7.1.4 OUR MOON[M36]

The Moon is the Earth's only natural satellite. It occupies an elliptical orbit, on average 384,403 km from the Earth. With a diameter of 3,476 km (27% of that of the Earth), only Pluto's Charon is larger (~50% the size of Pluto) when compared to its 'host', resulting in a more intimate relationship between the Earth and its moon than is experienced by most other planets.

When viewed from Earth's North Pole, the Earth and Moon rotate counter-clockwise about their respective axes; the Moon orbits Earth counter-clockwise and Earth orbits the Sun counter-clockwise.

Note also that the Moon is inverted when viewed from Earth's southern hemisphere when compared to how it is seen from the northern hemisphere. It still moves from east to west in the sky, but while the Moon's north pole is uppermost when viewed from Earth's northern hemisphere, its south pole is uppermost in the sky when viewed from the southern hemisphere. As a consequence, the phases of the Moon (see below) appear to wax and wane from right to left when viewed from Earth's northern hemisphere, but from left to right when viewed from the southern hemisphere.

Typical View of the Full Moon from Earth's Northern Hemisphere (USA)[1]

Typical View of the Full Moon from Earth's Southern Hemisphere (New Zealand)[2]

7.1.4.1 The Moon's Orbit

The Moon makes a complete orbit about the Earth approximately once a month, the exact time depending on how an orbit is defined. The sidereal month is the time it takes the Moon to make a complete Earth orbit, relative to the stars, about 27.3 days. The synodic month, or, as it is more commonly known, the lunar month, is the time it takes to reach the same phase (*i.e.* one New Moon to the next), about 29.5 days. These differ because, while the Moon orbits Earth, the Earth and Moon have both orbited some distance around the Sun.

1 http://www.mreclipse.com
2 http://nzphoto.tripod.com/astro/moon1.htm

Each hour the Moon moves relative to the stars by an amount roughly equal to its angular diameter, or by about 0.5°. The Moon differs from most satellites of other planets in that its orbit is close to the plane of the ecliptic and not in the Earth's equatorial plane.

The plane of the lunar orbit is inclined at about 5.15° with respect to the ecliptic (the orbital plane of the Earth around the Sun), and the lunar axis is tilted at about 1.54° with respect to the normal to its orbital plane. The lunar orbital plane also precesses (*i.e.* its intersection with the ecliptic rotates clockwise)—one cycle every 6793.5 days (18.5 years)—mostly because of the gravitational perturbation induced by the Sun. During that period, the lunar orbital plane thus sees its inclination with respect to the Earth's equator (itself inclined 23.45° to the ecliptic) vary between 28.60° (23.45° + 5.15°) and 18.30° (23.45° - 5.15°). Simultaneously, the axis of lunar rotation sees its tilt with respect to the Moon's orbital plane vary between 6.69° (5.15° + 1.54°) and 3.60° (5.15° - 1.54°). Note that the Earth's tilt reacts to this process and itself varies by 0.00256° on either side of its mean value. This is called *nutation* and manifests itself as the precession of the equinox.

The points where the Moon's orbit crosses the ecliptic are called the *lunar nodes*: the North (or ascending) node is where the Moon crosses to the north of the ecliptic; the South (or descending) node where it crosses to the south. Solar eclipses occur when a node coincides with the New Moon, and lunar eclipses occur when a node coincides with the Full Moon (see below). Due to the precession of the lunar orbital plane (see above), the time between each passage of the Moon through the ascending node is slightly shorter than the sidereal month and is known as the draconitic month.

Finally, the Moon's perigee (the point in its elliptical orbit when it is closest to the Earth) is moving forwards in its orbit, and makes a complete circuit in about 9 years. The time between one perigee and the next is known as the anomalistic month.

Just to add to the confusion, a (Gregorian) calendar month is different again!

7.1.4.1.1 Lunar Libration

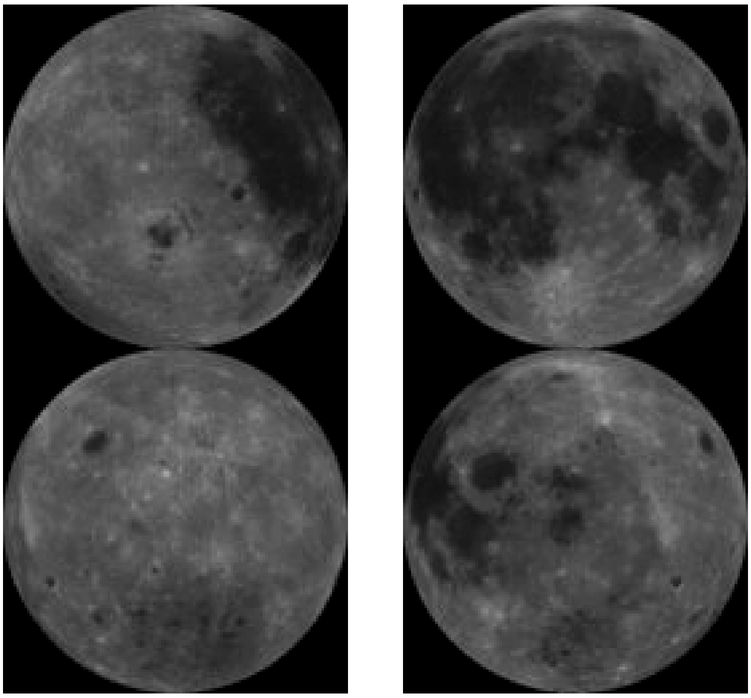
The Moon is in synchronous rotation, meaning that it keeps the same face turned towards Earth at all times. This synchronous rotation is only true on average because the Moon's orbit is slightly elliptical. When the Moon is at its perigee (closest to the Earth), its rotation is slower than its orbital motion, and this allows us to see up to an extra eight degrees of longitude of its East (right) side. Conversely, when the Moon reaches its apogee (furthest away from the Earth), its rotation is faster than its orbital motion and reveals another eight degrees of longitude of its West (left) side. This is called longitudinal libration.

Because the lunar orbit is also inclined to the Earth's equator, the Moon also seems to oscillate up and down (as a person's head does when nodding) as it moves in celestial latitude (declination). This is called latitudinal libration and reveals the Moon's polar zones over about seven degrees of latitude. Finally, because the Moon is only at about 60 Earth radii distant, an observer at the equator who observes the Moon throughout the night moves by an Earth diameter sideways. This is diurnal libration and also reveals approximately one degree's worth of lunar longitude.

7.1.4.1.2 The Far Side of the Moon

In spite of the fact that the Moon is in synchronous rotation with Earth, we have been able to collect images of the far side of the moon from satellites sent into Moon orbit. The far side of the Moon is relatively featureless, with very few of the maria (dark regions) which characterise the side we can see from Earth.

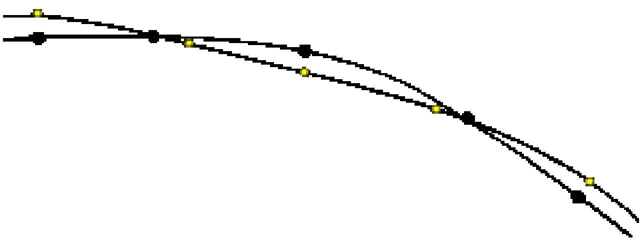
90° W Near side



Far side 90° E

7.1.4.1.3 Double Planet Hypothesis

Several characteristics of the Earth-Moon system distinguish it from the satellite systems of most other planets in the Solar System. Among these are the unusually large relative size of the Moon, its great orbital distance from Earth, and the fact that the Moon's path around the Sun is always concave to that star, like that of Earth but unlike that of most other satellites in the Solar System(see figure below[3]). As a result, some observers hold that the Earth-Moon system is a double planet rather than a planet with a satellite.



The Paths of the Earth and Moon around the Sun

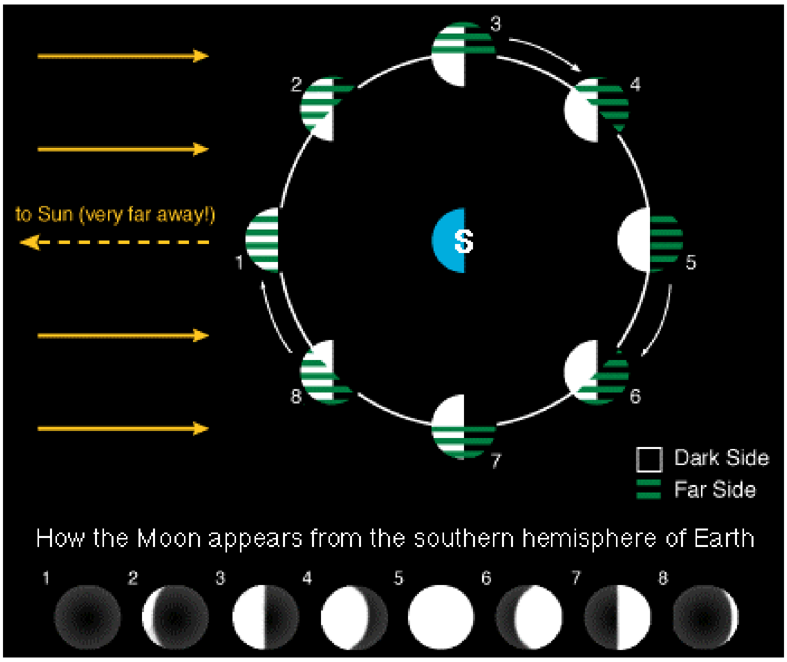
The Earth and Moon actually orbit about their barycenter, or common centre of mass, which lies about 4700 km from Earth's centre (about 3/4 of the way to the surface). Since the barycenter is located below the Earth's surface, Earth's motion is more commonly described as a 'wobble'.

3 http://en.wikipedia.org/wiki/Moon

7.1.4.2 The Moon's Phases

As the Moon orbits Earth, it appears to change shape, from a crescent to a full disc and on to a crescent again before is seems to disappear then start all over again. This is a direct result of the Moon's orbit around Earth, and the different shapes we observe are called *lunar phases*.

The following diagram[4] shows the Moon in different positions along its orbit around Earth, and the phases when viewed from the southern hemisphere of Earth.



The Sun is off in the distance, lighting the Earth-Moon system. At any point, half of the Moon is illuminated by the Sun (the light side of the Moon) and half is not (the dark side). Also, half of the Moon is visible to the Earth (the near side of the Moon) and half is not (the far side). As the Moon moves around the Earth, we can see different fractions of the illuminated half of the Moon. When the Moon is between the Earth and the Sun (1), the near side of the Moon is the dark side. The Moon cannot be seen. We call this New Moon, the beginning of a new cycle of lunar phases. When the Earth is between the Sun and the Moon (5), the near side is the light side. We call this Full Moon, even though we only see half the Moon. Halfway in between these times (3 & 7), only half of the near side of the moon is illuminated by the Sun. So we can only see one quarter of the Moon. We call these phases First and Third Quarters. All the phases of the Moon have special names that indicate how much of the

[4] http://www.windows.ucar.edu/tour/link=/the_universe/uts/moon2.html

illuminated Moon can be seen from Earth, and whether this part is going to grow or shrink.

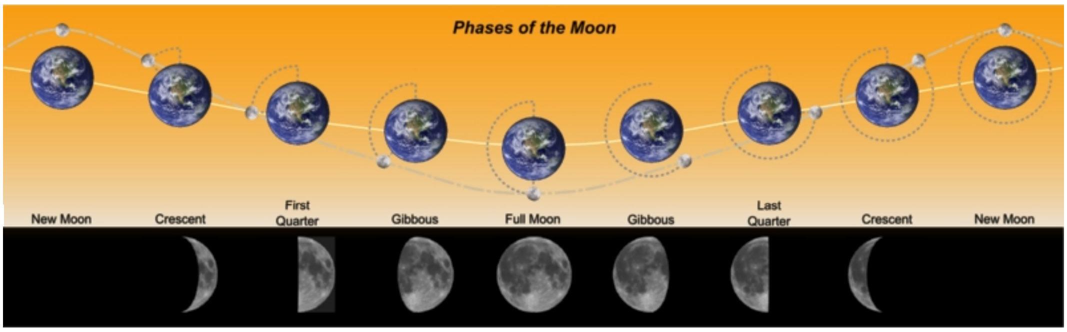
Note that the New Moon rises at sunrise and sets at sunset, and the Full Moon rises at sunset and sets at sunrise.

To many early civilisations, the Moon's monthly cycle was an important tool for measuring the passage of time. In fact many calendars are synchronised to the phases of the Moon. The Hebrew, Muslem and Chinese calendars are all lunar calendars. The New Moon phase is uniquely recognized as the beginning of each calendar month just as it is the beginning on the Moon's monthly cycle. When the Moon is New, it rises and sets with the Sun because it lies very close to the Sun in the sky. Although we cannot see the Moon during New Moon phase, it has a very special significance with regard to eclipses.

7.1.4.2.1 How Do the Phases Get Their Names?[5]

When the Moon appears smaller than a quarter, we call it a crescent. When the Moon appears larger than a quarter, we call it gibbous. When the moon is getting bigger (phases New to Full) it is waxing. When it is getting smaller (phases Full to New) it is waning. For example, if today the Moon were a waxing crescent, then tomorrow the crescent shape would continue to grow larger, approaching First Quarter. After First Quarter, the Moon would be a waxing gibbous, and continue growing until it reached Full. The Moon would then begin to shrink, becoming first a waning gibbous and eventually reaching Last (or Third) Quarter. Following Last Quarter it becomes a waning crescent, and continues to shrink until it becomes invisible at New Moon.

Note that, when viewed from the southern hemisphere of Earth, the Moon always grows or shrinks from the left to the right. When viewed from the northern hemisphere, everything is the other way around—the Moon grows or shrinks from right to left and the phases are the mirror images of the ones illustrated above.

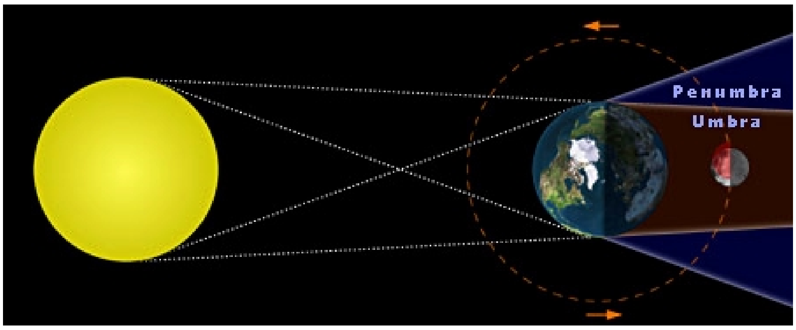


7.1.4.3 Eclipses

7.1.4.3.1 Lunar Eclipses

A lunar eclipse occurs when the Moon passes through the Earth's shadow. The image below[6] helps to explain how the Earth's shadow causes a lunar eclipse. Notice the difference between the umbra and the penumbra.

[5] http://www.windows.ucar.edu/tour/link=/the_universe/uts/moon3.html
[6] http://www.mreclipse.com/Special/LEprimer.html



Geometry of the Sun, Earth and Moon
During an Eclipse of the Moon

Lunar eclipses are special events that only occur when certain conditions are met. First of all, the Moon must be in Full phase. Secondly, the Sun, Earth and Moon must be in a perfectly straight line. If both of these conditions are met, then the Earth can block the Sun's light from the Moon.

There are three types of lunar eclipse. Note first that the Earth's shadow comprises two parts: the umbra, the darker part of the shadow, where no part of the Sun can been seen, and the penumbra, the lighter part of the shadow where part of the Sun can be seen. When part of the Moon passes through the umbra, we see a partial eclipse. When all of the Moon passes through the umbra, we see a total eclipse. Finally, when the Moon only passes through the penumbra, we see a penumbral eclipse.

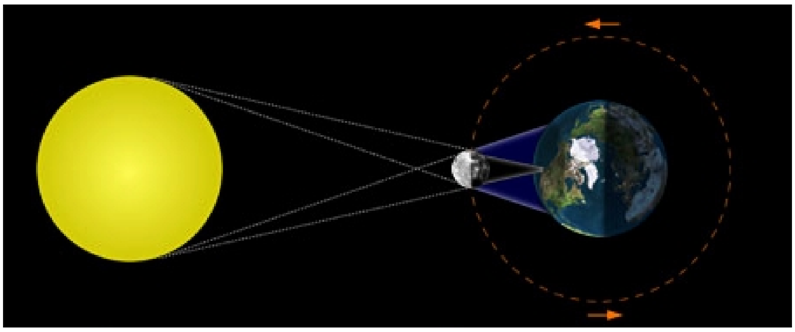
The next lunar eclipse that will be visible in Australia will be a total eclipse and will occur on 28 August 2007[7].

7.1.4.3.2 Solar Eclipses[8]

An eclipse of the Sun (or solar eclipse) can only occur at New Moon, when the Moon passes between Earth and the Sun. If the Moon's shadow happens to fall upon Earth's surface at that time, we see some portion of the Sun's disc covered or 'eclipsed' by the Moon.

The term eclipse is actually a misnomer in this case because the phenomenon of the Moon's passing in front of the Sun is actually an *occultation*. Properly speaking, an eclipse occurs when an object passes into the shadow cast by another object. When the Moon disappears at Full Moon by passing into Earth's shadow, the event is properly called an eclipse, but when the Moon passes in front of the Sun, we see an occultation of the Sun by the Moon.

[7] "Australian Sky Guide", Dr Nick Lomb, Powerhouse Publishing, 2006 [ISBN 1 86317 118 5]
[8] http://en.wikipedia.org/wiki/Solar_eclipse



Geometry of the Sun, Moon and Earth During a Solar Eclipse[9]

As previously noted, the Moon's orbit around the Earth is inclined at an angle of just over 5° to the plane of the Earth's orbit around the Sun (the ecliptic). Because of this, at the time of a New Moon, the Moon will usually pass above or below the Sun. A solar eclipse can occur only when the New Moon occurs close to one of the points (known as nodes) where the Moon's orbit crosses the ecliptic – hence the name.

The elliptical nature of the Moon's orbit also means that the distance of the Moon from the Earth can vary by about 6% from its average value. This means that the apparent size of the Moon is sometimes larger or smaller than average, and it is this effect that leads to the difference between total and annular eclipses (the distance between the Earth and the Sun also varies during the year, but this has a smaller effect). On average, the Moon appears to be slightly smaller than the Sun, so the majority (about 60%) of central eclipses are annular. It is only when the Moon is closer to the Earth than average (near its perigee) that a total eclipse occurs.

The next solar eclipse that will be visible in Australia will occur on 14 November 2012[18]. This will only be seen as a total eclipse in North Queensland, elsewhere in Australia, it will only be seen as a partial eclipse.

7.1.4.3.3 Types of Solar Eclipse

The Moon's shadow actually has two parts:

Penumbra	Faint outer shadow; partial eclipses are seen from within this shadow.
Umbra	Dark inner shadow; total eclipses are seen from within this shadow.

When only the Moon's penumbral shadow strikes Earth, we see a partial eclipse of the Sun from that region. Partial eclipses are dangerous to look at because the un-eclipsed part of the Sun is still very bright. You must use special filters or a home-made pinhole projector to safely watch a partial eclipse of the Sun (see: Eclipses & Eye Safety).

However, if the Moon's dark umbral shadow sweeps across Earth's surface, then a total eclipse of the Sun is seen. The track of the Moon's shadow across Earth's surface is called the Path of Totality. It is typically 10,000 miles long but only 100 miles or so wide. In order to see the Sun totally eclipsed by the Moon, you must be in the path of totality.

There are four types of solar eclipse:

- A **total eclipse** occurs when the Sun is completely obscured by the Moon. The intensely bright disk of the Sun is replaced by the dark outline of the Moon, and the much fainter corona is visible. During any one eclipse, totality is visible only from at most a narrow track on the surface of the Earth.

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[9] http://www.mreclipse.com/Special/SEprimer.html

- An **annular eclipse** occurs when the Sun and Moon are exactly in line, but the apparent size of the Moon is smaller than that of the Sun. Hence the Sun appears as a very bright ring surrounding the outline of the Moon.
- A **hybrid eclipse** is intermediate between a total and annular eclipse. At some points on the Earth it is visible as a total eclipse, while at others it is annular. The generic term for a total, annular or hybrid eclipse is a **central eclipse**.
- A **partial eclipse** occurs when the Sun and Moon are not exactly in line, and the Moon only partially obscures the Sun. This phenomenon can usually be seen from a large part of the Earth outside of the track of a central eclipse. However, some eclipses can only be seen as a partial eclipse, because the central line never intersects the Earth's surface.

The reason some solar eclipses are total and others are annular has to do with the elliptical nature of the Moon's orbit around Earth. One of the most remarkable coincidences in nature is that (i) the Sun lies about 400 times as far from Earth as does the Moon, and (ii) the Sun is also about 400 times the diameter of the Moon. As seen from Earth, therefore, the Sun and the Moon appear to be about the same size in the sky - about 1/2 of a degree in angular measure. Because the Moon's orbit around Earth is an ellipse rather than a circle, however, at some times during the month the Moon is further away, and at other times it is closer to Earth, than average.

When a solar eclipse occurs while the Moon is at its closest (near its perigee), it appears large enough to cover the bright disk, or photosphere, of the Sun completely, and a total eclipse occurs. When it is at its farthest, however (near apogee), it appears smaller, and it cannot cover the Sun completely. In that case, at the time of greatest eclipse there remains a thin annulus (or ring) of brilliant Sun left uncovered. Hence the term annular eclipse. Slightly more annular eclipses than total eclipses occur, because on average the Moon lies too far away from Earth to cover the Sun completely.

7.1.4.3.4 Path of a Solar Eclipse

During a central eclipse, the Moon's umbra (or antumbra, in the case of an annular eclipse) moves rapidly from west to east across the Earth. The Earth is also rotating from west to east, but the umbra always moves faster than any given point on the Earth's surface, so it almost always appears to move in a roughly west-east direction across a map of the Earth (there are some rare exceptions to this which can occur during an eclipse of the midnight sun in Arctic or Antarctic regions).

The width of the track of a central eclipse varies according to the relative apparent diameters of the Sun and Moon. In the most favourable circumstances, when a total eclipse occurs very close to perigee, the track can be over 250 km wide and the duration of totality may be over 7 minutes. Outside of the central track, a partial eclipse can usually be seen over a much larger area of the Earth.

7.1.4.3.5 Frequency of Solar Eclipses

The Moon's orbit intersects with the ecliptic at two nodes that are 180° apart. Therefore, the New Moon occurs close to the nodes at two periods of the year approximately six months apart, and there will always be at least one solar eclipse during these periods. Sometimes the New Moon occurs close enough to a node during two consecutive months. This means that in any given year, there will always be at least two solar eclipses, and there can be as many as five. However, some are visible only as partial eclipses, because the umbra passes either above or below the earth, and others are central only in remote regions of the Arctic or Antarctic.

Total solar eclipses are rare events. Although they occur somewhere on Earth approximately every 18 months, it has been estimated that they recur at any given place only once every 370 years, on average (Stephenson[10], p.54). Then, after waiting so long, the total eclipse only lasts for a few minutes, as the Moon's umbra moves eastward at over 1700 km/h. Totality can never last more than 7 min 40 s, and is usually much shorter. During each millennium there are typically fewer than 10 total solar eclipses exceeding 7 minutes. The last time this happened was June 30, 1973. Observers aboard a Concorde aircraft were able to stretch totality to about 74 minutes by flying along the path of the Moon's umbra. The next eclipse of comparable duration will not occur until June 25, 2150. The longest total solar eclipse during the 8,000-year period from 3000 BC to 5000 AD will occur on July 16, 2186, when totality will last 7 min 29 s. (eclipse predictions by Fred Espenak, NASA/GSFC.)

For astronomers, a total solar eclipse forms a rare opportunity to observe the corona (the outer layer of the Sun's atmosphere). Normally this is not visible because the photosphere is much brighter than the corona.

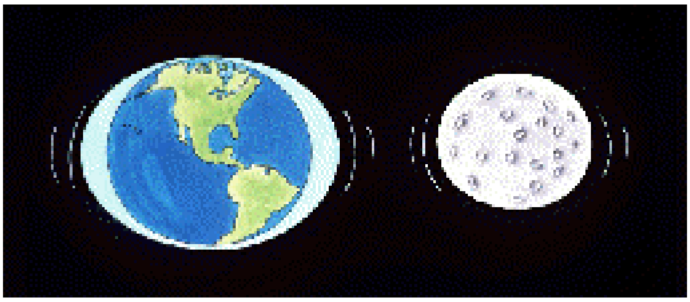
7.1.4.3.6 Summary

- The Moon is eclipsed when it moves into the Earth's shadow and thus does not receive the Sun's light;
- The Sun is eclipsed (occulted) when the Moon's shadow falls on part of the Earth, thus cutting off the Sun's light from that part of the Earth;
- An eclipse of the Moon occurs when the Moon is Full;
- An eclipse (occultation) of the Sun occurs at New Moon.

7.1.4.4 Tidal Forces

Tidal forces are secondary effects resulting from gravitational forces. They exist because the gravitational force imposed by one body on another is greater on the near side of the second body than it is on the far side—a tidal force is not a force as such, it is really only a force differential. Because planets are not perfectly rigid, they deform when subjected to external gravitational fields as if they were being pushed from the top and bottom, bulging out at the sides. Earth also bulges at the Equator because it is spinning, but this is more regular than the bulging caused by tidal deformation. The gravitational forces imposed by the Moon are the ones most responsible for the tidal forces experienced on Earth. The Sun's gravitational field also has an effect in this regard, but it is smaller, only about 46% of that of the Moon.[11]

On Earth, near the ocean, the effect of tidal forces can be seen as the regular rising and falling of the ocean's surface—the ocean water rises high along the beach, twice each day.



[10] Stephenson F.R., *Historical Eclipses and Earth's Rotation*, Cambridge Univ. Press, 1997

[11] http://en.wikipedia.org/wiki/Tide

The illustration[12] shows the Earth and the Moon, and the bulges produced on each side of both bodies as a result of tidal forces. While on Earth we see the effect of tidal forces in the rising and falling of the oceans, on the Moon, where there are no oceans, the effect is not so obvious. Nonetheless, the surface of the Moon is also deformed by the tidal forces imposed by the Earth.

Unlike the more or less uniform bulging at the Equator caused by the Earth's rotation, tidal bulging occurs on either side of a body, in line with the relevant gravitational force. In the case of the Earth, tidal bulges occur on the sides of the Earth nearest to and farthest away from the Moon, although the bulging on the side facing the Moon is greater than that on the opposite side.

The tidal flow period on Earth, but not the phase, is, in fact, synchronised to the Moon's orbit around Earth. The tidal bulges on Earth, caused by the Moon's gravity, are carried ahead of the apparent position of the Moon by the Earth's rotation, in part because of the friction of the water as it slides over the ocean bottom and into or out of bays and estuaries. As a result, some of the Earth's rotational momentum is gradually being transferred to the Moon's orbital momentum, resulting in the Moon slowly receding from Earth at the rate of approximately 38 mm per year. At the same time the Earth's rotation is gradually slowing, the Earth's day thus lengthens by about 15 μs every year.

7.1.4.4.1 The Ocean Tides

The ocean tides are the most obvious manifestation of the tidal forces that play on the Earth and they vary with the relative positions of the Sun and the Moon.

When the moon is Full or New, the gravitational pull of the Sun and Moon are combined because they are aligned. At these times, the high tides are very high and the low tides are very low—these are known as *Spring Tides*, although they have nothing to do with the season Spring.

During the Moon's quarter phases, the gravitational forces of the Sun and Moon work at right angles and their respective tidal forces cancel each other out to some extent. The result is a smaller difference between high and low tides—these are known as *Neap Tides*.

The *Proxigean Spring Tide* is a rare, unusually high tide. It occurs at most once every 1.5 years, when the Moon is both unusually close to the Earth (at its closest perigee, called the proxigee) and in the New Moon phase (when the Moon is between the Sun and the Earth).

7.1.4.4.2 Tidal Terminology

The maximum water level is called "high tide" or "high water" and the minimum level is "low tide" or "low water". High water occurs as two bulges in the height of the oceans; one bulge faces the Moon and the other, on the opposite side of the Earth, faces away from the Moon. For an explanation see below under Tidal physics. There are two low waters positioned at about 90° of longitude from the high waters. At any given point on the ocean, there are normally two high tides and two low tides each day. The common names of the two high tides are the "high high" tide and the "low high" tide; the two low tides are called the "high low" tide and the "low low" tide. On average, high tides occur 12 hours 24 minutes apart. The 12 hours is due to the Earth's rotation, and the 24 minutes to the Moon's orbit. The 12 hours is half of a solar day

[12] http://www.windows.ucar.edu/tour/link=/glossary/tidal_forces.html

and the 24 minutes is half of a lunar extension, which is 1/ (29-day lunar cycle). The lunar cycle is what is tracked by tide clocks.

The time between high tide and low tide, when the water level is falling, is called the "ebb". The time between low tide and high tide, when the tide is rising, is called "flow" or "flood". At the times of high tide and low tide, the tide is said to be "turning".

The height of the high and low tides (relative to mean sea level) also varies. Around new and full Moon when the Sun, Moon and Earth form a line, the tidal forces due to the Sun reinforce those of the Moon, due to the syzygy found at those times.

The tides' range is then at its maximum: this is called the "spring tide", or just "springs" and is derived not from the season of spring but rather from the Dutch verb springen, meaning "to leap up". When the Moon is at first quarter or third quarter, the sun and moon are at 90° to each other and the forces due to the Sun partially cancel out those of the Moon. At these points in the Lunar cycle, the tide's range is at its minimum: this is called the "neap tide", or "neaps".

Spring tides result in high waters that are higher than average, low waters that are lower than average, slack water time that is shorter than average and stronger tidal currents than average. Neaps result in less extreme tidal conditions. Normally there is a seven day interval between springs and neaps.

The relative distance of the Moon from the Earth also affects tide heights: When the Moon is at perigee the range increases, and when it is at apogee the range is reduced. Every 7.5 lunations, perigee and (alternately) either a New or Full Moon coincide; at these times the range of tide heights is greatest of all, and if a storm happens to be moving onshore at this time, the consequences (in the form of property damage, *etc.*) can be especially severe (surfers are aware of this, and will often intentionally go out to sea during these times, as the waves are more spectacular than ever). The effect is enhanced even further if the line-up of the Sun, Earth and Moon is so exact that a solar or lunar eclipse occurs concomitant with perigee.

7.1.4.4.3 Timing

In most places there is a delay between the phases of the Moon and its effect on the tide. Springs and neaps in the North Sea, for example, are two days behind the new/full Moon and first/third quarter, respectively. The reason for this is that the tide originates in the southern oceans, the only place on the globe where a circumventing wave (as caused by the tidal force of the Moon) can travel unimpeded by land.

The resulting effect on the amplitude, or height, of the tide travels across the oceans. It is known that it travels as a single broad wave pulse northwards over the Atlantic. This causes relatively low tidal ranges in some locations (nodes) and high ones in other places. This is not to be confused with tidal ranges caused by local geography, as can be found in Nova Scotia, Bristol, the Channel Islands, and the English Channel. In these places tidal ranges can be over 10 metres.

The Atlantic tidal wave arrives after approximately a day in the English Channel area of the European coast and needs another day to go around the British Isles in order to have an effect in the North Sea. Peaks and lows of the Channel wave and North Sea wave meet in the Strait of Dover at about the same time but generally favour a current in the direction of the North Sea.

The exact time and height of the tide at a particular coastal point is also greatly influenced by the local topography. There are some extreme cases: the Bay of Fundy, on the east coast of Canada, features the largest well-documented tidal ranges in the world, 16 metres (53 feet), because of the shape of the bay. Southampton in the United Kingdom has a double high tide caused by the flow of water around the Isle of Wight, and Weymouth, Dorset has a double low tide because of the Isle of Portland. Ungava Bay in Nunavut, north eastern Canada, is believed by some experts to have higher tidal ranges than the Bay of Fundy (about 17 metres or 56 feet), but it is free of pack ice for only about four months every year, whereas the Bay of Fundy rarely freezes even in the winter.

There are only very slight tides in the Mediterranean Sea and the Baltic Sea due to their narrow connections with the Atlantic Ocean. Extremely small tides also occur for the same reason in the Gulf of Mexico and Sea of Japan. On the southern coast of Australia, because the coast is extremely straight (partly due to the tiny quantities of runoff flowing from rivers), tidal ranges are equally small.

7.1.4.4.4 Tidal Physics

Ignoring external forces, the ocean's surface defines a geopotential surface or geoid, where the gravitational force is directly towards the centre of the Earth and there is no net lateral force and hence no flow of water.

Now consider the effect of added external, massive bodies such as the Moon and Sun. These massive bodies have strong gravitational fields that diminish with distance in space. It is the spatial differences, called the gradient in these fields that deform the geoid shape. This deformation has a fixed orientation relative to the influencing body and the rotation of the Earth relative to this shape drives the tides around. Gravitational forces follow the inverse-square law (force is inversely proportional to the square of the distance), but tidal forces are inversely proportional to the cube of the distance. The Sun's gravitational pull on Earth is on average 179 times bigger than the Moon's, but because of its much greater distance, the Sun's field gradient and thus its tidal effect is smaller than the Moon's (about 46% as strong). For simplicity, the next few sections use the word "Moon" where also "Sun" can be understood.

The Moon exerts its gravitational pull differently on different parts of the earth. The farther the Moon, the weaker its pull.

The Moon's gravity differential field at the surface of the earth is known as the Tide Generating Force. This is the primary mechanism that drives tidal action and explains two bulges, accounting for two high tides per day. Other forces, such as the Sun's gravity, also add to tidal action.

Since the Earth's crust is solid, it moves with everything inside as one whole, as defined by the average force on it. For a geoid shape this average force is equal to the force on its centre. The water at the surface is free to move following forces on its particles. It is the difference between the forces at the Earth's centre and surface which determine the effective tidal force.

At the point right "under" the Moon (the sub-lunar point), the water is closer than the solid Earth; so it is pulled more and rises. On the opposite side of the Earth, facing away from the Moon (the antipodal point), the water is farther than the solid earth, so it is pulled less and moves away from Earth, rising as well. On the lateral sides, the water is pulled in a slightly different direction than at the centre. The vectorial difference with the force at the centre points almost straight inwards to Earth. It can be shown that the forces at the sub-lunar and antipodal points are approximately equal and that the inward forces at the sides are about half that size. Somewhere in between (at 55° from the orbital plane) there is a point where the tidal force is parallel to the Earth's surface. Those parallel components actually contribute most to the formation of tides, since the water particles are free to follow. The actual force on a particle is only about a ten millionth of the force caused by the Earth's gravity.

These minute forces all work together:

- pull up under and away from the Moon
- pull down at the sides
- pull towards the sub-lunar and antipodal points at intermediate points

So two bulges are formed pointing towards the Moon just under it and away from it on Earth's far side.

7.1.4.4.5 Tidal Amplitude and Cycle Time

Since the Earth rotates relative to the Moon in one lunar day (24 hours, 48 minutes), each of the two bulges travels around at that speed, leading to one high tide every 12 hours and 24 minutes. The theoretical amplitude of oceanic tides due to the Moon is about 54 cm at the highest point. This is the amplitude that would be reached if the ocean were uniform with no landmasses and Earth not rotating.

The Sun similarly causes tides, of which the theoretical amplitude is about 25 cm (46% of that of the Moon) and the cycle time is 12 hours.

At spring tide the two effects add to each other to a theoretical level of 79 cm, while at neap tide the theoretical level is reduced to 29 cm.

Real amplitudes differ considerably, not only because of global topography as explained above, but also because the natural period of the oceans is in the same order of magnitude as the rotation period: about 30 hours (by comparison, the natural period of the Earth's crust is about 57 minutes). This means that, if the Moon suddenly vanished, the level of the oceans would oscillate with a period of 30 hours with a slowly decreasing amplitude while dissipating the stored energy. This 30 hour value is a simple function of terrestrial gravity and the average depth of the oceans.

The distances of Earth from the Moon or the Sun vary, because the orbits are not circular, but elliptical. This causes a variation in the tidal force and theoretical amplitude of about ±18% for the Moon and ±5% for the Sun. So if both are in closest position and aligned, the theoretical amplitude would reach 93 cm.

7.1.4.4.6 Tidal Lag

Because the Moon's tidal forces drive the oceans with a period of about 12.42 hours (half of the Earth's synodic period of rotation), which is considerably less than the natural period of the oceans, complex resonance phenomena take place. The lag between the Moon's passage and the tidal response varies between 2 hours in the southern oceans, to two days in the North Sea. The global average tidal lag is six hours (which means low tide occurs when the Moon is at its zenith or its nadir, a result that goes against common intuition). Tidal lag and the transfer of momentum between sea and land causes the Earth's rotation to slow down and the Moon to be moved further away in a process known as tidal acceleration.