The Earth

- Earth is basically spherical in shape
- The dimensions of the Earth are:
  - Radius: \( R_\oplus = 6,378 \text{ km} \)
  - Volume: \( V_\oplus = \frac{4}{3} \pi R_\oplus^3 \)
    \[ V_\oplus = 10^{12} \text{ km}^3 = 10^{27} \text{ cm}^3 \]

- Most of the Earth’s mass is contained in the interior rather than in the surface or atmosphere:
The Earth

- The mass of the Earth is determined by observing motions of objects in Earth's gravitational field:

\[ F = mA = -\frac{GM_\oplus m}{R^2_\oplus} \]

- We find that the acceleration at the surface of the Earth is given by

\[ A = -\frac{GM_\oplus}{R^2_\oplus} \]

The Earth

- We can compute the mass of the Earth from an observation of the acceleration of an object at the Earth's surface using

\[ A = -\frac{GM_\oplus}{R^2_\oplus} \quad \quad M_\oplus = -\frac{AR^2_\oplus}{G} \]

- We find that the mass of the Earth is given by

\[ M_\oplus = 6 \times 10^{27} \text{ g} \]

The Earth

- The average density of the Earth is calculated by taking the ratio of the total mass and the total volume:

\[ \rho_\oplus = \frac{M_\oplus}{V_\oplus} = \frac{6 \times 10^{27} \text{ g}}{10^{27} \text{ cm}^3} \]

- We find that the average density of the Earth is equal to

\[ \rho_\oplus = 6 \text{ g cm}^{-3} \]
The Earth

• The average density of the Earth is equal to
  \[ \rho_{\oplus} = 6 \text{ g cm}^{-3} \]

• The density of water is
  \[ \rho_{\text{water}} = 1 \text{ g cm}^{-3} \]

• The density of surface rock is
  \[ \rho_{\text{rock}} = 2 - 4 \text{ g cm}^{-3} \]

We conclude that very dense material must exist inside the Earth.

Due to the centrifugal force associated with its 24-hour rotation, Earth has an equatorial bulge.

The bulge in diameter at the equator due to rotation is about 40 km.
The Hydrosphere

- The Earth is the only known planet that has liquid water on its surface.
- 71% of the surface is covered by water, to an average depth of 3.6 km!
- Tides: There are 2 low tides and 2 high tides every day.
- The change in water depth is given by
  \[ \Delta H = 1 \text{ m} \] typical variation in open ocean
  \[ \Delta H = 18 \text{ m} \] most extreme variation is in the Bay of Fundy, Canada

The Tides

- Tides are caused by the combined gravitational influence of the Moon and Sun on the Earth.
- Moon’s effect:
  \[ \text{Moon’s effect: Total Bulge} \]
  \[ \text{Oceans} \]
- The differences between the forces on opposite sides of the Earth cause the tidal bulge.
The Sun also causes a tidal bulge on the Earth, about half as large as the Moon’s.
Why is the Sun's bulge smaller, even though the Sun is much, much more massive than the Moon?
Because the Sun is much, much farther away from the Earth than the Moon is.
The largest tides (Spring Tides) occur when the Sun, Earth, and Moon are all aligned.
Tides

- The weakest tides (Neap Tides) occur when the Sun, Earth, and Moon form a right angle.

Tidal Friction

- Due to the friction associated with the moving tidal bulge, the Earth day has lengthened over time (by 1 second per 50,000 years).
- 500 million years ago, the day was 22 hours long and the year had 400 days.
- This is indicated by the fossil record of growth in coral reefs.
- The angular momentum of the Earth is decreasing as a result.

The Earth will stop spinning (with respect to the Moon) in about $10^{12}$ years.

- The total angular momentum of the Earth-Moon system must be conserved.
- Therefore, the angular momentum of the Moon is increasing.
- The Moon is gradually moving further away from the Earth about 3.8 centimeters per year.
Earth's Atmosphere

- Air is composed of:
  - 78% $N_2$ Nitrogen
  - 21% $O_2$ Oxygen
  - 0.4% $Ar$ Argon
  - 0.03% $CO_2$ Carbon dioxide
  - 0.1-3% $H_2O$ Water vapor

- The atmosphere protects us from:
  - Freezing
  - Rocky debris from space
  - Harmful radiation and particles
  - Suffocating

Atmospheric Structure

- Most weather occurs in the Troposphere (clouds, storms, etc.)
- Convection occurs in the Troposphere
- Above the Thermosphere lies the electrically-conducting Ionosphere
Atmospheric Structure

- The Ozone layer forms high in the atmosphere because ultraviolet (UV) radiation splits O₂ to produce ozone, O₃.
- This process protects us from harmful UV radiation.

Surface Heating

- The surface re-radiates with a Planck (blackbody) spectrum, with flux given by Stefan's law:
- Solar radiation heats the Earth's surface with an energy flux equal to $F_{solar}$.

\[ F_{BB} = \sigma T^4 \]

- The temperature of the surface adjusts due to heating or cooling until there is a balance between the two fluxes:

\[ F_{BB} = F_{solar} \]

- Balance occurs when the temperature reaches the equilibrium value, $T_{eq}$.
Surface Heating

• In the morning, the surface temperature is cold.
• When the Sun rises, heating begins and the surface temperature rises because heating is stronger than cooling.
• The surface temperature is always close to the balance point.

\[ T = T_M \]

\[ T = T_A > T_M \]

• The re-radiated energy is in the infrared (IR) because the surface temperature \( T \) is about 300 K (Wien's Law).

Surface Heating

• Not all of the re-radiated energy gets out!
• Much of it gets blocked by CO₂ molecules.

• The amount blocked depends sensitively on the concentration of CO₂ in the atmosphere.
Surface Heating

• The equilibrium temperature, $T_{eq}$, gets higher and higher as more CO$_2$ is added

• This is called the “Greenhouse effect”
• The amount of CO$_2$ has been rising during the past century, due to industrial activity and the burning of large forests

Atmospheric Convection

• Solar radiation heats the ground, which heats the air near the ground:

• The hot air near the ground expands, and therefore it has a lower density than the cool air higher up
• The hot air rises, and the cool air moves down to replace it
• This forms a convection cell
Hurricanes and Cyclones

- The Earth rotates as a solid object
- The rotation of the Earth has a higher velocity at the equator than at the poles:
  - Solar heating causes the air at the equator to be the hottest
  - This forms a convection cell
  - Warm air from the equator travels towards the poles
  - The warm air moves eastward faster than the surrounding air

- The warm air from the equator therefore arcs to the east
- Cool air approaching the equator moves to the west because it is traveling more slowly than the air at the equator

- The combined motion is clockwise in the northern hemisphere
- The opposite occurs in the southern hemisphere, and the motion is therefore counter-clockwise

Gas is deflected to the right
Gas is deflected to the left
Hurricanes and Cyclones

- Hurricanes have low-pressure centers
- Air pulled into the hurricane is deflected to the right in the northern hemisphere
- Air pulled into the hurricane is deflected to the left in the southern hemisphere
- Hurricanes spin counter-clockwise in the northern hemisphere

The force that causes the deflection of the gas is called the Coriolis force.
- It also causes the regular pattern of the trade winds.
Hurricanes and Cyclones
• The same force can be felt when walking around on a spinning merry-go-round.

Very few bowling alleys are located on merry-go-rounds.

Earth’s Atmosphere
• When Earth formed, the primary atmosphere consisted of Hydrogen, Helium, Methane, Ammonia, Water vapor.

• These were the most common gases in the early solar system.

• They are “light gases,” meaning that they have low molecular weights.

• The speed of a molecule at temperature \( T \) depends on the mass of the molecule:

\[
\frac{1}{2} m v^2 = \frac{3}{2} k T
\]

Earth’s Atmosphere
• The speed of a molecule at temperature \( T \) depends on the mass of the molecule:

\[
v = \left( \frac{3 k T}{m} \right)^{1/2}
\]

• The escape velocity from the Earth’s atmosphere into space is given by

\[
V_{\text{esc}} = \left( \frac{2GM_\oplus}{R_\oplus} \right)^{1/2}
\]

• A molecule will escape from the atmosphere if \( v > V_{\text{esc}} \).

• Therefore, more molecules escape if the mass of the planet is lower, or the mass of the molecule is lower, or the temperature is higher.
Earth's Atmosphere

• Light gases have higher thermal speeds.
• If the temperature is high enough, the light gases can achieve escape velocity and escape from the atmosphere into space.
• That is what happened to most of the light gas present in the primary atmosphere (at the time of the Earth's formation).

![Graph showing average molecular speed and escape velocity for high- and low-mass planets.]

Earth's Atmosphere

• About one billion years later, the secondary atmosphere was outgassed from the interiors of volcanoes.
  - Water vapor
  - Carbon dioxide
  - Sulfur dioxide
  - Nitrogen
• The temperature had fallen by this time, so these gases remained in the atmosphere.
• The CO₂ and SO₂ dissolved into the oceans or was bound inside rocks via chemical reactions.
• Little free oxygen appeared at this time.

\[ v = \sqrt{\frac{3kT}{m}} \]
Earth's Atmosphere

- The appearance of life led to further profound changes in the atmosphere about $3.5 \times 10^9$ years ago
- Plants produce free oxygen and remove carbon dioxide
- The Earth's surface is a giant terrarium, with interdependent species and ecosystems

The blue color of the sky is due to the strong scattering of blue light relative to red light

Earth's Interior

- Drills only penetrate the outer 10 km of the Earth's crust
- Therefore, in order to study the deep interior, we must use seismic waves generated by earthquakes
- There are two types of seismic waves: P (longitudinal) and S (transverse)