New Zealand Science Curriculum: Astronomy Year 8

What Causes the Tides?

Part 1: The Moon mainly causes the Tides

It is mostly the Moon's gravitational effect that causes the tides on Earth (Lunar Tides). The tides are caused mainly by the difference in distance between the near side of the Earth to the Moon and the far side of the Earth to the Moon. Clearly, the near side of the Earth is closer to the Moon and so experiences greater gravitational attraction to the Moon than the far side, and so ocean water is pulled towards the Moon more strongly on the near side than the ocean water on the far side. It was Isaac Newton who gave the first scientific descriptions of the tides in 1687.

In fact, the solid part of the Earth also experiences tides that scientists can measure, but the apparent effect is much smaller than on the oceans because rock is solid and doesn't move much, while, of course, water flows. The Sun has a tidal effect too (Solar Tides), but has a much smaller effect on the tides than the Moon, as we will see in Part 3.

Figure 1 (sourced from Physics Stack Exchange) shows how the Moon's difference in gravity between the near side and the far side causes tides.

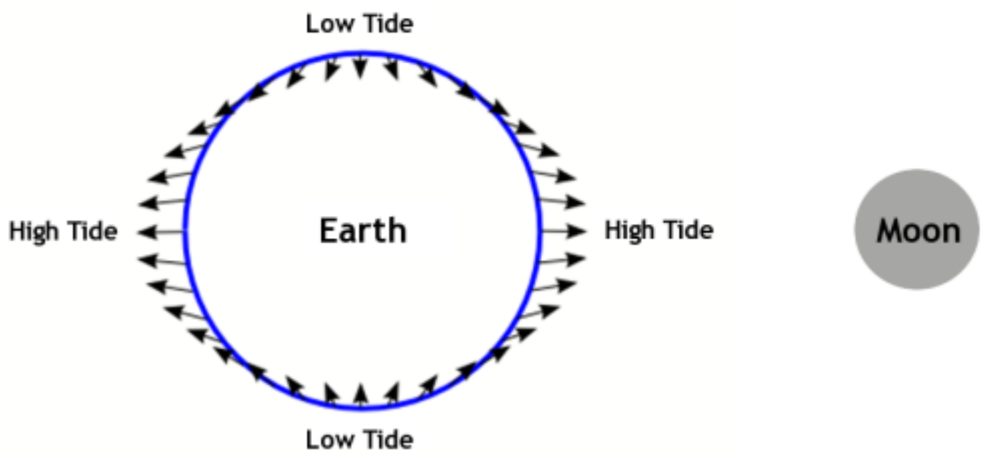

Figure 1: Moon's Gravity causing the Tides

Remember, though the forces that cause tides result from gravitational attraction, it's really the difference between the strength of Moon's gravitational force at the near side of the Earth and that at the far side that causes the tides. Now we know that high tides occur on both the near side of the Earth to the Moon and the far side of the Earth to the Moon. We see why this happens in Part 2.

Some Mathematics you may wish to Skip

Feel free to skip this next section if you are in Year 8 but, for those of you who want to know the mathematics behind the difference between the Gravitational Force at the near side and that at the far side, we need Newton's equation for the gravitational attraction between any two objects. The gravitational force is given by Newton's formula:

$$F = G M_1 M_2 / r^2$$

F is the gravitational force between the two bodies. M_1 is the Mass of the first object and M_2 is the mass of the second object. The distance between the two objects is r.

G is called the Gravitational Constant, which has the value: 6.67×10^{-11} N $m^2 kg^{-2}$. Please do not worry about the complicated units in this constant for now. Just think of it as a number.

Now, let's simplify everything so we can apply Newton's formula to understand the tides! Think of the gravitational force of the Moon on a single kilogram of seawater (or solid rock), so $M_1 = 1$ Kg. Now let M be the mass of the Moon, r be the distance from the center of the Earth to the Moon and R be the Radius of the Earth. The radius of the Earth is approximately 6,371 km and so the diameter is approximately 12,742 km.

Figure 2 (sourced from worldbuilding.stackexchange.com) shows why the gravitational effect of the Moon is larger at the near side of the Earth to the Moon than that of the far side of the Earth to the Moon. Remember that when we divide G by a larger number $(r + R)^2$, we get a smaller force than if we divide by a smaller number $(r - R)^2$, and vice-versa.

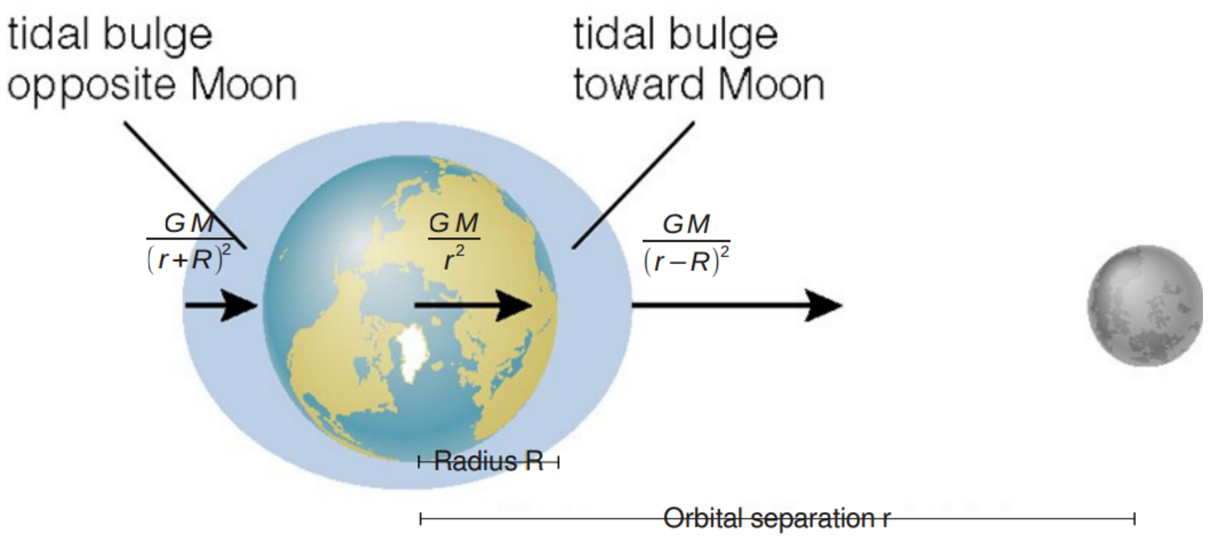

Figure 2: Gravitational Effect of the Moon at the near and far Side of the Earth to the Moon

So, the attraction on one kilogram of water or rock at the near side to the Moon is:

$$GM / (r - R)^2$$

This force on the near side is bigger than the force at the far side because the distance is smaller than at the far side (and, of course) the distance is greater at the far side (to find the force at the far side at the far side we divide G by $(r + R)^2$, instead of dividing G by $(r - R)^2$, where r – R is the distance we use to find the force at the near side).

The gravitational attraction on one kilogram of water or rock at the far side of the Earth to the Moon is:

$$GM / (r + R)^2$$

The force at the near side is also greater than the force at the centre of the Earth because the distance at the center is just r (bigger than r – R at the near side, but smaller than r + R at the far side).

Finally, the attraction on one kilogram of water or rock at the Earth's centre is:

$$GM / r^2$$

This force lies between the forces at the near side and the far side.

Part 2: Tides Occur on the Far Side of the Earth from the Moon

We see the tides as rises and falls of water, mainly in the seas, but also in lakes and rivers (but we can measure a much smaller tide in the solid Earth as well). Although the gravitational attraction of the Moon causes the oceans to pull the water in the direction of the Moon (a high tide), another high tide is created on the far side of the Earth, the side that is farther away from the Moon. This second high tide on the far side is created mainly because of the centrifugal force due to the Earth's rotation around its own axis. All rotating objects (including fluids such as seawater) experience a centrifugal force when rotating, and the water on the far side is pushed away from the Moon (just as the centrifugal force pushes water towards the Moon at the near side), like any object rotating in a circle when held to a piece of string. Often, we refer to this this centrifugal force effect as inertia. The centrifugal force that pushes water towards the Moon at the near side makes the tide even higher there.

Figure 3 shows that we get high tides on both the near side to the Moon and at the far side.

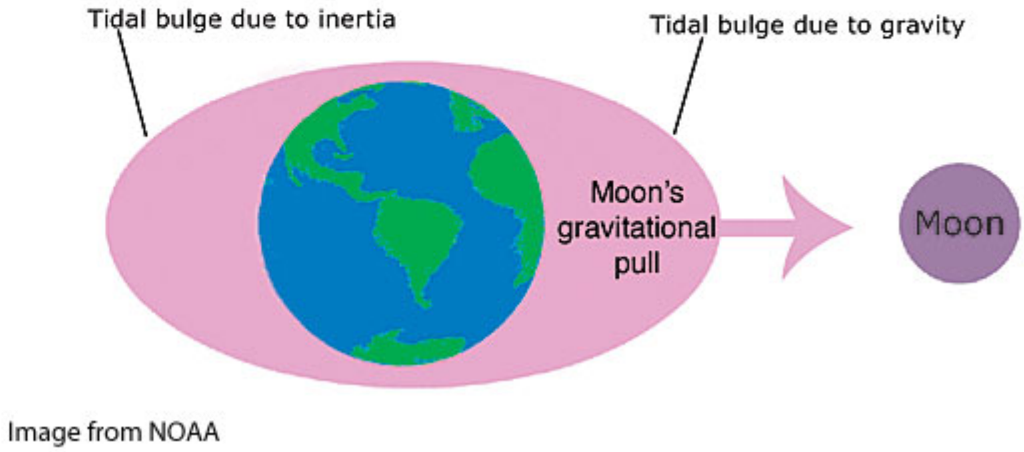

Figure 3: High Tides on both Sides of the Earth

In addition, there is another, smaller, effect that gives rise to the high tide on the far side. The part of the Earth, located between the centre of the Earth and the oceans on the far side, is attracted to the Moon more strongly than the oceans on the far side surface, because on average all that rock between the centre and the oceans is much closer to the Moon than the oceans on the surface of the far side. Thus, the rock between the centre and the far side is attracted to the Moon more strongly than the oceans on the far side (and therefore is pulled slightly closer to the Moon than the water on the surface of the far side). In fact, a similar effect applies on the near side, but the rock is attracted less strongly than the surface and is pulled away from the ocean by a small amount, again making the tide just a little higher.

For example, half-way between the Earth's centre and the ocean on the far side, the gravitational force is:

$$GM / (r + R/2)^2$$

This is a larger force than that at the ocean surface on the far side, which is given by:

$$GM / (r + R)^2$$

. . . because dividing G by $(r + R/2)^2$ gives a larger result than dividing G by $(r + R)^2$

So, the rock between the Earth's centre is pulled more strongly than rock and ocean at the surface at the far side, and the rock is pulled away from the ocean surface at the far side by a small amount.

Part 3: The Sun's Effect on the Tides is Real but smaller than the Moon's

Even though the Sun's gravitational attraction is much greater than that of the Moon, its effect on our tides is much less than that of the Moon. In fact, our Sun is approximately 27 million times more massive than the Moon, but it is much farther away (throughout the year it is on average a little less than 390 times further than the Moon). Therefore, the Sun's overall gravitational pull on the Earth is smaller (at approximately 46% that of the Moon). However, just as with the Moon's effect, it is not really the gravitational pull of the Sun that causes the Sun's smaller contribution to the tides, but the smaller difference in the Sun's gravitational force between the near side of the Earth to the Sun and the far side of the Earth to the Sun.

The distance from the Sun to the Earth varies throughout the year because the Earth orbits the Sun in an ellipse (not a circle), averaging approximately 149,597,870 km throughout the year. The distance from Earth to the sun is called an Astronomical Unit (AU), which is the standard distance that we use to measure distances across our Solar System. By comparison, the distance from the Earth to the Moon averages approximately 384,400 km, or about 30 times the diameter of the Earth. When the Earth and Moon are farthest from each other, the distance is nearly 32 Earth diameters. When they are closest to each other, the distance is approximately 28 to 29 Earth diameters. Thus, the gravitational pull of the Moon on the Earth does vary at different times. In spite of the much greater distance of the Sun to us, the gravitational attraction between the Sun and Earth is over 177 times that between the Moon and Earth. The Moon dominates the tides because of the much larger difference in its gravitational force between the near side and the far side of the Earth than the difference in the Sun's attraction at the near and far side.

Now - back to the Sun's effect on the tides. The radius of the Earth is approximately 1.7% of the distance between the Earth and the Moon. The radius of the Earth represents a much smaller percentage of the distance between the Sun and the Earth (approximately 0.005%). To summarise - even though the Moon's overall gravitational force is much smaller than that of the Sun's gravitational force, the difference between the Moon's tidal force at the near side and far side are greater than the difference between Sun's tidal force at the near side and far side. Therefore, lunar tides are stronger than solar tides.

In fact, the overall effect of the Sun and Moon tides are very complicated because the both the Sun and Moon move constantly relative to the Earth and to each other (though remember that the Earth orbits the Sun while the Moon orbits the Earth!), but the Sun and Moon are rarely in alignment, except at New Moons and Full Moons. So, most of the time the Sun and Moon pull at the Earth and its oceans from different angles at different times, and the tides actually result from both the Sun's effect and the Moon's effect – it's just that the Moon's effect is greater.

Part 4: How many Tides do we get each Day?

We see two high tides and two low tides every lunar day (24 hours and 50 minutes). Of course, our solar day (our Earth's day) lasts for 24 hours, but a lunar day is 50 minutes longer. The lunar day is the time that the Moon takes to complete one rotation about its axis. Note that the Moon takes the same time to complete one orbit around the Earth (also 24 hours and 50 minutes), because of an effect known as 'tidal locking'. Also note that we only ever see one side of the Moon because the Moon rotates on its axis at the same rate as the Moon orbits the Earth.

We can think of a lunar month as the total time between two New Moons. By the way – a lunar month lasts about 29.5 solar days (the days that we experience on Earth). So, if we ever colonise the Moon, a lunar month would seem much like an Earth month to us.

When thinking about the tides, the lunar day is the time taken for any place on the Earth to rotate from a point beneath the Moon to the same point beneath the Moon. The lunar day is only 50 minutes longer than a solar day because the Moon rotates around the Earth in the same direction as the Earth rotates around its own axis, but it rotates at a slightly slower rate than the Earth.

We experience two high tides and two low tides every 24 hours and 50 minutes. We have high tides every 12 hours and 25 minutes and the time between high tides and low tides is about six hours and 12.5 minutes.

Part 5: Spring Tides and Neap Tides

Spring Tides at New Moon and Full Moon
Spring Tides are high tides that occur when the Earth, Moon and Sun are in approximate alignment and the gravitational forces of the Moon and Sun work together to produce a very high tide. Spring tides occur during both the Full Moon and the New Moon. The name Spring Tide dates back to a time when people saw those very high tides as "springing up". The name has nothing to do with the season that we call Spring.

Figures 4 and 5 (sourced from TimeandDate.com) show the high tides at New Moon on both the near side of the Earth to the Moon and the far side of the Earth to the Moon during a Spring Tide.

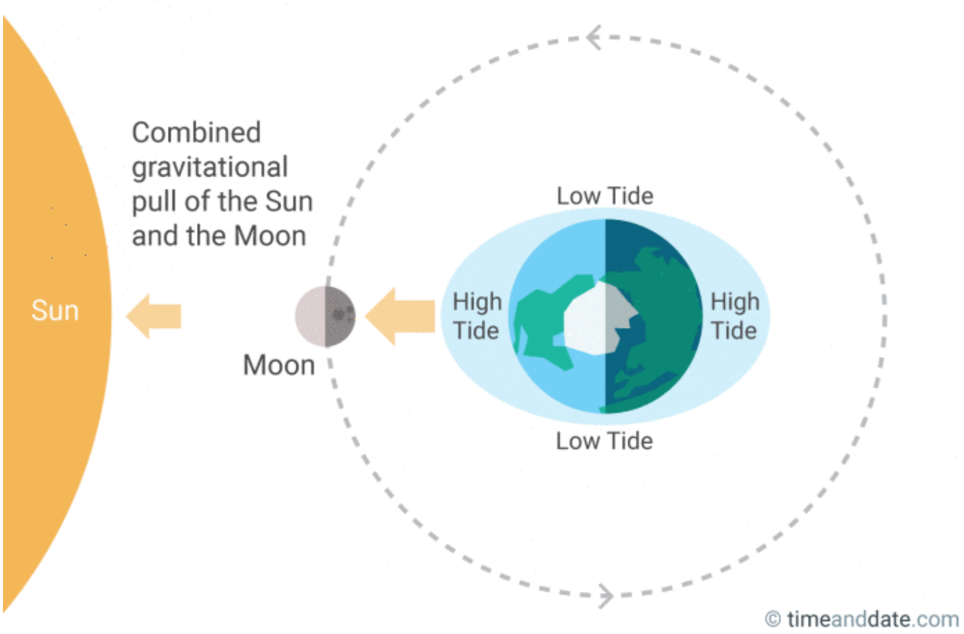

Figure 4: High Tides during a Spring Tide at New Moon

Figure 5: Another picture of the High Tides during a Spring Tide at New Moon

The New Moon occurs when the Moon lies directly between the Sun and the Earth and both are in alignment. Here, the gravitational forces that cause the tides are greater than normal because the Sun and Moon pull in the same direction and their forces add together. At the time of the New Moon, we see the Moon in darkness, rather than as a bright disc. During the New Moon, the Sun lights up only the far side of the Moon that we never see.

Figure 6 (sourced from Education.com) shows the high tides on both the near side of the Earth to the Moon and the far side of the Earth to the Moon during a Spring Tide at both New Moon and Full Moon. At the time of the Full Moon we see the Moon as a bright disc, whereas we see the whole face of the New Moon in darkness.

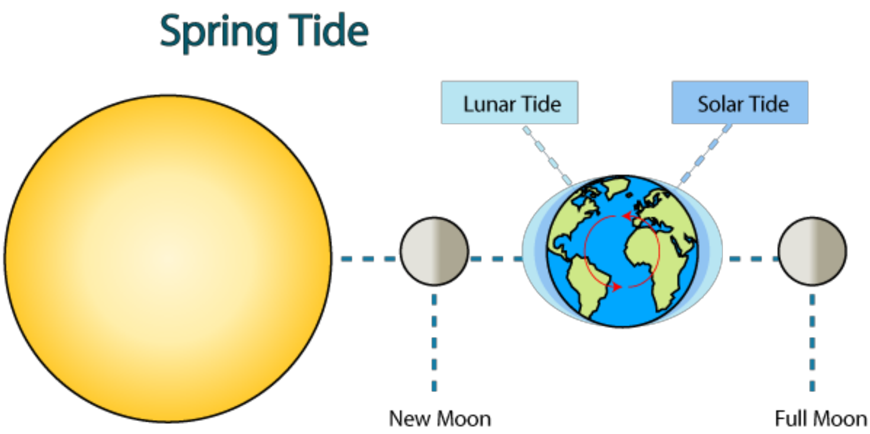

Figure 6: Spring Tides during New Moon and Full Moon

We also get a high Spring Tide at the Full Moon, when we see the entire Moon's face (the side that always faces us) because the Sun's light falls directly on the Moon and is not really blocked by the Earth, even though Figure 6 may suggest that it is blocked. Low tides are lower than normal tides during both the New Moon and the Full Moon. Thus, the differences between high tides and low tides are greatest during the New Moon and Full Moon.

Neap Tides when the Sun and Moon pull the Earth from Perpendicular Directions

Neap Tides are very low tides that happen when the alignment of the Moon and the Sun are perpendicular relative to the Earth. Figure 7 (sourced from Education.com) shows the high tides during a Neap Tide on both the near side of the Earth to the Moon and the far side of the Earth to the Moon.

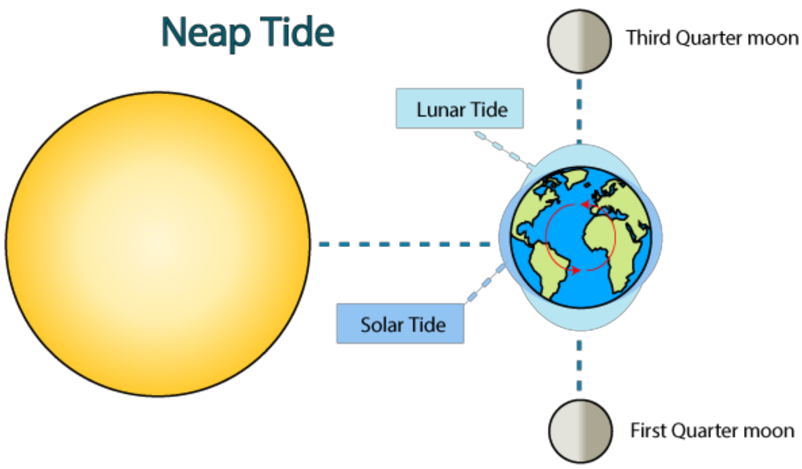

Figure 7: Neap Tides around the Earth

David Lillis. 9 November 2018