Lunar Exploration

Apollo 17 astronaut Harrison Schmitt working next to a huge boulder with the Lunar Roving Vehicle nearby. Since there is no atmosphere or weather on the Moon, the imprints of the astronauts' boots and the tracks made by the lunar rover will remain unchanged for many millions of years, until they are gradually obliterated by the impacts of micro-meteorites.

More than **50 missions** to the Moon have been launched by the USA and Russia (formerly the USSR) since 1959. Lunik 3, which flew past the Moon in 1959, was **the first to photograph its far side**. The ambitious Apollo project sent **27 astronauts** to the Moon between 1968 and 1972, twelve of whom landed on the surface. During the last three Apollo missions, more than 50 tonnes of men and equipment were transported from Earth to the lunar bases at Hadley Rille, Cayley Plain and Taurus-Littrow. A total of **381.7 kg of rock samples** were brought back. Three quarters of it is still preserved for future researchers.

The astronauts found the Moon a **barren and forbidding** place. Because **there is no atmosphere**, the sky is permanently black and starry. However, to see the stars during lunar daytime would be difficult because of the direct sunlight and the sunlight scattered from the surface. The lunar night lasts a little over two weeks because the Moon takes 27.3 days to rotate once on its axis and another two days to catch up with its motion around the Sun. The temperature at night drops to **–190 °C** – so cold that oxygen would liquefy. In contrast, during the lunar day the surface can get as hot as **120 °C**, above the boiling point of water. The surface is **very dry**. Any water would immediately boil off into the vacuum of space. As a result, **there is no trace whatsoever of life** on the surface.

The Earth in the sky over the Moon's horizon as the Apollo 11 ascent stage approaches the orbiter.

Exploring the Moon

Experiments on the Moon

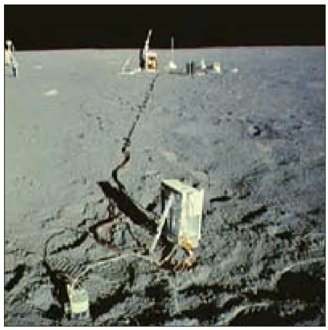
Apollo 11 Solar Wind Collector.

Many **scientific experiments** were done during the Apollo missions. In one, astronauts used a length of aluminium foil to trap particles streaming from the Sun in what is called the "**solar wind**".

Moonquakes

Apollo astronauts set up **seismic stations** to detect moonquakes and to radio the results back to Earth. Over a period of eight years the largest quakes were equivalent to a modest magnitude 4 on the Richter scale. These are weak by Earth standards and indicate that the Moon **does not have active tectonic plates**. Also, after a quake, the energy "echoes" around the inside of the Moon for many minutes – we can say that the Moon "**rings like a bell**". This shows that the interior is made mainly of **solid** and not liquid material. With molten rock, the energy would be absorbed much more quickly.

The seismometers have also measured the effects of **objects hitting the Moon**. Seismic waves were created by deliberately crashing Apollo Lunar Ascent Modules onto the surface. This allowed the seismometers to be calibrated and the nearby subsurface structure to be investigated. Also, as expected, many **meteorite impacts** have been detected.



Apollo 14 seismometer.

Apollo missions also set up special **reflectors** on the surface. Even today, **pulses of laser light** are sent from the Earth and the time taken for the pulse to return is measured. Using the speed of light, the **distance to the Moon** is calculated. Studies show that the Moon is **moving away** from the Earth by a few centimetres per year.

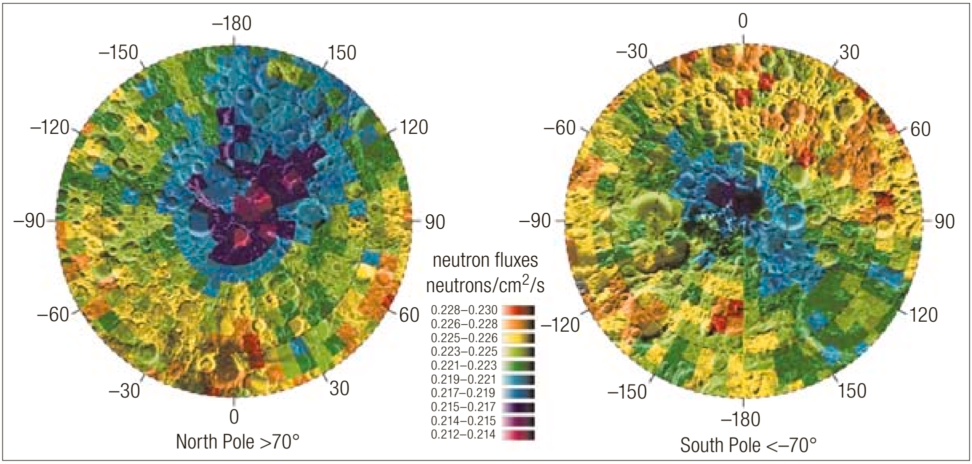
The laser results show that **the Moon wobbles** a little. As the outer layers must have cooled and solidified long ago, the wobble might well be caused by a partially molten inner region.

Apollo 14 reflector and astronaut's footprint.

After the Apollo Missions

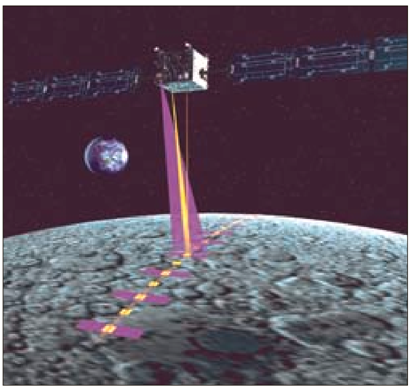
Clementine (1994) made images of the surface in several colours to determine the nature of the **surface rocks**. It also used a **laser altimeter** to make surface height maps and its radar gave some indication of **ice near the poles**.

Lunar Prospector (1998/9) was placed in a low polar orbit. In particular it looked for **ice deposits**. To do this it measured the **energy of neutrons** emitted from the surface. Their energy spectrum showed that **hydrogen** was present and by implication **water**. There could be as much as **300 million tonnes** of water ice on the floors of deep craters where the Sun never shines.



Evidence of water (purple) at the poles of the Moon. (LUNAR PROSPECTOR. LOS ALAMOS NATIONAL LABORATORY)

SMART-1 (2003/5) is a European Space Agency mission to orbit the Moon and **test miniaturized technologies** needed for missions to the planets. To reach lunar orbit it has used a solar-powered ion drive engine. From orbit it has taken images even of the poorly lit **polar regions**. Its infrared spectrometer has searched for water and carbon dioxide ice in the permanently shadowed craters near the poles. Its X-ray spectrometer has made the first complete **chemical map** of the Moon's surface. See: **http://www.esa.int**



Three remote-sensing instruments on SMART-1 scanned the Moon's surface simultaneously. (AOES MEDIALAB, ESA)

Moon rocks

If anyone had been in any doubt, **samples of rock** from the Moon soon proved that the "**mare**" areas could not possibly be dried-up seas. All Moon rocks are of the kind called **igneous**. They have all at one time in the past been **hot and molten**.

The dark mare rocks are **basalts**, relatively rich in iron and titanium. From 3000 to 4000 million years ago giant impacts created **huge basins** in the surface. At various times, over a period of several hundred million years, molten basalt rock flooded out from the mantle to **fill these basins**. After the Moon's interior cooled, molten rock no longer erupted and most of the familiar features of the Moon had been created.

The light-coloured **highland rocks** are different from those in the maria. They are called **anorthosites** and are rich in aluminium and calcium. They are not as dense as the rocks containing iron, so they "floated" on top of the iron-containing rocks when the Moon was molten.

Apollo 15 Mare Basalt. This dark rock has small holes covering about a third of its surface. They were created when the lava from which it formed was exposed to the vacuum of the lunar surface. Gas that had been dissolved in the lava came out of solution to form bubbles, some of which were frozen in place as the rock cooled. (NASA)

Apollo 16 Polymict Breccia. This light-coloured rock is like many lunar rocks and is made from pieces of older rocks, shattered by early impacts. These kinds of rocks are called breccias. This example from the lunar highlands was probably pressed together 3.9 billion years ago, but its small component rocks are up to half a billion years older still. (NASA)

A meteorite from the Moon

Fragments ejected from the Moon by **impacts** are sometimes found on Earth as meteorites. It is possible to tell that they have come from the Moon by comparing them with the samples collected on the lunar surface. They are important because they come from all over the Moon, including **the far side**. This one was found in the Allan Hills of Antarctica in 1981 and was the first lunar meteorite to be identified. It came from the **lunar highlands** and is made up of **particles of all sizes**. This is one of the ways to tell that a meteorite came from the Moon. For scale, the block is a 1 cm cube. (NASA/JSC)

Borrow some Moon rock! Some of the 382 kg of lunar material brought back by the Apollo astronauts has been set aside for **educational use**. In the UK, the Particle Physics and Astronomy Research Council (PPARC) administers a **free loan scheme** for schools, universities, museums and astronomical societies. For details, contact: PPARC, Polaris House, North Star Avenue, Swindon, SN2 1SZ. Tel: 01793 442030. www.pparc.ac.uk

This amazing mosaic image was created by UK amateur astronomer Ken Florey. Using a 4 inch refracting telescope, Ken photographed the surface near the terminator (the line dividing the sunlit from the night-time surface of the Moon) over the whole range of Moon phases. Near the terminator, the “dawn shadow” on the Moon greatly accentuates the topography. Ken then combined the images digitally.

The Moon

The Moon is **the Earth’s closest neighbour** in space and can be the brightest object in the sky other than the Sun. The distance from the centre of the Moon to the centre of the Earth is less than one hundredth the distance to the nearest planet, Venus. As the Moon’s orbit is **slightly elliptical**, the Earth–Moon distance varies from 356 400 km to 406 700 km. The Moon orbits the Earth every 27.3 days but the interval between Full Moons is two days longer than this because the Earth is orbiting the Sun. The Moon always keeps **one side facing towards Earth**, apart from slight “wobbles”, called “**librations**”, which cause 59% of the Moon’s surface to be visible from the Earth at some time.

The Moon is 3476 km in diameter, roughly **one quarter of that of the Earth**. This makes it bigger than Pluto and 71% the size of Mercury. As a proportion of its parent planet our Moon is larger than any other moon in the solar system, with the exception of Pluto's moon, Charon, and some Edgeworth–Kuiper Belt objects. For this reason, astronomers sometimes describe the Earth and the Moon as a “**double planet**”. However, the two worlds could hardly be more different. The Moon has a dry, grey, rocky surface and **no atmosphere**.

The age of the Solar System is 4.567 billion years and the age of the Earth–Moon system is about **4.5 billion years**.

ROYAL ASTRONOMICAL SOCIETY QUICQUID NITET NOTANDUM 1820
Advancing Astronomy and Geophysics

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The Moon through the Year

First sighting after New Moon

Many **calendars** are based on lunar months. Often the new month starts the day after a declared first sighting of the **young crescent Moon**. The first glimpsing of the thin crescent is particularly important for Muslims when it marks the start of the holy month of Ramadan. The record for sighting the new crescent with a telescope or binoculars is about 12 hours past actual new Moon. The record for a naked-eye sighting is about 15.5 hours.

Names for the Full Moon

Many people have heard of the names "Harvest Moon" and "Hunter's Moon" for the Full Moons of September and October, but there are other less well-known names handed down in folklore, which reflect the passing of the seasons with the lunar months. Here are some of them:

January	Wolf Moon, Winter Moon
February	Snow Moon, Hunger Moon
March	Crow Moon, Lenten Moon
April	Egg Moon, Planter's Moon
May	Milk Moon, Flower Moon
June	Rose Moon, Strawberry Moon
July	Thunder Moon, Hay Moon
August	Green Corn Moon, Grain Moon
September	Harvest Moon, Fruit Moon
October	Hunter's Moon, Falling Leaves Moon
November	Frosty Moon, Freezing Moon
December	Long Night Moon, Christmas Moon

Blue Moon

In recent years the phrase "**Once in a Blue Moon**" has been used to describe the occurrence of two Full Moons in one calendar month. This relatively rare event occurs, on average, about seven times every 19 years.

Why do Harvest Moons look so large?

When the Moon is full and low in the sky, it looks much larger than normal. This is an **optical illusion**. Your eye and brain see the bright Moon near objects on the ground and so "think" it is large. You can check that the Moon is not larger than normal by holding your hand at arm's length and checking that you can **just cover the Moon with your thumb**. This is also true when the Moon is high in the sky. You can also make the Harvest Moon return to its "normal" size by bending over and looking at it through your legs! Or you can look at it in a mirror. Both these tricks break the brain's links to the surrounding objects.

Easter

Easter occurs on the first Sunday after the theoretical Full Moon that occurs on or after 21 March, although the true vernal (spring) equinox currently occurs around 20 March. If the Full Moon falls on a Sunday, Easter is celebrated on the next Sunday. This method is used by Western Christian Churches and Easter can fall between 22 March and 25 April. Eastern Churches can celebrate Easter up to five weeks later. See: **www.nmm.ac.uk**

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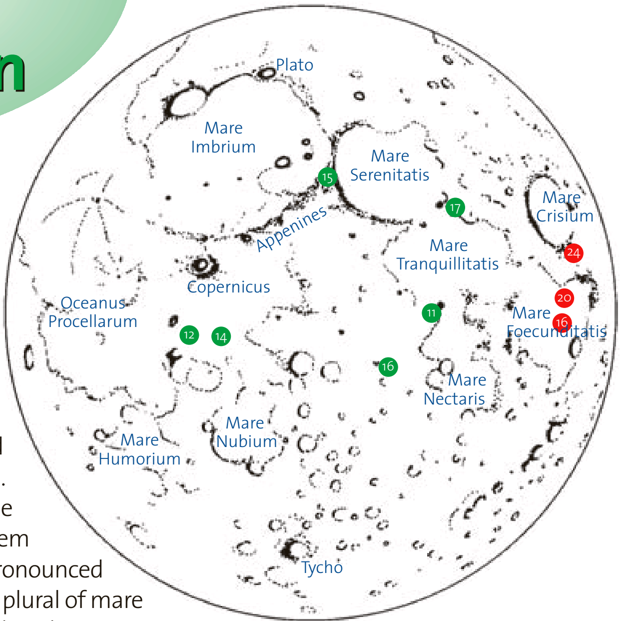
The Face of the Moon



The main features of the Moon visible from Earth, showing the landing sites for missions that brought back surface samples: Luna (red), Apollo (green).

The Moon always keeps the same side facing Earth, so until the Soviet spacecraft **Lunik 3** went round the Moon, nobody had seen **the far side**. The map here shows the main features on the side visible from Earth. The larger features can be seen with the **naked eye**, and a wealth of detail is revealed using binoculars or a small telescope.

Early astronomers thought that the dark grey areas were seas, so gave them names including the word "**mare**" (pronounced "mar-ray"), which is Latin for sea. The plural of mare is **maria** ("mar-er-a"). We now know that these areas are **solidified lava** and never had water in them. Early in its history the Moon suffered **massive impacts** from asteroids that created very large basins (e.g. Mare Imbrium). These then filled with molten lava to make the basins smooth like seas. When the lava cooled it formed darker rocks called **basalts**. The maria are mainly found on the near-side of the Moon. The lighter areas of the Moon's surface are the **lunar highlands** and are largely composed of the white rock **anorthosite**.

Craters are circular depressions ranging in size from about 300 km in diameter down to tiny pits only a few millimetres across. Almost all of these craters were excavated when rocks of various sizes rained down on the lunar surface; they are not the result of volcanic activity. Most of the cratering took place more than **3000 million years ago** when there were still many large rocky objects left over from the formation of the Solar System. As time went by, the large rocks were swept up and only smaller asteroids and meteorites were left. You can see this by looking at the maria. In their flat surfaces, you only see medium to small craters that have been formed more recently. Some of the craters formed within the last few hundred million years are surrounded by **bright rays of ejected rocks** stretching for many hundreds of kilometres.

On the far side of the Moon there are **more craters but fewer maria**.

Rate of crater formation

During the first 800 million years of the Moon's history there were **frequent impacts**. The earliest history of cratering is not well understood, because **the most ancient craters have been erased** by subsequent ones. Near the end of this intense bombardment, several large impacts created **the mare basins**. For the last 3.5 billion years, the impact rate has been only one ten-thousandth of that during the most intense bombardment.

The Lunar Surface and Beneath

There is no atmosphere around the Moon to shield its surface and it does not have a magnetic field to deflect electrically charged particles streaming out from the Sun. The surface rocks are bombarded continuously by **micro-meteorites**, by **cosmic rays** and by **the solar wind**. Over the Moon's lifetime, these tiny impacts have broken up the surface and made a layer of fine-grained rubble called the "**regolith**". It is a bit like soil, except that it is made only of rocks and minerals. The mixing of the regolith by constant bombardment on this small scale is sometimes called "**lunar gardening**". Over the highland regions, which are the oldest parts of the Moon's surface, the regolith is more than 15 metres thick in places. In the maria it is more usually 2 to 8 metres thick.

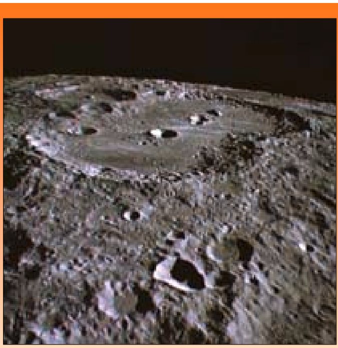
A foot-pad of Apollo 14, showing the surface texture ranging from dust to small rocks. Apollo 14 landed in the lunar highlands near the crater Fra Mauro.

The rocks on the surface are continuously altered by cosmic rays. These are mostly **very high-speed protons, helium and carbon nuclei**. As a result, the rocks contain a unique record of cosmic ray and solar activity over the last 5 billion years.

The Moon probably has a **crust, mantle and core**. The crust is on average about 60 km thick on the Earth-facing side and about 110 km thick on the far side. However, its thickness is almost zero under the Mare Crisium.

The crust and solid upper mantle form a fairly uniform **lithosphere** about 1000 km thick. Below this there is probably a partly liquid **asthenosphere**. If the Moon has an **iron-rich core**, it is probably less than 700 km in diameter.

Some rocks collected from the surface hint at an **ancient magnetic field**, but the Moon has no magnetic field now.



Craters

Craters feature everywhere on the lunar surface. The large oval crater in this picture – taken by the Apollo 17 orbiter – is Van de Graaff, and is on the far side of the Moon. It is 243 km across and has the form of **two large craters merged together**. There are several fresher looking craters inside it that were formed by **later impacts**. The crater beyond and to the left of Van de Graaff has a central peak caused by material that rebounded after the initial impact. Sunlight is coming from the right, casting deep shadows within the craters.

The Origin of the Moon

Here are four ways that the Earth could have acquired its Moon:

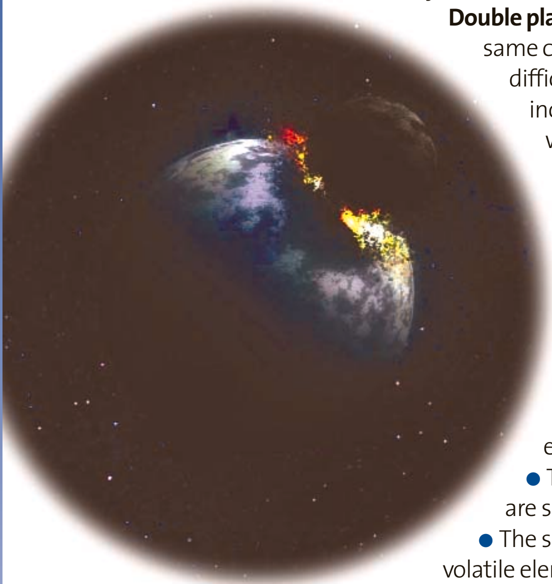
Capture: The Moon could have been fully formed in another part of the Solar System before it was captured by the Earth. However, capture is unlikely as the Moon would have needed exactly the correct speed and direction for capture to be possible. Also, the surface rocks of the Moon and the Earth are quite similar. It is difficult to imagine this happening by chance, so ruling out capture.

Fission (splitting): George Darwin (1845–1912) proposed that, early in its life, the Earth may have been spinning so quickly that a bulge formed and was thrown off to form the Moon. However, there is no evidence that there have ever been such rapidly spinning objects in our Solar System.

Double planet: The Earth and Moon formed out of the same cloud of gas and dust. However, it is then difficult to explain why the orbit of the Moon is inclined at 5° to that of the Earth (ecliptic). Also why the Earth is 1.6 times as dense as the Moon.

Giant impact: Now the preferred explanation. At a time when the Earth was molten and after the heavier elements had collected in its core, a "Mars-sized" planet struck the Earth a severe blow. This lifted a large amount of the Earth's crust and mantle into orbit. The crust and mantle of the impactor were also thrown into orbit. This mixture of material went on to form the Moon. This explains why:

- The surface rocks of the Moon and the Earth are similar but not identical in type.
- The surface rocks of the Moon lack water and volatile elements. These evaporated into space as a result of the high temperatures generated by the impact.
- The density of the Moon is lower than that of the Earth. It is mainly made of crustal and mantle material.
- The Moon probably has only a very small iron core. There was very little iron in the Earth's crust and mantle.



A monstrous collision 5 billion years ago between the newly formed Earth and a Mars-sized planet. (ESA 2002. ILLUSTRATION BY MEDIALAB)

Shaping the Moon

After the surface of the Moon solidified, **the inside heated up and melted** because of energy released by the radioactive decay of elements such as **uranium and thorium**. Some of the debris left over from the formation crashed back onto the surface, perhaps producing some of the giant old craters we see today. **Molten lava** then welled up to fill the low-lying regions, giving rise to the maria. These processes had largely ended by 3000 million years ago.

Phases of

The appearance of the Moon as seen in the night sky changes gradually from night to night and from season to season. Each month the Moon goes through its cycle of phases.

Why does the Moon have phases?

The Moon shines by **reflecting sunlight**. Only the side of the Moon facing the Sun is bright. As the Moon travels round the Earth over the course of a month, the portion of the sunlit half facing the Earth changes so we see the Moon go through its phases. The Moon rises (and sets) about an hour later each night because of its motion in orbit around the Earth.

New Moon

When the Moon lies in the direction of the Sun, its unlit side is facing us. This side is very dark and at this time of the month the Moon is very close to the Sun in the sky so that it is impossible to see the Moon at all. This is called the time of "New Moon". A couple of days later, when the Moon has moved around its orbit a little, we can see the narrow crescent of the sunlit side. This phase is often called "New Moon", although the Moon is already about two days "old". Sometimes the remaining dark part of the face can be seen as "The Old Moon in the Young Moon's Arms", as it shines by light reflected from the nearby fully illuminated Earth.

First Quarter

A week after New Moon, the Moon has gone a quarter of the way round its orbit. The phase at this stage is called "First Quarter" and we see half of the sunlit side, i.e. a quarter of the whole surface.

Towards Full Moon

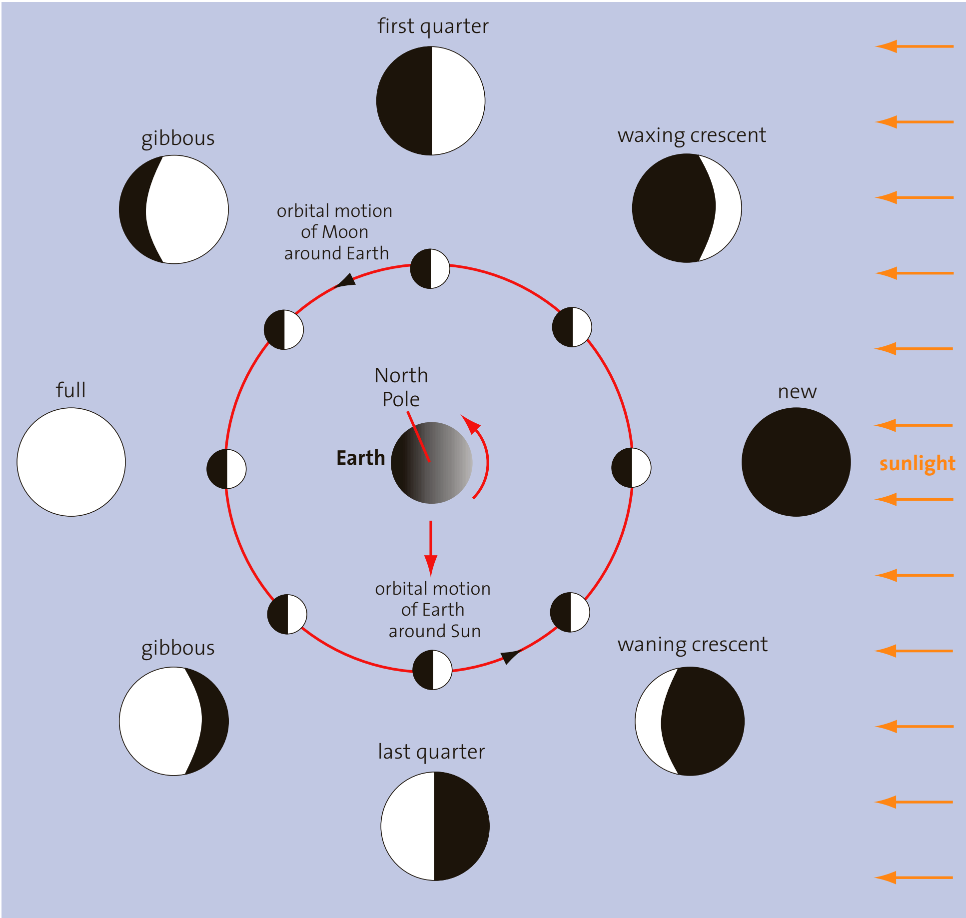
Over the next few days the sunlit part grows larger than a semicircle and the phase is called "**gibbous**". It grows until it becomes a bright full circle, the Full Moon, two weeks after New Moon. The Moon has now moved half way around its orbit of the Earth and is in the direction opposite to the Sun. This means that the Full Moon is due south in the sky at midnight. It is bright enough to cast shadows and people and many animals can see easily by moonlight.

Last Quarter

Next the Moon appears to shrink or "**wane**". It becomes gibbous again for a few days until, at the end of the third week, we see only a half-circle again. This phase is called "Last Quarter". Finally, during the fourth week, the Moon appears as a shrinking crescent, visible in the east just before sunrise. Finally it vanishes in the morning twilight to become a New Moon again.

The phase month

It takes the Moon approximately **27.3 days** to orbit once around the Earth, but it takes the Moon **29.5 days** to complete its cycle of phases. The extra two days occur because the Earth is orbiting the Sun. As the Moon goes through its phases, the Earth moves approximately one-twelfth of the way along its orbit around the Sun. This means that the Moon has to make slightly more



The moon always keeps the same face to the Earth. The Sun always illuminates half of the Moon. The phases occur because we see the Moon from continuously changing points-of-view.

than one full orbit of the Earth before it is back in line with the Sun.

As seen from the Moon, our Earth would go through monthly phases but would appear almost stationary in the lunar sky.

For variations on the theme of “The Man in the Moon” see The Armagh Observatory website at **http://www.arm.ac.uk/moon_fun.html**.

Tides

Most of the Earth's seas experience two high and two low tides each day. There is also a tide **in the solid surface** of the Earth of about half a metre. Tides are caused by the **gravitational pull** of the Moon and the Sun. To understand why there are two tides each day we must consider the force of gravity acting on the sea and the fact that the whole system is in rotation.

Each month, the Earth and the Moon both orbit their common **centre of gravity**, G, located about 4600 km from the centre of the Earth, O, in the direction of the Moon. Consider the point B on the Earth's surface nearest the Moon. Here the pull of the Moon's gravity is greatest. On the opposite side of the Earth at A, the pull of the Moon's gravity is weakest.

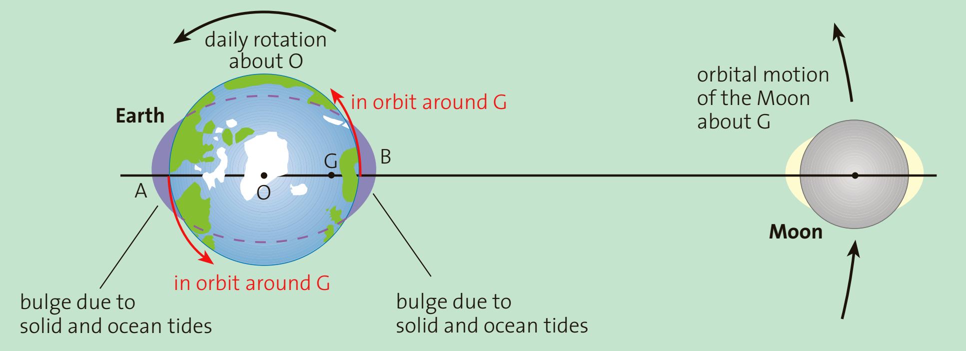
We must also include the effect of the **centripetal force** associated with points B and A rotating once a month about point G, which is below the Earth's surface. The overall result is that there are equal-sized **oceanic bulges** on opposite sides of the Earth. The oceanic tidal bulges are fixed with respect to the direction of the Moon, while the solid Earth rotates about point O, beneath the oceans, giving rise to two high tides each day.

Exactly the same types of tidal bulge are created by the interaction of the Sun and the Earth. The sizes of the **tidal bulges due to the Sun** are slightly less than half the size of those due to the Moon, giving rise to the phenomena of **spring and neap tides**. Roughly twice a month, the Sun and Moon line up and then the effects of the Sun and Moon reinforce each other to produce the largest tides, the spring tides. When the effects of the Sun and Moon are at right angles to each other, the sizes of the tidal bulges are at a minimum, corresponding to the neap tides.

In the deep ocean, the times of the tides follow the simple pattern described. However, in the complex waters of the continental shelf and of estuaries, the times of the tides can be delayed by several hours, even for places that are quite close together.

The Moon is moving away!

The rotation of the Earth pushes the tidal bulges slightly forward of the line joining the centres of the Earth and the Moon. In this position, the bulges exert a **turning effect** on the Moon that **accelerates it** slightly. This raises the Moon's orbit by about 4 cm per year. It also **slows the rotation of the Earth** by about 1.5 milliseconds per century. In a few hundred million years the Moon will be too far away to cause a total eclipse of the Sun. Only annular eclipses will be possible.



How the rotations of the Earth and the Moon lead to two tides a day.