

Earth's Composition and Structure:

A Journey to the Center of the Earth

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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

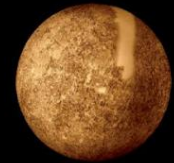
- Human perceptions have changed.
 - Early history – Planets as moving lights.
 - 1600s – 1st telescopes saw hazy spheres.
 - Today – A complex, evolving system.
 - Structure
 - History
- Space probes have photographed and analyzed planets.
- Scientists have hypothesized likely origins of the solar system.



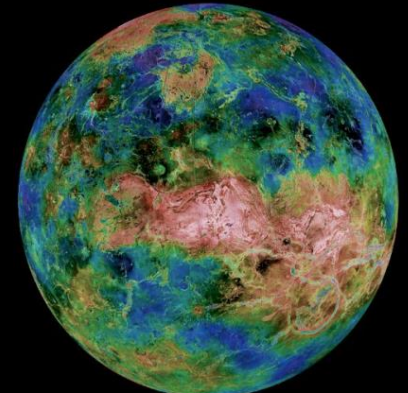
Earth



Mars



Mercury



Venus

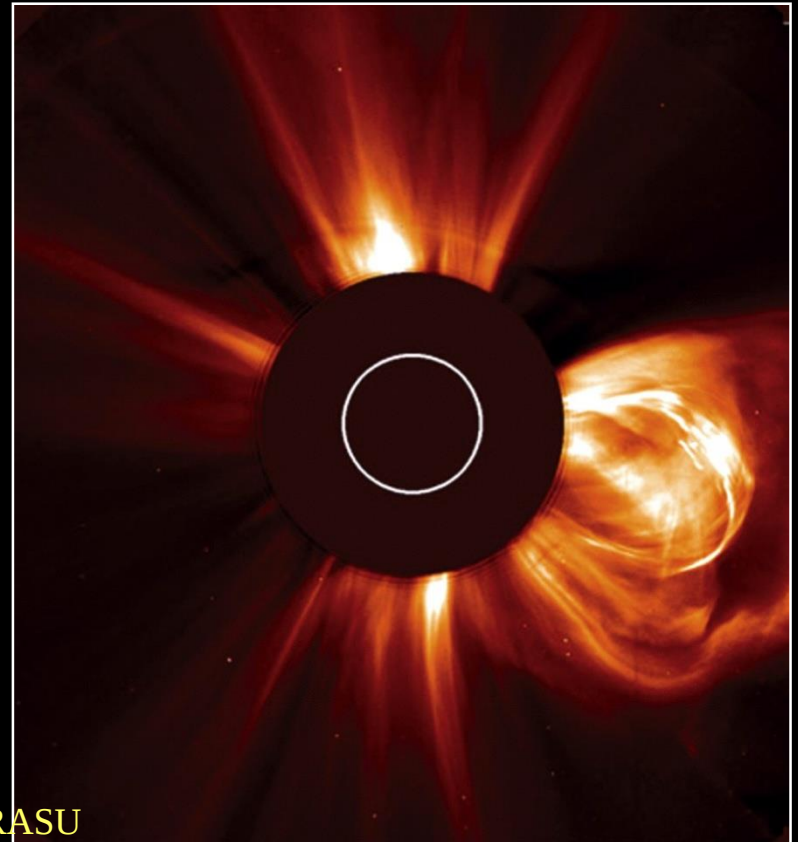
Earth and the Solar System

- 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 (N₂) and oxygen (O₂)**
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***

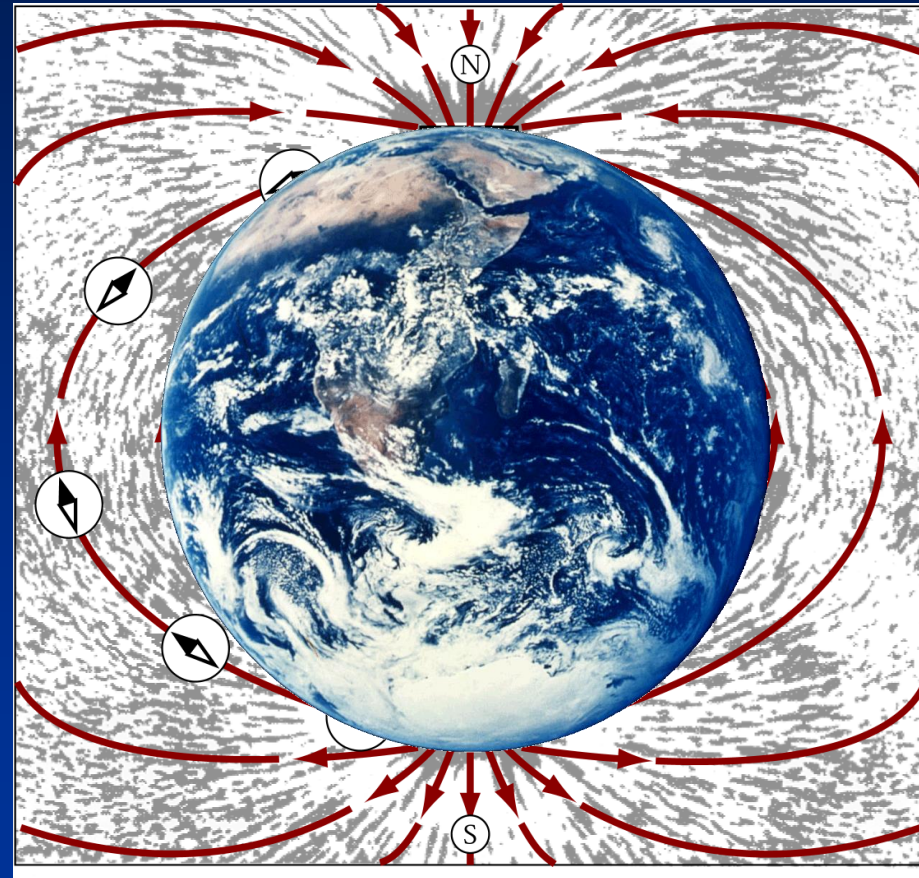
Earth's Magnetic Field

Geodynamo

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

Magnetic field

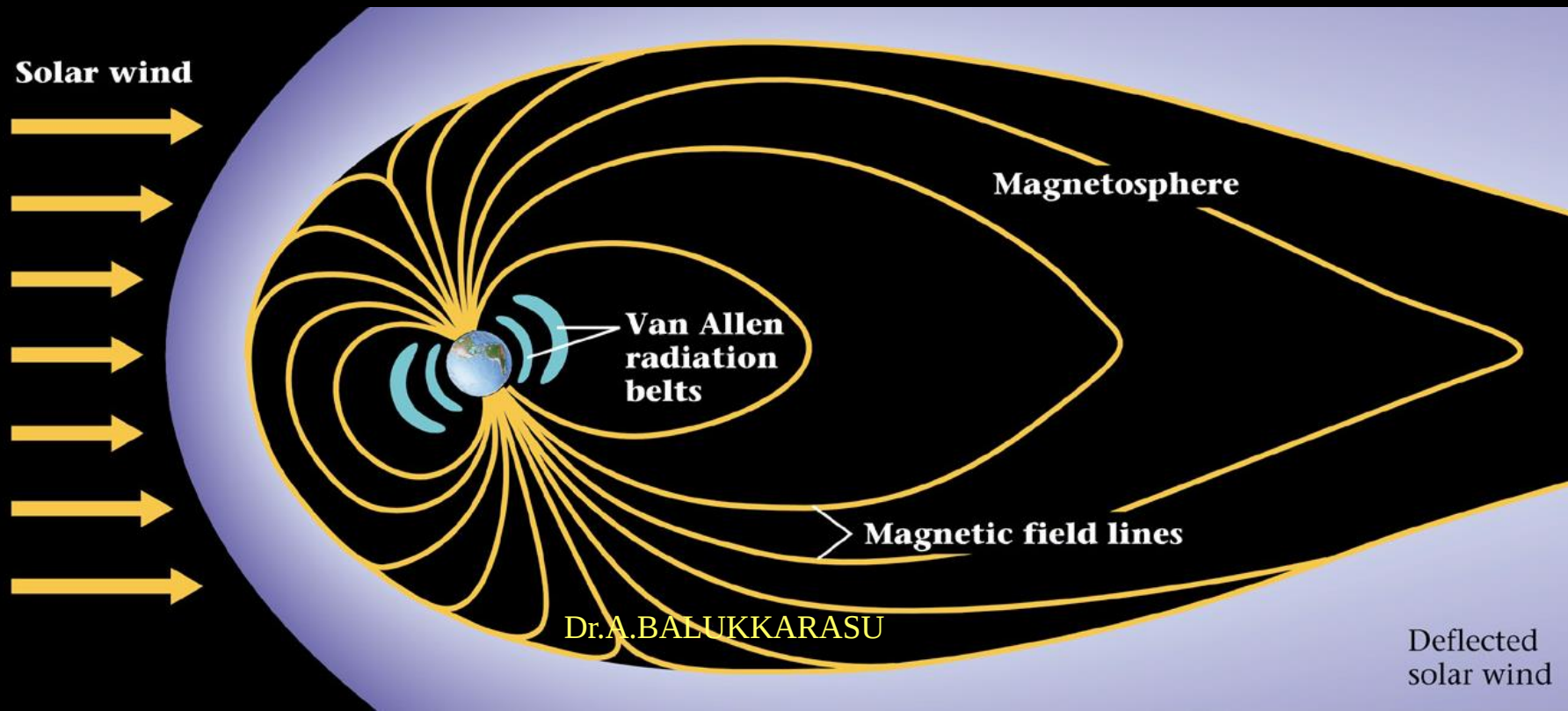
- region affected by force emanating from a magnet
- grows stronger as separating distance decreases
- attracts or repels magnetically charged or moving electrically charged objects
- compasses work because Earth is a large magnet



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!



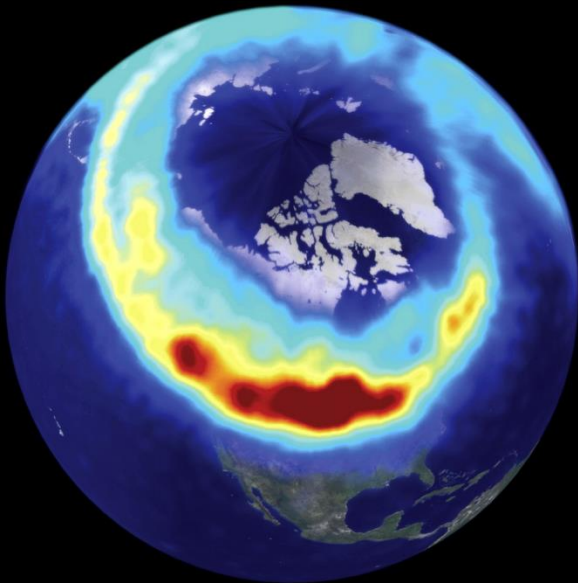
Northern & Southern Lights

Form because of our dipole magnetic field!

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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.



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Earth's Atmosphere

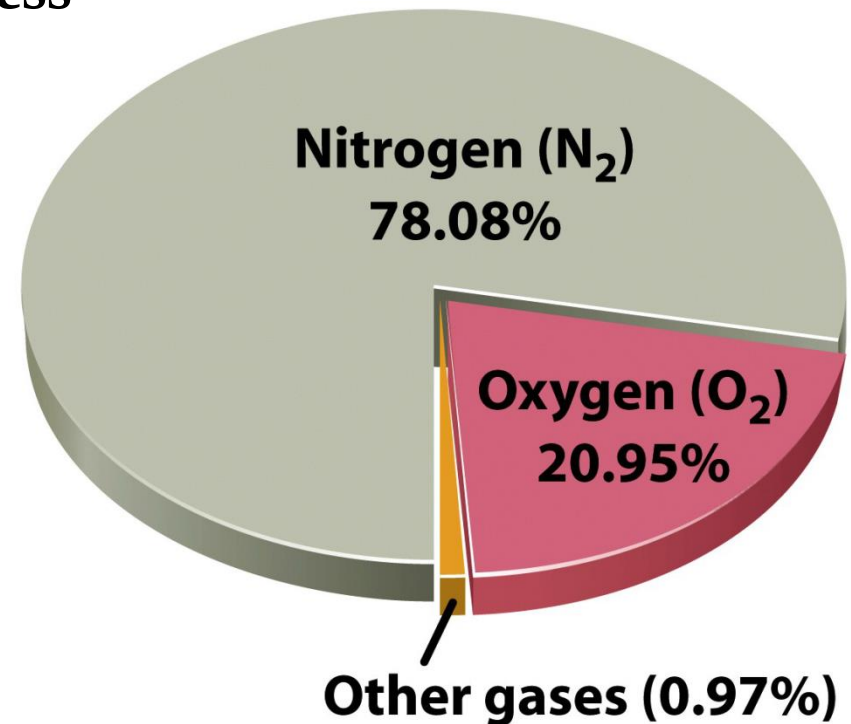
Distinct layers of gas surround the solid portion of the earth.

- **Composition is ~uniform regardless of altitude**

- 78% N₂
- 21% O₂
- All others ~1%
 - Ar, CO₂, CH₄, H₂O, Ne, CO, SO₂

- Some other Planets have atmospheres too!
 - None have N₂ & O₂ as dominant gasses

- Earth was oxygen-free until ~2.5 Ga



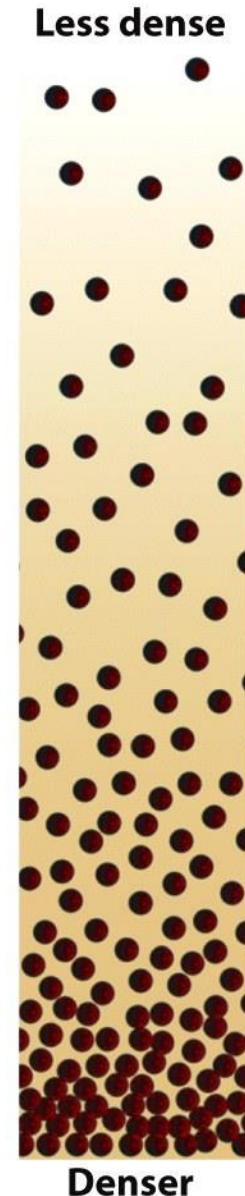
Earth's Atmosphere

○ Pressure decreases with increasing altitude

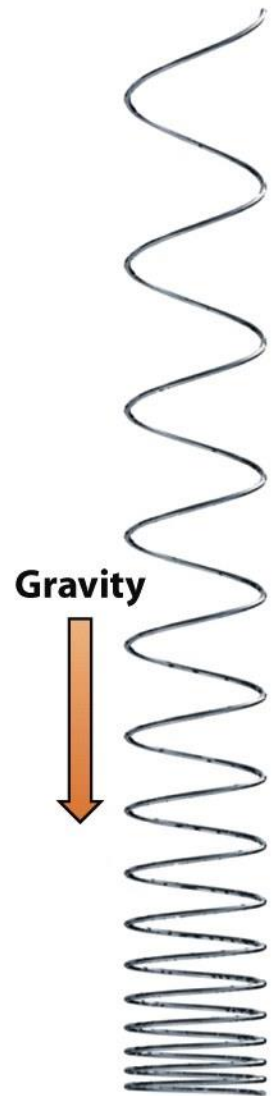
- Reflects # of molecules/volume
- Lower pressure = less molecules/volume
- Air pressure @ sea level = $14.7 \text{ lb/in}^2 = 1 \text{ bar}$

○ 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.



(a)

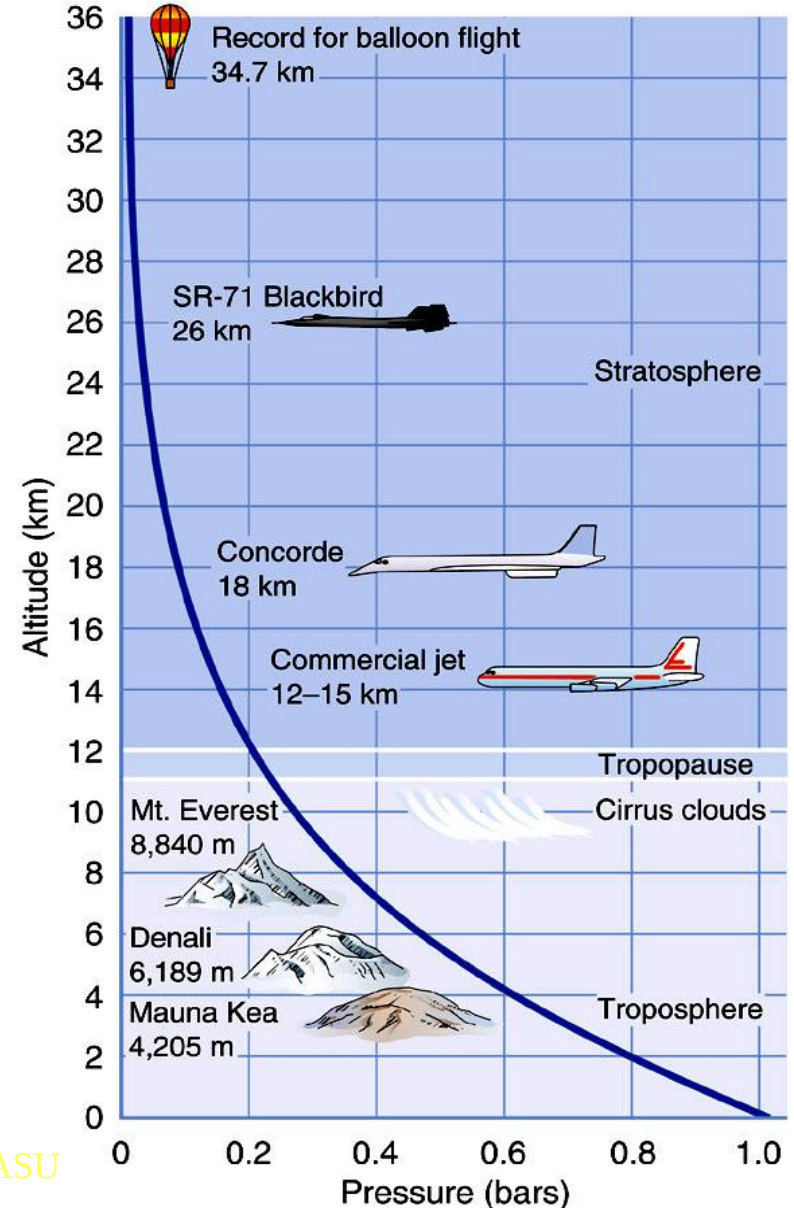


(b)

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

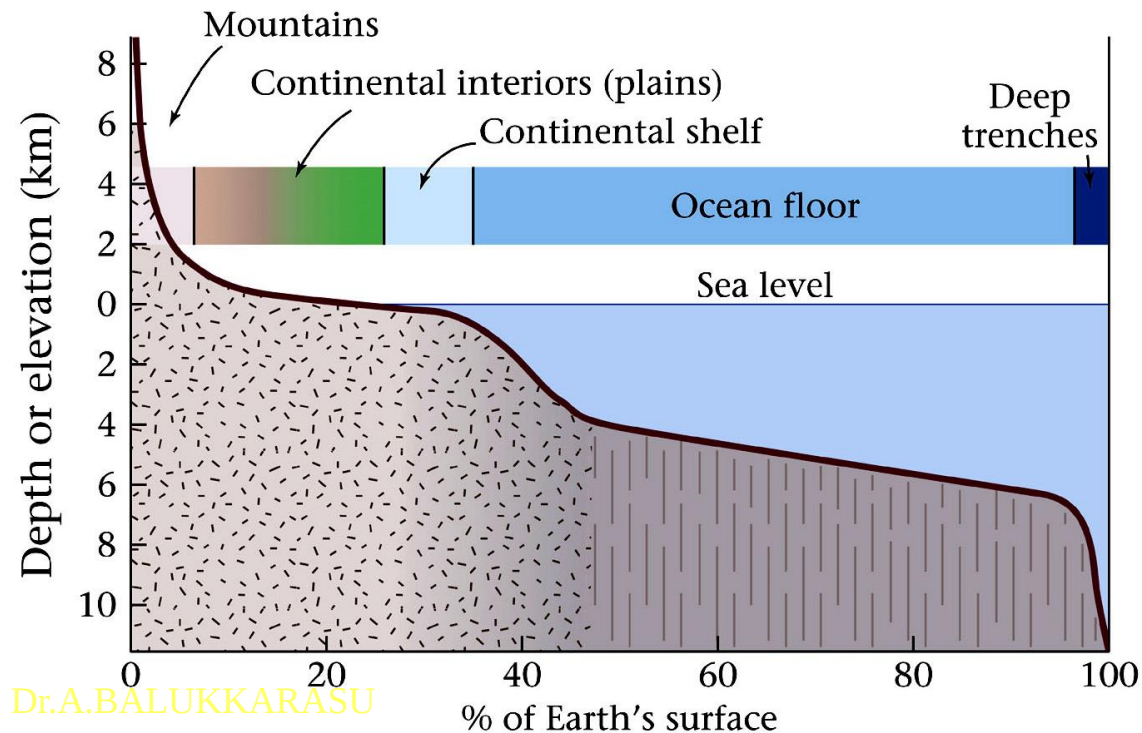


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...this guy likes convection

Earth's Components

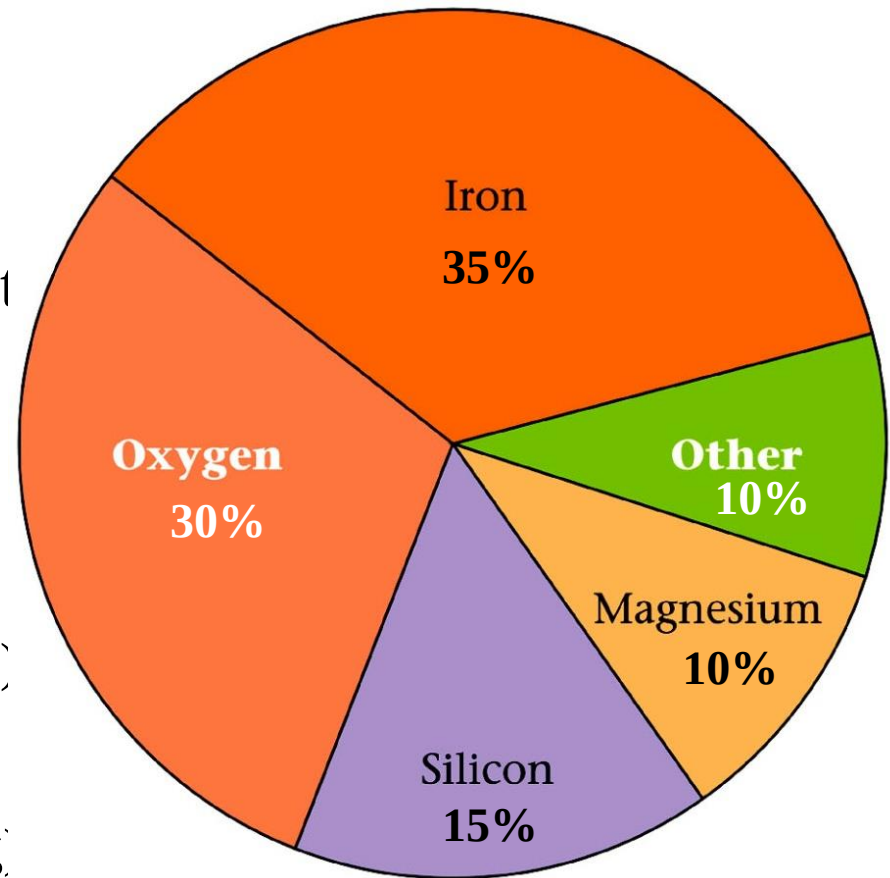
- Earth's surface = ~30% land, ~70% water
 - unlike any other known planet
- **Hydrosphere** = includes oceans, lakes, seas, rivers, & groundwater
- **Cryosphere** = glaciers, snow, and sea ice

- 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

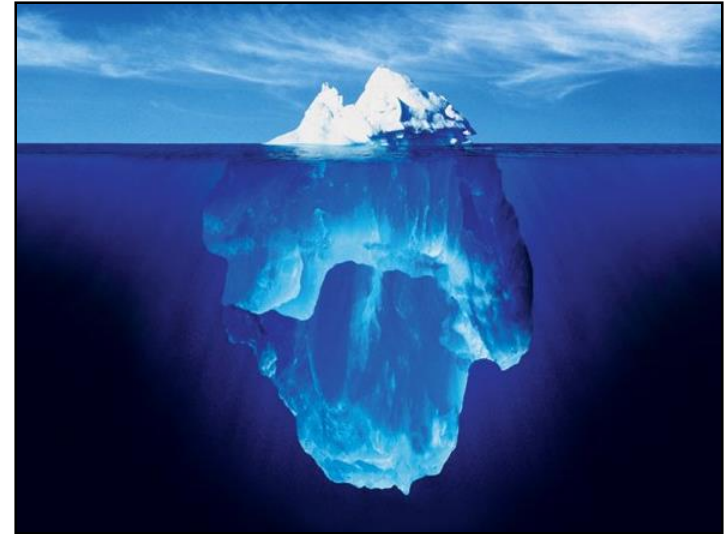
- We live on the thin outer skin of Earth.
- Early perceptions about Earth's interior were wrong.
 - Open caverns filled with magma, water, and air.
 - Furnaces and flames.
- We now know that Earth is comprised of layers.
 - The Crust.
 - The Mantle.
 - The Core.
 - Outer Core.
 - Inner Core.
- Some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

Earth's Density

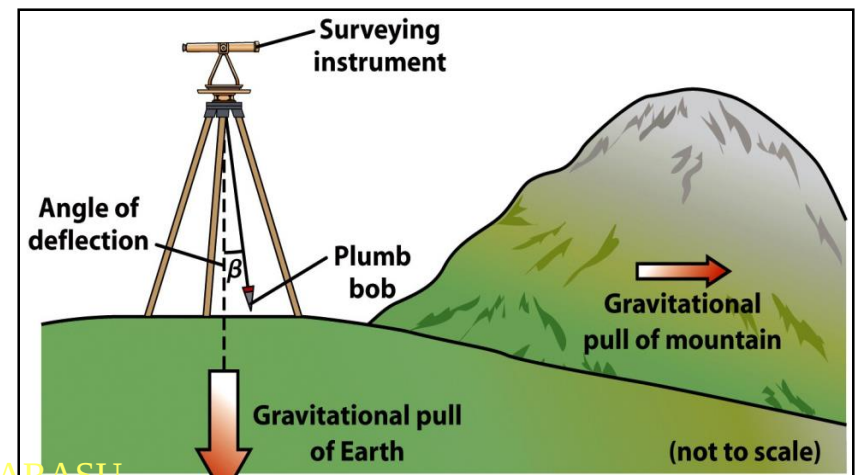
- **Earth's Density gives us clues about its internal structure**

- ***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 $\sim 5.5 \text{ g/cm}^3$
- Typical rocks at the surface of the Earth have a density of $2.0\text{-}2.5 \text{ g/cm}^3$
- *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....



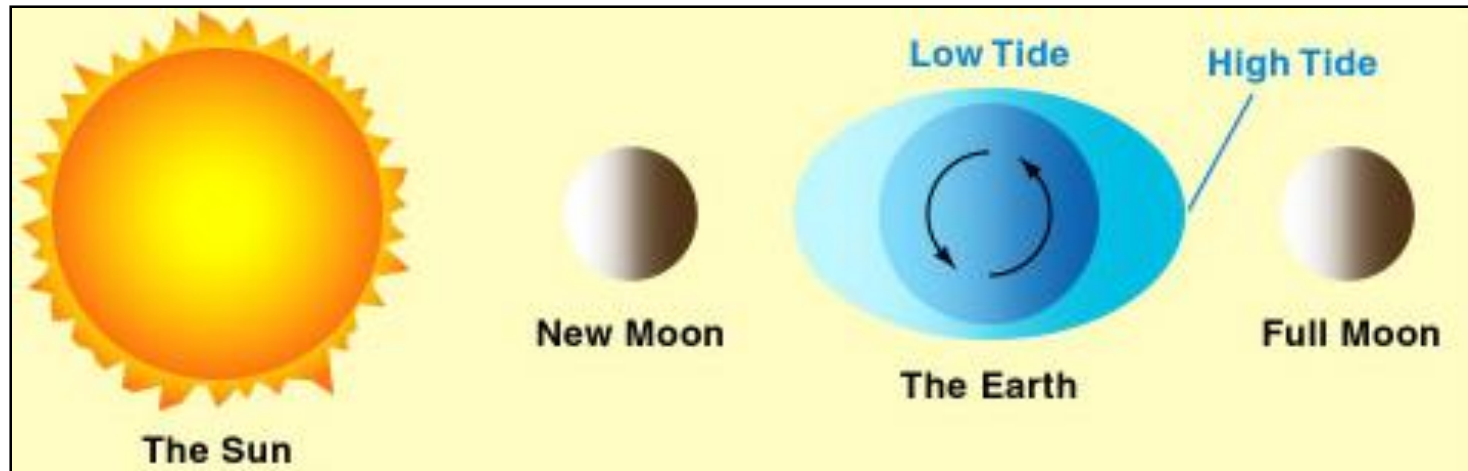
Then ***centrifugal*** force (not centripetal) would cause the planet to flatten into a disk.
This has (obviously) not happened.

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Earth's Layers

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

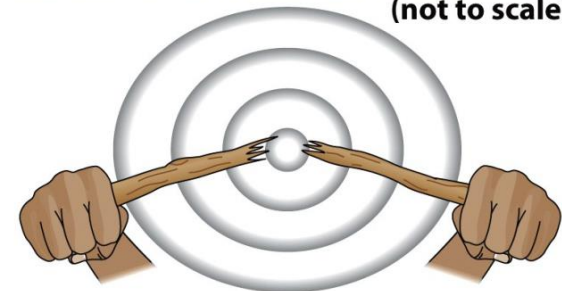
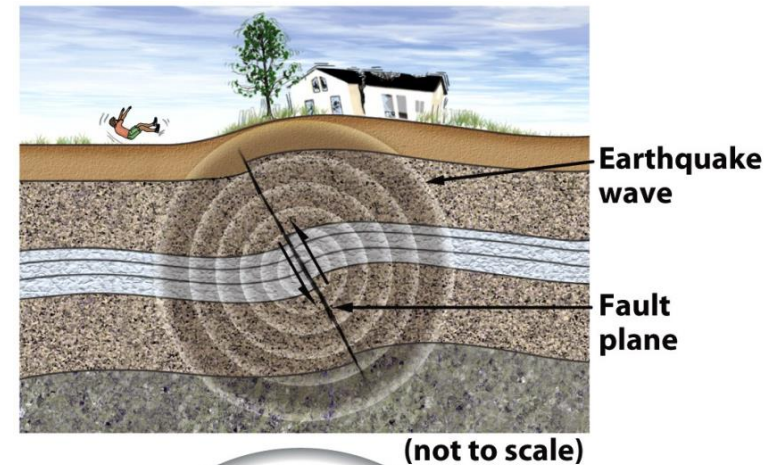
- If the Earth consisted of a thin solid shell over a thick liquid center, then the surface would rise and fall with tides like the ocean – This does not happen; only the oceans rise and fall.



- 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.**



Earth's Interior Layers

- The Earth (and other planets) have layered interiors.

- Crust

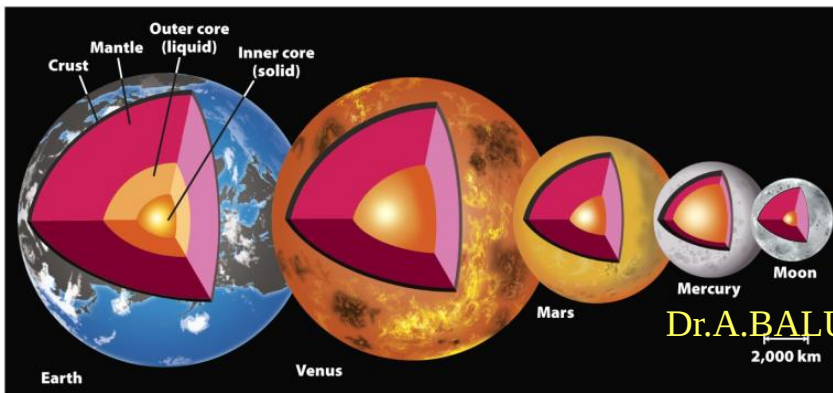
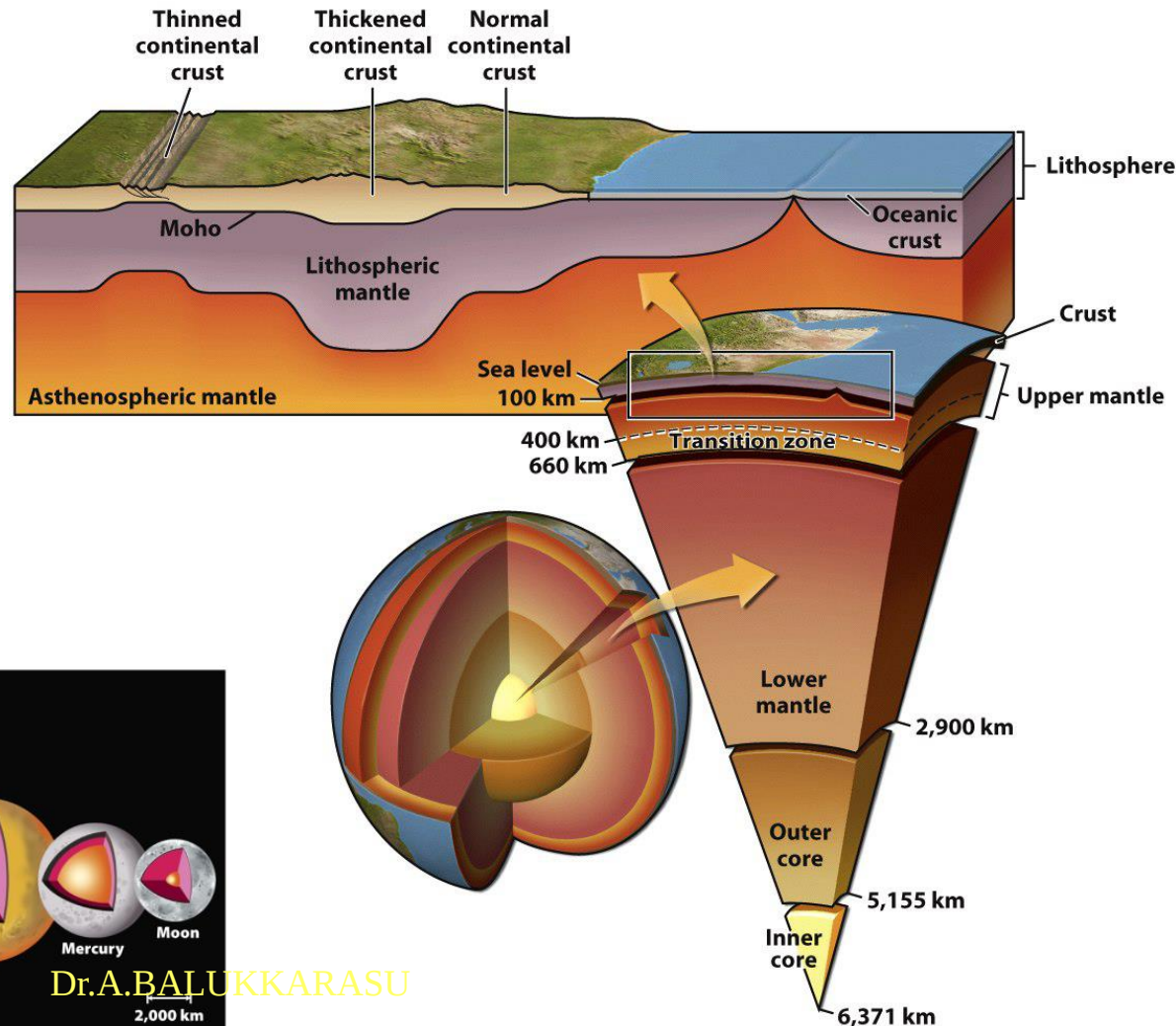
- Continental
- Oceanic

- Mantle

- Upper
- Lower

- Core

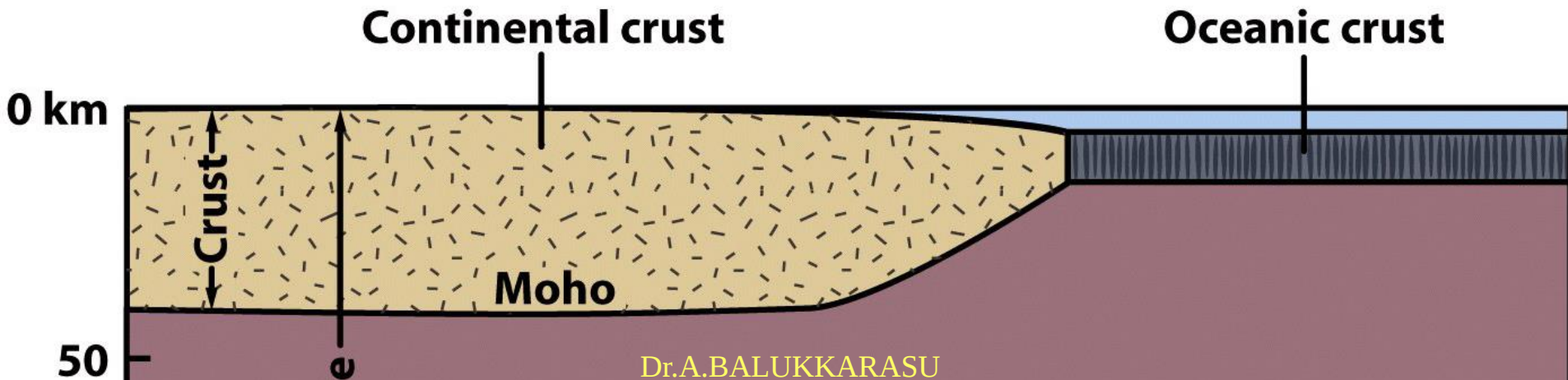
- Outer – Liquid
- Inner – Solid



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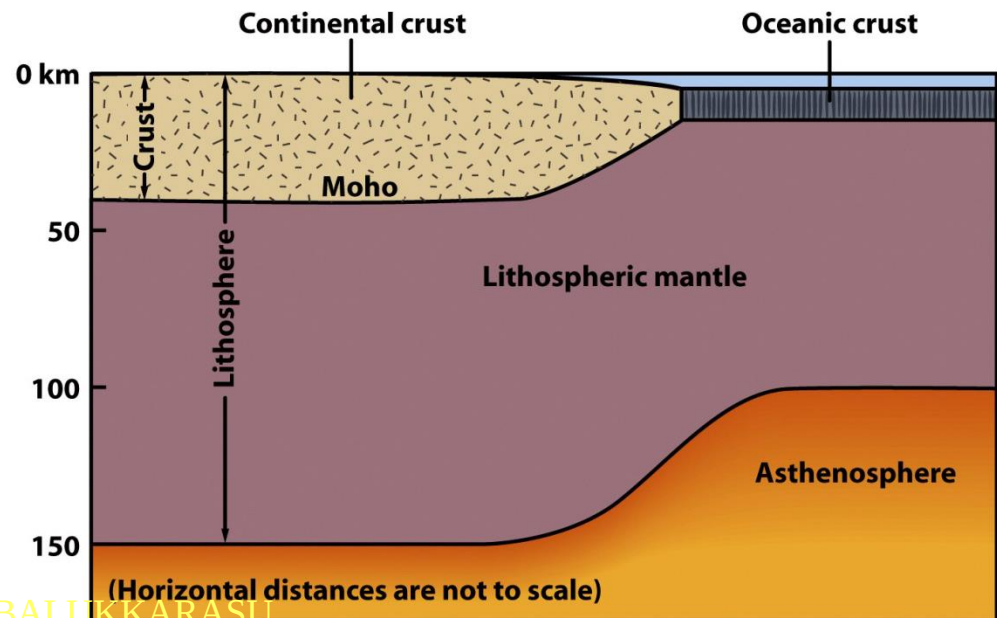
The Crust

- 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.



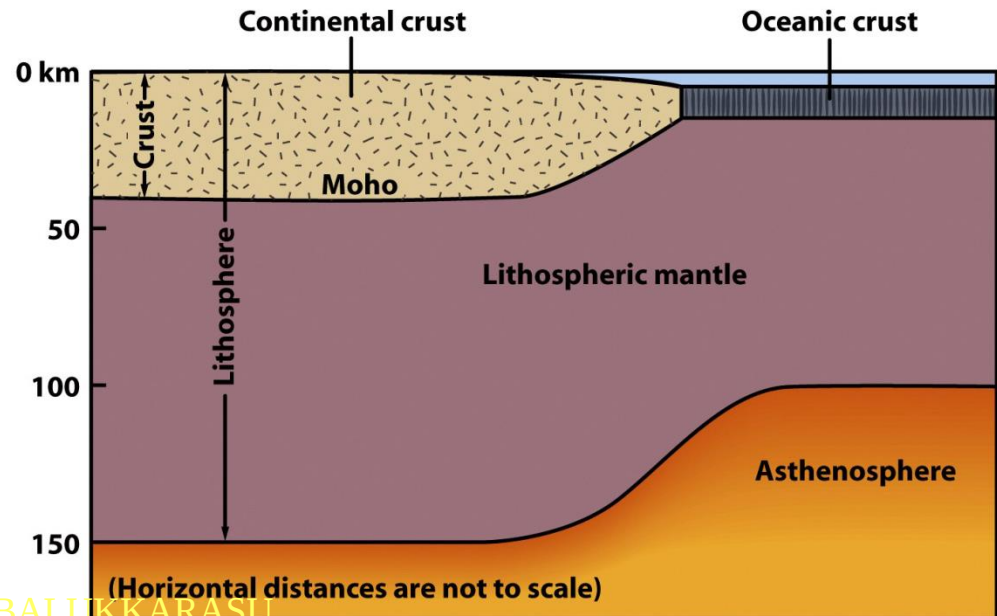
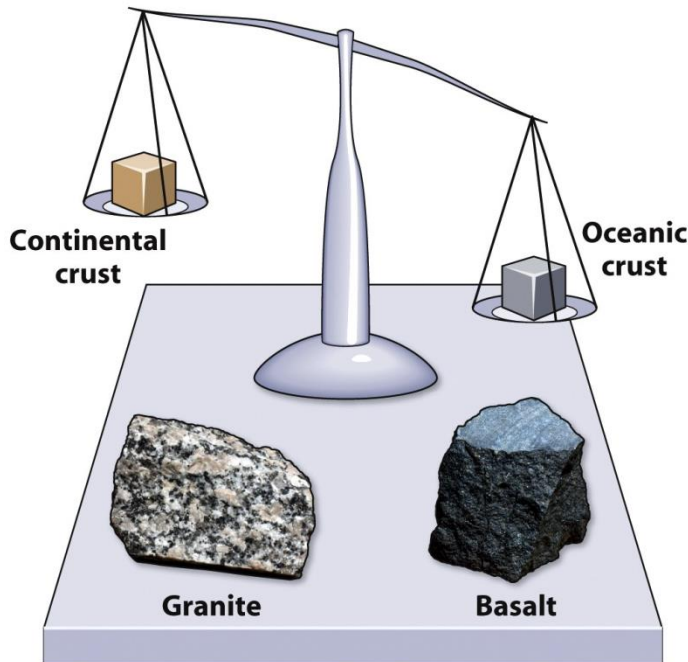
Two Types of Crust

- **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



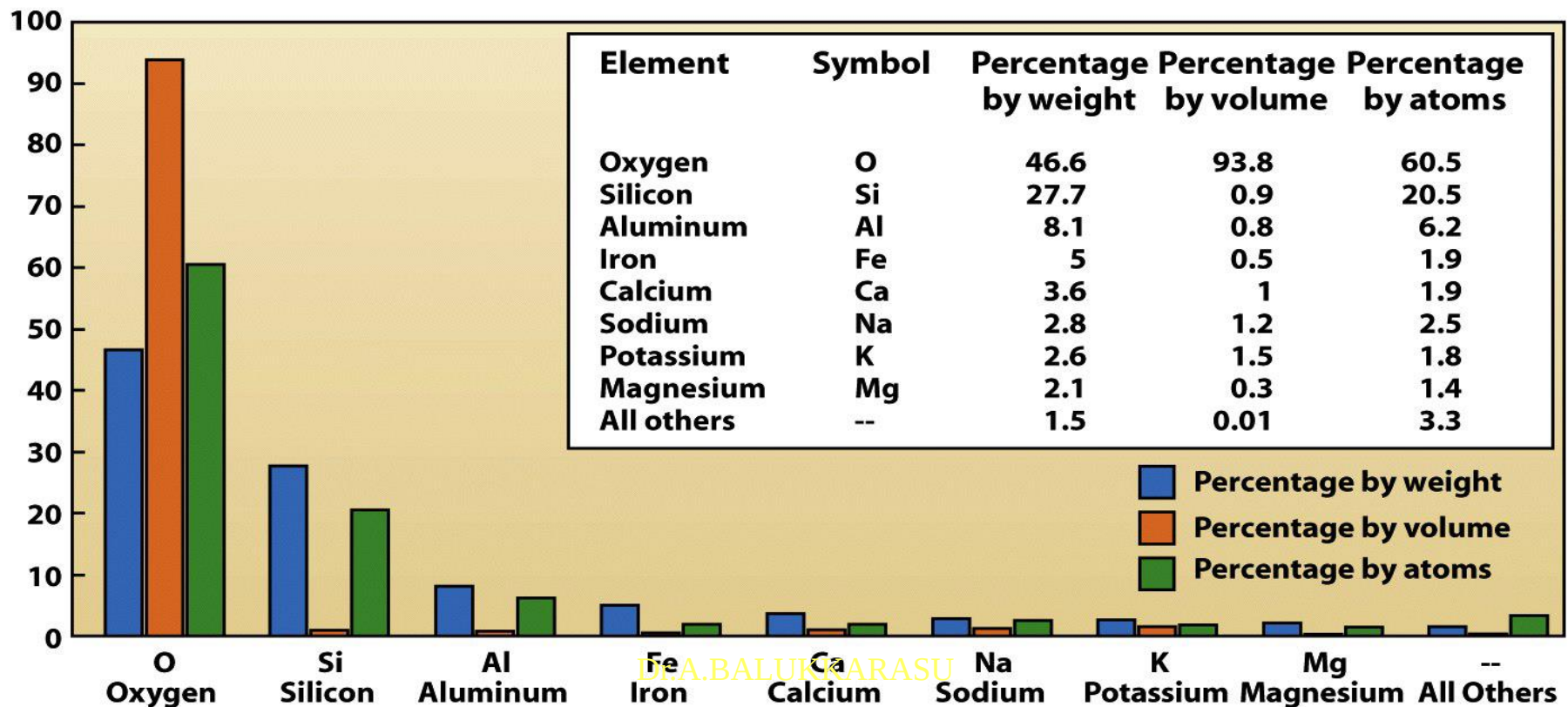
Two Types of Crust

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

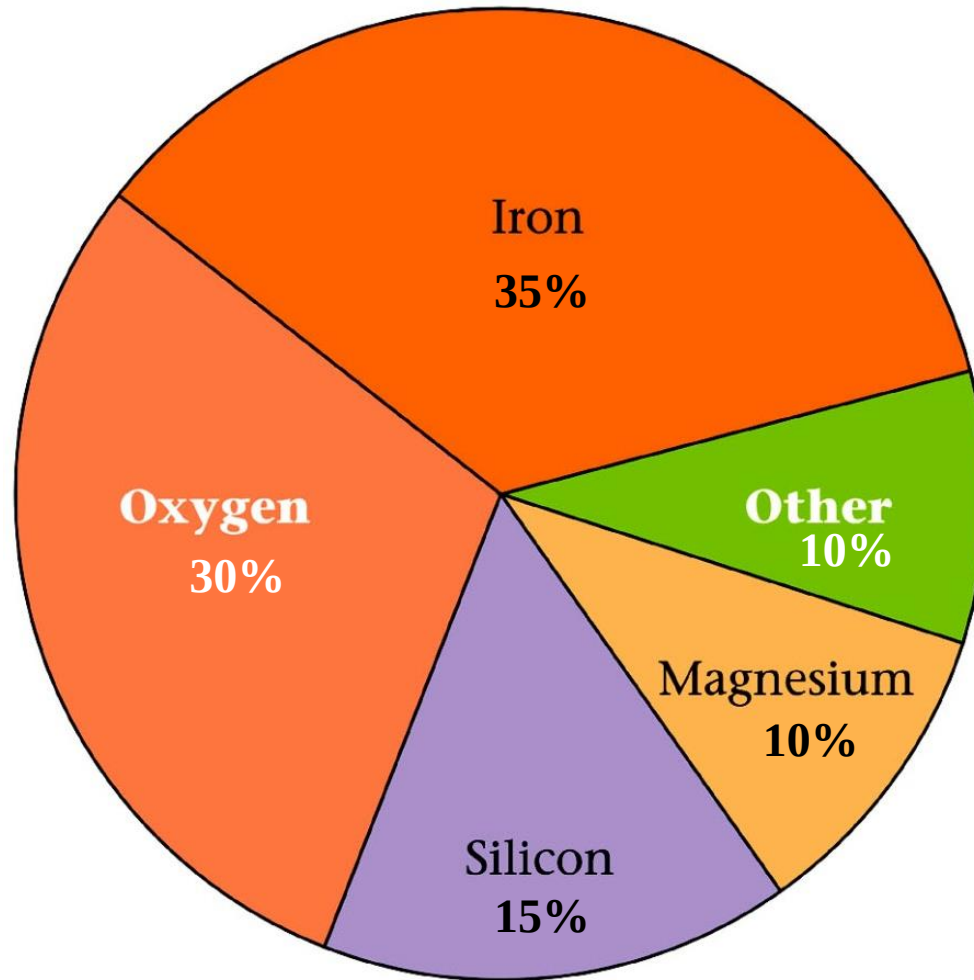


Crustal Composition

- 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.

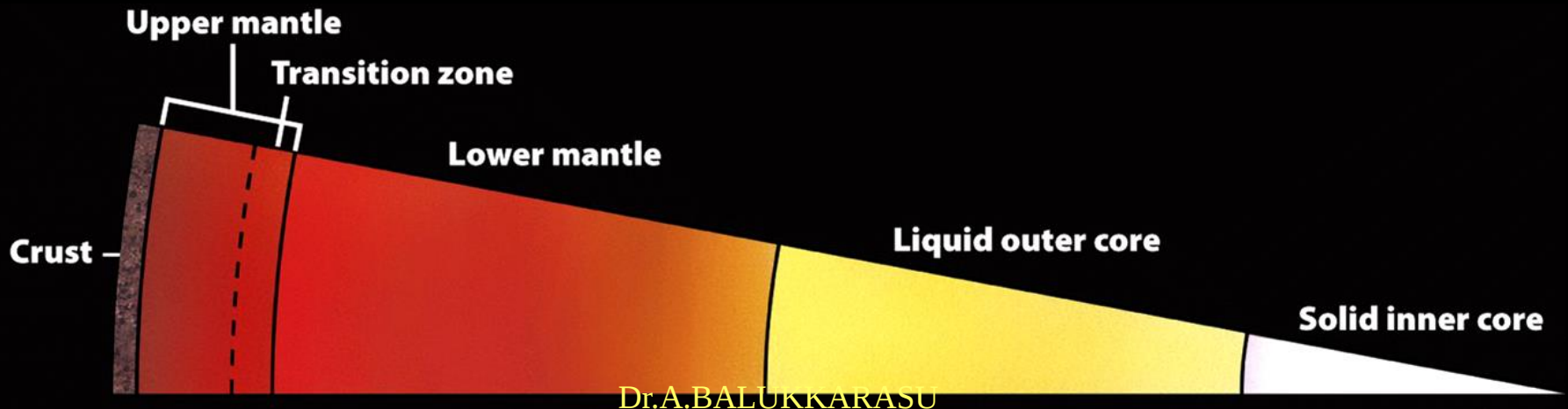


Bulk Earth Composition



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

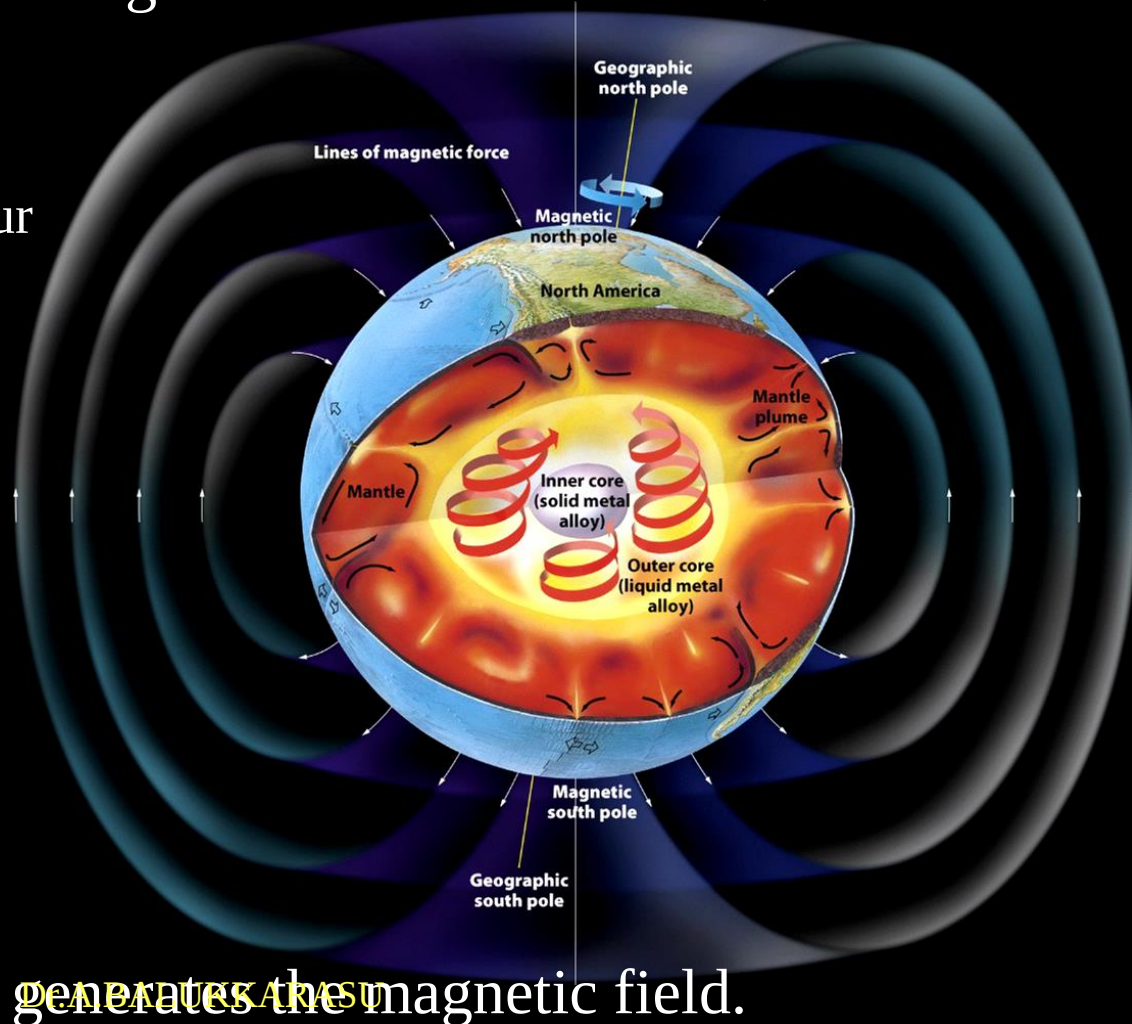
- An iron-rich sphere with a radius of 3,471 km.
- 2 components with differing seismic wave behavior.

– Outer core

- Liquid iron-nickel-sulfur
- 2,255 km thick
- Density – $10\text{--}12\text{ g/cm}^3$

– Inner core

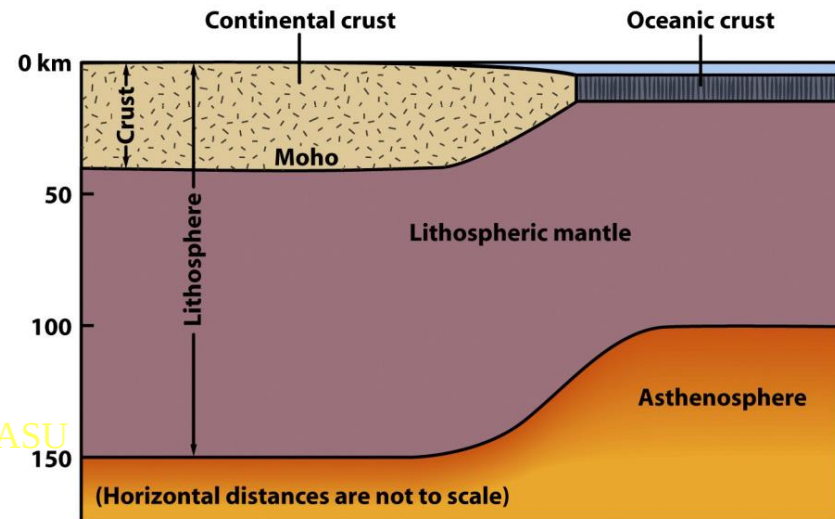
- Solid iron-nickel alloy
- Radius of 1,220 km.
- Density – 13 g/cm^3



- 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 ($< 2\%$)



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150

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 $\neq$ Crust

