Chap 9: Atmospheres of Terrestrial Planets
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- How did the terrestrial planets’ atmospheres form?
  - Primary and secondary atmospheres
  - Atmosphere retention: mean molecular velocity & magnetosphere
- How do we understand the density structure of the atmosphere?
  - Hydrostatic equilibrium under isothermal condition
- How has Earth’s atmosphere been changed over time?
  - Oh, life has changed everything!
- Climate effects from astronomical, geological, and biological mechanisms
The Origin of Atmospheres

a brief history
New planets formed **primary atmospheres** by sweeping up gas in the accretion disk.

1. Gases in a protoplanetary disk, mostly hydrogen and helium...
2. ...were captured by young planets, forming **primary atmospheres**.
3. Sunlight heated the atmospheres. Rapid thermal motion of light atoms and molecules caused the primary atmospheres to escape.
Primary/Primitive Atmospheres are retained in the Giant Planets

- The Gas Giants have no solid surfaces. We just see the cloud layers in the atmospheres.
- They are called giant planets because of their mass—from 14.5 Earth masses (Uranus) to 318 (Jupiter)—and also their physical size.
Secondary Atmospheres from volcanism and small bodies

- All terrestrial bodies lost their primary atmospheres.
- Secondary atmospheres were acquired later by:
  - volcanism
  - comet impacts
- Only Venus, Earth, and Mars have significant secondary atmospheres.
- Mercury and the Moon have no significant atmosphere.
The Condensation Process (Minerals)

As elements condense out of the solar cocoon nebula, they form solid microscopic mineral grains in the following sequence:

1. High temperature refractories (e.g., Tungsten [W], spinel [MgAl$_2$O$_4$], and perovskite [CaTiO$_3$])

2. Nickel-Iron alloy, and Silicates (e.g., olivine [Fe$_2$SiO$_4$ and Mg$_2$SiO$_4$]).

3. Carbonaceous condensates (graphite-like material mixed with organic molecules and silicates)

4. Ices ($500 > T > 200$ K, hydrated minerals [serpentine - hydrated olivine]; $T < 200$ K, ices of water, ammonia, methane, and hydrated ices; $T < 170$ K, surface ice)
Volcanism releases volatiles: Volcán de Fuego, GUATEMALA
Meteorite Bombardment: remember the sodium-layer laser guide stars in adaptive optics?

- Sodium layer: 90 km high, 10 km thick (mesosphere). Origin - micrometeorites
The habitable zone of a star is where liquid water can exist on the surface. In the early Solar System, there was liquid water on Venus, Earth, and Mars. Venus was too hot and Mars too cold to keep liquid water. Earth is just the right temperature to keep its water.

### Table 9.1
**Atmospheres of the Terrestrial Planets**

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Summary: the Accretion, Loss, and Regeneration of Atmospheres

- **The primary atmosphere** is the gas initially gathered from the disk.
  - This is primarily hydrogen and helium (low mass gases).
  - The process of gathering atmosphere is called **core accretion–gas capture**.
- **Secondary atmospheres** occur around some low-mass planets because the initial atmosphere is lost.
  - The low-mass planets do not have enough gravity to keep the initial atmosphere from escaping.
  - **Volcanoes** emit heavy gases from the planetary interiors that the planet can hold onto for a very long time.
  - **Comets & asteroids** bring water and other volatiles to planets, which evaporate and add to the secondary atmosphere.
The Retention of Atmospheres

*molecular velocity vs. escape velocity*
Velocities of Gas Molecules in the Atmosphere: Boltzmann Distribution

Mean Kinetic Energy per Particle: $\mu m_h v^2/2 = 3kT/2$
The Mean Molecular Weight/Mass

\[
\mu = \frac{M_{\text{gas}}/N_{\text{particle}}}{m_H} = \frac{\bar{m}}{m_H}
\]

Examples:
- neutral atomic hydrogen gas: \( \mu = 1 \)
- ionized atomic hydrogen gas: \( \mu = 0.5 \)
- what is the mean molecular weight/mass (\( \mu \)) of pure \( \text{CO}_2 \) gas?
The temperature of a gas is a measure of the average kinetic energy of its molecules. With the average kinetic energy, we can calculate the average velocity if we know the mean molecular weight (mu).

How does the mean velocity of the CO\textsubscript{2} molecules (mu=44) at 27 C (300 K) compare with the escape velocity from the surface of the Earth?

Constants: \( k = 1.38 \times 10^{-23} \text{ J/K} \), \( m_H = 1.67 \times 10^{-27} \text{ kg} \)

\[
\overline{v}_{\text{molecule}} = \sqrt{\frac{3kT}{\mu m_H}} = 0.4 \text{ km/s} \left( \frac{T}{300 \text{ K}} \right)^{0.5} \left( \frac{\mu}{44} \right)^{-0.5}
\]

\[
v_{\text{esc}} = \sqrt{\frac{2GM}{R}} = 11.2 \text{ km/s} \left( \frac{M}{M_{\text{Earth}}} \right)^{0.5} \left( \frac{R}{R_{\text{Earth}}} \right)^{-0.5}
\]
- If the speed of a gas molecule is significantly less than a planet’s escape speed, it will be more easily retained.
- The speed is related to the temperature and the mean molecular mass — lighter gas (e.g., H) move faster than heavier gas (e.g., Ar, Ne)
- If the mean molecular speed is less than 1/6 of the escape speed, the planet will be able to retain this gas in its atmosphere.
### Atmospheres of the Terrestrial Planets

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- Earth has about 200 times more atmospheric mass than Mars, and Venus has almost 100 times more atmospheric mass than Earth.
- The difference with Mars is from the differences in the amount of surface gravity.
- Venus and Earth (being bigger) were able to keep more atmosphere than Mars.
The Retention of Atmospheres

solar wind & the importance of the magnetosphere
The Solar Wind

The solar wind is ionized gas emitted from the Sun flowing radially outward through the solar system and into interstellar space.
Solar winds blow a comet’s tails away from the Sun
Solar winds blow a comet’s tails away from the Sun.
Without the Earth’s Magnetosphere, the Earth’s atmosphere would have been blown away by the solar winds.
Particles from the solar wind collide with the upper atmosphere, creating auroras.
- Earth’s **magnetosphere** extends out to $10 \ R_{\text{Earth}}$, much larger than the atmosphere (~0.015 $R_{\text{Earth}}$).
- It blocks much of the solar wind, trapping the charged particles from the Sun, protecting our atmosphere.
Recap of Atm Part 1
The Accretion, Loss, and Regeneration of Atmospheres

- The **primary atmosphere** is the gas initially gathered from the disk.
  - This is primarily hydrogen and helium (low mass gases).
  - The process of gathering atmosphere is called **core accretion–gas capture**.
- **Secondary atmospheres** occur around some low-mass planets because the initial atmosphere is lost.
  - The low-mass planets do not have enough gravity to keep the initial atmosphere from **escaping**.
  - **Volcanoes** emit volatiles from the planetary interiors that were incorporated in solid rock form during the condensation phase (e.g., hydrated minerals like **serpentine**).
  - **Comets & asteroids** bring water and other volatiles to planets, which evaporate and add to the secondary atmosphere.
Atmosphere Retention - Primary Atmosphere

- The temperature of a gas is a measure of the average kinetic energy of its molecules. With the average kinetic energy, we can calculate the average velocity if we know the mean molecular weight (\(\mu\)).

- How does the mean velocity of the \(\text{H}_2\) molecules (\(\mu=?\)) at 600 K compare with the escape velocity from the surface of the Earth?

- Constants: \(k = 1.38 \times 10^{-23} \text{ J/K}\), \(m_H = 1.67 \times 10^{-27} \text{ kg}\)

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\bar{v}_{\text{molecule}} = \sqrt{\frac{3kT}{\mu m_H}} = 0.4 \text{ km/s} \left(\frac{T}{300 \text{ K}}\right)^{0.5} \left(\frac{\mu}{44}\right)^{-0.5}
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\]
A model of Temperature Gradient + Condensation + Stellar Wind can explain the distance-dependency of the chemical composition.
- Earth’s magnetosphere extends out to 10 $R_{\text{Earth}}$, much larger than the atmosphere (~0.015 $R_{\text{Earth}}$).
- It blocks much of the solar wind, trapping the charged particles from the Sun, protecting our atmosphere.
Understanding the vertical density structure of the atmosphere

*ideal gas law, hydrostatic equilibrium, & isothermal*
The higher you go, the less air there is, why?
Pressure & Density Profile of Earth’s Atmosphere

\[
\frac{P}{P_0} = \frac{n}{n_0} = \exp\left(-\frac{h}{h_s}\right)
\]
Ideal Gas Law & Mean Molecular Weight

The law states that pressure is 2/3 of the kinetic energy density:

\[ P = nkT = \left( \frac{\rho}{\mu m_H} \right) kT \]

where in the above we expressed the particle number density \((n)\) as the ratio between the mass density \((\rho)\) and the mean particle mass \((\mu m_H)\).

These quantities are related in the following way given the definition of the mean molecular weight:

\[ \mu m_H = \bar{m} = \frac{M}{N} = \frac{\rho}{n} \]

The equation above shows the importance of the mean molecular weight in the conversion between mass density and number density.
Mean Molecular Weight of Mixed Gas

• What need to be known? the mean molecular weight of each component ($\mu_i$), and their percentages by volume ($f_{i}^v$)

$$\mu = \sum_i \mu_i f_{i}^v$$

Practice:
- CO$_2$: $\mu = 44$
- N$_2$: $\mu = 28$
- What is the mean molecular weight of a mixed gas consisting of 40% CO$_2$ & 60% N$_2$ (by volume)?
Winds and Circulation

- **Convection** distributes surface heating.
- **Hadley circulation** transports heat between the equator and poles with **global winds**
- The Earth rotates fast enough to break up the large convection cells into smaller ones via the **Coriolis effect**.
- The Coriolis effect creates **zonal winds**, which blow in the east–west direction.
A Map of the Trade Winds
Hydrostatic Equilibrium Derivation

- consider the force balance in a packet of air at an altitude of \( h \). The packet has a cylindrical shape with an area of \( A \) and an infinitesimal height of \( dh \).
- this packet of air can stay stationary because of a force balance
  - upward force from pressure = \([P(h) - P(h + dh)] \cdot A = -dP \cdot A\)
  - downward gravitational force = \( \rho \cdot (A \cdot dh) \cdot g \)
Hydrostatic Equilibrium Derivation

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• Equating the two forces means **hydrostatic equilibrium**:
  
  \[-dP = \rho \cdot g \cdot dh \Rightarrow -d(nkT) = (\mu m_H n) \cdot g \cdot dh\]

where we have applied the **ideal gas law** and expressed mass density as number density. If the temperature is constant, i.e., the **isothermal condition**, we can take \( kT \) out of the differentiation, and we can also move \( n \) to the left side (assuming also **thin atmosphere** so that \( g \) is constant):

\[
\frac{dn}{n} = -\frac{\mu m_H g}{kT} \; dh
\]

• Integrating both side from altitude of 0 to altitude of \( h \), we have a solution:

\[
n(h) = n_0 \exp\left(-\frac{h}{h_S}\right) \text{ where } h_S = \frac{kT}{\mu m_H g} \text{ is the **scale height**.}
\]
Recap: Understanding the vertical density structure of the atmosphere

*ideal gas law, hydrostatic equilibrium, & isothermal*
• consider the force balance in a packet of air at an altitude of \( h \). The packet has a cylindrical shape with an area of \( A \) and an infinitesimal height of \( dh \).
• this packet of air can stay stationary because of a force balance
  • upward force from pressure = \([P(h) - P(h + dh)] \cdot A = - dP \cdot A\)
  • downward gravitational force = \( \rho \cdot (A \ dh) \cdot g \)

\( P(h + dh) \) : Pressure at altitude of \( h + dh \)

\( P(h) \) : Pressure at altitude of \( h \)

mass of air = \( \rho \cdot (A \ dh) \)
Hydrostatic Equilibrium Derivation

• consider the force balance in a packet of air at an altitude of \( h \). The packet has a cylindrical shape with an area of \( A \) and an infinitesimal height of \( dh \).

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Practice: Calculate the scale height of $N_2$

$$n(h) = n_0 \exp\left(-\frac{h}{h_S}\right)$$ where $h_S = \frac{kT}{\mu m_{Hg}}$ is the scale height.

For an 100% $N_2$ atmosphere, $\mu = ?$.
Assume a mean temperature of 280 K (+7 C).
Constants: $k = 1.38 \times 10^{-23}$ J/K, $m_H = 1.67 \times 10^{-27}$ kg, $g = 9.8$ m/s$^2$, $e = 2.718$

1. What’s the scale height?
2. What are the $N_2$ densities at 1x and 3x the scale height if its density at sea level ($n_0$) is set to be at 1 unit (~$10^{25}$ m$^{-3}$).

Answer: 8.4 km, 0.37 unit at 1 $h_s$, 0.05 unit at 3 $h_s$
Understanding the vertical density structure of the protoplanetary disks

ideal gas law, hydrostatic equilibrium, & isothermal
Vertical density structure of proto-planetary disks
\[ n(h) = n_0 \exp\left(-\frac{h}{h_S}\right) \]

where \( h_S = kT_\mu m_H g \) is the scale height.

Vertical density structure of proto-planetary disks
Vertical density structure of proto-planetary disks

Instead of an exponential function, it follows a Gaussian function

\[
\frac{n}{n_0} = \exp\left(-\frac{h^2}{h_S^2}\right) \quad \text{where} \quad h_S = \sqrt{\frac{2kT r^3}{\mu m_H G M^*}}
\]

\[
\frac{n}{n_0} = \exp\left(-\frac{h}{h_S}\right) \quad \text{where} \quad h_S = \frac{kT}{\mu m_H g}
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The Evolution of Earth’s Atmosphere

terraforming the early Earth
Why is the Earth’s atmosphere so different, if not unique?

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The 9.7-micron Biomarker in the mid-Infrared spectra
**Miller-Urey Experiment (1952)**

A chemistry experiment that simulated the conditions in the atmosphere of the early Earth.

**Goal:** to test the hypothesis of the chemical origin of life.

**Result:** Over 20 different amino acids (building blocks of protein and genetic code) were produced from simple gas mixtures of $\text{CH}_4$, $\text{NH}_3$, $\text{H}_2\text{O}$, and $\text{H}_2$, after only 1 week.
our story in one minute: a spark of life changed everything!
The Evolution of the Earth’s Atmospheric Composition

[Diagram showing the evolution of atmospheric composition over time with key gases such as ammonia, methane, oxygen, and nitrogen, and eons including Hadean, Archean, Proterozoic, and Phanerozoic periods.]
Oxygen Level in Earth’s Atmosphere vs. Time (log-scale)

Only in the past 250 million years have oxygen levels approached those of today.
Marine cyanobacteria (aka blue-green algae) is an important group of Phytoplankton, which accounts for half of the oxygen production today. *Prochlorococcus*, a marine cyanobacterium just 0.6-um across, produced much of the world's oxygen.
The Oxygen level in the atmosphere works like a bathtub

- The level of O$_2$ in the atmosphere depends on the relative strength between the inflow (production) rate and the outflow (consumption) rate.

**Diagram:**

- **Photosynthesis**
- **Atmospheric Oxygen Level**
- cellular respiration, combustion, rusting
To maintain the Oxygen level, we need Oxygen production from Phytoplankton’s photosynthesis, but its population is decreasing as the ocean warms.
Natural & Human Factors affecting the Condition of the Earth’s atmosphere

an extension of “Milankovitch Cycles” (Ch02_Part6)
Climate is the average state of an atmosphere. It can be affected by astronomical, geological, and biological mechanisms.

Astronomical mechanisms that influence climate are changes in the average solar power received from the Sun:

- Solar luminosity
- Orbit eccentricity
- Spin obliquity
- Spin precession
Biological mechanisms are photosynthesis by bacteria and plants, methane by-products, and human activity.
The Correlation between Greenhouse Gas Concentration and Temperature

Some infrared radiation escapes to space...

...but some is trapped by greenhouse gases and is reradiated back to the ground, heating it further.

The temperature climbs until the escaping infrared radiation balances the absorbed sunlight.
Geological Mechanisms: Longterm Cycles

- volcanic and tectonic activity on million-year time scales.

The Carbonate-Silicate Geochemical Cycle (Harold Urey 1952)
The Carbonate-Silicate Cycle works also like a bathtub

- The level of CO\textsubscript{2} locked in the carbonate reservoir depends on the inflow and outflow rates
- The carbonate reservoir level anti-correlates with the atmospheric CO2 level
The Burial of Pompeii, Roman Empire, 79 AD

Pompeii, with Vesuvius towering in the background.
Chile’s Puyehue Eruption in 2011
Puyehue Volcano in March 2015
Geological mechanisms - volcanic eruptions

Mt. Pinatubo, Philippine, June 1991
Effects of volcanic eruptions on global temperature can be felt on really short timescale, a few years.

Mt. Pinatubo eruption
June, 1991 (Phillipines)
Our atmosphere is alive and it is fragile. It’s only ~100 km thin and one millionth of the Earth’s mass. Its current state is maintained by a number of delicate balances.
Drake Equation:
How long can a civilization exist before its self-destruction?

\[ N \approx L_{\text{year}} \]

- \( R_* = 10 \text{ yr}^{-1} \) (100 billion star formed over 10 billion years)
- \( f_p = 0.5 \) (one half of all stars formed will have planets)
- \( n_e = 0.2 \) (20\% chance of hosting life-supporting planets)
- \( f_l = 1 \) (100\% of the above will develop life)
- \( f_i = 1 \) (100\% of the above will develop intelligent life)
- \( f_c = 1 \) (100\% of the above will develop advanced civilizations)
Orion Spacecraft, Earth, and the Moon, Nov 28, 2022

Earth

“the pale blue dot”
Chap 9: Equations

$\mu = \sum_{i} \mu_{i} f_{i}^{\nu}$

$P = nkT = \left(\frac{\rho}{\mu m_H}\right)kT$  \hspace{0.5cm} $\mu m_H = \bar{m} = \frac{M}{N} = \frac{\rho}{n}$

$n(h) = n_0 \exp\left(-\frac{h}{h_S}\right)$ where the scale height is:

$h_S = \frac{kT}{\mu m_H g} = 7.4 \text{ km} \left(\frac{T}{280 \text{ K}}\right)\left(\frac{32}{\mu}\right)\left(\frac{9.8 \text{ m/s}^2}{g}\right)$

$\bar{v}_{\text{molecule}} = \sqrt{\frac{3kT}{\mu m_H}} = 0.4 \text{ km/s} \left(\frac{T}{300 \text{ K}}\right)^{0.5} \left(\frac{\mu}{44}\right)^{-0.5}$

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