Chapter 10
Planetary Atmospheres:
Earth and the Other Terrestrial Worlds
10.1 Atmospheric Basics

- Our goals for learning
- What is an atmosphere?
- How does the greenhouse effect warm a planet?
- Why do atmospheric properties vary with altitude?
What is an atmosphere?

An atmosphere is a layer of gas that surrounds a world.
Earth’s Atmosphere

- About 10 km thick
- Consists mostly of molecular nitrogen ($N_2$) and oxygen ($O_2$)
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
Where does an atmosphere end?

- There is 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”
Where does an atmosphere end?

- Small amounts of gas are present even at $>300$ km
Effects of Atmospheres

• Create pressure that determines whether liquid water can exist on surface
• Absorb and scatter light
• Create wind, weather, and climate
• Interact with solar wind to create a magnetosphere
• Can make planetary surfaces warmer through greenhouse effect
How does the greenhouse effect warm a planet?
Greenhouse Effect

- Visible light passes through atmosphere and warms planet’s surface
- Atmosphere absorbs infrared light from surface, trapping heat
Planetary Temperature

- A planet’s surface temperature is determined by balance between the energy of sunlight it absorbs and the energy of outgoing thermal radiation.
Temperature and 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.
Temperature and Reflectivity

- A planet’s reflectivity (or albedo) is the fraction of incoming sunlight it reflects.
- Planets with low albedo absorb more sunlight, leading to hotter temperatures.
“No Greenhouse” Temperatures

<table>
<thead>
<tr>
<th>World</th>
<th>Average Distance from Sun (AU)</th>
<th>Reflectivity</th>
<th>“No Greenhouse” Average Surface Temperature*</th>
<th>Actual Average Surface Temperature</th>
<th>Greenhouse Warming (actual temperature minus “no greenhouse” temperature)</th>
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<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>12%</td>
<td>163°C</td>
<td>425°C (day), -175°C (night)</td>
<td>—</td>
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<tr>
<td>Venus</td>
<td>0.723</td>
<td>75%</td>
<td>-40°C</td>
<td>470°C</td>
<td>510°C</td>
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<tr>
<td>Earth</td>
<td>1.00</td>
<td>29%</td>
<td>-16°C</td>
<td>15°C</td>
<td>31°C</td>
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<tr>
<td>Moon</td>
<td>1.00</td>
<td>12%</td>
<td>-2°C</td>
<td>125°C (day), -175°C (night)</td>
<td>—</td>
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<tr>
<td>Mars</td>
<td>1.524</td>
<td>16%</td>
<td>-56°C</td>
<td>-50°C</td>
<td>6°C</td>
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</tbody>
</table>

- Venus would be 510°C colder without greenhouse effect
- Earth would be 31°C colder (below freezing on average)
What do atmospheric properties vary with altitude?
Light’s Effects on Atmosphere

- **Ionization:** Removal of an electron
- **Dissociation:** Destruction of a molecule
- **Scattering:** Change in photon’s direction
- **Absorption:** Photon’s energy is absorbed
Light’s Effects on Atmosphere

- X rays and UV light can ionize and dissociate molecules
- Molecules tend to scatter blue light more than red
- Molecules can absorb infrared light
Earth’s Atmospheric Structure

- **Troposphere**: lowest layer of Earth’s atmosphere
- Temperature drops with altitude
- Warmed by infrared light from surface and convection
Earth’s Atmospheric Structure

- **Stratosphere**: Layer above the troposphere

- Temperature rises with altitude in lower part, drops with altitude in upper part

- Warmed by absorption of ultraviolet sunlight
Earth’s Atmospheric Structure

- **Thermosphere:** Layer at about 100 km altitude
- Temperature rises with altitude
- X rays and ultraviolet light from the Sun heat and ionize gases
Earth’s Atmospheric Structure

- **Exosphere**: Highest layer in which atmosphere gradually fades into space
- Temperature rises with altitude; atoms can escape into space
- Warmed by X rays and UV light
Why the sky is blue

- Atmosphere scatters blue light from Sun, making it appear to come from different directions

- Sunsets are red because red light scatters less
Atmospheres of Other Planets

- Earth is only planet with a stratosphere because of UV-absorbing ozone molecules ($O_3$).

- Those same molecules protect us from Sun’s UV light.

No-greenhouse temperatures
• Magnetic field of Earth’s atmosphere protects us from charged particles streaming from Sun (solar wind)
Aurora

- Charged particles can enter atmosphere at magnetic poles, causing an aurora
What have we learned?

• What is an atmosphere?
  – A layer of gas that surrounds a world

• How does the greenhouse effect warm a planet?
  – Atmospheric molecules allow visible sunlight to warm a planet’s surface but absorb infrared photons, trapping the heat.

• Why do atmospheric properties vary with altitude?
  – They depend on how atmospheric gases interact with sunlight at different altitudes.
10.2 Weather and Climate

- Our goals for learning
- What creates wind and weather?
- What factors can cause long-term climate change?
- How does a planet gain or lose atmospheric gases?
What creates wind and weather?
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
Global Wind Patterns

- Global winds blow in distinctive patterns
  - Equatorial: E to W
  - Mid-latitudes: W to E
  - High-latitudes: E to W
Circulation Cells: No Rotation

- Heated air rises at equator
- Cooler air descends at poles
- Without rotation, these motions would produce two large circulation cells
Coriolis Effect

- Conservation of angular momentum causes a ball’s apparent path on a spinning platform to change direction
Coriolis Effect on Earth

- Air moving from pole to equator is going farther from axis and begins to lag Earth’s rotation.

- Air moving from equator to pole goes closer to axis and moves ahead of Earth’s rotation.
Coriolis Effect on Earth

- Conservation of angular momentum causes large storms to swirl

- Direction of circulation depends on hemisphere
  - N: counterclockwise
  - S: clockwise
Circulation Cells with Rotation

- Coriolis effect deflects north-south winds into east-west winds

- Deflection breaks each of the two large “no-rotation” cells breaks into three smaller cells
Prevailing Winds

• Prevailing surface winds at mid-latitudes blow from W to E because Coriolis effect deflects S to N surface flow of mid-latitude circulation cell
Clouds and Precipitation

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.
What factors can cause long-term climate change?
Solar Brightening

- Sun very gradually grows brighter with time, increasing the amount of sunlight warming planets.
Changes in Axis Tilt

- Greater tilt makes more extreme seasons, while smaller tilt keeps polar regions colder
Changes in Axis Tilt

- Small gravitational tugs from other bodies in solar system cause Earth’s axis tilt to vary between 22° and 25°
Changes in Reflectivity

• Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming
Changes in Greenhouse Gases

- Increase in greenhouse gases leads to warming, while a decrease leads to cooling
How does a planet gain or lose atmospheric gases?
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
Thermal Escape

\[ v_{\text{thermal}} = \sqrt{\frac{2kT}{m}} \]

The most common speed is the peak thermal velocity.

Although most atoms do not have escape velocity...

...a small fraction of the atoms can and do escape permanently into space.
What have we learned?

• What creates wind and weather?
  – Atmospheric heating and Coriolis effect

• What factors can cause long-term climate change?
  – Brightening of Sun
  – Changes in axis tilt
  – Changes in reflectivity
  – Changes in greenhouse gases
What have we learned?

• How does a planet gain or lose atmospheric gases?
  – Gains: Outgassing, evaporation/sublimation, and impacts by particles and photons
  – Losses: Condensation, chemical reactions, blasting by large impacts, sweeping by solar winds, and thermal escape
10.3 Atmospheres of Moon and Mercury

- Our goals for learning
- Do the Moon and Mercury have any atmosphere at all?
Do the Moon and Mercury have any atmosphere at all?
Exospheres of Moon and Mercury

- Sensitive measurements show Moon and Mercury have extremely thin atmospheres
- Gas comes from impacts that eject surface atoms
What have we learned?

• Do the Moon and Mercury have any atmosphere at all?
  – Moon and Mercury have very thin atmospheres made up of particles ejected from surface
10.4 The Atmospheric History of Mars

- Our goals for learning
- What is Mars like today?
- Why did Mars change?
What is Mars like today?
Seasons on Mars

- 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
Dust Storms on Mars

- Seasonal winds can drive dust storms on Mars
- Dust in the atmosphere absorbs blue light, sometimes making the sky look brownish-pink
Changing Axis Tilt

- Calculations suggest Mars's axis tilt ranges from 0° to 60° over long time periods.
- Such extreme variations cause dramatic climate changes.
- These climate changes can produce alternating layers of ice and dust.
Why did Mars change?
Climate Change on Mars

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

- Magnetic field may have preserved early Martian atmosphere
- Solar wind may have stripped atmosphere after field decreased because of interior cooling
What have we learned?

• What is Mars like today?
  – Mars is cold, dry, and frozen
  – Strong seasonal changes cause CO$_2$ to move from pole to pole, leading to dust storms

• Why did Mars change?
  – Its atmosphere must have once been much thicker for its greenhouse effect to allow liquid water on the surface
  – Somehow Mars lost most of its atmosphere, perhaps because of declining magnetic field
10.5 The Atmospheric History of Venus

- Our goals for learning
- What is Venus like today?
- How did Venus get so hot?
What is Venus like today?
Atmosphere of Venus

- Venus has a very thick carbon dioxide atmosphere with a surface pressure 90 times Earth’s.

- 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 escapes this fate because most of its carbon and water is in rocks and oceans
How did Venus get so hot?
Atmosphere of Venus

- Reflective clouds contain droplets of sulphuric acid
- Upper atmosphere has fast winds that remain unexplained
Runaway Greenhouse Effect

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

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.

Runaway greenhouse effect:
- Additional water vapor further strengthens the greenhouse effect.

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

...making Earth hotter than Venus.
What have we learned?

• What is Venus like today?
  – Venus has an extremely thick CO$_2$ atmosphere
  – Slow rotation means little weather

• How did Venus get so hot?
  – Runaway greenhouse effect made Venus too hot for liquid oceans
  – All carbon dioxide remains in atmosphere, leading to a huge greenhouse effect
10.6 Earth’s Unique Atmosphere

• Our goals for learning
• How did Earth’s atmosphere end up so different?
• Why does Earth’s climate stay relatively stable?
• How might human activity change our planet?
How did Earth’s atmosphere end up so different?
Four Important Questions

• 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 CO$_2$

- Earth’s temperature remained cool enough for liquid oceans to form

- Oceans dissolve atmospheric CO$_2$, enabling carbon to be trapped in rocks
Nitrogen and Oxygen

- Most of Earth’s carbon and oxygen is in rocks, leaving a mostly nitrogen atmosphere
- Plants release some oxygen from CO$_2$ into atmosphere
Ozone and the Stratosphere

- Ultraviolet light can break up $O_2$ molecules, allowing ozone ($O_3$) to form
- Without plants to release $O_2$, there would be no ozone in stratosphere to absorb UV light
Why does Earth’s climate stay relatively stable?
Carbon Dioxide Cycle

1. Atmospheric CO$_2$ dissolves in rainwater

2. Rain erodes minerals which flow into ocean

3. Minerals combine with carbon to make rocks on ocean floor
Carbon Dioxide Cycle

4. Subduction carries carbonate rocks down into mantle

5. Rock melt in mantle and outgas CO$_2$ back into atmosphere through volcanoes
Earth’s Thermostat

- Cooling allows $\text{CO}_2$ to build up in atmosphere
- Heating causes rain to reduce $\text{CO}_2$ in atmosphere
Long-Term Climate Change

- Changes in Earth’s axis tilt might lead to *ice ages*
- Widespread ice tends to lower global temperatures by increasing Earth’s reflectivity
- CO$_2$ from outgassing will build up if oceans are frozen, ultimately raising global temperatures again
How might human activity change our planet?
Dangers of Human Activity

• Human-made CFCs in atmosphere destroy ozone, reducing protection from UV radiation

• Human activity is driving many other species to extinction

• Human use of fossil fuels produces greenhouse gases that can cause global warming
Global Warming

• Earth’s average temperature has increased by 0.5°C in past 50 years

• Concentration of CO₂ is rising rapidly

• An unchecked rise in greenhouse gases will eventually lead to global warming
CO$_2$ Concentration

- Global temperatures have tracked CO$_2$ concentration for last 500,000 years

- Antarctic air bubbles indicate current CO$_2$ concentration is highest in at least 500,000 years
CO$_2$ Concentration

- Most of CO$_2$ increase has happened in last 50 years!
Modeling of Climate Change

- Complex models of global warming suggest that recent temperature increase is indeed consistent with human production of greenhouse gases.
Consequences of Global Warming

• Storms more numerous and intense

• Rising ocean levels; melting glaciers

• Uncertain effects on food production, availability of fresh water

• Potential for social unrest
What have we learned?

• How did Earth’s atmosphere end up so different?
  – Temperatures just right for oceans of water
  – Oceans keep most CO$_2$ out of atmosphere
  – Nitrogen remains in atmosphere
  – Life releases some oxygen into atmosphere

• Why does Earth’s climate stay relatively stable?
  – Carbon dioxide cycle acts as a thermostat
What have we learned?

• How might human activity change our planet?
  – Destruction of ozone
  – High rate of extinction
  – Global warming from production of greenhouse gases