Unit 6

The Earth

The Moon

Our Home, The Earth

- Earth's beauty is revealed from space through blue seas, green jungles, red deserts, and white clouds.
- From our detailed knowledge of Earth, astronomers hope to understand what properties shape other worlds
- Earth is a dynamic planet with its surface and atmosphere having changed over its lifetime.
- Slow and violent motions of the Earth arise from heat generated within the planet
- Volcanic gases accumulate over billions of years creating an atmosphere conducive to life, which in turn together with water affects the air's composition

Size and Shape of the Earth

- In simple terms, the Earth is a huge, rocky sphere spinning in space and moving around the Sun at a speed of about 100 miles every few seconds
- Earth also has a blanket of air and a magnetic field that protects the surface from the hazards of interplanetary space

12,800 kilometers
(about 8000 miles)

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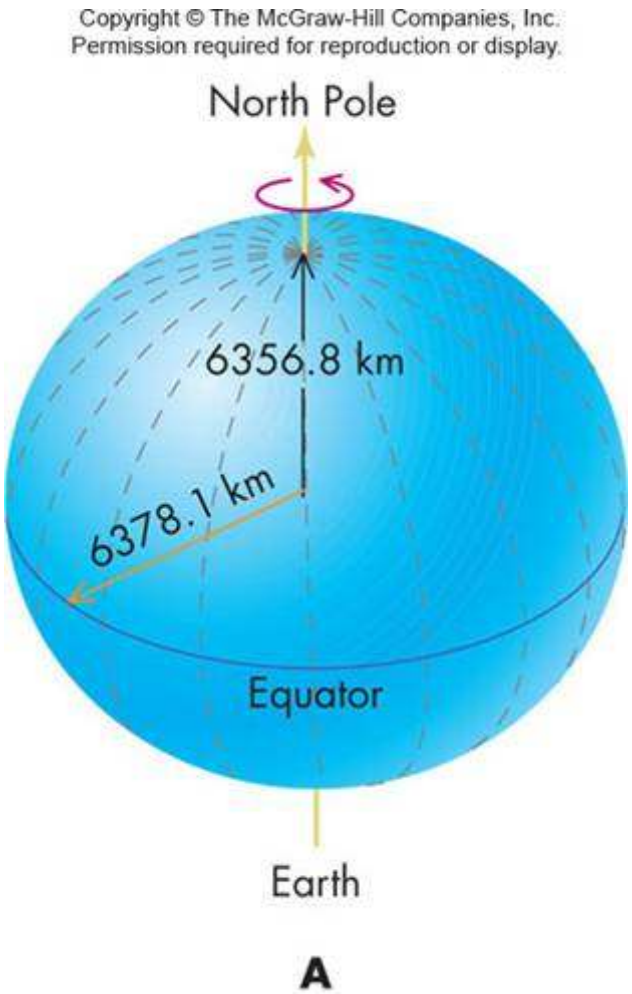
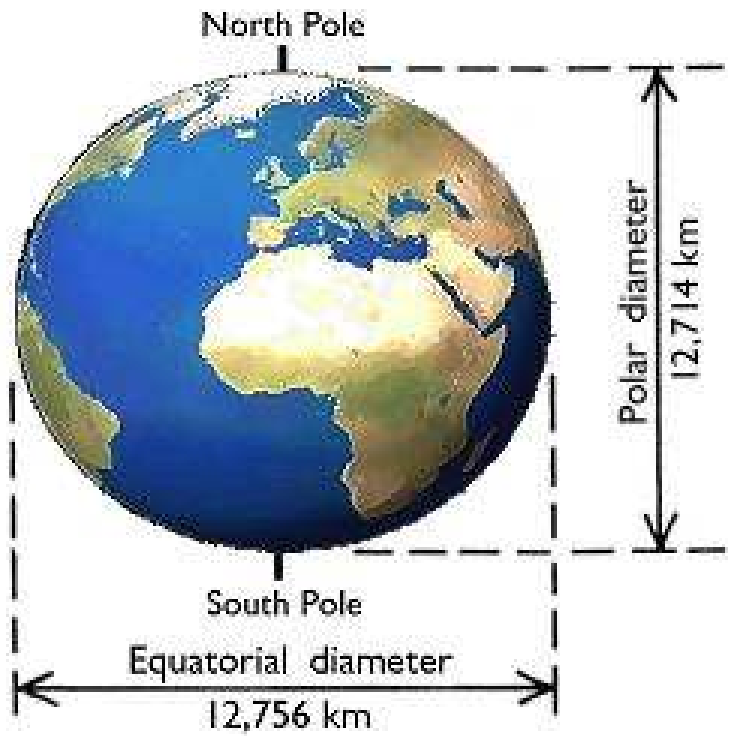
Size and Shape of the Earth



- The Earth is large enough for gravity to have shaped it into a sphere
- More precisely, Earth's spin makes its equator bulge into a shape referred to as an oblate spheroid – a result of inertia



Composition of the Earth

- The most common elements of the Earth's surface rocks are:
  - oxygen (45.5% by mass),
  - silicon (27.2%),
  - aluminum (8.3%),
  - iron (6.2%),
  - calcium (4.66%), and
  - magnesium (2.76%)
- Silicon and oxygen usually occur together as ***silicates***
- Ordinary sand is the silicate mineral quartz and is nearly pure silicon dioxide

Density of the Earth

- ***Density*** is a measure of how much material (mass) is packed into a given volume
- Typical unit of density is grams per cubic centimeter
- Water has a density of 1 g/cm^3, ordinary <u>surface</u> rocks are 3 g/cm^3, while iron is 8 g/cm^3
- For a spherical object of mass M and radius R, its <u>average density</u> is given by

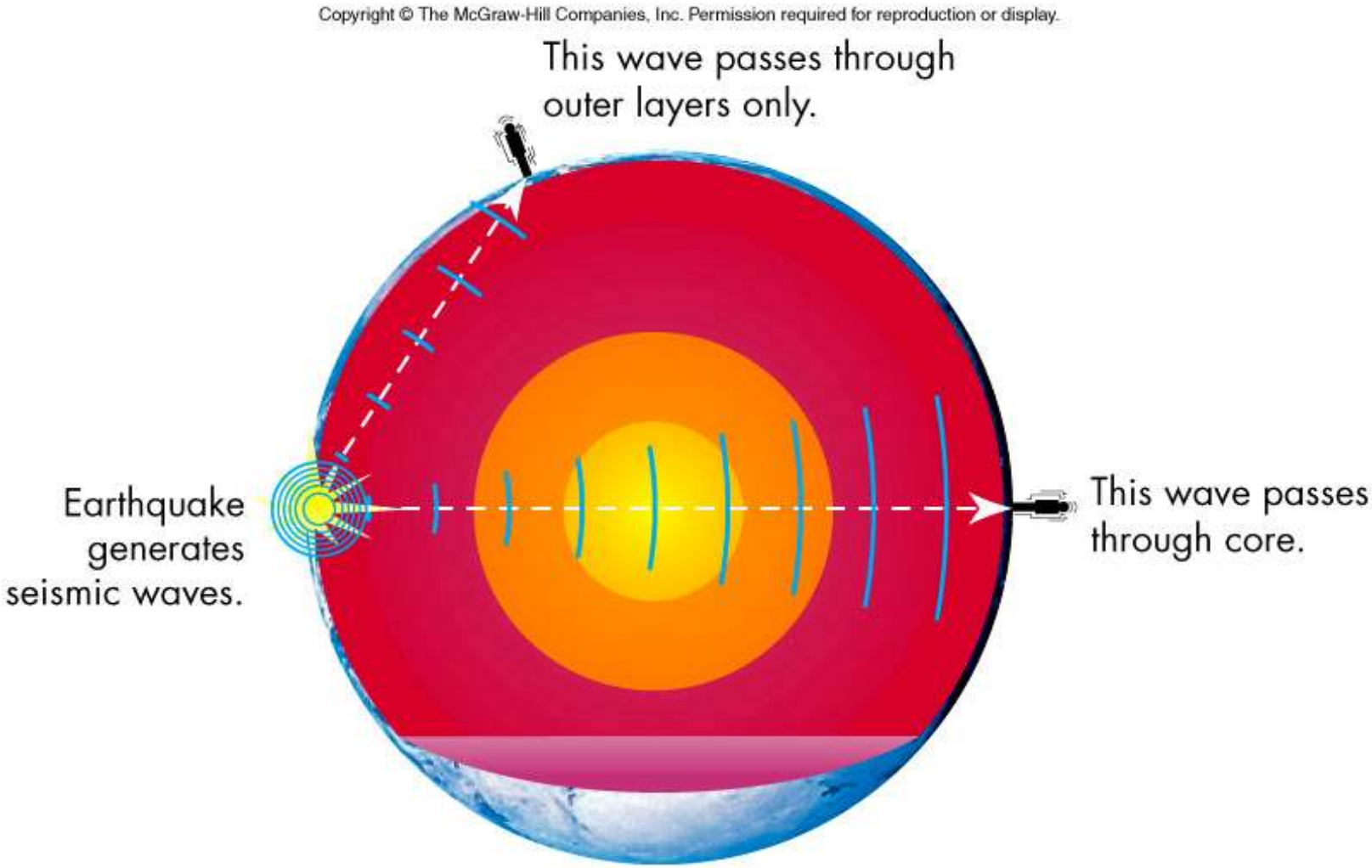
$$\frac{M}{\frac{4}{3}\pi R^3}$$

- For Earth, this density is found to be 5.5 g/cm^3
- Consequently, the Earth's interior (core) probably is iron (which is abundant in nature and high in density)
- Calculate the density of a glass sphere.

The Earth's Interior

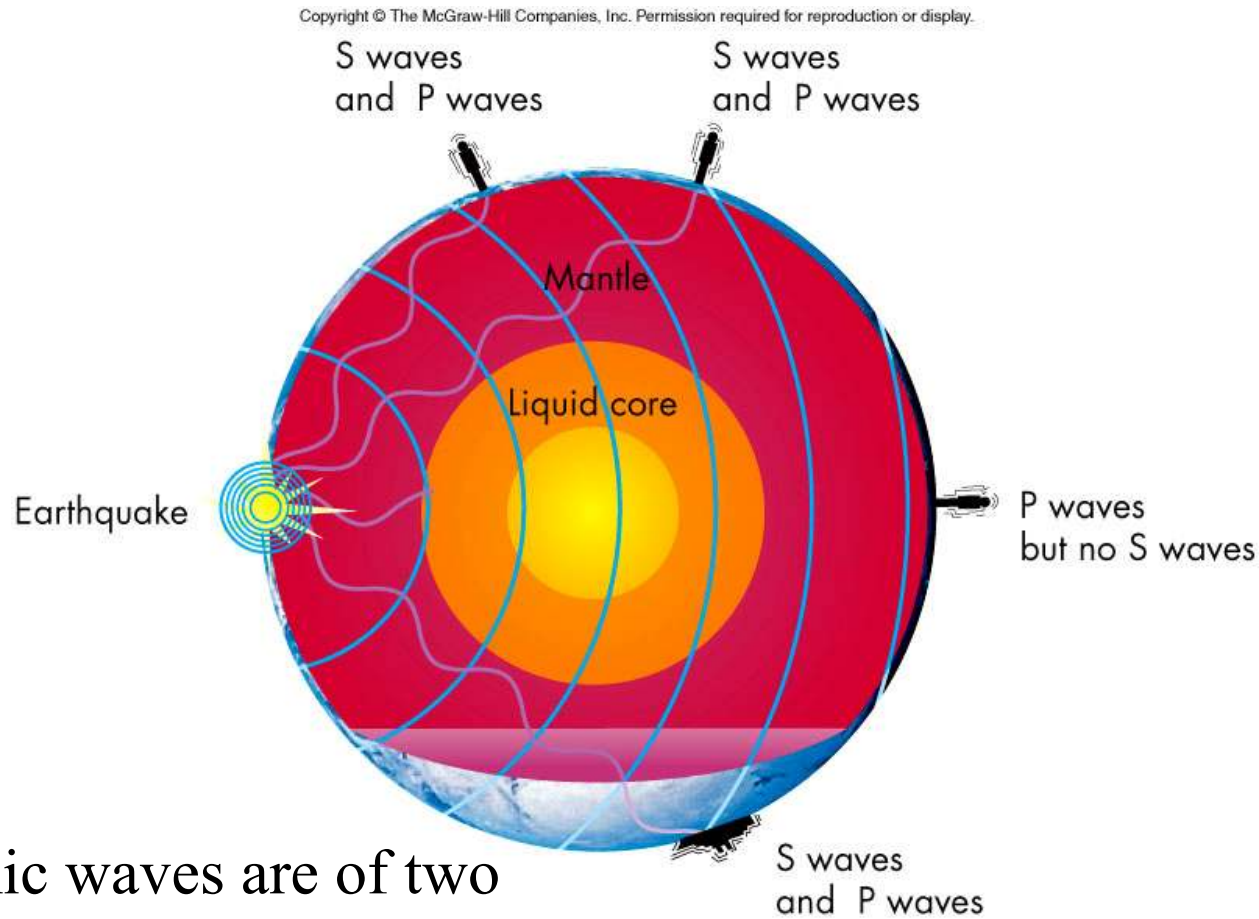
- Earthquakes generate ***seismic waves*** that move through the Earth with speeds depending on the properties of the material through which they travel
- These speeds are determined by timing the arrival of the waves at remote points on the Earth's surface
- A seismic "picture" is then generated of the Earth's interior along the path of the wave

A Sonogram of the Earth!



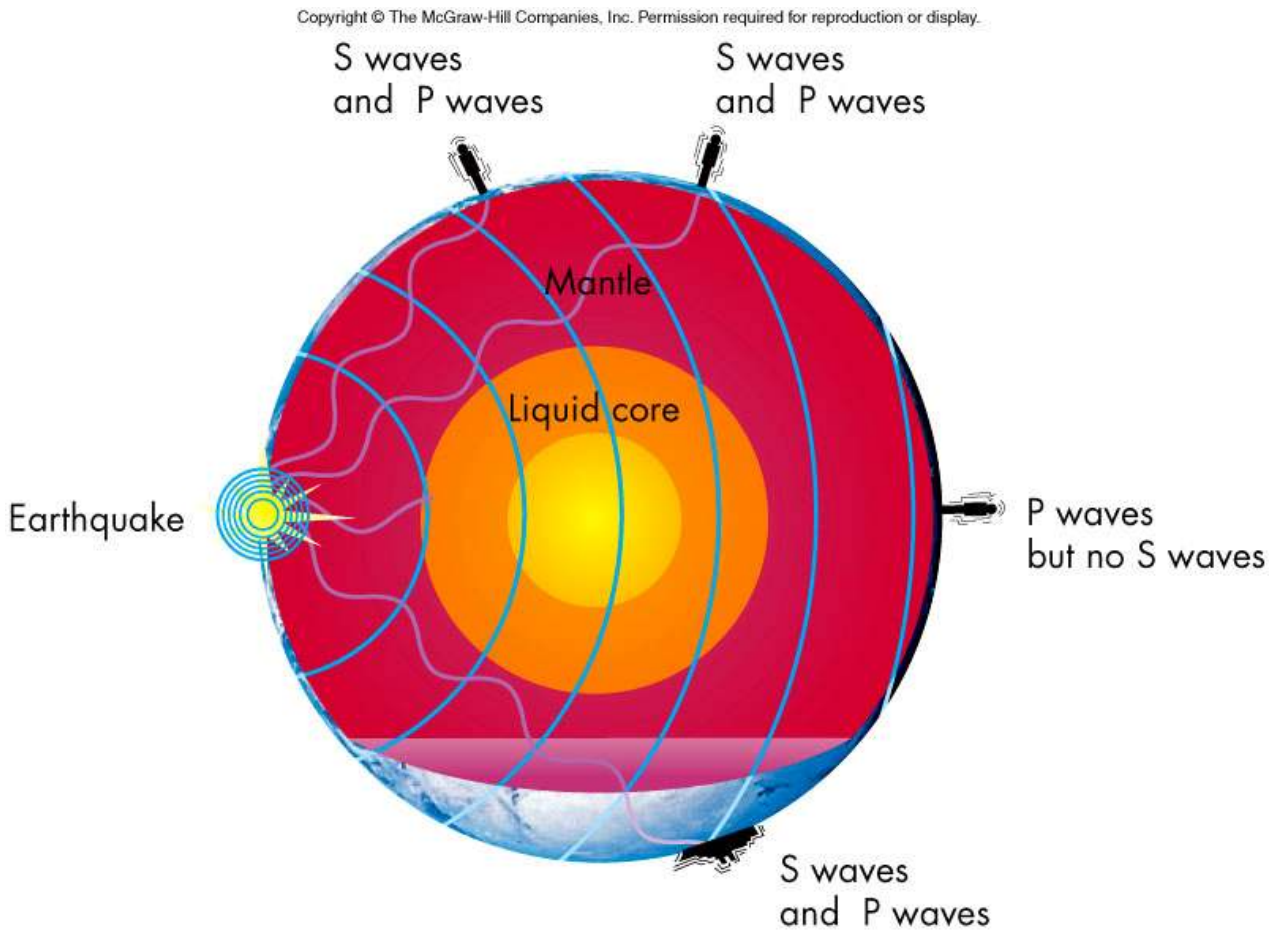
- This is the only way we have to probe the Earth's interior!

Probing the Interior of the Earth



- Seismic waves are of two types: S and P
  - P waves compress material and travel easily through liquid or solid
  - S waves move material perpendicular to the wave direction of travel and only propagate through solids

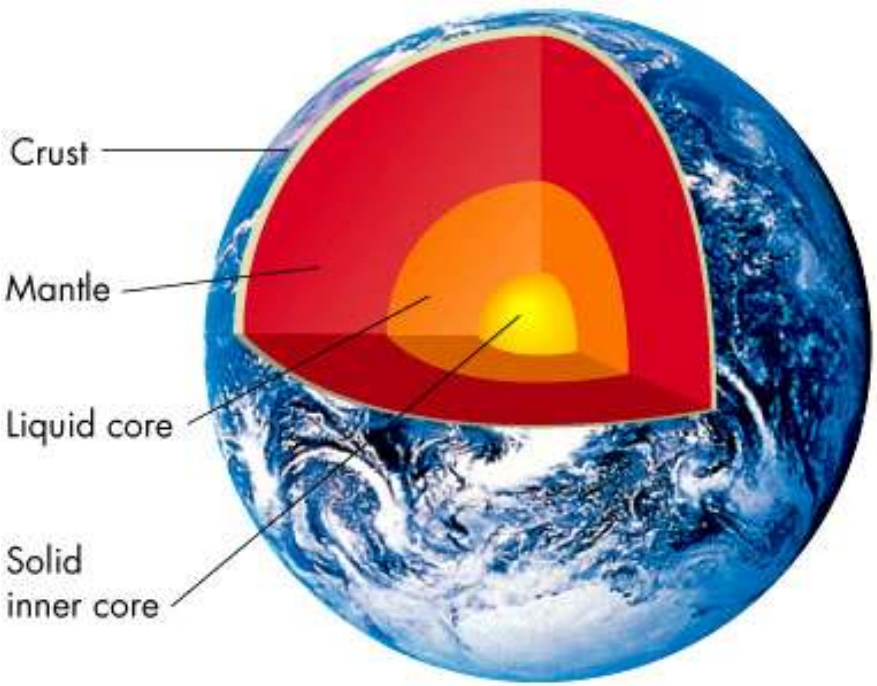
Interior Structure

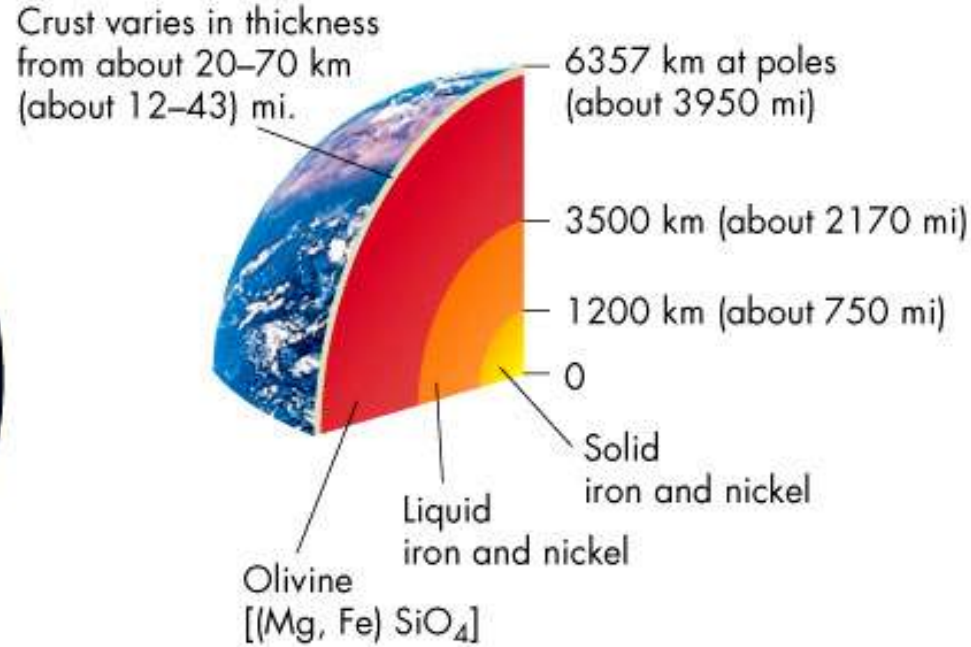


- Observations show P waves but no S waves at detecting stations on the opposite side of the Earth from the origin of an Earthquake

  $\Rightarrow$ the Earth has a liquid core!

Interior Structure of the Earth



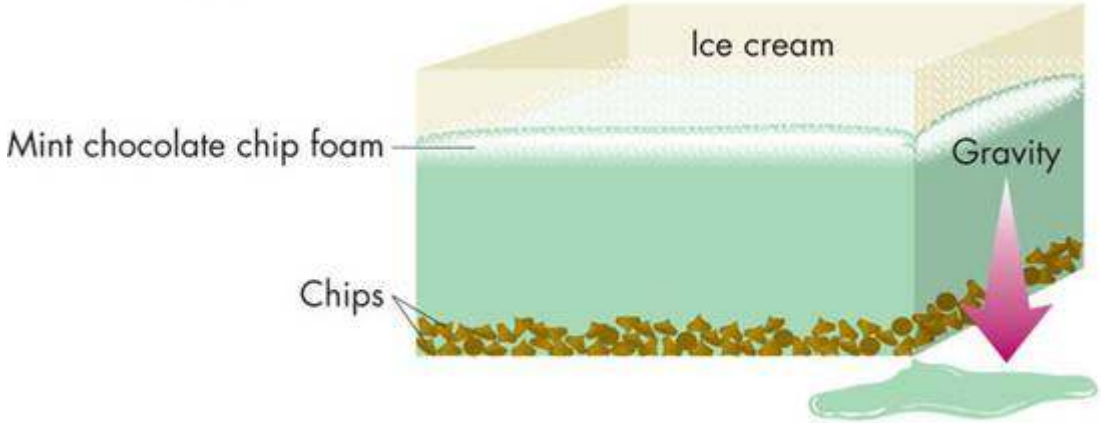


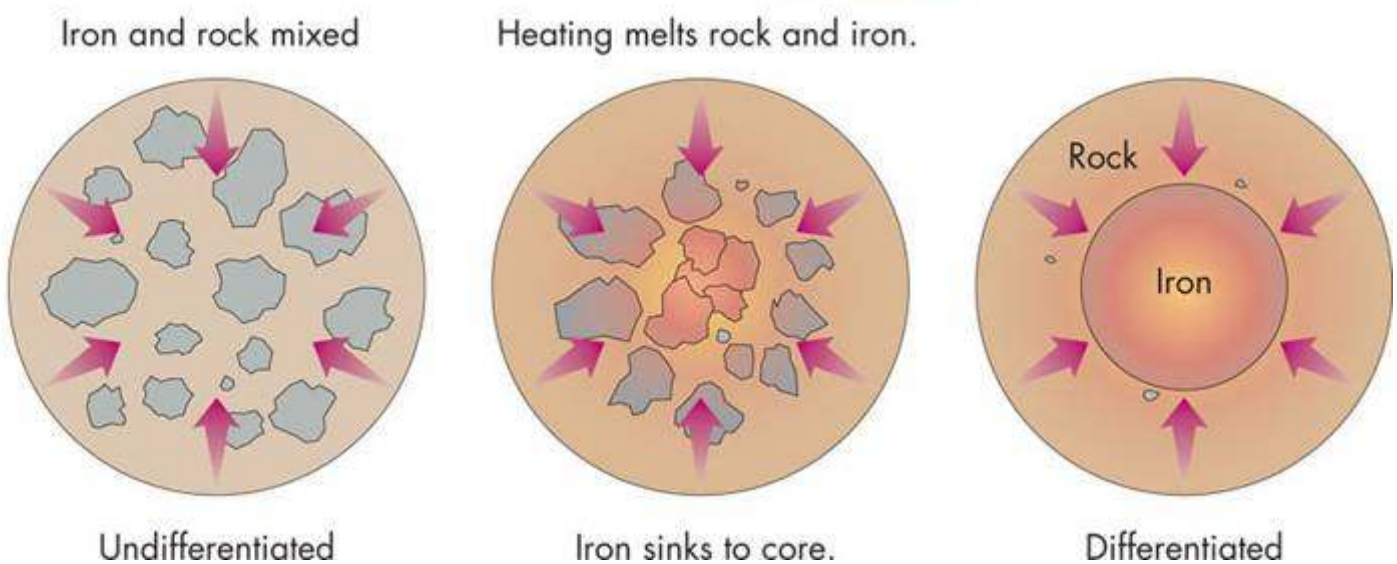
- A solid, low-density and thin ***crust*** made mainly of silicates
- A hot, thick, not-quite-liquid ***mantle*** with silicates
- A ***liquid, outer core*** with a mixture of iron, nickel and perhaps sulfur
- A ***solid, inner core*** of iron and nickel

Layers of the Earth

- The Earth is layered in such a fashion that the densest materials are at the center and the least dense at the surface – this is referred to as ***differentiation***
  - Differentiation will occur in a mixture of heavy and light materials if these materials are liquid for a long enough time in a gravitational field
  - Consequently, the Earth must have been almost entirely liquid in the past
- The Earth's inner core is solid because it is under such high pressure (from overlying materials) that the temperature there is not high enough to liquefy it – this is not the case for the outer liquid core

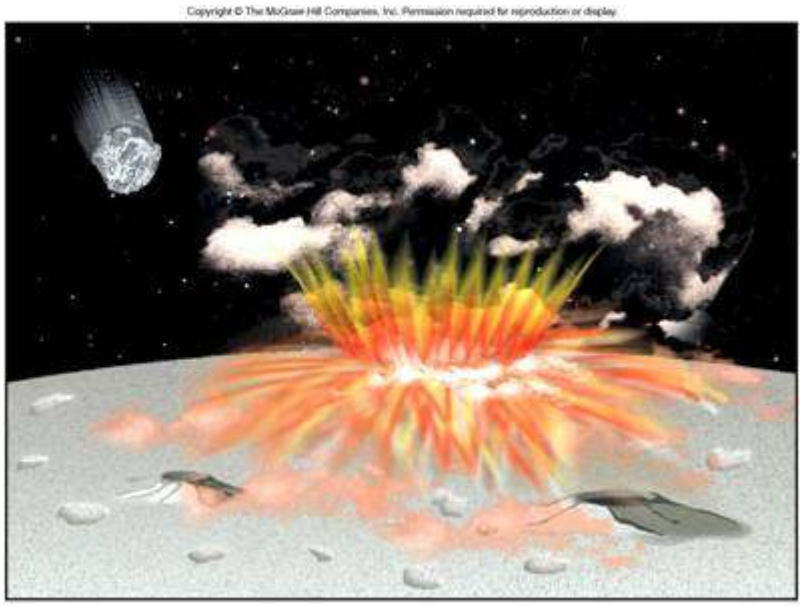
Differentiation





Temperature Inside the Earth

- Heating the Earth's Core
  - The estimated temperature of the Earth's core is 6500 K
  - This high temperature is probably due to at least the following two causes:
    - **Heat generation** from the impact of small bodies that eventually formed the Earth by their mutual gravitation



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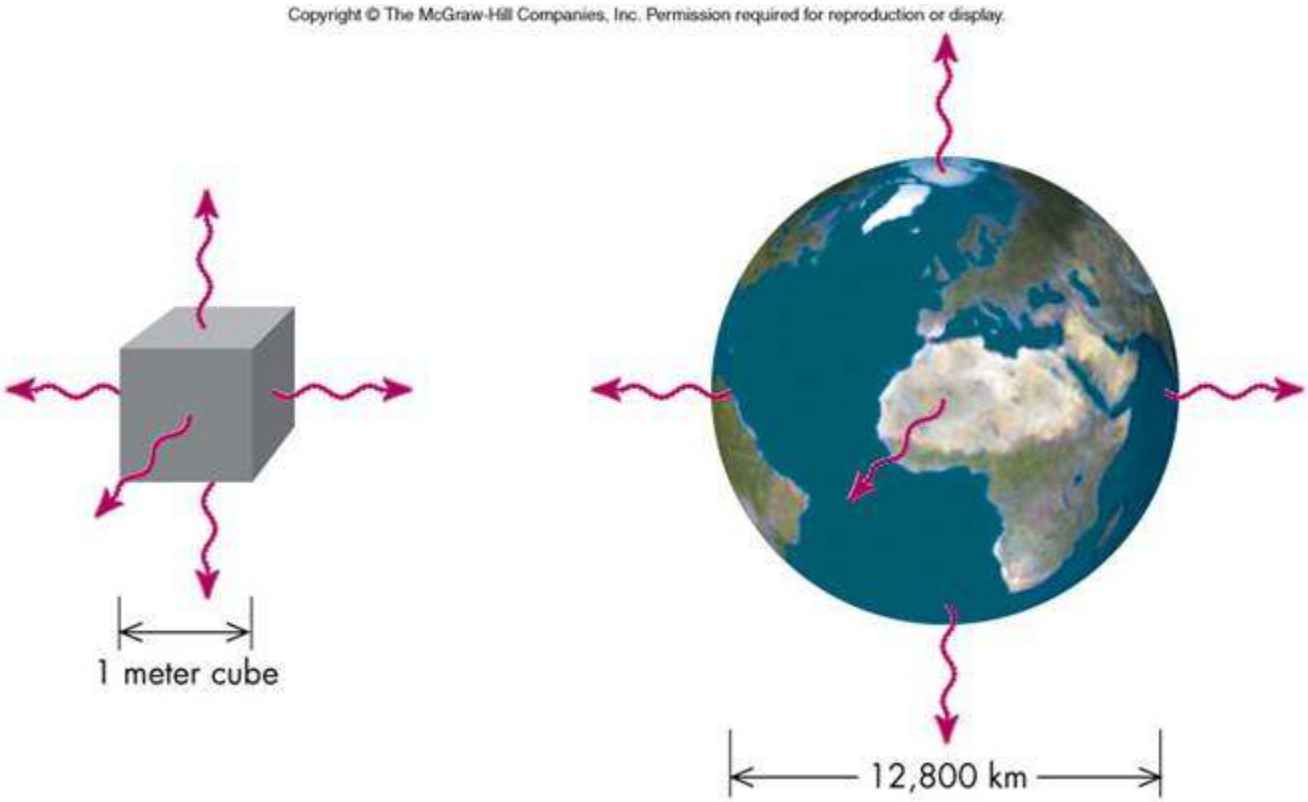
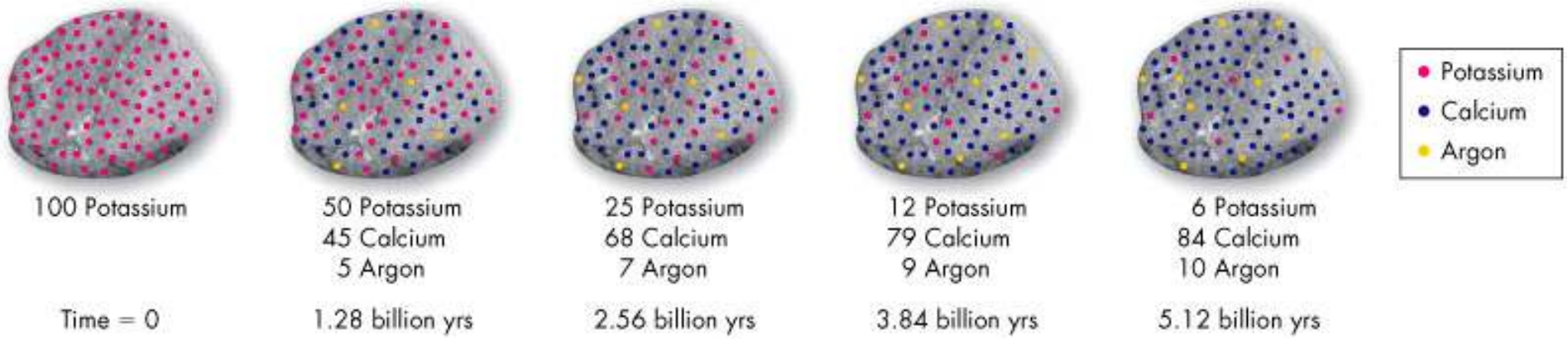
- The ***radioactive decay*** of ***radioactive elements*** that occur naturally in the mix of materials that made up the Earth

Temperature Inside the Earth



- In either case, the thermal energy generated is trapped inside the Earth's interior due to the long time it takes to move to the surface and escape

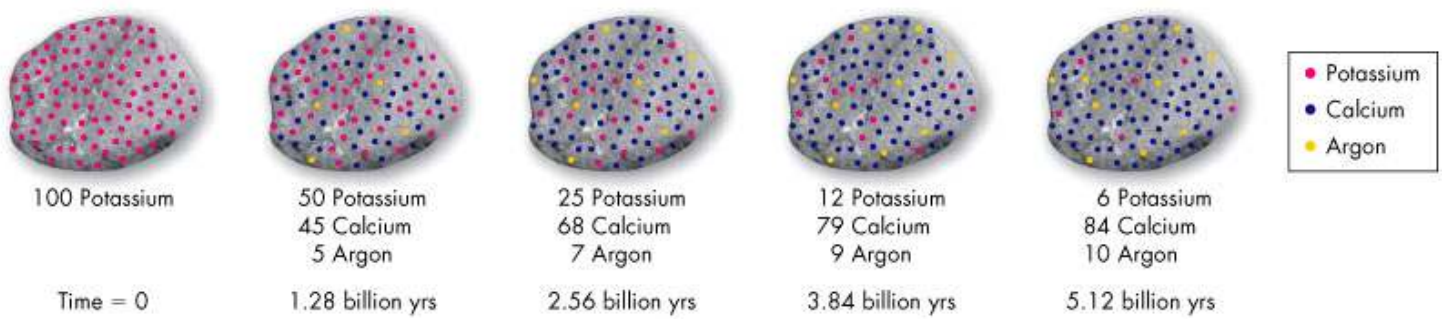
Age of the Earth



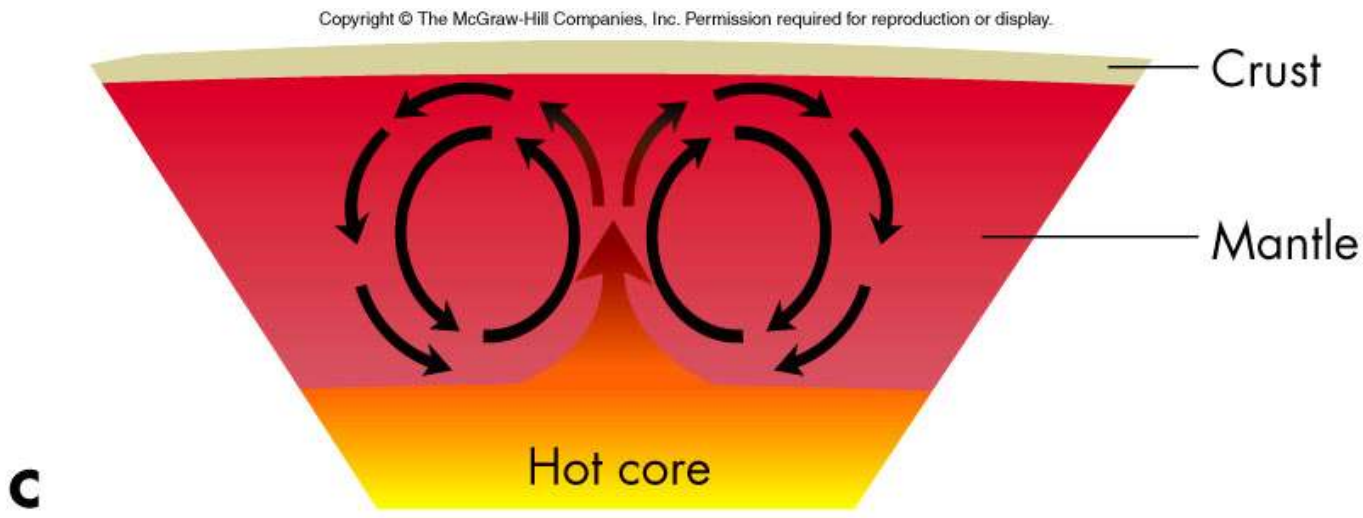
- Radioactive decay used to determine the Earth's age
  - Radioactive atoms decay into ***daughter atoms***
  - The more daughter atoms there are relative to the original radioactive atoms, the older the rock is

Age of the Earth

- Radioactive potassium has a half-life of 1.28 billion years and decays into argon, which is a gas that is trapped in the rock unless it melts
  - Assume rock has no argon when originally formed
  - Measuring the ratio of argon atoms to potassium atoms gives the age of the rock
  - This method gives a minimum age of the Earth as 4 billion years
  - Other considerations put the age at 4.5 billion years

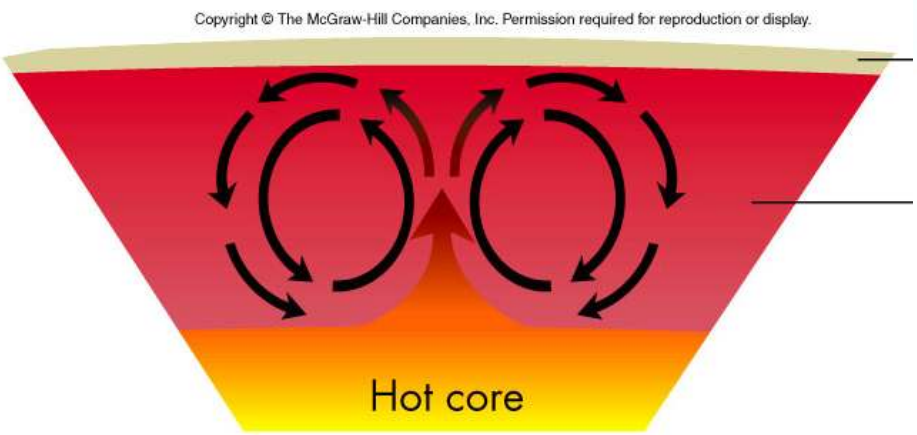


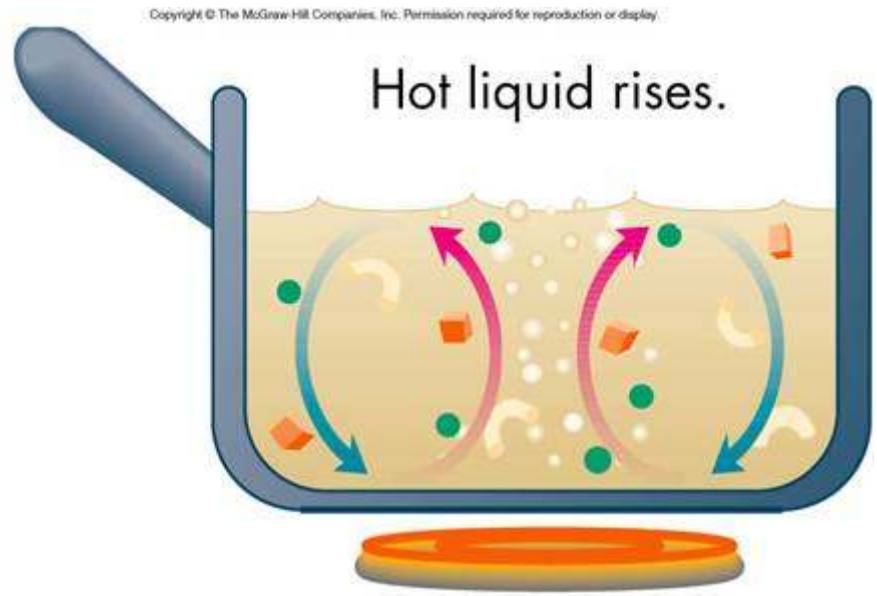
Motion in the Earth's Interior



- Heat generated by radioactive decay in the Earth creates movement of rock
- This movement of material is called ***convection***
- Convection occurs because hotter material will be less dense than its cooler surroundings and consequently will rise while cooler material sinks

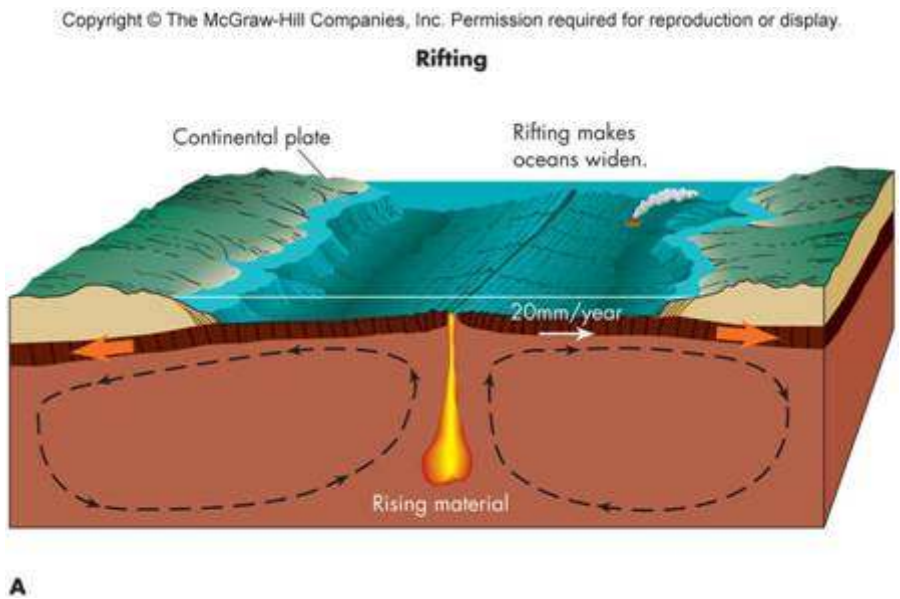
Convection





- Convection in the Earth's interior
  - The crust and mantle are solid rock, although when heated, rock may develop convective motions
  - These convective motions are slow, but are the cause of: earthquakes, volcanoes, the Earth's magnetic field, and perhaps the atmosphere itself

Plate Tectonics



- Rifting
  - Hot, molten material rises from deep in the Earth's interior in great, slow plumes that work their way to the surface
  - Near the surface, these plumes spread and drag the surface layers from below
  - The crust stretches, spreads, and breaks the surface in a phenomenon called ***rifting***

Subduction

- Subduction
  - Where cool material sinks, it may drag crustal pieces together buckling them upward into mountains
  - If one piece of crust slips under the other, the process is called ***subduction***

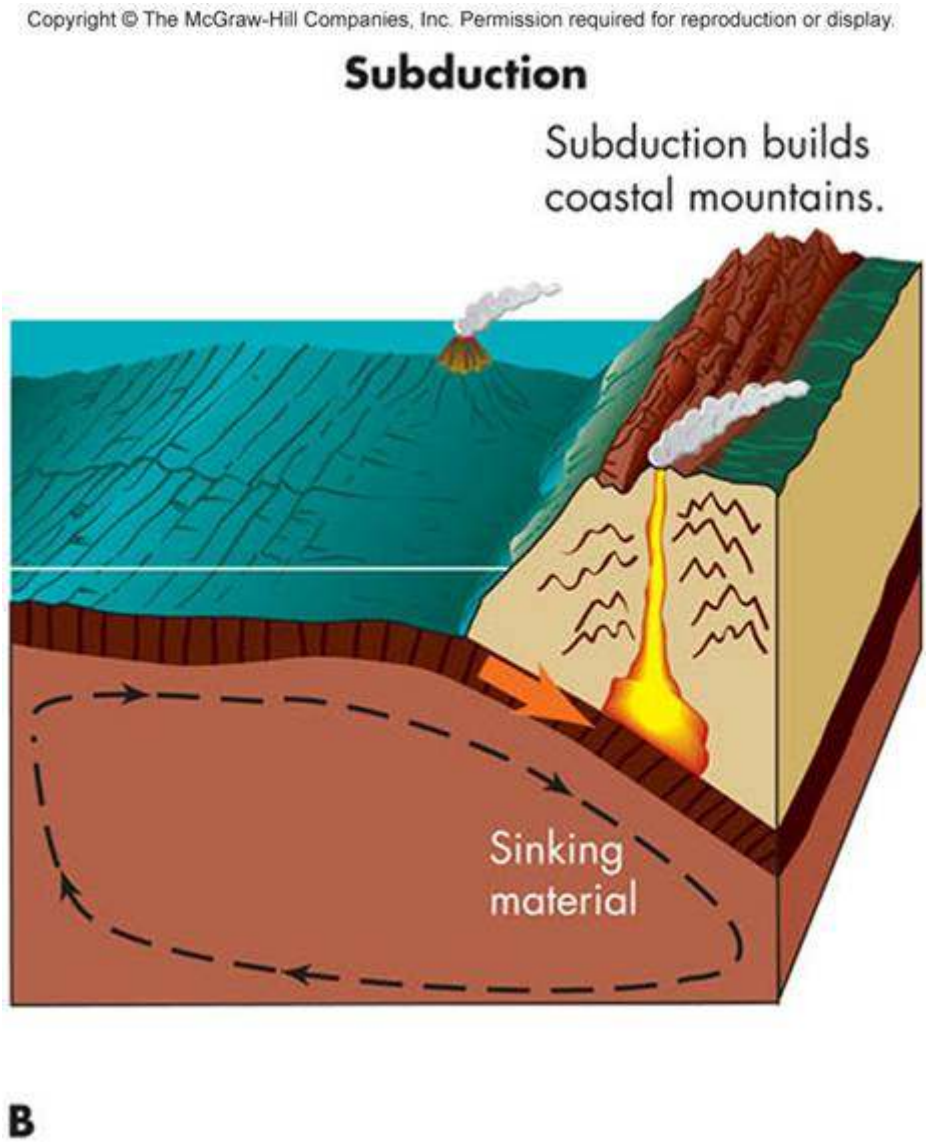
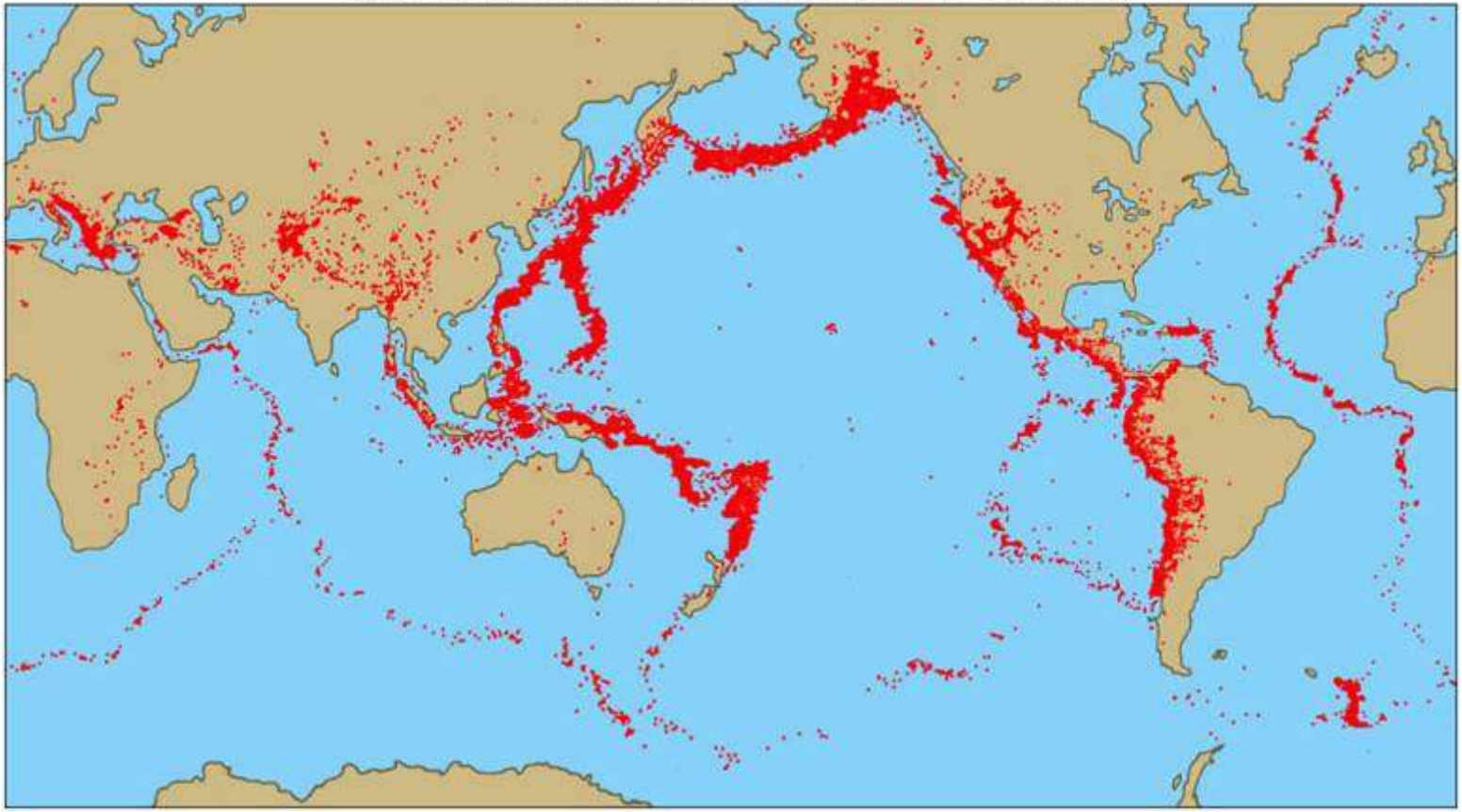


Plate Tectonics

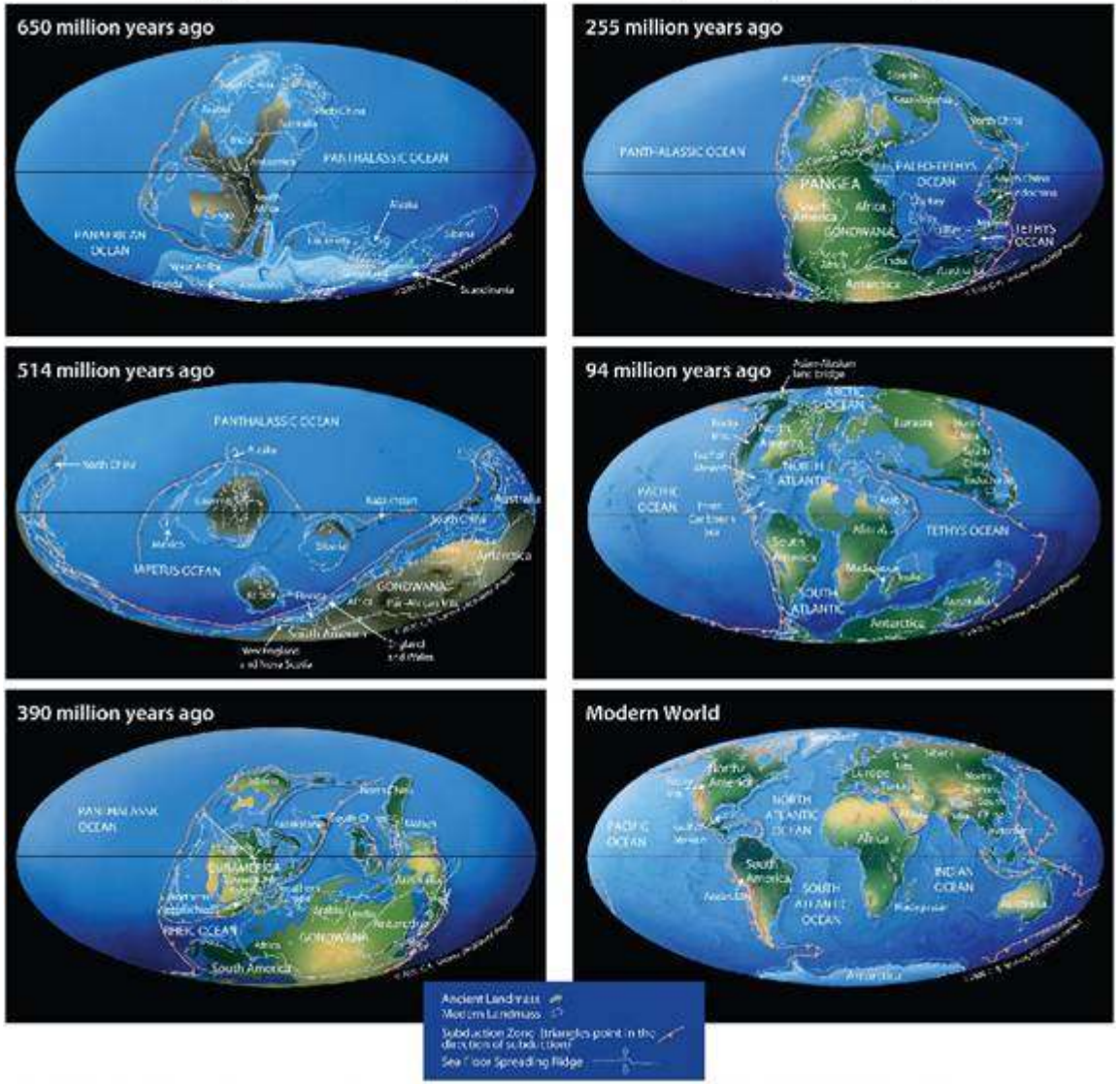


- Rifting and subduction are the dominant forces that sculpt the landscape – they may also trigger earthquakes and volcanoes

Plate Tectonics

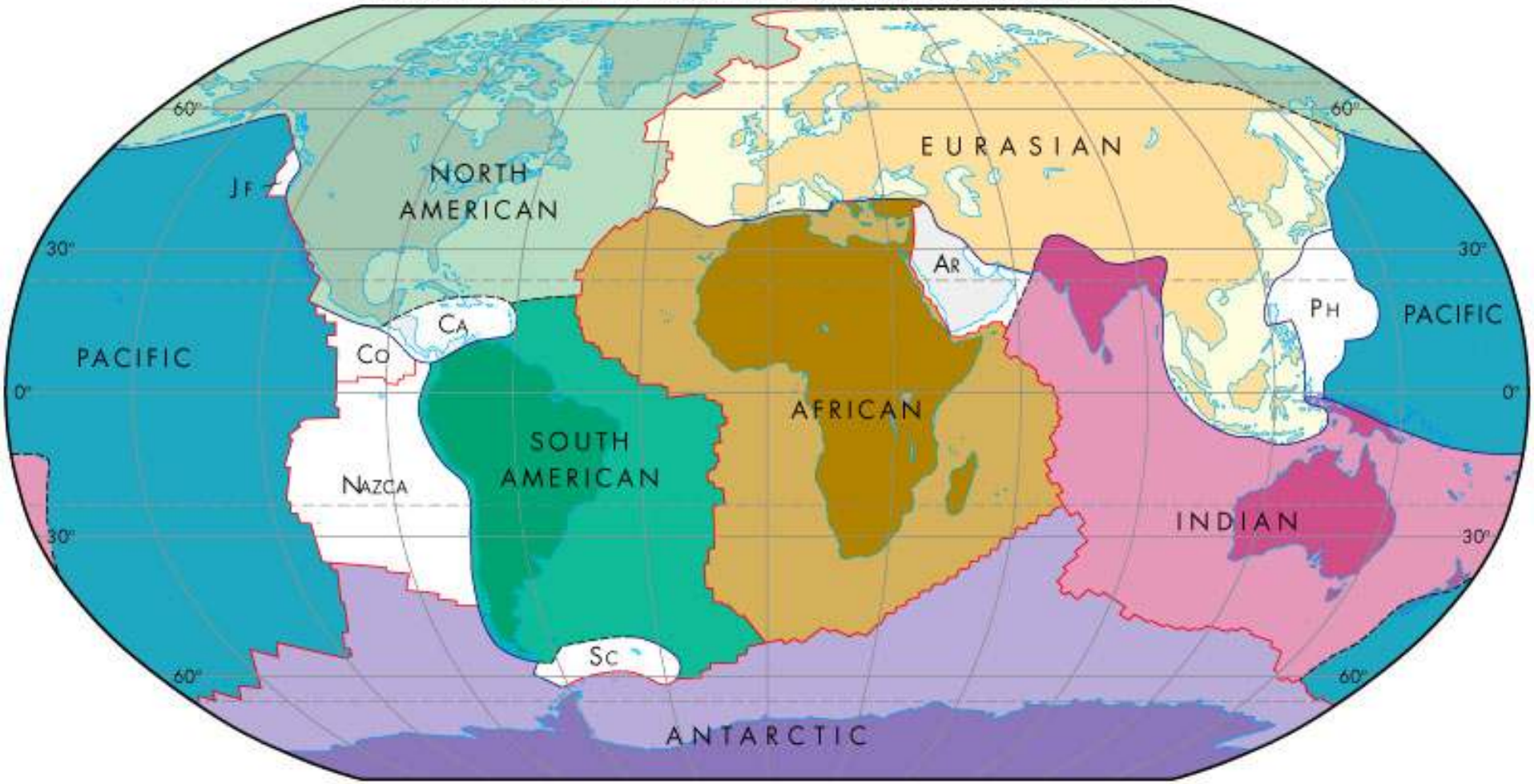
- The shifting of large blocks of the Earth's surface is called ***plate tectonics***
  - Early researchers noted that South America and Africa appeared to fit together and that the two continents shared similar fossils
  - It was later proposed (1912) that all of the continents were once a single supercontinent called Pangea
  - The Earth's surface is continually building up and breaking down over time scales of millions of years

Continental Drift



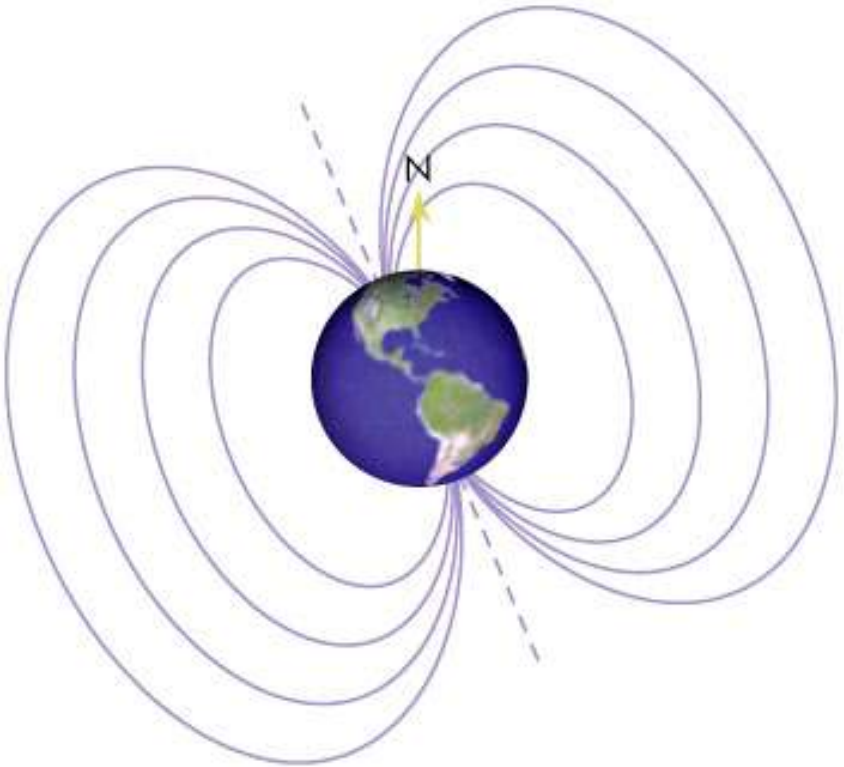
(all): Plate Tectonic and Paleogeographic maps and animations by C.R. Scotese, © 2009, PALEOMAP Project (www.scotese.com)

Continental Plates

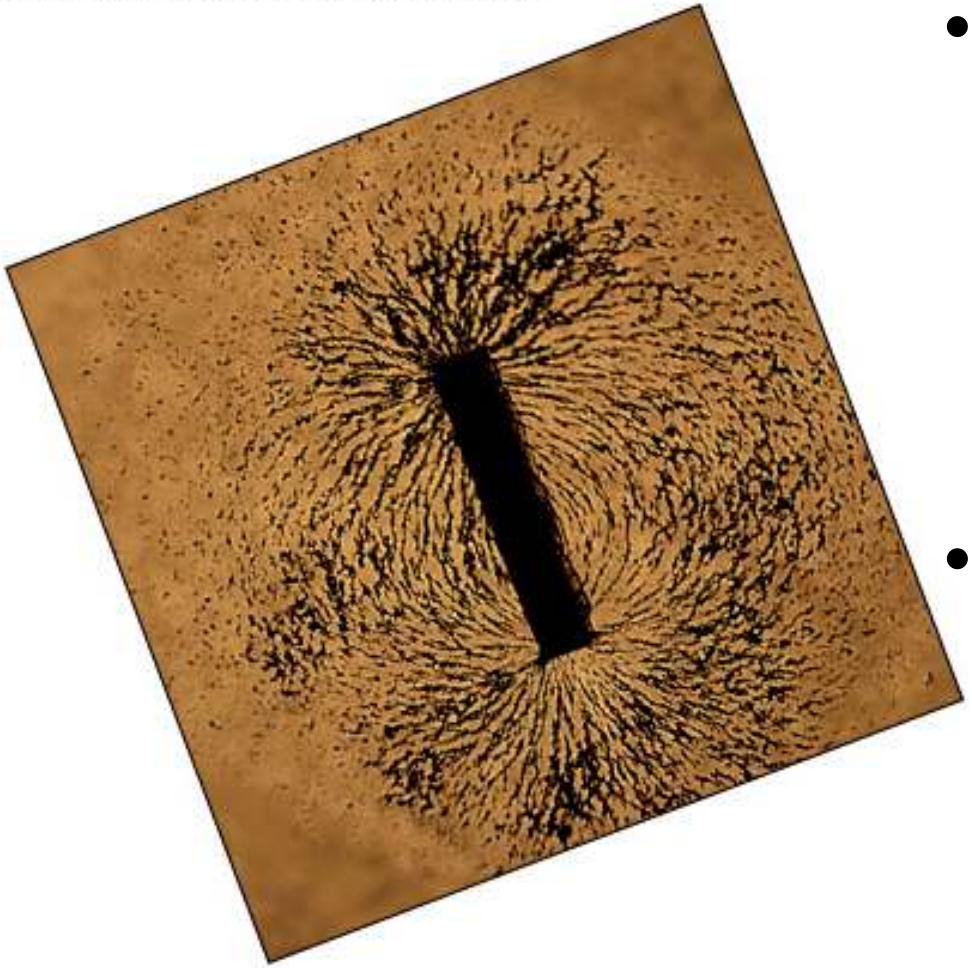


The Earth's Magnetic Field

- Magnetic forces are communicated by a ***magnetic field*** – direct physical contact is not necessary to transmit magnetic forces
- Magnetic fields are depicted in diagrams by ***magnetic lines of force***
  - Each line represents the direction a compass would point
  - Density of lines indicate strength of field



The Earth's Magnetic Field

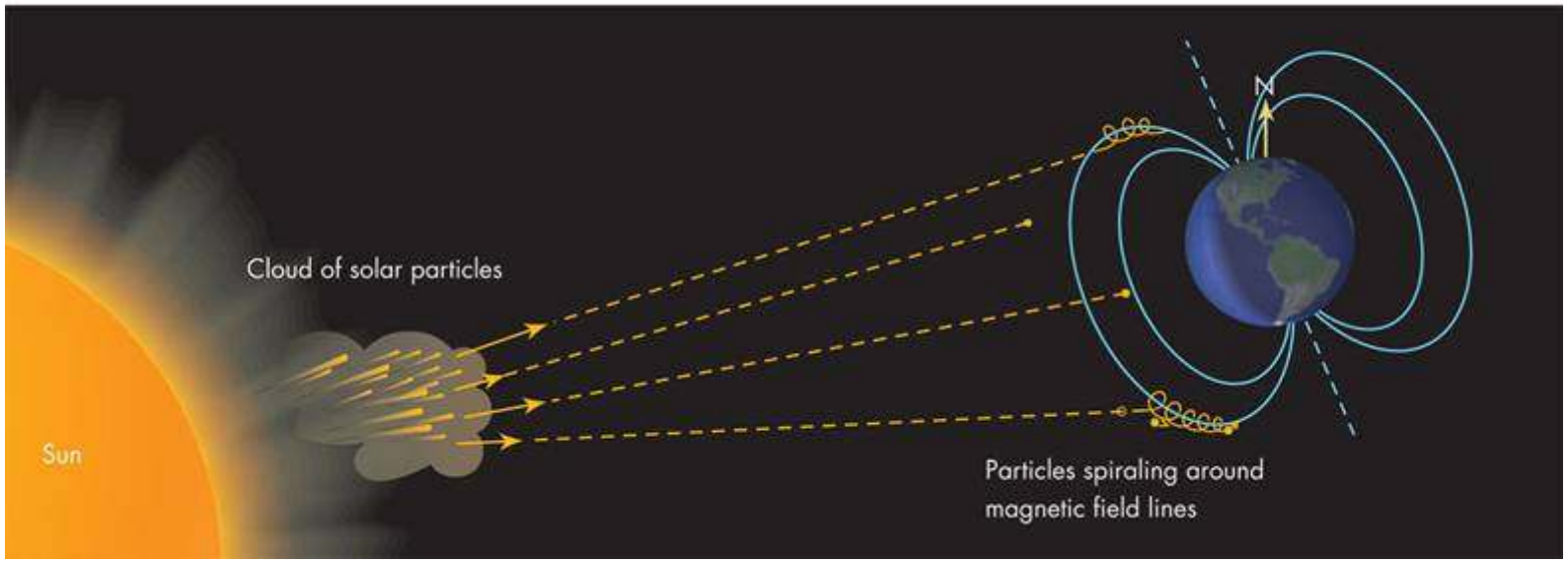


- Magnetic fields also have ***polarity*** – a direction from a north magnetic pole to a south magnetic pole
- Magnetic fields are generated either by large-scale currents or currents on an atomic scale

Origin of the Earth's Magnetic Field

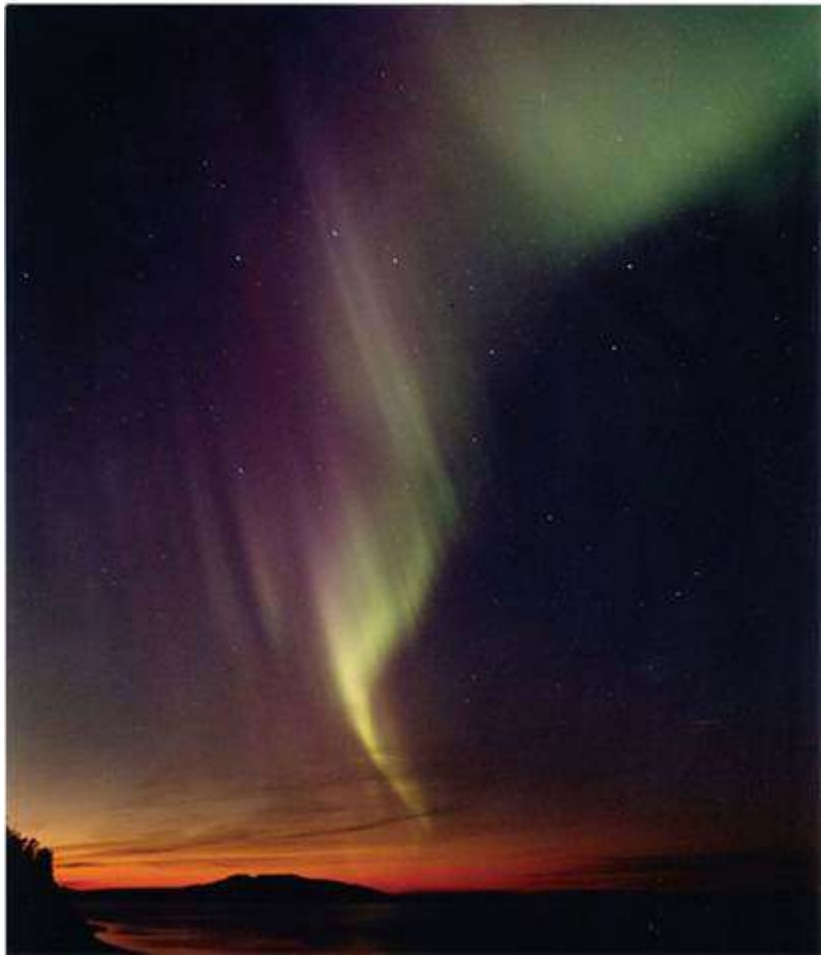
- The magnetic field of the Earth is generated by currents flowing in its molten iron core
- The currents are believed to be caused by rotational motion and convection (magnetic dynamo)
- The Earth's geographic poles and magnetic poles do not coincide
- Both the position and strength of the poles change slightly from year to year, even reversing their polarity every **10,000 years** or so

Magnetic Effects in the Upper Atmosphere



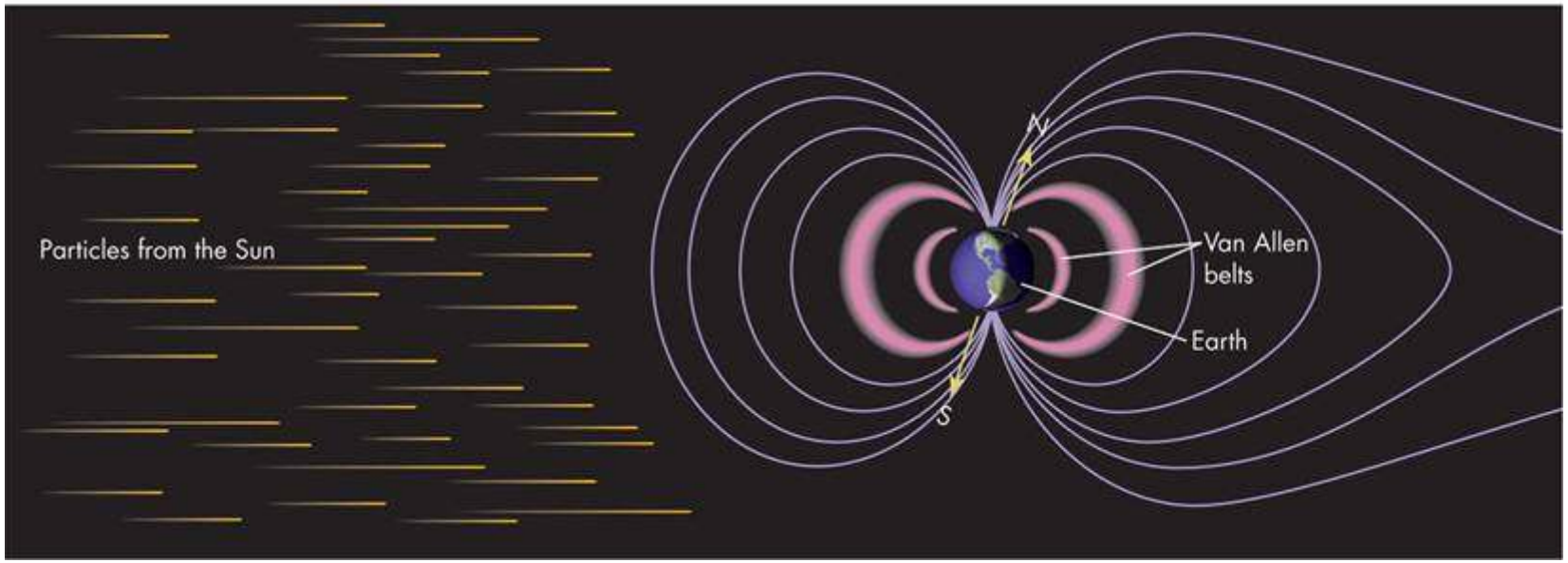
- Earth's magnetic field screens the planet from charged particles emitted from the Sun
- The Earth's magnetic field deflects the charged particles into spiral trajectories and slows them down

Aurora



- As the charged solar particles stream past Earth, they generate electrical currents in the upper atmosphere
- These currents collide with and excite molecules
- As the molecules de-excite, light photons are given off resulting in ***aurora***

The Magnetosphere



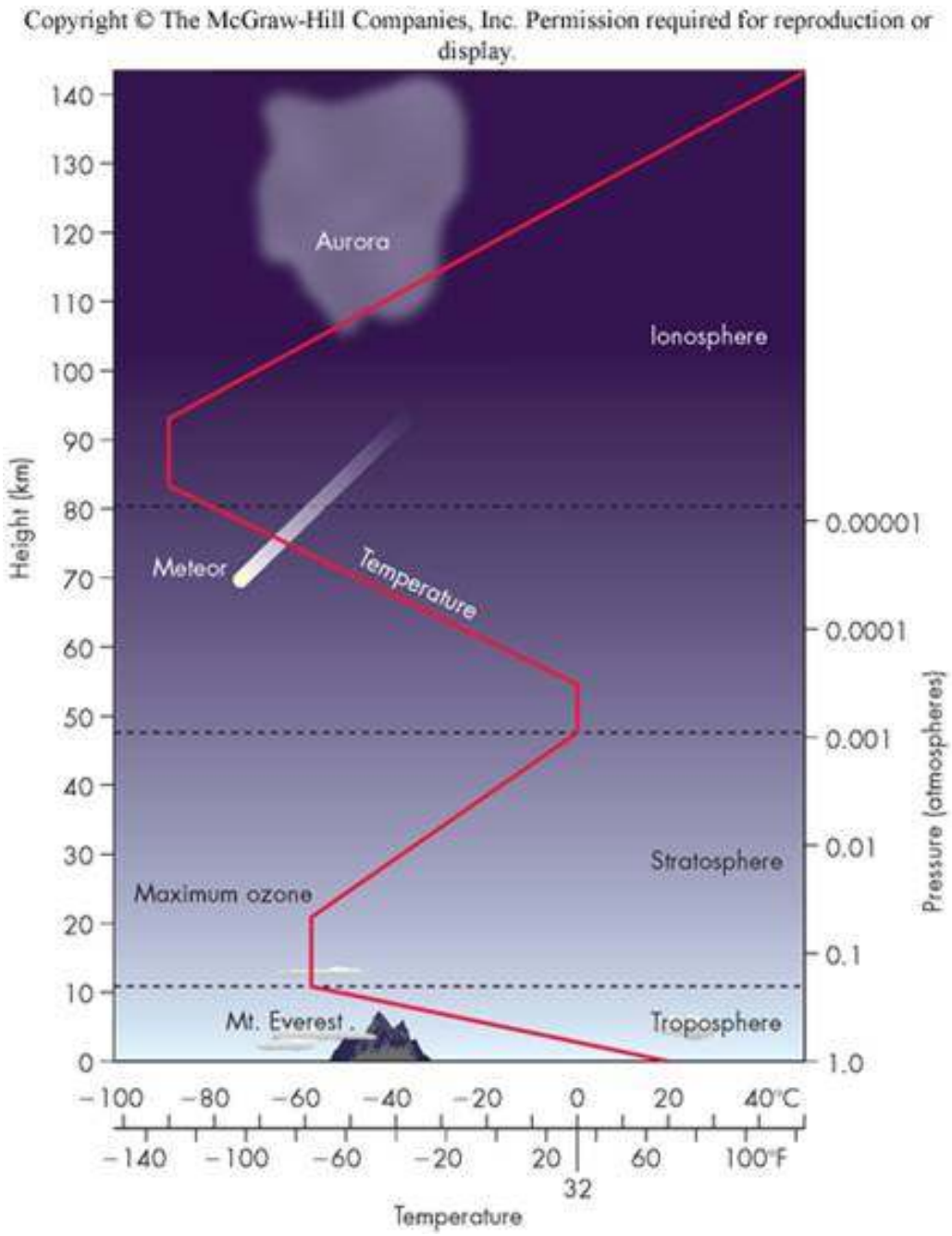
- Region of the Earth's environment where the Earth's magnetic field affects particle motion is called the ***magnetosphere***
- Within the magnetosphere charged particles are trapped in two doughnut shaped rings that encircle the Earth and are called the ***Van Allen radiation belts***

The Earth's Atmosphere

- Veil of gases around Earth constitutes its atmosphere
- Relative to other planetary atmospheres, the Earth's atmosphere is unique
- However, studying the Earth's atmosphere can tell us about atmospheres in general

Earth's Atmosphere

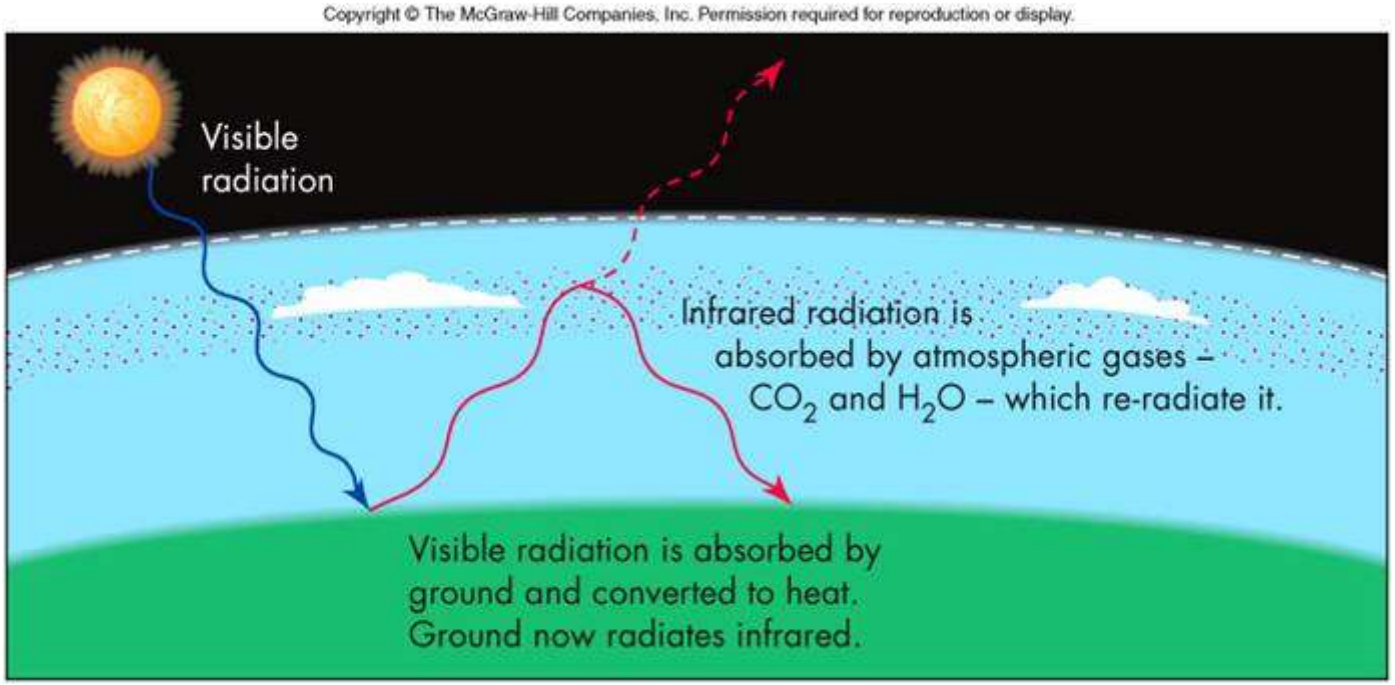
- Atmosphere extends to hundreds of kilometers becoming very tenuous at high altitudes
- The atmosphere becomes less dense with increasing altitude
- Half the mass of the atmosphere is within the first 4 kilometers
- The atmosphere eventually merges with the vacuum of interplanetary space



Composition of the Earth's Atmosphere

- The Earth's atmosphere is primarily nitrogen (78.08% by number) and oxygen (20.95% by number)
- The remaining gases in the atmosphere (about 1%) include: carbon dioxide, ozone, water, and argon, the first three of which are important for life
- This composition is unique relative to the carbon dioxide atmospheres of Mars and Venus and the hydrogen atmospheres of the outer large planets

The Greenhouse Effect



- Visible light reaches the Earth's surface and is converted to heat
- As a result, the surface radiates infrared energy, which is trapped by the atmosphere at infrared wavelengths
- This reduces the rate of heat loss and makes the surface hotter than it would be otherwise

The Ozone Layer

- Oxygen in the atmosphere provides a shield against solar UV radiation
- O_2 provides some shielding, but O_3, or **ozone,** provides most of it
- Most ozone is located in the ozone layer at an altitude of 25 km
- Shielding is provided by the absorption of UV photons by oxygen molecules (both O_2 and O_3) and their resultant dissociation
- Single O atoms combine with O and O_2 to replenish the lost O_2 and O_3
- It is doubtful that life could exist on the Earth's surface without the ozone layer

Origin of the Earth's Atmosphere

- Several theories to explain origin of Earth's atmosphere
  - Release of gas (originally trapped when the Earth formed) by volcanism or asteroid impacts
  - From materials brought to Earth by comet impacts

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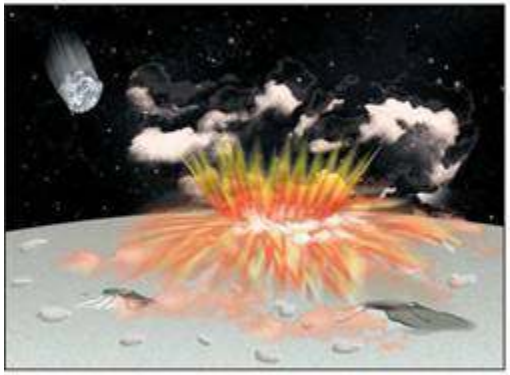

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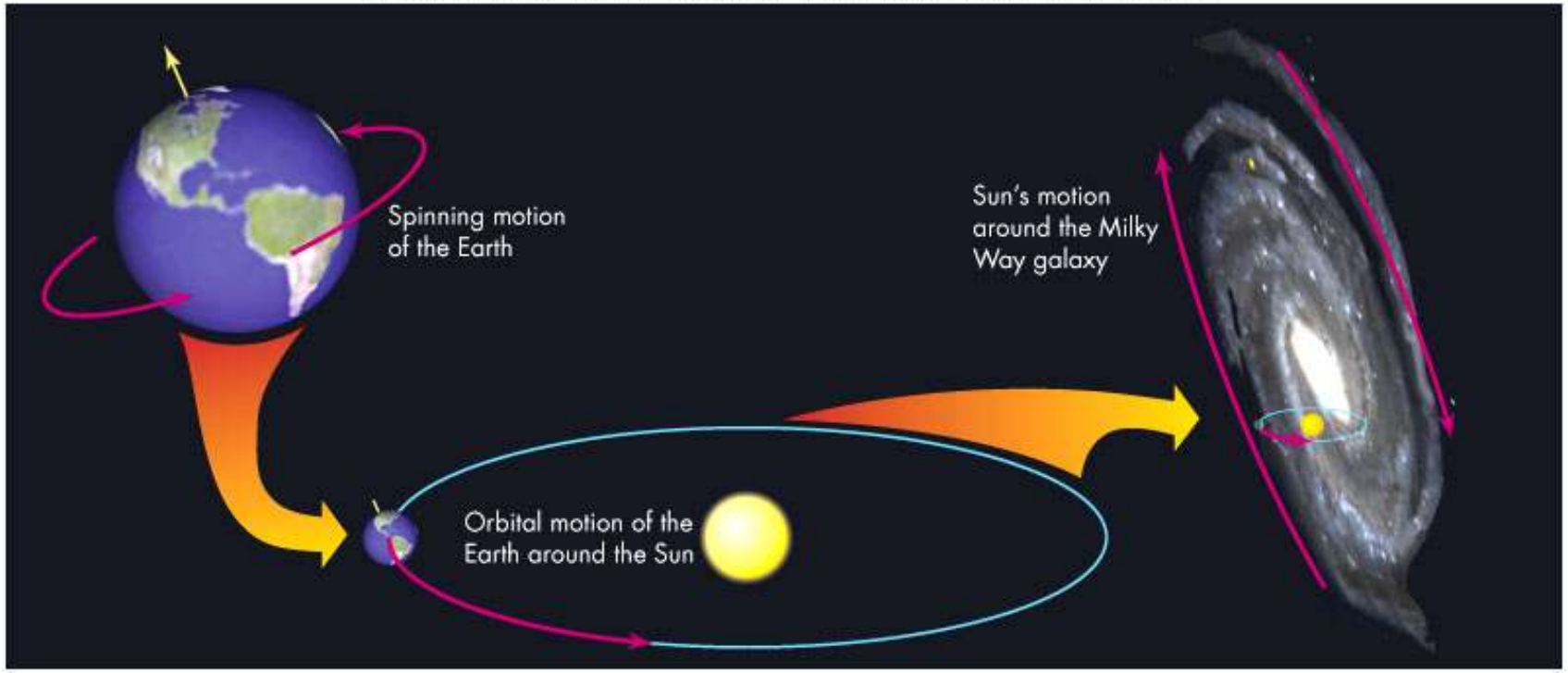
The Early Atmosphere

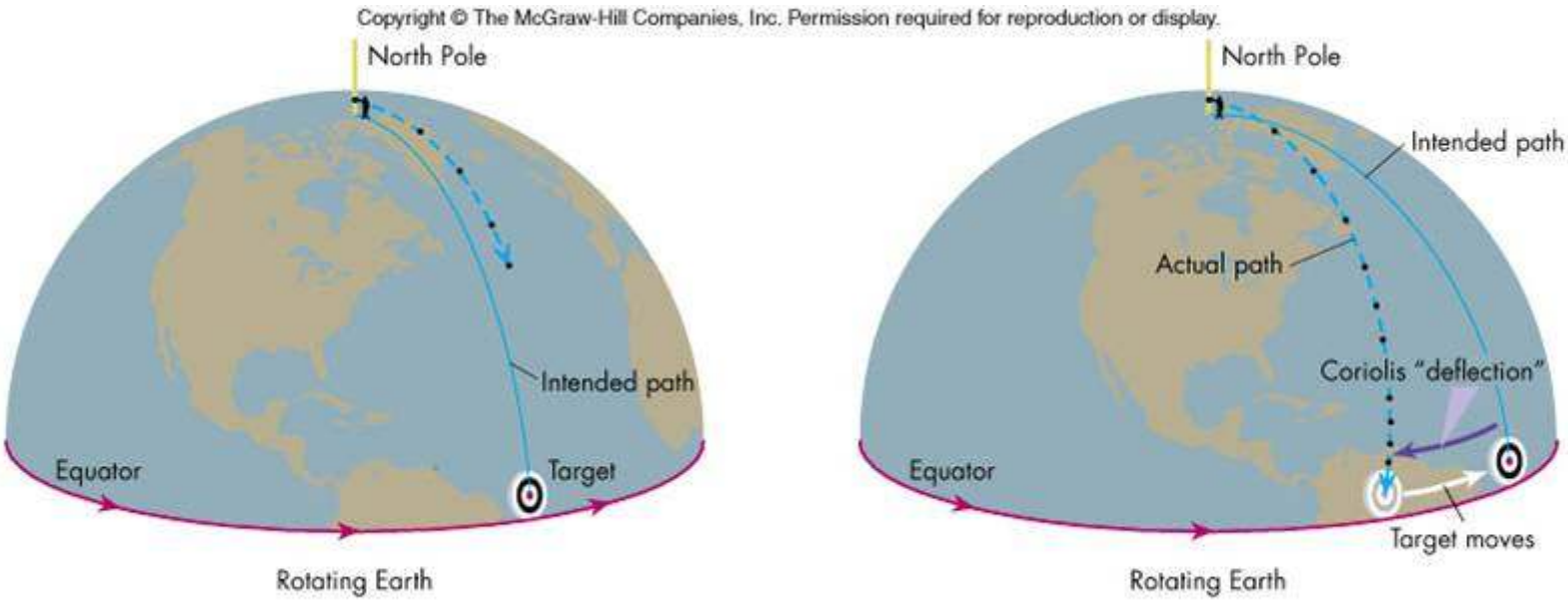
- Early atmosphere different than today
  - Contained much more methane (CH_4) and ammonia (NH_3)
  - Solar UV was intense enough to break out H from CH_4, NH_3 , and H_2O leaving carbon, nitrogen, and oxygen behind while the H escaped into space
  - Ancient plants further increased the levels of atmospheric oxygen through photosynthesis

Motions of the Earth



- Rotational and orbital motions define the day and year and cause the seasons
- But our planet's motions have other effects

Air and Ocean Circulation



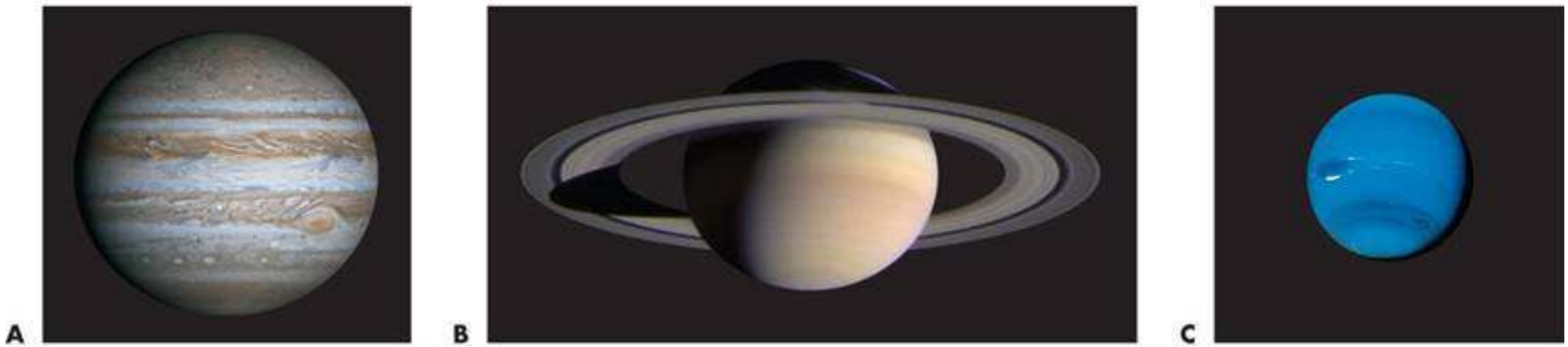
- In the absence of any force an object will move in a curved path over a rotating object
- This apparent curved motion is referred to as the ***Coriolis effect***

The Coriolis Effect

- Responsible for:
  - The spiral pattern of large storms as well as their direction of rotation
  - The trade winds that move from east to west in two bands, one north and one south of the equator

- The direction of the ***jet streams,*** narrow bands of rapid, high-altitude winds
- The deflection of ocean currents creating flows such as the Gulf Stream

The Coriolis Effect

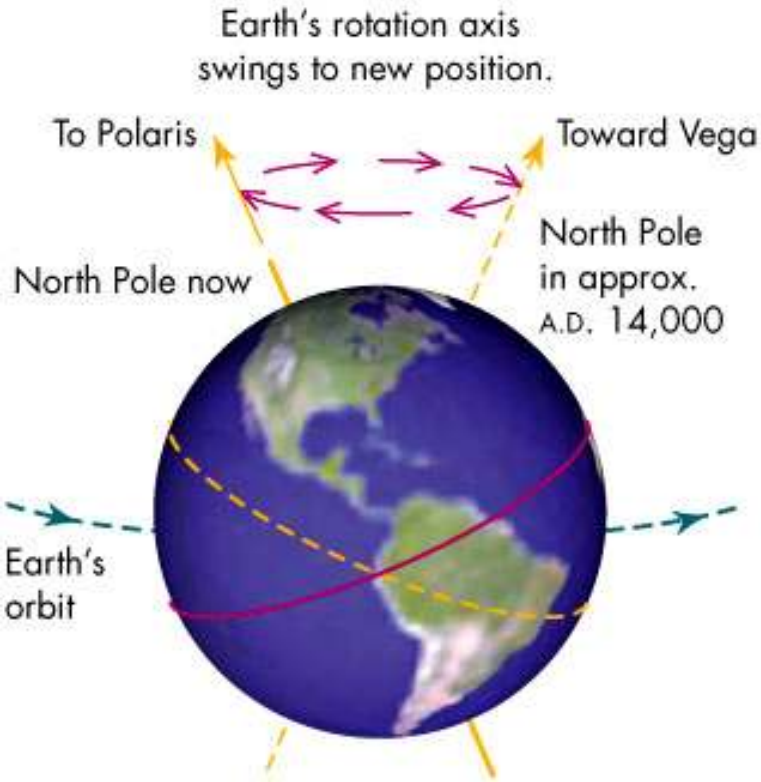


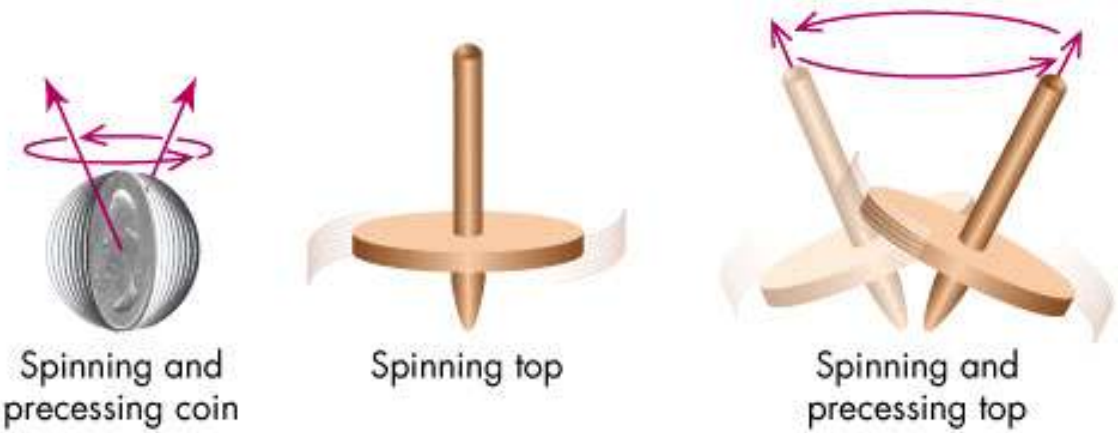
- Also…
  - The atmospheric band structure of the rapidly rotating Jupiter, Saturn, and Neptune

Precession

- As the Earth moves around the Sun over long periods of time, the direction in which its rotation axis points changes slowly
- This changing in direction of the spin axis is called ***precession***
- Precession is caused by the Earth not being a perfect sphere – its equatorial bulge allows the Sun and Moon to exert unbalanced gravitational forces that twist the Earth's spin axis
- The Earth's spin axis precesses around once every 26,000 years
- Currently the spin axis points at Polaris – in A.D. 14,000 it will point nearly at the star Vega
- Precession may cause climate changes

Precession





Chapter 7

The Moon

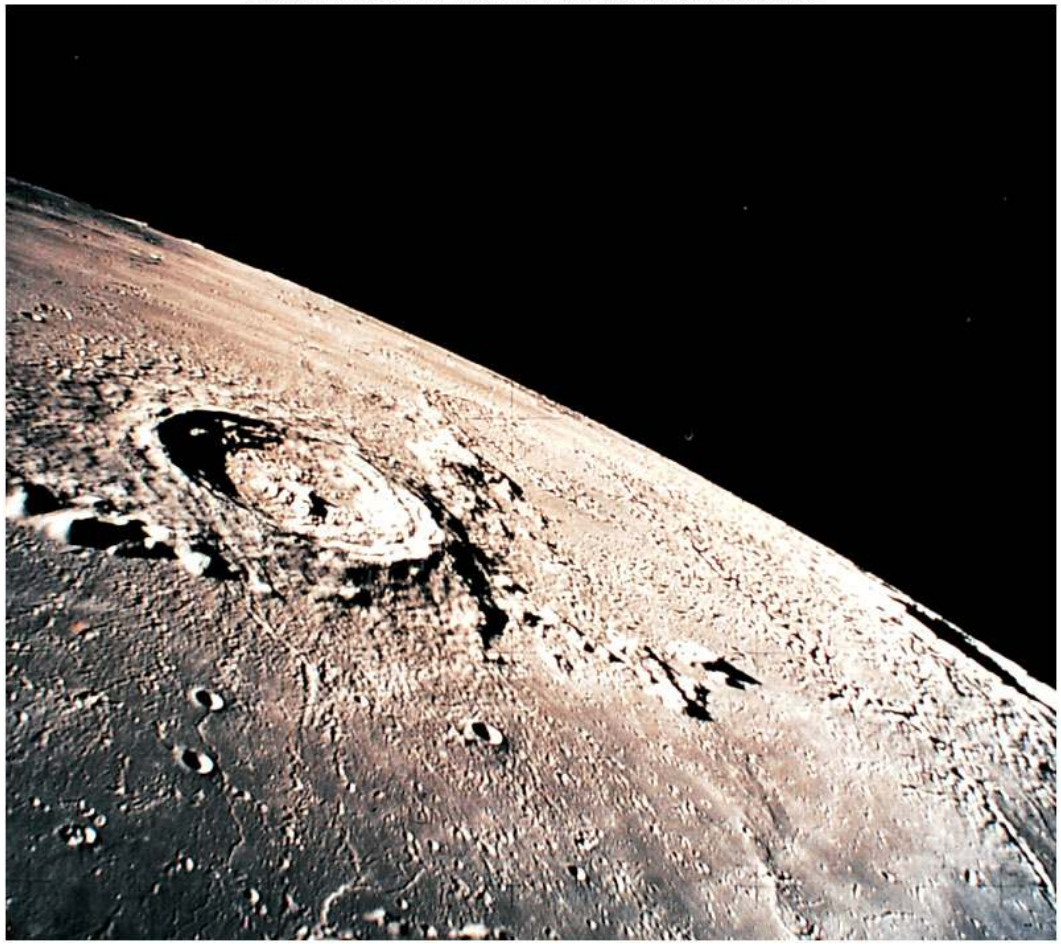
The Earth's Moon

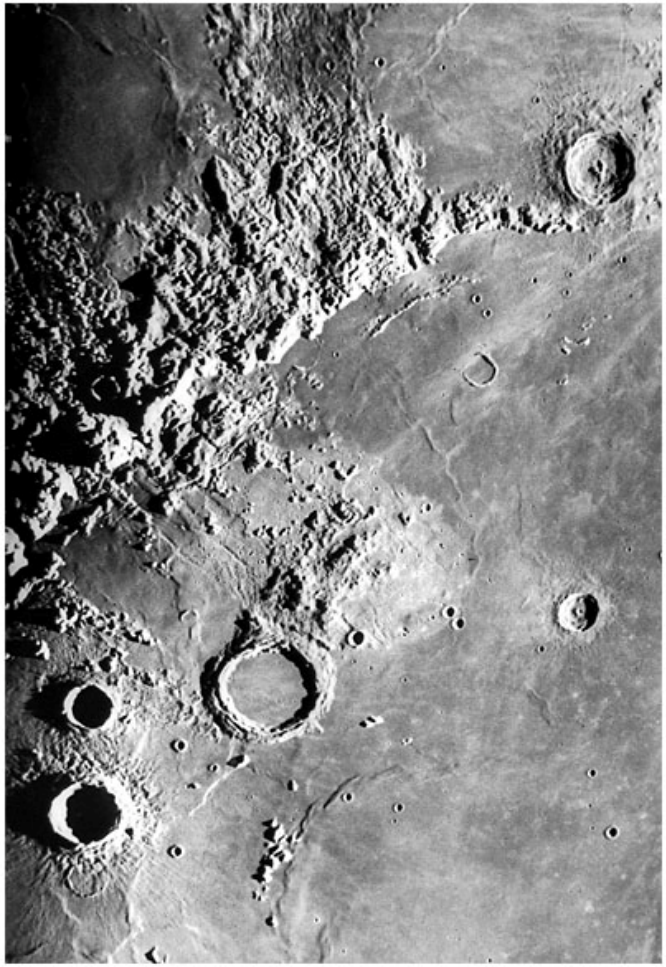
- Earth's nearest neighbor is space
- Once the frontier of direct human exploration
- Born in a cataclysmic event into an original molten state, the Moon is now a dead world – no plate tectonic or volcanic activity and no air
- Suffered early impact barrage
- Plays major role in eclipses and tides

The Moon

- Moon is 1/4 the Earth's diameter
- Gravity is 1/6 as strong
- A place of "magnificent desolation" – shapes of gray without color

“Magnificent Desolation”

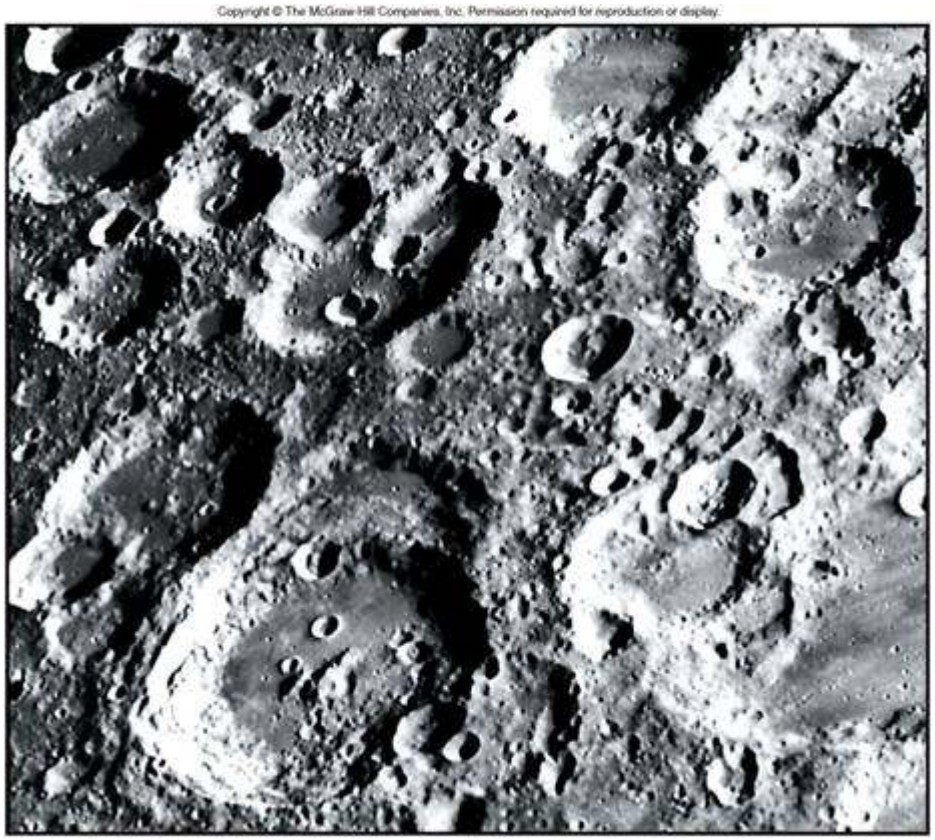




Surface Features

- Surface divided into two major regions
  - ***Highlands*** – Bright rugged areas composed mainly of anorthosite (a rock rich in calcium and aluminum silicates) and pitted with craters
  - ***Maria*** – Large, smooth, dark areas surrounded by highlands and composed primarily of basalt (a congealed lava rich in iron, magnesium, and titanium), which is more dense than anorthosite

Craters



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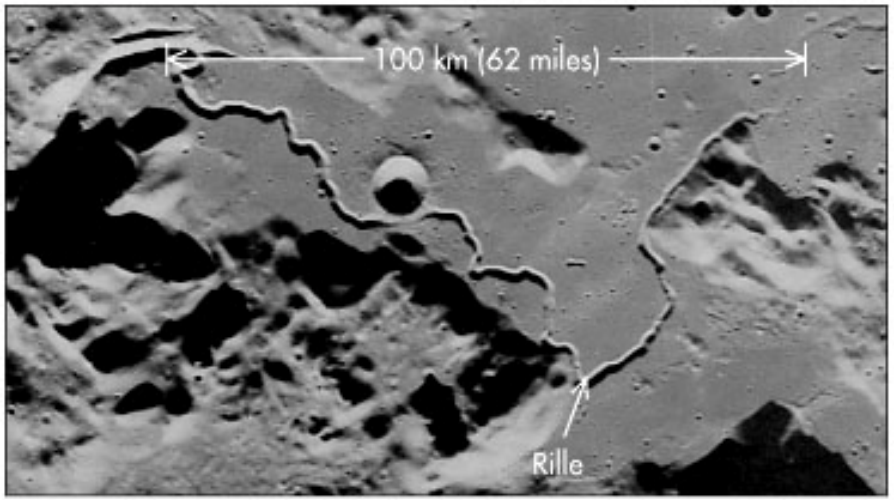
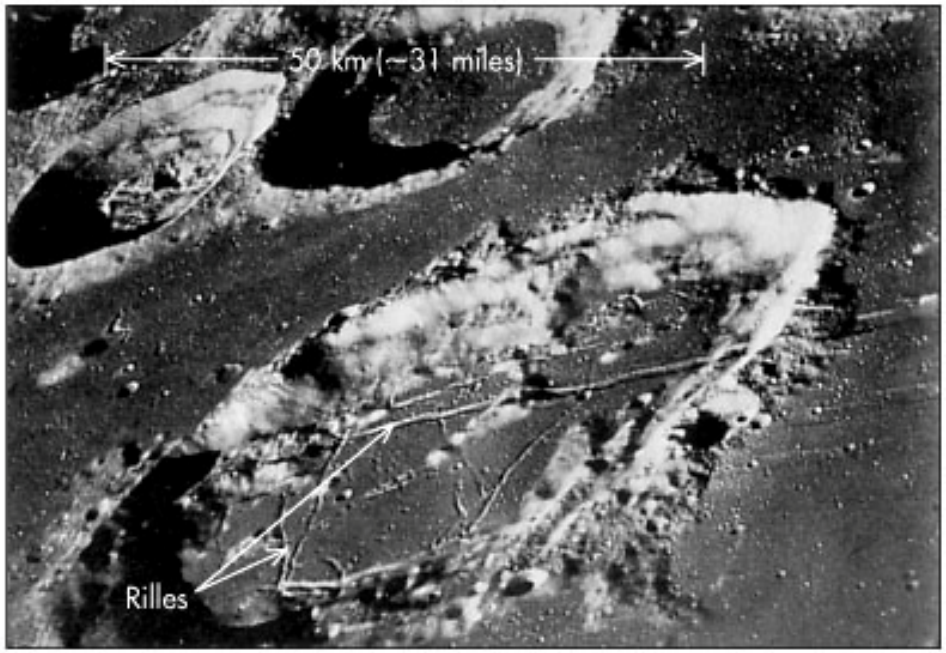
- ***Craters*** – circular features with a raised rim and range in size from less than a centimeter to a few hundred kilometers – some of the larger craters have mountain peaks at their center

Rays

- Long, light streaks of pulverized rock radiating away from many craters and best seen during full Moon

Rilles



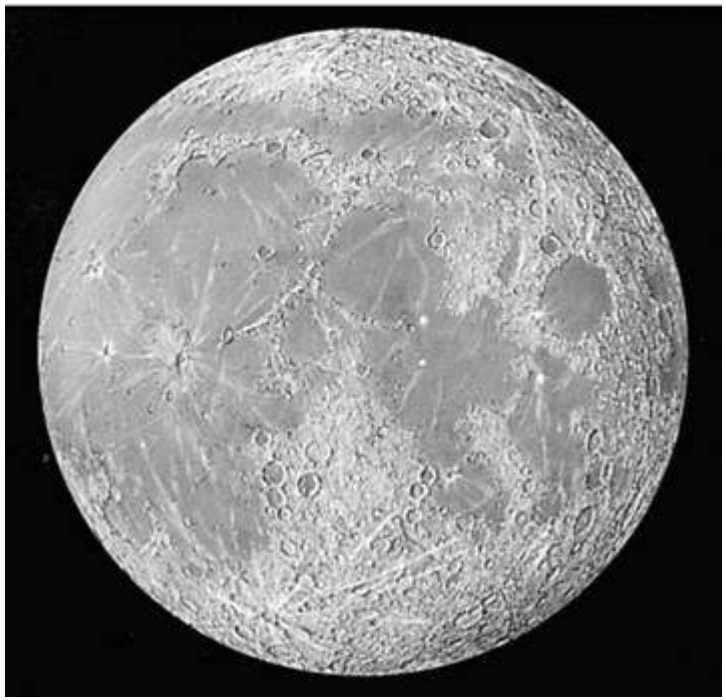


- Lunar canyons carved either by ancient lava flows or crustal cracking

Origin of Lunar Surface Features

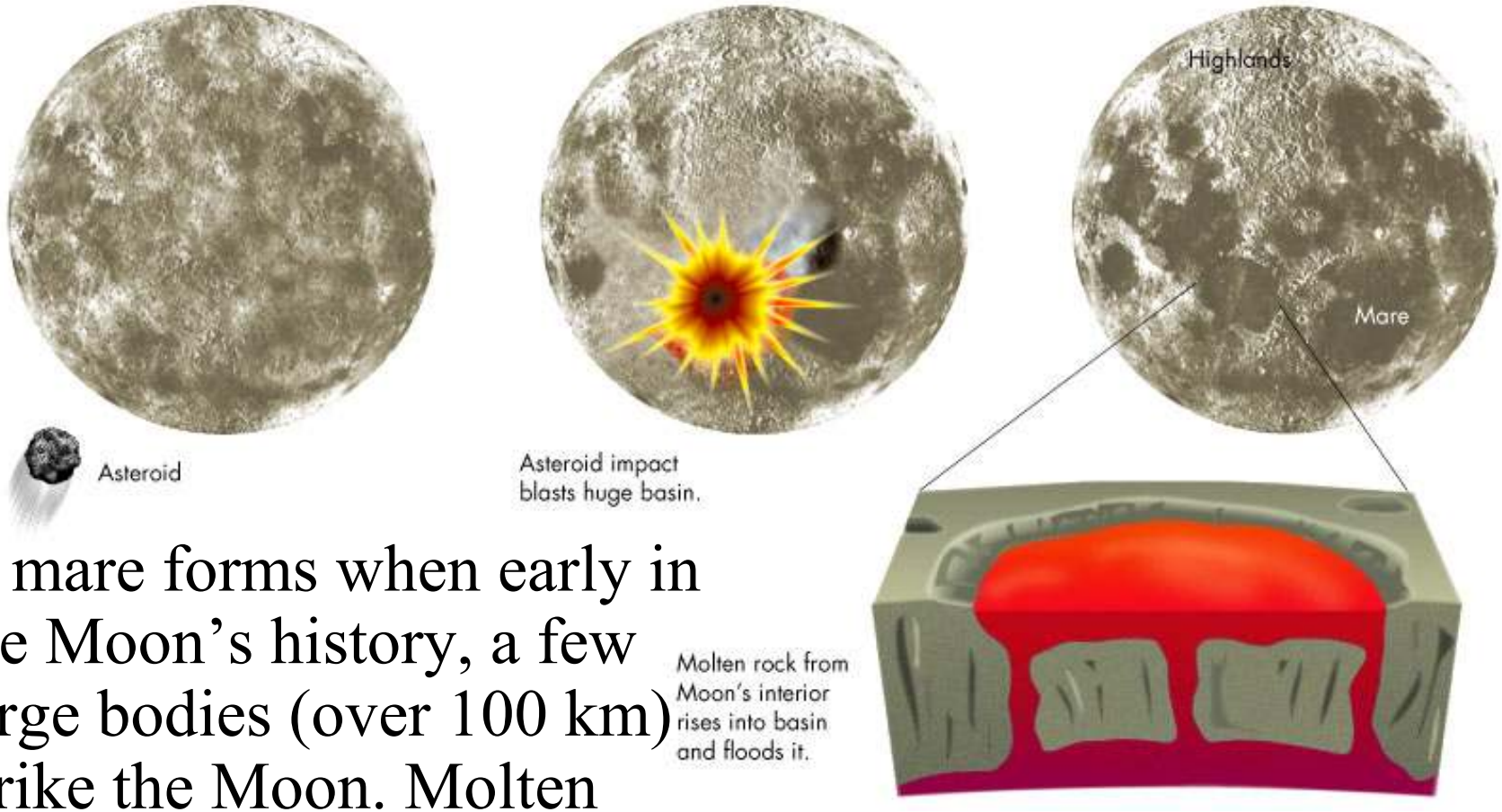
- Nearly all lunar features (craters, maria, rays) are the result of impacts by solid bodies early in the Moon's history
- A circular crater forms when a high-velocity projectile disintegrates upon impact in a cloud of vaporized rock and fragments that blast a hole in the surface

Origin of Lunar Surface Features



- The highlands are the result of the very intense bombardment by solar system bodies soon after the Moon formed and created a solid surface

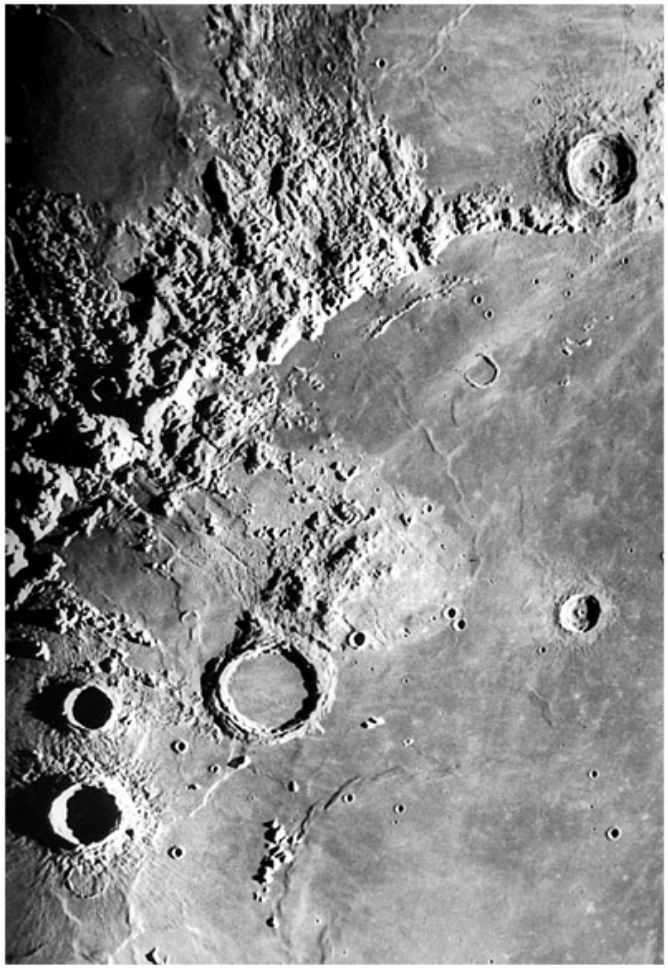
Formation of Maria



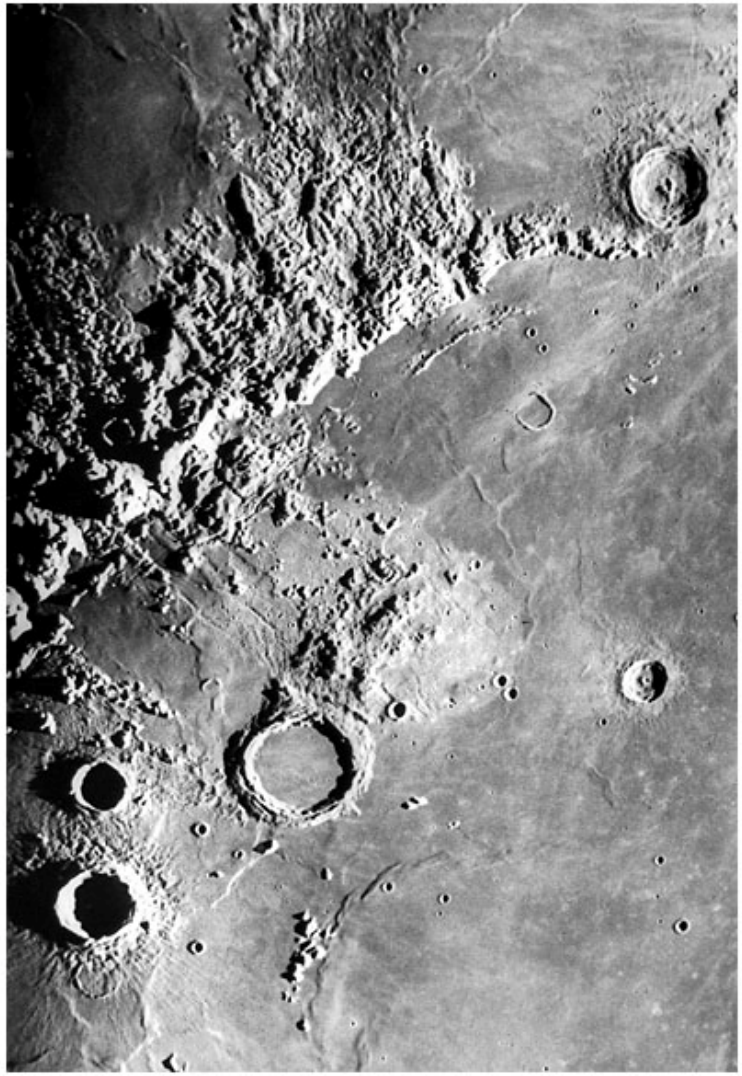
- A mare forms when early in the Moon's history, a few large bodies (over 100 km) strike the Moon. Molten material floods the newly formed lunar depression and eventually congeals

Structure of the Moon

- The Moon lacks the folded mountain ranges and variety of volcanic peaks seen on Earth
- Lack of activity due to Moon cooling off much faster than Earth
  - Moon's higher surface-to-volume ratio (relative to Earth) allows heat to escape from it faster
  - Being much less massive than the Earth, the Moon also has a smaller source of radioactive material to supply heat



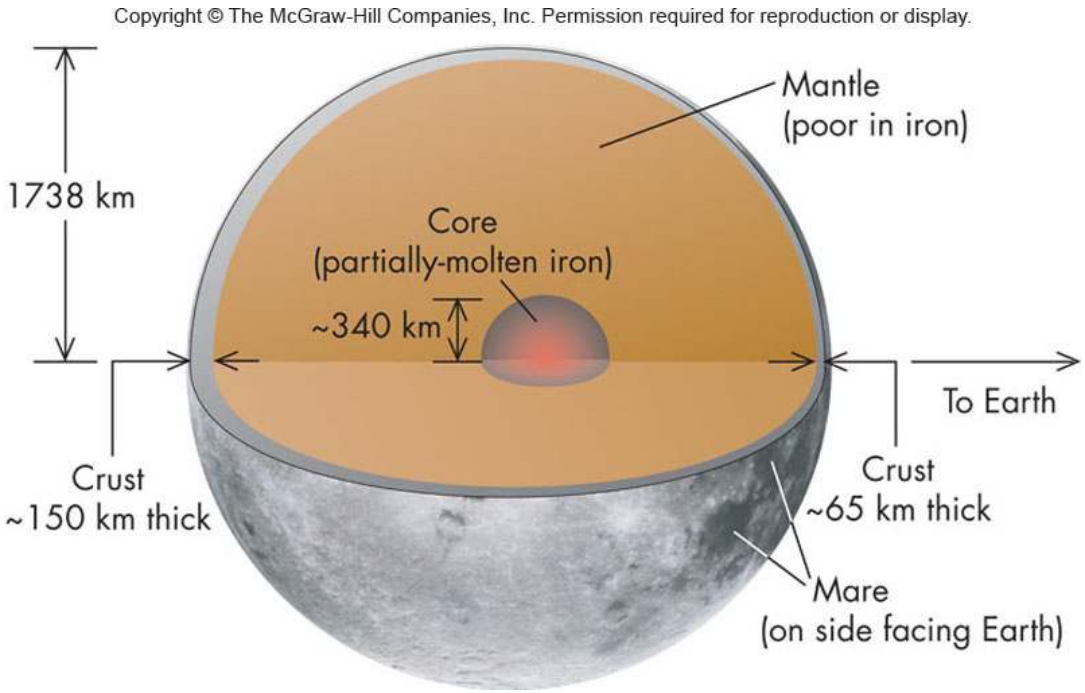
The Interior of the Moon



- Interior (including crust) studied by seismic detectors set up on Moon by astronauts – essentially found to be inactive and has simpler structure than Earth's

The Surface of the Moon - Regolith

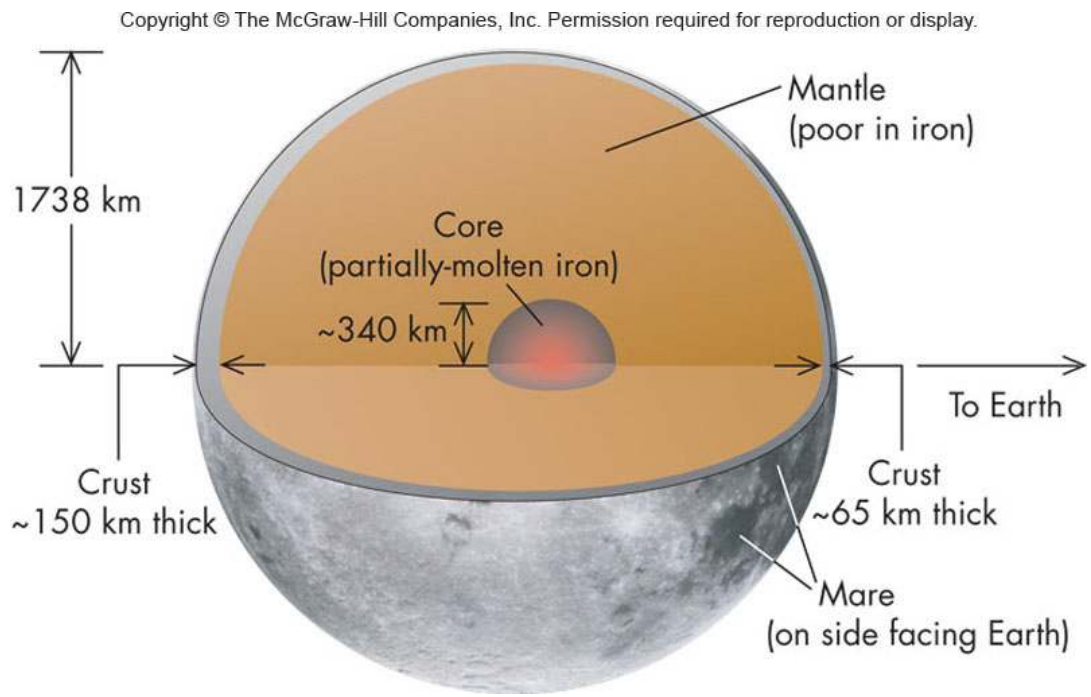
- Surface layer is shattered rock chunks and powder (from repeated impacts) forming a ***regolith*** tens of meters thick



- Regolith is basaltic in maria and anorthostic in highlands
- Regolith may extend to several hundred meters in some places

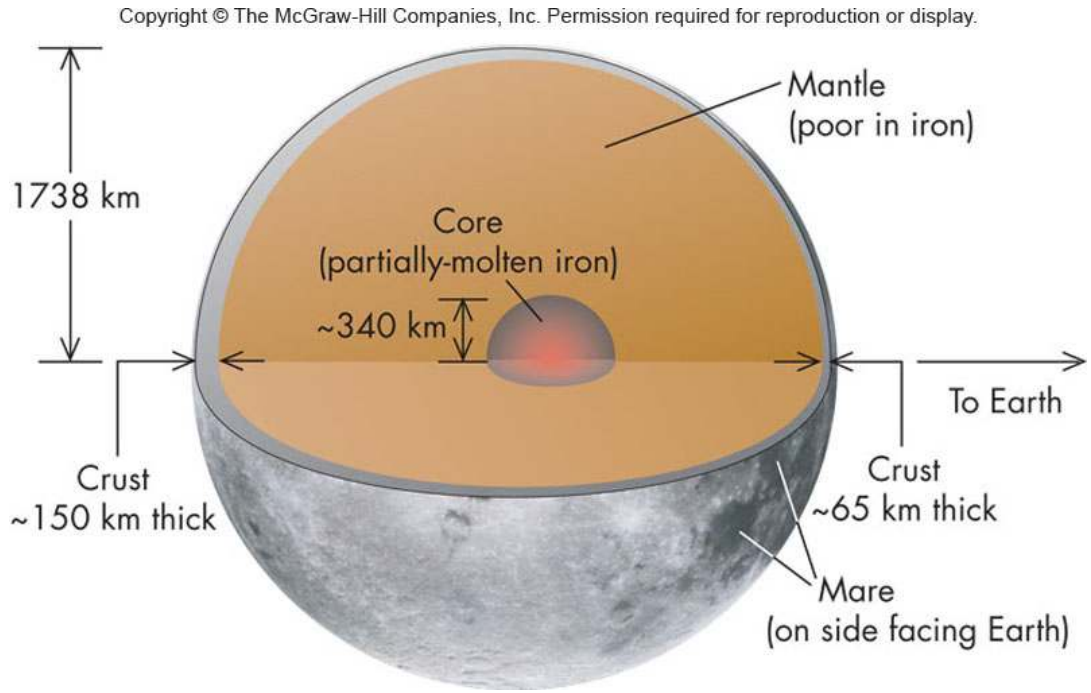
The Interior of the Moon - Crust

- Average thickness of 100 km, although crust is thinner on side that faces Earth
- Reason for asymmetry is not clear, but may be related to the difference in the Earth's gravitational force across the Moon



- Very few maria exist on side of Moon away from Earth
- Crust is composed of silicate rocks rich in aluminum and poor in iron

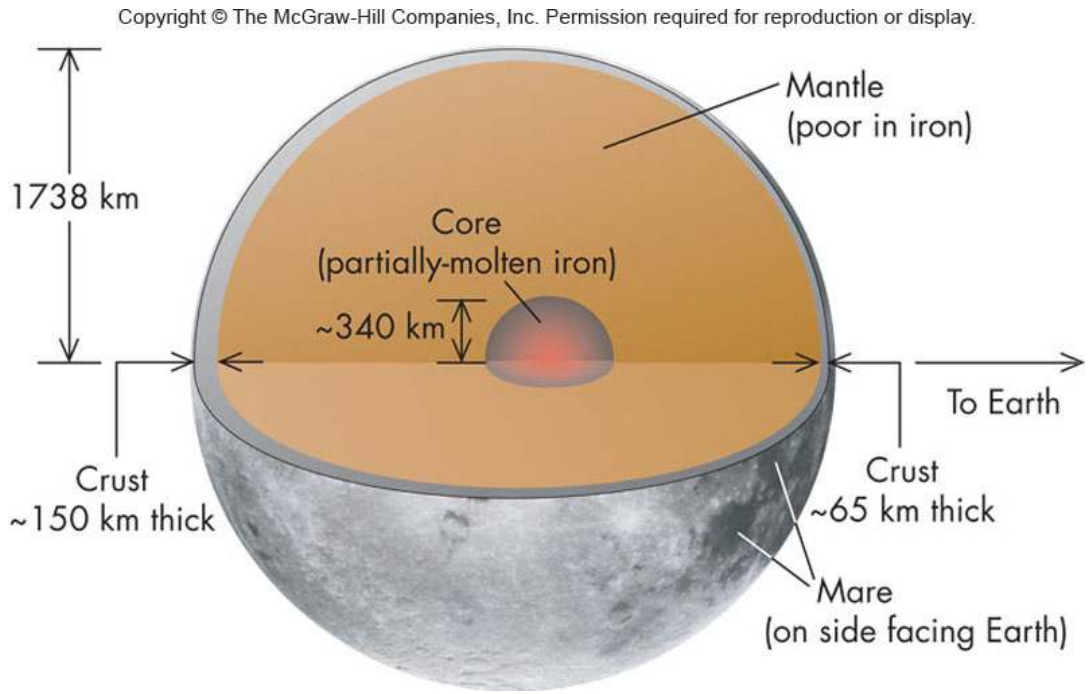
The Interior of the Moon - Mantle



- Relatively thick, extending 1000 km down
- Probably rich in olivine
- Appears too cold and rigid to be stirred by the Moon's feeble heat

The Interior of the Moon - Core

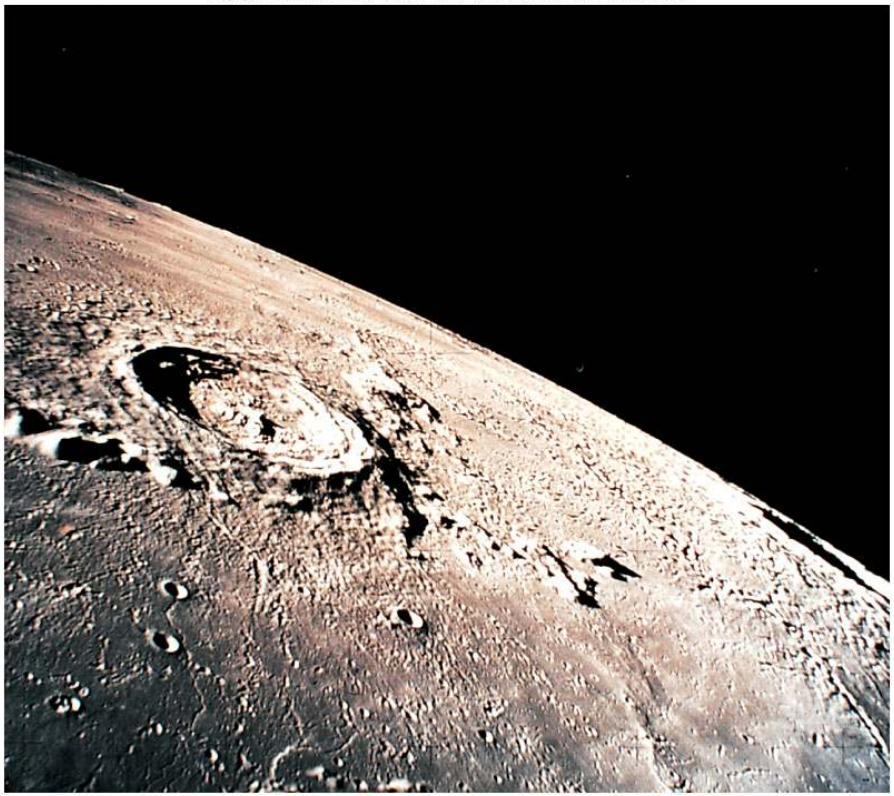
- The Moon's low average density (3.3 g/cm^3) tells us interior contains little iron
- Some molten material may be below mantle, but core is smaller and contains less iron and nickel than Earth's



- The relatively cold Moon interior, low iron/nickel content, and slow rotation imply no lunar magnetic field – found to be the case by the Apollo astronauts

Lunar Atmosphere

- Moon's surface is never hidden by lunar clouds or haze, nor does reflected spectrum show any signs of gas and hence no winds
- Lack of an atmosphere means extreme changes in lunar surface temperature from night to day



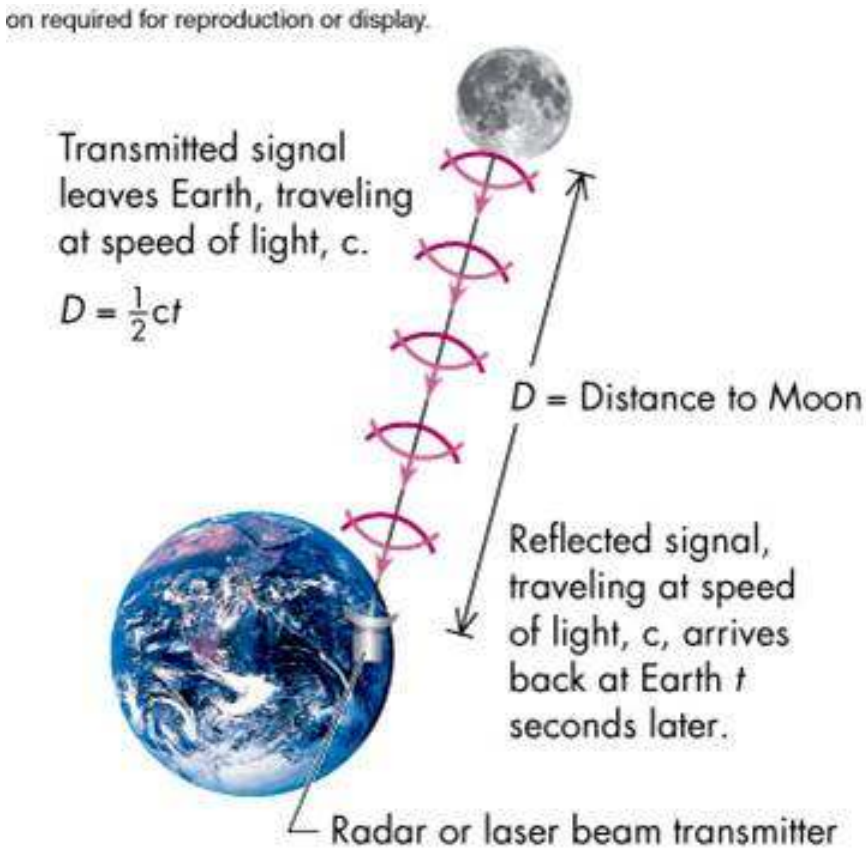
Lunar Atmosphere

- No atmosphere for two reasons
  - Lack of volcanic activity to supply source of gas
  - Moon's gravitational force not strong enough to retain gases even if there was a source

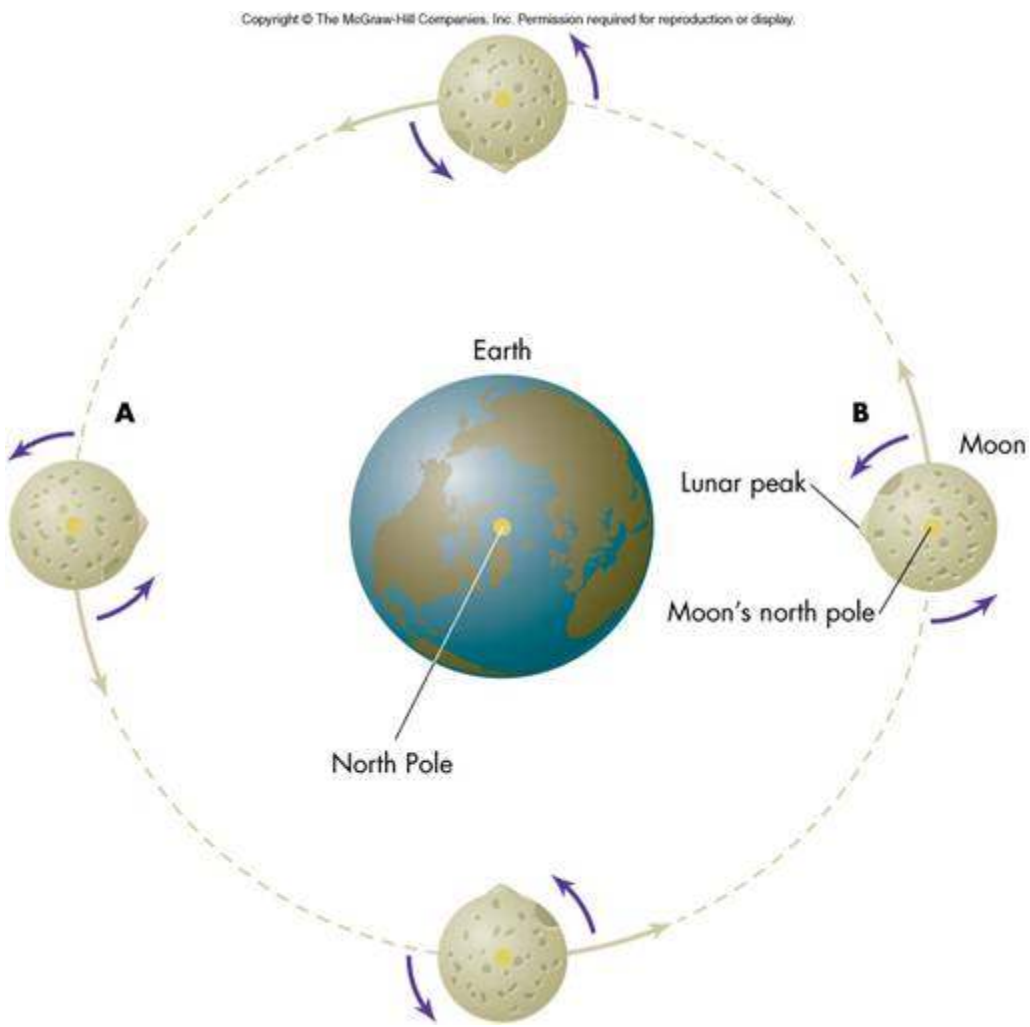
- Lack of atmosphere and plate tectonics implies that the Moon has been relatively unchanged for billions of years and will continue to be so into the foreseeable future

Orbit and Motion of the Moon

- The Moon's orbit around the Earth is elliptical with an average distance of 380,000 km and a period of 27.3 days relative to the stars
- Determining the Moon's distance can be done with high precision by bouncing a radar pulse or laser beam off the Moon

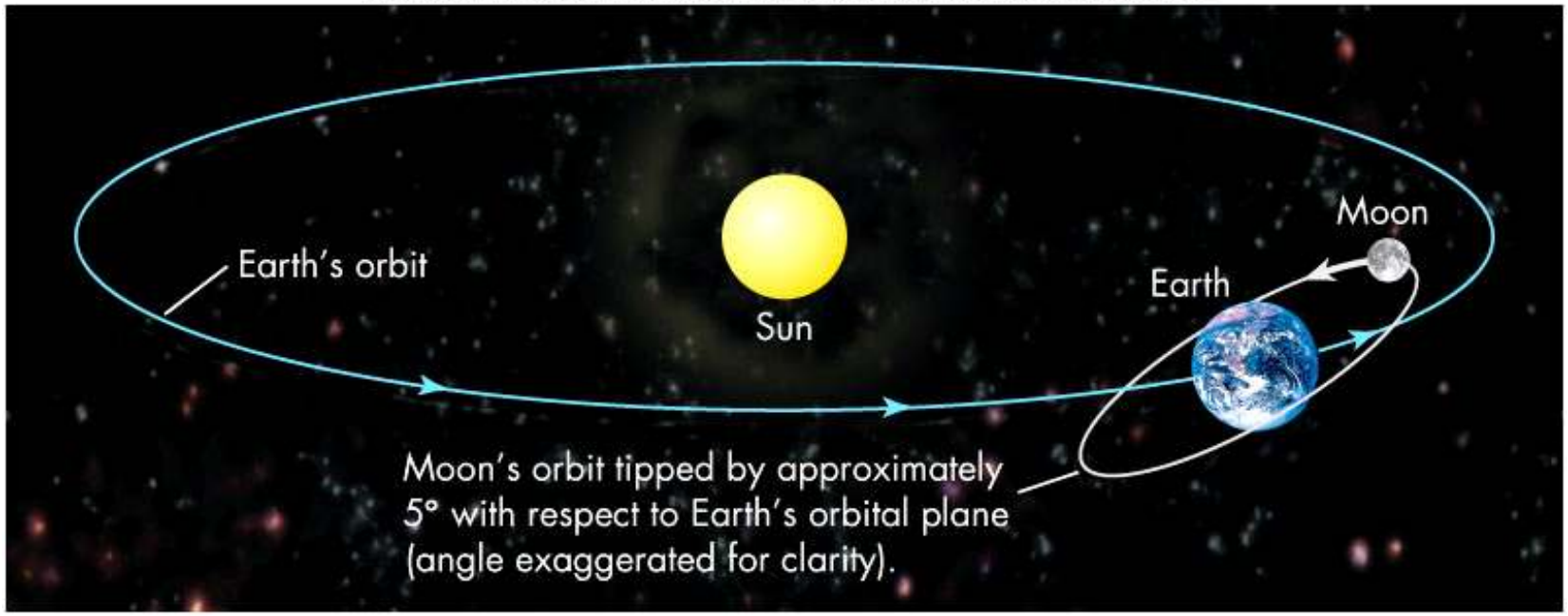


Synchronous Rotation



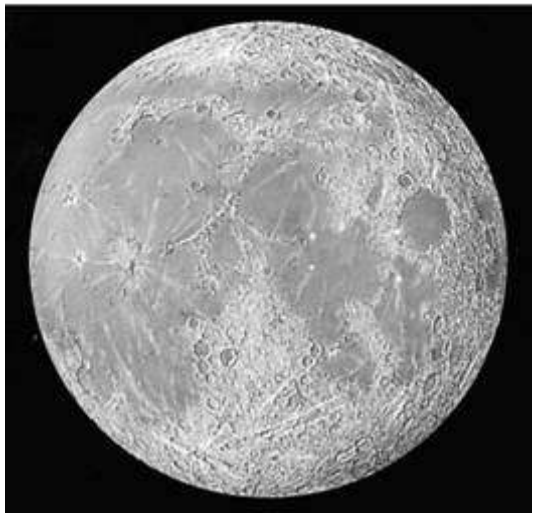
- The Moon keeps the same face toward the Earth as it orbits
- The fact that the Moon rotates at the same rate as it orbits the Earth is called ***synchronous rotation***

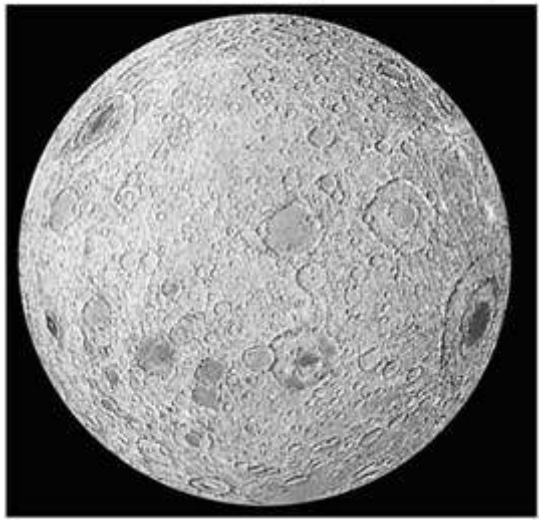
The Moon's Orbit



- The Moon's orbit is tilted about 5° with respect to the ecliptic plane
- It is also tilted with respect to the Earth's equator – very unlike most of the moons in the solar system

Origin and History of the Moon





- The Moon is also very large relative to its central planet – again unlike most of the other moons in the solar system
- These oddities indicate that the Moon formed differently from the other solar system moons!

Lunar Formation Hypotheses

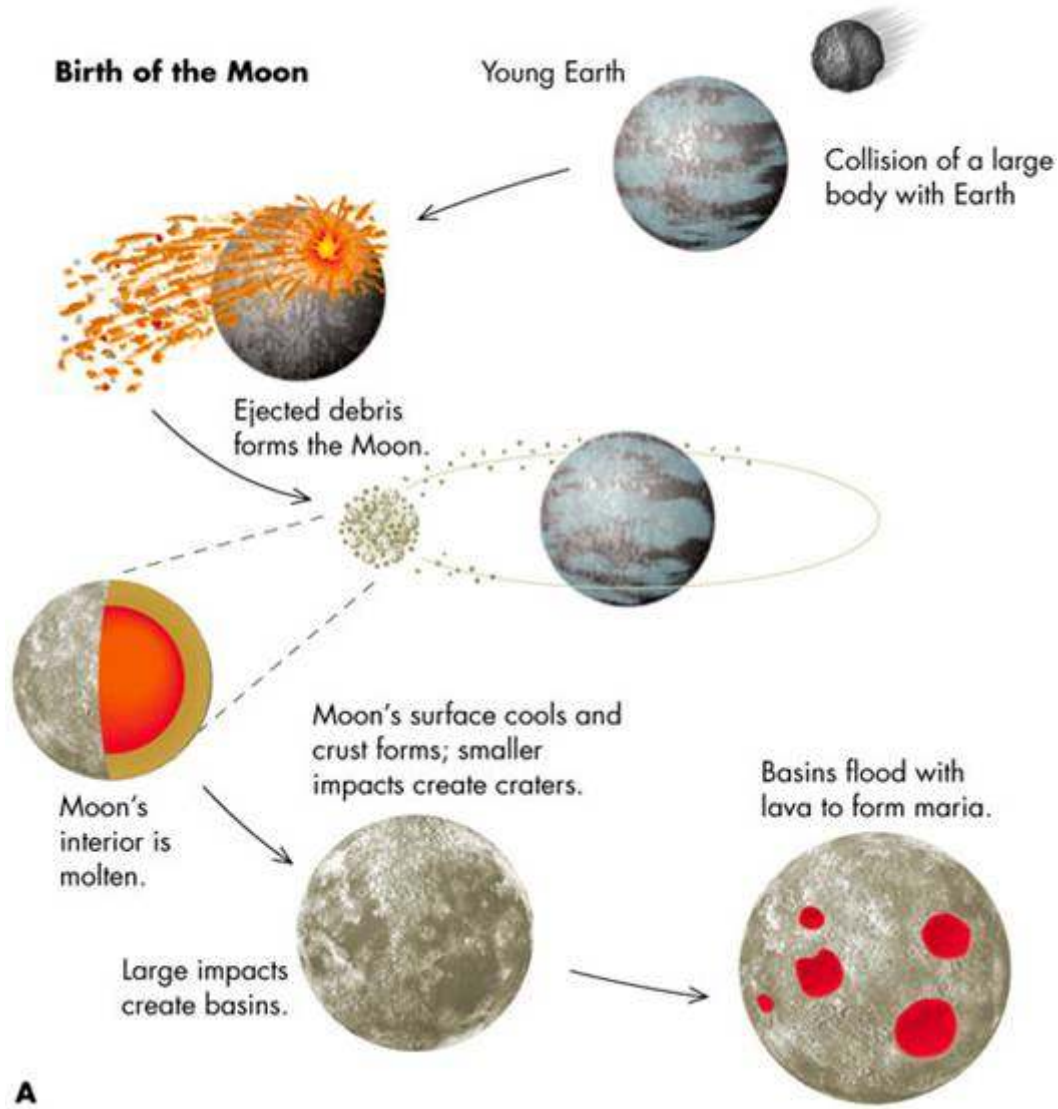
- Before Apollo missions, three hypotheses of the Moon's origin:
  - Moon originally a small planet orbiting the Sun and was subsequently captured by Earth's gravity during a close approach (***capture theory***)
  - Earth and Moon were twins, forming side by side from a common cloud of gas and dust (***twin formation theory***)
  - The Moon spun out of a very fast rotating Earth in the early day of the Solar System (***fission theory***)

Lunar Formation Hypotheses

- Each of these hypotheses gave different predictions about Moon's composition:
  - In capture theory, the Moon and Earth would be very different in composition, while twin theory would require they have the same composition
  - In fission theory, the Moon's composition should be close to the Earth's crust
- Moon rock samples proved surprising
  - For some elements, the composition was the same, but for others, it was very different
  - None of the three hypotheses could explain these observations

The Large Impact Hypothesis

- The new Moon formation hypothesis:
  - Moon formed from debris blasted out of the Earth by the impact of a Mars-sized body
  - Age of lunar rocks and lack of impact site on Earth suggests collision occurred at least 4.5 billion years ago

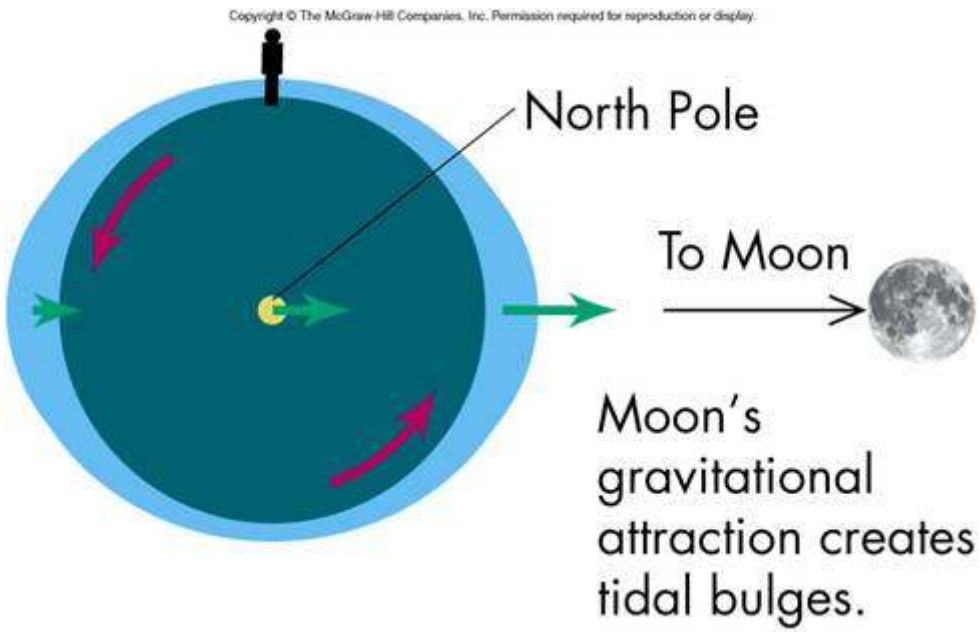


The Large Impact Solution

- This “large impact” idea explains:
  - The impact would vaporize low-melting-point materials (e.g., water) and disperse them explaining their lack in the Moon
  - Only surface rock blasted out of Earth leaving Earth’s core intact and little iron in the Moon
  - Easily explains composition difference with Earth
  - The splashed-out rocks that would make the Moon would more naturally lie near the ecliptic than the Earth’s equatorial plane
  - Earth’s tilted rotation axis is explained

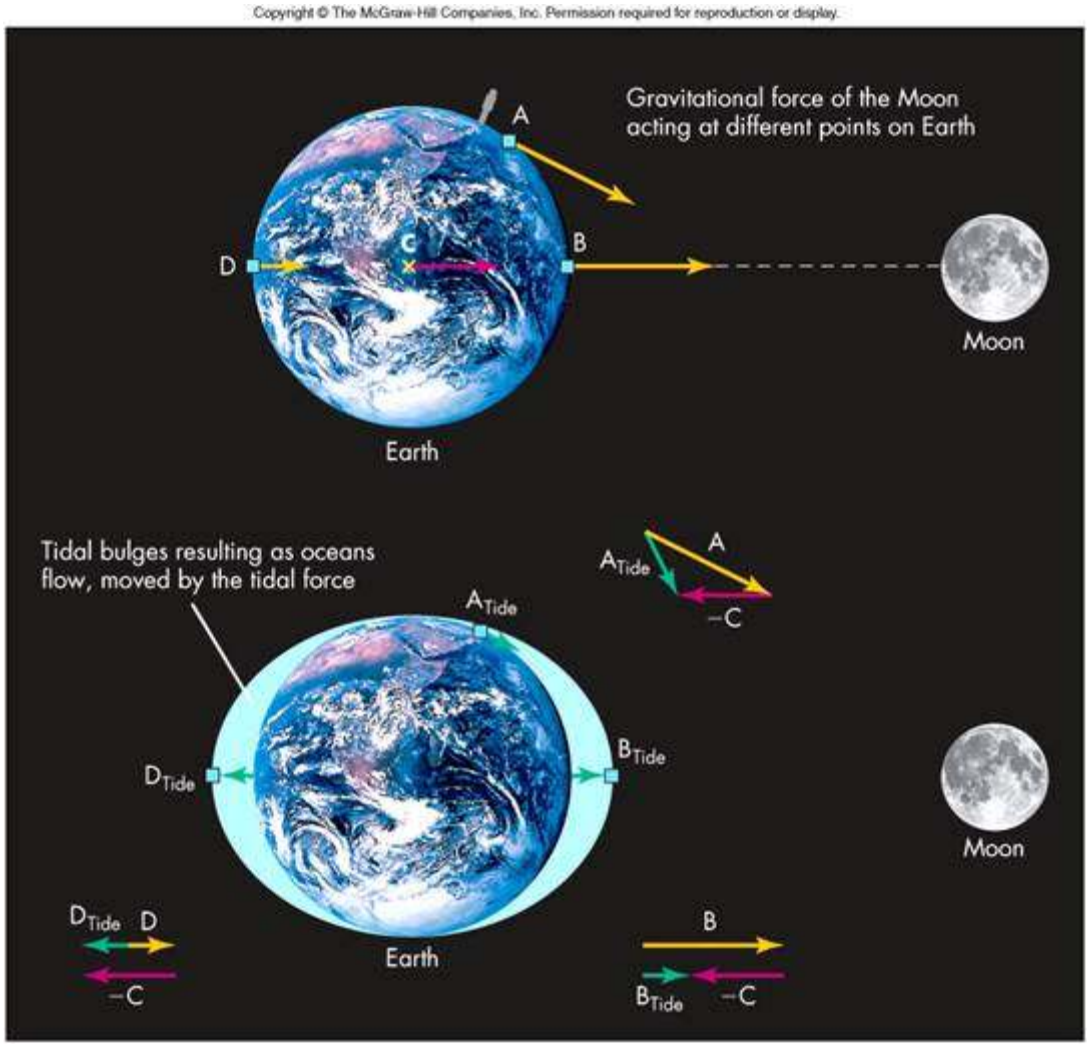
Tides

- The Moon exerts a gravitational force on the Earth that is stronger on the side closest to the Moon and weakest on the far side
- This difference in force from one side of an object to the other is called a ***differential gravitational force***



Tides

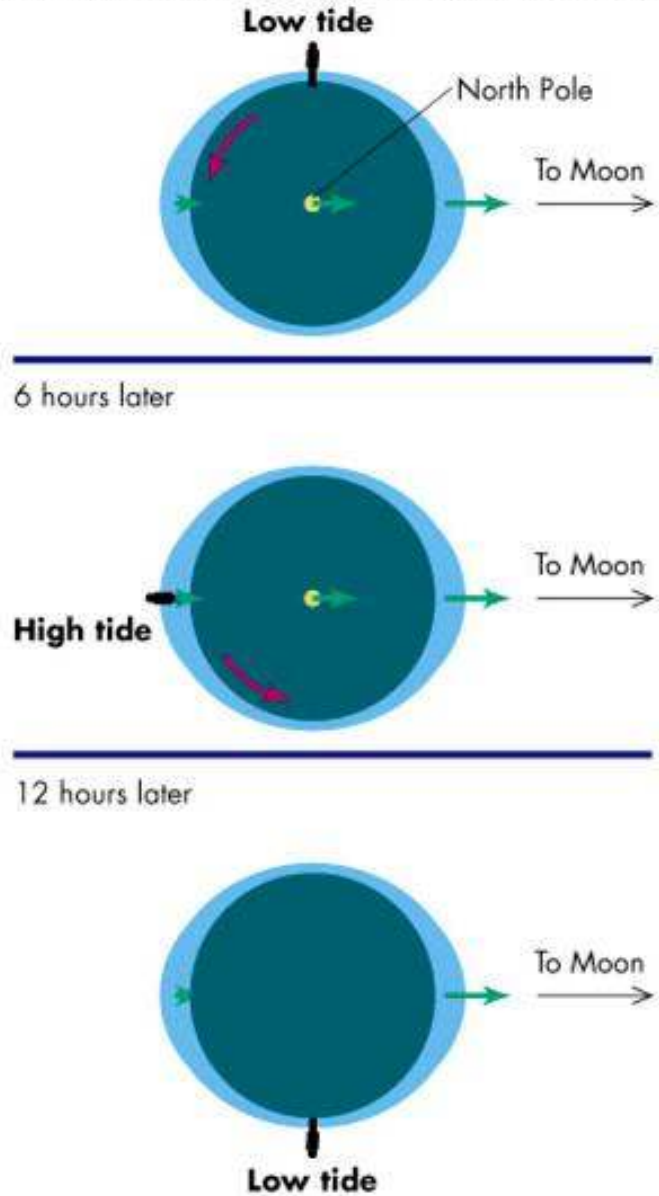
- This differential force draws water in the ocean into a ***tidal bulge*** on the sides facing and opposite the Moon



Tides

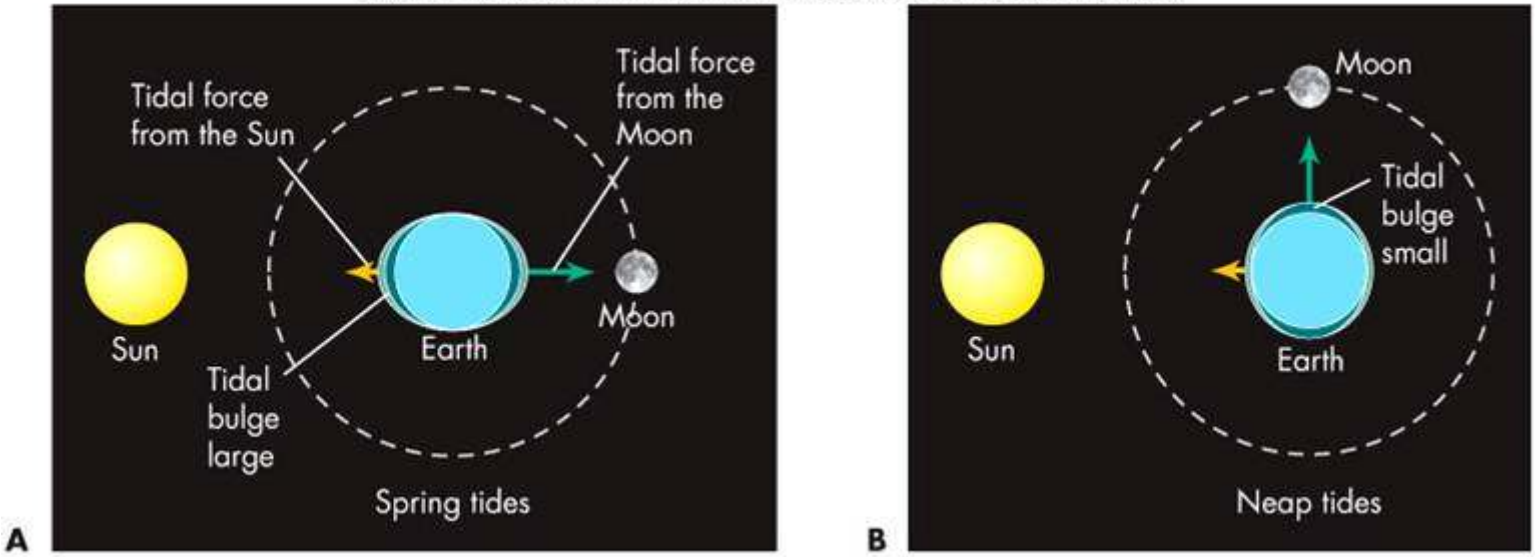
- Earth's rotation leads to two high/low tides per day

B Low tide



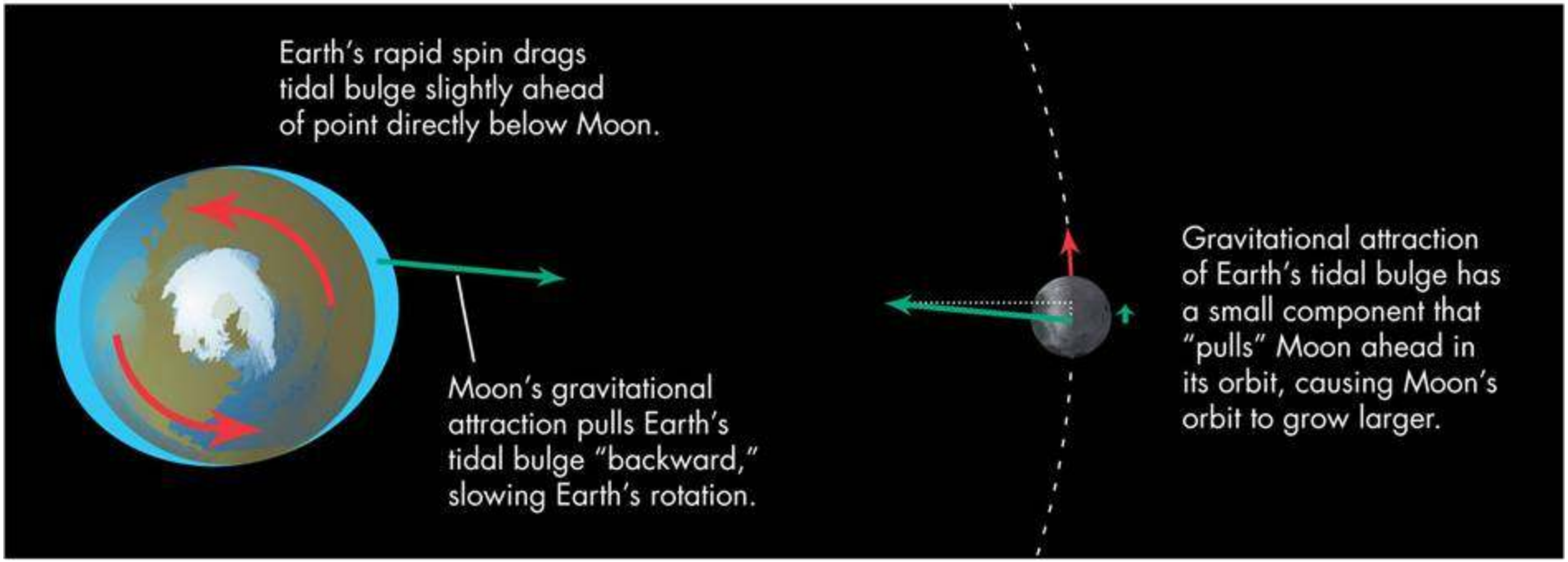
A

Solar Contributions to Tides



- When the Sun and Moon line up (new and full Moon), abnormally large ***spring tides*** occur
- With the Moon at first or third quarter, the so-called ***neap tides*** occur, with tides not as extreme as normal tides

Tidal Braking



- Tides create forces that slow the Earth's rotation and move the Moon farther away – ***tidal braking***
- Tidal braking caused the Moon's synchronous rotation