10. Planetary Atmospheres

Earth and the Other Terrestrial Worlds

"For the first time in my life, I saw the horizon as a curved line. It was accentuated by a thin seam of dark blue light – our atmosphere. Obviously this was not the ocean of air I had been told it was so many times in my life. I was terrified by its fragile appearance."

Ulf Merbold (1941 –)
German Astronaut

10.1 Atmospheric Basics

Our goals for learning:

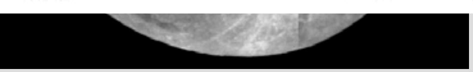
- Describe the general atmospheric properties of each of the five terrestrial worlds.
- What is atmospheric pressure?
- Summarize the effects of atmospheres.

Comparing Terrestrial Atmospheres

Table 11.1 Atmospheres of the Terrestrial Worlds

World	*Composition*	*Surface Pressure**	*Average Surface Temperature*	*Winds, Weather Patterns*	*Clouds, Hazes*
Mercury	helium, sodium, oxygen	10^{-14} bar	day: 425°C (797°F); night: −175°C (−283°F)	none: too little atmosphere	none
Venus	96% carbon dioxide (CO_2) 3.5% nitrogen (N_2)	90 bars	470°C (878°F)	slow winds, no violent storms, acid rain	sulfuric acid clouds
Earth	77% nitrogen (N_2) 21% oxygen (O_2) 1% argon H_2O (variable)	1 bar	15°C (59°F)	winds, hurricanes	H_2O clouds, pollution
Moon	helium, sodium, argon	10^{-14} bar	day: 125°C (257°F); night: −175°C (−283°F)	none: too little atmosphere	none
Mars	95% carbon dioxide (CO_2) 2.7% nitrogen (N_2) 1.6% argon	0.007 bar	−50°C (−58°F)	winds, dust storms	H_2O and CO_2 clouds, dust

*1 bar ≈ the pressure at sea level on Earth.



*1 bar ≈ the pressure at sea level on Earth.
Copyright © 2004 Pearson Education, publishing as Addison Wesley.

What is an Atmosphere?

- A layer of gas which surrounds a world is called an **atmosphere**.
  - they are usually very thin compared to planet radius
- **Pressure** is created by atomic & molecular collisions in an atmosphere.
  - heating a gas in a confined space increases pressure
  - number of collisions increase
  - unit of measure: 1 bar = 14.7 lbs/inch^2 = Earth's atmospheric pressure at sea level
- Pressure balances gravity in an atmosphere.

Effects of an Atmosphere on a Planet

- greenhouse effect
  - makes the planetary surface warmer than it would be otherwise
- scattering and absorption of light
  - absorb high-energy radiation from the Sun
  - scattering of optical light brightens the daytime sky
- creates pressure
  - can allow water to exist as a liquid (at the right temperature)
- creates wind and weather
  - promotes erosion of the planetary surface
- creates auroras
  - interaction with the Solar wind when magnetic fields are present

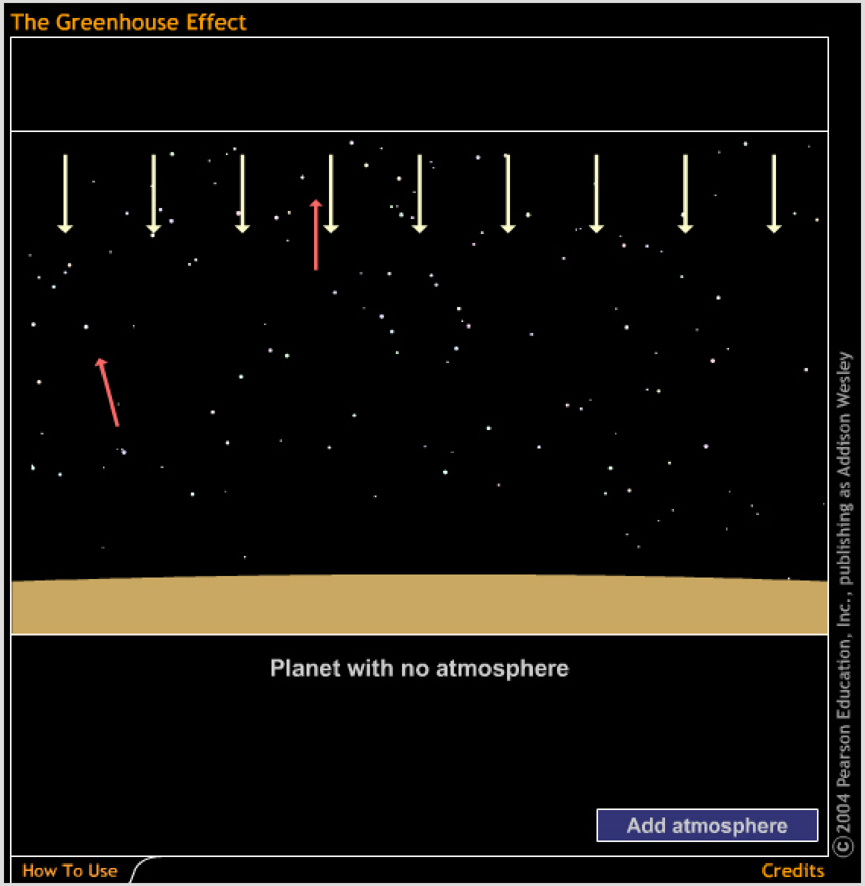
10.2 The Greenhouse Effect and Planetary Temperature

Our goals for learning:

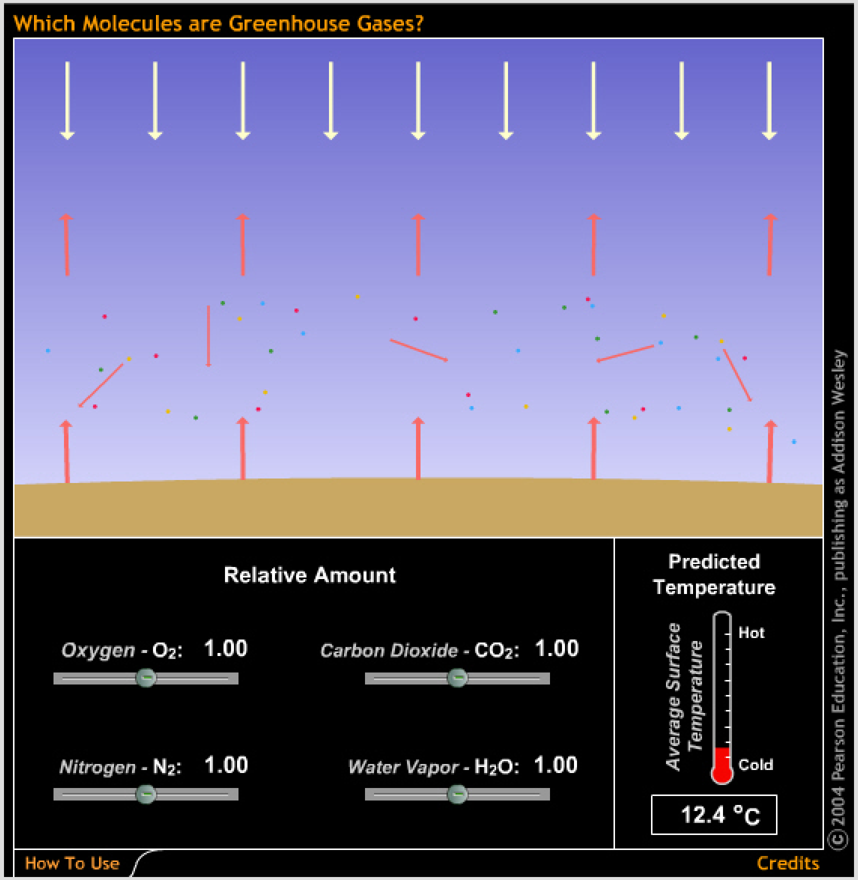
- What is the greenhouse effect?
- How would planets be different without the greenhouse effect?
- Compare the greenhouse effect on Venus, Earth, and Mars.

The Greenhouse Effect

- Visible Sunlight passes through a planet's atmosphere.
- Some of this light is absorbed by the planet's surface.
- Planet re-emits this energy (heat) as infrared (IR) light.
  - planet's temperature lower than Sun
- IR light is "trapped" by the atmosphere.
  - its return to space is slowed
- This causes the overall surface temperature to be higher than if there were no atmosphere at all.



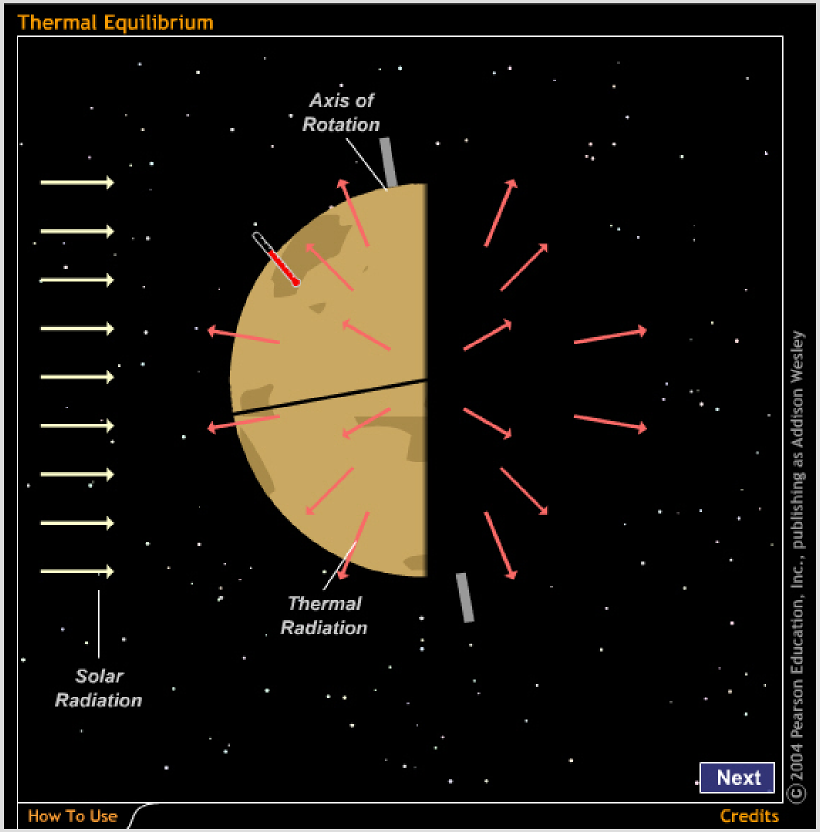
Greenhouse Gases



- Key to Greenhouse Effect…gases which absorb IR light effectively:
  - water [H_2O]
  - carbon dioxide [CO_2]
  - methane [CH_4]
- These are molecules which rotate and vibrate easily.
  - they re-emit IR light in a random direction
- The more greenhouse gases which are present, the greater the amount of surface warming.

Planetary Energy Balance

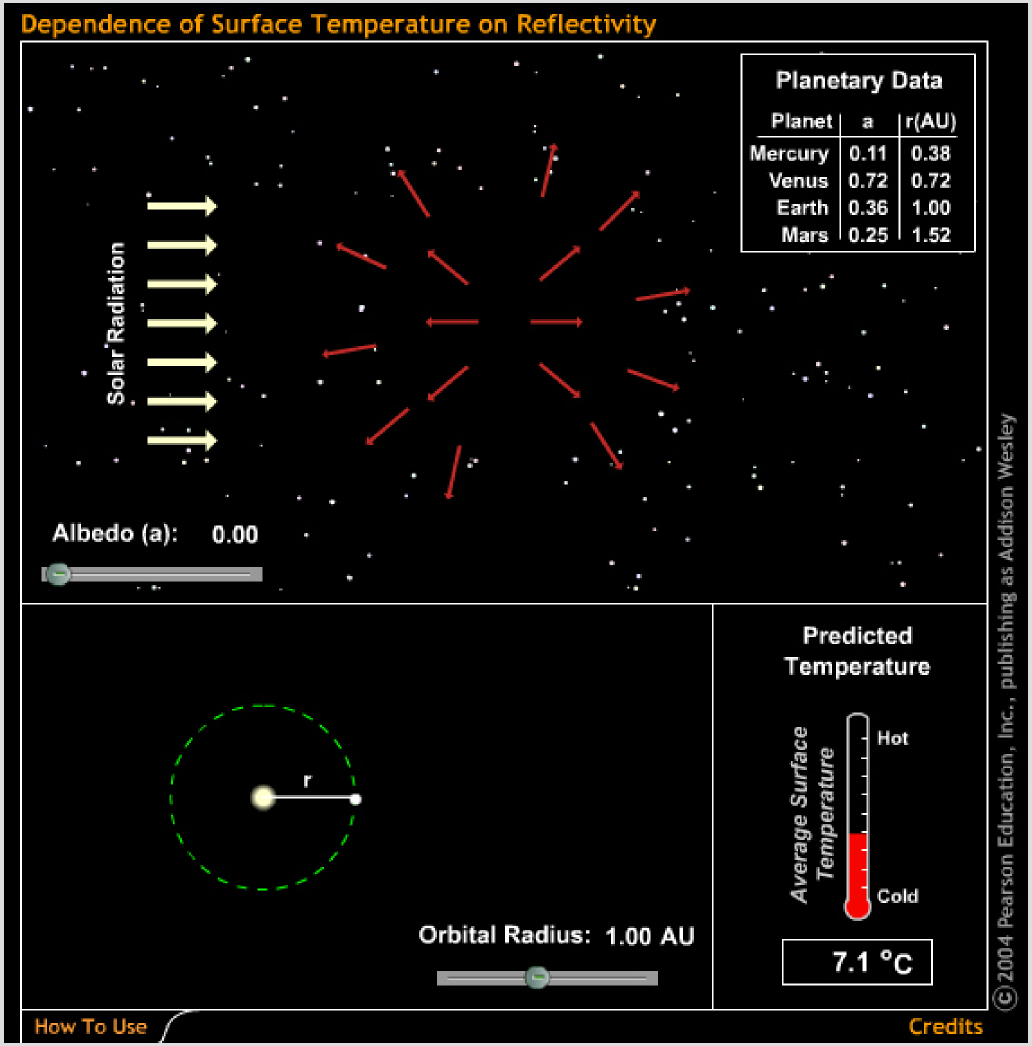
- Solar energy received by a planet must balance the energy it returns to space
  - planet can either reflect or emit the energy as radiation
  - this is necessary for the planet to have a stable temperature



What Determines a Planet's Surface Temperature?

- Greenhouse Effect cannot change incoming Sunlight, so it cannot change the total energy returned to space.
  - it increases the energy (heat) in lower atmosphere
  - it works like a blanket
- In the absence of the Greenhouse Effect, what would determine a planet's surface temperature?
  - the planet's distance from the Sun
  - the planet's overall reflectivity
  - the higher the albedo, the less light absorbed, planet cooler
  - Earth's average temperature would be –17º C (–1º F) without the Greenhouse Effect

What Determines a Planet's Surface Temperature?



Greenhouse Effect on the Planets

Table 11.2. The Greenhouse Effect on the Terrestrial Worlds

World	Average Distance from Sun (AU)	Reflectivity	"No Greenhouse" Average Surface Temperature*	Actual Average Surface Temperature	Greenhouse Warming (actual temperature minus "no greenhouse" temperature)
Mercury	0.387	11%	164°C	425°C (day), −175°C (night)	—
Venus	0.723	72%	−43°C	470°C	513°C
Earth	1.00	36%	−17°C	15°C	32°C
Moon	1.00	7%	0°C	125°C (day), −175°C (night)	—
Mars	1.52	25%	−55°C	−50°C	5°C

*The "no greenhouse" temperature is calculated by assuming no change to the atmosphere other than lack of greenhouse warming. Thus, for example, Venus ends up with a lower "no greenhouse" temperature than Earth even though it is closer to the Sun, because the high reflectivity of its bright clouds means that it absorbs less sunlight than Earth.

- Greenhouse Effect warms Venus, Earth, & Mars
  - on Venus: it is very strong
  - on Earth: it is moderate
  - on Mars: it is weak
  - avg. temp. on Venus & Earth would be freezing without it

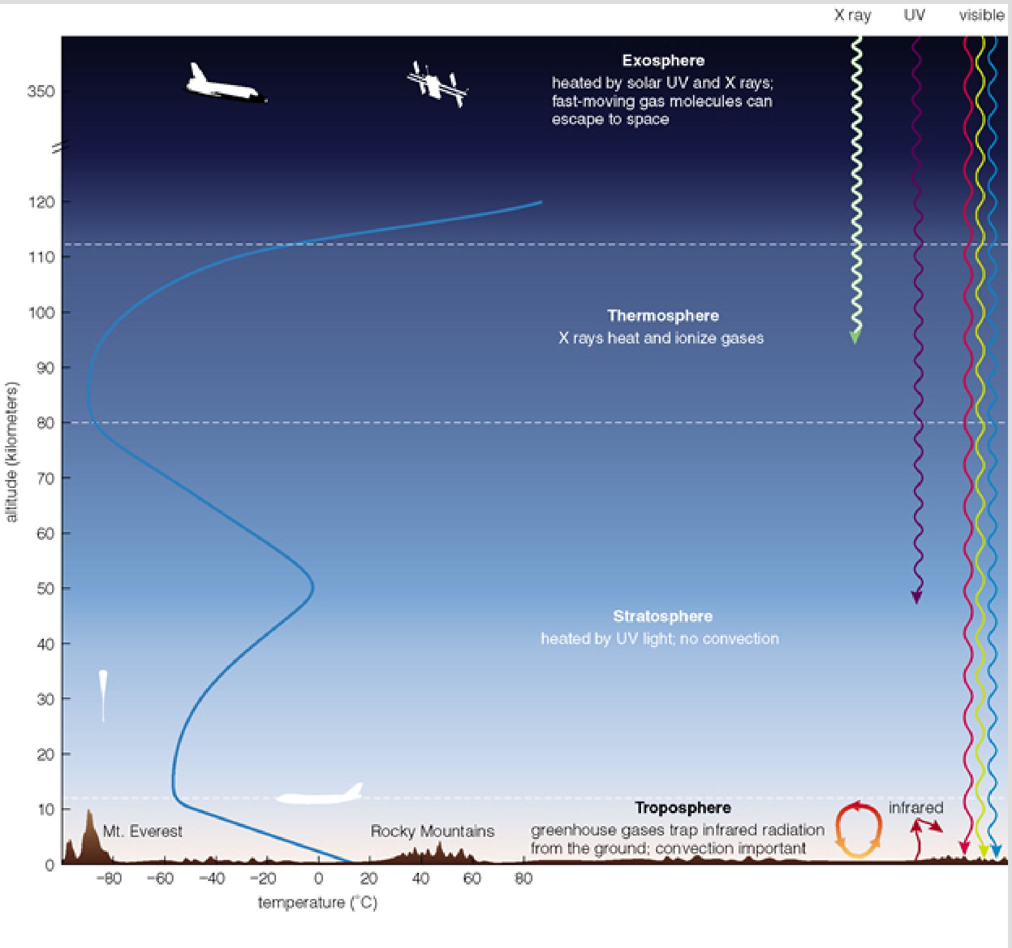
10.3 Atmospheric Structure

Our goals for learning:

- Describe the basic structure of Earth's atmosphere.
- How do interactions with light explain atmospheric structure?
- Contrast the atmospheric structures of Venus, Earth, and Mars.
- What is a magnetosphere?

Structure of Earth's Atmosphere

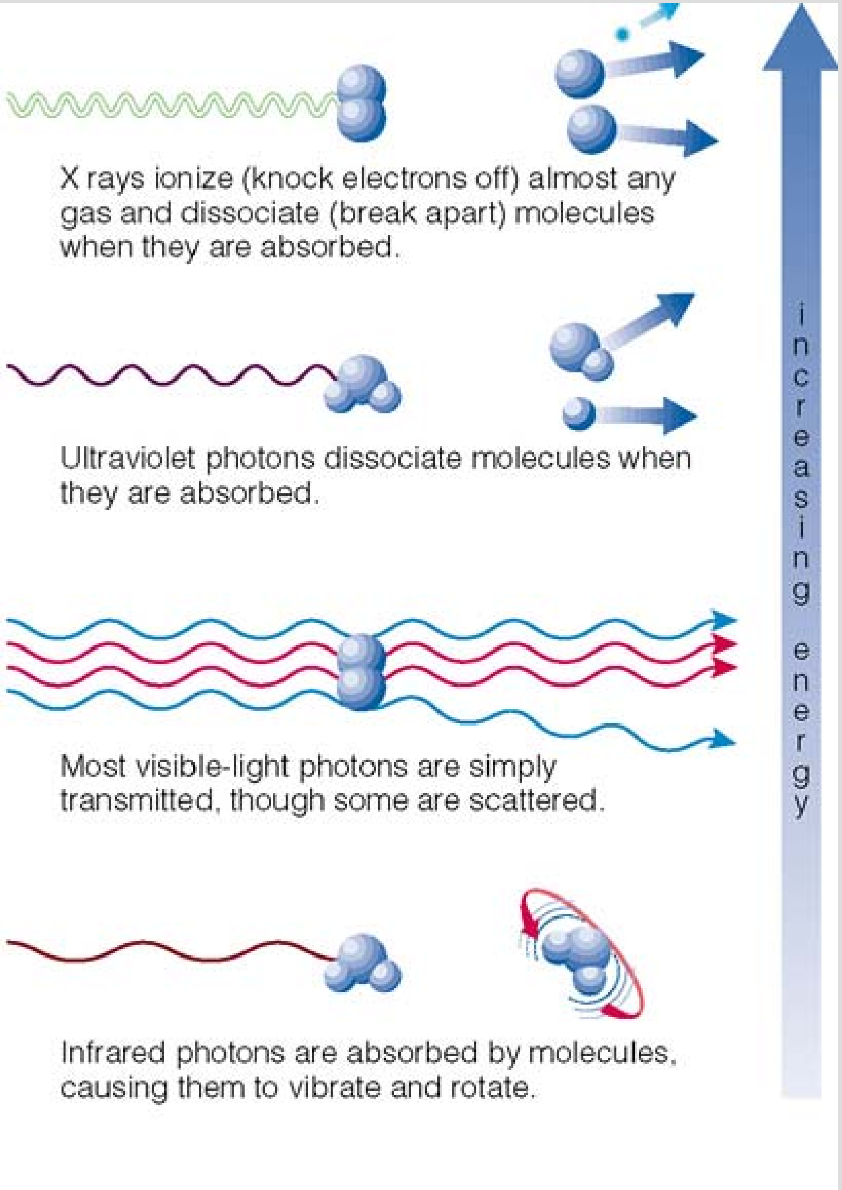
- pressure & density of atmosphere decrease with altitude
- temperature varies "back and forth" with altitude
  - these temperature variations define the major atmospheric layers



- **exosphere**
  - low density; fades into space
- **thermosphere**
  - temp begins to rise at the top
- **stratosphere**
  - rise and fall of temp
- **troposphere**
  - layer closest to surface
  - temp drops with altitude

Atmospheres Interact with Light

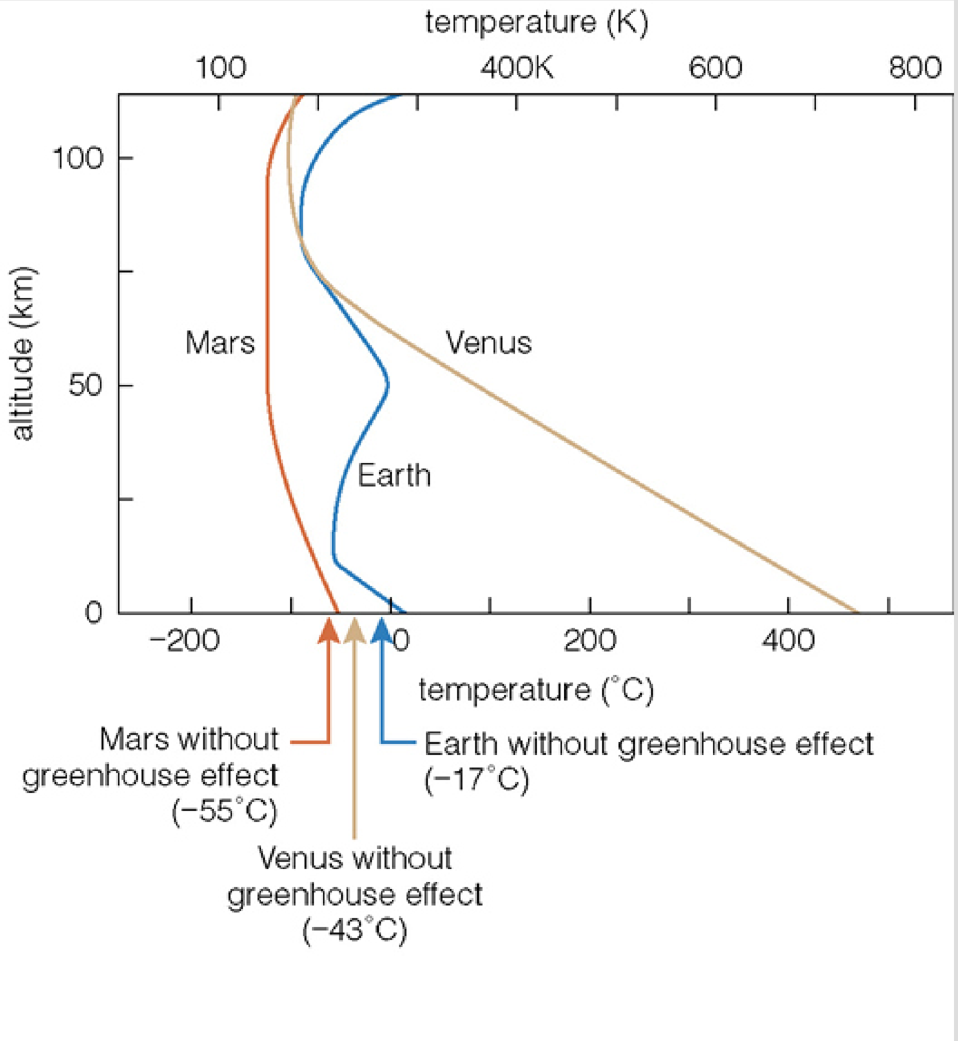
- X rays
  - ionize atoms & molecules
  - dissociate molecules
  - absorbed by almost all gases
- Ultraviolet (UV)
  - dissociate some molecules
  - absorbed well by O_3 & H_2O
- Visible (V)
  - passes right through gases
  - some photons are scattered
- Infrared (IR)
  - absorbed by greenhouse gases



Reasons for Atmospheric Structure

- Light interactions are responsible for the structure we see.
- Troposphere
  - absorbs IR photons from the surface
  - temperature drops with altitude
  - hot air rises and high gas density causes storms (convection)
- Stratosphere
  - lies above the greenhouse gases (no IR absorption)
  - absorbs heat via Solar UV photons which dissociate ozone (O_3)
  - UV penetrates only top layer; hotter air is above colder air
  - no convection or weather; the atmosphere is stratified
- Thermosphere
  - absorbs heat via Solar X-rays which ionizes all gases
  - contains ionosphere, which reflects back human radio signals
- Exosphere
  - hottest layer; gas extremely rarified; provides noticeable drag on satellites

Structure of Terrestrial Planet Atmospheres

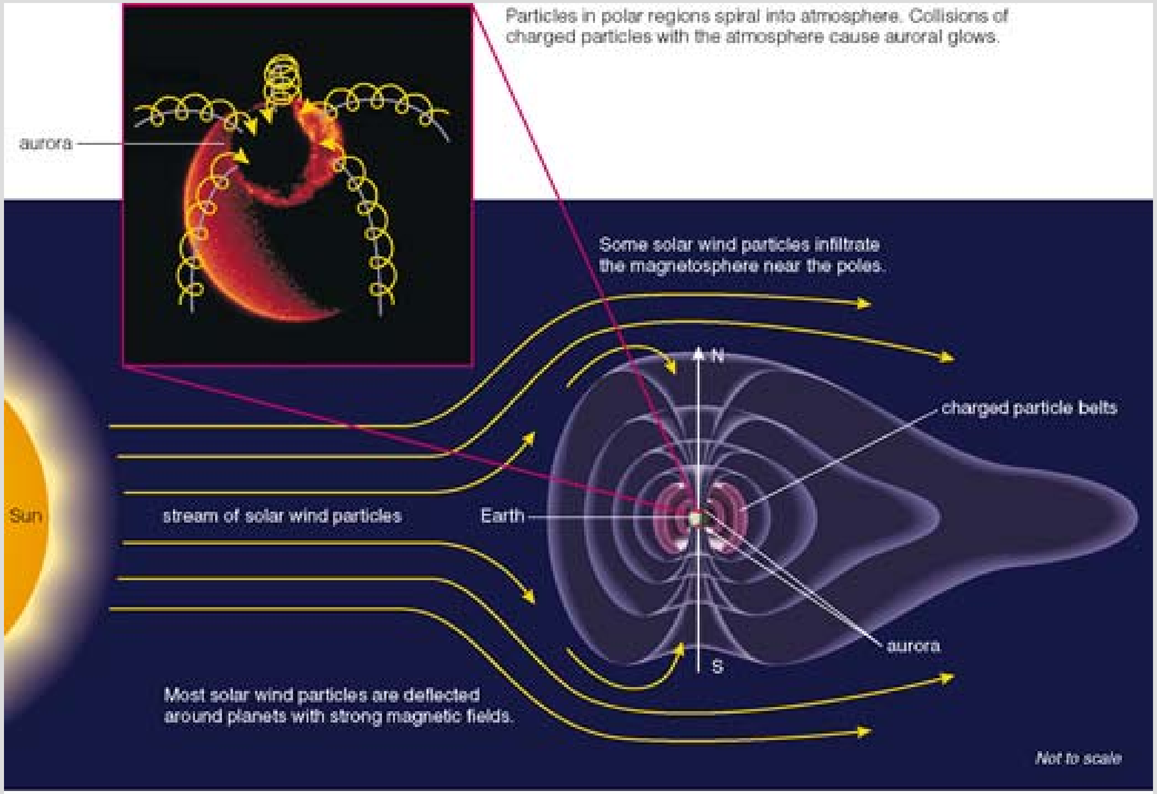


- Mars, Venus, Earth all
  - have warm tropospheres (and greenhouse gases)
  - have warm thermospheres which absorb Solar X rays
- Only Earth has
  - a warm stratosphere
  - an UV-absorbing gas (O_3)
- All three planets have warmer surface temps due to greenhouse effect

Magnetospheres

- The Sun ejects a stream of charged particles, called the **solar wind**.
  - it is mostly electrons, protons, and Helium nuclei
- Earth's magnetic field attracts and diverts these charged particles to its magnetic poles.
  - the particles spiral along magnetic field lines and emit light
  - this causes the **aurora** (aka northern & southern lights)
  - this protective "bubble" is called the **magnetosphere**
- Other terrestrial worlds have <u>no</u> strong magnetic fields
  - solar wind particles impact the exospheres of Venus & Mars
  - solar wind particles impact the surfaces of Mercury & Moon

Earth’s Magnetosphere



10.4 Weather and Climate

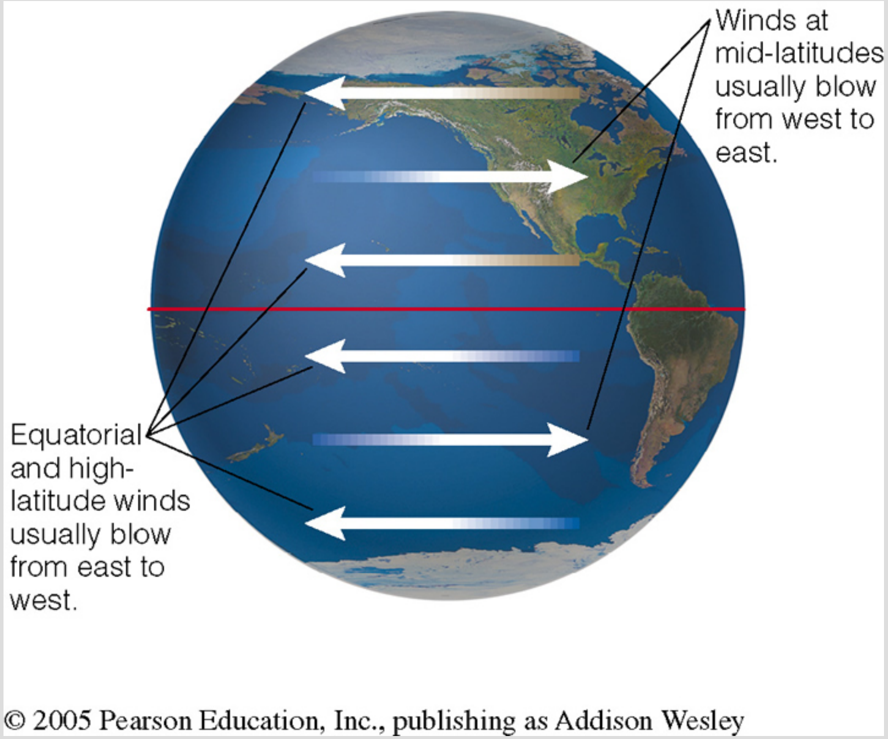
Our goals for learning:

- What is the difference between weather and climate?
- What two factors determine global wind patterns?
- What causes rain or snow to fall?
- Describe four factors that can cause long-term climate change.

What are Weather and Climate?

weather – short-term changes in wind, clouds, temperature, and pressure in an atmosphere at a given location

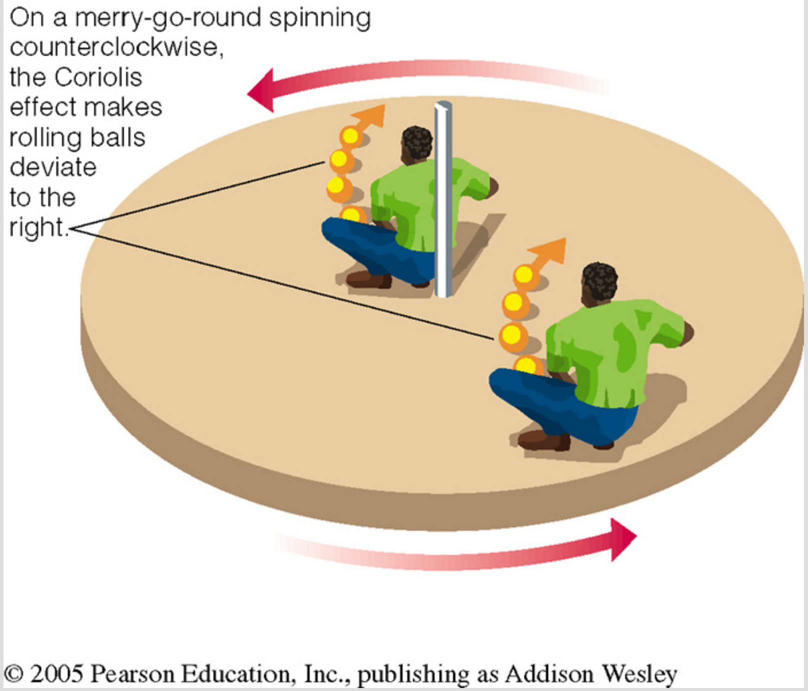
climate – long-term average of the weather at a given location

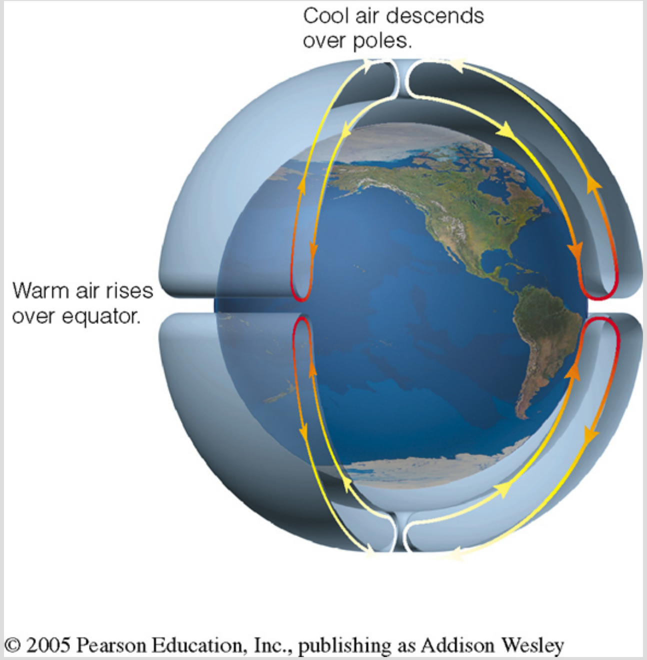


- These are Earth's **global wind patterns** or circulation
  - local weather systems move along with them
  - weather moves from W to E at mid-latitudes in N hemisphere
- Two factors cause these patterns
  - atmospheric heating
  - planetary rotation

Global Wind Patterns

- air heated more at equator
  - warm air rises at equator; heads for poles
  - cold air moves towards equator along the surface
- two circulation cells are created in each hemisphere

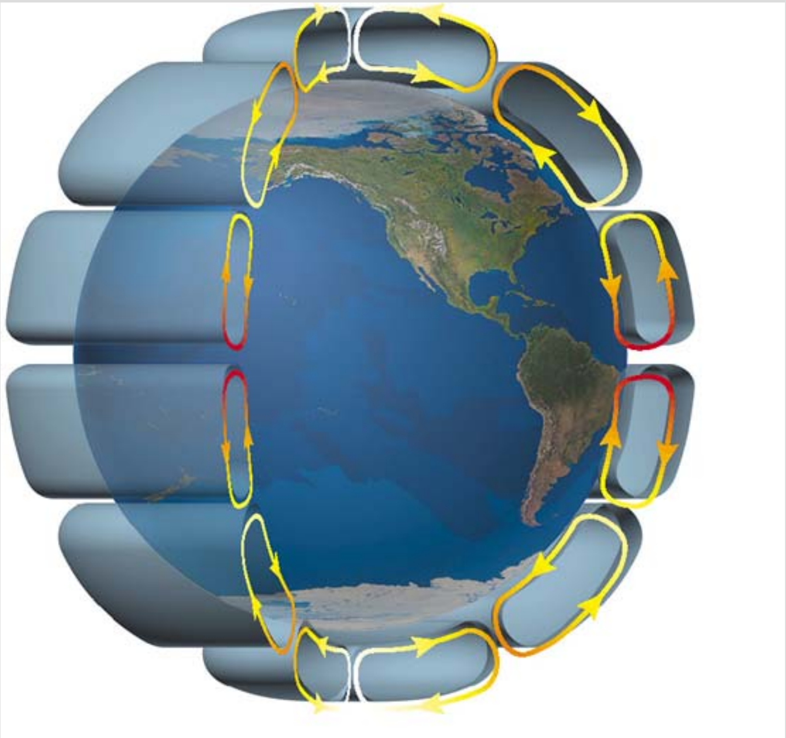




- cells do not go directly from pole to equator; air circulation is diverted by…
- Coriolis effect
  - moving objects veer *right* on a surface rotating *counterclockwise*
  - moving objects veer *left* on a surface rotating *clockwise*

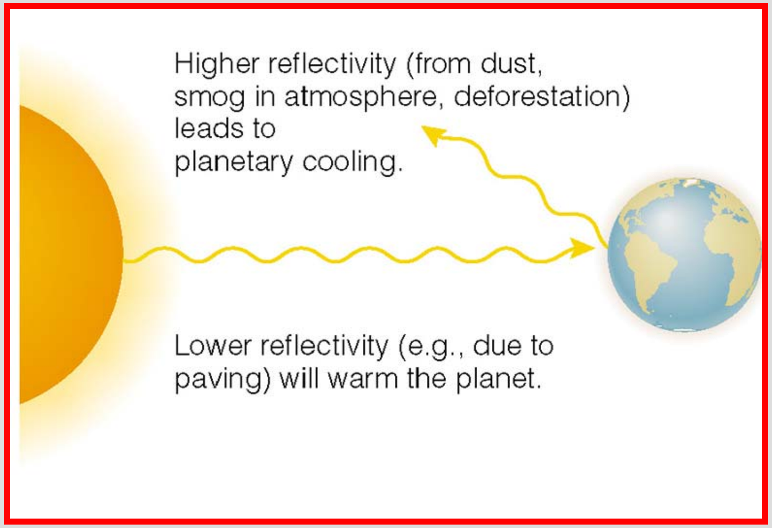
Global Wind Patterns

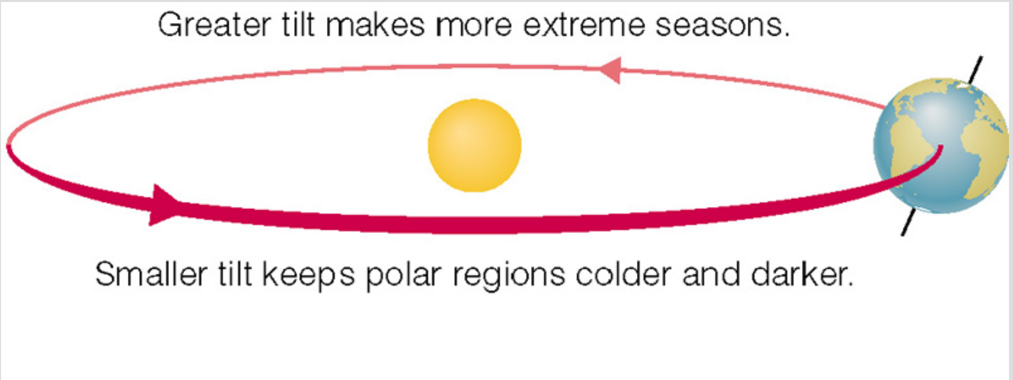
- On Earth, the Coriolis effect breaks each circulation cell into three separate cells
  - winds move either W to E or E to W

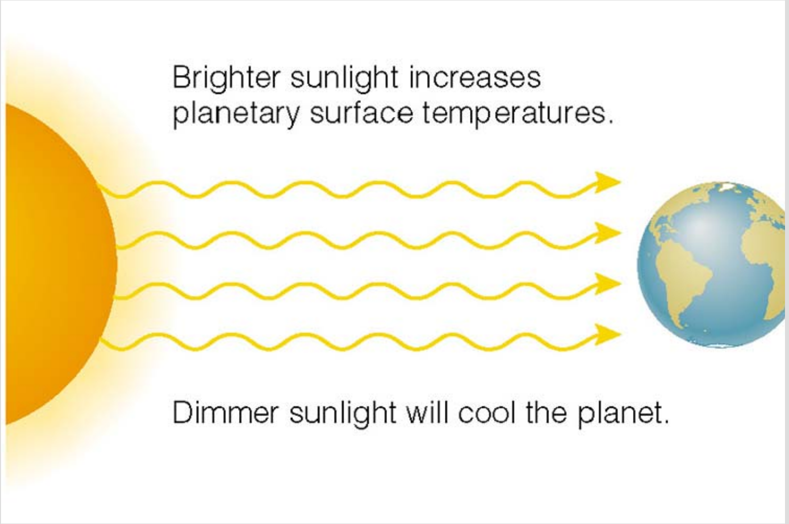


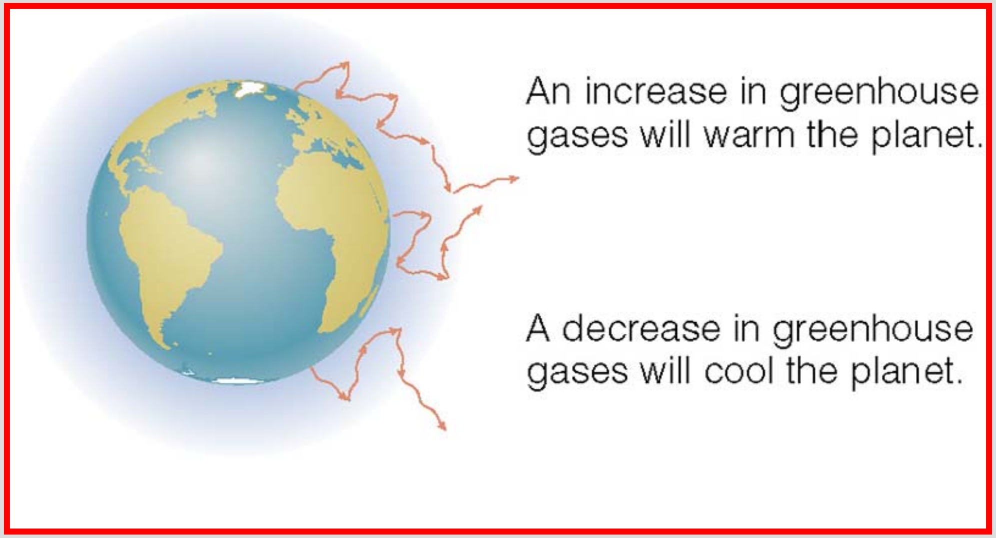
- Coriolis effect not strong on Mars & Venus
  - Mars is too small
  - Venus rotates too slowly
- In thick Venusian atmosphere, the pole-to-equator circulation cells distribute heat efficiently
  - surface temperature is uniform all over the planet

Four Major Factors which affect Long-term Climate Change









10.5 Sources and Losses of Atmospheric Gas

Our goals for learning:

- Describe the processes by which an atmosphere can gain and lose gas.
- Why are the atmospheres of the Moon and Mercury "all exosphere"?

Gain/Loss Processes of Atmospheric Gas

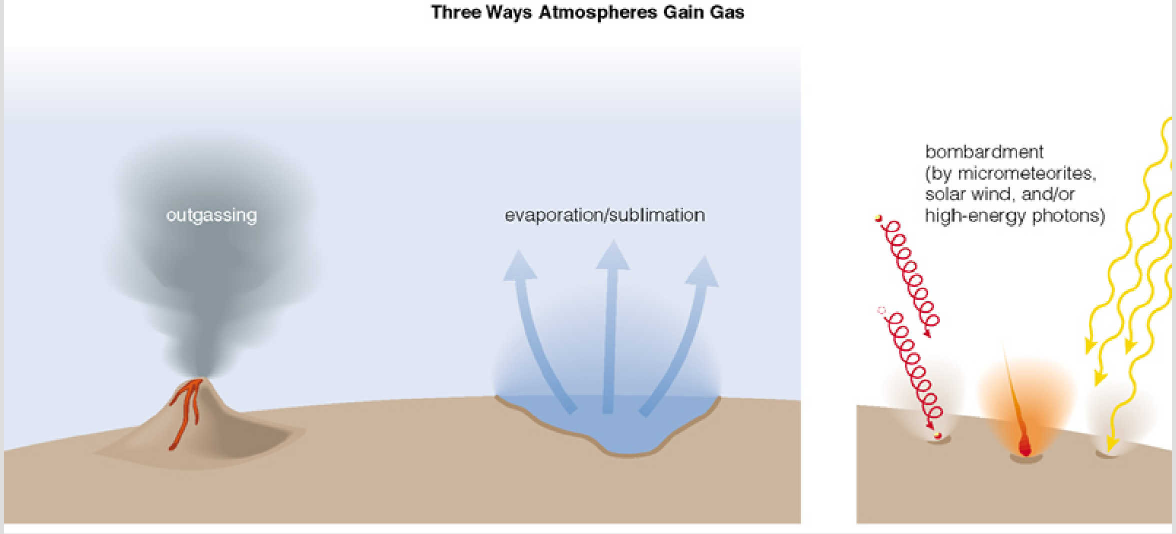
- Unlike the Jovian planets, the terrestrials were too small to capture significant gas from the Solar nebula.
  - what gas they did capture was H & He, and it escaped
  - present-day atmospheres must have formed at a later time
- Sources of atmospheric gas:
  - **outgassing** – release of gas trapped in interior rock by volcanism
  - **evaporation/sublimation** – surface liquids or ices turn to gas when heated
  - **bombardment** – micrometeorites, Solar wind particles, or high-energy photons blast atoms/molecules out of surface rock
    - occurs only if the planet has no substantial atmosphere already

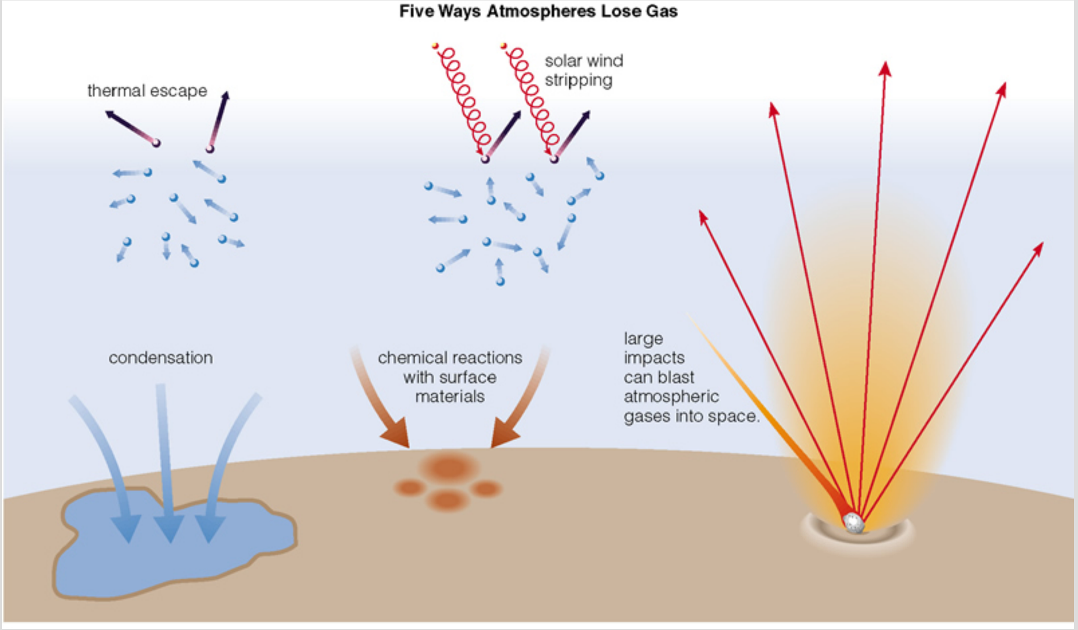
Gain/Loss Processes of Atmospheric Gas

- Ways to lose atmospheric gas:
  - **condensation** – gas turns into liquids or ices on the surface when cooled
  - **chemical reactions** – gas is bound into surface rocks or liquids
  - **stripping** – gas is knocked out of the upper atmosphere by Solar wind particles
  - **impacts** – a comet/asteroid collision with a planet can blast atmospheric gas into space
  - **thermal escape** – lightweight gas molecules are lost to space when they achieve escape velocity

gas is lost forever!

Gain/Loss Processes of Atmospheric Gas





Origin of the Terrestrial Atmospheres

- Venus, Earth, & Mars received their atmospheres through outgassing.
  - most common gases: H_2O, CO_2, N_2, H_2S, SO_2
- Chemical reactions caused CO_2 on Earth to dissolve in oceans and go into carbonate rocks (like limestone.)
  - this occurred because H_2O could exist in liquid state
  - N_2 was left as the dominant gas; O_2 was exhaled by plant life
  - as the dominant gas on Venus, CO_2 caused strong greenhouse effect
- Mars lost much of its atmosphere through impacts
  - less massive planet, lower escape velocity

Origin of the Terrestrial Atmospheres

- Lack of magnetospheres on Venus & Mars made stripping by the Solar wind significant.
  - further loss of atmosphere on Mars
  - dissociation of H_2O, H_2 thermally escapes on Venus
- Gas and liquid/ice exchange occurs through condensation and evaporation/sublimation:
  - on Earth with H_2O
  - on Mars with CO_2
- Since Mercury & the Moon have no substantial atmosphere, fast particles and high-energy photons reach their surfaces
  - bombardment creates a rarified exosphere

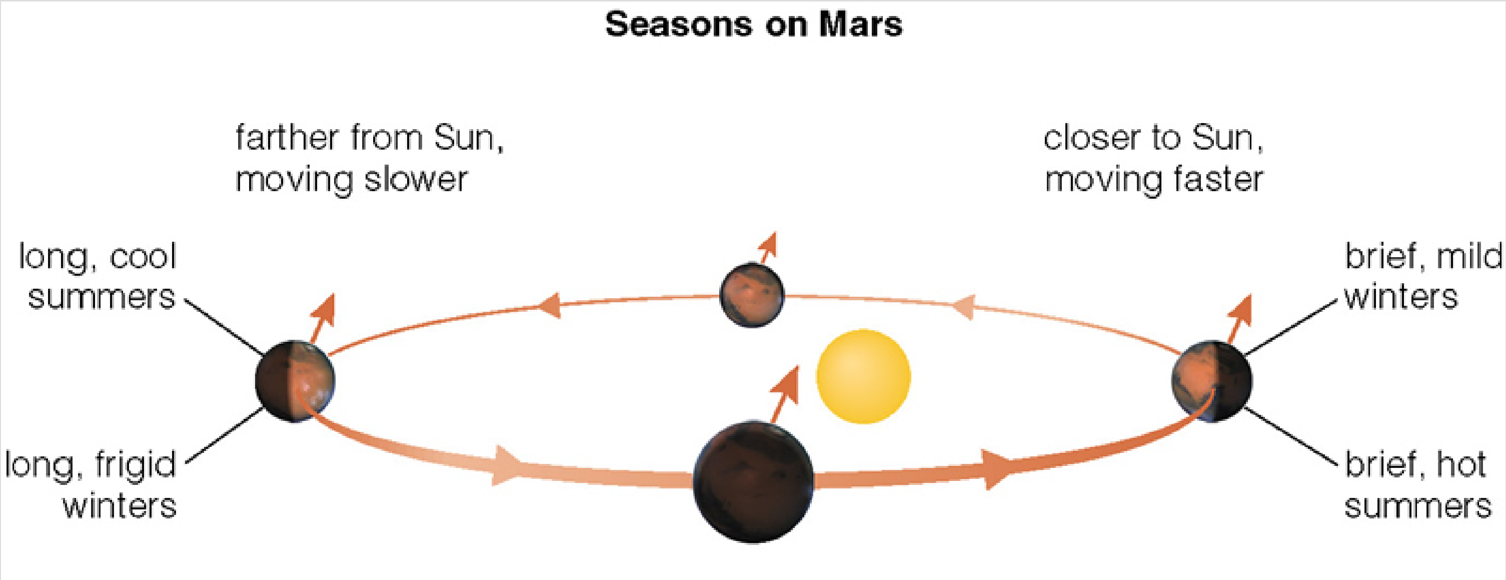
10.6 The Climate Histories of Venus, Earth, and Mars

Our goals for learning:

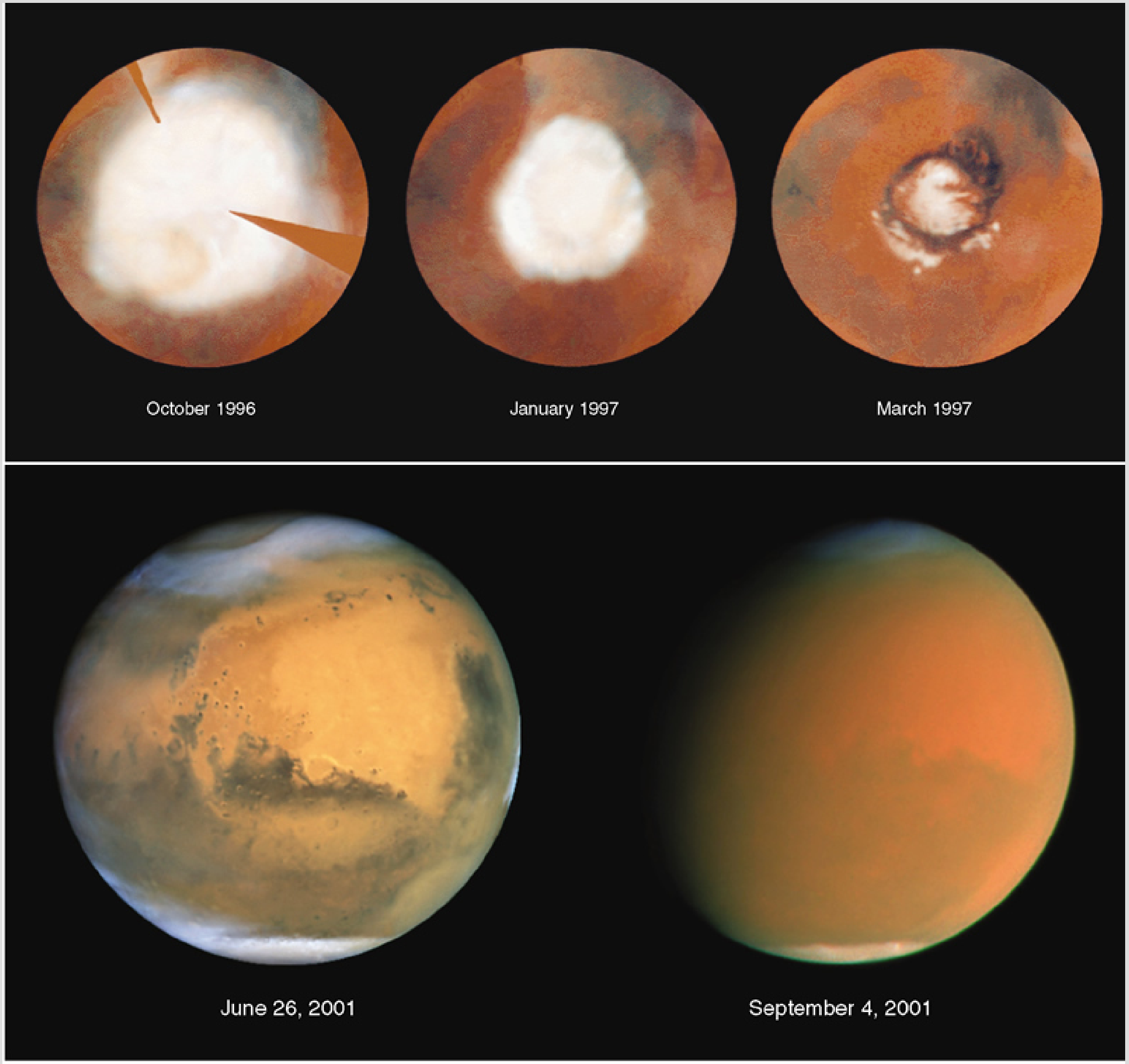
- Describe major, seasonal features of Martian weather today.
- Why did Mars's early warm and wet period come to an end?
- Why is Venus so hot?
- Could Venus ever have had oceans?
- After studying Mars and Venus, why does Earth's atmosphere seem surprising?

Martian Weather Today

- Seasons on Mars are more extreme than on Earth
  - Mars' orbit is more elliptical
- CO_2 condenses & sublimes at opposite poles
  - changes in atmospheric pressure drive pole-to-pole winds
  - sometimes cause huge dust storms



Martian Weather: N Polar Ice Cap & Dust Storm



Climate History of Mars

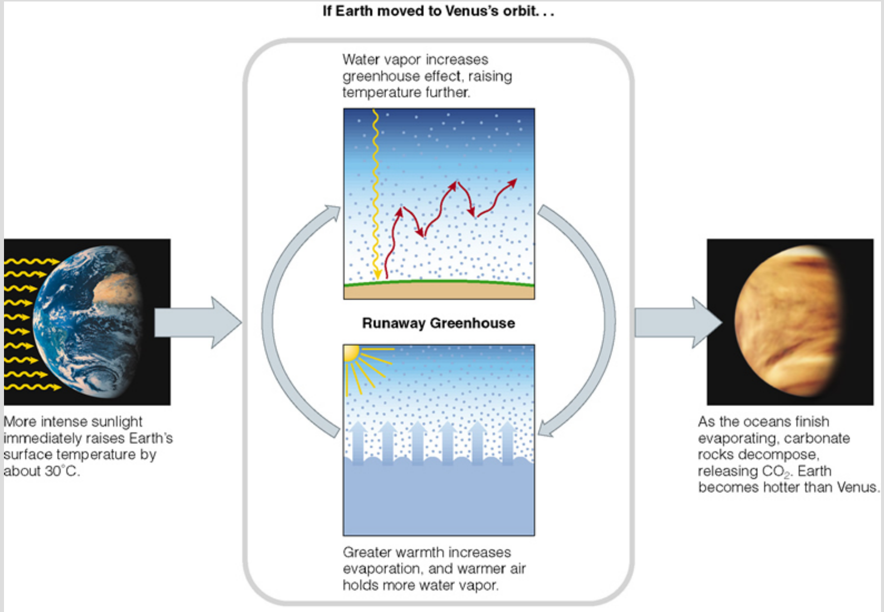
- More than 3 billion years ago, Mars must have had a thick CO_2 atmosphere and a strong greenhouse effect.
  - the so-called "warm and wet period"
- Eventually CO_2 was lost to space.
  - some gas was lost to impacts
  - cooling interior meant loss of magnetic field
  - Solar wind stripping removed gas
- Greenhouse effect weakened until Mars froze.

Venusian Weather Today

- Venus has no seasons to speak of.
  - rotation axis is nearly 90º to the ecliptic plane
- Venus has little wind at its surface
  - rotates very slowly, so there is no Coriolis effect
- The surface temperature stays constant all over Venus.
  - thick atmosphere distributes heat via two large circulation cells
- There is no rain on the surface.
  - it is too hot and Venus has almost no H_2O
- Venusian clouds contain sulfuric acid!
  - implies recent volcanic outgassing?

Climate History of Venus

- Venus should have outgassed as much H_2O as Earth.
  - Early on, when the Sun was dimmer, Venus may have had oceans of water
- Venus' proximity to the Sun caused all H_2O to evaporate.
  - H_2O caused runaway greenhouse effect
  - surface heated to extreme temperature
  - UV photons from Sun dissociate H_2O; H_2 escapes, O is stripped



What have we learned?

- Describe the general atmospheric properties of each of the five terrestrial worlds.
  - Moon and Mercury: essentially airless with very little atmospheric gas. Venus: thick CO_2 atmosphere, with high surface temperature and pressure. Mars: thin CO_2 atmosphere, usually below freezing and pressure too low for liquid water. Earth: nitrogen/oxygen atmosphere with pleasant surface temperature and pressure.
- What is atmospheric pressure?

  The result of countless collisions between atoms and molecules in a gas. Measured in *bars* (1 bar = Earth's pressure at sea level.)
- Summarize the effects of atmospheres.
  - Atmospheres absorb and scatter light, create pressure, warm the surface and distribute heat, create weather, and interact with the Solar wind to make auroras.

What have we learned?

- What is the greenhouse effect?
  - Planetary warming caused by the absorption of infrared light from a planet's surface by greenhouse gases such as carbon dioxide, methane, and water vapor.
- How would planets be different without the greenhouse effect?
  - They would be colder, with temperatures determined only by distance from the Sun and reflectivity.
- Compare the greenhouse effect on Venus, Earth, & Mars.
  - All three planets are warmed by the greenhouse effect, but it is weak on Mars, moderate on Earth, and very strong on Venus.

What have we learned?

- Describe the basic structure of Earth's atmosphere.
  - Pressure and density decrease rapidly with altitude. Temperature drops with altitude in the troposphere, rises with altitude in the lower part of the stratosphere, and rises again in the thermosphere and exosphere.
- How do interactions with light explain atmospheric structure?
  - Solar X rays heat and ionize gas in the thermosphere. Solar ultraviolet is absorbed by molecules such as ozone, heating the stratosphere. Visible light warms the surface (and colors the sky), which radiates infrared light that warms the troposphere.
- Contrast the atmospheric□ structures of Venus, Earth, and Mars.
  - Venus and Mars lack and ultraviolet-absorbing stratosphere.

What have we learned?

- What is a magnetosphere?
  - Created by a global magnetic field, it acts like a protective bubble surrounding the planet that diverts charged particles from the Solar wind, channeling some to the magnetic poles where they can lead to auroras.
- What is the difference between weather and climate?
  - Weather refers to short-term changes in wind, clouds, temperature, and pressure. Climate is the long-term average of weather.
- What creates global wind patterns?
  - Atmospheric heating at the equator creates two huge equator-to-pole circulation cells. If the Coriolis effect is strong enough, these large cells may split into smaller cells. This split occurs on Earth, but not on Venus (because of slow rotation) or Mars (because of small size).

What have we learned?

- What causes rain or snow to fall?
  - Convection carries evaporated (or sublimated) water vapor to high, cold altitudes, where it condenses into droplets or ice flakes, forming clouds. When the droplets or ice flakes get large enough, convection cannot hold them aloft and they fall as rain, snow, or hail.
- Describe four factors that can cause long-term climate change.
  - The gradual brightening of the Sun over the history of the Solar System. Changes in a planet's axis tilt. Changes in a planet's reflectivity. Changes in a planet's abundance of greenhouse gases.

What have we learned?

- Describe the processes by which an atmosphere can gain and lose gas.
  - Gains come from outgassing, evaporation/sublimation, or bombardment, but the latter only if there’s very little atmosphere. Gases can be lost by condensation, chemical reactions with surface materials, stripping from the upper atmosphere by small particles or photons, being blasted away by impacts, or by achieving thermal escape velocity.
- Why are the atmospheres of the Moon & Mercury “all exosphere”?
  - They have no current source for outgassing and they are too small and warm to hold any atmosphere they may have had in the past. They have small amounts of gas above their surfaces only because of bombardment by Solar wind particles.

What have we learned?

- Describe major, seasonal features of Martian weather today.
  - Seasonal changes in temperature cause carbon dioxide to alternately condense and sublime at the polls, driving pole-to-pole winds and sometimes creating huge dust storms.
- Why did Mars' early warm and wet period come to an end?
  - Mars once had a thick carbon dioxide atmosphere and strong greenhouse effect. Most of the CO_2 was eventually lost to space, probably because the cooling interior could no longer create a strong magnetic field to protect the atmosphere from the Solar wind. As CO_2 to was lost, the greenhouse effect weakened until the planet froze.

What have we learned?

- Why is Venus so hot?
  - At its distance from the Sun, any liquid water was destined to evaporate, alternately driving a runaway greenhouse effect that dried up the planet and heated it to its extreme temperature.
- Could Venus ever have had oceans?
  - Venus probably outgassed plenty of water vapor. Early in the Solar System's history, when the Sun was dimmer, it is possible that this water vapor could have condensed to make rain and oceans, though we cannot be sure.
- After studying Mars and Venus, why does Earth's climate seem surprising?
  - Mars and Venus both underwent dramatic and permanent climate change early in their histories. Earth has somehow maintained a relatively stable climate, even as the Sun has warmed with time.