Week 13: Chapter 10
Planetary Atmospheres:
Earth and the Other Terrestrial Worlds

10.1 Atmospheric Basics

- Learning Goals
  - What is an atmosphere?
  - More phase issues and pressure
  - How does the greenhouse effect warm a planet?
  - How do atmospheric properties vary with altitude?

Reminders

- Gases are fluid
  - Move around easily
  - Greased pigs of the planetary world
- Gases are highly compressible
  - Will self-compress in a gravitational field
  - Pressure changes easily
  - Dissolve in liquids easily
- Sensitive to temperature changes
  - Heated gases rise
  - Cooled gases sink

Terrestrial Atmospheres

- Initially H and He → lost quickly
- Secondary Atmosphere from volcanic outgassing: primarily CO₂ and H₂O vapor.
- Tertiary Atmosphere results from planetary variables
  - Mercury → too little gravity, almost all lost
  - Venus → Water Vapor driven off by hydrodynamic escape
  - Earth → CO₂ sequestered in crust by biogenic action
  - Mars → marginal gravity retains some CO₂ atmosphere
- Starting composition identical

What is an atmosphere?

A layer of gas that surrounds a world
Lower density than interior, therefore on top
Generically, these gases are called volatiles

Terrestrial Atmospheres

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
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<tr>
<td>Surface Pressure</td>
<td>100,000 mb</td>
<td>1,000 mb</td>
<td>6 mb</td>
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<td>Atmosphere composition</td>
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<tr>
<td>CO₂</td>
<td>&gt;90%</td>
<td>0.02%</td>
<td>96%</td>
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<tr>
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<td>1%</td>
<td>38%</td>
<td>2.5%</td>
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<tr>
<td>O₂</td>
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<td>1%</td>
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<tr>
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<td>21%</td>
<td>2.5%</td>
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<tr>
<td>Other</td>
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</table>
Earth’s Atmosphere

- About 10 km thick
- Leftover gases
- Mostly molecular nitrogen (N₂) and oxygen (O₂)
  - Many trace gases

Atmospheric Pressure

- Gas pressure depends on both density and temperature.
- Adding air molecules increases the pressure in a balloon.
- Heating the air also increases the pressure.

Atmospheric Pressure

- Pressure and density decrease with altitude because the weight of overlying layers is less
- Earth’s pressure at sea level is
  - 1.03 kg per sq. meter
  - 14.7 lbs per sq. inch
  - 1 bar = 1,000 mbar

Where does it end?

- No clear upper boundary
- Most of Earth’s gas is <10 km from surface, but a small fraction extends to >100 km
- Altitudes >60 km are considered “space”

Gases in space

Small amounts of gas are present > 300 km

Atmospheric Effects

- Liquid water can exist if there is enough atmospheric pressure to keep it in liquid phase
- Absorb and scatter radiation (light)
- Create wind, weather, and climate
- Can warm planetary surfaces through greenhouse effect
How does greenhouse effect warm a planet?

Some gases are transparent to short wavelengths
But opaque to longer wavelengths

Thermal Equilibrium

- Surface temperature determined by a balance between the energy of sunlight it absorbs and the energy of outgoing thermal radiation it emits

Incoming Energy vs. Distance

- A planet’s distance from the Sun determines the total amount of incoming sunlight

Temperature and Rotation

- A planet’s rotation rate affects the temperature differences between day and night

Outgoing Energy vs. Reflectivity

- A planet’s reflectivity (albedo) is the fraction of incoming sunlight reflected back to space
- Planets with low albedos absorb more sunlight, leading to hotter temperatures

“No Greenhouse” Temperatures

- Venus would be 510°C colder without greenhouse effect
- Earth would be 31°C colder (below freezing on average)
The Adiabat: Temperature vs. Altitude

Atmospheres of Other Planets

• Earth is only planet with a stratosphere because of UV-absorbing ozone molecules (O₃).
• Ozone molecules absorb solar UV radiation

Beyond the atmosphere: Magnetosphere

• Magnetic field of Earth’s atmosphere protects us from charged particles streaming from Sun (solar wind)

Aurora

• Charged particles enter atmosphere at magnetic poles, exciting gas molecules and causing an aurora

10.2 Weather and Climate

• Learning Goals
  – What factors modulate long-term climate?
  – How does a planet gain or lose atmospheric gases?

Weather and Climate

• Weather is the ever-varying combination of wind, clouds, temperature, and pressure
  – Local complexity of weather makes it difficult to predict

• Climate is the long-term average of weather
  – Long-term stability of climate depends on global conditions and is more predictable
Long Term Climatic Cycles

Long term weather patterns → Climate

Δ in solar output
Δ in surface reflectivity
Milankovitch Cycles
Δ in greenhouse gases

Solar Output

• Sun very gradually grows brighter with time, increasing the amount of sunlight warming planets

Orbital Changes
Milankovitch Cycles

• Tilt varies from 22-25°. Greater tilt = more extreme seasons. Smaller tilt keeps polar regions colder.
• Changes in eccentricity (nearer or farther from sun)
• Wobbling of spin axis

Roughly 100,000 years per cycle

Changes in Reflectivity

• Higher reflectivity (lower absorption) cools a planet, while lower reflectivity (higher absorption) leads to warming

Changes in Greenhouse Gases

• Increase in greenhouse gases leads to warming, while a decrease leads to cooling
  – Most common and powerful greenhouse gas is H₂O vapor
  – Complex feedback loops
Sources of Gas

- Outgassing from volcanoes
- Evaporation of surface liquid; sublimation of surface ice
- Impacts of particles and photons eject small amounts

Losses of Gas

- Thermal escape of atoms
- Sweeping by solar wind
- Condensation onto surface
- Chemical reactions with surface
- Large impacts blast gas into space

Hydrodynamic (Thermal) Escape

- Exospheres of Moon & Mercury
- Sensitive measurements show Moon and Mercury have extremely thin atmospheres
- Gas comes from impacts that eject surface atoms

Atmospheres of the Moon & Mercury

- A cold 6 mbars: Mars Atmosphere
**Mars Orbit and Axial Tilt**

- Similar axial tilt gives Mars seasons
- But, the ellipticity of Mars’s orbit makes seasons more extreme in the southern hemisphere

**Polar Ice Caps of Mars**

- Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole

**Polar Ice Caps of Mars**

- Residual ice of polar cap during summer is primarily water ice
- So CO₂ is active in seasonal cycling while H₂O is dormant

**Annual Dust Storms**

- Seasonal winds drive planetary dust storms on Mars
- Initiated by ice-popping
- Millions of dust devils in Martian spring

**Changing Axial Tilt**

- Extreme range of variations: axial tilt ranges from 0° to 60° over long time periods
- Extreme variations cause dramatic climate changes
- Climate changes produce alternating layers of ice and dust in polar caps

**Climate Change on Mars**

- Mars has not had widespread surface water for ~3 billion years
- Greenhouse effect probably kept surface warmer before that
- Mars lost most of its atmosphere?
  - In storage?
Climate Change on Mars

- Primordial magnetic field may have preserved early Martian atmosphere
- Solar wind may have stripped atmosphere after field decreased as a result of interior cooling

Atmosphere of Venus

- Very thick carbon dioxide atmosphere with a surface pressure 90 times Earth’s (90 bars)
- Slow rotation produces very weak Coriolis effect and little weather

Greenhouse Effect on Venus

- Thick carbon dioxide atmosphere produces an extremely strong greenhouse effect
- Earth’s primordial CO₂ atmosphere is locked (sequestered) in rocks and oceans

Runaway Greenhouse Effect

- Runaway greenhouse effect would account for why Venus has so little water

Why so different?

- Why did Earth retain most of its outgassed water?
- Why does Earth have so little atmospheric carbon dioxide, (unlike Venus)?
- Why does Earth’s atmosphere consist mostly of nitrogen and oxygen?
- Why does Earth have a UV-absorbing stratosphere?
Earth’s Water and CO₂

- Earth’s temperature remained cool enough for liquid oceans to form
- Atmospheric pressure remained high enough for liquid oceans to form
- Oceans dissolve atmospheric CO₂, enabling atmospheric carbon to be trapped in rocks

Nitrogen and Oxygen

- If most of the CO₂ is removed…
- Then what is left over is a mostly nitrogen atmosphere
- Plant respiration releases leftover oxygen from CO₂ into atmosphere

Earth’s Thermostat

- Cooling allows CO₂ to build up in atmosphere
- Heating causes rain to reduce CO₂ in atmosphere

Long-Term Climate Change

- Changes in Earth’s axis tilt lead to ice ages
- Earth currently in an interglacial stage of an ice age
- Widespread ice tends to lower global temperatures by increasing Earth’s reflectivity
- CO₂ from outgassing will build up if oceans are frozen, ultimately raising global temperatures again

CO₂ Concentration

- Global temperatures have tracked CO₂ concentration for last 500,000 years
- Antarctic air bubbles indicate current CO₂ concentration is highest in at least 500,000 years

- Most of CO₂ increase has happened in last 50 years!
Modeling Climate Change

- Complex models suggest that recent temperature increase is indeed consistent with human production of greenhouse gases
- Scientific Conclusion?
  - An Inconvenient Fact

Climatic Stability

- Climate modulated by feedback mechanisms
  - Positive feedback drives system away from stability (e.g. recent CO2 increases)
  - Negative feedback keeps system stable (e.g. warmer temperatures increase cloud cover)
- Both Earth and Mars appear to have extremely stable climates
  - Current Ice Ages on Earth started 2.1 Mybp

Chapter 11: Jovian Planet Systems

Onward to the Saturnian system

1972-1979: Pioneer 10 & 11 flyby
  - Very low quality images
  - Good radio science
1977-89: Voyagers 1 & 2 flyby
  - Excellent images
  - Detailed mapping of magnetospheres

Orbiters
1989-2003:
  - Galileo @ Jupiter
1997-present:
  - Cassini @ Saturn

Pioneers & Voyagers

11.1 The Middle Solar System

- Intro to “jovian” planets
  - Internal Structure
  - Surface weather and atmospheres
  - Magnetospheres
  - Moons
The Outer Solar System

- Beyond the frost line
- More area to sweep out
- More mass to sweep up

Jovian planets are big!

- Jupiter 300X Earth
- Saturn 100X Earth
- Uranus 15X Earth
- Neptune 17X Earth
- Jupiter (failed star) is still 100,000X too small to sustain fusion

Ring Systems

- All 4 jovian planets have them
- Made up of numerous, tiny individual particles
- Orbit in equatorial plane (even on Uranus where they are tilted 90° along with the planet)
- Very thin and sparse
- Built from collisions

Gas Giant Ring Systems

Internal “banding” due to Gap Moons, Shepherd Moons, and orbital resonances

What and Where from?

- Created by dust from impacts on moons orbiting those planets
- Are not leftover from planet formation because particles are too small to have survived this long.
  - Must be a continuous replacement of tiny particles….ergo ongoing collisions today!
  - Most likely source is impacts of comets and collisions of captured objects (aka moons).
Ring Formation

- Jovian planets all have rings because they all possess many small moons close-in
- Impacts on these moons are random
- Saturn’s particularly incredible rings may be an “accident” of our time

Internal Comparisons

- Phase transitions for Hydrogen
- Increasing depth → increasing T and P

Another way to think about Jovian planets

- Jupiter and Saturn: Mostly H and He gas
- Uranus and Neptune: Mostly H compounds: methane (CH₄), ammonia (NH₃), water (H₂O), + rock, H and He

Mostly gas balls

- No solid surface.
- Layers under high pressure and temperatures.
- Cores (~10 Earth masses) made of hydrogen compounds, metals & rock
- Different layers on each of the 4 Jovian planets
Inside Jupiter

- High pressures inside Jupiter cause phase transitions with depth
- Hydrogen becomes metallic at great depths
- Core about same size as Earth but 10X more massive

Comparing Jovian Interiors

- Models suggest cores of jovian planets have similar composition
- Lower pressures inside Uranus and Neptune mean no metallic hydrogen

Weather on Jovian Planets

All have strong winds and intense storms

Jupiter’s Great Red Spot

- Twice as wide as Earth
- At least 3 centuries old

Jupiter Atmospheric Structure

- Hydrogen compounds in Jupiter form clouds
- Different cloud layers correspond to freezing points of different hydrogen compounds
  - Ammonium sulfide clouds (NH₄SH) reflect red/brown.
  - Ammonia, the highest, coldest layer, reflects white.

Jupiter’s Bands

White ammonia clouds form where air rises
Between white clouds we see deeper reddish clouds of NH₄SH
Coriolis effect changes N-S flow to E-W winds
Warmer red bands are brighter in IR
Other Jovian Planet Atmospheres

- Other jovian planets have cloud layers similar to Jupiter’s
- But different compounds make clouds of different colors

Methane on Uranus and Neptune

- Methane gas of Neptune and Uranus absorb red light but transmit blue light
- Blue light reflects off methane clouds, making those planes look blue

Magnetospheres

- Jupiter’s strong magnetic field gives it an enormous magnetosphere
- Gases escaping Io feed the donut-shaped Io torus

Other Magnetospheres

- Moving molten metal makes magnetospheres
- All jovian planets have substantial magnetospheres, but Jupiter’s is largest by far

Other Magnetospheres

- Uranus field oriented upside down
- Neptune field strongly offset