Tides – Earth, Moon, planets and beyond

The Earth is within the Moon's "gravity gradient" - the way the gravity from the Moon varies in space - and this basic mechanism has wider application elsewhere. But before looking further afield, how useful is this simple theory for predicting the actual tides in the sea?

It does explain roughly how big the tides are, and roughly how often we can expect them to be. But this picture is too simple to apply in practice.

In principle, the tidal bulges would stay put opposite the Moon while the Earth rotates on its own axis underneath. Also, as the Moon completes one circuit round the Earth, which is tilted on its axis, the bulges would also appear to sweep back and forth in a north/south direction across the tropics. On average, the Moon reaches its highest point over a given spot every 24.84 hours, so a bulge should go past every 12 hours and 25 minutes. (The smaller bulges caused by the Sun should pass every 12 hours.)

But seawater is viscous, and the oceans are not deep enough to allow disturbances to travel as quickly as that. In any case, the continents and the ocean basins interfere. In shallow bays and estuaries, local resonances are set up and have a considerable effect. It all becomes very complicated. Nevertheless, in many places the dominating frequency of the tide is once every 12 hours 25 minutes.

Earth tide

There is also an Earth tide. The body of the Earth is fairly elastic, and the outer part of its core is liquid. It all duly responds to the Moon's gravity gradient. The size and position of Earth tide bulges turn out to be quite close to what a straightforward interaction with the Moon predicts. Sometimes the actual movements are counteracted by the weight of contrary marine tides in the ocean above. Movement occurs sideways as well as vertically, but the sideway movement is several times smaller. The classical theory of Earth tides was not developed until 1905.

Volcanologists can use the movements from the predicted Earth tide when calibrating their instruments. Some sensitive engineering projects have to allow for Earth tides, for example, the 8.6 km diameter Large Hadron Collider at CERN.

Tidal acceleration

As the Earth rotates on it axis, one of the ocean tidal bulges always keeps ahead of the point directly below the Moon. The Moon pulls back on the bulge, acting as a giant brake. The bulge, in turn, gives the Moon an extra tug in the direction of its orbit around the Earth. This process is called tidal acceleration.

Just as a brake dissipates energy by heating up, the tides dissipate energy too. The estimated average rate of dissipation is 3750 gigawatts. Water turbulence accounts for 98% of this, particularly near the seabed in shallower areas. The remaining dissipation arises from friction inside the Earth itself.

Because of the braking action, the rotation of the Earth about its own axis is slowing down. The Moon also picks up a little energy from the Earth (amounting to about 1/30th of energy lost by tidal dissipation). The speed of the Moon in its orbit actually decreases, but it also moves further away. Its kinetic energy decreases, but its potential energy increases even more.

[Techie bit: Angular momentum is conserved. Because the Moon is further away, the moment of inertia of the Earth-Moon system about its centre of mass (the barycentre) increases. The angular velocity of the system does decrease slightly, but the net effect is for the angular momentum about the barycentre to increase. This increase is at the expense of the angular momentum lost by the Earth as its rotation about its own axis slows down.]

These processes have been going on for a long time. The geological record from 620 million years ago shows that the solar day was then around 22 hours, with about 400 days in a year. There were just over 13 full moons per year, compared with 12.37 now.

Currently the Moon is receding at 38.14 millimetres a year. The length of the day is increasing by 1.7 milliseconds a century. (It would be greater than this, at 2.3 milliseconds a century, but for a contrary speeding-up effect. The Earth is changing shape as the polar diameter increases following the Ice Ages – the so-called 'post-glacial rebound'. The result is analogous to a rotating ice-skater who speeds up when she raises her arms above her head.)

Tidal locking

Just as the Moon is now slowing down the axial rotation of the Earth, in times gone by the Earth was slowing down the axial rotation of the Moon. Because the Earth is so much bigger, the effect on the Moon was more marked. The Moon's rotation has now slowed so much that it spins just once in the time it takes to revolve around the Earth. Because of this synchronous rotation the Moon always shows us the same side. Its tidal bulges do not move around on it, and it is said to be tidally locked.

The larger planetary moons are all tidally locked, except for Saturn's satellite Hyperion. This rotates chaotically, from a combination of factors – eccentric orbit, highly irregular shape, and gravity from the large moon Titan.

Pluto has a relatively large moon, Charon, in a close orbit. Not only is Charon tidally locked to Pluto, but Pluto is locked to Charon. In effect they rotate around each other, as if joined by a rod connected to points on the two surfaces.

It used to be thought that Mercury was tidally locked to the Sun, but space probes show that a resonance has been achieved, caused by Mercury's eccentric orbit. Mercury is now known to rotate 3 times on its axis for every 2 times it goes around the Sun.

A reversal of roles was discovered in the star system Tau Boötis. It is a binary, and the primary star is slightly bigger than the Sun. The secondary is a distant red dwarf, which takes thousands of years to go round it, and has little influence. However, an extra-solar planet with four times the mass of Jupiter also goes round the primary, in a very close, eccentric orbit. It has tidally locked the star, and the primary rotates every 79.5 hours on its own axis, exactly matching the orbital period of its planet.

Io's volcanos

Jupiter's moons Io, Europa and Ganymede have orbital periods which are fixed in a 1:2:4 ratio, owing to a gravitational effect called Laplace resonance. The tides raised on Jupiter by the innermost moon, Io, should cause Io to move further away, but the resonance does not allow this to happen. Io's own rotation is tidally locked by Jupiter. However, Io has an eccentric orbit, and as it goes round Jupiter there is some variation in the size and position of the tidal bulges which Io experiences. Normally this eccentricity would be smoothed out, but again it is countered by the resonance.

In practice there is an enormous difference between the heights of the bulges on Io as it makes its closest and furthest approaches to Jupiter. This difference may be 100 metres. The consequent internal heating leads to violent geological activity. Only one publication had previously speculated on this possibility, and most of the astronomical community was amazed when Voyager 1 discovered volcanoes on Io in 1979.

Tidal accretion

White dwarfs are stars at a final stage in stellar evolution. Typically they have a mass 50% to 70 % that of the Sun, but they are only about the size of the Earth, and a million times denser. If a white dwarf is a member of a binary system, and close to a giant companion star, it can raise a tidal bulge on the giant. The bulge can be so large that matter from the top of it becomes more attracted to the dwarf than to the giant. Matter moves across, and this process of tidal accretion increases the mass of the dwarf. There is a limit – the Chandrasekhar limit – to how heavy the dwarf can become before it becomes unstable. The limit is 1.4 times the mass of the Sun. When it is exceeded, the white dwarf usually collapses to become a neutron star or a black-hole. However, a carbon-oxygen white dwarf may react differently. The temperature of the dwarf increases through compressional heating, and the rate of the internal fusion reactions increases. Eventually a thermonuclear flame ignites, and the dwarf explodes in a spectacular way. This is a leading explanation for Type Ia supernovae.

A similar thing can happen in binary systems where the small companion is a neutron star or a black-hole. Then the matter transferred from the larger star heats up, so that it emits X-ray radiation. There can be further emissions, but only if the matter subsequently hits a surface – which a neutron star will have, but a black-hole will not. The variations in such sources are a way in which we can 'see' evidence for the existence of black-holes.

Joe Startin