Chapter 4: Planetary Atmospheres

Astro 9601

Planetary Atmospheres: Topics to be covered

- Density and Scale Height (4.1)
- Thermal Structure (4.2)
- Observations (4.3.3) – All
- Clouds (4.4) – All
- Meteorology (4.5) – All
- Atmospheric Escape (4.8) – All
- Planetary Atmosphere Evolution (4.9)
Part I: Scale height, heat sources, energy transport, and thermal structure
Hydrostatic Equilibrium

- In equilibrium, there is a relation between pressure, density and gravity.
- Consider a slab with thickness \( dz \) and density \( \rho \).
- This slab exerts a force on the slab below it due to its mass and gravity.
- This force, per unit area, is a pressure.
- There is a change in pressure across the slab due to its mass.

\[
F_G = -Mg \quad F_P = (P + dP)dA - (P)dA \\
F_G = -\rho \, dA \, dz \, g = dP \, dA
\]

For equilibrium:

\[
dP = -\rho g \, dz \\
dP = -\rho g
\]

H. Equilibrium and Scale Height

- We can combine the expression for hydrostatic equilibrium with the ideal gas law to get the density as a function of height:
  
  Gas law: \( P = nkT \)

  where \( n \) is the number density.

  Assume \( n \sim \rho / m \)

  \[
P(z) \sim \rho(z) kT / m
  \]

  \[
  \frac{dP}{dz} = \frac{d\rho}{dz} \frac{kT}{m} = -g \rho
  \]

- If \( g \) and \( T \) are approx. constant, the solution to this is an exponential:

  \[
  \rho \propto e^{-z/H}
  \]

  \[
  H \approx \frac{kT}{gm}
  \]

  Note that \( T \) and \( g \) are not really constant with \( z \), but it’s a useful approx.

  Rearranging the equation shows that \( P, \rho \) and \( n \) all have the same height dependence.
The mass of the Earth is about $1/300^{th}$ that of Jupiter.
The radius of the Earth is about $1/10^{th}$ that of Jupiter.
The ratio of gravitational accelerations is about $1/3$.

- Oddly, the scale heights of the atmospheres of terrestrial and giant planets are similar, and about 10-20 km.
- Exceptions are the tenuous atmospheres of Mercury, Pluto and various moons, which have larger scale heights.

Vertical structure

- Note that the scale height estimate ignored the possibility that the temperature could depend on height.
- To get a better model of atmospheric structure, we must also consider the thermal structure.
- $P=nkT$. Even though the atmospheric scale heights of most planets are similar, their densities and so pressures are NOT similar.
- Chemical processes and phases are dependent upon pressure as well as temperature. So planets have a wide variety of chemical structure and composition.
Processes affecting the thermal structure of atmospheres

- Solar radiation is absorbed at the top of the atmosphere and by certain layers.
- Internal heat sources and reradiated energy from sunlight heat the atmosphere from below.
- Clouds, dust and photochemical haze change the opacity and thermal structure.
- Changes in composition can also change the opacity and thermal structure.
  - Volcanoes
  - Chemical interactions between the air and crust
  - Biological processes
Vertical structure of Venus’s atmosphere

- In the **troposphere** the temperature decreases with increasing height because of the greenhouse effect.
- As the temperature decreases in the **troposphere**, gas can condense, forming clouds.

Haze/Cloud layer forms at level where sulfuric acid condenses (50 km and up); too hot for most other gases to condense

Pressure scale-height ~11 km compared to H~6 km on Earth
Atmospheres of the Giant Planets

- In the **thermosphere**, the temperature increases with height as more energy from the Sun and solar wind is deposited into the atmosphere.

- The **mesosphere** is the intermediate region which in some cases can be considered isothermal.

Temperature structure in Earth’s atmosphere

- Air heated by IR emission+convection near the surface
  - Temperature drops with altitude initially near surface
- UV absorption by Ozone from 30-50 km strongly heats stratosphere
- Temperature rises again in the Thermosphere due to lack of collisions/inability to radiate away solar absorbed energy
Earth-Atmosphere System Radiative Balance

Note that the solar constant (1370 W m⁻²) is the value measured directly by satellites hovering over the earth’s noon-side atmosphere. If we distribute this amount over the entire globe, we yield a global mean incoming solar radiation of about 342 W m⁻².


Part II : Observations of Planetary Atmospheres and Evolution / Thermal Escape
Earth, Venus, and Mars

- Earth’s atmosphere is primarily Nitrogen (78% by volume) and Oxygen (21%), but also contains CO$_2$, H$_2$O, and Ar.
- Mars and Venus are dominated by CO$_2$ (98%)
- Ozone has been identified on both Mars and Earth
- Spectra from the planets varies with latitude.
- All three planets have deep CO$_2$ absorption bands; much of the atmospheric opacity is from CO$_2$.
- On Earth, much of the atmospheric opacity is from water.

Venus’ atmosphere

- Almost all carbon dioxide
- Very uniform surface temperature
- Much less water than in Earth’s atmosphere
  - Water must be removed from Venus somehow
  - D/H ratio higher than Earth indicating more water in distant past?
- S & SO$_2$ (from volcanic outgassing) combines with small amounts of water to form sulfuric acid clouds at 30 km altitude
- Temperature structure determined by radiation from surface and distribution of greenhouse gases
No liquid water to remove CO$_2$ which builds up to increase temperature via greenhouse effect. Water is able to diffuse upward to great heights (no atmospheric cold trap at low altitudes) and there H$_2$O is dissociated by UV radiation from the sun. Some H molecules are then able to acquire enough velocity to escape from Venus.

**Water loss at Venus**

- Lack of Oxygen means no Ozone and no "cold" temperature layer to trap water vapour.
- Dissociated H atoms collided with excited ions of H or excited O and can reach escape speeds at ~100 km
- Current rate of water loss is same as input rate from comets
- No primordial water left as total escape of all remaining water is of order 50 Ma.
Origin and Evolution of Venus’ Atmosphere

- Atmosphere today is secondary and controlled by outgassing from volcanos
- Two main models of atmospheric evolution:
  - Runaway greenhouse model:
    - Thick atmosphere always present; high temperatures from day one prevent liquid water from occurring
    - Large “steam” atmosphere denser than today’s would result
    - Water vapor high in the atmosphere dissociated by solar UV rays and H escapes removing water
    - Process should have stopped once water became minor atmospheric constituent (~20% of atmosphere)
    - But no water (<1 %) detected today?
  - Wet Greenhouse theory:
    - Early atmosphere much less dense – Venus’ surface supported water/oceans
    - Heating caused ~50% of water to evaporate until atmosphere reached water saturation
    - Water still lost at the top of the atmosphere and (ultimately) all oceans evaporate
    - BUT, key point is oceans exist for ~millions years before totally boiled away
    - Lots of the initial CO₂ locked into carbonate rocks
    - Leads to a much less dense early atmosphere
    - Hence when 20% water vapor level reached at equilibrium with hydrodynamic escape, it is 20% of a much less dense (and hence less massive) atmosphere
    - Hence, much more water lost in this theory than in runaway greenhouse approach
What happened on Mars?

1. Weaker gravity
2. Low temperature, leading to freezing out of less volatile gasses.
3. Incorporation into rocks

Theories for thin Martian Atmosphere

1. Loss by large impact early in its history
2. Solar wind ion collisions removing atmospheric gases (some dissociation and thermal escape as well as on Venus), particularly water and carbon dioxide
3. Failed carbonate cycle locking up most of the gases (particularly CO$_2$) as rock deposits with very little CO$_2$ being outgassed due to weak/absent volcanism
Water in Mars’ atmosphere

- Surface morphological evidence for water suggests liquid surface water existed in the past
- Water either lost (via dissociation and escape as on Venus) or trapped beneath surface as permafrost (ice).
- Evidence for a warmer, wetter climate for short periods (maybe several periods)?
Martian average atmospheric pressure is just below the point where water could exist as a liquid in warmest areas. If the atmosphere were to become thick enough for sufficient greenhouse warming to facilitate liquid water periodically at the surface, the CO$_2$ would get removed as carbonates and tend to draw the atmosphere gradually back down to 6.1 millibars. This may be the reason for the particular value of the atmospheric pressure (and hence density) on Mars that we observe today. Thus the Martian atmosphere may be self-limiting with respect to water.

Planets and Satellites with Tenuous Atmospheres

- All planets and satellites (and dwarf planets) have an atmosphere, but it may be so tenuous it's difficult to detect.
- Bombardment by energetic particles from the solar wind and micro-meteorites kick up atoms and molecules from the surface.
- Sputtering forms a corona which can sometimes be seen in emission lines.
- For small bodies, the acceleration from gravity is small and the tenuous atmosphere can have large scale heights.
Mercury and the Moon

- Mercury’s atmosphere was first detected from space with Mariner 10’s airglow spectrometer. Later on, ground based observations in sodium have also detected it.
- It consists of atomic species Na, K, Mg and O.
- The density is a few thousand atoms per cm$^3$.
- H, He are captured from the solar wind.
- Apollo spacecraft detected a similar atmosphere on the Moon with mass and UV spectrometers.
- The Moon’s atmosphere is denser in the day time.

Mercury’s tenuous atmosphere

Spectroscopic measurements of sodium in Mercury’s atmosphere. High Na abundance is red, low abundance blue. The dotted line is the “seeing disk”: slit measurements have been interpolated to make an “image”.

Anne Sprague
Pluto and Triton

• Both extremely cold (40 – 60 K)
• However, surface temperatures are high enough to partly sublime some ices (N₂, CH₄ (methane), CO₂)
• The amount of vapour on these objects can be estimated from the equations for vapour pressure equilibrium.
• N₂ is believed to be the dominant molecule in Pluto’s atmosphere.
• We know Pluto has an atmosphere because of stellar occultations.

Io

• Io’s atmosphere is primarily sulfur dioxide; there is SO₂ ice on the surface.
• Other gases include SO, Na, K and O.
• Cl is inferred from its presence in the plasma torus.
Europa and other icy satellites

• Europa is covered by water ice.
• Has an oxygen rich atmosphere.
• Sputtering knocks H₂O apart. Hydrogen is more likely to escape. This leaves oxygen behind.
• A tenuous oxygen atmosphere has also been detected on Ganymede.

Enceladus

• Enceladus is a small moon of Saturn. Its diameter is approximately 500 kilometers.
• This means the amount of gravity present on the moon is not enough to hold an atmosphere for very long.
• Therefore, a strong source must be present on the moon to “feed” Enceladus's atmosphere.
Enceladus

- Volcanic or geyser eruptions are possible source of Saturn's icy E ring.

- Enceladus is the most reflective object in the Solar System, reflecting about 90 percent of the sunlight that hits it.

- If Enceladus does have ice volcanoes, the high reflectivity of the moon's surface might result from continuous deposit of icy particles originating from the volcanoes.

Atmospheres of giant planets

- Mostly composed of Molecular hydrogen
- At UV wavelengths, opacity provided by Rayleigh scattering: you can only see the upper atmosphere.
- Optical and IR light is reflected from clouds.
- Opacity at longer wavelengths provided by molecular hydrogen excitation and by scattering from cloud particles.
- Ammonia absorbs in the radio.
Atmospheres of giant planets

• Thermal infrared spectra reveal presence of H$_2$O, CH$_4$ (methane), NH$_3$ (ammonia) and H$_2$S (hydrogen sulphide) on Jupiter.
• However, mixing ratios measured by Galileo probe are difficult to account for and the abundances are less than expected.
• Noble gasses such as Ar, Kr, Xe are 2.5 times solar!
Saturn, Neptune and Uranus

- CH₄ and NH₃ are detected on Saturn, but only CH₄ on Uranus and Neptune.
- Heavy elements in general are more abundant on planets more distant than Jupiter.
- There is evidence that the amount of gas incorporated into each planet depends on the radial distance from the Sun.
- The balance of CO vs CH₄ and N₂ vs NH₃ depends on temperature and pressure.

Saturn, Neptune and Uranus

- Even in Jupiter, the upper atmosphere contains CO rather than CH₄.
- Convection causes methane to rise and be heated, where it is converted to CO.
- Convection also accounts for the production of clouds at different heights. As the pressure drops, water clouds, followed by ammonia sulfide (NH₄SH), followed by ammonia clouds.
Atmosphere Evolution: Terrestrial Planet Atmospheres
– In the beginning…

- The primary atmosphere for every terrestrial world was probably composed mostly of light gases that accreted during initial formation.
- These gases are presumed to be similar to the primordial mixture of gases found in the Sun and Jupiter: 94.2% H, 5.7% He and everything else less than 0.1%.
- The evidence for this stage is weak and so there are many variations on just what the first “early” atmosphere of the inner planets was like.

- In general none of the terrestrial worlds has any significant amount of primary atmosphere today.
- Loss processes (escape of atoms into space), removal by collisional bombardment and replacement by geological outgassing (volcanos) have modified the original, primary atmosphere.
- These processes (which vary in degree and stages on all three terrestrial planets with atmospheres) produce the secondary atmospheres we see today on Venus, the Earth and Mars.
Inert gases as tracers of early conditions

• Inert gases such as Ne are not produced by radioactive decay, and are too heavy to escape thermally.
• The amount of Ne probably hasn’t changed much.
• However, the Ne/H, Ne/O, and Ne/N abundance ratios on Earth, Mars and Venus are much smaller than Solar abundances.
• Either primitive atmospheres were removed, swept away, or primitive atmospheres were initially very small.

Did the Terrestrial Worlds have Primitive Atmospheres at any time?

One line of reasoning:
• Neon is heavy and so none can escape from Earth's atmosphere.
• It is inert so it does not bond with rocks or have any other way of escaping into the Earth from the atmosphere.
• It is not produced via radioactive decay, so whatever neon is presently in our atmosphere is a measure of the upper limit for the total amount of neon left over from a primitive atmosphere (note that some neon could have entered the atmosphere via outgassing over Earth's history).
• Given the known ratio of neon to hydrogen and helium and other gases in the sun, we can estimate the total mass of the Earth's primitive atmosphere. The result is that the primitive atmosphere could have been no more than 0.9% of Earth's present day atmosphere.
• Therefore, the Earth never had a primitive atmosphere of any significance.

BUT – what about early heavy bombardment?
This could easily have totally removed most of the primitive Ne!
Secondary Atmospheres

- Volcanoes outgas, particularly in CO₂ and H₂O.
- Over a long period of time, much of our atmosphere could have been made from volcanic outgassing.
- Venus, Mars and Earth all have evidence for volcanoes.
- Iron rusts, removing oxygen. This could have caused a hydrogen rich atmosphere in early times.
- There is little evidence for an oxygen rich atmosphere for 1/3 of the Earth’s lifetime.
- Oxygen is produced by dissociation of water by UV light, and by photosynthesis.

Biological modification of Earth’s atmosphere

- Anaerobic life forms (e.g. blue-green algae) "poisoned" atmosphere over 1.5 Gyr with O₂.
- Photosynthesis converted CO₂+water to O₂
- Aerobic lifeforms arose which used the O₂
- Plants and Algae act as CO₂ “scrubbers” and O₂ “producers”.
- Only biological systems can produce large amounts of oxygen in a terrestrial atmosphere.
- Presence of O₂ indicates non-equilibrium processes (life)
Oxygen evolution in the atmosphere

Secondary atmospheres today...

Mars is cold, rarified atmosphere
Venus is hot, dense atmosphere
Earth is moderate, with liquid water on surface and Oxygen-rich (!!)

<table>
<thead>
<tr>
<th>Chemical Compositions of Three Planetary Atmospheres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
</tr>
<tr>
<td>Water vapor (H₂O)</td>
</tr>
<tr>
<td>Other gases</td>
</tr>
</tbody>
</table>
Terrestrial Atmospheres - Water

• Water is the key to the final outcome of the evolution of the secondary atmosphere
• On Earth, because of its distance from the sun, liquid water formed at the surface and CO$_2$ produced by volcanic outgassing was dissolved in the water to form carbonate rock.
• This “locked” the CO$_2$ into rock and controlled the amount present in the atmosphere limiting its ability to heat (through the Greenhouse effect) the atmosphere to higher temperatures
• No such water cycle was present on Mars and Venus and they retained their CO$_2$ in the atmosphere

Carbon Dioxide Cycle and Temperature

• As more CO$_2$ released, temperature increases, which increases evaporation of water
• More rain removes CO$_2$ faster, reducing levels again, dropping temperature etc.
• Self-regulating cycle (feedback mechanism)
Faint Sun Paradox…

The Faint Young Sun Paradox. Solid line is solar luminosity relative to present ($S/S_0$). $T_s$ is Earth’s surface temperature and $T_e$ is Earth’s effective radiating temperature. Thick vertical bars are glaciations.


- One problem with this view – the early sun was 25-30% fainter than today and so liquid water would NOT be present under current atmospheric conditions

Possible solution:
- Ultraviolet radiation from the sun, could combine with existing methane to form solid hydrocarbons in the upper atmosphere. This in turn would shield ammonia (otherwise broken up by the UV) long enough for the ammonia to produce a greenhouse warming adequate for liquid water.
- Organic haze/smog layer like this exists on Titan
- OR lots of CO$_2$ early on, but this is not supported by rock evidence which shows an absence of siderite (FeCO$_3$) in ancient soil profiles.
Oxidizing vs Reducing Atmospheres

\[ \begin{align*}
\text{Giant planets} & \quad \text{Terrestrial planets} \\
\text{CH}_4 + \text{H}_2\text{O} & \leftrightarrow \text{CO} + 3\text{H}_2 \\
2\text{NH}_3 + 2\text{H}_2\text{O} & \leftrightarrow \text{N}_2 + 3\text{H}_2 \\
\text{H}_2\text{S} + 2\text{H}_2\text{O} & \leftrightarrow \text{SO}_2 + 3\text{H}_2 \\
\text{CO} + \text{H}_2\text{O} & \leftrightarrow \text{CO}_2 + \text{H}_2 \\
\text{CH}_4 & \leftrightarrow \text{C} + 2\text{H}_2
\end{align*} \]

Atmospheric Escape

- A particle can escape from an atmosphere if its kinetic energy exceeds the gravitational binding energy of the planet, and if it moves on an upward trajectory without intersecting another particle.
- The region of escape is called the exosphere.
- The location and size of the exosphere can be estimated from the mean free path of molecules.
Maxwellian velocity distribution function

- For a gas in thermal equilibrium, the velocity distribution of particles of mass $m$ is given by a distribution function:

$$f(v)dv = N \left( \frac{2}{\pi} \right)^{1/2} \left( \frac{m}{kT} \right)^{3/2} v^2 e^{-mv^2/(2kT)} dv$$

- Note the Maxwellian distribution $f(v) \propto e^{-KE/kT}$

- Similar to a blackbody distribution of photons

$$B_\nu \propto e^{-h\nu/kT}$$

Maxwellian velocity distribution function - continued

- For a gas in thermal equilibrium, the velocity distribution of particles of mass $m$ is given by:

$$f(v)dv = N \left( \frac{2}{\pi} \right)^{1/2} \left( \frac{m}{kT} \right)^{3/2} v^2 e^{-mv^2/(2kT)} dv$$

- This comes from:

$$f(v)dv_x dv_y dv_z = N \left( \frac{m}{2\pi kT} \right)^{3/2} e^{-m(v_x^2 + v_y^2 + v_z^2)/(2kT)} dv_x dv_y dv_z$$

- Assuming spherical symmetry gives $dv_x dv_y dv_z = v^2 dv$

- Integrating over all angles gives the $4\pi$
Equipartition

• The Maxwellian distribution has the following properties:

\[ \int_{-\infty}^{\infty} dx \ e^{-\frac{x^2}{2\sigma^2}} = \sqrt{2\pi\sigma^2} \text{ Normalization} \]

\[ <x^2> = \frac{1}{\sqrt{2\pi\sigma^2}} \int_{-\infty}^{\infty} dx \ x^2 \ e^{-\frac{x^2}{2\sigma^2}} = \sigma^2 \text{ Variance.} \]

• Different molecules have approximately the same temperature, providing there are lots of collisions. The result is equipartition of energy, where

\[ m_1v_1^2 = m_2v_2^2 \]

• Lower mass molecules have higher mean velocities
• Lighter molecules are more likely to escape.

Thermal Escape
aka Jean’s Escape

\[ f(v)dv = N \left( \frac{2}{\pi} \right)^{1/2} \frac{m}{kT}^{3/2} v^2 e^{-mv^2/(2kT)} dv \]

• Because of the exponential, most particles have velocities less than most probable velocity \( v_0 \)

\[ v_0 = \sqrt{\frac{2kT}{m}} \]

• Compare this to the escape velocity:

\[ v_e \approx \sqrt{\frac{2GM}{r}} \]

• Condition for escape:

\[ \frac{mv^2}{2} = \frac{GMr}{r} \]

• Define \( \lambda_{\text{escape}} = (v_e / v_0)^2 \)
• The rate at which particles escape can be estimated by integrating the high velocity tail of the Maxwellian dist.
Thermal escape (continued)

\[ f(v)dv = N \left( \frac{2}{\pi} \right)^{1/2} \left( \frac{m}{kT} \right)^{3/2} v^2 e^{-mv^2/(2kT)} dv \]

- To estimate an escape rate we consider the number of atoms with velocities \( v_z > v_e \)
- Their flux is \( f(v) v_z \)
- The number of atoms which escape per unit area per unit time:

\[
N_{\text{escape}} \sim \int_{v_{\text{escape}}}^{\infty} dv_z v_z^3 e^{-mv_z^2/(2kT)} \sim e^{-\lambda_{\text{escape}}}
\]

\[
\lambda_{\text{escape}} = mv_e^2 / 2kT
\]
**Timescale for reducing the atmosphere via thermal escape**

The flux of escaping particles is: \( \phi \sim N v_0 (1 + \lambda) e^{-\lambda} \)

\( N \) is the number density of particles at the exobase (height at which a particle travelling upward is unlikely to hit another particle).

Consider the total number of particles in the atmosphere:

\[ T \sim N A H \]

(\( A \) is the area of the planet, \( H \) is the scale height). The number of particles lost per second is:

\[ \frac{dT}{dt} = \varphi A = \frac{T}{H} v_0 (1 + \lambda) e^{-\lambda} \]

So the timescale to reduce the density by 1/e (assuming \( \lambda > 1 \)):

\[ t_{\text{escape}} \sim \frac{H}{v_0} e^{\lambda} \]

**Additional Processes that affect atmospheric escape**

- Non-thermal distributions
- Photodissociation and H escape
- Interactions with high speed solar wind particles

These additional processes are needed to explain things like how Venus lost its water (if it ever had any).