“Beautiful, beautiful.
Magnificent desolation”
- Buzz Aldrin
Moon

Photo: Dave Woods
**The Moon**

**Copernicus**
This crater (left) is easy to spot. It formed about 800 million years ago, and is 57 miles (92 km) wide. Note central peaks and terraced walls, caused by impact.

**Mare Serenitatis**
The Sea of Serenity is solid lava, some 380 miles (610 km) across.

**Mare Tranquillitatis**
The Sea of Tranquility is a smooth plain filled with once-molten lava that welled up from below after an impact billions of years ago. The first humans to walk on the Moon, Apollo 11 astronauts, landed near the edge.

**Mare Humorum**
The Sea of Moisture is about 220 miles (350 km) across. You can spot it with the naked eye. With a telescope, you might notice two craters along its edge.

**Tycho**
Young crater best seen during a full Moon. Rays of bright material are ejecta blasted out of the crust when a large asteroid struck about 109 million years ago.

**Aristarchus**
Young crater. So bright that Sir William Herschel thought it was an active volcano.

**Kepler**
Small version of Copernicus.

**Grimaldi**
Lava-filled crater is one of the darkest spots you can see on the Moon. It's 145 miles wide (233 km).

**Apollo 11, 12, 14, 15, 16, 17**
Craters named after Apollo missions.
Apollo 11: First Moon Landing

Michael Collins
Stayed in orbit in the Command Module

Neil Armstrong
First person to walk on the Moon

Buzz Aldrin
Second person to walk on the Moon
Apollo Landing Missions

Apollo 11  
Mare Tranquillitatis (Sea of Tranquility)  
July 20, 1969  
Neil A. Armstrong, Buzz Aldrin, Michael Collins

Apollo 12  
Oceanus Procellarum (Ocean of Storms)  
Nov 19, 1969  
Charles Conrad, Jr., Alan Bean, Richard Gordon

Apollo 13  
Did Not land  
April 1970  
James A. Lovell, Jr., Fred W. Haise, Jr., John L. Swigert, Jr.

Apollo 14  
Fra Mauro  
Feb 5, 1971  
Alan B. Shepard, Jr., Edgar D. Mitchel, Stuart A. Roosa

Apollo 15  
Hadley Rille/Apennine Mountains  
July 30, 1971  
David R. Scott, James B. Irwin, Alfred M. Worden

Apollo 16  
Descartes Highlands  
April 21, 1972  
John W. Young, Charles M. Duke, Jr., Thomas K. Mattingly

Apollo 17  
Taurus-Littrow  
Dec 11, 1972  
Eugene A. Cernan, Harrison H. Schmitt, Ronald E. Evans
Tidal Locked Orbit

The moon keeps the same side facing the Earth.

Until the Apollo Missions, no one had ever seen the far side!

Photo: Dave Woods
Far Side

The Far Side of the Moon is clearly very different.

It should not be confused with the phrase The Dark Side of the Moon.
Theories of the Formation of the Moon

1. The Fission Theory
   The moon was once part of the Earth and broke away

2. The Capture Theory
   The Moon formed elsewhere in the solar system and was gravitationally captured by the Earth

3. The Condensation Theory
   The Moon formed from the same debris as the Earth, only very close to it.

4. Giant Impactor Theory
   A planetoid hit the Earth and from the debris the Moon formed.
The Evidence

Thanks to the Apollo missions, we now know a lot about the geology of the Moon...

Here is the evidence...
Density

The average density of the Moon is 3.3 grams/cm$^3$

The average density of Earth is 5.5 grams/cm$^3$

The Moon cannot have a substantial iron core like the Earth

Density of Ices is 1 gram/cm$^3$
Density of Rock (Silicates) 3 gram/cm$^3$
Density of Metals 8 gram/cm$^3$
Volatiles

Volatile substances are those that can boil off or evaporate. The Moon contains very little in terms of volatile substances. The Moon must have baked evaporating the volatiles.

http://turbulence.ocean.fsu.edu

Earth’s surface collected water

Moon rock has little volatiles
Oxygen Isotopes

The Earth and Moon have identical ratios of Oxygen isotopes. They must have formed at the same distance from the Sun.

Most oxygen atoms contain 8 neutrons and 8 protons. A small percentage have one or two extra neutrons. These atoms $^{16}\text{O}$, $^{17}\text{O}$, $^{18}\text{O}$ have different masses.

On Earth, the deviation of the ratio of $^{18}\text{O}/^{16}\text{O}$ from 1 is twice as much as the deviation of $^{17}\text{O}/^{16}\text{O}$. But this varies according to where the object formed in the Solar System.

Vesta (an asteroid) and Mars are shown in the plot on the left.

$\delta^{17}\text{O}$ means $^{17}\text{O}/^{16}\text{O}$ and $\delta^{18}\text{O}$ means $^{18}\text{O}/^{16}\text{O}$

http://www.psrd.hawaii.edu/Dec01/Oisotopes.html
The Moon is Escaping

A laser reflector put on the Moon has indicated that the Moon is moving away from the Earth at a rate of 3.8 cm per year.

This was actually predicted by George Howard Darwin (Charles Darwin's son) in the 1800s.
Evidence and the Theories

A. The Moon cannot have a substantial iron core like the Earth
B. The Moon must have baked evaporating the volatiles
C. They must have formed at the same distance from the Sun
D. The Moon is slowly moving away from the Earth

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Moon Formation

A planetoid the size of Mars is thought to have had a grazing impact with the Earth. The Earth’s iron core was left intact, and the Moon formed from the silicate debris.
Tidal Forces

Gravitational attraction decreases as you move further from an object. This means that different parts of a large object experience different forces.

This difference in gravitational force is called a Tidal Force.
Tidal Forces Stretch Objects

The planets are stretched into ellipsoidal shapes.

This effects the water on Earth the most.
Tides on Earth

The tides on Earth are due to the Moon pulling on the water that is closest to it more than the rest of the Earth. This causes a bulge in the water depth closest to the Moon.

This Moon also pulls the Earth more than the water on the far side. The Earth moves away from the water slightly leaving a second bulge.
Tides on Earth

The Moon revolves around the Earth, and the Earth rotates, but the bulge stays facing the Moon. This gives us two high tides and two low tides each day.

Water sloshes a lot, and it is dragged by the Earth’s rotation. So it leads the Moon slightly
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http://www.centralnovascotia.com/tides.php
The Sun Causes Tides Too

The Sun also has an effect.

When the Sun and Moon work together to make strong tides, they are the Spring Tides.

When they work against each other, the Sun forms very weak tides called Neap Tides.

http://www.oceanservice.noaa.gov/education/kits/tides/media/supp_tide06a.html
Tidal Effects on the Moon

The Moon is ellipsoidal in shape, and it rotates to keep its more massive side closest to Earth.

Friction has long since changed the rotation rate of the Moon so that it rotates once on its axis for every revolution around the Earth. This is called Tidal Locking.
These Forces affect the orbit of the Moon

The moving bulge on the Earth pulls on the Moon and speeds it up in its orbit. The Moon's orbital radius increases by 3.8 cm per year.

The friction from the water being pulled toward the Moon slows down the Earth’s rotation. The Earth’s day gets longer by 2 milliseconds per century.
The Changing Full Moon

This is an exaggerated picture of the Moon’s elliptical orbit around the Earth.
The Changing Full Moon

Since the Full Moon is opposite the Sun, and the Earth is going around the Sun, each successive Full Moon occurs when the Moon is at a different point in its orbit.
The Changing Full Moon

See the effect of the Moon’s elliptical orbit here:

http://www.pixheaven.net/geant/0505-0612.html
Geological Features of the Moon

Main geologic processes: Volcanism and Impact Craters

Important features: Mare, Highlands, Impact Craters, Rilles, Wrinkle Ridges, Graben, Domes, Regolith
Mare or “Seas”

Dark regions on the Lunar surface were once thought to be seas.

For this reason, Kepler introduced the term Mare, which is Latin for Sea.

Photo: Dave Woods
Mare or “Seas”

Instead the dark regions are dark basaltic plains formed from lava flows.

Basalt is a dark volcanic rock.

These plains were formed between 3 and 4 billion years ago.

Photo: Dave Woods
Highlands

Light regions are highlands or mountains.

The rocks there are anorthositic, which means that they are made from plagioclase feldspar.

Feldspar crystallizes from magma.

Photo: Dave Woods
Hills and Mountains on the Moon
Hills and Mountains on the Moon
Compare to Mountains on the Earth
The hills on the Moon are smooth because there is no erosion.
Impact Craters

Craters are formed from meteors impacting the Moon.

Photo: Dave Woods
Craters
Tycho

Tycho has a diameter of 85 kilometers (53 miles). The crater floor is 4,700 meters (15,400 feet) below the rim. The central peak is 2,400 meters (7,800 feet) above the crater floor.

Tycho is a young crater having been formed during a massive impact about 100 million years ago.
Anatomy of a Crater

- Rays
- Ejecta
- Central Peak
- Crater Floor
- Crater Rim
Topographic Map of Tycho

Copernicus
Rilles

Rilles are ancient lava rivers that meander across the lunar surface.

By following them upstream, one can find the volcanic vent from which the lava originated.

The flooded crater is Prinz Crater. Aristarchus and Herodotus can be seen at the far right.
Wrinkle Ridges

Letronne Crater is a lava-filled crater. The lave destroyed much of the crater wall.

Inside you can see a wrinkle ridge that forms from buckling in the mare.

In this case, this buckling is from a more ancient crater called Winthrop Crater that shares the western wall of Letronne.
Graben are depressed sections of the surface between parallel tectonic faults. This one, called Rima Ariadaeus, is over 300 km long.
Domes, like Mons Rümker in this picture, are shield volcanoes that are usually around 8-12 km in diameter. The lava is thought to be a viscous silicate that had erupted from volcanic vents.
Regolith

Regolith is a fine grained layer of charcoal-colored dust on the surface of the Moon. It is formed from billions of years of meteorite impacts. In the younger maria, the regolith is about 2 meters deep. In the older highlands, it can get up to 20 meters deep.

The astronaut here is covered in regolith, and you can see it around his footprints.
Atmosphere

The Moon’s gravity is too weak to hold an atmosphere.

The molecular motion of the air molecules are greater than the escape velocity, so the air molecules just fly off into space!

For this reason, the Sun is extremely bright. And there is no scattering of light that gives Earth its lovely blue sky. The sky on the Moon is black. The shadows are stark.

The fact that there is no atmosphere means that the temperatures cannot easily equilibrate. The surface is 123 C (253 F) in the sunlight and -233 C (-387 F) in the shade!
Moonquakes

There are four different kinds of Moonquakes:

1. deep moonquakes probably caused by tides
2. vibrations from meteorite impacts
3. thermal quakes caused by the expansion of the frigid crust when first illuminated by the morning sun after two weeks of deep-freeze lunar night
4. shallow moonquakes only 20 or 30 kilometers below the surface.

In 5 years, 28 moonquakes were recorded with a few getting up to 5.5 on the Richter scale. The moon’s surface is very stiff, so it rings like a bell and quakes last a couple of minutes rather than a couple of seconds!!!

Buzz Aldrin deploys a seismometer

http://science.nasa.gov/headlines/y2006/15mar_moonquakes.htm
Apollo 17 Landing Site
Apollo 17 Lunar Module
Apollo 17 - Lunar Module Pilot Jack Schmitt is running towards the Lunar Rover
Recent Exploration
Detecting Minerals and Water

The diagram illustrates the reflectance spectra of various substances across the visible and near-infrared wavelengths. The spectra for Anorthite, Pyroxene, Rock, Apollo 15 Soil, Hydroxyl, Water, and Ice are shown. The wavelengths are indicated on the x-axis, ranging from 500 to 4000 nm for the left side and from 2600 to 3600 nm for the right side. The reflectance values are on the y-axis, ranging from 0 to 0.7 for the left side and from 0.090 to 0.100 for the right side.
## Recent Missions

### Impactors

<table>
<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Landing date</th>
<th>Area</th>
<th>Mission type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>SMART-1</td>
<td>September 3, 2006</td>
<td>LQ26</td>
<td>Orbiter (systematically crashed at mission end)</td>
</tr>
<tr>
<td>India</td>
<td>MIP</td>
<td>November 14, 2008</td>
<td>LQ30</td>
<td>Impactor</td>
</tr>
<tr>
<td>Japan</td>
<td>Okina (RSAT)</td>
<td>February 12, 2009</td>
<td>LQ08</td>
<td>Orbiter (crashed at mission end)</td>
</tr>
<tr>
<td>China</td>
<td>Chang'e 1</td>
<td>March 1, 2009</td>
<td>LQ21</td>
<td>Orbiter (systematically crashed at mission end) [1]</td>
</tr>
<tr>
<td>Japan</td>
<td>Kaguya</td>
<td>June 10, 2009</td>
<td>LQ30</td>
<td>Orbiter (systematically crashed at mission end) [1]</td>
</tr>
</tbody>
</table>

### Orbiters

<table>
<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Launch date</th>
<th>Mission life time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>Ouna (VSAT)</td>
<td>September 14, 2007</td>
<td>1 year (mission complete at 29 June 2009)</td>
</tr>
<tr>
<td>India</td>
<td>Chandrayaan-1</td>
<td>October 22, 2008</td>
<td>2 years intended (Achieved only 315 days)</td>
</tr>
<tr>
<td>USA</td>
<td>Lunar Reconnaissance Orbiter</td>
<td>June 19 2009[3]</td>
<td>1 year (extended mission of up to 5 years)</td>
</tr>
<tr>
<td></td>
<td>LRO (Lunar Crater Observation and Sensing Satellite)</td>
<td></td>
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</tr>
</tbody>
</table>

Selene (JAXA – Japan Aerospace Exploration Agency)

Launch Date: September 14, 2007

A bird's-eye view of Jackson Crater (22.4 N / 163.1 W, diameter 71 km)
A single-band (750 nm) image and a color image showing rock types (the strengths of absorption bands characteristic of individual minerals are indicated in red: pyroxene, green: olivine, and blue: plagioclase)
Chandrayaan - 1

- To Achieve 100 x 100 km Lunar Polar Orbit.
- PSLV to inject 1050 kg in GTO of 240 x 36000 km.
- Lunar Orbital mass of 523 kg with 2 year lifetime.
- Scientific payload 55 kg.

Launch Date: 22 October 2008
Chandrayaan-1 Discovers Water on Moon
Lunar Reconnaissance Orbiter

Launch Date: June 19, 2009

Mission Site: http://lro.gsfc.nasa.gov/

Where is LRO Now?
http://lroc.sese.asu.edu/whereislro/
LRO Images Apollo 11 Landing Site
Apollo 14 lunar module, Antares.

*Image width: 538 meters (about 1,765 ft.)*
LRO Images Apollo 14 Landing Site

LRO Temperature Maps

*Diviner Channel 8 Daytime Temperature (K)*

*Diviner Channel 8 Nighttime Temperature (K)*
Boulders at Tsiolkovski Crater
Recent Lunar Crater

How can you tell its relatively recent?
Crater Copernicus
See Anything Unusual?
Lunar Reconnaissance Orbiter

Launched June 19, 2009

Mission Site: http://lro.gsfc.nasa.gov/

Where is LRO Now? http://lorc.sese.asu.edu/whereislro/
## Future Manned Missions

<table>
<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Launch due</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Orion 15</td>
<td>June 2019[ dubious – discuss][24]</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td>c. 2020; moonbase c. 2030[ dubious – discuss][25]</td>
</tr>
<tr>
<td>India</td>
<td></td>
<td>2020[ dubious – discuss][26][27]</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td>2022[ dubious – discuss]</td>
</tr>
<tr>
<td>Europe</td>
<td>Aurora programme[28]</td>
<td>2024[ dubious – discuss][29]</td>
</tr>
<tr>
<td>Russia</td>
<td></td>
<td>2025[ dubious – discuss][30]</td>
</tr>
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</table>

Why Go to the Moon?
Helium 3 has been blowing off the Sun for billions of years, and it is captured by the dust (regolith) on the Moon’s surface.

It is an excellent candidate for nuclear fusion!

Burning 1 kg of coal produces 24 MegaJoules of energy.

1 kg of He3 fused with 0.67 kg of Deuterium (H2) will produce 19 MegaWatt-years of energy! That is about 6,000,000,000 MegaJoules of energy!
Helium 3

It would take 25 tonnes of He3 to power the entire United States for a year.

The U.S. currently has 15 kg on reserve.

Given the current cost of energy, He3 would be worth about $3 Billion per metric tonne.

The world could use 100 Metric Tonnes per year. This is $300 Billion a year revenue!

The Moon has a 10,000 year supply!