Terrestrial Planet Atmospheres. II.
Atmospheric Scale Height

- $P(h) = P(0) \ e^{-h/h_0}$
- $h_0 = kT/mg$
  - $k = $Boltzmann constant
  - $T =$temperature
  - $m =$mass of particle
  - $g =$gravitational acceleration
- Density falls off exponentially with height
- Mathematically, atmosphere never ends
Atmospheric Scale Height

- \( P(h) = P(0) \, e^{-h/h_0} \)
- \( h_0 = kT/mg \)
  - \( k = \) Boltzmann constant
  - \( T = \) temperature
  - \( m = \) mass of particle
  - \( g = \) gravitational acceleration
- Density falls off exponentially with height
- \( h \) is the distance the pressure drop by a factor of \( e \) (2.718)

For Earth:
- \( T = 14^\circ C \) (287K)
- \( <m> = 28.9 \) AMU = 5 x 10^{-23} gm
- \( g = 980 \) cm/s^2
- \( h = 8.1 \) km = 5 miles

Examples (constant T):
- Denver (1 mile): \( P = 0.8 \) atm
- Mauna Kea: \( P = 0.6 \) atm
- Mt Everest: \( P = 0.33 \) atm
- 37000 ft: \( P = 0.25 \) atm
- 100 km: \( P = 4 \times 10^{-6} \) atm
The Moon’s Sodium Atmosphere
Mercury’s Atmosphere

Calcium

Magnesium

Anti-Sunward →

Mercury Radii ($R_M$)
Earth’s Exosphere. I.

Hydrogen as seen from the Moon – Apollo 16
Earth’s Exosphere. II.

Helium as seen from 6 Earth radii above the pole.
The Aurora
Magnetospheres
Atmospheric Escape

Planet with a magnetosphere:
• Atom ionized by solar UV or X-rays
• Ion is trapped in magnetic field

Planet without a magnetosphere:
• Atom ionized by solar UV or X-rays
• Ion can be blown away by solar wind

In either case, a neutral molecule or atom with thermal velocity > escape velocity will escape
Mars from Maven

Atomic Carbon

Atomic Oxygen

Atomic Hydrogen
Basic Atmospheric Circulation – no rotation

(Hadley cells)

Sunlight warms equatorial air, which rises and moves toward the poles at high altitude...

...while cool air at the poles descends and moves along the surface toward the equator.

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Coriolis Forces

Divert Northward motions to east
Cause Earth’s atmosphere to break into 3 cells
• Hadley Cell: at altitude winds blow E
• Temperate Cell: at surface winds diverted to E
Terrestrial Winds

- Polar cell: Jet stream, flows west to east
- Mid-latitude cell (Ferrel cell)
- Subtropical high-pressure belt
- Tropical cell (Hadley cell)
- Equatorial trough-low-pressure belt (Doldrums, ITCZ)
- Subtropical high-pressure belt
- Cool air falls
- Warm air rises
- Northeasterly trades
- Southeasterly trades
- Westerlies
- Equator

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Jupiter

Many atmospheric cells –
and a lot of storms!
What Winds do for a Planet

• Equator heated more than poles
• Hadley cell transport heat poleward
  – Earth's poles warmer than otherwise would be
  – Venus: dense atmosphere → pole and equator ~ same T.
  – Mars: atmosphere too thin—poles much colder than equator
Condensation in the Atmosphere: Clouds

- Allow precipitation (rain, snow, hail, ...)
- Alter energy balance
  - Sunlight reflected—cools planet (increases albedo)
  - Made of greenhouse gases—warms planet
- Water vapor carried to high altitude condenses
  - Large droplets fall → precipitation
- Linked to convection
  - Strong convection → more clouds and precipitation
  - Equatorial regions: high rainfall due to more sunlight
  - Moisture removed by the time convection reaches deserts
Water and Ice Clouds
H$_2$SO$_4$ Clouds on Venus
$\text{H}_2\text{O}$ Ice Clouds on Mars
The Water Cycle

1. Water evaporates into atmosphere.

2. Convection carries vapor higher, to cooler regions.

3. Water vapor condenses into droplets or flakes, forming clouds.

4. Drops and flakes grow larger.

5. Rain and snow fall to surface.
Climate Changes

**Solar brightening:** As the Sun brightens with time, the increasing sunlight tends to warm the planets.

**Changes in reflectivity:** Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming.

**Changes in axis tilt:** Greater tilt makes more extreme seasons, while smaller tilt keeps polar regions colder.

**Changes in greenhouse gas abundance:** An increase in greenhouse gases slows escape of infrared radiation, warming the planet, while a decrease leads to cooling.
Changes in Albedo

Volcanic eruptions add particulates to stratosphere
Origins of Atmospheres

• Outgassing
  – Volcanoes expel water, CO$_2$, N$_2$, H$_2$S, SO$_2$

• Evaporation/sublimation of condensed gases
  – As temperature rises, more H$_2$O evaporates
  – Clathrates sublimate

• Impacts
  – Micrometeorite impacts, solar wind particles, photons knock surface atoms and molecules into the atmosphere
  – Very low density
How to lose an atmosphere

• Condensation
  – Rain, ice caps
• Chemical reactions (e.g. rust)
• Impacts
• Solar wind interactions
• Thermal escape
  – Higher T?
  – Smaller planet mass?
  – Lightweight gases?
Venus and the Runaway Greenhouse

Troposphere:
• 90 bar pressure; 10% of density of water
• Mostly CO$_2$—almost no O$_2$
• Extremely thick clouds; tops ~ 70 km
• Very little surface weather
  – Slow rotation rate (243 days)
• Only two circulation cells
  – Surface temperatures uniform

Upper atmosphere:
• High surface T drives strong convection
• Clouds of sulfuric acid (H$_2$SO$_4$)
• Fast winds—circle Venus in ~ 4 days
• From 2006 – 2012 winds sped up, from 300 to 400 km/s

Venus in UV light from Mariner 10
Why Venus Went Bad

Both Venus and Earth outgassed water and CO$_2$

• **Earth:**
  – Water vapor condensed into oceans
  – CO$_2$ dissolved into water, makes rocks (e.g. limestone)

• **Venus:**
  – Surface too hot for liquid or ice, or water in mantle
  – 10,000x less water than on Earth
  – No oceans $\rightarrow$ no CO$_2$ absorbed in rock

• **Where did the water go?**
  – Solar UV breaks apart H$_2$O
  – O in surface rocks, lost via solar wind (no magnetic field)
Venus: What Went Wrong?

The CO₂ cycle

- Volcanoes outgas CO₂
- Atmospheric CO₂ dissolves in rainwater
- Rainfall erodes rock on land; rivers carry broken-down minerals to the sea
- Carbonate rocks subduct and melt, releasing CO₂
- Broken-down minerals react with dissolved CO₂ to form carbonate rocks

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Venus: Location, Location, Location

If Earth moved to Venus’s orbit

More intense sunlight…

…would raise surface temperature by about 30°C.

Higher temperature increases evaporation, and warmer air holds more water vapor.

Additional water vapor further strengthens the greenhouse effect.

Runaway greenhouse effect

Result: Oceans evaporate and carbonate rocks decompose, releasing CO₂…

…making Earth hotter than Venus.

Just a little too close to the Sun
Martian Polar Caps
Martian Polar Caps

- Permanent polar caps: H$_2$O ice
  - Some CO$_2$ ice at south pole
- Seasonal caps: CO$_2$ ice
  - About 30% of the atmosphere freezes out
  - CO$_2$ sublimation drives strong winds and planet-wide dust storms
Mars • Global Dust Storm
Hubble Space Telescope • WFPC2

NASA, J. Bell (Cornell University), M. Wolff (SSI), and the Hubble Heritage Team (STScI/AURA) • STScI-PRC01-31

June 26, 2001

September 4, 2001
Martian Weather

• Dust devils on summer afternoons
• Planet-wide dust storms spring and fall
• Thin cirrus clouds
• No precipitation
Dust Devils on Mars

- Caused by convective heating of lower atmosphere

- Elapsed time: 9m 35s
Martian Climate

• Calculated axial tilt varies from 0° – 60° over $10^5$ to $10^6$ years
  – Tides from Jupiter
  – No large moon to stabilize axis

• Big impact on seasons
  – Small tilt: poles stay frozen, atmosphere thins
  – Large tilt: lots of polar ice sublimes
    • More H$_2$O, CO$_2$ in atmosphere
    • Greenhouse effect strengthens
Mars – Long, Long Ago

• Atmosphere denser, warmer in past (evidence next week)
• Faint Young Sun means greenhouse effect needed
  – Just CO₂ is not enough
  – Clouds? Methane?
  – Lots of volcanoes —> lots of outgassing
• Most CO₂ lost
  – Coincides with end of Mars magnetic field?
  – Reduces greenhouse effect
• Water lost
  – UV splits water into H and O
  – H escapes
  – O eventually escapes or incorporated into rock (\(\text{Fe}_2\text{O}_3\))
Where the CO₂ Went

**Early Mars**
- Warmer core generated stronger magnetic field.
- Warmer interior caused extensive volcanism and outgassing.
- Stronger magnetosphere protected atmosphere from solar wind.
- Thicker atmosphere created warmer and possibly wetter climate.

**Mars Today**
- Lack of core convection means no global magnetic field.
- Cooler interior no longer drives extensive volcanism or outgassing.
- Some remaining gases condense or react with surface.
- Thinner atmosphere reduces greenhouse warming.
- Weaker magnetosphere allows solar wind to strip away much of the atmosphere.
Why is Earth so Different?

- Retained outgassed H$_2$O because temperature was right for condensation
- CO$_2$ dissolved in oceans
- N$_2$ exists because it too is outgassed
- O$_2$ is non-equilibrium
  - requires life (photosynthesis)
  - Would disappear quickly if not replenished
- O$_2$ + UV $\rightarrow$ ozone, and the stratosphere
- Temperature regulated through the CO$_2$ cycle
Earth: What Went Right?

The temperature cycle
Earth on the Edge: Snowball Earth

This is thought to have happened twice
The Future

Sun brightens

• Earth warms
• Evaporating oceans $\rightarrow$ runaway greenhouse

When?
• Oceans evaporate $\sim$ 1 Gyr