Watching the Moon: Time and Tide

Credit: Ruth Maddison

Summary

In this Activity, we will investigate

- tidal forces,
- synchronous rotation of the Moon, and
- the evolution of the length of days and months on Earth.

Tidal forces

As the Moon travels in its almost circular path around the Earth, it too is in free fall under gravity.

We tend to talk about the effects of gravity on the Earth and the Moon as if they are point objects – but they are not: each has a finite size, and this brings about interesting and important **tidal effects**.

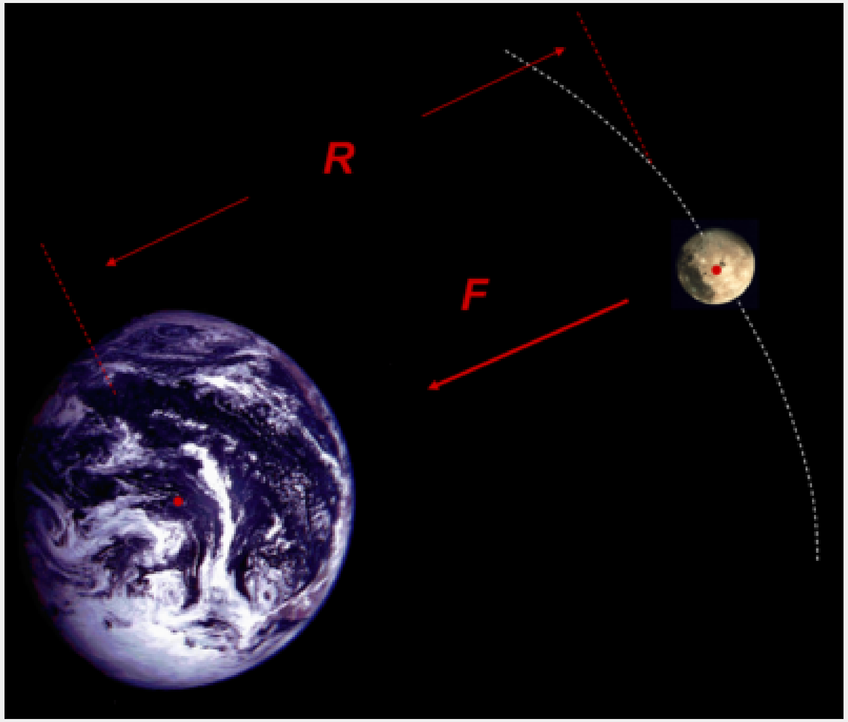
Credit: NASA/NSSDC

We usually think of the Earth's oceans when we talk about tides - but tidal effects are much more widespread.

The Moon as well as the Earth experiences sizable tidal forces, as do the natural satellites of other planets (particularly Jupiter). Tidal effects are also crucial in the regions surrounding black holes. We'll meet some of these other examples of tidal effects in later Modules - for now, we will concentrate on the Earth-Moon system.

Instead of starting with ocean tides on Earth, we'll look at an easier example to explain - tidal forces on the Moon.

The force of gravity ***F*** acting on the Moon's ***centre*** keeps it travelling along its almost circular orbit.



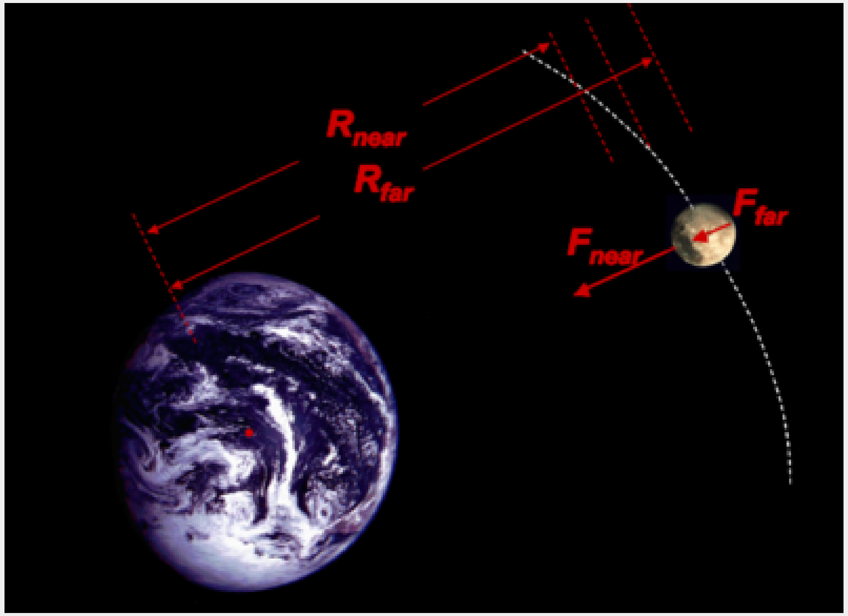
Not to scale!

Credit: Earth by: Dr. Edwin V. Bell, II (NSSDC/Raytheon ITSS)

However, the force of gravity acts on all parts of the Moon. Because the force of gravity is proportional to the inverse of distance squared,

$$F_{\rm grav} \propto \frac{1}{R^2}$$

this means that the force of gravity is stronger on the near side of the Moon than on the far side of the Moon.



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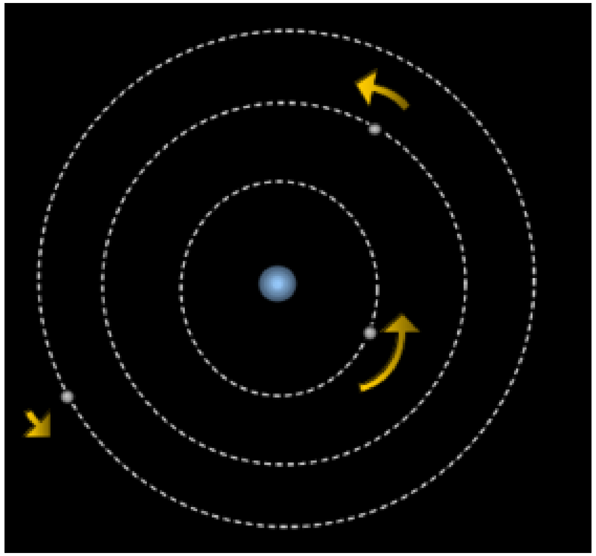
According to Kepler's third law, the orbital period squared is proportional to the orbital radius cubed:

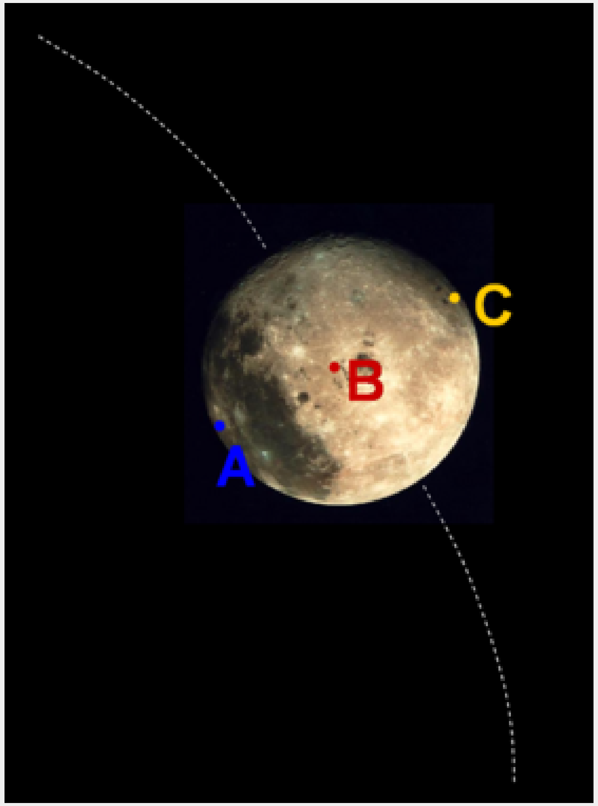
$$P^2 \propto R^3$$

So stable orbits at larger radii have lower orbital speeds, and vice versa. This comes about because the force of gravity decreases rapidly with distance.



Let's consider the motion of three points on the Moon:

- **A** - a point on the side facing Earth,
- **B** - a point at the centre of the Moon, and
- **C** - a point on the side furthest from Earth.

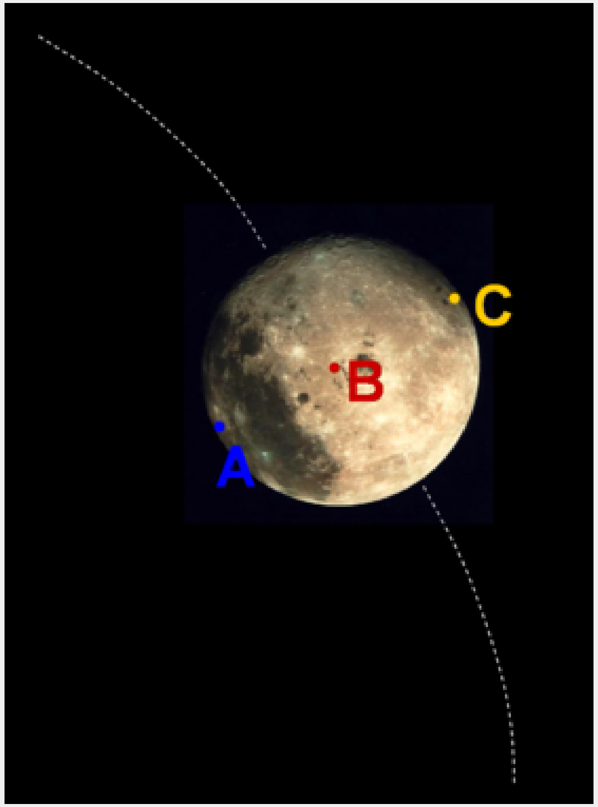


Credit: Moon by: NASA/NSSDC

If **A**, **B** and **C** were free to travel in independent orbits around the Earth, according to Kepler's third law **A** would travel faster than **B**, and **C** would travel more slowly than **B**.

However, because they are physically joined, all three points - **A**, **B** and **C** - have to travel around the Earth at the same orbital speed.

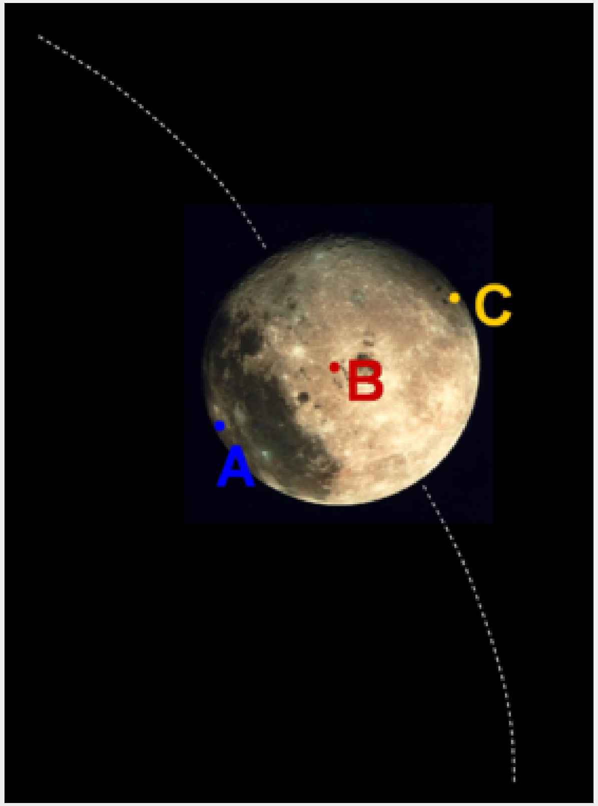
(The Moon's rotation on its axis is so slow compared to its orbital motion around the Earth that we can ignore it for now.)



Credit: Moon by: NASA/NSSDC

So for each point:

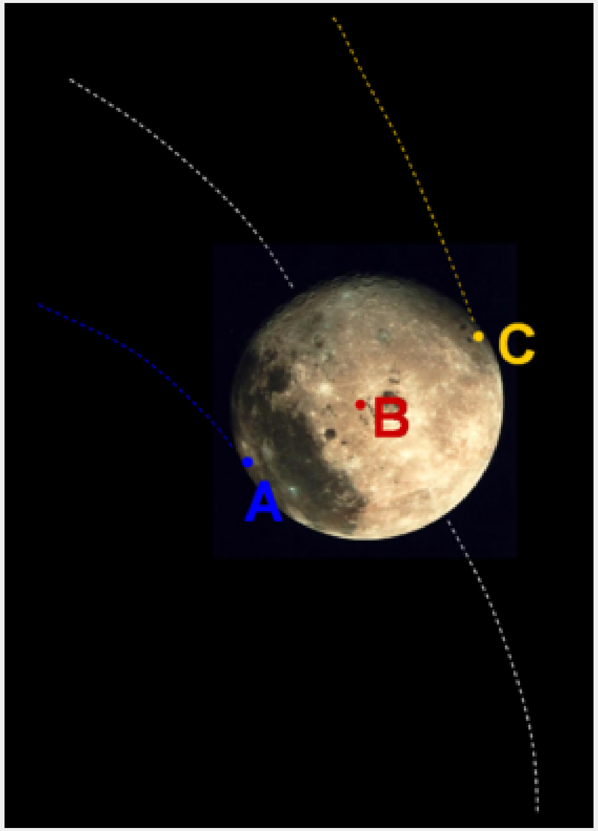
- **B** is travelling at the right speed for its orbit,
- **A** is closer to the Earth, and so is travelling too slowly for an independent orbit, and
- **C** is further from the Earth, so it is travelling too fast for an independent orbit.



Credit: Moon by: NASA/NSSDC

If **A** , **B** and **C** were not fixed to the Moon:

- **A** would move in towards the Earth (as it is not travelling fast enough to maintain its present orbit),
- **B** would continue on its original obit (as it is travelling at the right speed for its present orbit), and
- **C** would shift out further from the Earth (as it is travelling too fast to maintain its present orbit).



Credit: Moon by: NASA/NSSDC

Tidal bulge

The Moon, however, is a solid object, held together by both gravity and chemical bonds.

So the differential gravitational pull of the Earth on the Moon’s near and far sides only distort its shape.

The Moon does indeed have a small ***tidal bulge***, aligned roughly towards Earth.

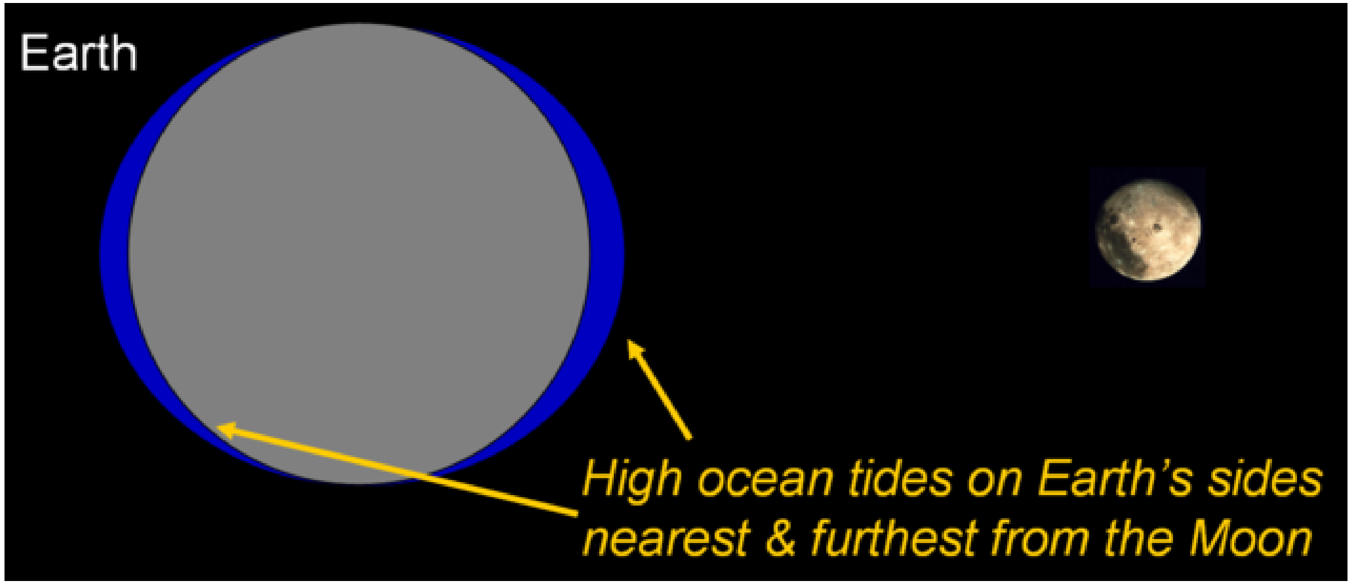
Credit: Moon by: NASA/NSSDC

Differences in the gravitational force on the near and far sides of orbiting objects such as the Moon tend to distort these objects (and can even pull loosely bound objects apart, as with comet Shoemaker-Levy 9).

These **tidal forces** act on the Earth too. The Earth's solid crust is tidally distorted by the Moon, causing movements in the Earth's surface of up to about 20 cm.

Because the Earth's mass is greater and the Moon is smaller in size and has a weaker surface gravity (i.e. things weigh less on the Moon), the tidal forces generated by the Earth on the Moon are about 20 times stronger that the tides that the Moon raises on the Earth. Thus the Moon has a much larger tidal bulge than the Earth does.

As we know, the Earth's oceans are strongly distorted by tidal forces. The two tidal bulges lead to two ocean high tides (and low tides) each day.

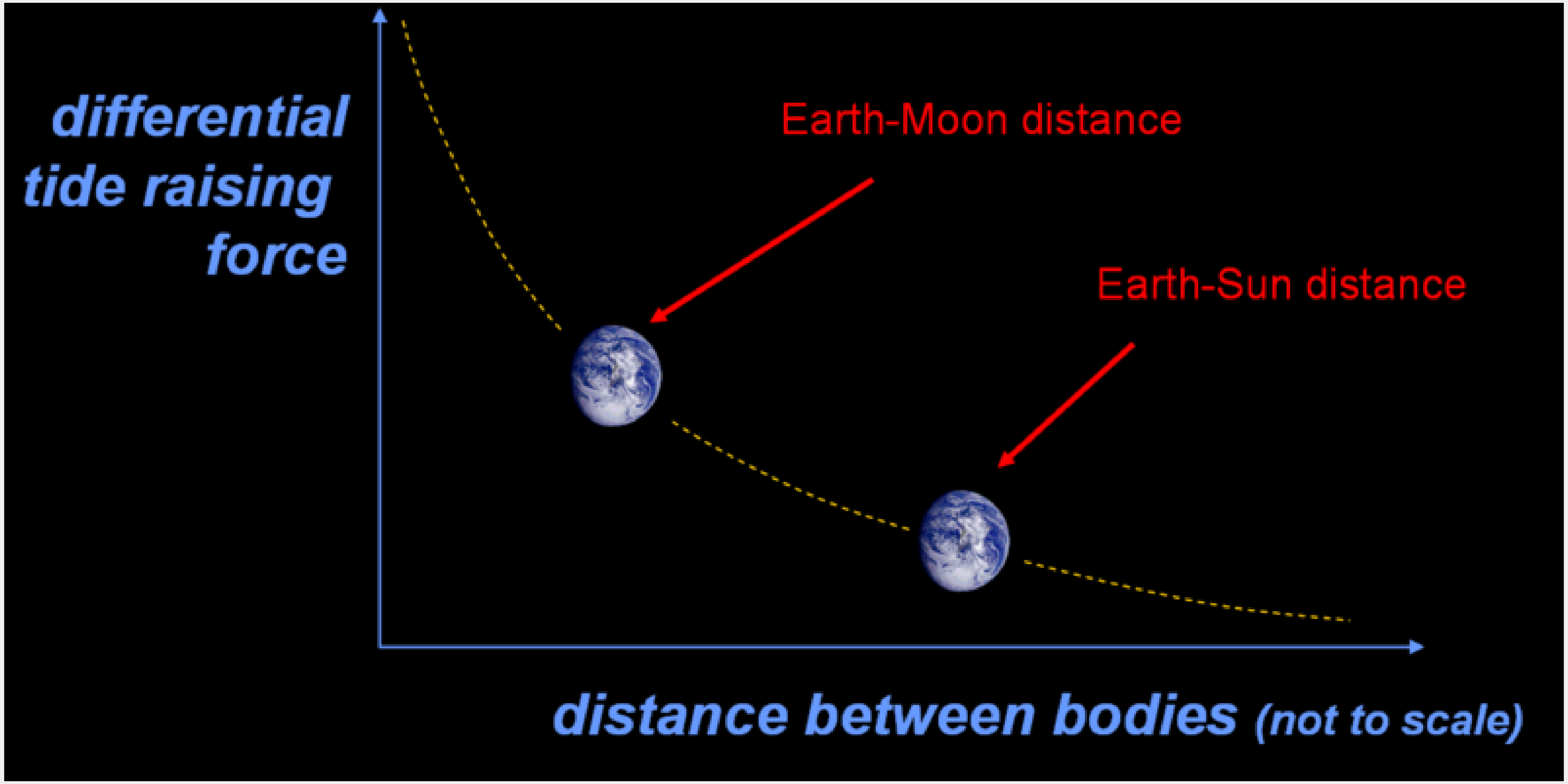


If the Earth were uniformly covered in ocean, we would expect tides of a few metres. However, the effect of continents and bays in obstructing and channeling water flow means that some locations on Earth have only one tide per day, while others have tides that are up to 15 m high!

The Sun also produces tidal effects on Earth, but only at about half the magnitude of those due to the Moon. How can this be, given that the gravitational force on the Earth due to the Sun is greater than that due to the Moon?

Think about this for a moment before moving on to the next slide.

The *differential* tide raising force is proportional to the inverse distance cubed, while the gravitational force is proportional to the inverse distance squared:



This distance is from centre to centre.

So even though the mass of the Sun is obviously a lot bigger than the mass of the Moon, it works out that the tidal force of the Sun on the Earth is about half the tidal force of the Moon on the Earth.

In case you want to try the numbers for yourself:

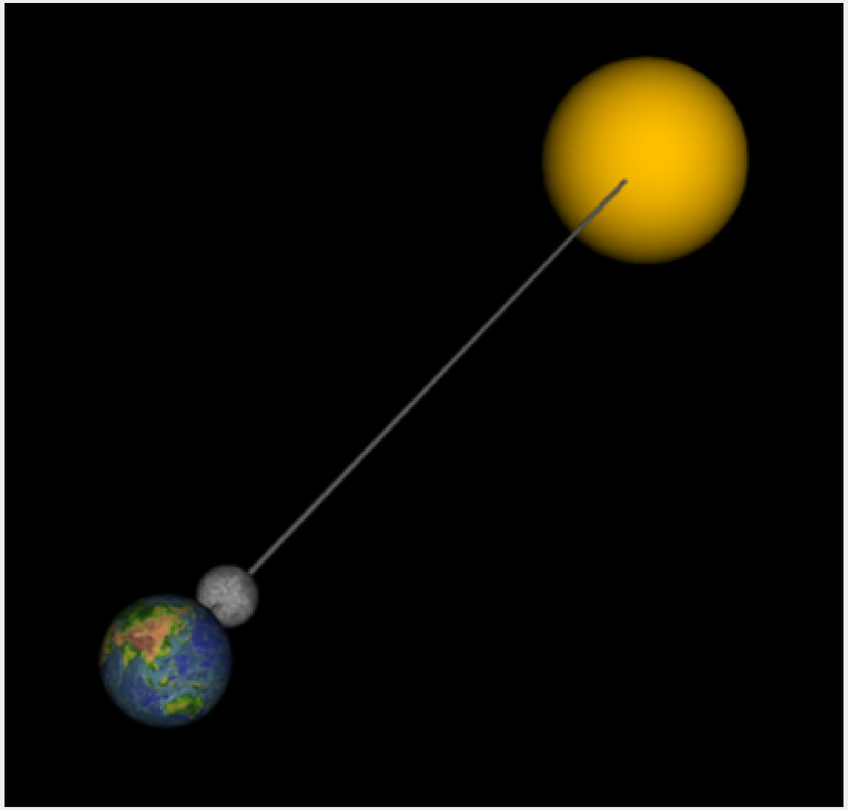
$$\begin{aligned} M_{\text{Moon}} &= 7.348 \times 10^{22}\,\text{kg} \\ M_{\text{Sun}} &= 1.99 \times 10^{30}\,\text{kg} \\ D_{\text{Earth}-\text{Moon}} &= 3.844 \times 10^{5}\,\text{km} \\ D_{\text{Earth}-\text{Sun}} &= 1.498 \times 10^{8}\,\text{km} \end{aligned}$$

and you need to compare

$$\frac{M_{\text{Moon}}}{(D_{\text{Earth}-\text{Moon}})^3} \quad \text{and} \quad \frac{M_{\text{Sun}}}{(D_{\text{Earth}-\text{Sun}})^3}$$

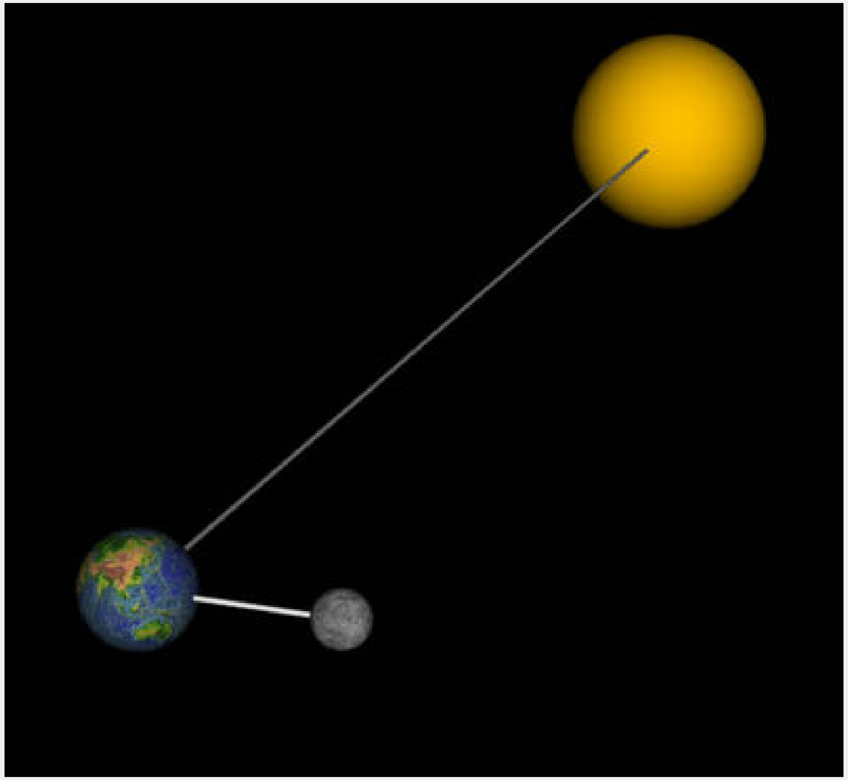
So even though the Sun exerts a greater gravitational force on the Earth then does the Moon, its tidal effects are not as great. But the Sun's tidal effects can be seen to effect the Earth's ocean tides:

The largest ocean tides on Earth, called *spring tides* (when the ocean 'springs up' - nothing to do with the season!) occur when the Sun, Earth and the Moon are aligned:



Not to scale!

The smallest ocean tides on Earth, called *neap tides*, occur when the Sun, Earth and the Moon are at right angles:



Not to scale!

Thus spring tides occur during full and new moons, while neap tides occur at first and third quarter moon.

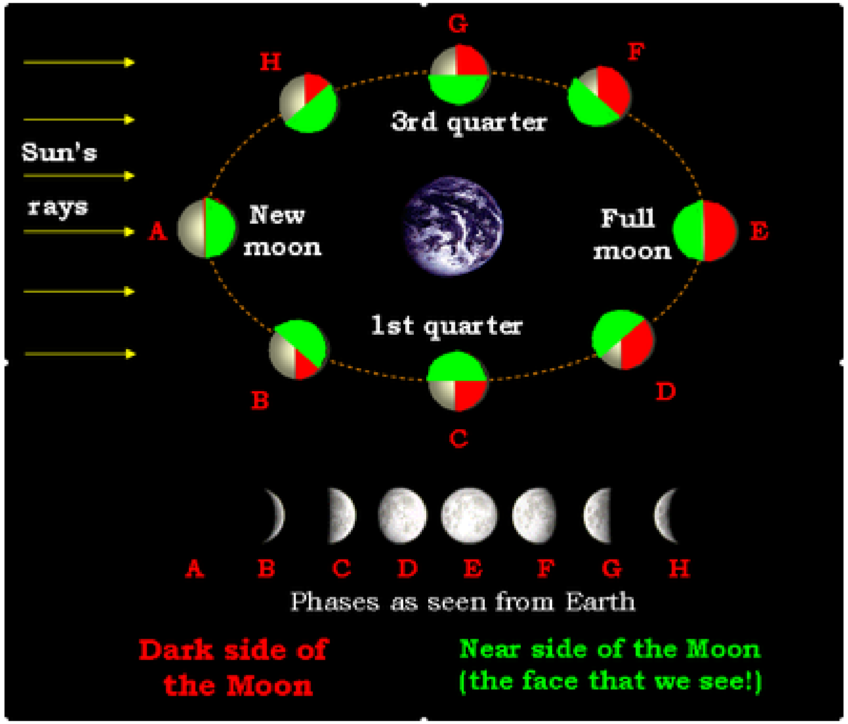
Synchronous rotation of the Moon

It's common for people to refer to "the dark side of the Moon". But in fact there is no one dark side of the Moon.

In the previous Activity we saw that as the Moon rotates around the Earth, it keeps essentially the same face turned towards us. (The face of the Moon that we see is not actually constant throughout the month, as we shall see in a moment.) Thus people incorrectly assume that the "other" side of the Moon is always in darkness.

But this is not the case. The part of the Moon which is in shadow isn't constant - it changes during the month.

Let’s have another look at the phases of the Moon:



The ”dark side” of the Moon is that which faces away from the Sun.

But since we see the same face of the Moon throughout the month, there can’t be one constant dark side.

This is because the Moon is in **synchronous rotation**, which means that the rate at which the Moon orbits around the Earth is equal to the rate at which it rotates on its axis. For the Moon this rotation rate is 27.3 days long (which is the sidereal period of the Moon).

How does this come about? It could hardly be a coincidence that the Moon keeps the same face towards us.

This is no coincidence – many of the natural satellites (“moons”) in the Solar System orbit in synchronous rotation.

As an extreme example, and as we will see in a later Activity, far-distant Pluto and its satellite Charon are *both* in synchronous rotation – each with one face eternally turned towards the other.

Pluto and Charon

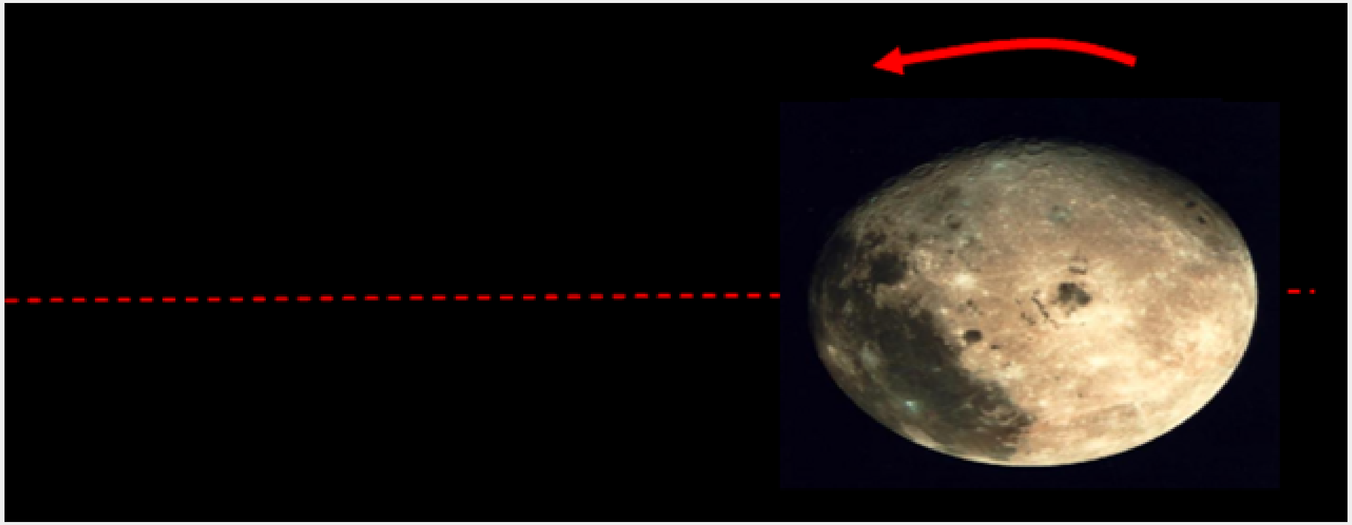
Credit: Dr. R. Albrecht, ESA/ESO Space Telescope European Coordinating Facility; NASA

To understand the synchronous rotation of the Moon (and other satellites), we need to have a closer look at the effect of *tidal bulges*.

Tidal locking

Theories of the formation of the Moon suggest that it rotated much faster in the past.

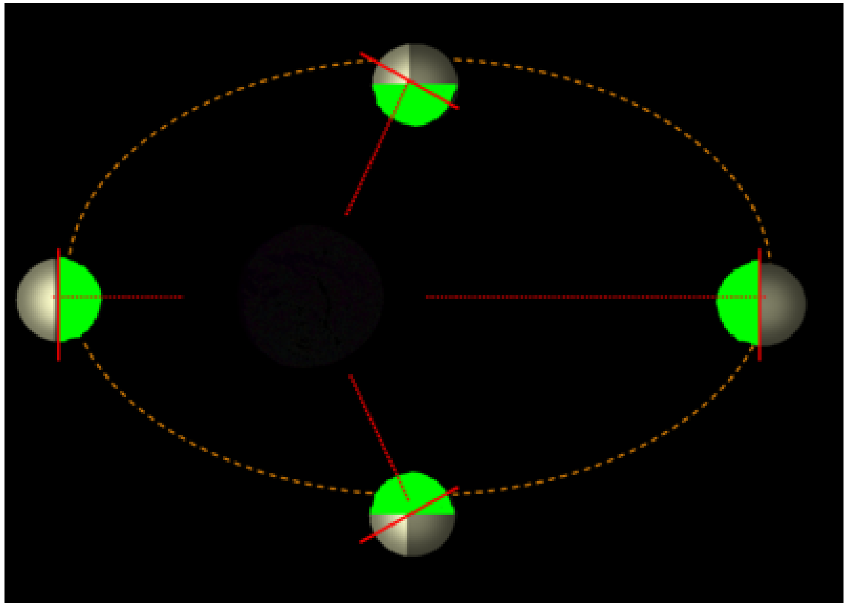
However, the Moon’s tidal bulge due to the Earth should remain directed (roughly) along a line connecting the Moon and Earth:



Credit: Original Moon by: NASA/NSSDC

So as the Moon rotated, the bulge continually moved through its crust, raising and lowering it. This generated *friction* in the form of heat in the crust, taking energy from the Moon’s rotation and therefore slowing its rate of rotation down until it reached its present ***tidally locked*** alignment.

As previously mentioned, we don't see *exactly* the same face of the Moon at all times. Because the Moon's orbit around the Earth isn't perfectly circular, we get slightly different views of the surface of the Moon during its orbit.



This allows us to see about 5/8th of the Moon's surface during the course of a month, instead of the 1/2 factor you would otherwise expect. This slight "turning" of the Moon is termed the ***libration of the Moon***.

The length of the day and the month

We have seen that both Pluto and its satellite Charon are tidally locked into synchronous rotation.

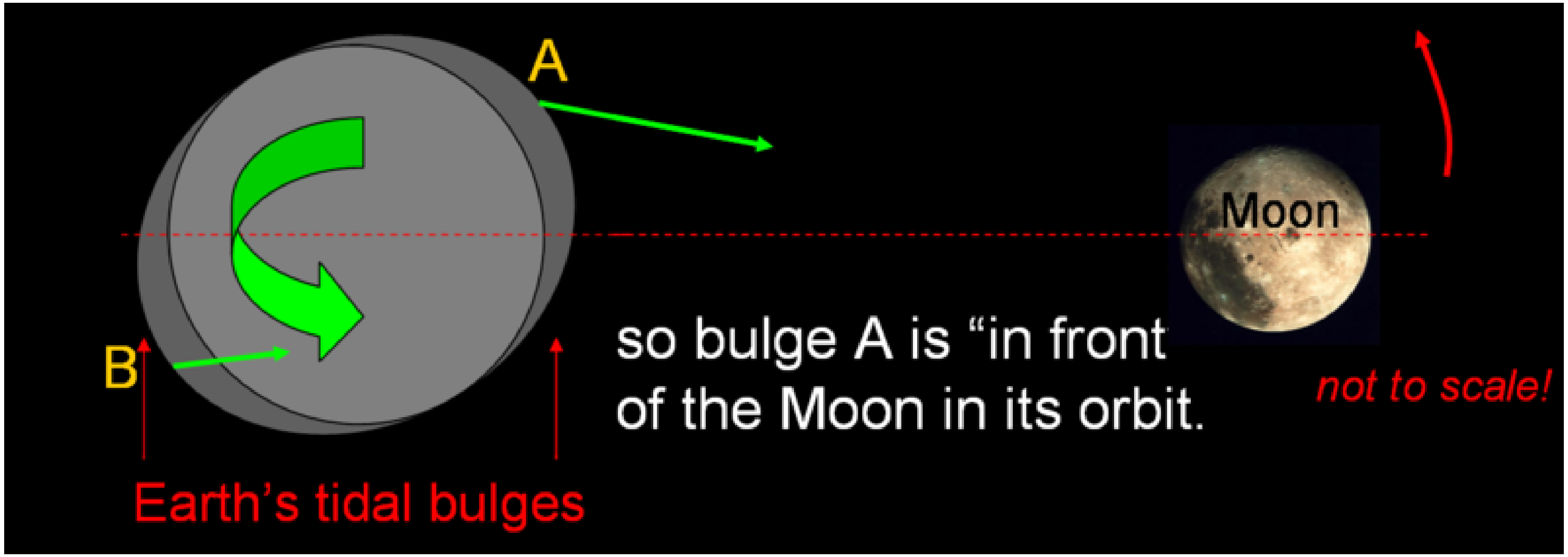
As our Moon is locked into synchronous rotation, it is reasonable to ask why the Earth is not also tidally locked - that is, why the Earth does not take the same amount of time to rotate as the Moon takes to orbit the Earth?

The answer is that the length of a day on Earth ***is*** slowly lengthening due to the effect of the tidal bulge moving through the Earth's crust, but the Earth is so massive that this change in length of the day is very slow.

The length of a day on Earth is increasing by about 0.001 seconds per century at present. When the Earth first formed, the day may have been only 5 to 6 hours long!

Note, however, that you cannot simply calculate the change in the length of the Earth's day by multiplying 0.001 seconds by the age of the Earth-Moon system (in centuries). This is because as the Earth-Moon distance changes, so too does the rate at which the Earth's spin slows.

Because of the Earth’s relatively rapid rotation, the tidal bulges are dragged off the Earth-Moon line:

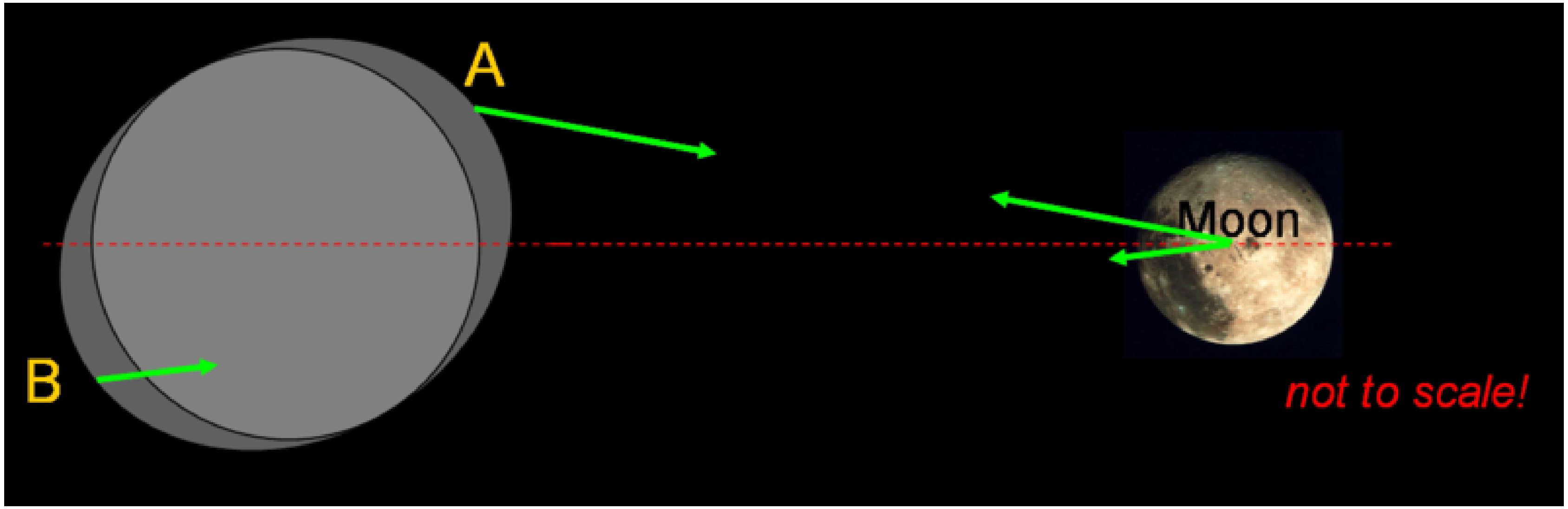


so bulge A is “in front of the Moon in its orbit.

Since bulge A is closer to the Moon than bulge B, it feels a great gravitational pull from the Moon, which results in a net *torque* (or twisting force) on the Earth in the opposite sense to its rotation direction, thus slowing it down.

At some time in the distant future, the Earth-Moon system will also become tidally locked like Pluto & Charon.

Let's have a closer look at the effect of the Earth's tidal bulges on the Moon. Remember that Newton showed us that to every action there is an equal and opposite reaction.



Since bulge A is closer to the Moon than bulge B, it exerts a greater gravitational pull on the Moon, which has the net effect over time of pulling the Moon ahead.

Thus the Moon slowly spirals outwards away from the Earth. This phenomena is called *tidal recession.*

Currently the Moon is very slowly spiraling outward, increasing its orbital radius at a rate of 4 cm/year. The marine record contains evidence of shorter months in the past for the Earth. Suggestions have been made that 2.8 billions years ago the length of the month was just 17 days. For a paper on this discussion click here.

Originally the Moon-Earth separation may have been as little as one-tenth its present value. Ocean tides on Earth would then have been roughly one thousand times greater than their present-day size. The weathering caused by such huge tides would have had a profound effect on the evolution of the Earth's surface.

Summary

In this Activity, we have discussed **tidal forces** and their effect on both the Earth and the Moon. Tidal forces act between bodies with a fixed size and result from the *differential gravitational force* acting along the line of centres. The near side of a body will feel a stronger gravitational pull than the far side, which results in a stretching of that body that form (almost) symmetric **tidal bulges**.

The tidal forces acting on the Moon due to the Earth produce tidal bulges in the Moon's crust, while the tidal forces acting on the Earth due to the Moon are the cause of the ocean tides.

Over time, the friction due to tidal forces have taken energy from the Moon's rotation, slowing it down until it has become locked in **synchronous rotation**. This means that the Moon's rotation rate is equal to its orbital period and hence it always keeps the same face towards the Earth. Because of the slightly eccentric orbit of the Moon around the Earth, however, we go get to see about 5/8th of the lunar surface. This is called the **libration** of the Moon.

Tidal friction also means that the Moon is slowly spiralling away from the Earth – called *tidal recession* – which increases the length of a (lunar) month. Tidal friction also effects the Earth, slowly down the Earth's rotational period and hence slowing increasing the length of an Earth day.

In the next Module, we will investigate current theories on the formation of the Solar System.