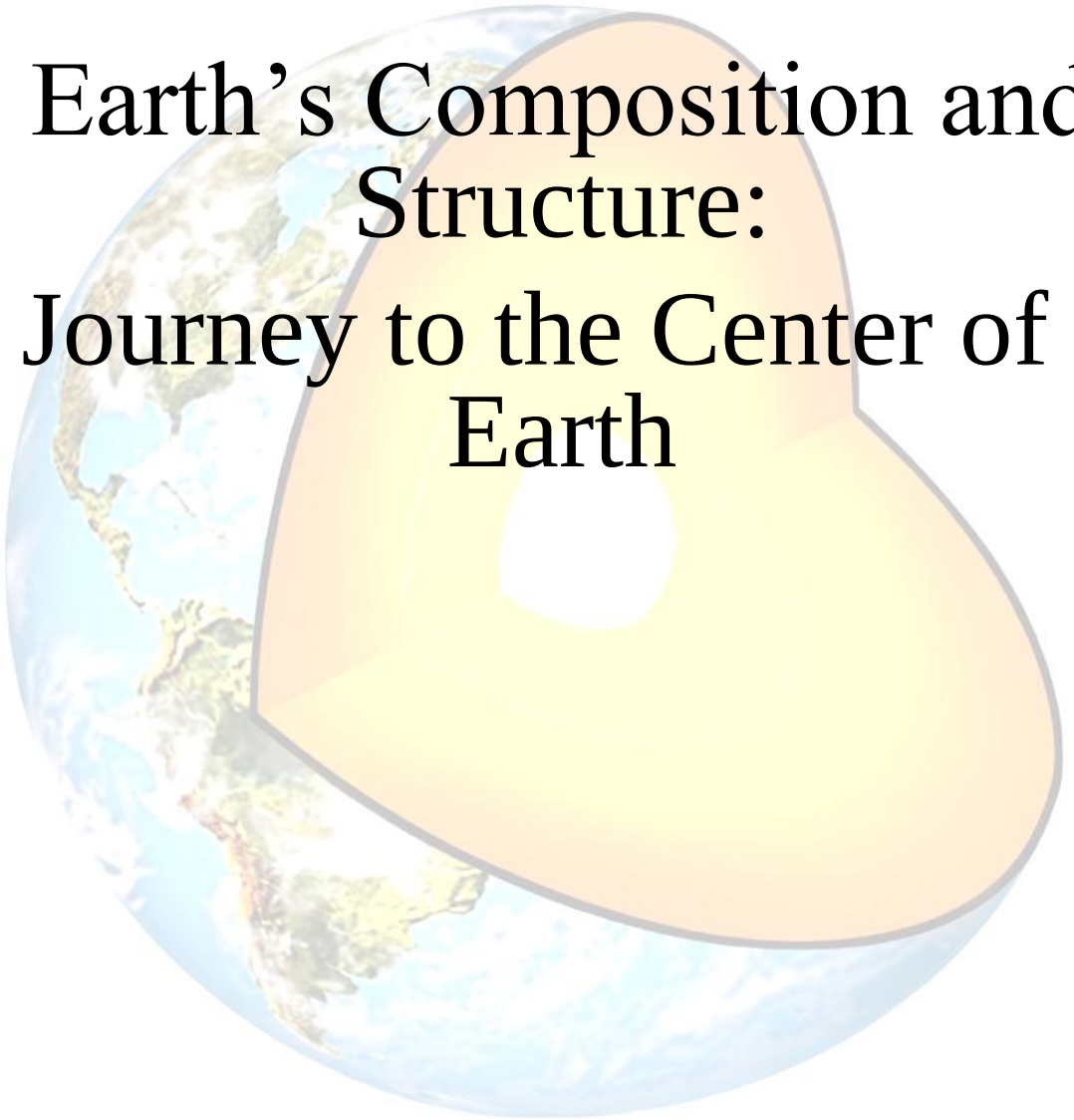
Earth's Composition and Structure:

A Journey to the Center of the Earth



Earth's Surface

- Our experience with Earth is limited to its surface.
- Yet Earth has a complicated interior.
- Earth is characterized by…
  - An internally generated magnetic field.
  - A layered interior
    - Solid and liquid layers.
  - A gaseous envelope.
    - i.e. atmosphere

The Black Canyon of the Gunnison, CO

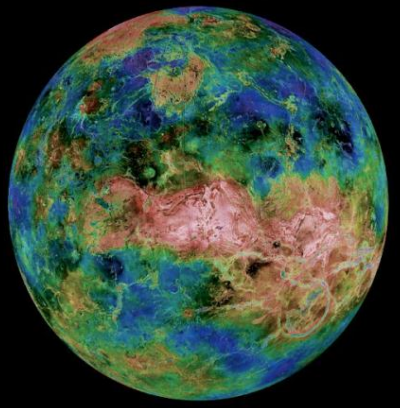
The Solar System

- Human perceptions have changed.
  - Early history – Planets as moving lights.
  - 1600s – 1st telescopes saw hazy spheres.
  - Today – A complex, evolving system.
    - Structure
    - History
- Space probes have photographed and analyzed planets.
- Scientists have hypothesized likely origins of the solar system.


Earth


Mars


Mercury

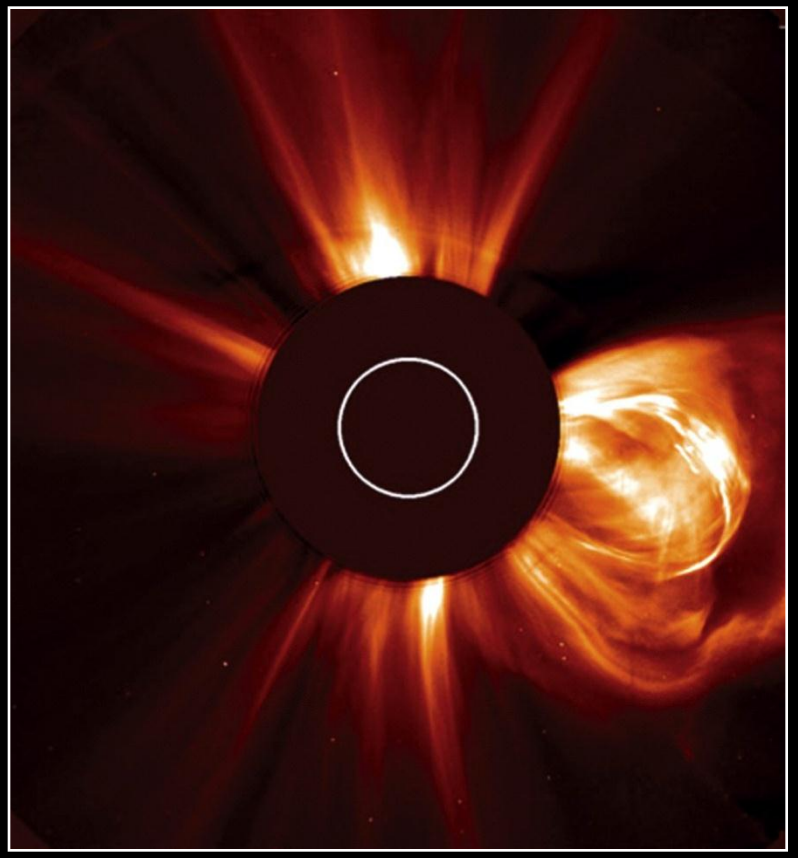

Venus

Earth and the Solar System

- What would solar system visitors notice?
  - Magnetic field.
  - Atmosphere.
  - Surface features.
    - Continents.
    - Oceans.
    - Polar ice caps.
    - Evidence of humanity?
      - Structures.
        - » Dams.
        - » Great Wall of China.
        - » Cities.
        - » Roads / canals.
      - Electric lights.

The Celestial Neighborhood

- Interstellar space: a ~vacuum with a virtual absence of matter.
- The amount of matter greatly increases approaching the Sun.
- The Sun ejects matter outward into space as the solar wind.
- Solar wind:
  - Magnetically & electrically charged particles.
  - Stream outward in all directions.
  - Consists of…
    - Protons (+ charge).
    - Electrons (– charge).
- Only a small percentage of the solar wind impinges upon Earth.



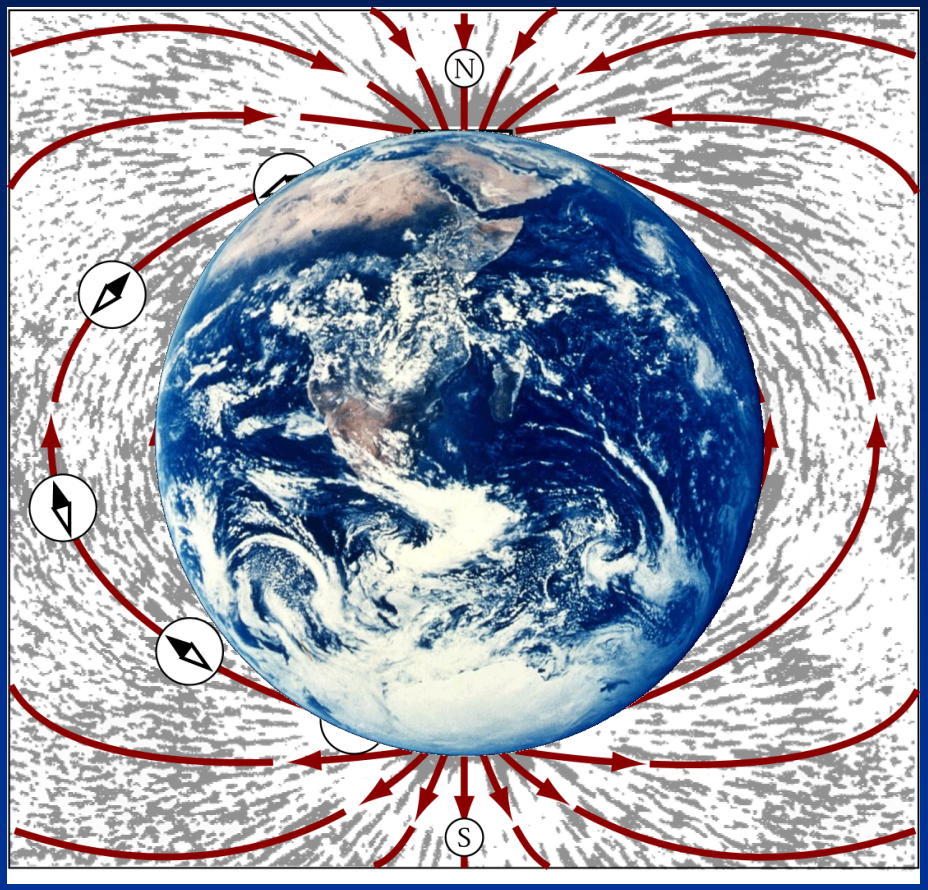
Five Key Characteristics About Earth's Structure:

1. Earth has a ***dipole*** magnetic field that deflects solar wind and protects earth's surface from solar radiation
2. Earth has a ***stratified*** atmosphere, **mainly composed of nitrogen (N_2) and oxygen (O_2)**
3. Earth is made of a variety of ***minerals, glasses, melts, fluids and volatiles***, all left behind during birth of the solar system
4. The Earth has layers: a thin silicate ***crust***, a thick iron- & magnesium silicate ***mantle***, and a thick metallic ***core***
5. Physically, the earth can be divided into a rigid outer ***lithosphere*** and a plastic/ductile ***asthenosphere***

Earth's Magnetic Field

Geodynamo

- The Earth's magnetic field is produced by the ***geodynamo***
  - -Flow in the **liquid iron** outer core creates a magnetic field



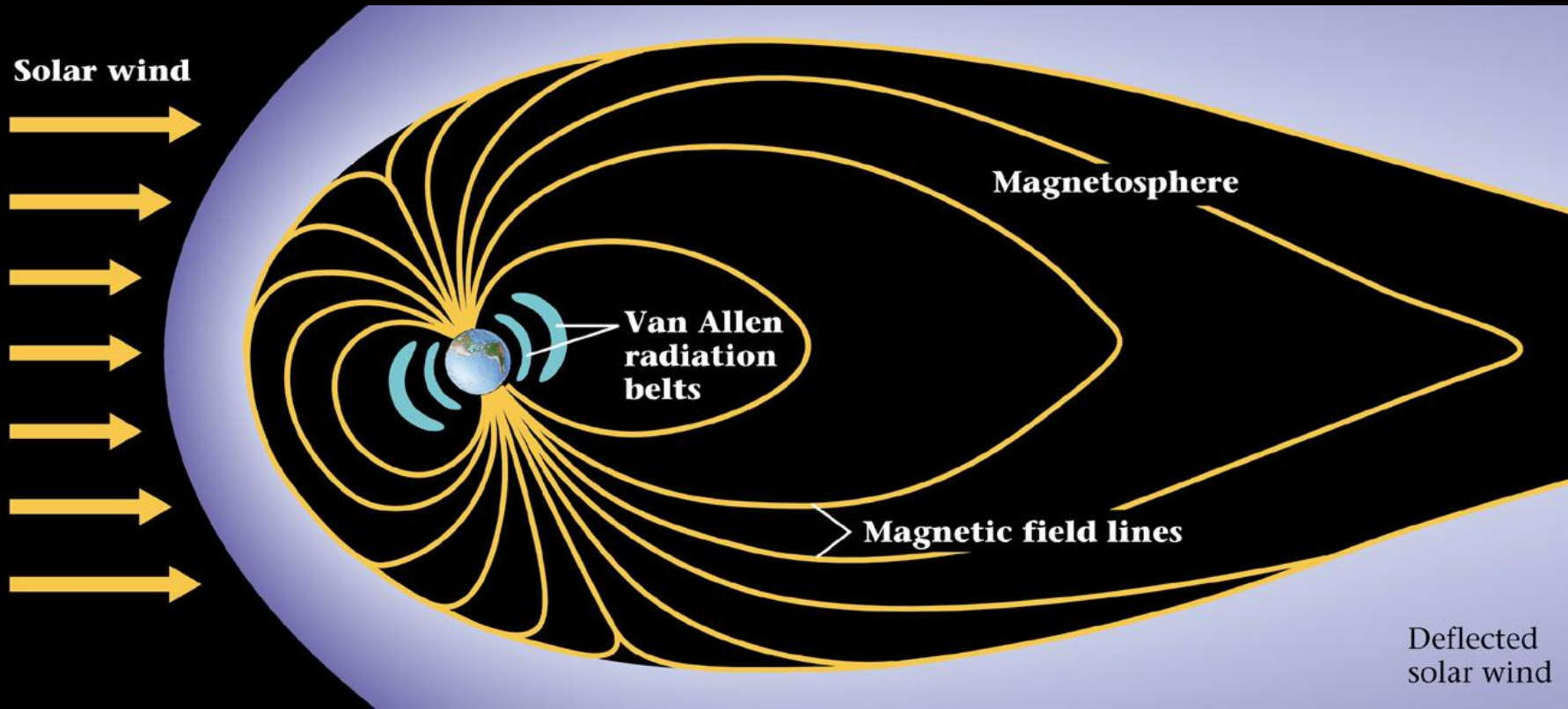
Magnetic field

- region affected by force emanating from a magnet
- grows stronger as separating distance decreases
- attracts or repels magnetically charged or moving electrically charged objects
- compasses work because Earth is a large magnet

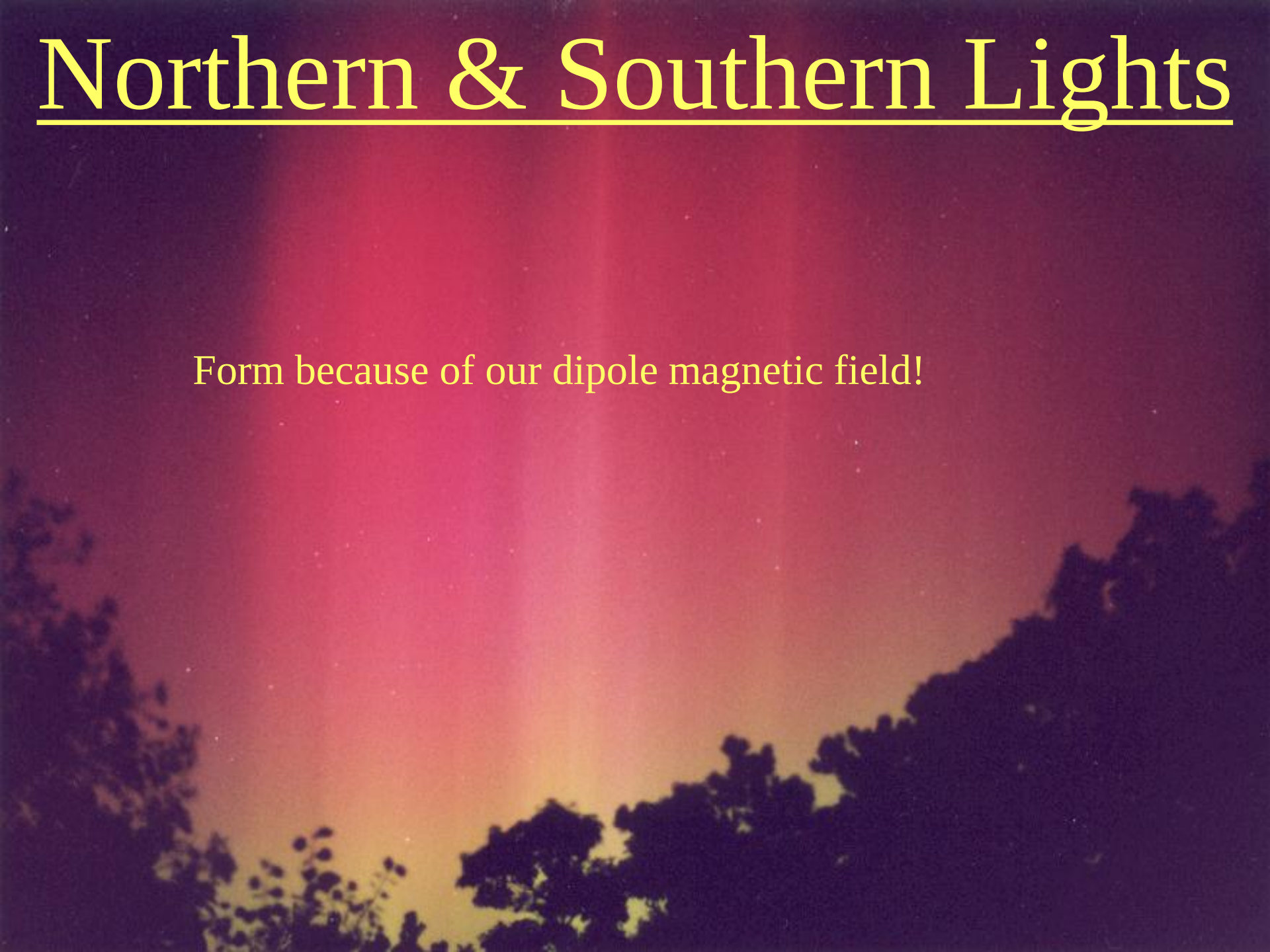
Earth's Magnetic Field

Magnetic field

- Like a bar magnet, Earth's magnetic field is a dipole, (has both a N and S pole)
- Solar wind contains electromagnetic particles that are deflected by earth's field. These particles distort the shape of earth's magnetic field in space
- Van Allen belts – two belts in the inner magnetic field where high energy cosmic rays are trapped. Protects us from solar radiation!



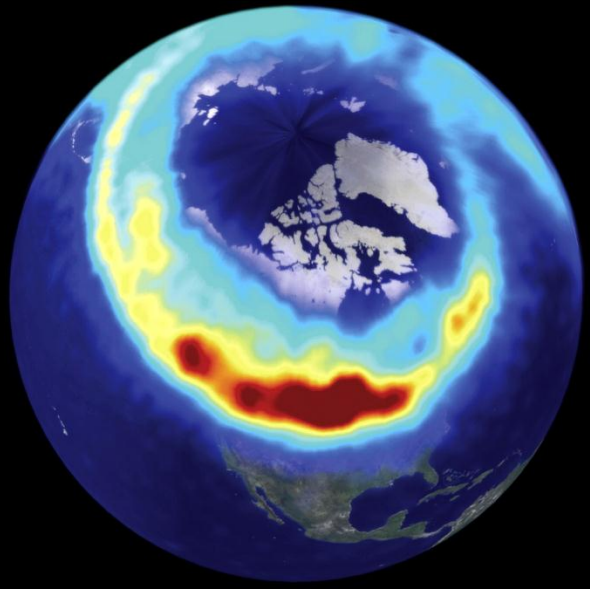
Northern & Southern Lights



Form because of our dipole magnetic field!

Aurorae

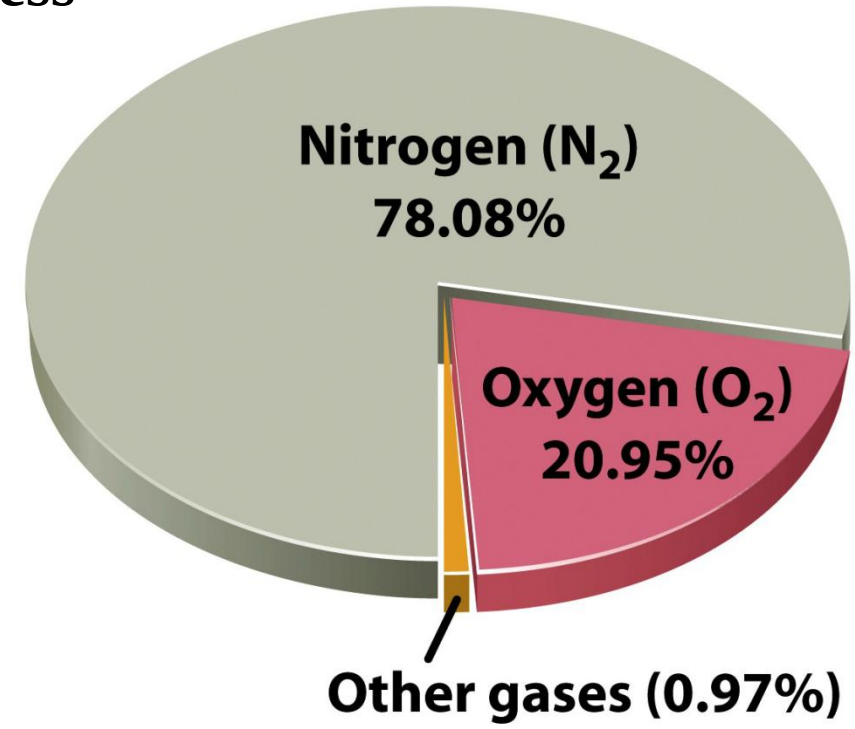
- Some ions escape Van Allen belts.
  - These ions are pulled to the magnetic poles.
  - The ions create light in the upper atmosphere.
- Spectacular aurora follow solar flares.
  - Aurora borealis – Northern lights.
  - Aurora australis – Southern lights.



Earth's Atmosphere

Distinct layers of gas surround the solid portion of the earth.

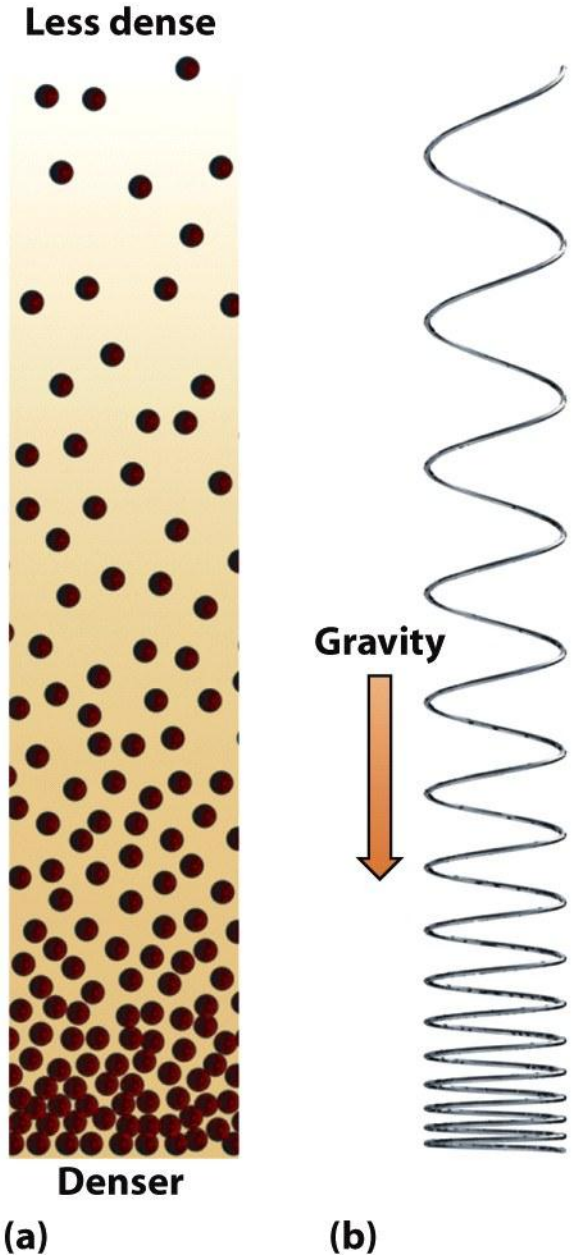
- **Composition is ~uniform regardless of altitude**
  - 78% N_2
  - 21% O_2
  - All others ~1%
    - Ar, CO_2, CH_4, H_2O, Ne, CO, SO_2
- Some other Planets have atmospheres too!
  - None have N_2 & O_2 as dominant gasses
- Earth was oxygen-free until ~2.5 Ga



Earth's Atmosphere

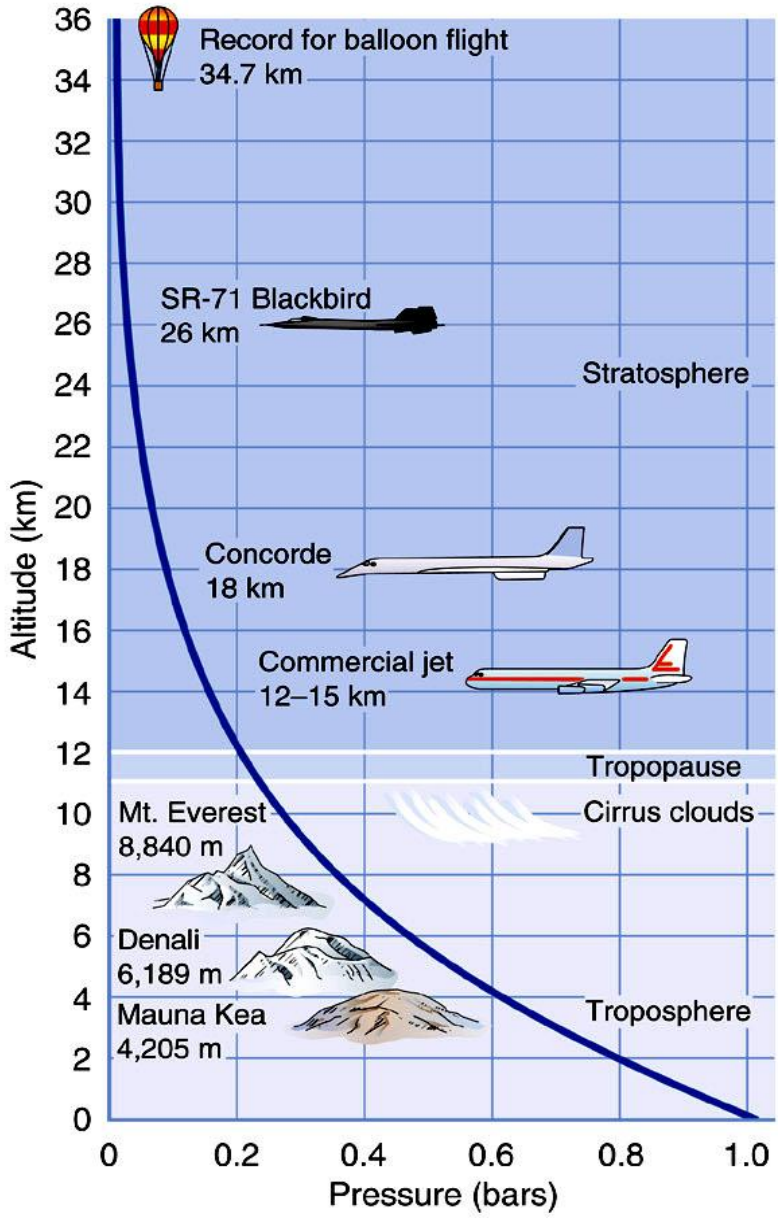
- **Pressure decreases with increasing altitude**
  - Reflects # of molecules/volume
  - Lower pressure = less molecules/volume
  - Air pressure @ sea level = 14.7 lb/in^2 = 1 bar

- **Pressure is caused by the weight of overlying material**
  - Upper atmosphere has less material above it
    - Pressure is lower
  - 99% of atmosphere is below 50 km, the rest is between 50 and 500 km.



Earth's Atmosphere

- **Earth's Atmosphere is divided into distinct layers based on altitude**
  - Exosphere (very thin ~500 km)
    - Atmosphere merges with space
  - Thermosphere (>90 km)
    - Where space shuttles orbit
  - Mesosphere (50-90 km)
    - Meteors burn up here
  - Stratosphere (12-50 km)
    - Stable air; good for jets
  - Tropopause (11-12 km)
  - Troposphere (0-11 km)
    - Mixing layer
    - All weather is limited to this layer
    - "Tropo" = Greek for "turning"



Earth's Atmosphere

- **Troposphere**
  - A well-mixed layer dominated by convection of air masses

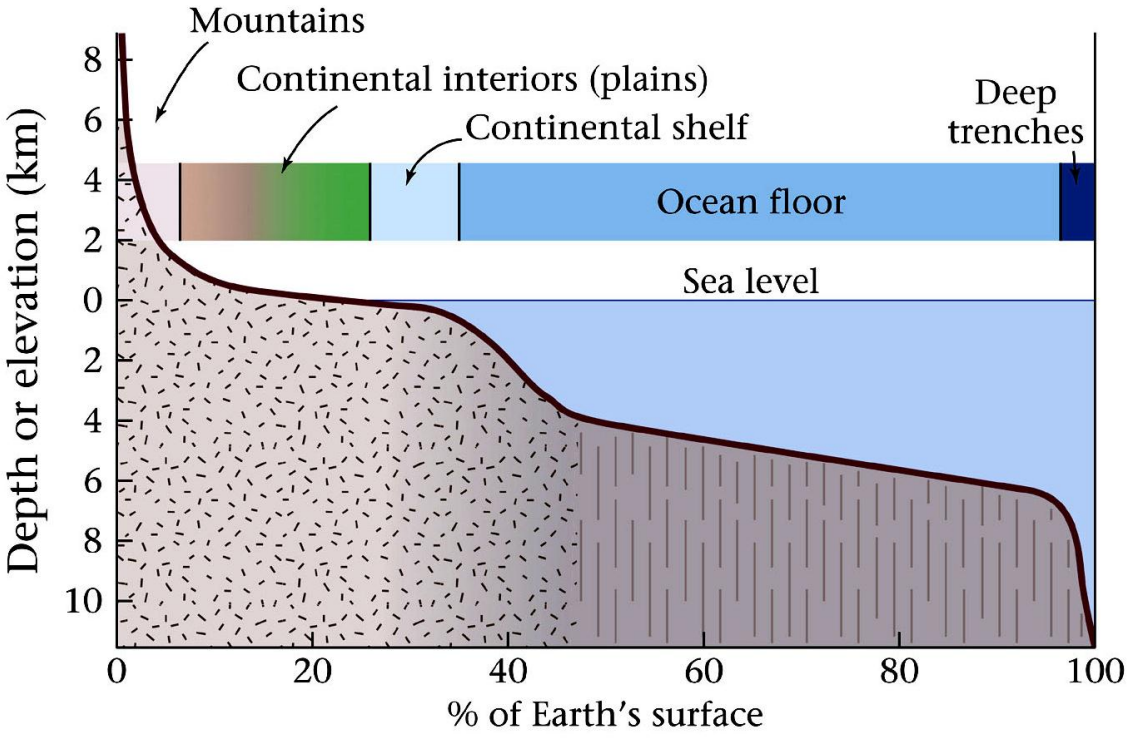
- **Convection**
  - Method of heat transfer in a fluid
    - Think lava lamp!
  - Cold is more dense = sinks
  - Hot is less dense = rises
  - This process results in circular convection cells
  - Also causes pressure gradients which create wind!
  - Also applies to the interior of the Earth

…this guy likes convection

Earth's Components

- Earth's surface = ~**30% land, ~70% water**
  - unlike any other known planet
- **Hydrosphere** = includes oceans, lakes, seas, rivers, & groundwater
- **Cryosphere** = glaciers, snow, and sea ice

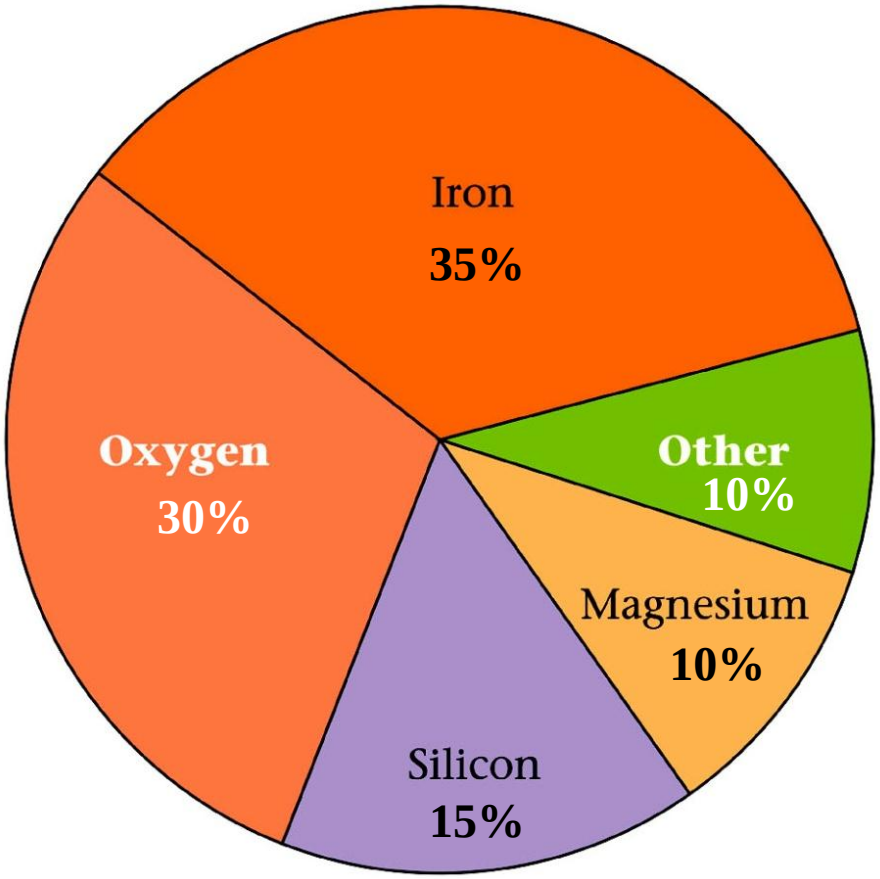
- Earth's surface is not flat; it has **topography**
- Ignoring oceans, Earth's surface is dominated by two distinct elevations:
  - Most land is 0-2 km above sea level
  - Most of the sea floor is 3-5 km below sea level



Earth's Components

- Earth's elemental composition reflects mostly heavier elements not blown away by solar wind during formation of the solar system

- Most abundant elements
  - Fe, O, Si, Mg
- Most common minerals consist of silica (SiO_2) mixed in varying proportions with other elements such as Fe, Mg, Al, Ca, K, Na
  - **Felsic** = more silica (less Fe/Mg) & less dense
    - E.g. Granite
  - **Mafic** = less silica (more Fe/Mg) & more dense
    - E.g. Gabbro / Basalt
  - Range: **Felsic / Intermediate / Mafic / Ultramafic**



Bulk Earth composition

Earth Materials

- Elements combine in a variety of Earth materials.
  - Organic compounds – Carbon-containing compounds.
    - Most are residue from once-living creatures.
    - Include wood, peat, lignite, coal, and oil.
    - Geologically rare (decomposes in contact with oxygen).

Earth Materials

- Elements combine in a variety of Earth materials.
  - Minerals – Inorganic crystalline solids.
    - Comprise rocks and, hence, most of the Earth.
    - Most rocks on Earth are silicates (based on Si and O).
  - Glasses – Non-crystalline mineral-like matter.
    - Cool too quickly to form structure
  - Rocks – Aggregates of minerals. There are many types.
    - Igneous – Cooled from a liquid (melt).
    - Sedimentary – Debris cemented from pre-existing rock.
    - Metamorphic – Rock altered by pressure and temperature.

Earth Materials

- Metals – Solids made of metallic elements.
- Melts – Rocks that have been heated to a liquid.
  - Magma – Molten rock beneath the surface.
  - Lava – Molten rock at the surface.
- Volatiles – Materials that turn into gas at surface temps.
  - H_2O, CO_2, CH_4, and SO_2
  - Volatiles are released from volcanic eruption.



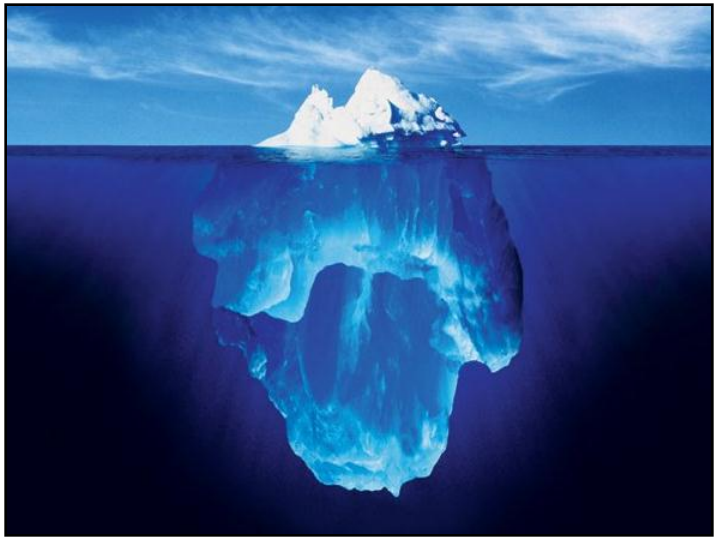
A Layered Earth

- We live on the thin outer skin of Earth.
- Early perceptions about Earth's interior were wrong.
  - Open caverns filled with magma, water, and air.
  - Furnaces and flames.
- We now know that Earth is comprised of layers.
  - The Crust.
  - The Mantle.
  - The Core.
    - Outer Core.
    - Inner Core.
- Some basic rules of physics give some clues…

From Milton's "Paradise Lost"

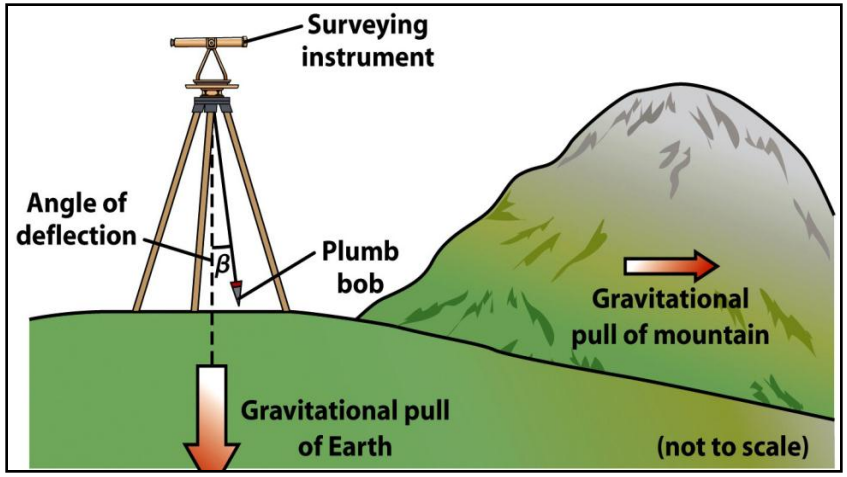
Earth's Density

- Earth's Density gives us clues about its internal structure



- ***Density = Mass/Volume***
  - Measures how much mass is in a given volume.
  - Expressed in units of mass/volume e.g. g/cm^3
  - Ice floats…why?

- Estimates of earth's mass and volume give a whole earth density of ~5.5 g/cm^3
- Typical rocks at the surface of the Earth have a density of 2.0-2.5 g/cm^3
- ***What does this require of the density of material in the Earth's interior?***



Earth's Density

Earth's shape as a clue to the internal structure of the Earth

If density increased gradually and uniformly towards the center, a significant portion of Earth's mass would be near the outer edges….

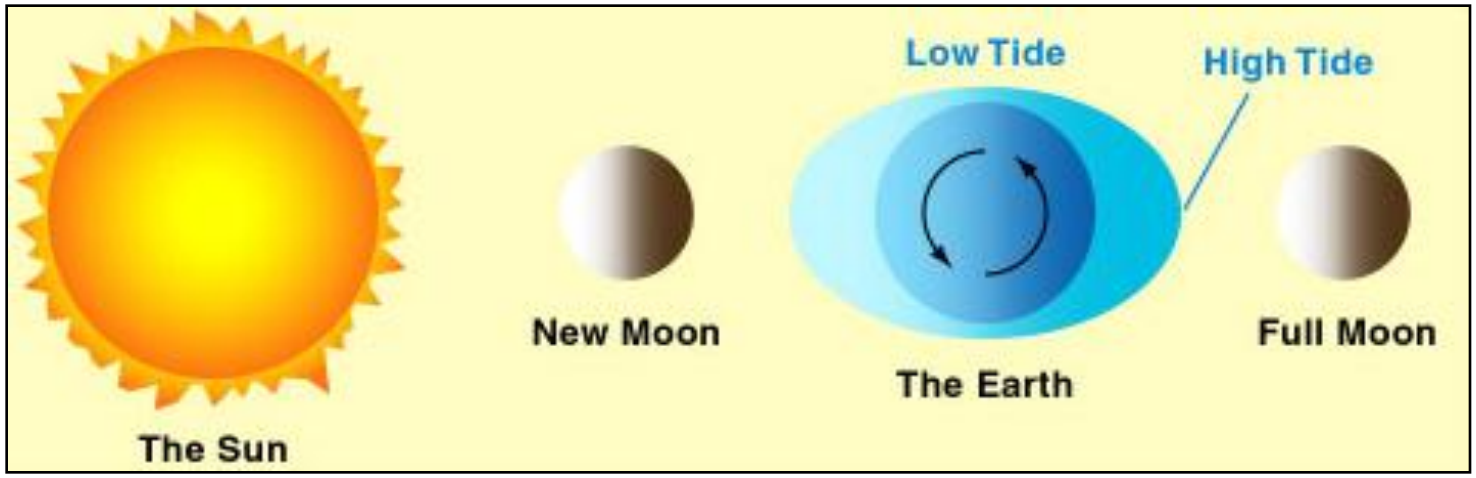
Then ***centrifugal*** force (not centripetal) would cause the planet to flatten into a disk.

This has (obviously) not happened…

Earth's Layers

Earth's shape as a clue to the layering of the earth

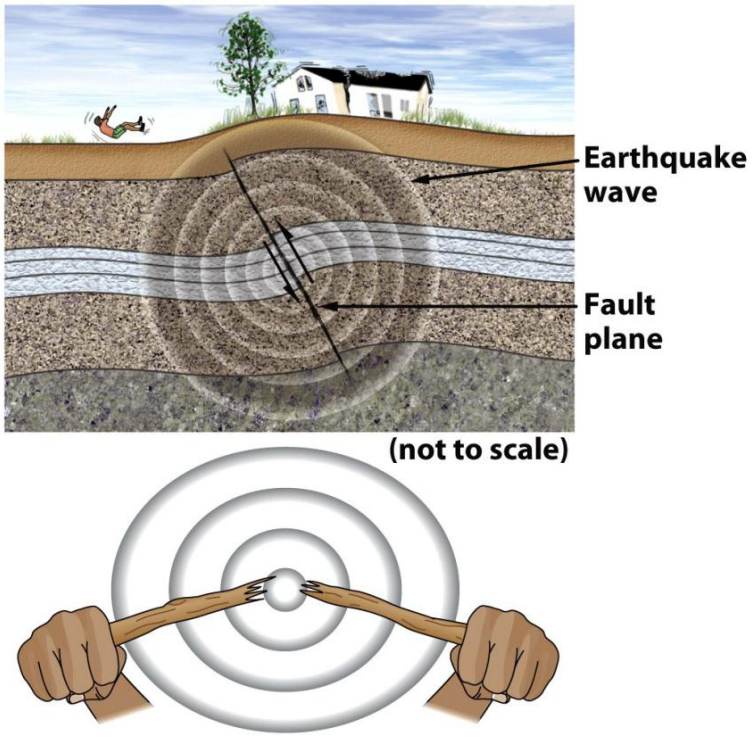
- If the Earth consisted of a thin solid shell over a thick liquid center, then the surface would rise and fall with tides like the ocean – This does not happen; only the oceans rise and fall.



- Thus, the Crust does not float over a liquid interior

A Layered Earth

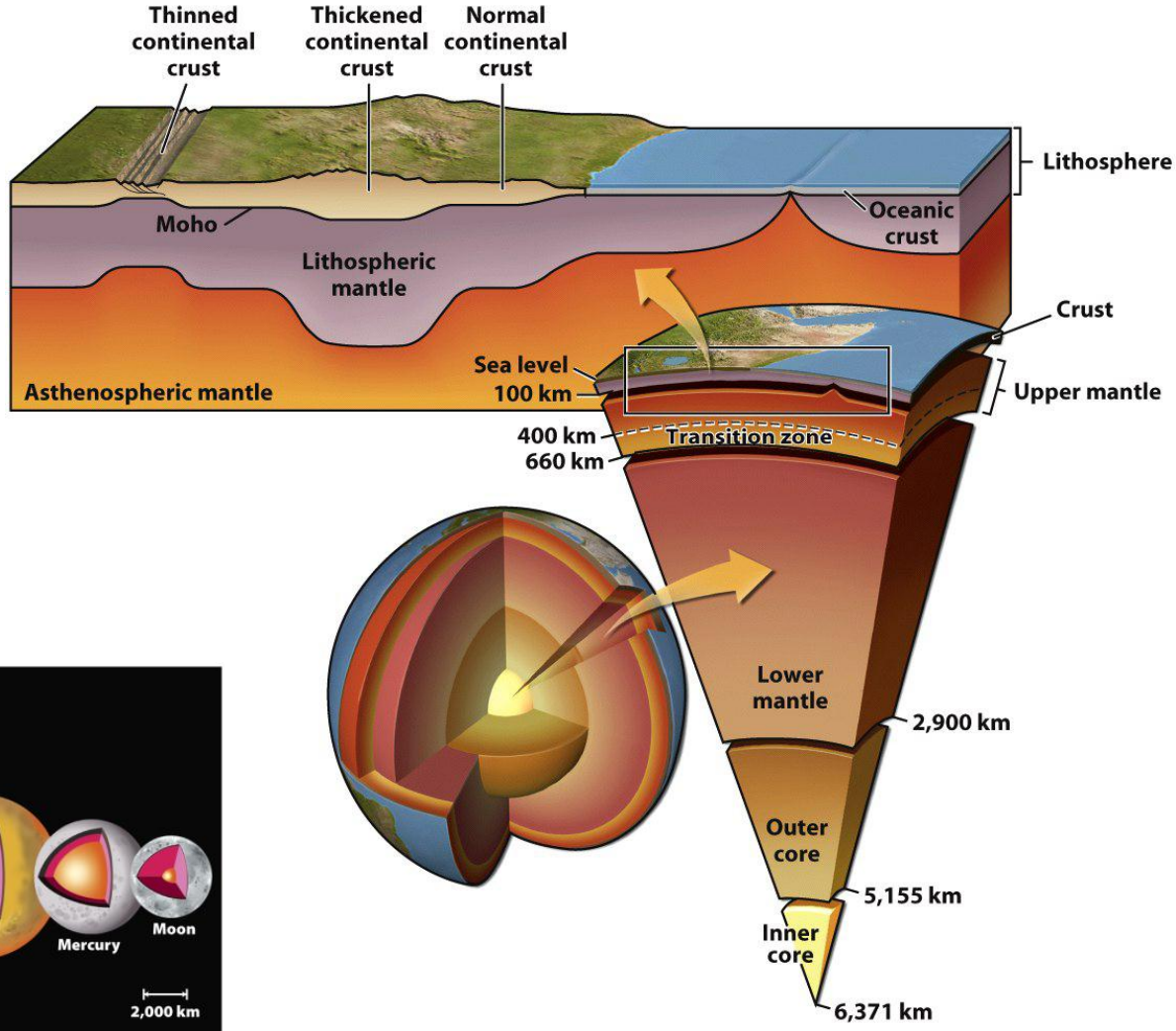
- Earthquake clues - Earthquake energy transmitted as seismic waves that pass through Earth.
  - Seismic waves have been used to probe the interior.
    - Wave velocity changes with density.
    - Velocity changes give depth of layer changes.
- Changes with depth.
  - Pressure.
  - Temperature.

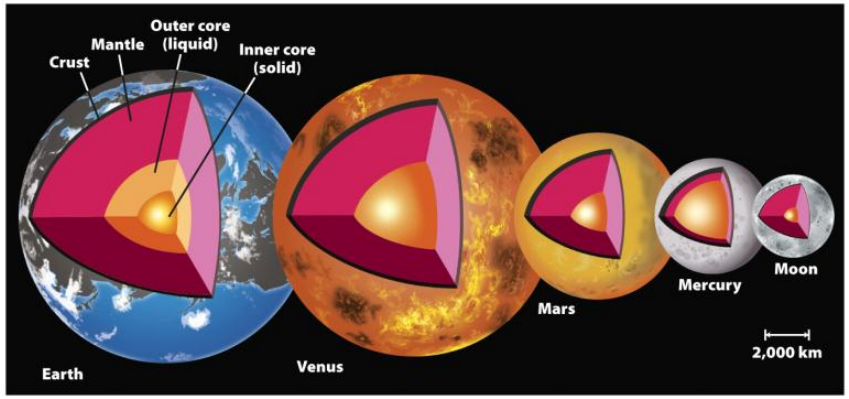


More on this in Chapter 10 and Interlude D!

Earth's Interior Layers

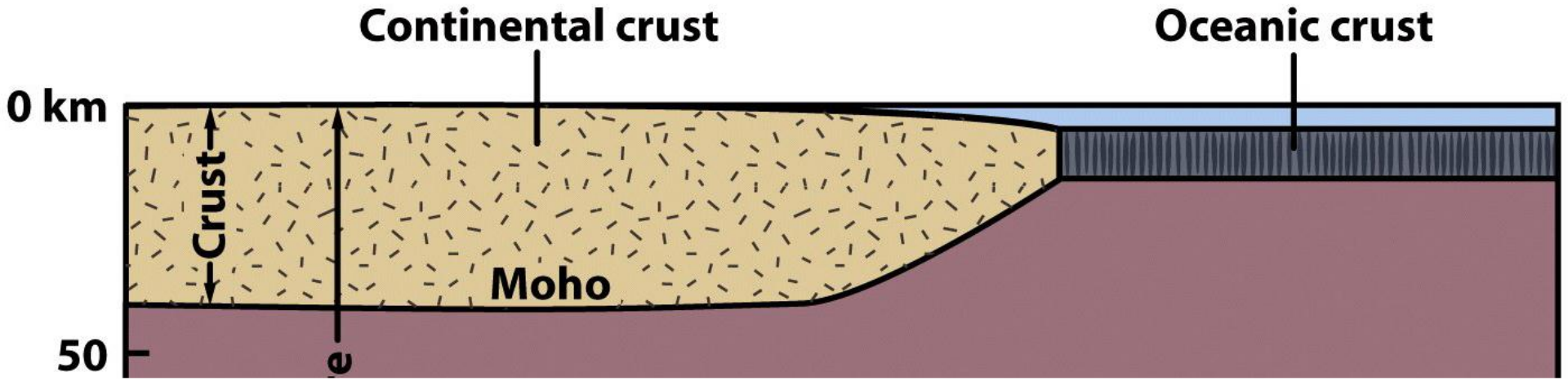
- The Earth (and other planets) have layered interiors.
  - Crust
    - Continental
    - Oceanic
  - Mantle
    - Upper
    - Lower
  - Core
    - Outer – Liquid
    - Inner – Solid





The Crust

- The outermost "skin" of Earth with variable thickness.
  - Thickest under mountain ranges (70 km – 40 miles).
  - Thinnest under mid-ocean ridges (3 km – 2 miles).
- The Mohorovičić discontinuity or "**Moho**" is the lower boundary.
  - Separates the crust from the upper mantle.
  - Discovered in 1909 by Andrija Mohorovicic.
  - Marked by a change in the velocity of seismic P waves.

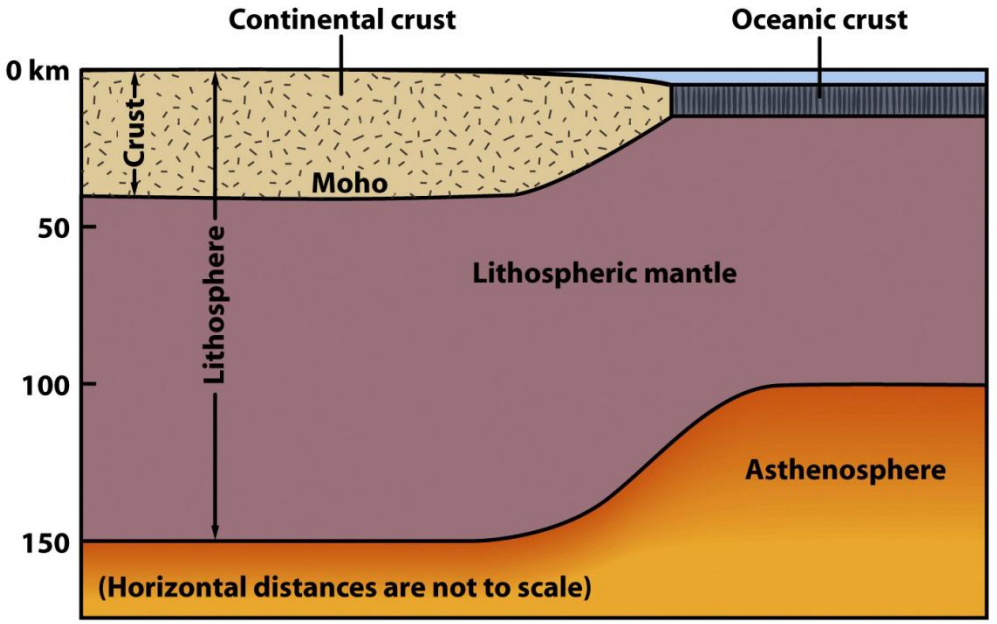


Two Types of Crust

- Continental crust – Underlies the continents.
  - Avg. rock density about 2.7 g/cm^3.
  - Avg. thickness 35-40 km.
  - Felsic composition. Avg. rock type = Granite
- Oceanic crust – Underlies the ocean basins.
  - Density about 3.0 g/cm^3.
  - Avg. thickness 7-10 km.
  - Mafic composition

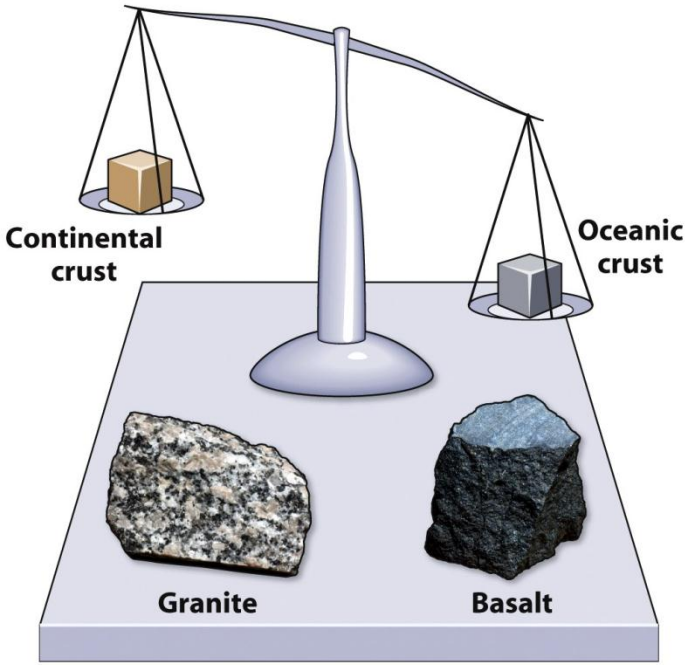
    Avg. rock type =

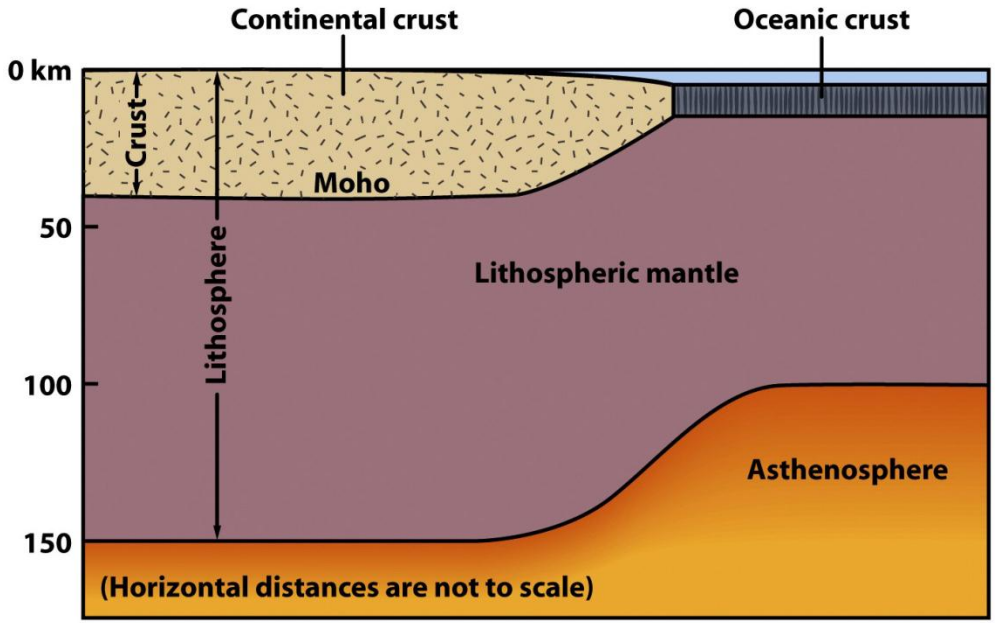
    Basalt/Gabbro



Two Types of Crust

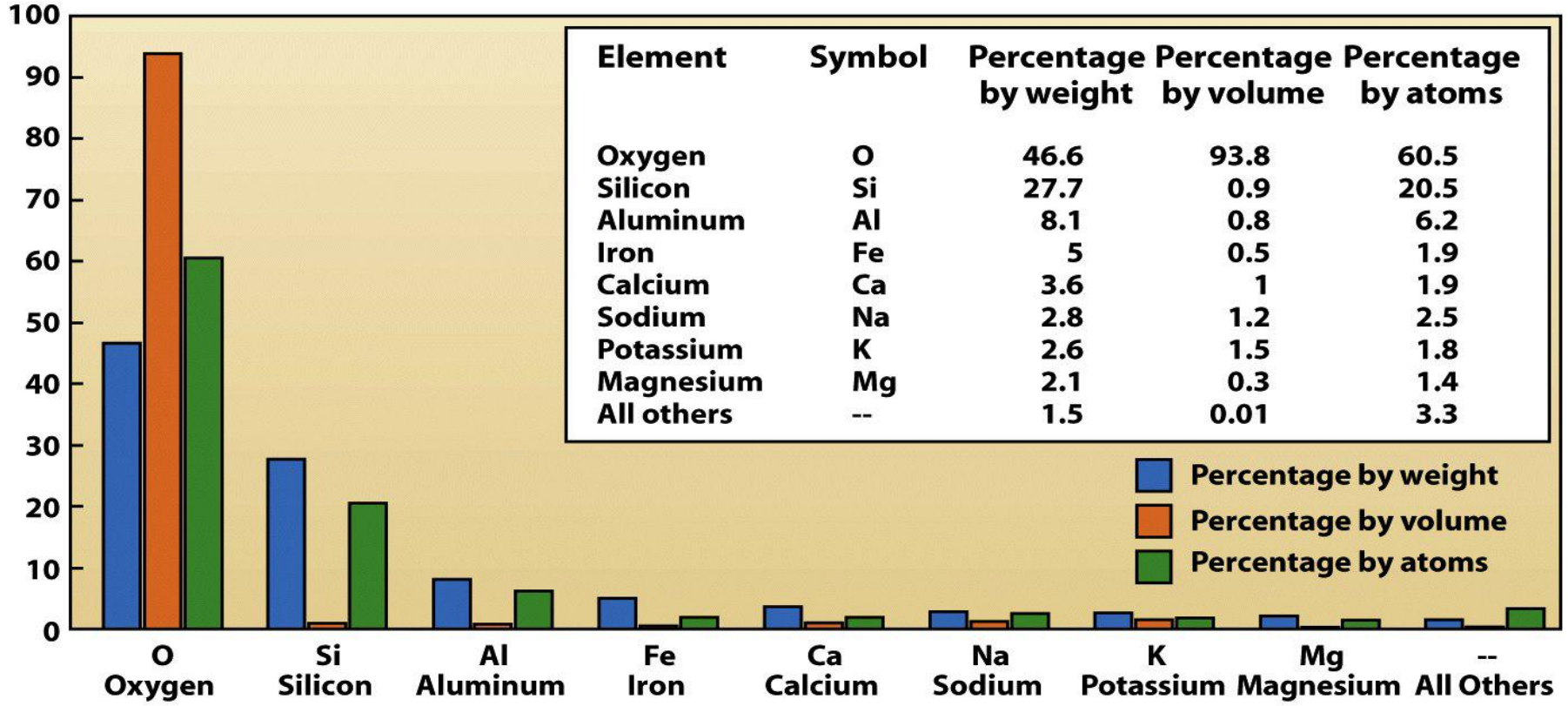
- Crustal density controls surface position.
  - Continental crust
    - Less dense; “floats higher.”
  - Oceanic crust
    - More dense: “floats lower.”





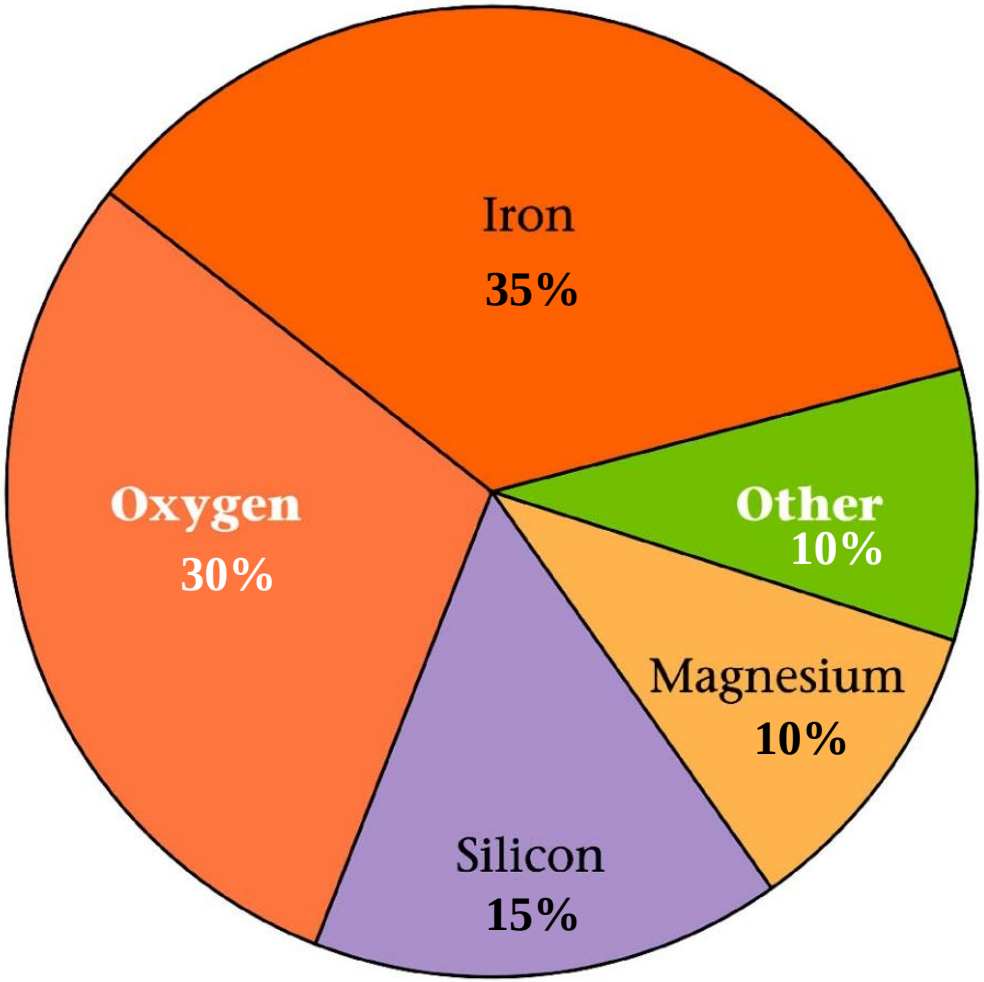
Crustal Composition

- 98.5% of the crust is comprised of just 8 elements.
- Oxygen is (by far!) the most abundant element in the crust.
  - This reflects the importance of silicate (SiO_2-based) minerals.
  - As a large atom, oxygen occupies ~93% of crustal volume.



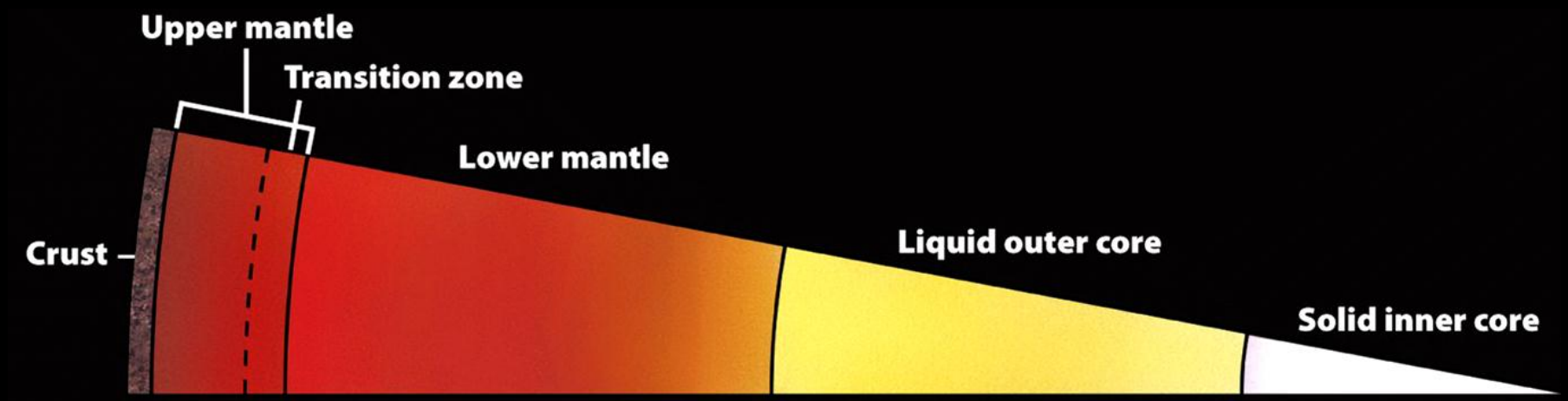
Element	Symbol	Percentage by weight	Percentage by volume	Percentage by atoms
Oxygen	O	46.6	93.8	60.5
Silicon	Si	27.7	0.9	20.5
Aluminum	Al	8.1	0.8	6.2
Iron	Fe	5	0.5	1.9
Calcium	Ca	3.6	1	1.9
Sodium	Na	2.8	1.2	2.5
Potassium	K	2.6	1.5	1.8
Magnesium	Mg	2.1	0.3	1.4
All others	--	1.5	0.01	3.3

Bulk Earth Composition



Earth's Mantle

- **Solid** rock layer between the crust and the core.
- 2,885 km thick, the mantle is 82% of Earth's volume.
- Mantle composition = ultramafic rock called **peridotite**.
- Below ~100-150 km, the rock is hot enough to flow.
- It convects: hot mantle rises, cold mantle sinks.
- Three subdivisions: upper, transitional, and lower.

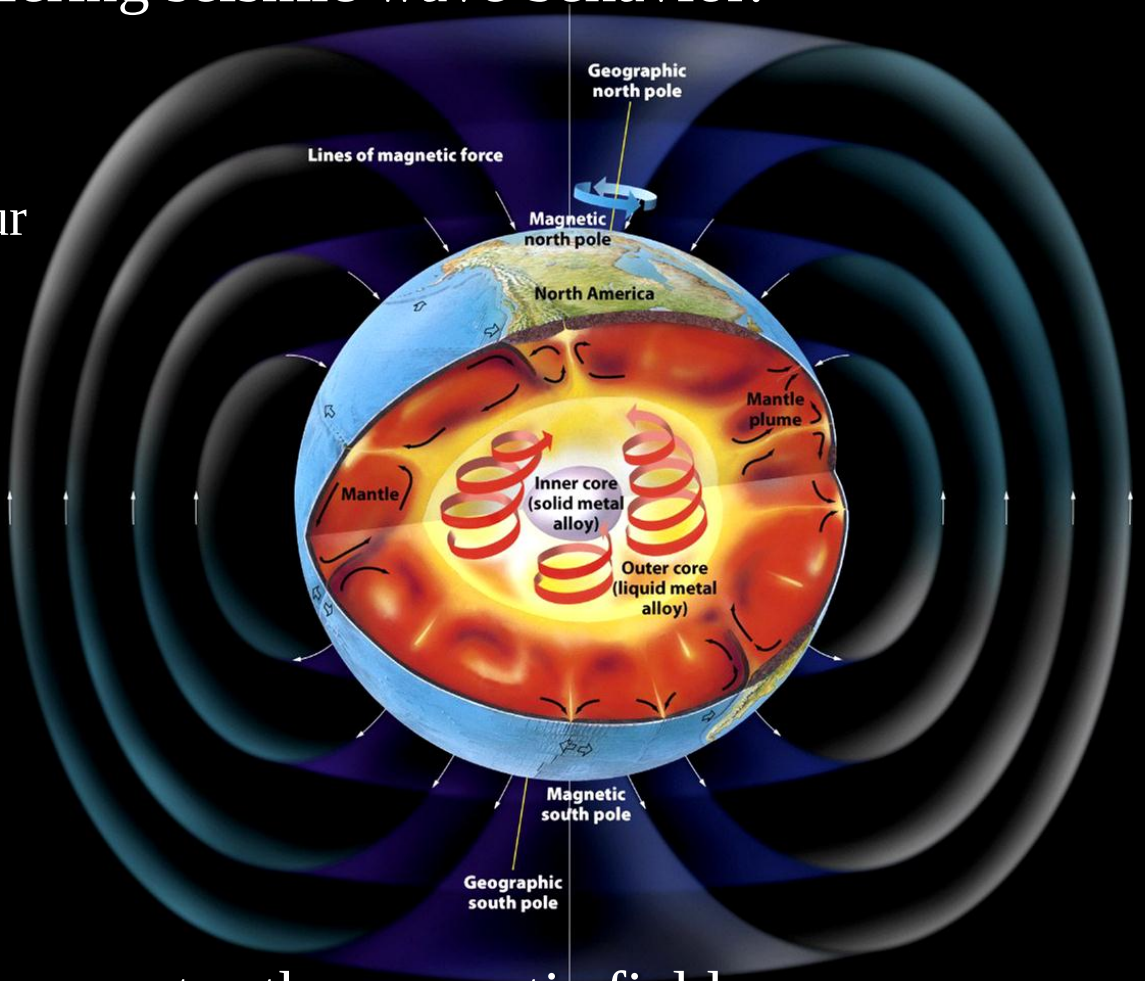


The Core

- An iron-rich sphere with a radius of 3,471 km.
- 2 components with differing seismic wave behavior.

– Outer core
  - Liquid iron-nickel-sulfur
  - 2,255 km thick
  - Density – 10-12 g/cm^3

– Inner core
  - Solid iron-nickel alloy
  - Radius of 1,220 km.
  - Density – 13 g/cm^3

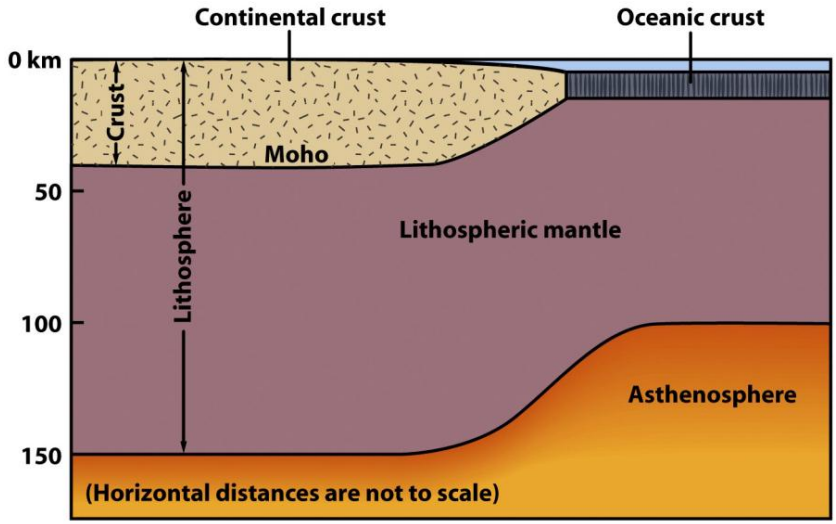


- Flow in the outer core generates the magnetic field.

Lithosphere-Asthenosphere

- The Crust, Mantle, Core boundaries
  - defined by composition

  …but sometimes we want to divide the layers of the Earth by their behavior or physical properties
- Lithosphere – The brittle portion of Earth's interior.
  - Behaves as a non-flowing, rigid material.
  - The material that moves as tectonic plates.
  - Made of 2 components: crust and upper mantle.
- Asthenosphere – The ductile portion of Earth's interior.
  - Shallower under oceanic lithosphere.
  - Deeper under continental lithosphere.
  - Flows as a soft **ductile solid**.
  - Contains a small percentage of melt (< 2%)



Boundaries Between Layers

- The Crust-Mantle boundary = **Moho**
  - defined by seismic discontinuity indicating significant *change in composition*.
- **Brittle-ductile transition**
  - Defined by a significant *change in rock physical properties* (viscosity)
  - Also defined as the depth below which earthquakes do not occur.
- Lithosphere ≠ Crust