar Laser Ranging: A Continuing Legacy of the Apollo Program" by J. O. Dickey et al (*Science*, vol 265, p 482, 1994).

[27] In a system of two large bodies bound together by gravity, the Lagrange points are locations at which the combined gravitational pull of the two bodies provides precisely the centripetal force (see chapter 1) required to orbit with them. There are five such points, which are abeled L1 to L5.

[28] "Tidal dissipation in the early Eocene and implications for ocean mixing" by J. Green and Matthew Huber (*Geophysical Research Letters*, vol 40, 2013).

[29] The Sun is actually using just about the most inefficient nuclear reaction imaginable. It is turning "nuclei" of the lightest element, hydrogen, into nuclei of the next heaviest, helium. Hydrogen consists of 1 nuclear lego brick and helium 4, so "hydrogen-burning" is a multi-step process. The first step is the "fusion" of two hydrogen nuclei, or protons. However, on average, it takes two protons in the Sun 10 billion years to meet each other and stick. This is the reason Sun will take about 10 billion years to burn its hydrogen fuel – it is

about half way through its life – and there has been sufficient time for the evolution of complex life like us. The Sun is so inefficient at generating heat that, if you were to take your stomach and a piece of the core of the Sun the same size and shape as your stomach, your stomach would generate more heat. You might then ask: How come the Sun is so hot? The answer is that the Sun does not simply contain one chunk of matter the size and shape of your stomach; it contains countless quadrillion chunks, all stacked together.

Further reading

"The Severn Bore: A natural wonder of the world" http://www.severn-bore.co.uk/

"A concise history of the theories of tides, precession-nutation and polar motion (from antiquity to 1950)" by Martin Ekman, 1993; http://www.afhalifax.ca/magazine/wp-content/sciences/vignettes/supernova/nature/marees/histoiremarees.pdf

The Physical Universe by Frank Shu (University Science Books, Mill Valley, 1982).

"Tidal Misconceptions" by Donald Simanek (https://www.lhup.edu/~dsimanek/scenario/tides.htm)