# Planetary Atmospheres

## Earth and the Other Terrestrial Worlds

**Next (and last) homework posted to website**
**due on Friday 19th**

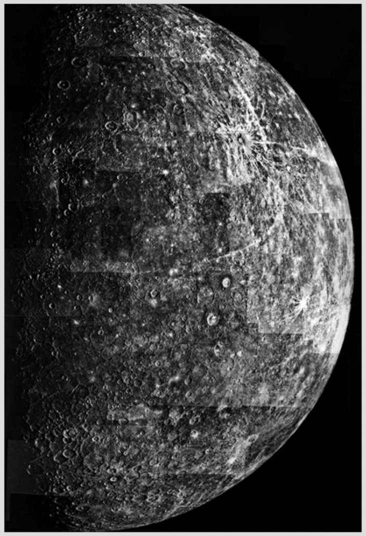
**Next (and last) in-class exam – Wednesday Dec. 1**

**(Note:  Still have final on December 13 7:30pm)**

# Planetary Atmospheres

- All planets have an atmosphere to some extent
- Jovian planets are atmosphere throughout while planets with surfaces have little to no atmosphere, relatively.
- A few basic principles can explain nearly all atmospheric properties.

# Comparing Terrestrial Atmospheres





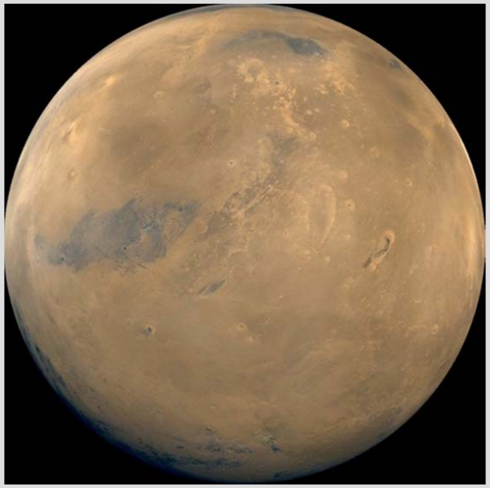


**Table 11.1 Atmospheres of the Terrestrial Worlds**

| *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.

# What is an Atmosphere?

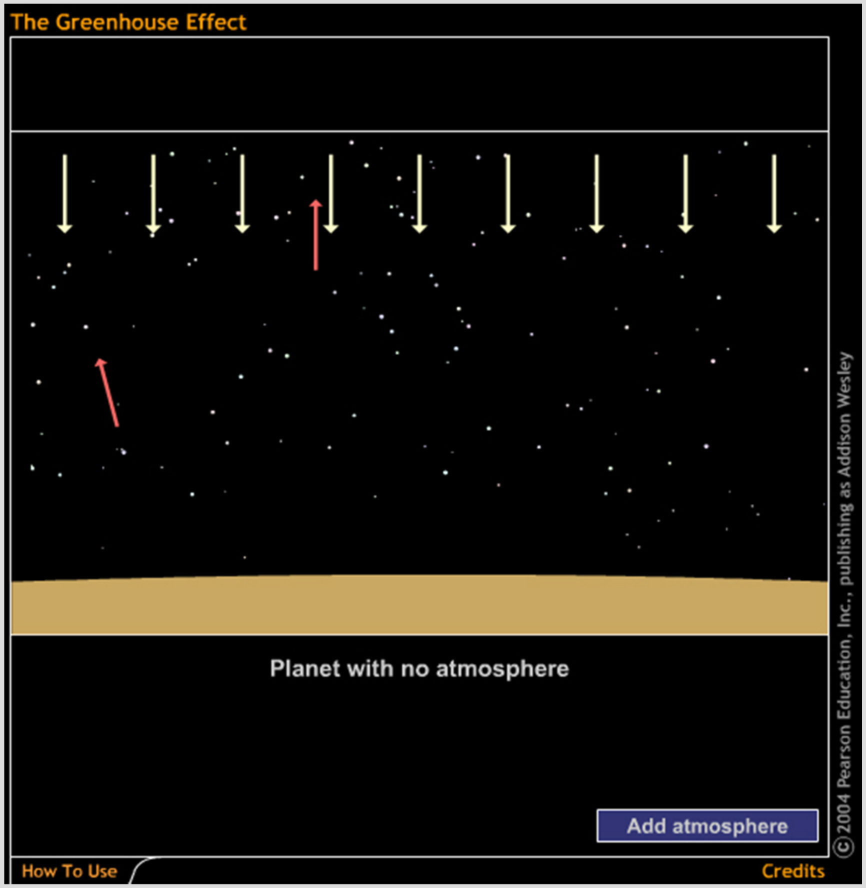
- A layer of gas which surrounds a world is called an **atmosphere**.
  - they are usually very thin compared to planet radius
- Atmospheres are in molecular form ($N_2$, $H_2O$, $CO_2$, etc.)
- **Pressure** is created by atomic & molecular collisions in an atmosphere.
  - heating a gas in a confined 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

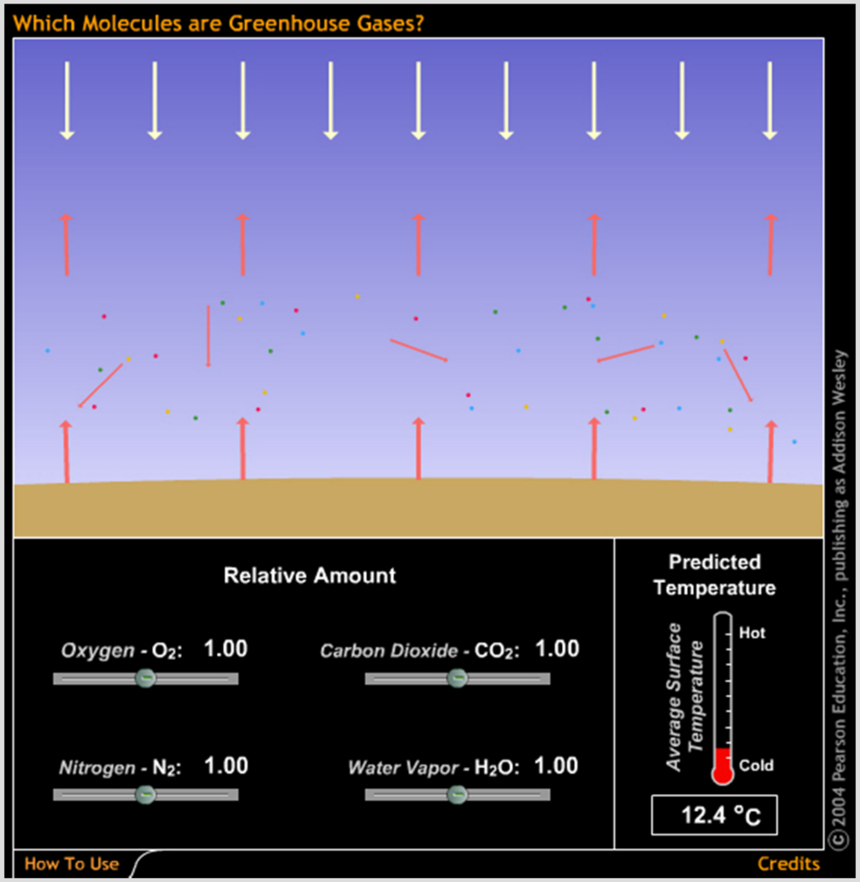
- greenhouse effect
  - makes the planetary surface warmer than it would be otherwise
- scattering and absorption of light
  - absorb high-energy radiation from the Sun
  - scattering of optical light brightens the daytime sky
- creates pressure
  - can allow water to exist as a liquid (at the right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

# The Greenhouse Effect

- One of the most important effects of an atmosphere on a planet. Critical for life, not like the stigma from global warming.
- 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.



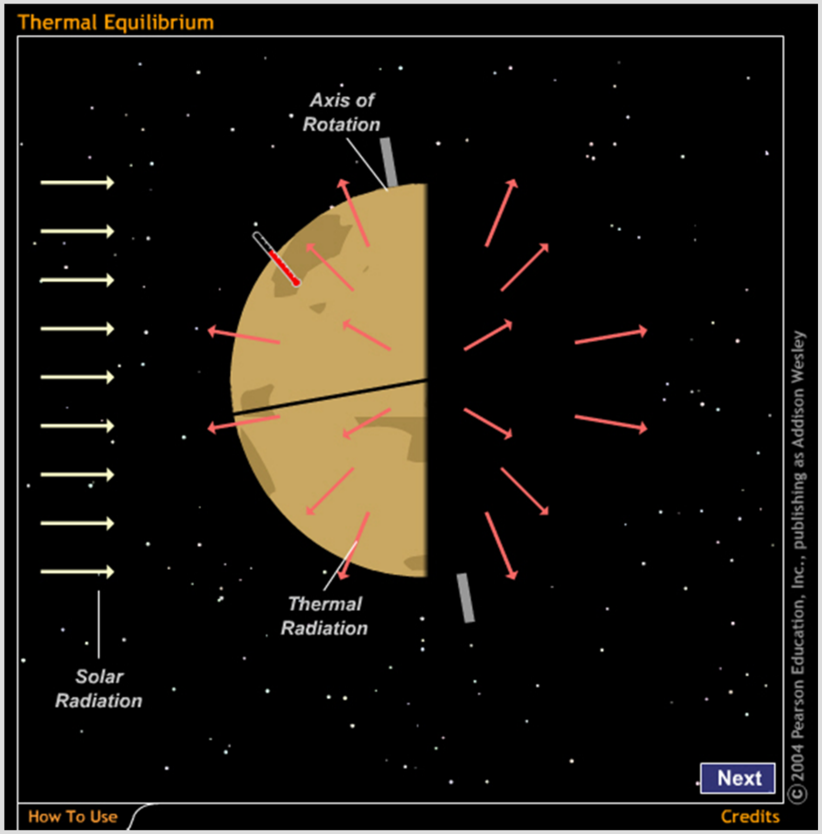
# Greenhouse Gases




- 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

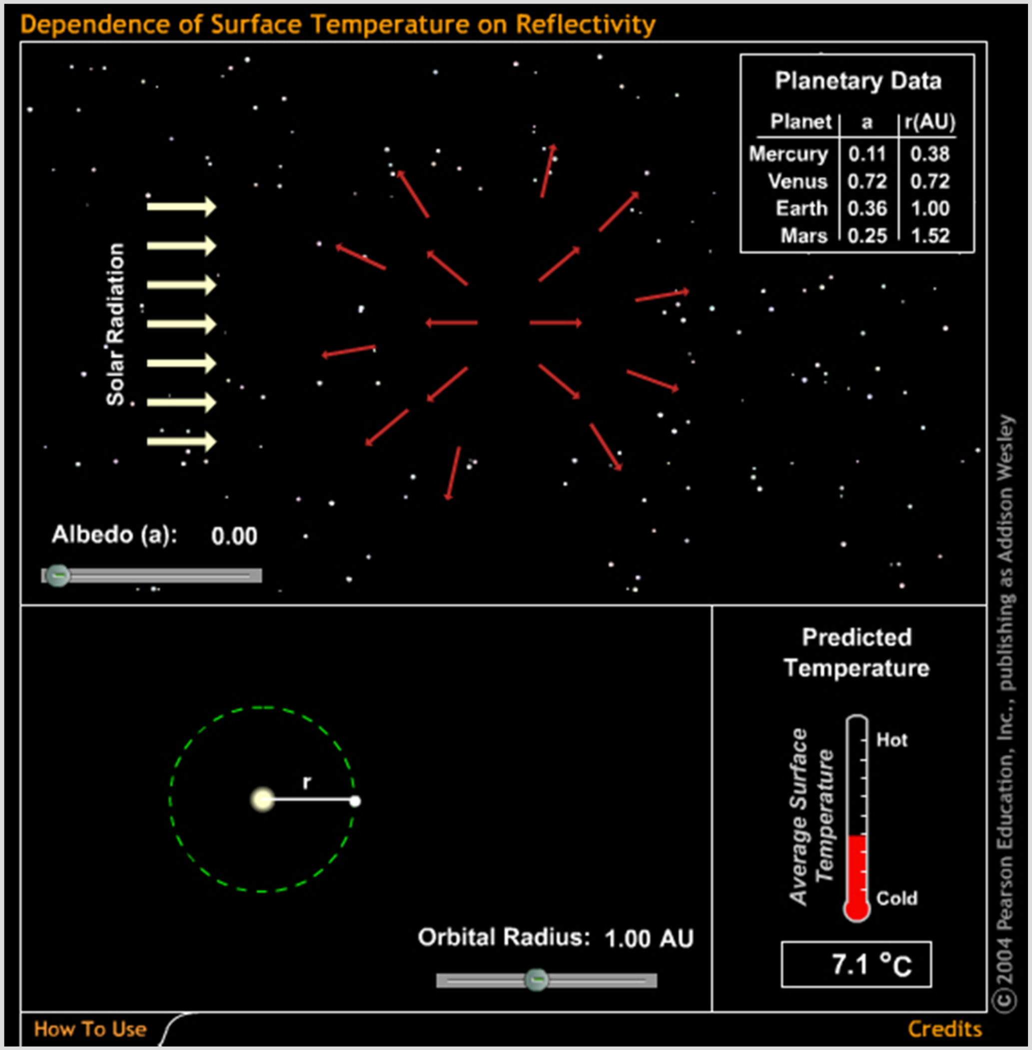
- Solar energy received by a planet must balance the energy it returns to space
  - planet can either reflect or emit the energy as radiation
  - this is necessary for the planet to have a stable temperature



# 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 (important to life!)

# What Determines a Planet's Surface Temperature?



# Greenhouse Effect on the Planets

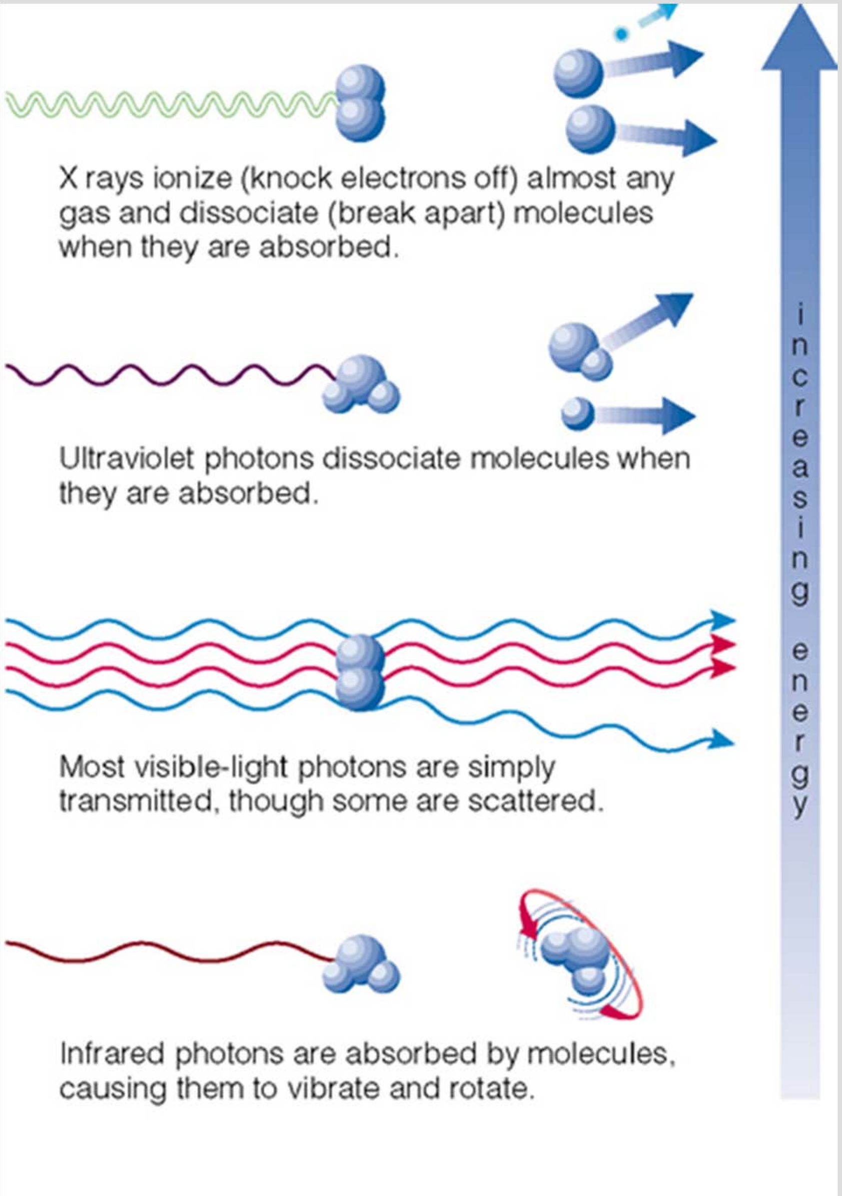
**Table 11.2. The Greenhouse Effect on the Terrestrial Worlds**

| 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.

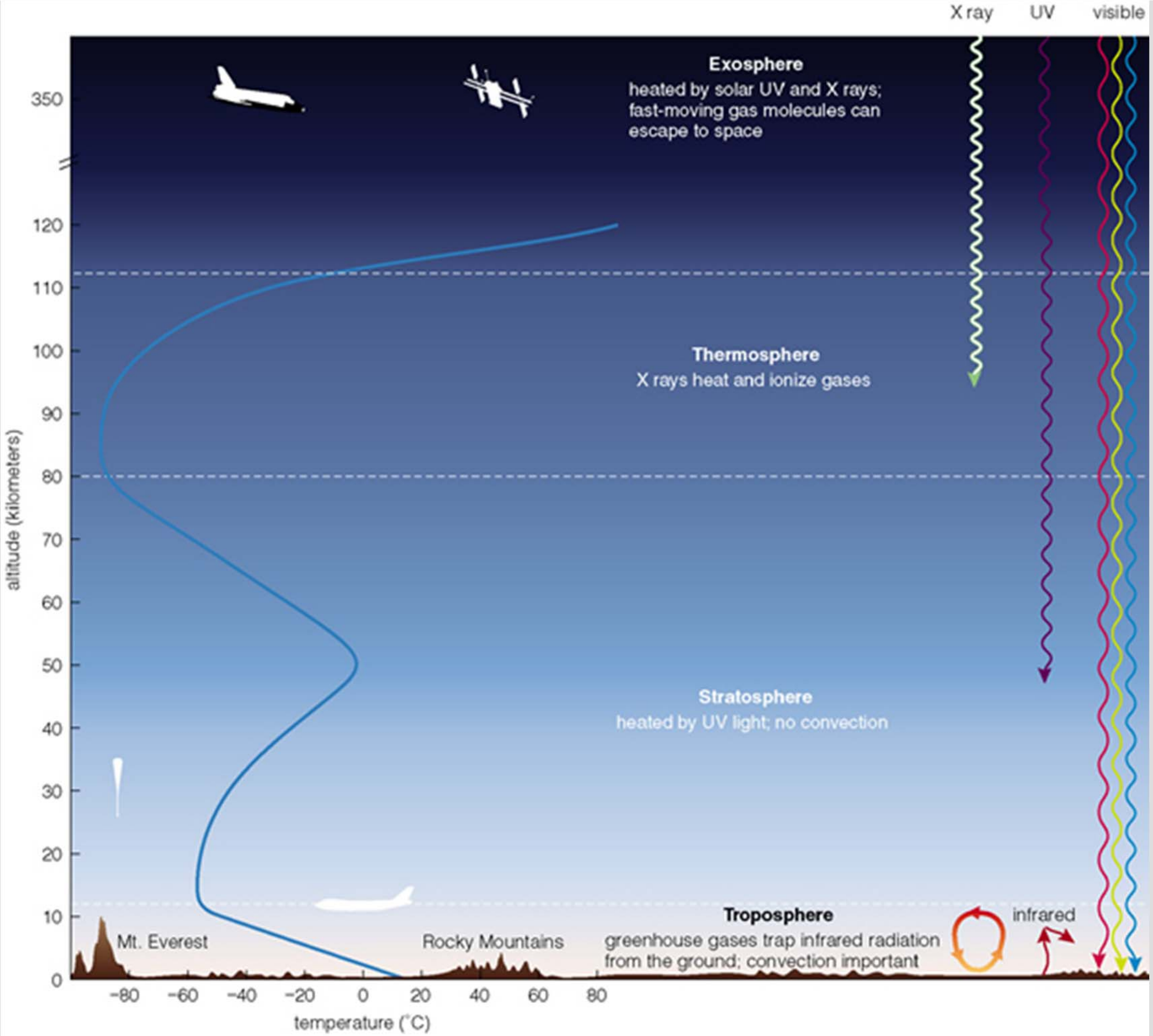
# Atmospheres Interact with Light

- 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



# Structure of Earth’s Atmosphere

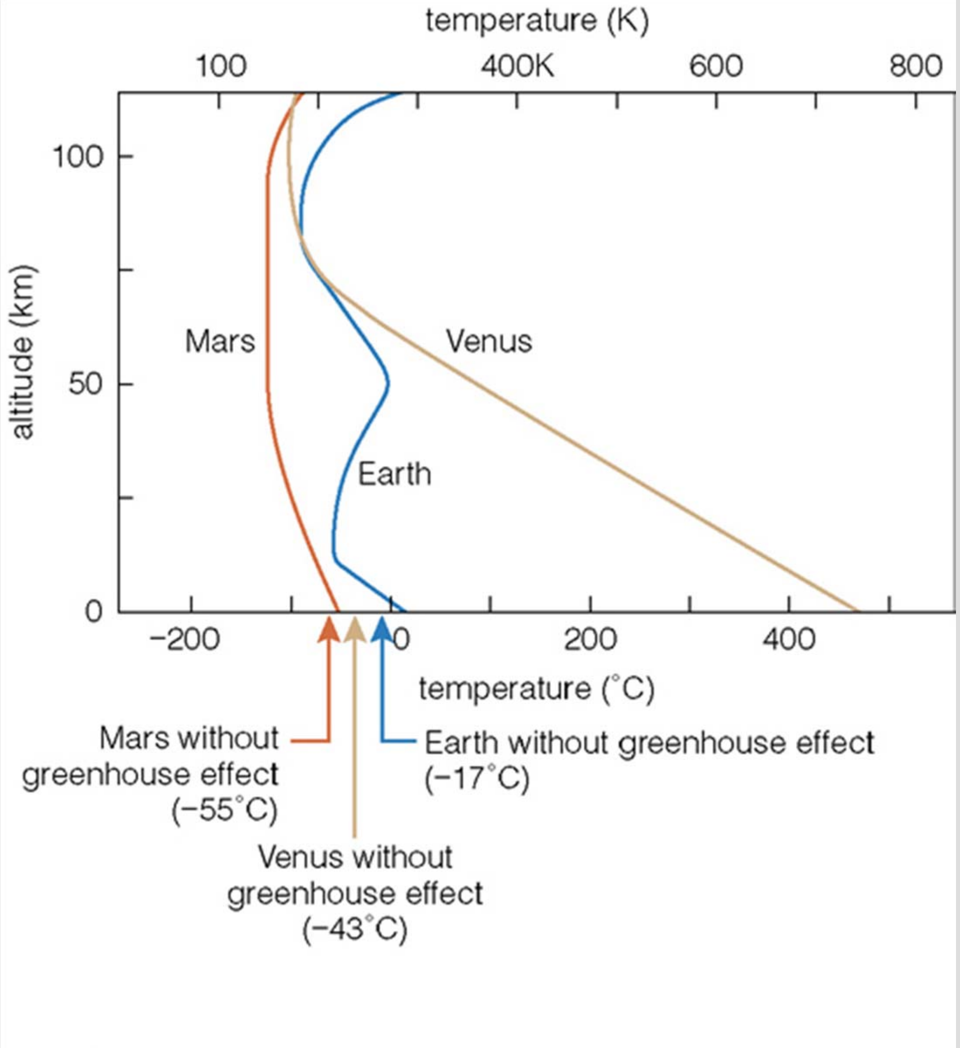
- pressure & density of atmosphere decrease with altitude
- temperature varies “back and forth” with altitude
  - these temperature variations (determined by light interactions) define the major atmospheric layers
    - **exosphere**
      - temp continues to rise, low density; fades into space
    - **thermosphere**
      - temp begins to rise at the top
    - **stratosphere**
      - rise and fall of temp
    - **troposphere**
      - layer closest to surface
      - temp drops with altitude


X ray
UV
visible
Exosphere
heated by solar UV and X rays; fast-moving gas molecules can escape to space
Thermosphere
X rays heat and ionize gases
Stratosphere
heated by UV light; no convection
Troposphere
greenhouse gases trap infrared radiation from the ground; convection important
infrared
Mt. Everest
Rocky Mountains
altitude (kilometers)
350
120
110
100
90
80
70
60
50
40
30
20
10
0
-80
-60
-40
-20
0
20
40
60
80
temperature (°C)

# Reasons for Atmospheric Structure

- Light interactions are responsible for the structure we see.
- Troposphere
  - Visible light warms the surface (also some low energy UV)
  - absorbs IR photons from the surface
  - temperature drops with altitude (b/c more IR absorbed closer to the ground)
  - hot air rises and high gas density causes storms (convection causing storms)
- Stratosphere
  - lies above the greenhouse gases (no IR absorption, IR escapes to space)
  - 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 ionize all gases
  - contains ionosphere, which reflects back human radio signals
- Exosphere
  - hottest layer; gas extremely rarified

# Structure of Terrestrial Planet Atmospheres

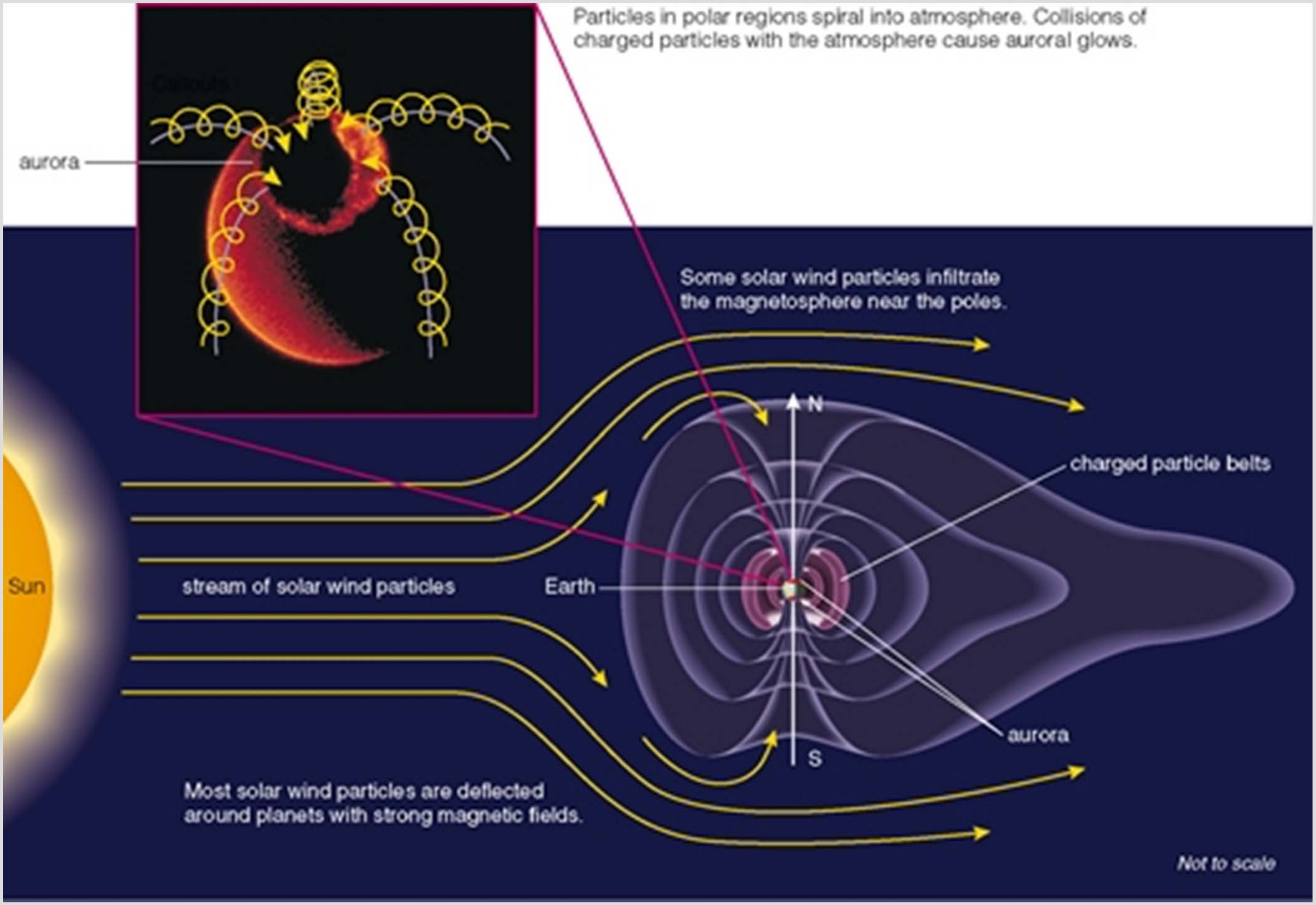




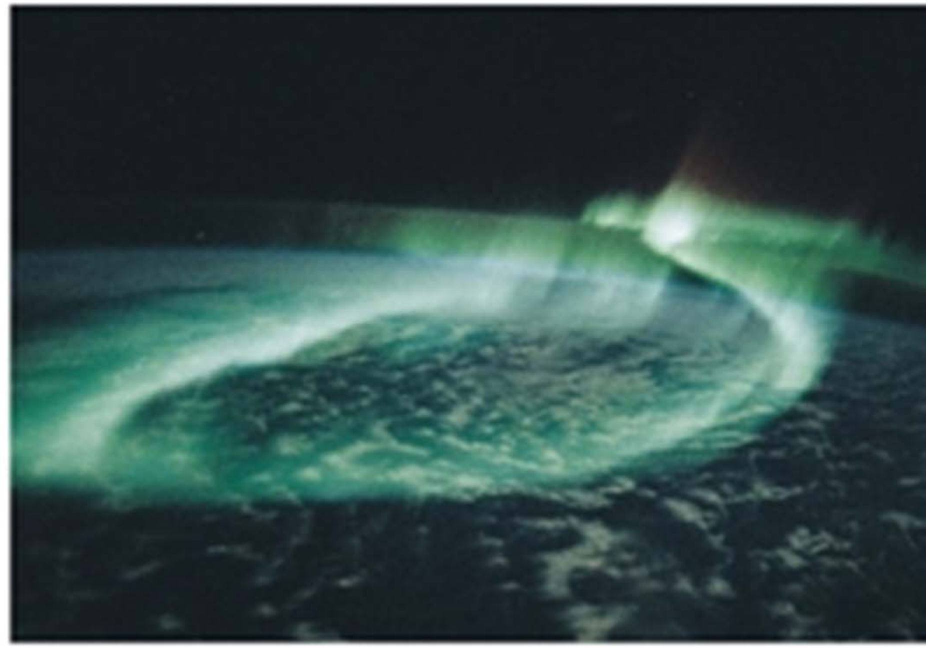

- Mars, Venus, Earth all
  - have warm tropospheres (and greenhouse gases)
  - have warm thermospheres which absorb Solar X rays
- Only Earth has
  - a warm stratosphere
  - an UV-absorbing gas ($O_3$)
- All three planets have warmer surface temps due to greenhouse effect

# 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.
  - this protective "bubble" is called the **magnetosphere**
  - the particles spiral along magnetic field lines, toward the poles and into the atmosphere where they excite atoms and molecules in the atmosphere to radiate
  - this causes the **aurora** (aka northern & southern lights)
- 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
- Jovian planets have magnetospheres and aurora as well



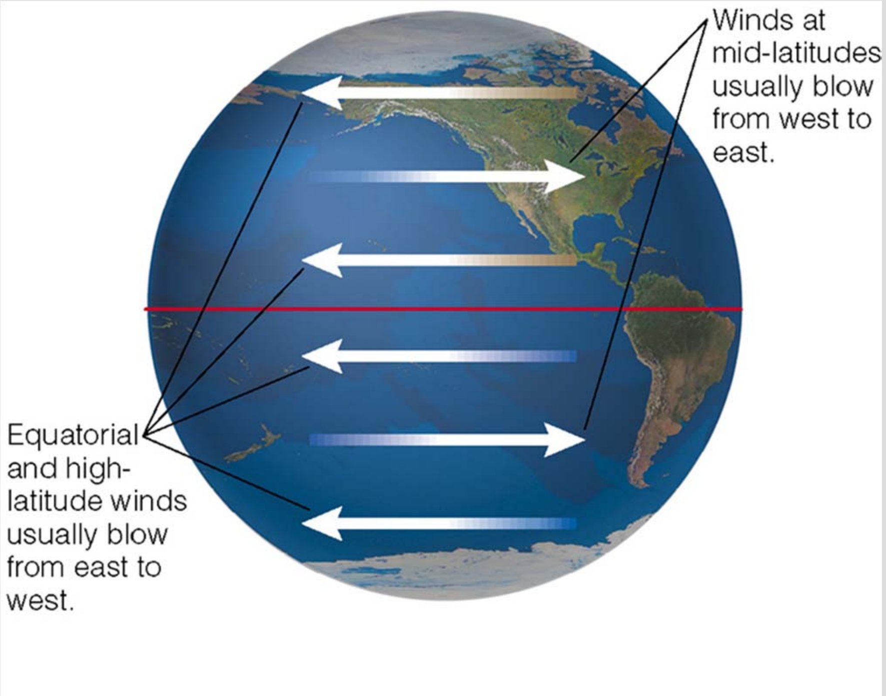
Particles in polar regions spiral into atmosphere. Collisions of charged particles with the atmosphere cause auroral glows.
aurora
Some solar wind particles infiltrate the magnetosphere near the poles.
N
charged particle belts
Sun
stream of solar wind particles
Earth
aurora
S
Most solar wind particles are deflected around planets with strong magnetic fields.
Not to scale



# 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

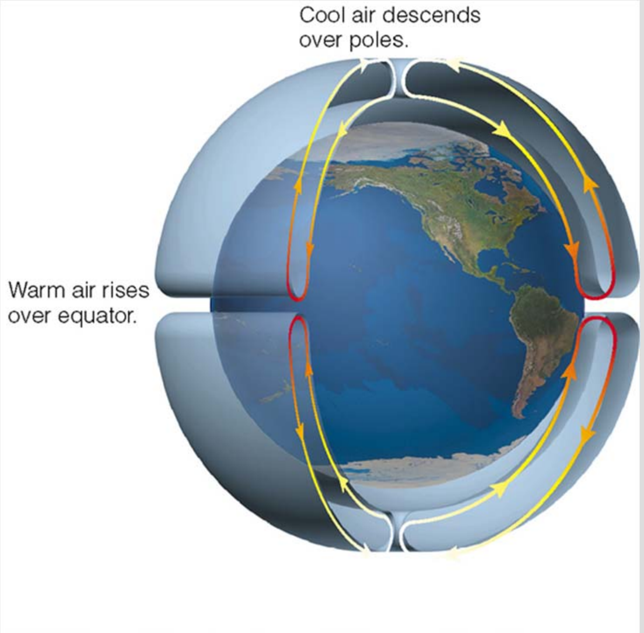




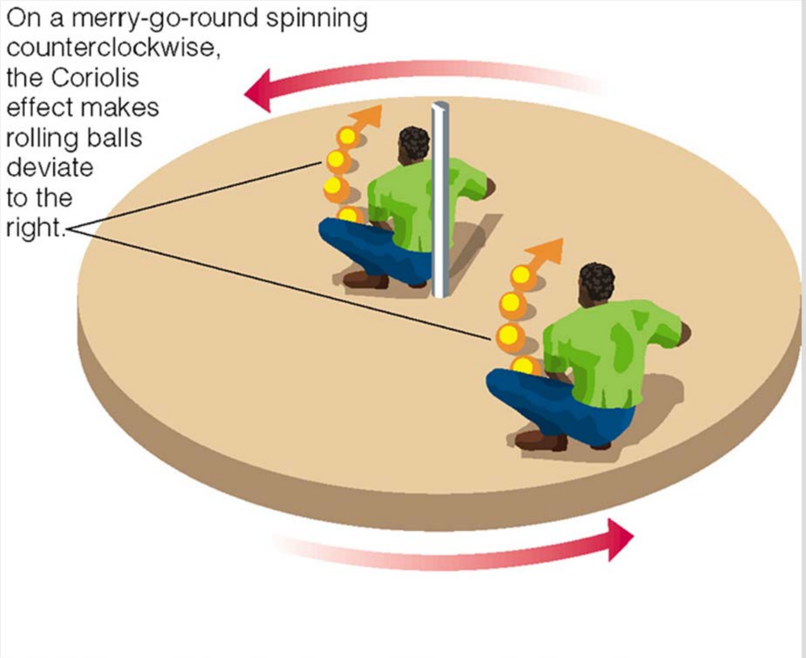
- These are Earth's **global wind patterns** or circulation
  - local weather systems move along with them
  - weather moves from W to E at mid-latitudes in N hemisphere
- Two factors cause these patterns
  - atmospheric heating
  - planetary rotation

# 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, one in each hemisphere





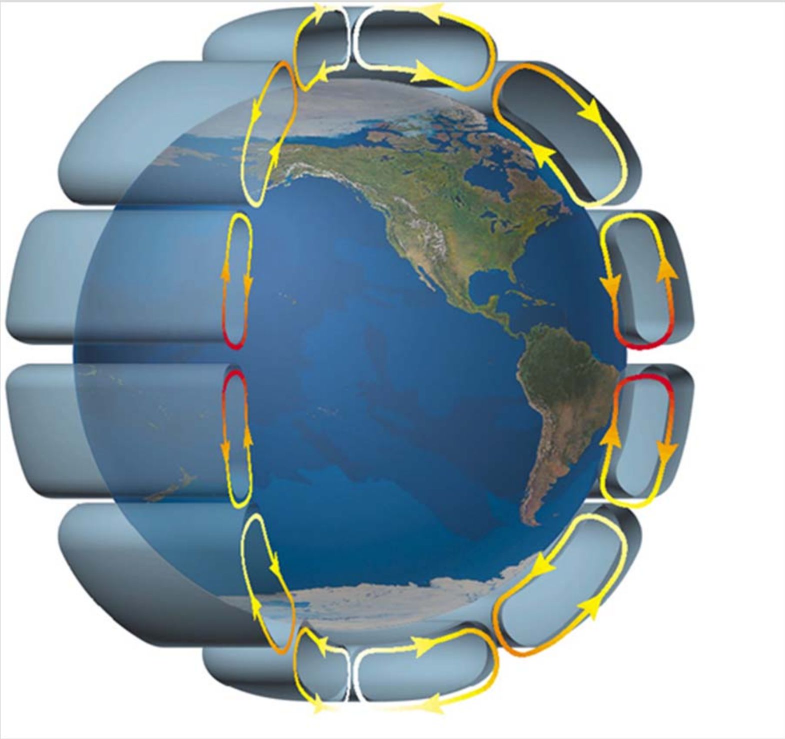




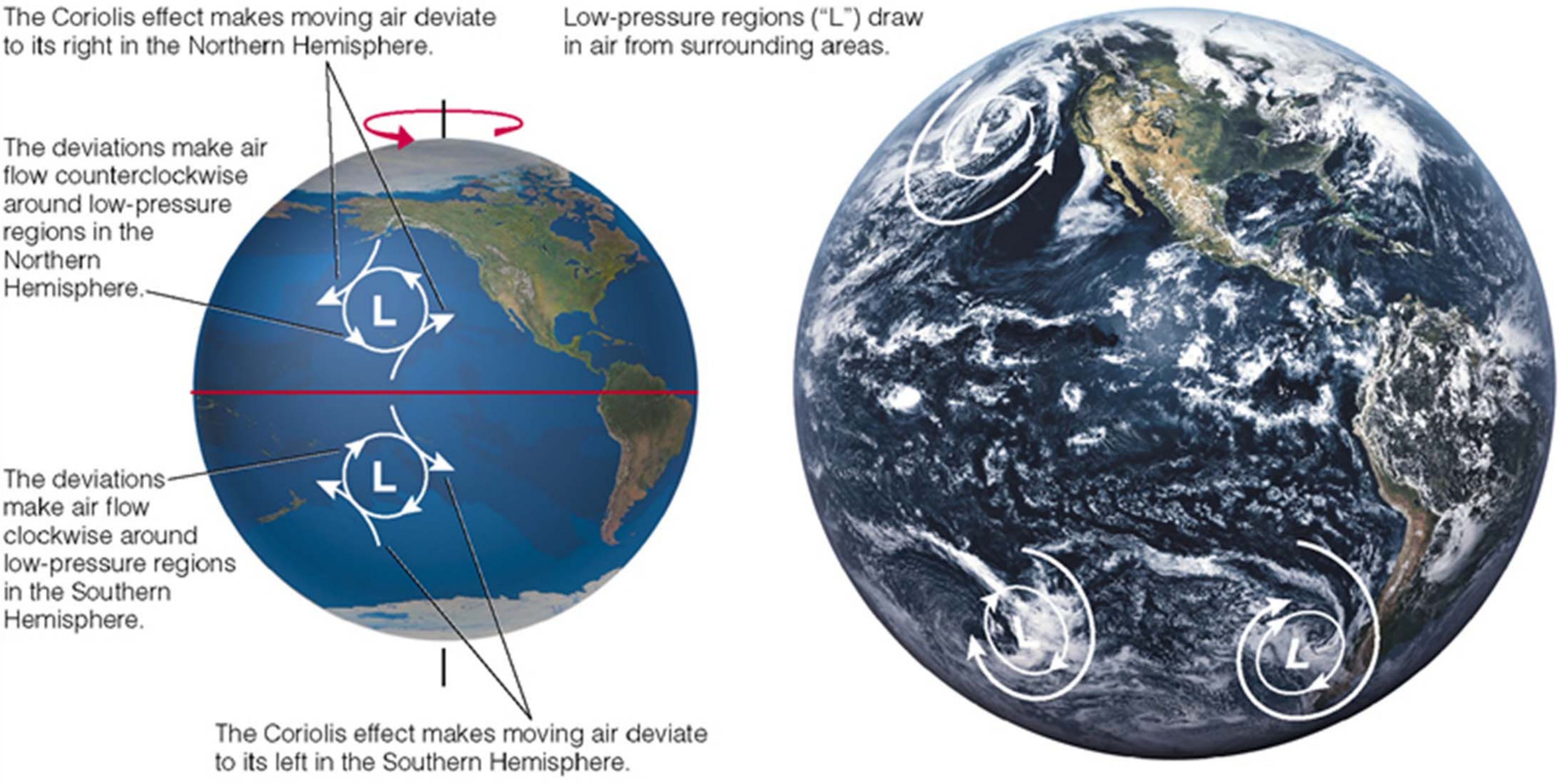
- cells do not go directly from pole to equator; air circulation is diverted by…
- Coriolis effect
  - moving objects veer *right* on a surface rotating *counterclockwise*
  - moving objects veer *left* on a surface rotating *clockwise*

# Coriolis effect

- Equator rotates faster than the poles – Coriolis effect
- On Earth, the Coriolis effect breaks each circulation cell into three separate cells
  - N and S winds are diverted E and W



# Coriolis effect

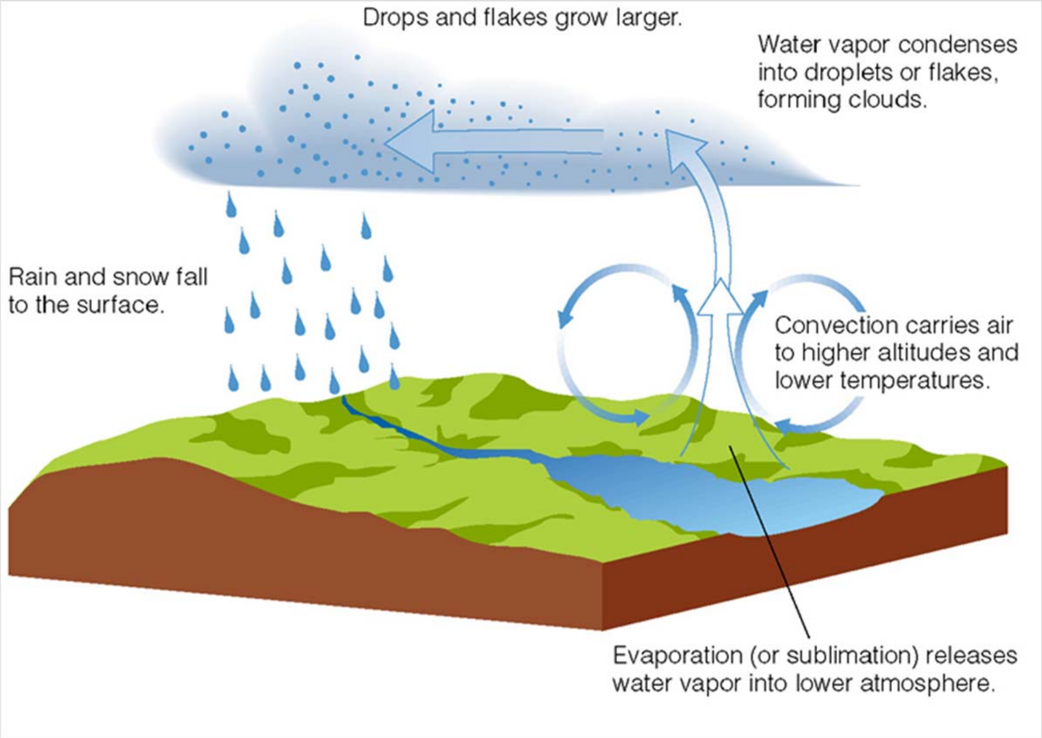


# Terrestrial planet comparison

- 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

# Clouds, Rain and Snow

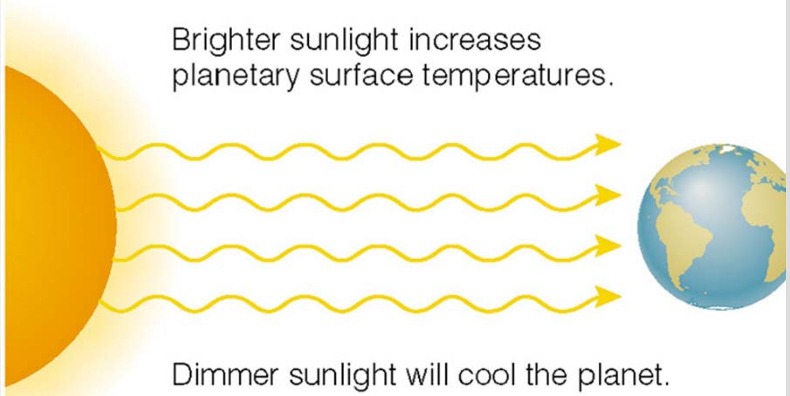
- Clouds strongly affect the surface conditions of a planet
  - they increase its albedo, thus reflecting away more sunlight
  - they provide rain and snow, which causes erosion
  - Circulation cells correlate to areas of lots of rainfall (rainforests) or little rainfall (desert)
- Formation of rain and snow:



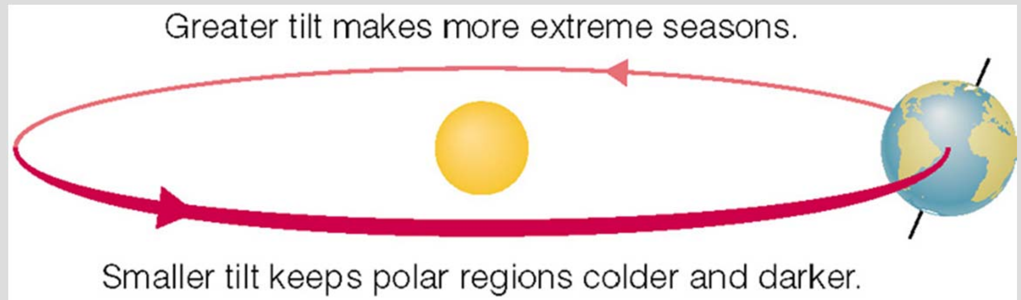
# Long-term climate change

- 1. Solar brightening
  - The Sun is 30% brighter now than when it was young, should warm planets, effects all planets
- 2. Changes in axis tilt
  - Earth's axis tilt changes from 22° - 25° due to gravitational influences from other planets.  Correlates well with ice ages.
- 3. Changes in reflectivity
  - Lots of dust (volcanism) reflects sunlight and cools a planet.
  - Deforestation removes light absorbing plants.
  - Smog increases albedo
- 4. Changes in greenhouse gas abundance
  - More gases = warmer planet = increased evaporation = more gases/more pressure and vice versa

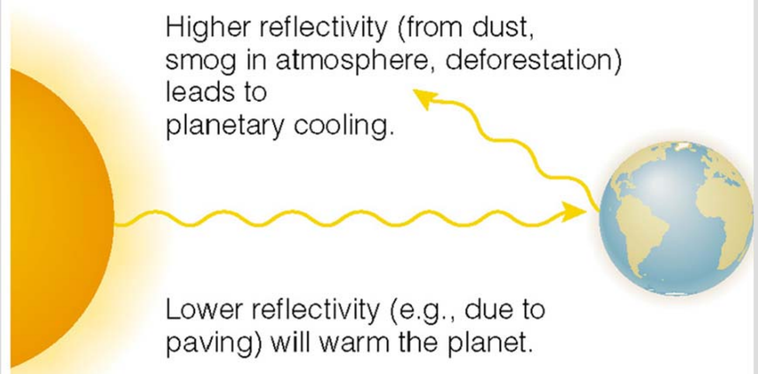
# Four Major Factors which affect Long-term Climate Change



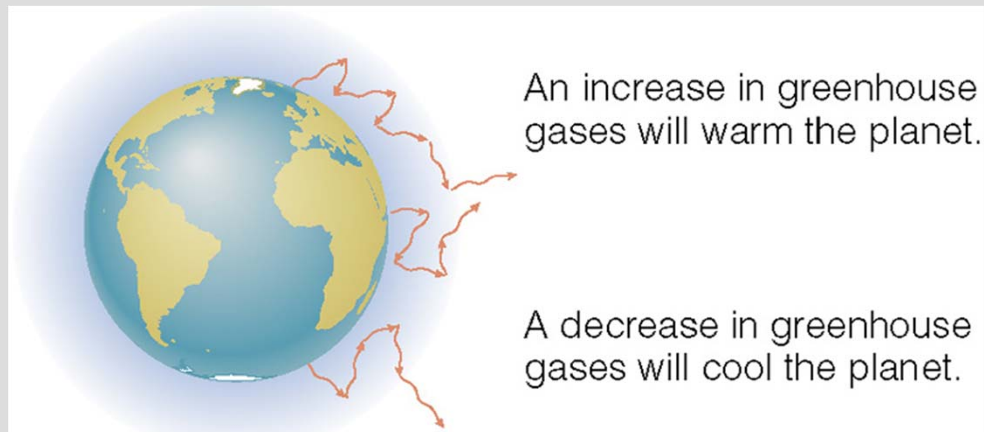

1. Solar brightening




2. Changes in axis tilt



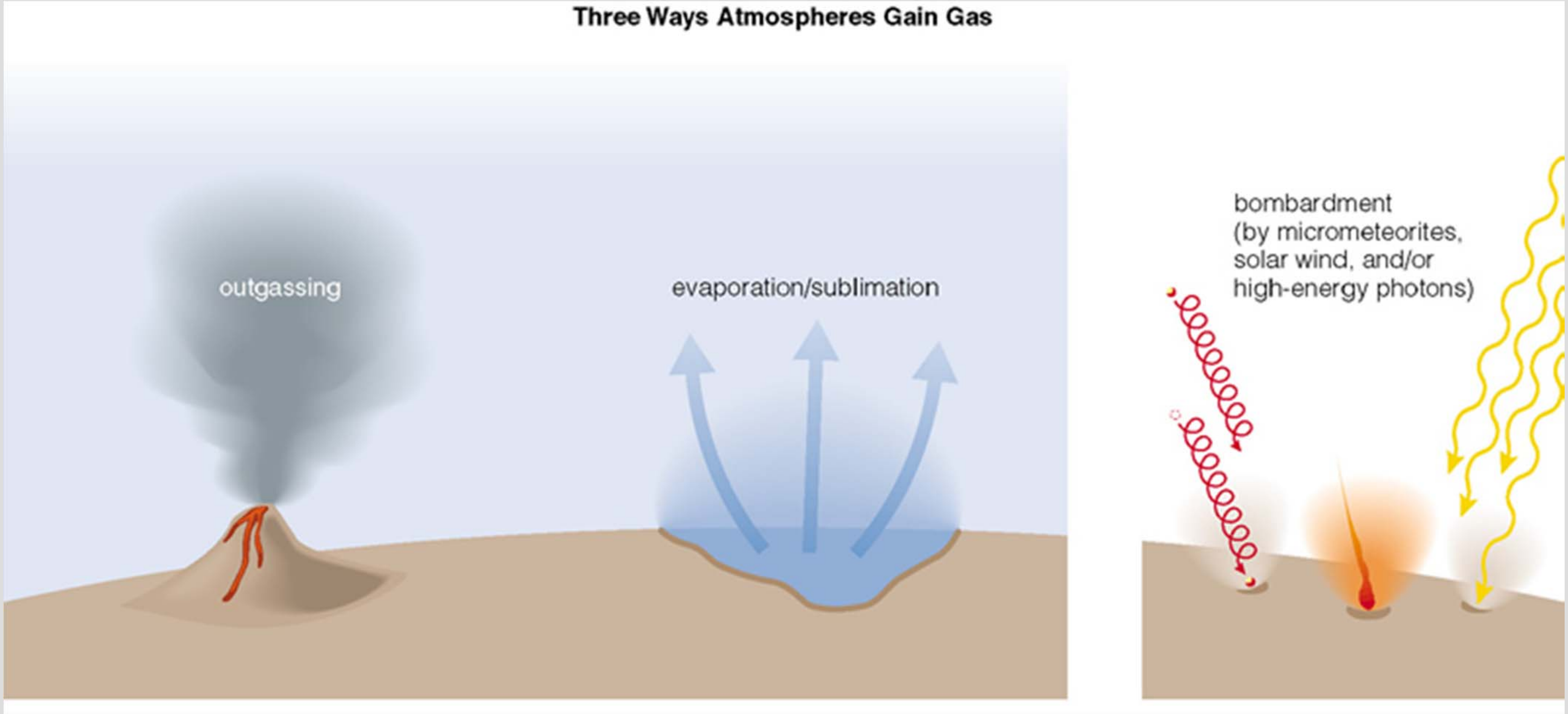

3. Changes in reflectivity




4. Changes in greenhouse gas abundance

# 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




Outgassing is most important

$H_2O$, $CO_2$, $N_2$, $SO_2$, $H_2S$ (only water present during formation)

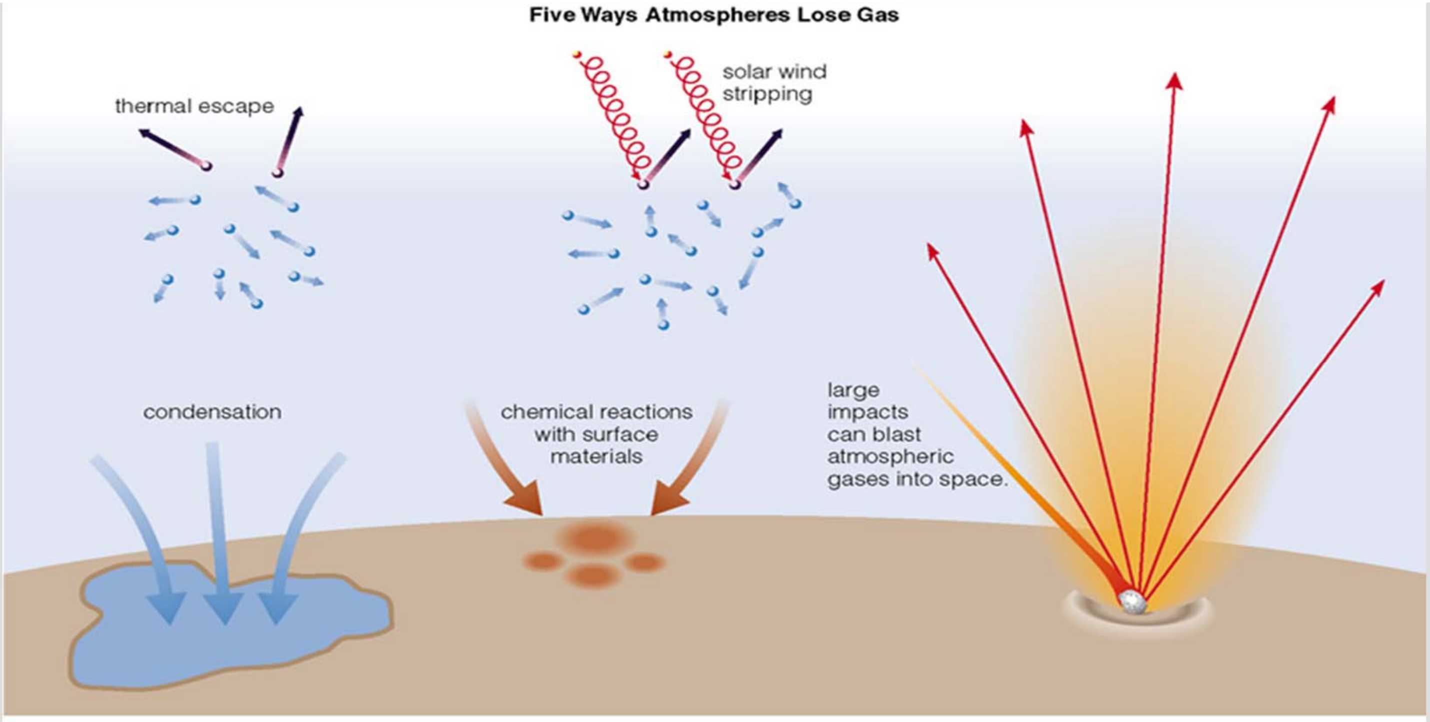
Evaporation/sublimation only adds to an atmosphere after it has formed

Bombardment only important for planets without substantial atmospheres

# 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




Condensation – rain, snow, polar caps, etc

$CO_2$ dissolves in water and makes carbonate rocks like limestone.

Stripping important on planets without magnetospheres

Impacts more important in the early solar system, gravity dependent.

Thermal escape depends on gravity, temperature and particle mass

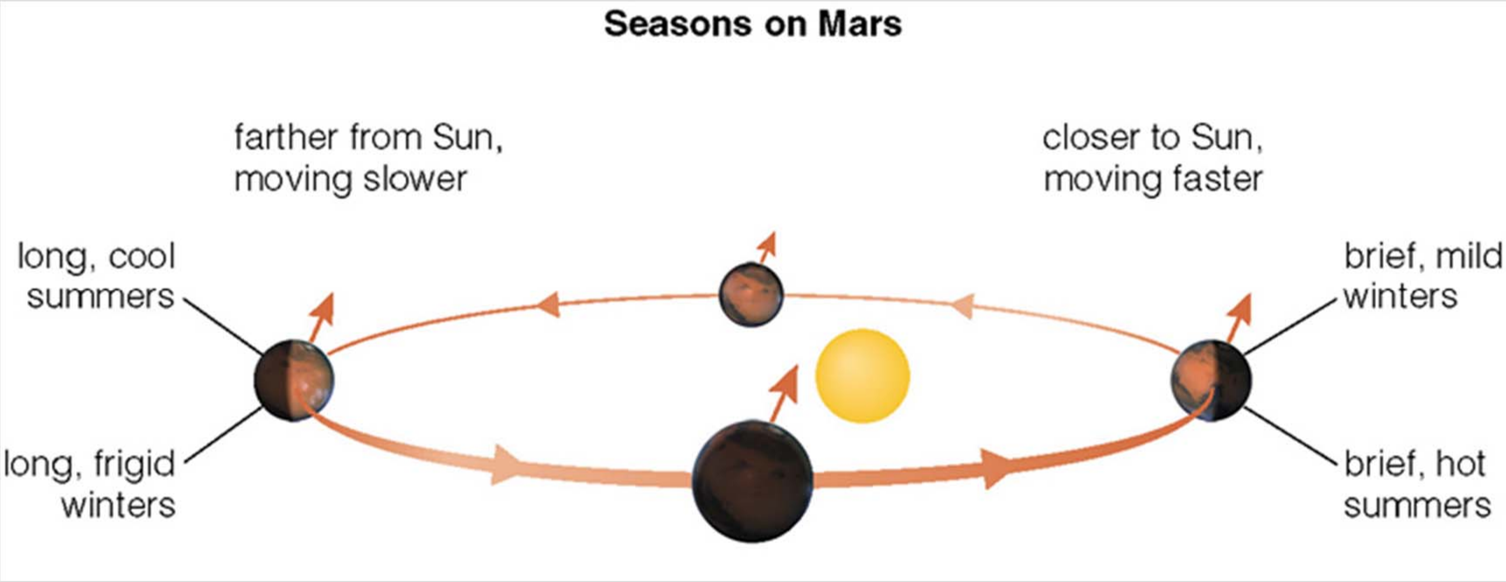
# Origin of the Terrestrial Atmospheres

- 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

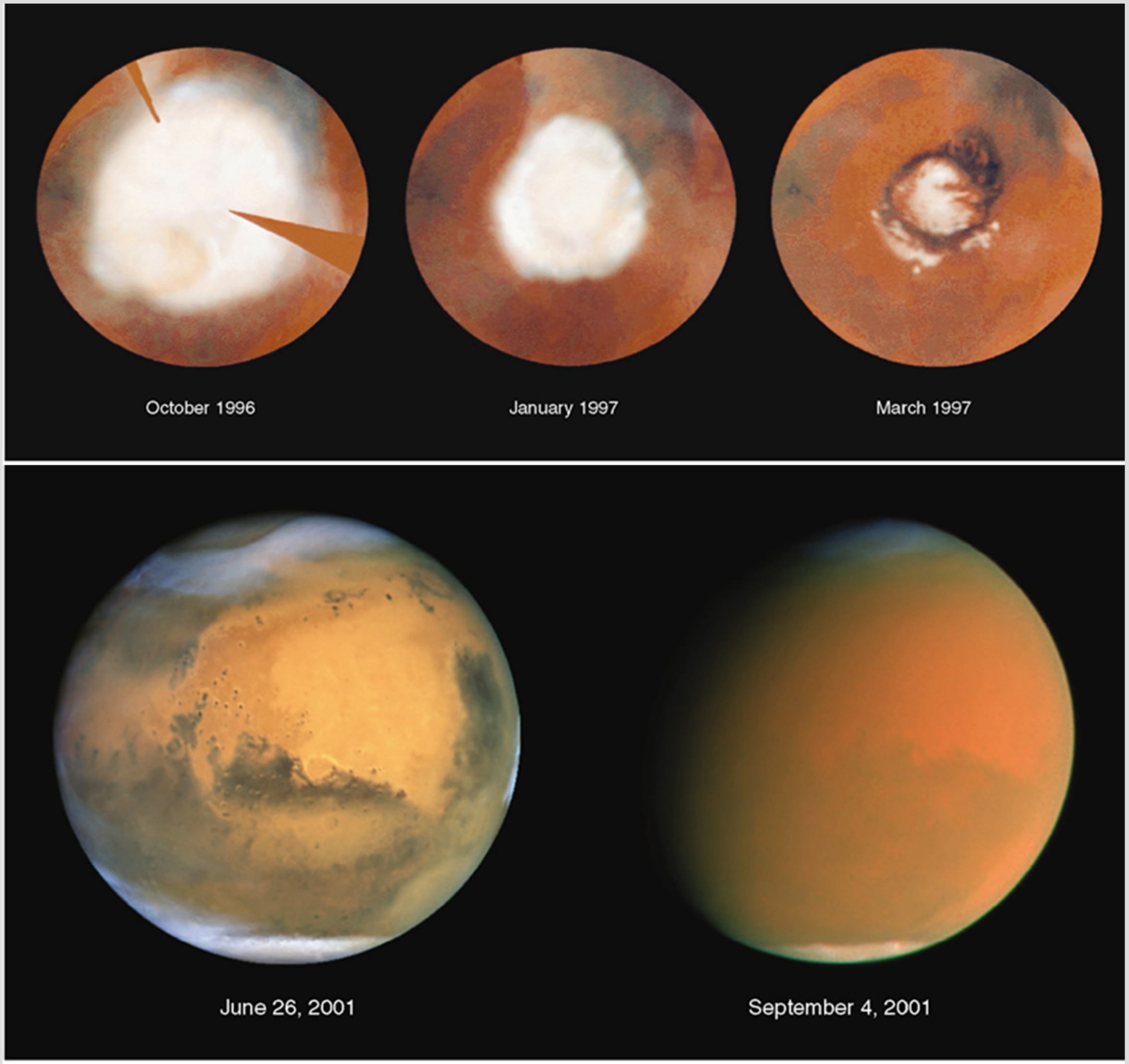
- Lack of magnetospheres on Venus & Mars made stripping by the Solar wind significant.
  - further loss of atmosphere on Mars
  - dissociation of $H_2O$, $H_2$ thermally escapes on Venus
- Gas and liquid/ice exchange occurs through condensation and evaporation/sublimation:
  - on Earth with $H_2O$
  - 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
  - Gas eventually lost to thermal escape
  - Possibility of water ice at poles

# Martian Weather Today

- Dry, no O (UV radiation), thin atmosphere, mild greenhouse effect
- Seasons on Mars are more extreme than on Earth
  - Especially in the southern hemisphere
  - 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"
  - Atmosphere created by large (now extinct) volcanoes
- Eventually $CO_2$ was lost.
  - some in the polar caps
  - some gas was lost to impacts
  - cooling interior meant loss of magnetic field
  - Solar wind stripping removed remaining gas
- Greenhouse effect weakened until Mars froze.
- Again, all due to planetary size

# 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, $SO_2$ would be taken up by surface rocks

# 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 - $H_2O$ only in atmosphere not on surface
  - UV photons from Sun dissociate $H_2O$;
    - $H_2$ lost to thermal escape
    - O lost to chemical reaction with surface rocks and solar wind stripping
  - Dissociation of "heavy" water has left tracers of deuterium
  - Explains dominance of $CO_2$ in atmosphere

# Why did Earth keep its water?