

Lecture 12: Atmospheres of the Terrestrial Planets

**Please remind me
to take a break at
12:45 pm!**



**Earth's atmosphere
seen from space**

**Claire Max
May 15, 2014
Astro 18: Planets and Planetary Systems
UC Santa Cruz**

Topics for Today



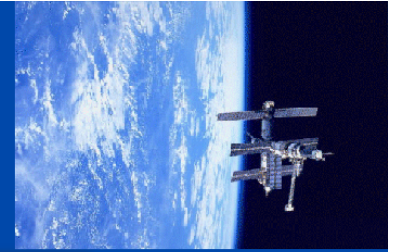
- **Part 1: Introduction to Class Projects**
- **Part 2: Lecture on Planetary Atmospheres**

Why projects?



- **Reading, homework, lectures: “content”**
 - What we know about our Solar System and others, and the scientific tools used to discover this knowledge
- **Class Projects: “enterprise of science”**
 - The way we *really* do science – starting with hunches, making guesses, making many mistakes, going off on blind roads before hitting on one that seems to be going in the right direction
- **You will choose a general topic. Then you will formulate your own specific questions about the topic, and figure out a strategy for answering them**
- **I will provide structure via “milestones” along the way, so you won’t get lost**

Projects: Getting started



- **Today:**
 - Brainstorming about potential topics
 - Topic selection
 - Group formation
 - First meeting of your group
- **Weekly e-mails to Claire from each of you: how are things going? (be sure to put “Astro18” in subject line)**
- **Final project outcomes: last two days of class (June 3rd and 5th)**
 - Presentation in class
 - Written report due June 5th

Topics chosen in the past (just a taste of what's possible)



- **Life elsewhere in the universe**
- **Hazards from Outer Space: Killer asteroids and comets**
- **New theories of Solar System formation**
- **Global warming on Earth: What's the evidence? Are people causing warming? How are predictions made?**
- **Were Mars and Venus more hospitable in the past?**
- **Mars exploration by humans (or by robots)**
- **Moons of Jupiter and Saturn**

First task today



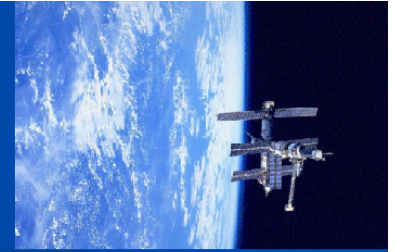
- **Brainstorm about potential project topics**
- **How to “brainstorm”:**
 - One person serves as scribe
 - Everyone suggests ideas
 - Scribe writes each one down
 - No criticisms allowed! Just put all the ideas down
 - Later you’ll decide which questions are most important, most interesting, etc. DON’T do that now.
- **Split into groups of 2 or 3 (your nearest neighbors?)**
- **Spend 10 minutes brainstorming about project topics**
 - Toss around as many questions as you can, write them down
 - What are you curious about?

Brainstorming, continued



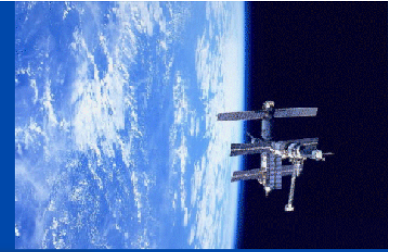
- **Main point of brainstorming is to build on each others' ideas**
- **Keeping the discussion positive (no criticisms allowed) encourages creativity.**
 - Nobody should feel “turned off” or discouraged
- **Brainstorming a generally useful method**
 - Used in businesses, arts, as well as science

***When 10 minutes have passed,
we'll try to categorize the topics***



- **Make groupings of related topics**
- **Write them on board or on sign-up sheets**
- **Ask each of you to sign up for your first choice**
 - **Include your name and email address**
- **Form groups for each topic, get together in class to get to know each other**

Example of brainstorming list for “Pluto” questions



- **What is Pluto made of? How do we know? How can we learn more?**
- **How come Pluto's orbit is so elliptical?**
- **Did Pluto used to be an asteroid? How do we know?**
- **Are there other Plutos? How would we find them?**
- **Does Pluto have an atmosphere?**
- **What will we learn from sending the New Horizons spacecraft to Pluto and Charon? Could we have learned these things from observations on the ground or in earth orbit?**
- **Does Pluto have seasons? What are they like?**

Example of brainstorming list for “planetary migration”



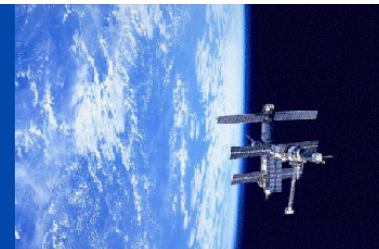
- **If we observe a solar system in which there is evidence that the planets have migrated, how can we tell what mechanism caused it?**
- **What prevents migrating giant planets from spiraling all of the way into the star?**
- **Can planets migrate outwards as well as inwards?**
- **How many of the exo-solar systems that we have observed so far need to be explained by planetary migration?**
- **Is planetary migration still happening in our own Solar System? How can we tell?**

Once you've chosen a general topic:



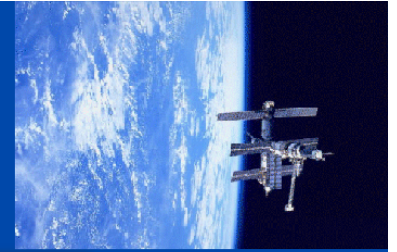
- **What specific questions can you ask (and later answer) about your general topic?**
- **Think about which of your questions are most interesting or important**
- **Think about how you would address each one**
- **Using these criteria, narrow down your list of questions to 3 – 5**
- **Take 10 minutes now**
- **Hand in your list at end of class today (be sure to keep copies for yourselves!)**

By next Tuesday May 20th



- **Each group look into their 2-3 questions to decide:**
 - Does each question still make sense?
 - Flesh it out: use reference books (in Science and Engineering Library), websites (links on class web page)
 - Why is each question important?
 - How are they related to each other?
 - What resources are available to address each question
 - Textbooks or reference books? Articles in magazines such as *Science* or *Scientific American* or *Sky and Telescope*? Websites? Journal articles?
 - Which group members is most interested in which questions?
- **Each group member sign up to address 1 or 2 specific questions**
- **Put “Astro 18” in subject line, send to max@ucolick.org before May 20th**

By Thursday May 22nd



- **(Group): Together write a 2 page summary of what your project is:**
 1. **what are your 2 or 3 questions**
 2. **why are they each important (one by one)**
 3. **how are they related to each other**
 4. **what methods can you use to address them:**
Books? Articles in magazines such as Science or Scientific American? Websites? Journal articles?
Be specific.
 5. **What help can I give you**
- **Put “Astro 18” in subject line, send to max@ucolick.org**

By Thursday May 22nd, continued



- **From each individual (each of you): email to me**
 - A short email giving me feedback on how your group is going: did everyone participate in your brainstorming session, did you feel included or left out, did you enjoy it?
 - Is someone dominating the group too much?
 - Are you finding the work interesting? Here's a place to ask advice about sources, etc.
- **Put "Astro 18" in subject line, send to max@ucolick.org**

Timetable for Projects: 2.5 weeks



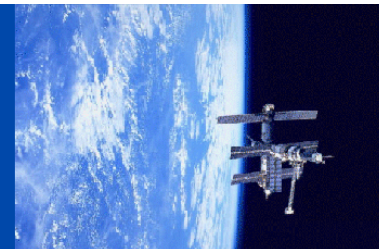
- **Today: brainstorm, choose general topics, form groups, refine questions**
- **Tuesday May 20th: read about your topic and your questions, refine them if needed, commit to specific topic**
- **Thursday May 22nd: each group write 2-page summary of project plan, each individual send me email about how project is going**
- **Week of May 26th: dig into your topics (read textbooks, other books, articles, reputable websites); meet in person with your group to collaborate; start drafting slides**
- **June 3rd and 6th: present your results in class (PowerPoint or Keynote)**
- **June 6th: final write-up due (one paper from each group)**

Planetary atmospheres: Outline



- **What is an atmosphere? What is its structure?**
- **Temperature of a planet, if the atmosphere weren't there (“no-greenhouse temperatures”)**
- **Generic atmospheric structure**
- **Global climate on**
 - Earth
 - Venus
 - Mars

The Main Points



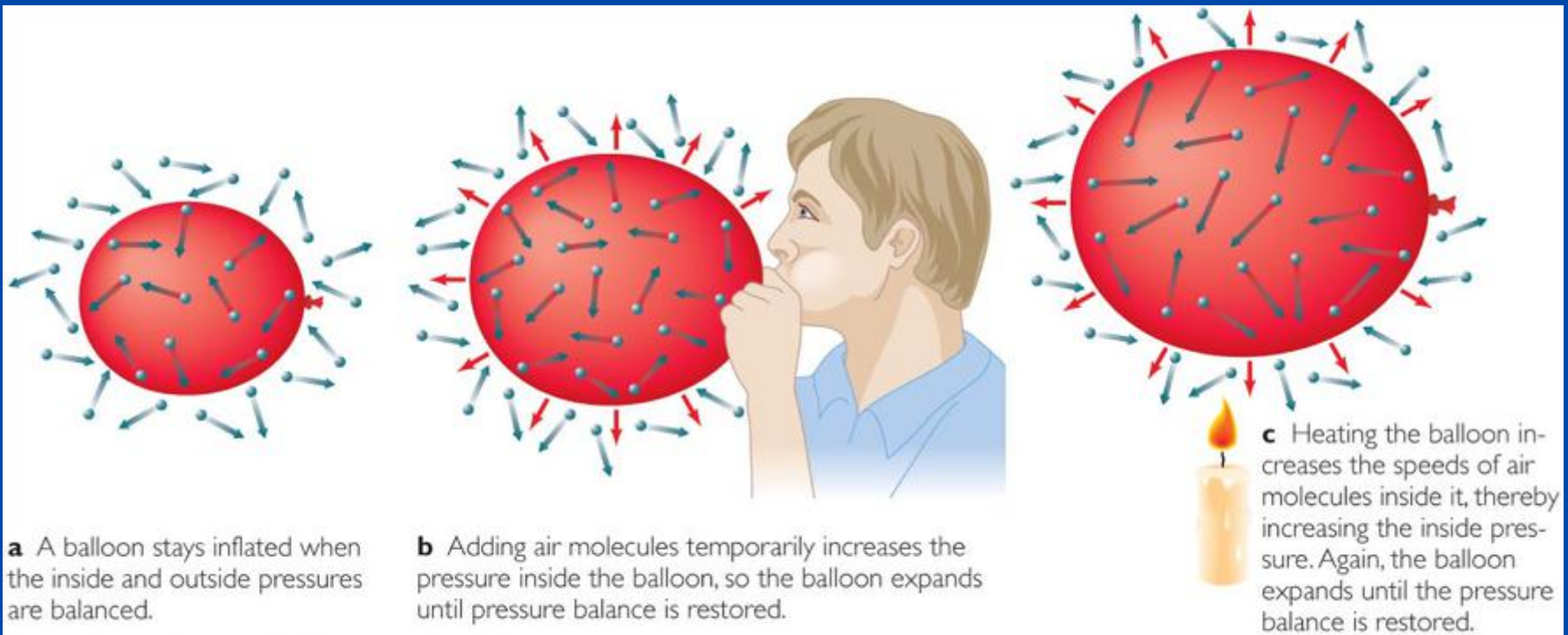
- **Planetary atmospheres as a balancing act:**
 - Gravity vs. thermal motions of air molecules
 - Heating by Sun vs. heat radiated back into space
 - Weather as a way to equalize pressures at different places on a planet's surface
- **Atmospheres of terrestrial planets are very different now from the way they were born**
 - Formation: volcanoes, comets
 - Destruction: escape, incorporation into rocks, oceans, UV light
 - Huge changes over a billion years or less
- **Prospect of human-induced global warming on Earth is a serious issue. Can be approached scientifically.**

Earth's Atmosphere: Thin blue line



- About 10 km thick
- Earth's diameter 12,000 km, 1000 times bigger
- Consists mostly of molecular nitrogen (N_2) and oxygen (O_2)
- Fractions:
 - 78% Nitrogen
 - 21% Oxygen
 - 0.04% CO_2

Atmospheric Pressure

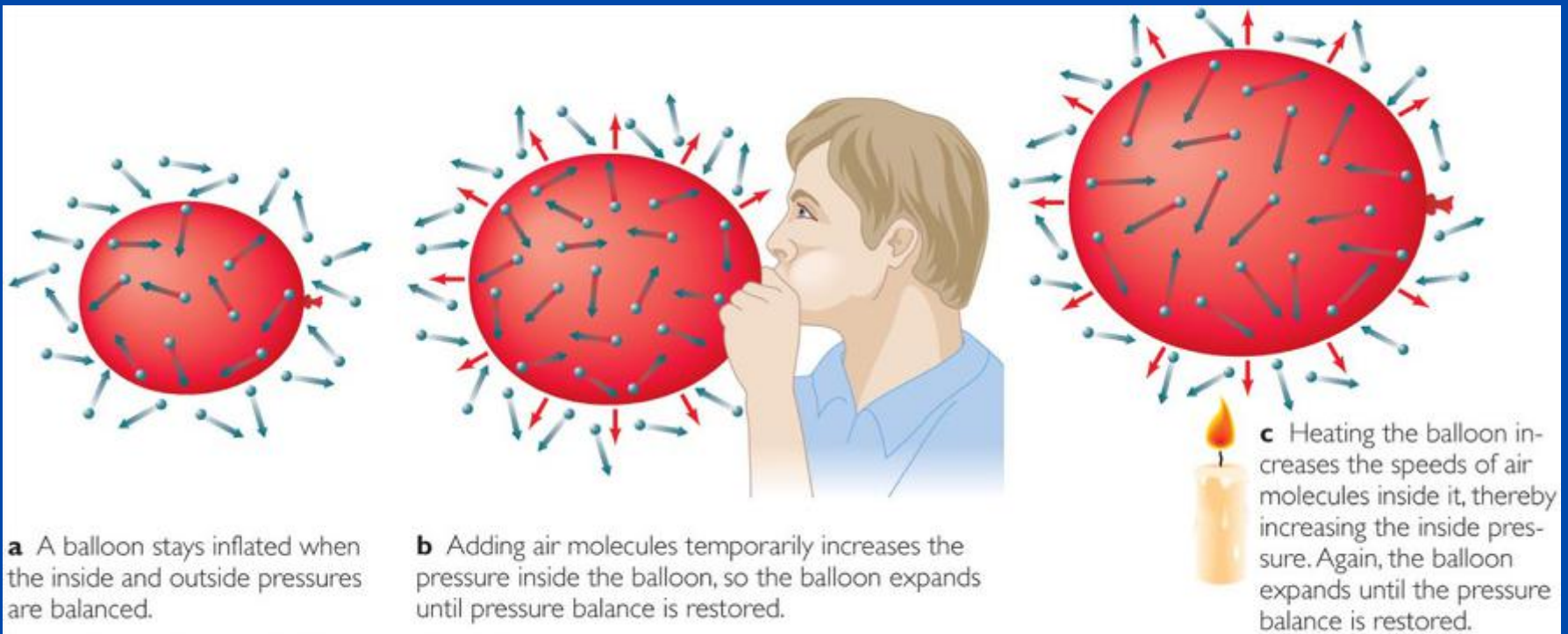
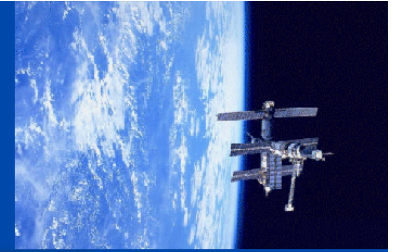


Gas pressure depends on both density and temperature.

Adding air molecules increases the pressure in a balloon.

Heating the air also increases the pressure.

Atmospheric Pressure



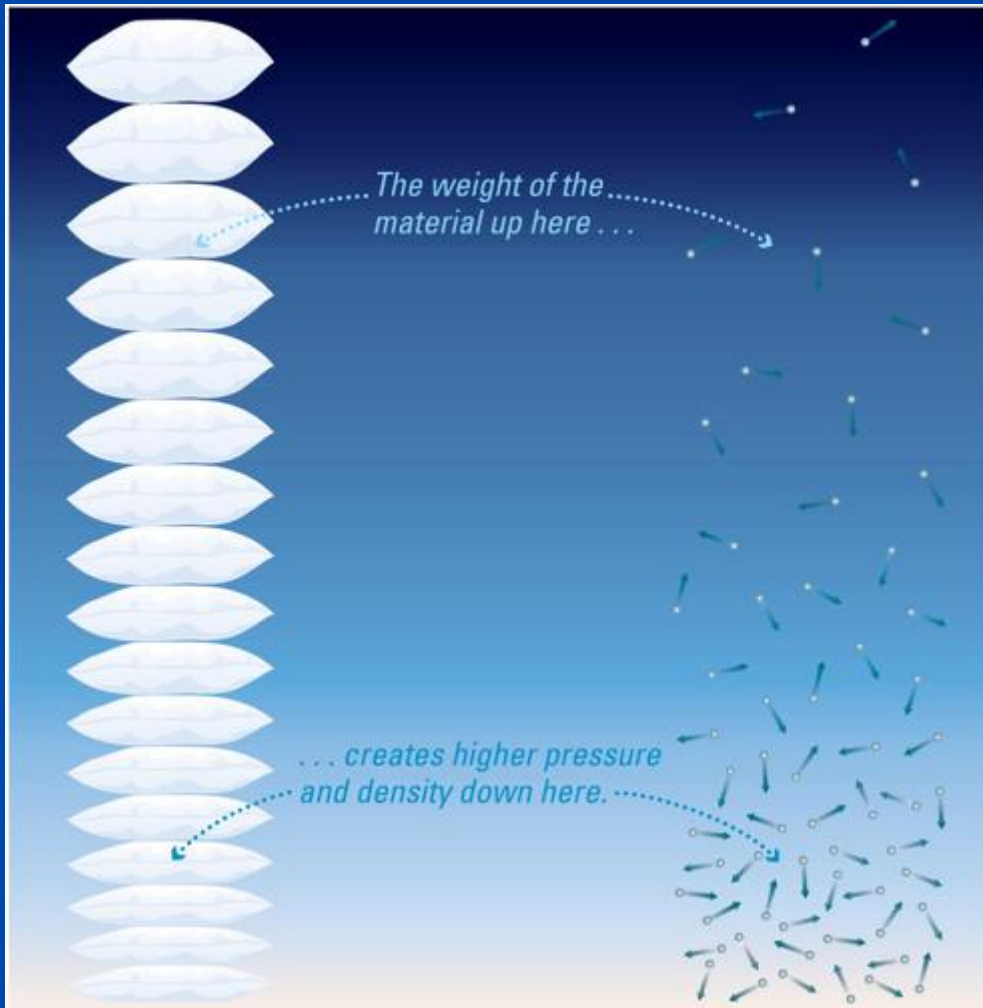
Mathematically: pressure = $p = nkT$.

Units: energy per unit volume or force per unit area

n = number density (molecules per cubic cm),

T = temperature (deg Kelvin), k = Boltzmann constant, Units of kT : energy

Atmospheric Pressure: variation with altitude



- **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

In an atmosphere in equilibrium, pressure gradient balances gravity



Pressure = Net Force / Area

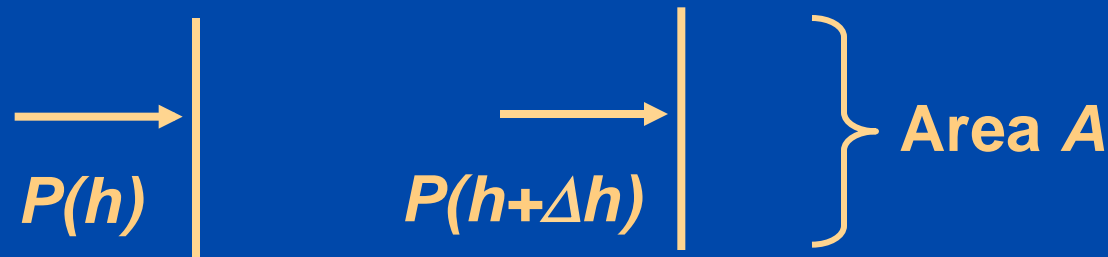
$$\text{Force} = [P(h) - P(h + dh)] \times \text{Area} = \Delta P \times A$$

$$\text{Gravitational force} = -Mg = - \left(\frac{\text{mass}}{\text{volume}} \right) \times (A\Delta h) \times g = -\rho g \times (A\Delta h)$$

$$\Delta P \times A = -\rho g \times A\Delta h$$

← volume

$$\frac{\Delta P}{\Delta h} = -\rho g \quad \text{or, in calculus language,} \quad \frac{dP}{dh} = -\rho g$$



Profile of density with altitude (a calculus-based derivation)



$$P = nkT = \left(\frac{\rho}{m}\right)kT$$

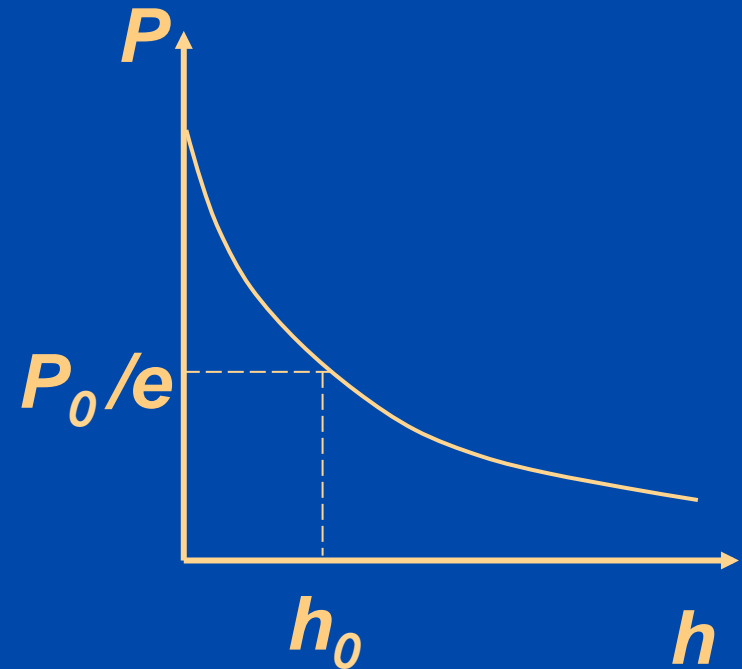
$$\frac{dP}{dh} = \frac{d}{dh}\left(\rho \frac{kT}{m}\right) = -\rho g$$

If temperature \approx const, $\frac{d}{dh}\left(\rho \frac{kT}{m}\right) = \frac{kT}{m} \frac{d\rho}{dh} = -\rho g$

Divide both sides by $\frac{kT}{\rho m}$:

$$\frac{1}{\rho} \frac{d\rho}{dh} = -\frac{mg}{kT} = \text{const}$$

Solution: $\rho = \rho_0 e^{-(h/h_0)}$ where $h_0 = \frac{kT}{mg}$



- Pressure, density fall off exponentially with altitude
- Higher temperature $T \rightarrow$ larger “scale height” h_0
- Stronger gravity $g \rightarrow$ shorter “scale height” h_0

How big is pressure scale height?



- $h_0 = kT / mg$
 - height at which pressure has fallen by $1/e = 0.368$
- Earth $h_0 = 8 \text{ km}$ ← Hence the “thin blue line”
- Venus $h_0 = 15 \text{ km}$
 - (g a bit lower, T higher)
- Mars $h_0 = 16 \text{ km}$
 - (both g and T lower)

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**

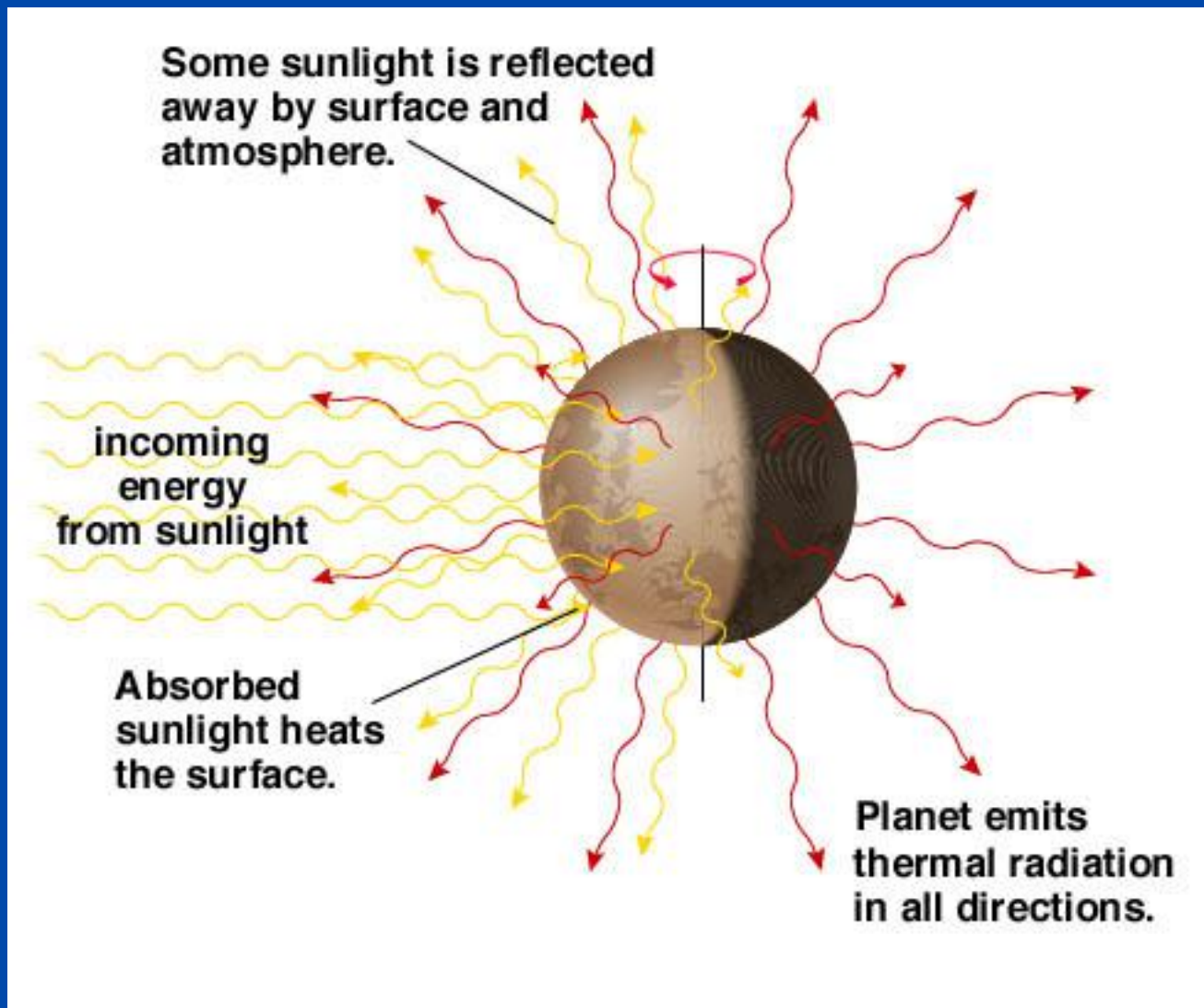
Weather and Climate



- **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.

Equilibrium atmospheric temperature (no atmosphere)



Equilibrium temperature: balance solar heating against cooling



Equilibrium or steady state: balance $W/m^2 = \text{joules/sec per } m^2$

W / m^2 absorbed from sunlight = W / m^2 emitted in thermal radiation

Scale to Earth: incident power from Sun = $1,360 \frac{W}{m^2}$ at top of atmosphere

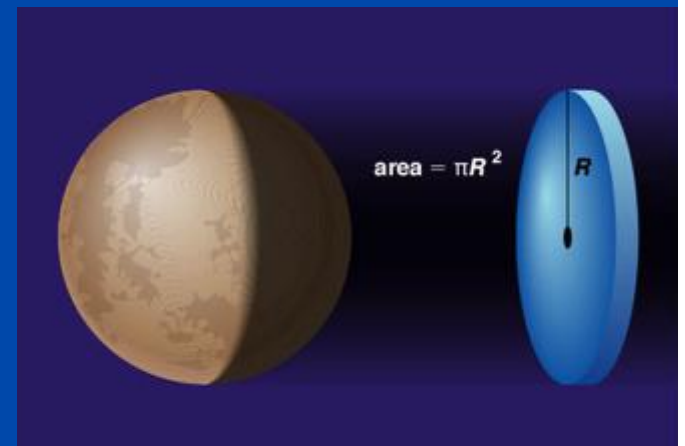
$$1,360 \frac{W}{m^2} \times \left(\frac{1 \text{ AU}}{\text{dist. from Sun}} \right)^2 \times \pi (R_{\text{planet}})^2 \times (1 - \text{albedo}) = \sigma T^4 \times 4\pi (R_{\text{planet}})^2$$

Solve for T :

$$T = \left[\frac{1,360 \text{ W} / m^2 \times (1 - \text{albedo})}{4\sigma (\text{dist. from Sun}/1 \text{ AU})^2} \right]^{1/4} = 280K \left[\frac{1 - \text{albedo}}{(\text{dist. from Sun}/1 \text{ AU})^2} \right]^{1/4}$$

“No-greenhouse”
temperature

**albedo = fraction of sunlight
that is reflected by a surface**



“No-greenhouse” temperatures



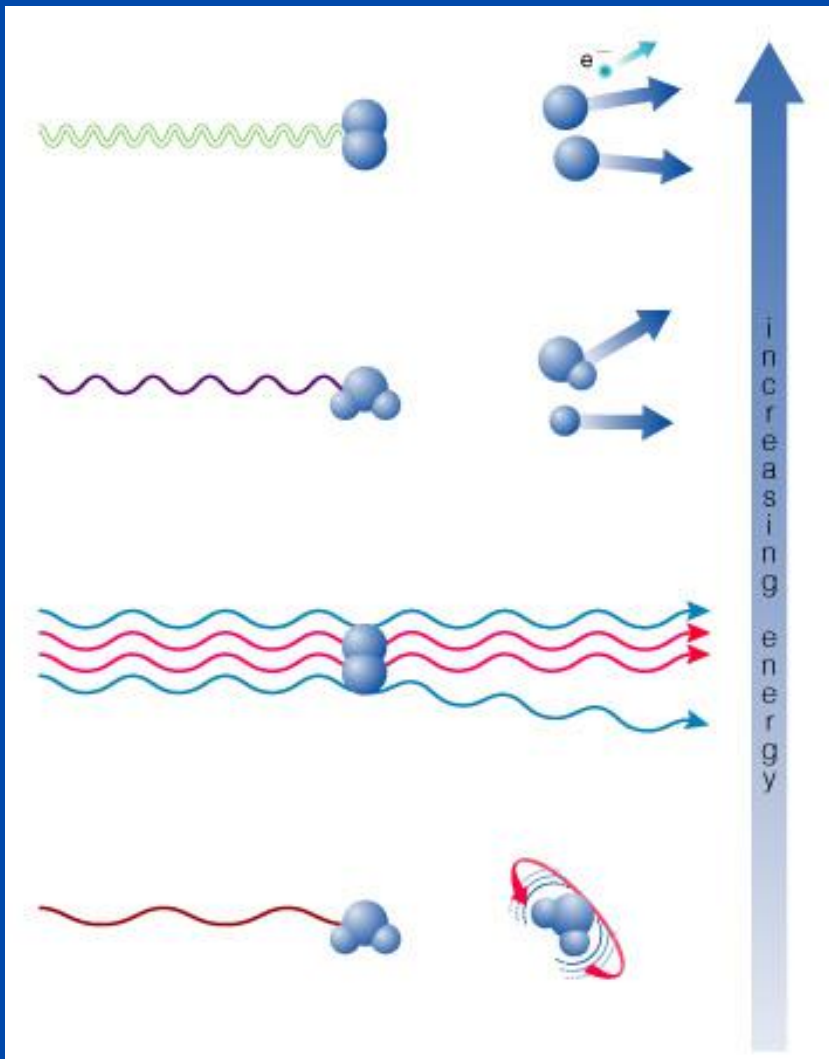
Table 10.2 The Greenhouse Effect on the Terrestrial Worlds

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	12%	163°C	425°C (day), -175°C (night)	—
Venus	0.723	75%	-40°C	470°C	510°C
Earth	1.00	29%	-16°C	15°C	31°C
Moon	1.00	12%	-2°C	125°C (day), -175°C (night)	—
Mars	1.524	16%	-56°C	-50°C	6°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.

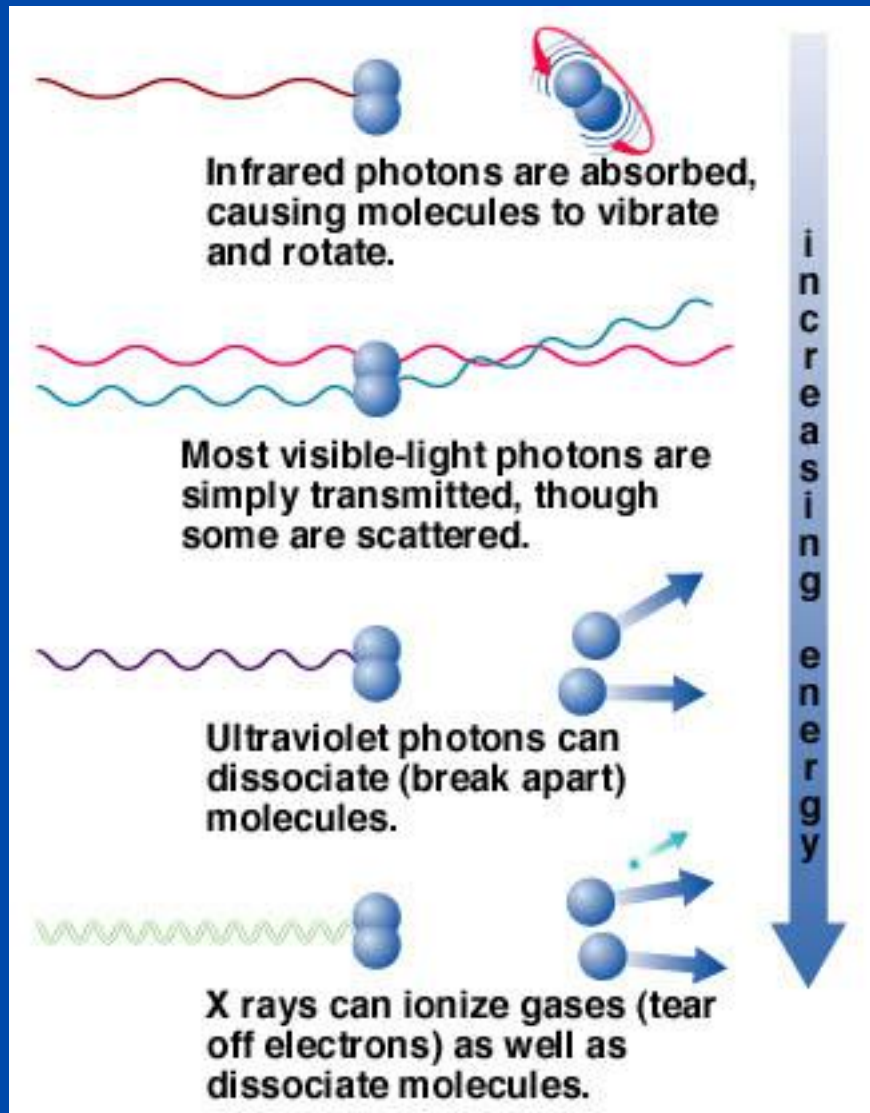
- **Conclusion: for Venus and Earth, at least, something else is going on! (not just radiation into space)**

Light's Effects on the Atmosphere

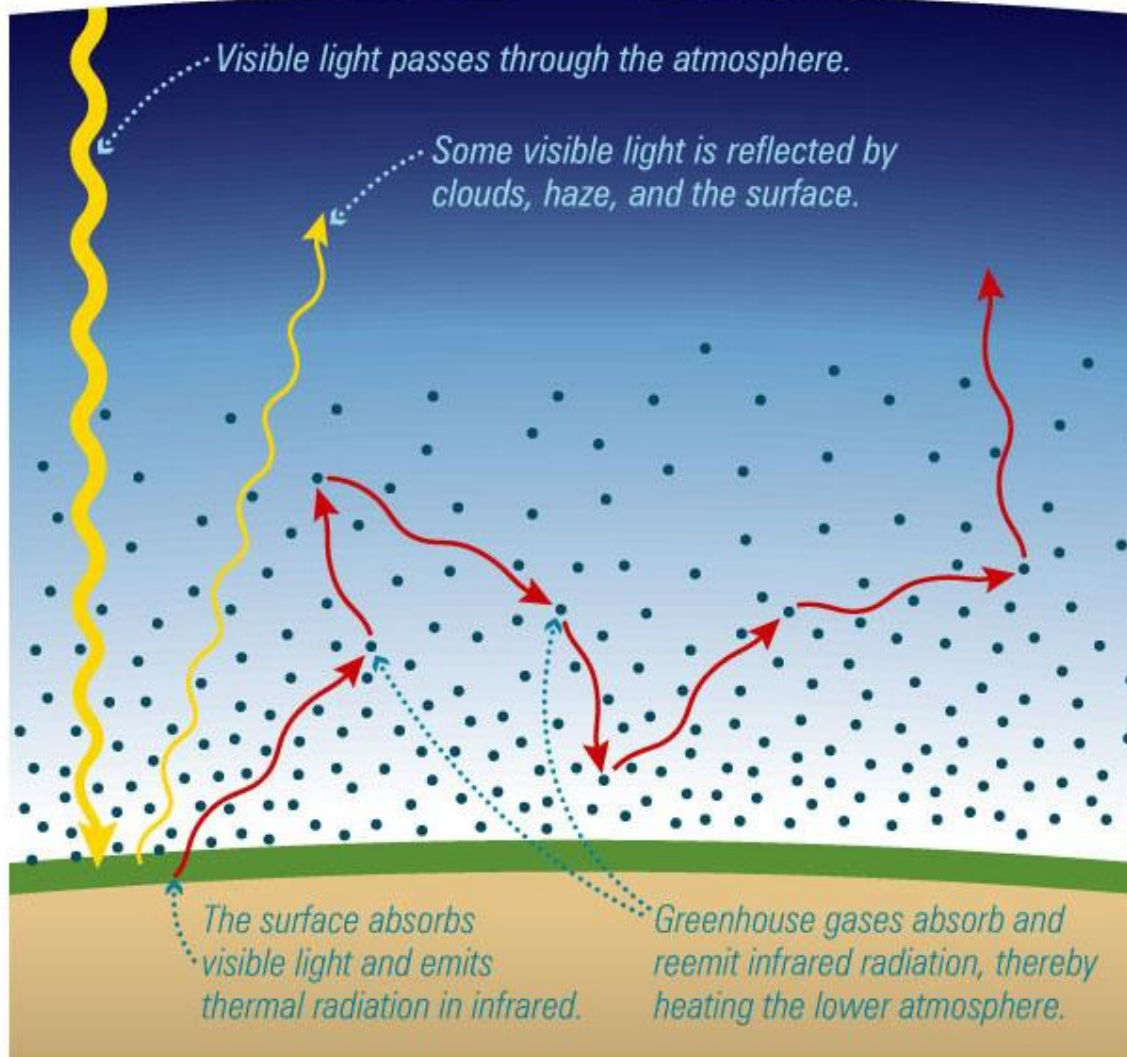


- **Ionization: Removal of an electron**
- **Dissociation: Destruction of a molecule**
- **Scattering: Change in photon's direction**
- **Absorption: Photon's energy is absorbed**

How do different energy photons interact with atmosphere?



How does the greenhouse effect warm a planet?



Greenhouse gases



- carbon dioxide CO_2
- water vapor H_2O
- methane CH_4
- others too (NO_2 ,)
- More greenhouse gases in atmosphere can lead to higher surface temperatures

Concept Question



What would happen to Earth's temperature if Earth's surface were less reflective?

- a) It would go up.**
- b) It would go down.**
- c) It wouldn't change**

Concept Question



- **What would happen to Earth's temperature if Earth's surface were less reflective?**
 - a) It would go up.
 - b) It would go down.
 - c) It wouldn't change

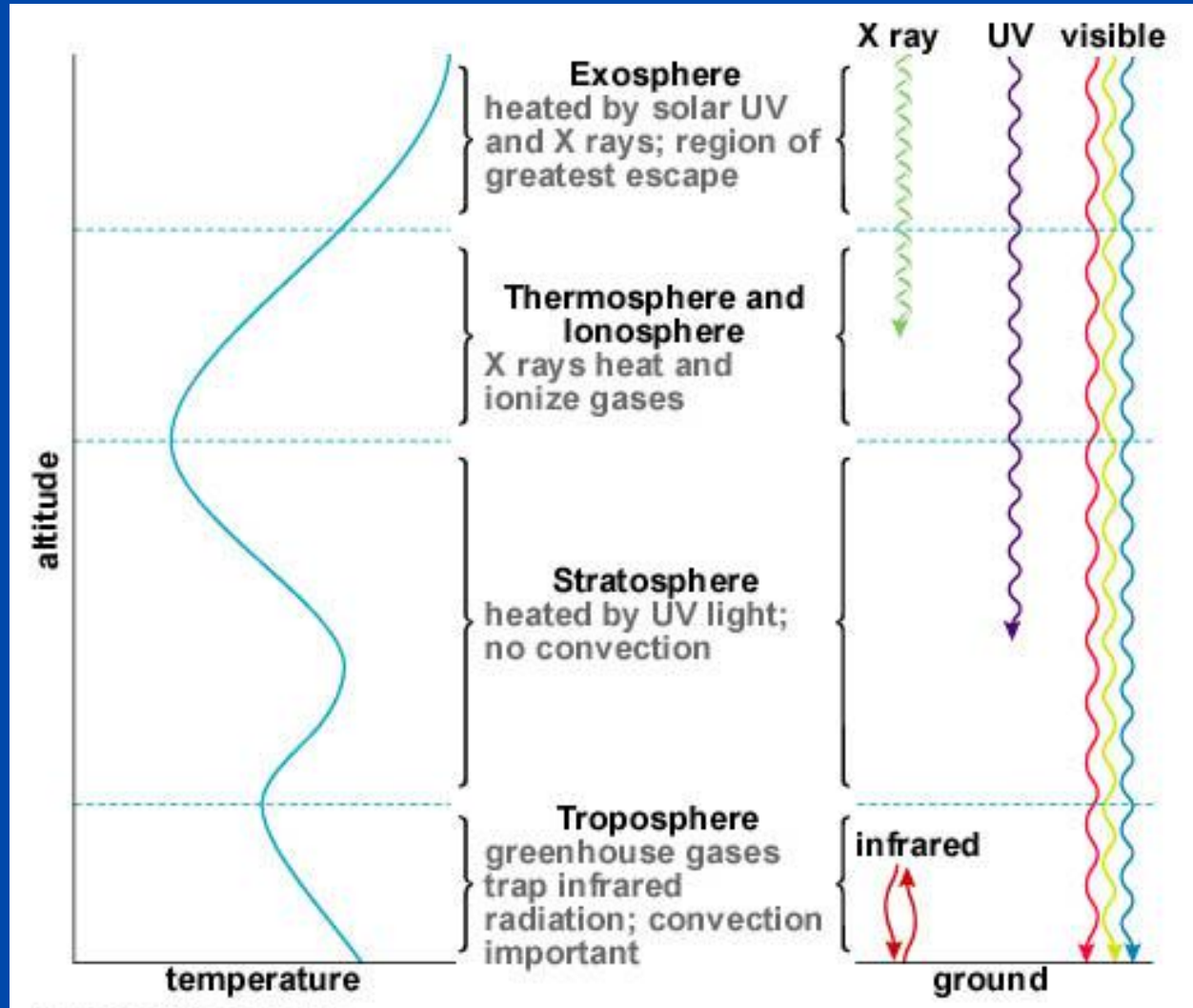
Melting sea ice lowers reflectivity, so Earth heats up more



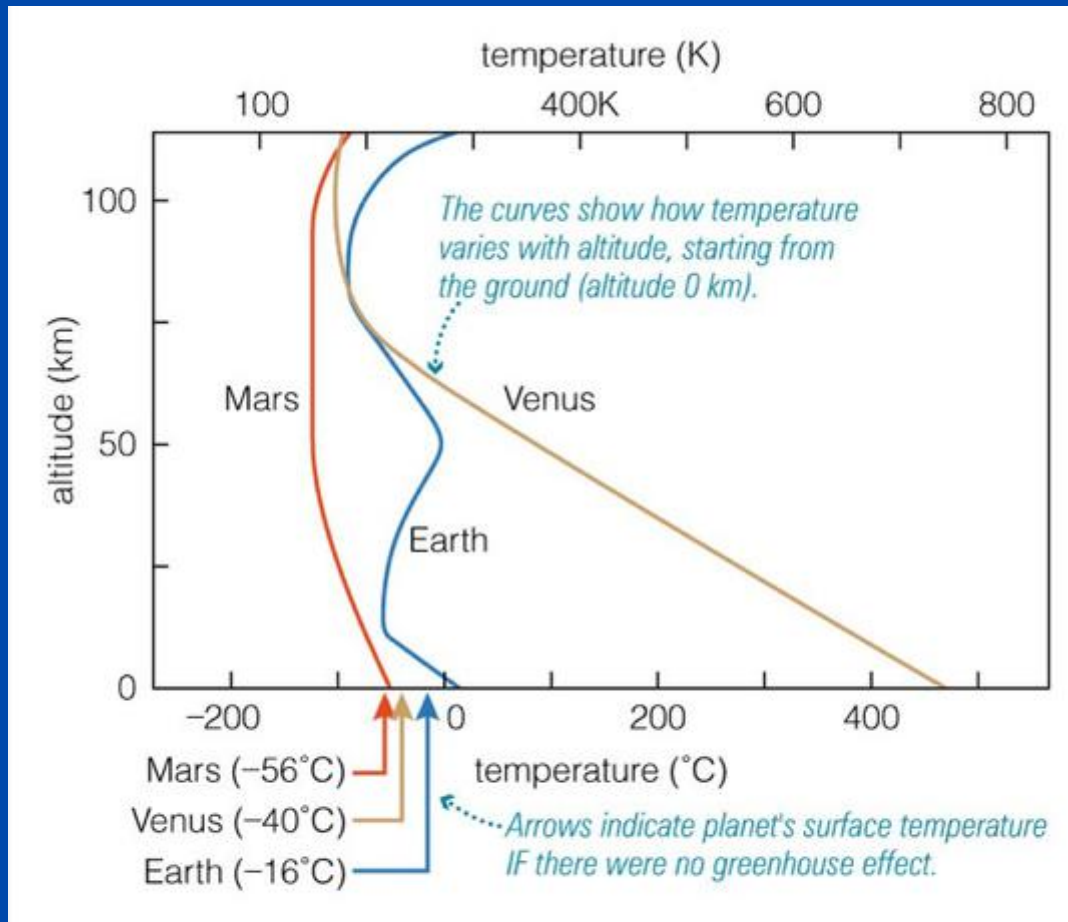
- **This is one of the factors exacerbating global warming.**
- **As more arctic ice melts in summer, arctic ocean absorbs more light, temperature rises**



Generic atmospheric structure



Compare Earth, Venus, Mars



- 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.

History of atmospheres on Venus, Earth, Mars

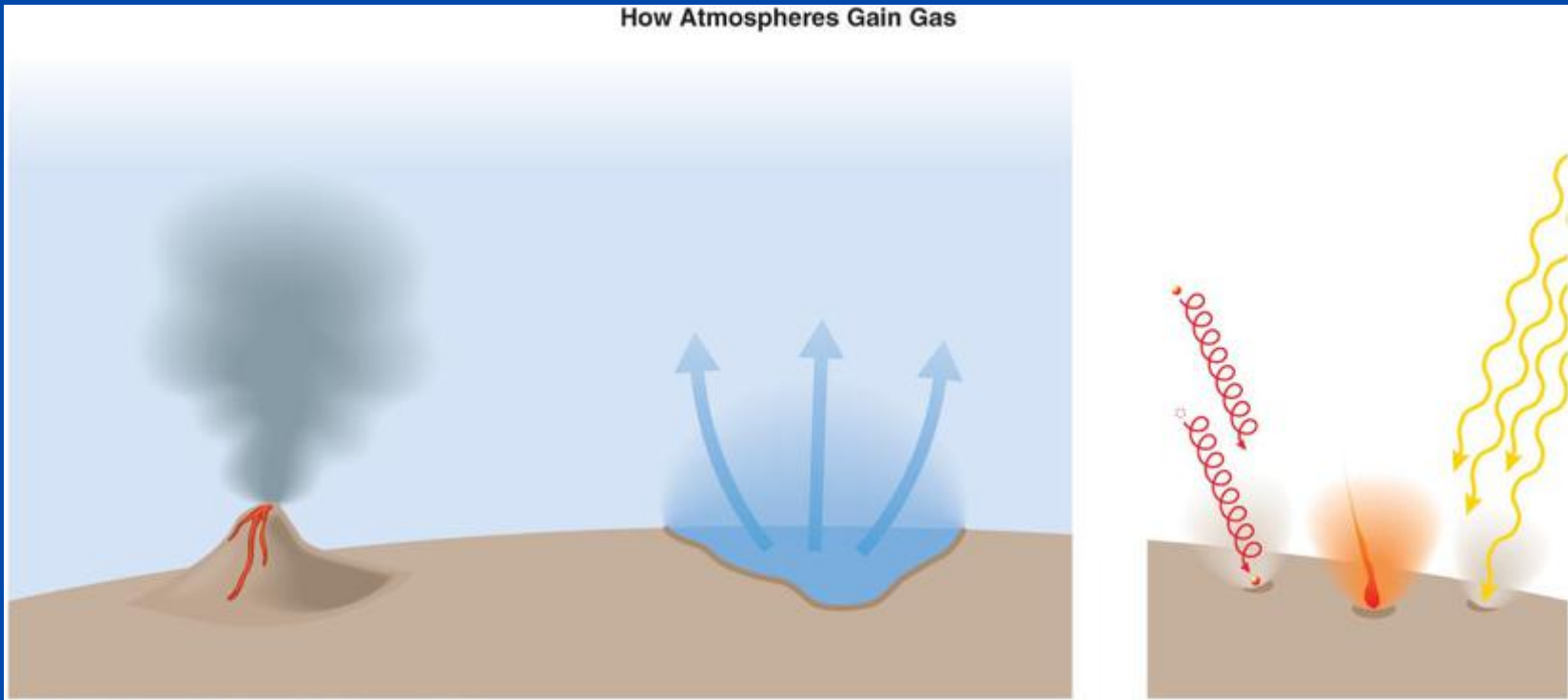


- **Huge changes took place over the 4.6 billion years since planets formed!**
 - Both Venus and Mars had more temperate atmospheres in the past than today
 - Venus was cooler, Mars was warmer
- **Question: why are atmospheres of Venus, Earth, Mars so different?**

Sources of atmospheric gases



How Atmospheres Gain Gas



Outgassing
from
volcanoes

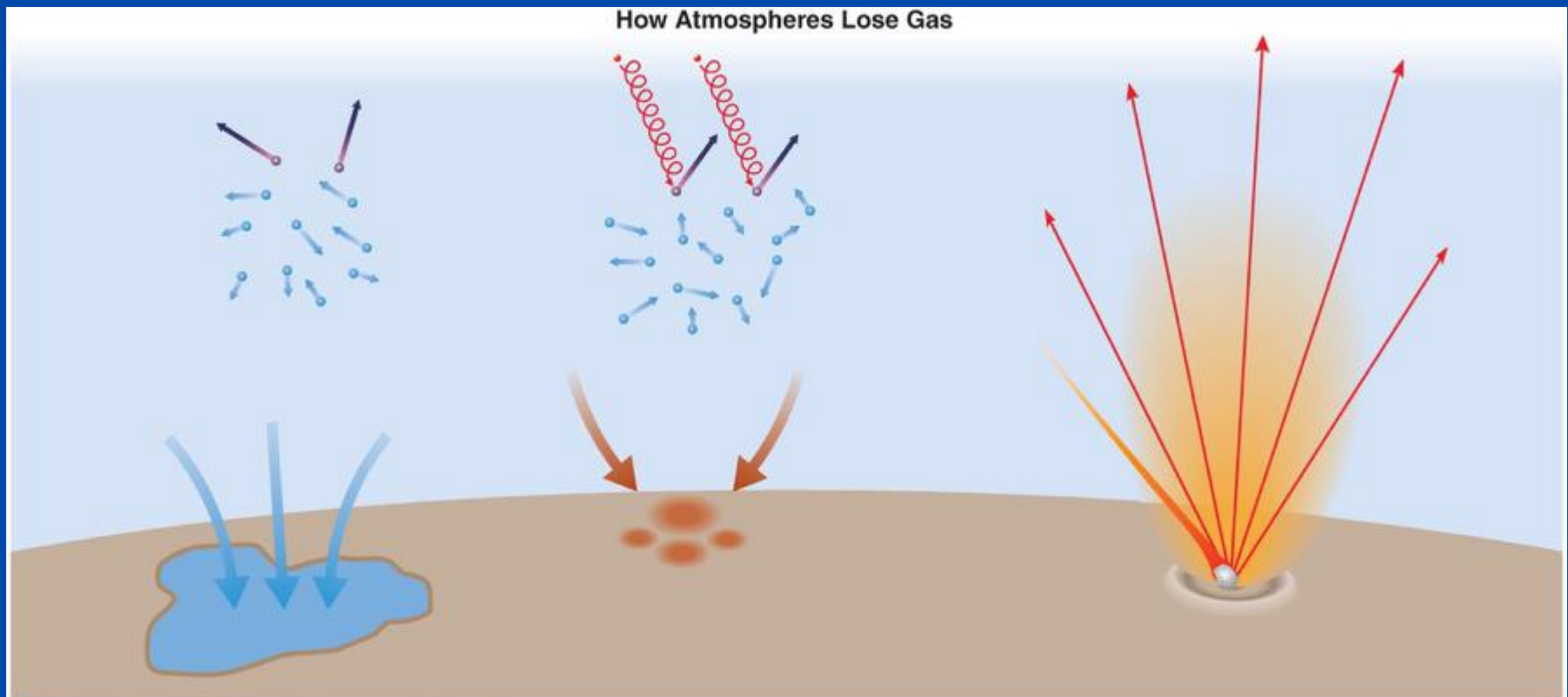
Evaporation of
surface liquid;
sublimation of
surface ice

Impacts of
particles and
photons eject
small amounts

Kilauea volcano outgassing



Losses of Atmospheric Gases

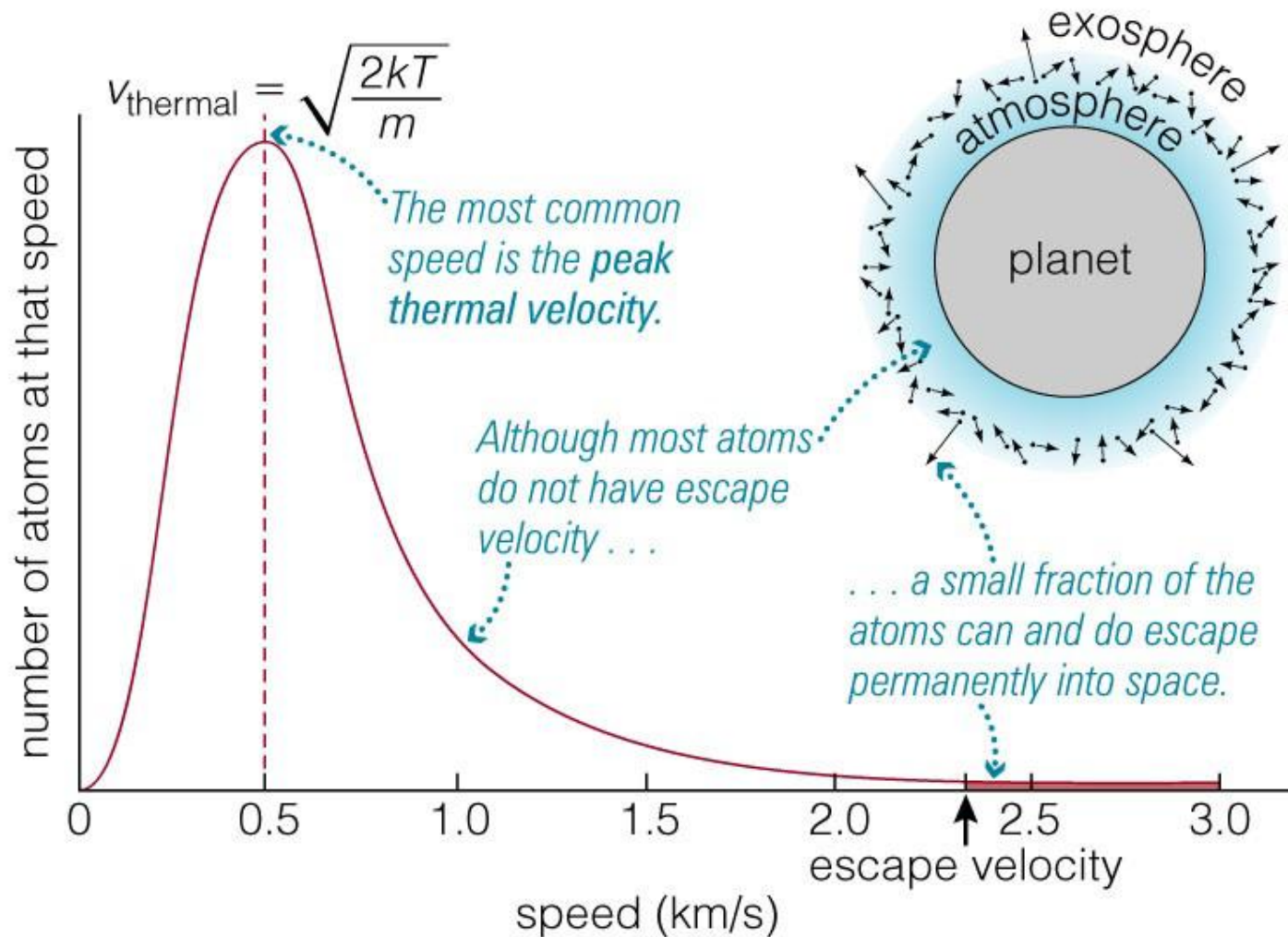


Condensation
onto surface

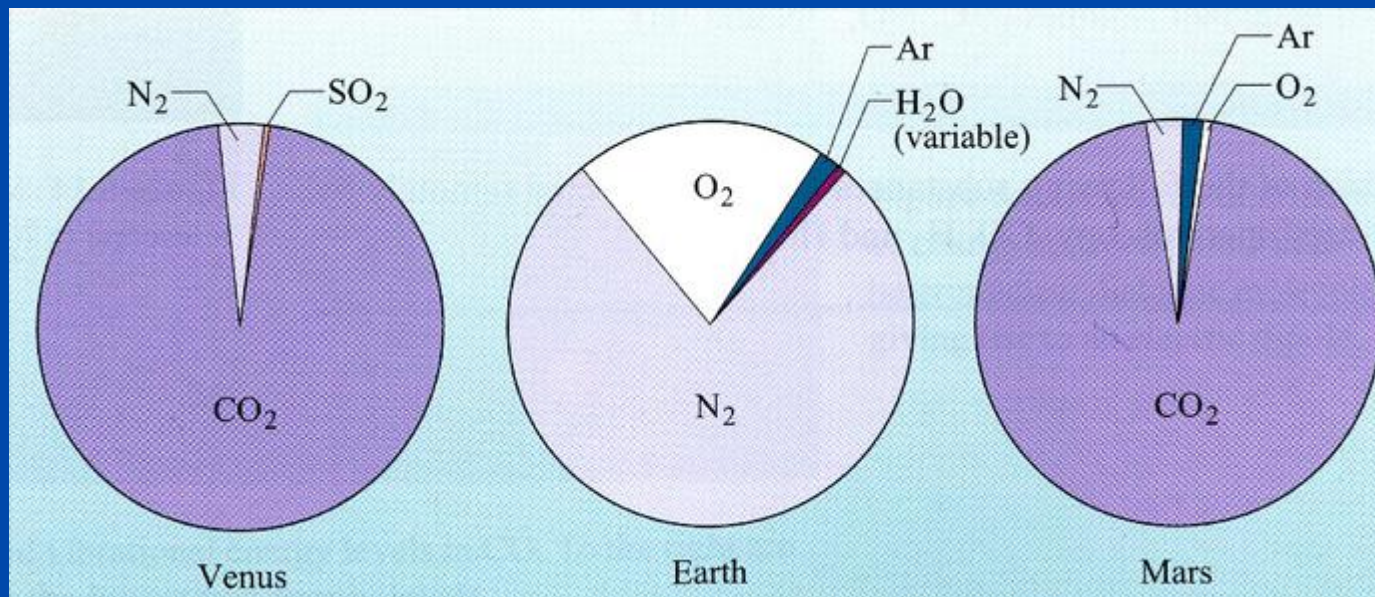
Chemical
reactions
with surface

Large impacts
blast gas into
space

Thermal Escape of atmospheric gases



Components of atmospheres on Venus, Earth, Mars



- Why are they so different?
- Were they always this different from each other?

The three atmospheres of Earth: “First Atmosphere”



- **First Atmosphere: Primordial elements**
 - Composition - Probably H₂, He
- **Today these gases are relatively rare on Earth compared to other places in the universe.**
- **Were probably lost to space early in Earth's history because**
 - Earth's gravity is not strong enough to hold lightest gases
 - Earth still did not have a differentiated core (solid inner/liquid outer core) which creates Earth's magnetic field (magnetosphere = Van Allen Belt) which deflects solar wind. Magnetosphere protects any atmosphere from the solar wind.
- **Once the core differentiated, gases could be retained.**

“Second atmosphere”: produced by volcanic outgassing



- Gases similar to those from modern volcanoes (H_2O , CO_2 , SO_2 , CO , S_2 , Cl_2 , N_2 , H_2) and NH_3 (ammonia) and CH_4 (methane)
- No free oxygen (O_2 not found in volcanic gases)
- Ocean Formation - As Earth cooled, H_2O produced by outgassing could exist as liquid
- CO_2 could then dissolve in ocean, be sequestered in marine sediments



“Third atmosphere”: Free oxygen, lower CO₂

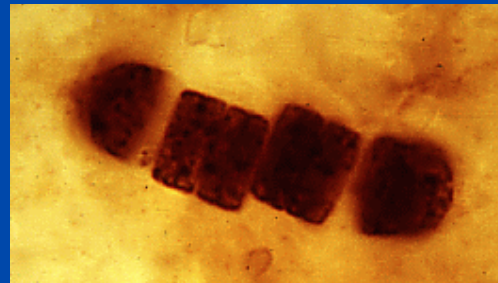


- Today, atmosphere is ~21% free oxygen. How did oxygen reach this level?
- **Oxygen Production**
 - Photochemical dissociation - breakup of water molecules by ultraviolet light
 - » Produced O₂ levels 1-2% current levels
 - » At these levels O₃ (Ozone) could form to shield Earth surface from UV
 - Photosynthesis: CO₂ + H₂O + sunlight = organic compounds + O₂ - Supplied the rest of O₂ to atmosphere.
- **Oxygen Consumers**
 - Chemical Weathering - through oxidation of surface materials (early consumer)
 - Respiration of plants and animals (much later)
 - Burning of Fossil Fuels (much, much later)
- **Once rocks at the surface were sufficiently oxidized, more oxygen could remain free in the atmosphere**

Cyanobacteria and stromatolites made early oxygen for atmosphere



- **The first photosynthesis**
 - Consumes CO₂, release O₂



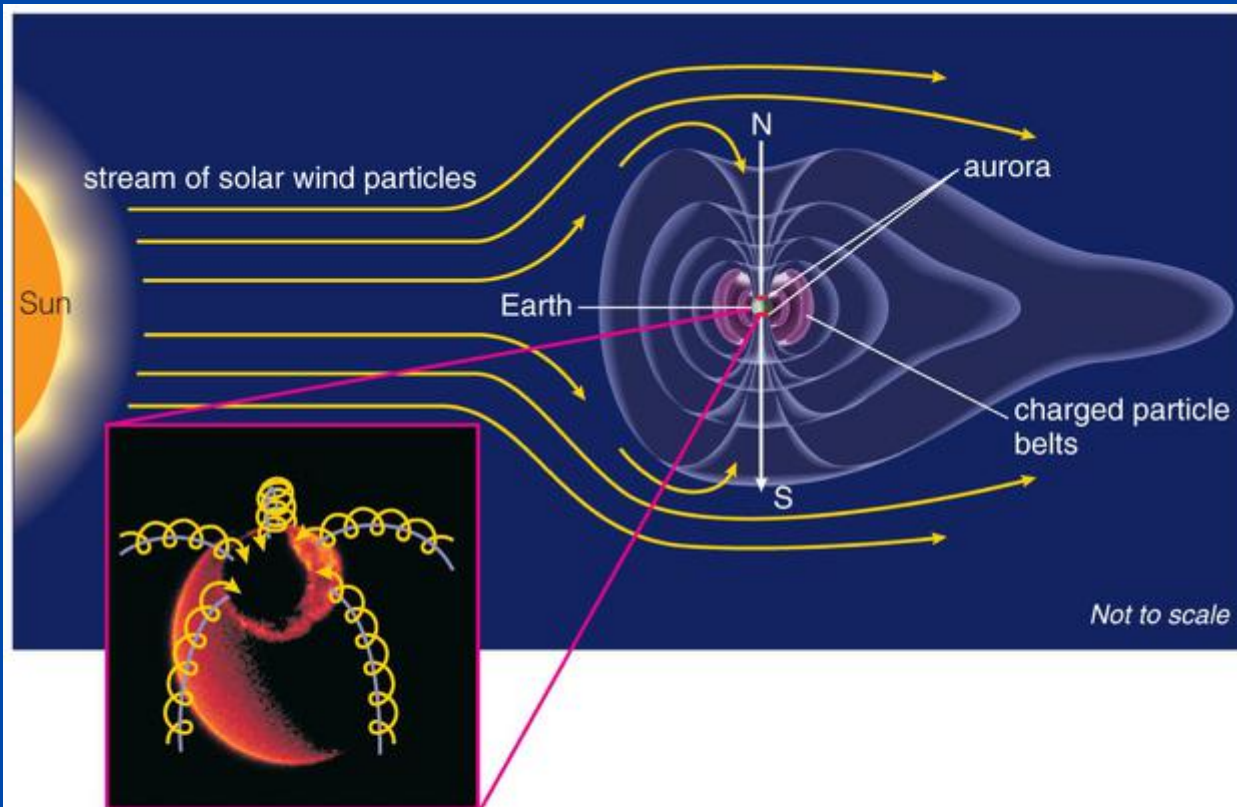
Cyanobacteria: colonies are called stromatolites

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 ultraviolet light.**

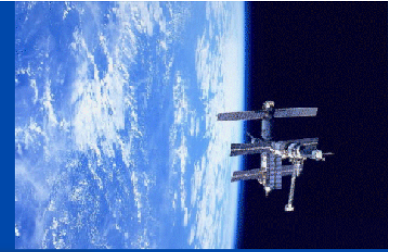
Earth's Magnetosphere



a This diagram shows how Earth's magnetosphere deflects solar wind particles. Some particles accumulate in charged particle belts encircling our planet. The inset is a photo of a ring of auroras around the North Pole; the bright crescent at its left is part of the day side of Earth.

- **Magnetic field of Earth's atmosphere protects us from charged particles streaming from Sun (the solar wind).**

Aurora (“Northern lights”)



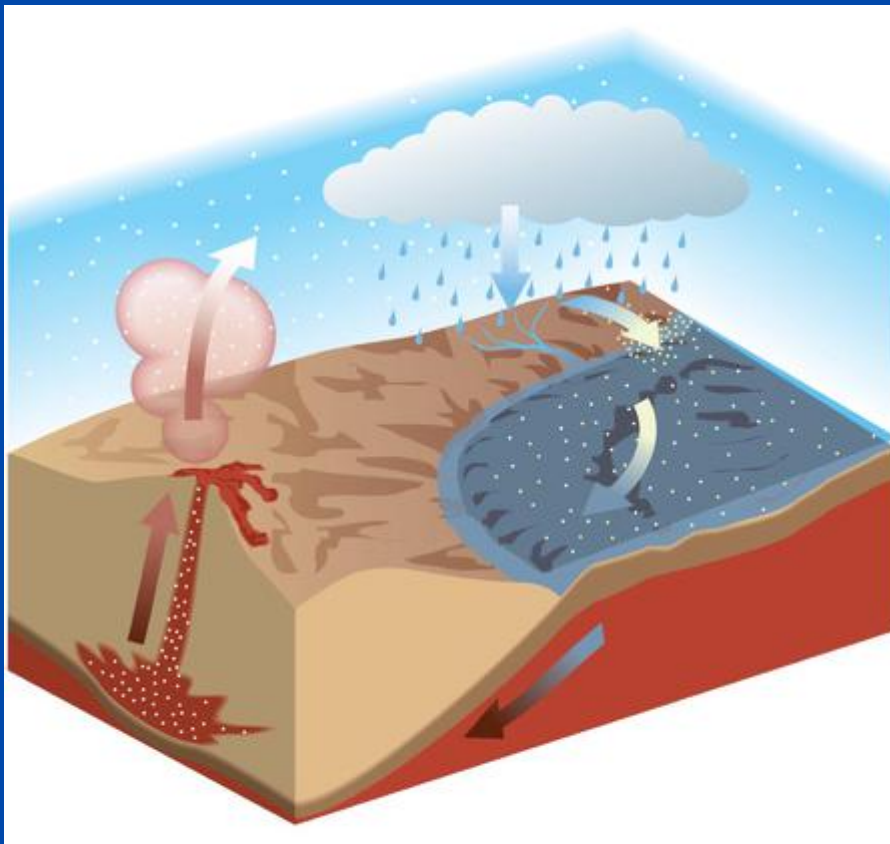
b This photograph shows the aurora near Yellowknife, Northwest Territories, Canada. In a video, you would see these lights dancing about in the sky.

- Charged particles from solar wind energize the upper atmosphere near magnetic poles, causing an aurora.
- Different colors are caused by different atomic species (oxygen, nitrogen, etc) that are excited by the energetic particles.

Why does Earth's climate stay relatively stable?

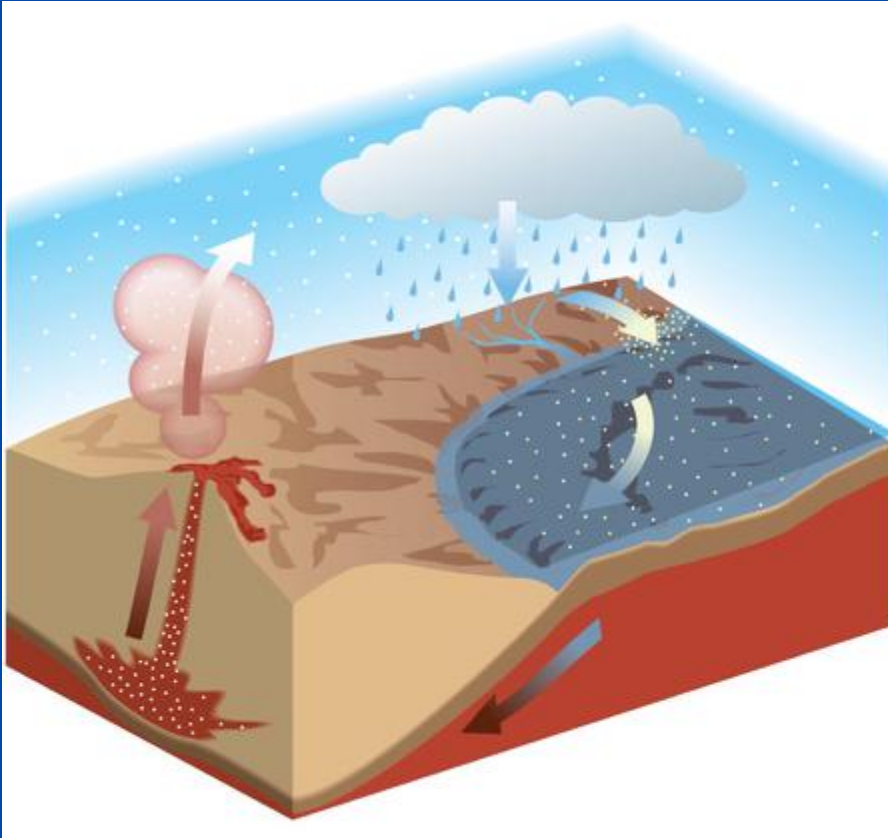
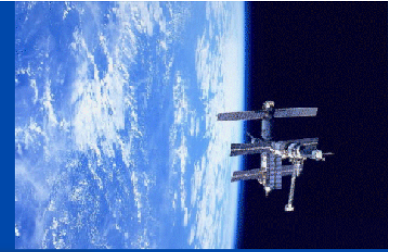


The Carbon Dioxide Cycle



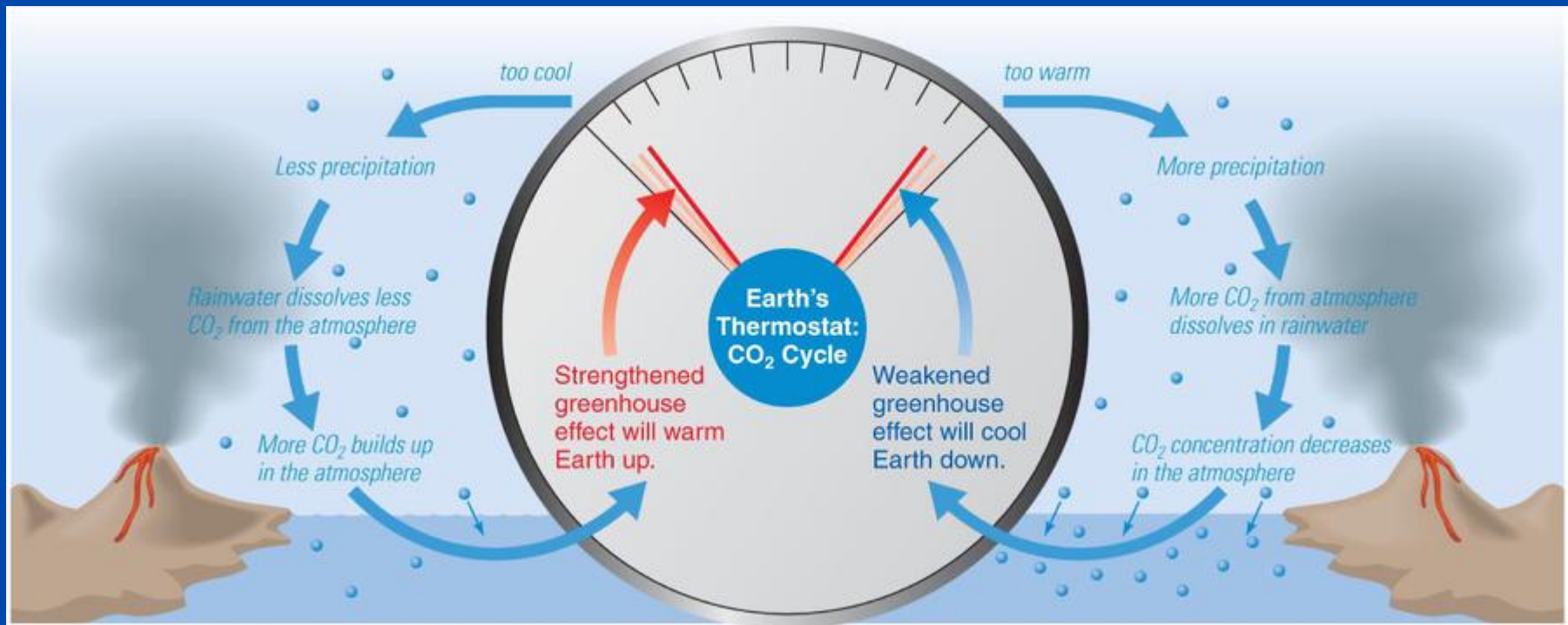
1. Atmospheric CO_2 dissolves in rainwater
2. Rain erodes minerals which flow into ocean
3. Minerals combine with carbon to make rocks on ocean floor

Why does Earth's climate stay relatively stable?



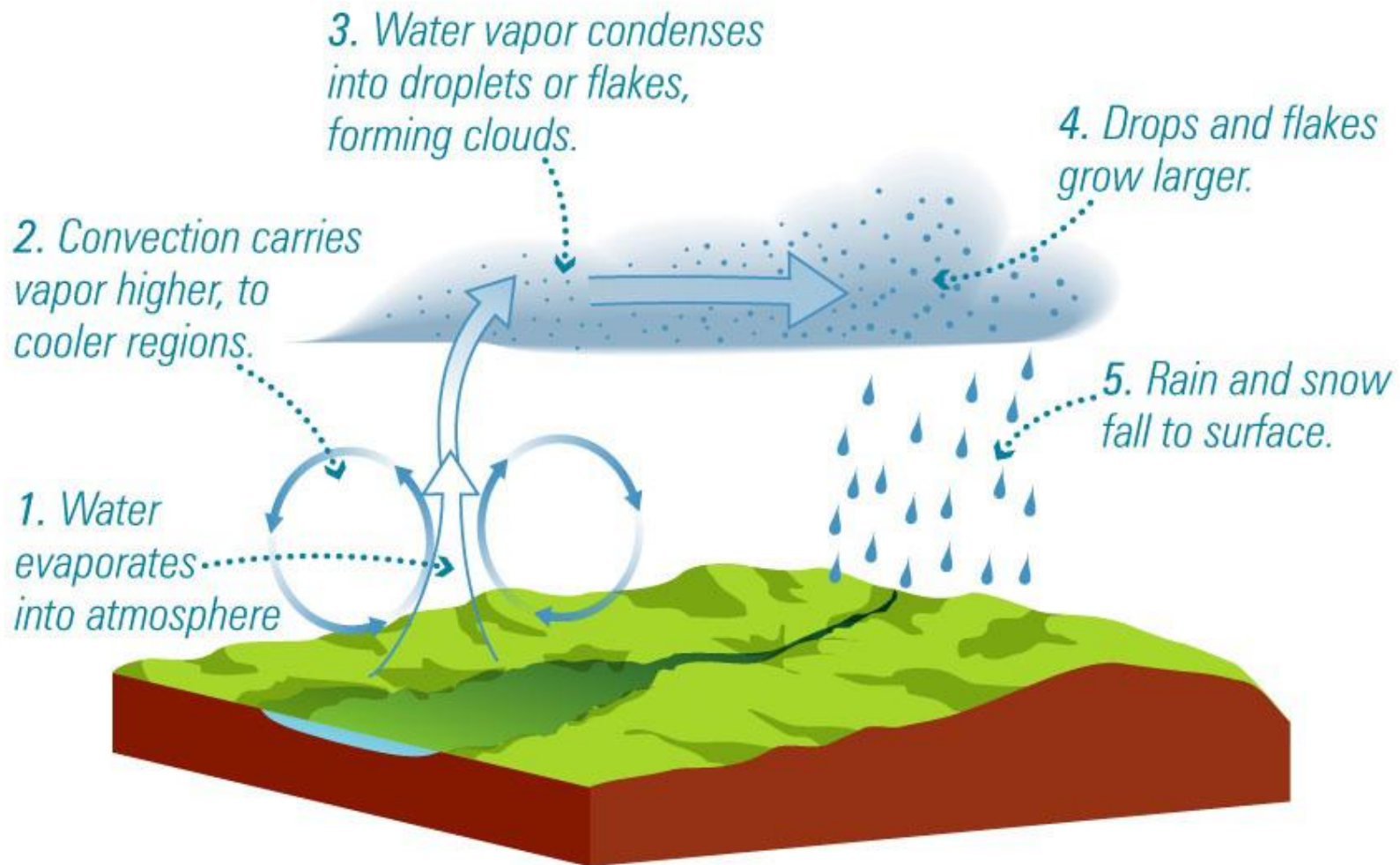
4. Subduction carries carbonate rocks down into mantle
5. Rocks melt in mantle and outgas CO₂ back into atmosphere through volcanoes
6. Note that Plate Tectonics is essential component of this cycle

Earth's Thermostat



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

Earth: hydrological cycle



Did Earth get its water from comets?

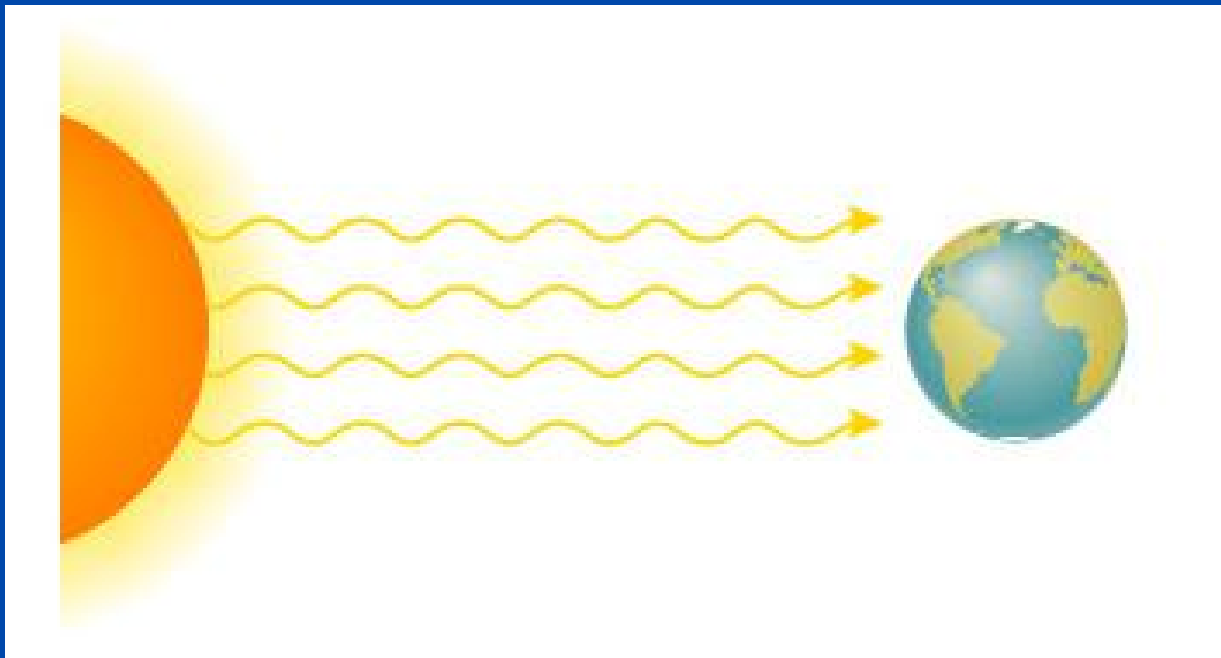


- **Some water from outgassing volcanoes**
- **Second potential source of the Earth's ocean water is comet-like balls of ice.**
- **Enter atmosphere at rate of about 20/second.**
- **Four billion years of such bombardment would give enough water to fill the oceans to their present volume.**
- **Possible problems: isotope ratios don't match. Under active research.**



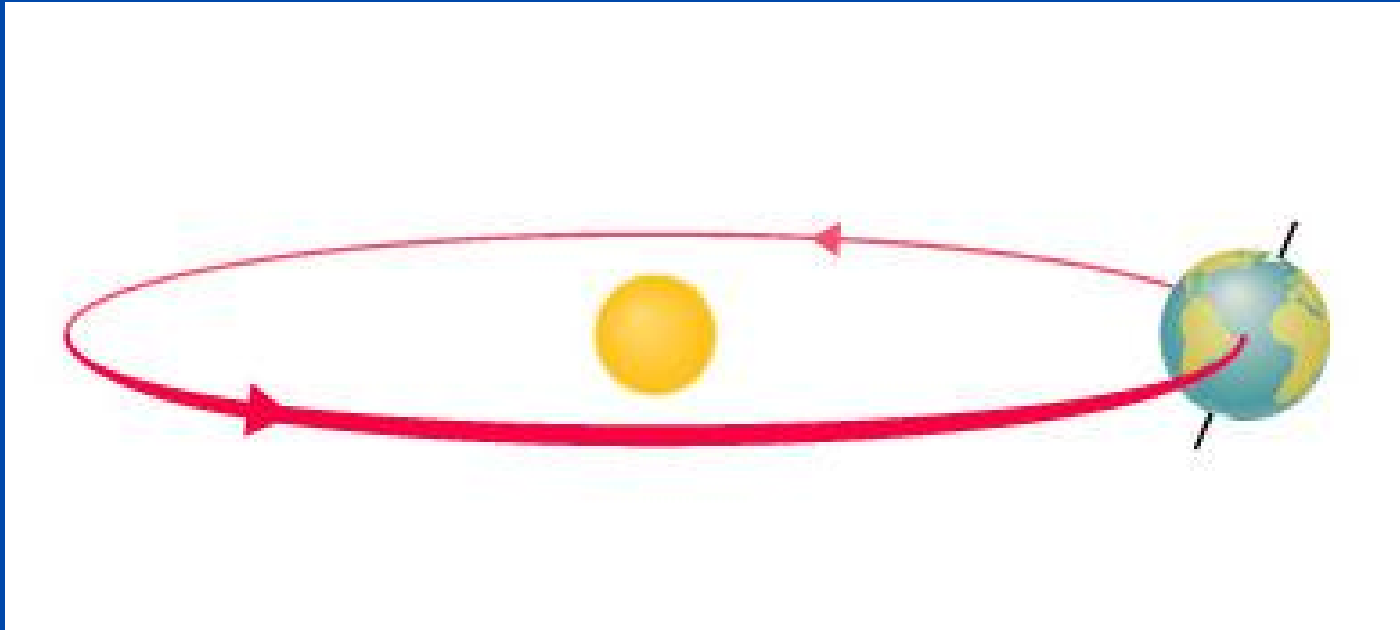
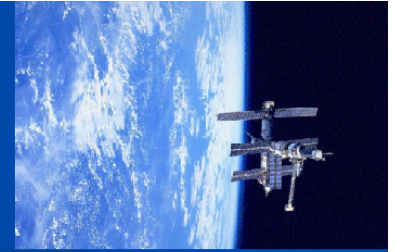
***What factors can cause long-term
climate change?***

Solar Brightening



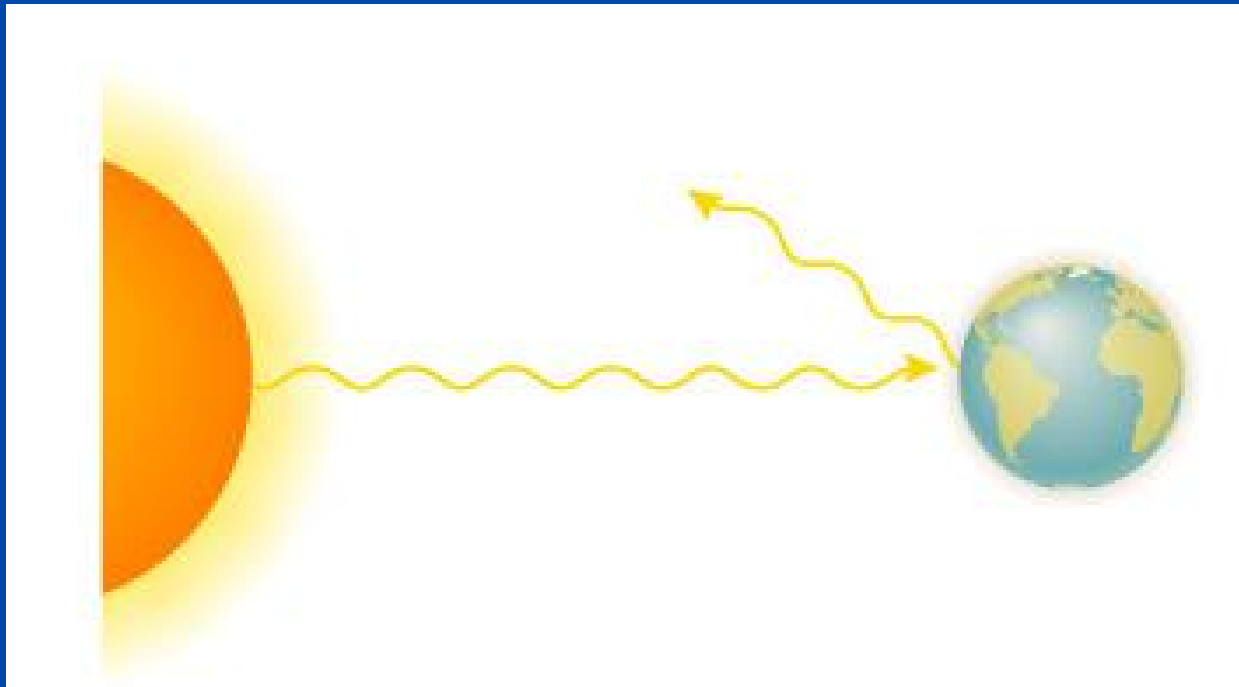
- **Sun very gradually grows brighter with time, increasing the amount of sunlight warming planets**

Changes in Axis Tilt



- **Greater tilt makes more extreme seasons, while smaller tilt keeps polar regions colder**

Changes in Reflectivity



- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming

Changes in Greenhouse Gases

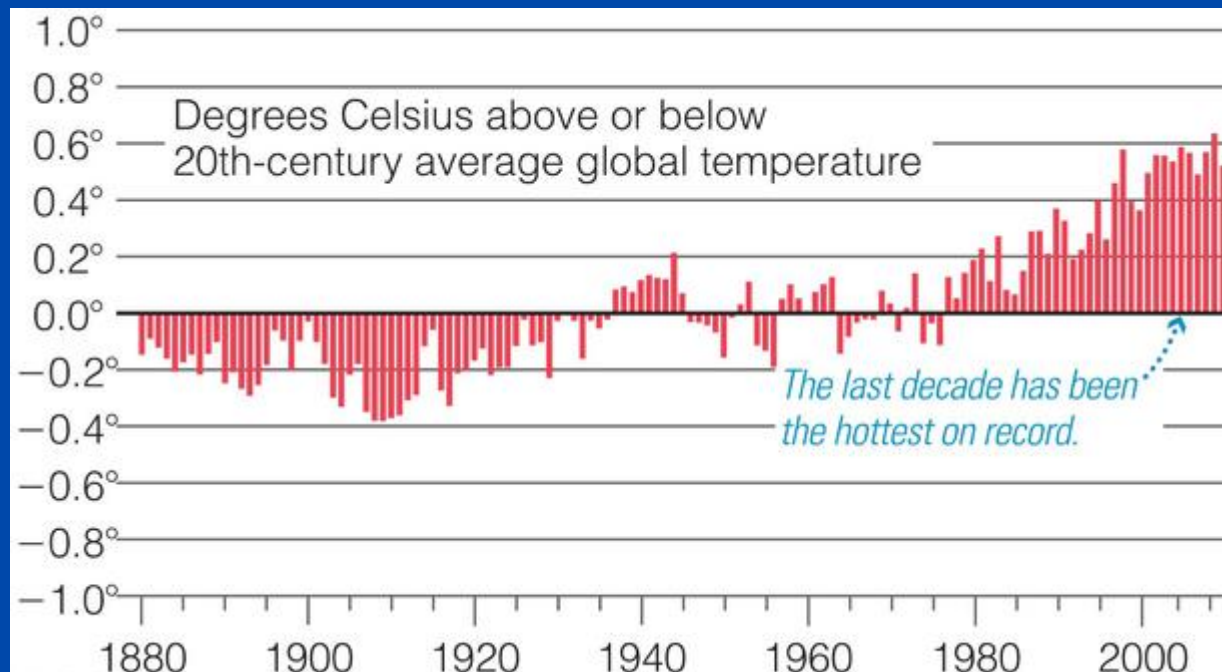


- **Increase in greenhouse gases leads to warming, while a decrease leads to cooling**

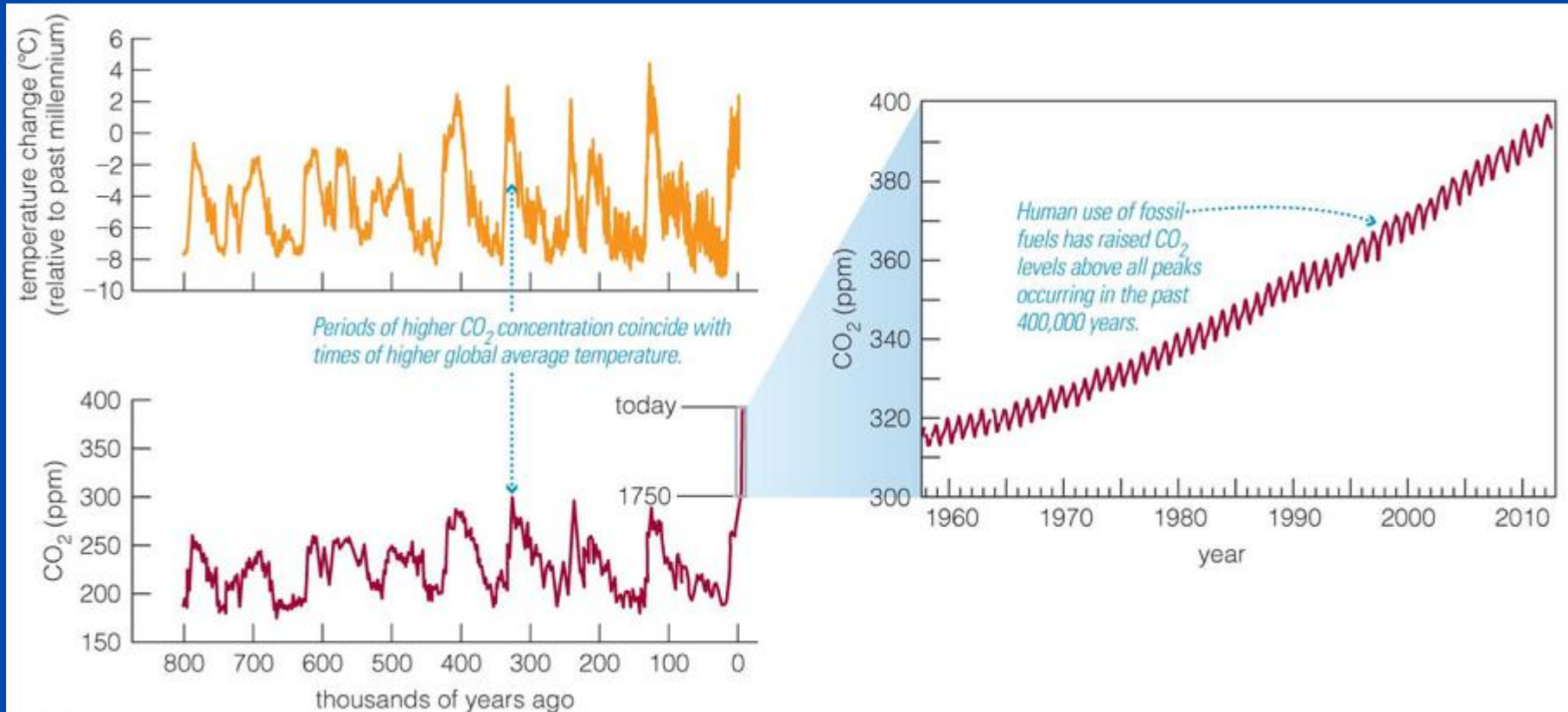
Evidence for Global Warming on Earth



- Earth's average temperature has increased by 0.5°C in past 50 years.
- Most likely contributor to increased temperatures: concentration of CO₂ is rising rapidly.



Temperature increases as CO₂ concentration goes up



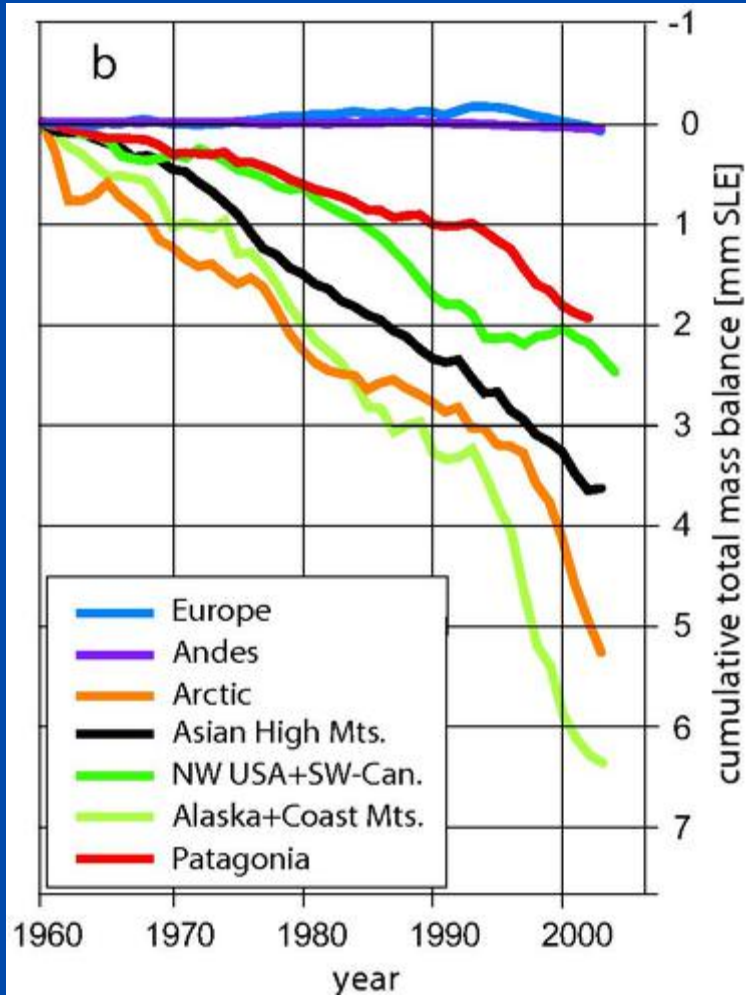
- Most of the CO₂ increase has happened in last 50 years
- Largely due to human endeavors (fossil fuels)

Intergovernmental Panel on Climate Change (IPCC)

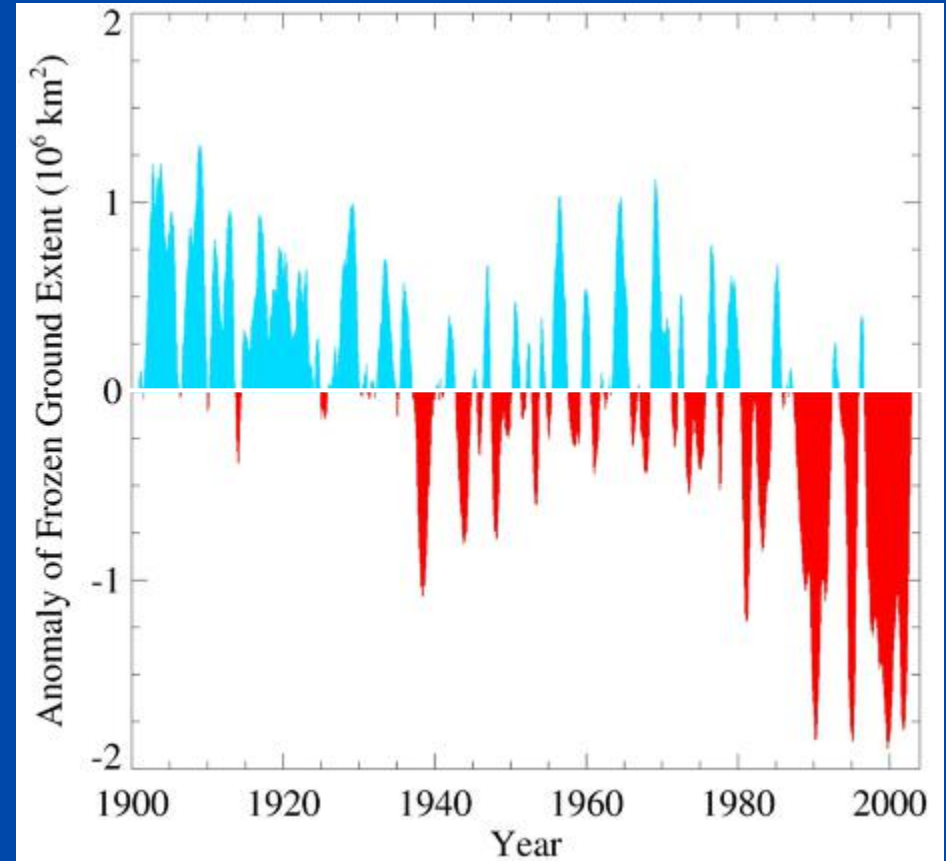


- **International scientific consensus**
 - The majority of atmospheric scientists agree
 - A few do not agree
- **Series of important reports based on scientific method (not infallible, but high quality)**
- **Nobel Peace Prize**
- **Look for yourselves: Good website**
<http://www.ipcc.ch/>

Glaciers and frozen ground are receding



Increased Glacier retreat since the early 1990s

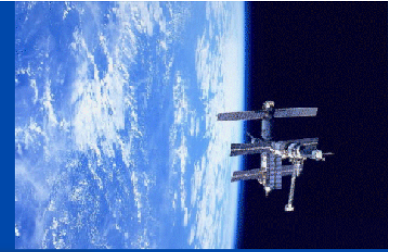


Area of seasonally frozen ground in NH has decreased by 7% from 1901 to 2002

The Chacaltaya Glacier and Ski Lift, Bolivia



Melting of Alaska's Muir Glacier between 1948 and 2004

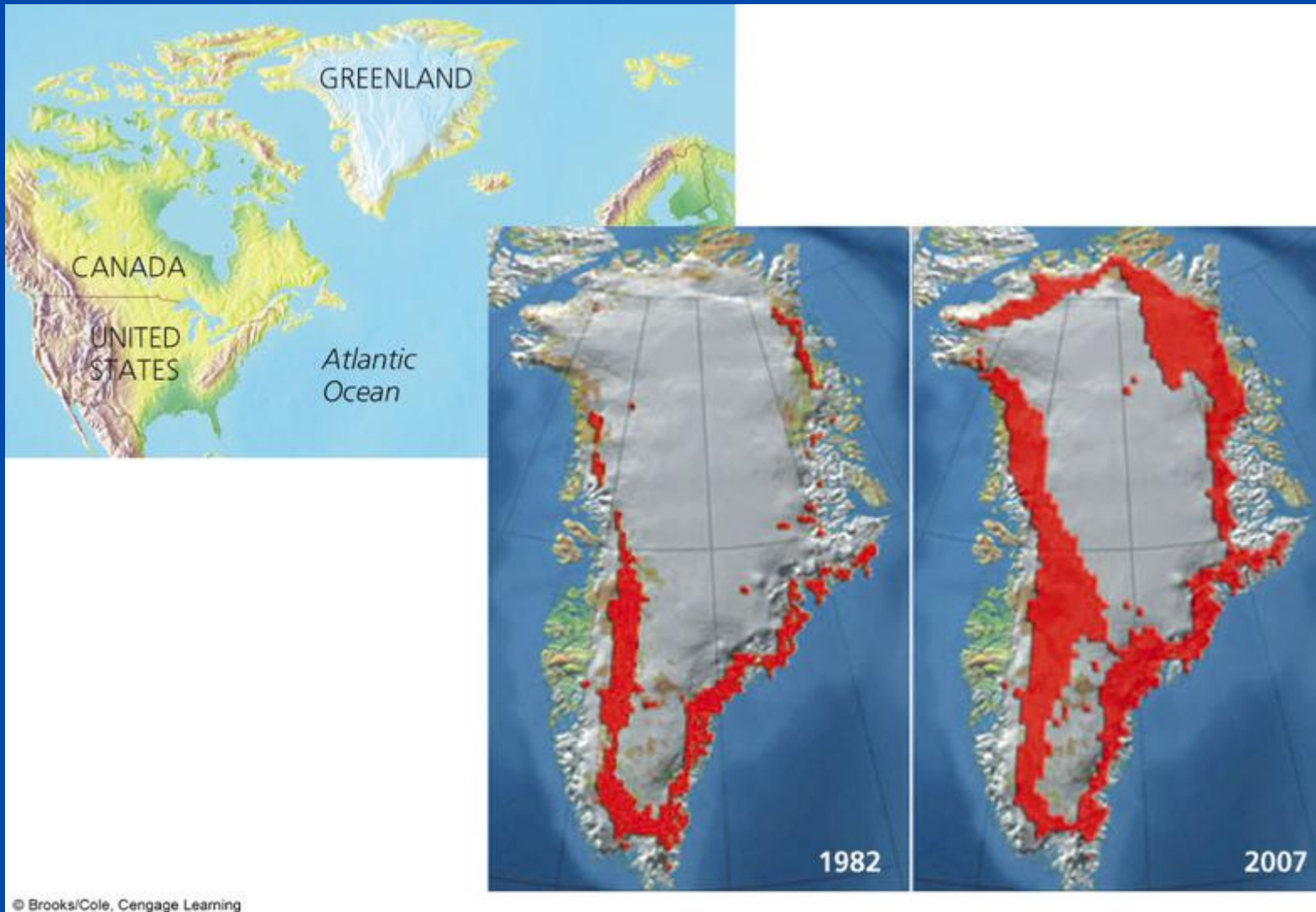


© Brooks/Cole, Cengage Learning



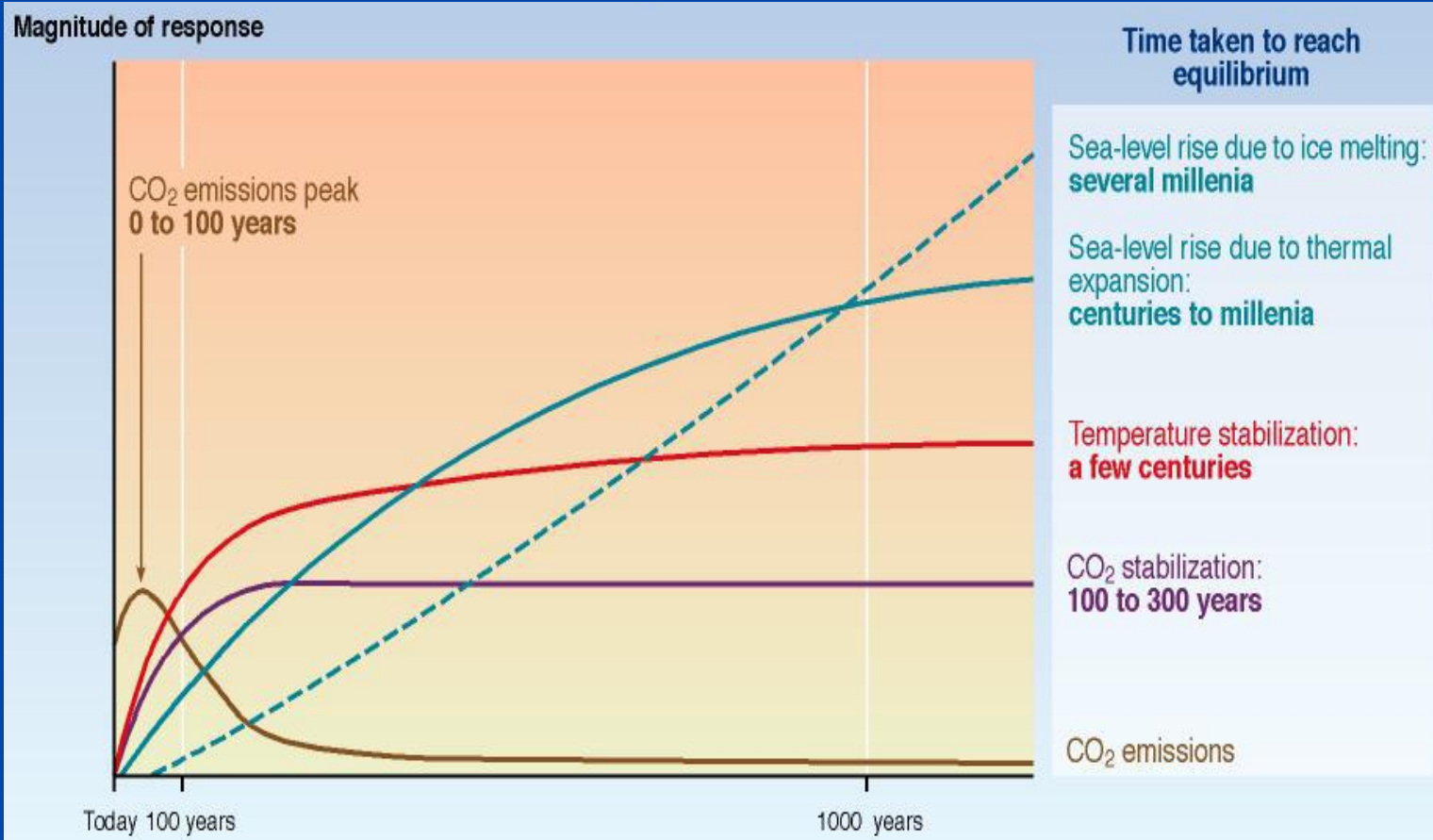
© Brooks/Cole, Cengage Learning

Summer Glacial Ice Melting in Greenland, 1982 - 2007





Global temperature will keep rising even after CO₂ emissions are reduced



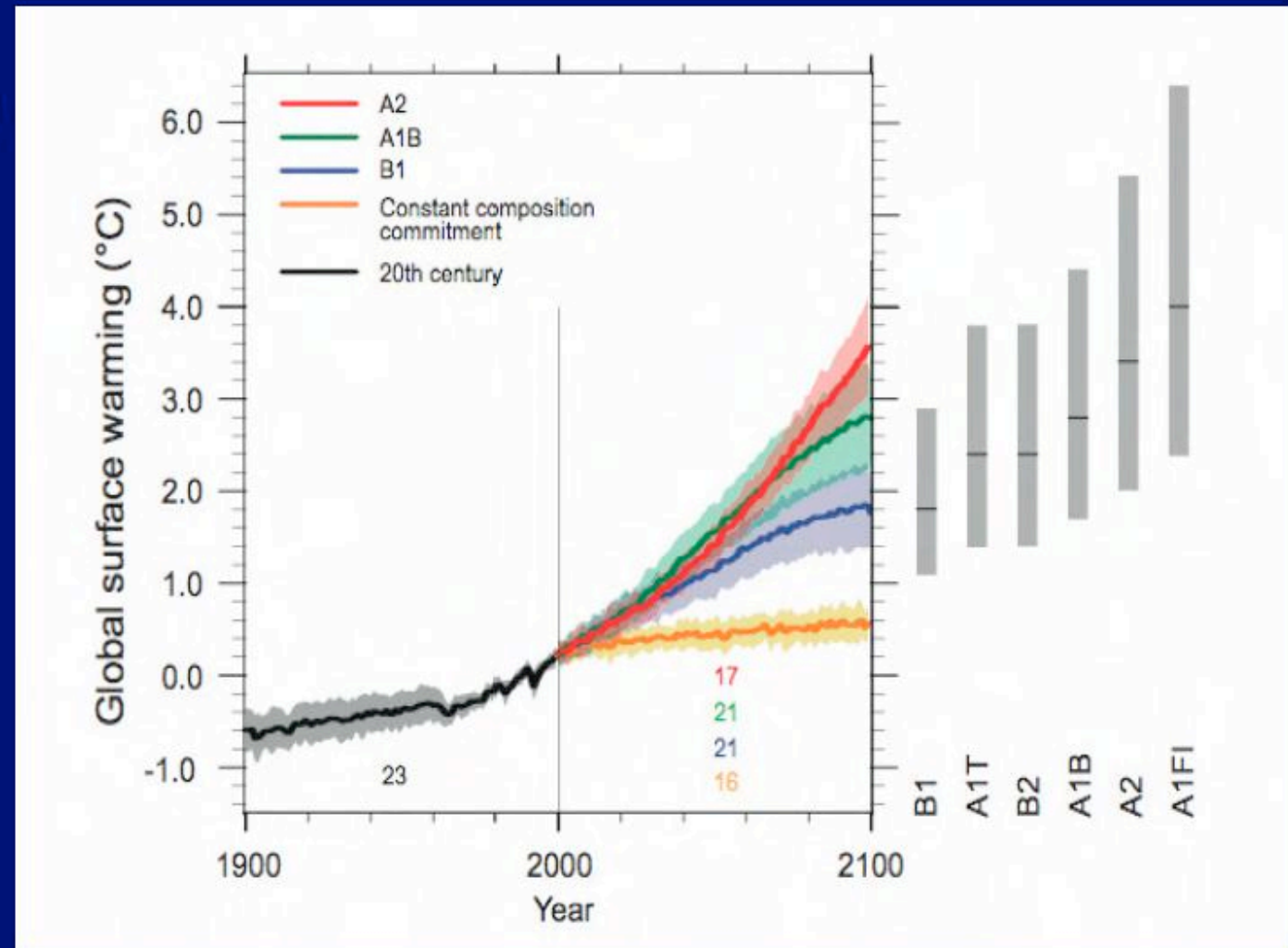
Once CO₂ gets into atmosphere, it stays there for hundreds of years!

Projections of Future Changes in Climate

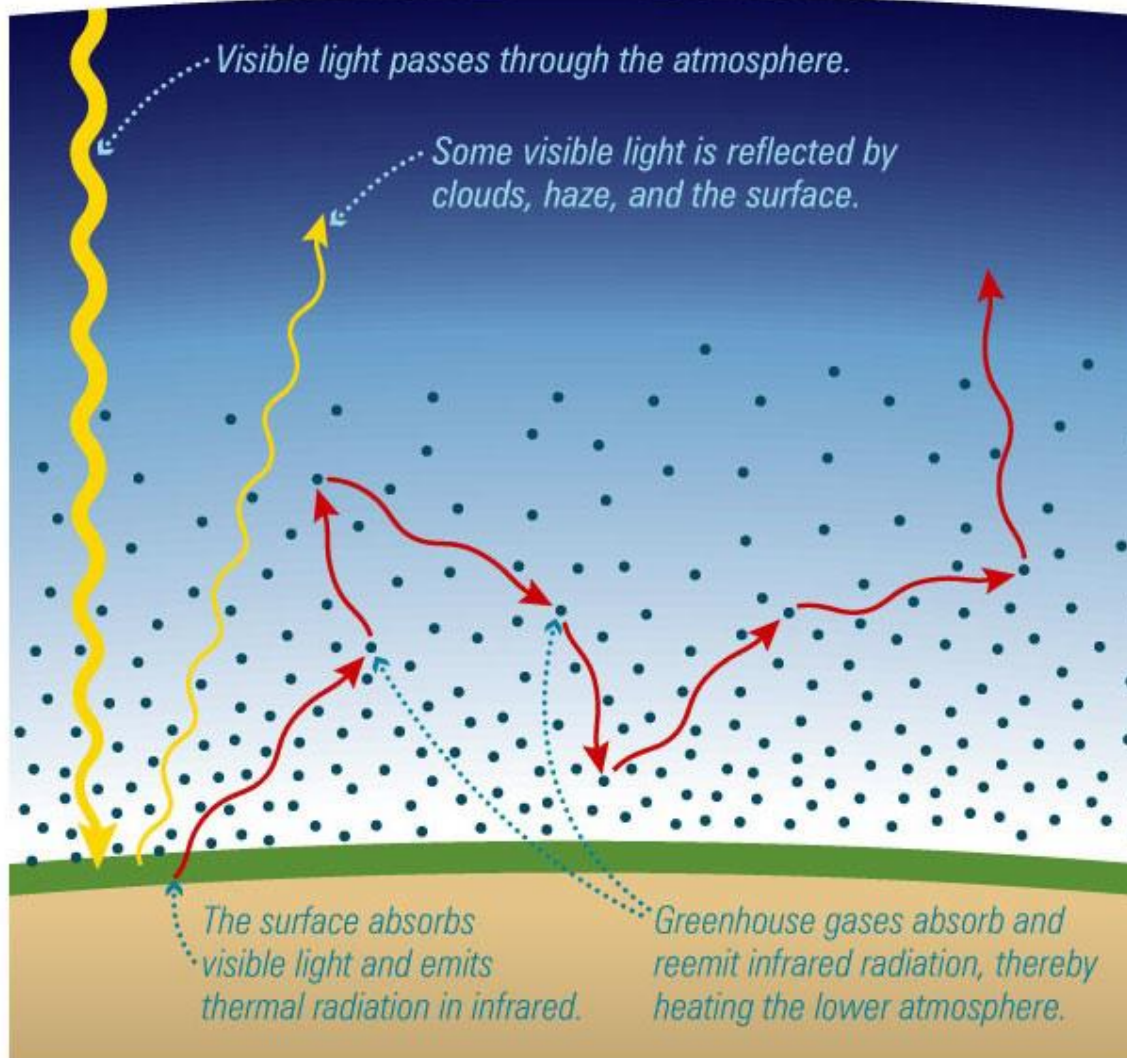
Best estimate for low scenario (B1) is 1.8°C (*likely range is 1.1°C to 2.9°C*),

and

for high scenario (A1FI) is 4.0°C (*likely range is 2.4°C to 6.4°C*).



The greenhouse effect: What about Venus and Mars?

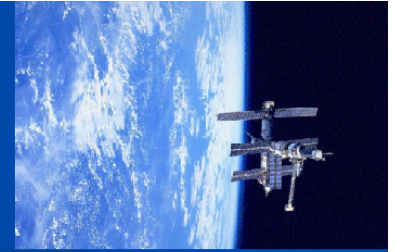


The Atmospheric History of Mars

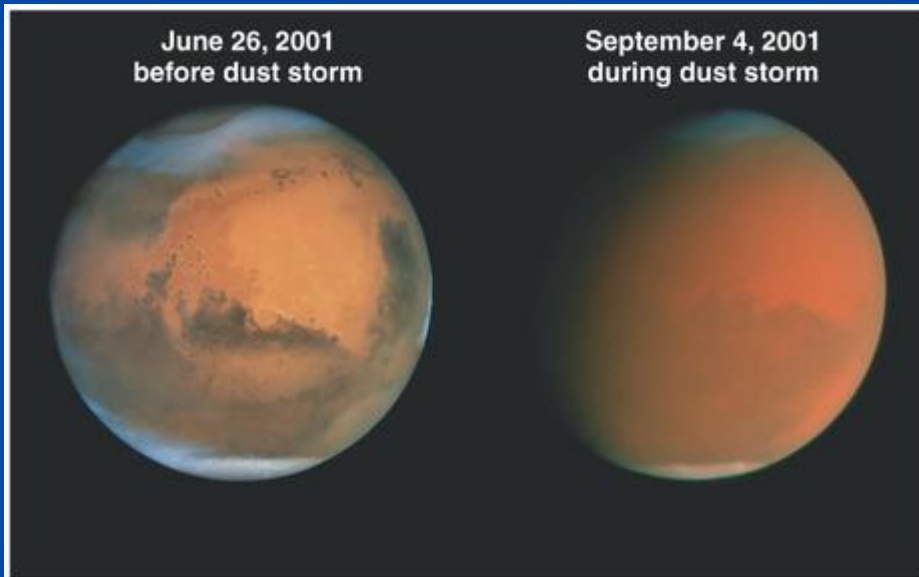


- **Main questions:**
 - What is Mars like today?
 - Why did Mars change?

Mars' surface today: dry and barren

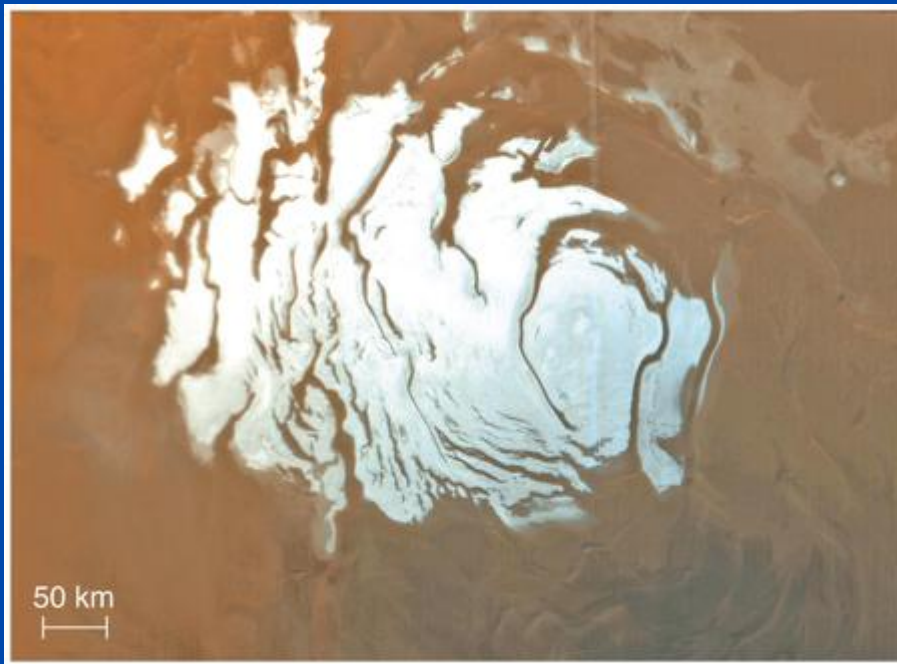


Dust Storms on Mars



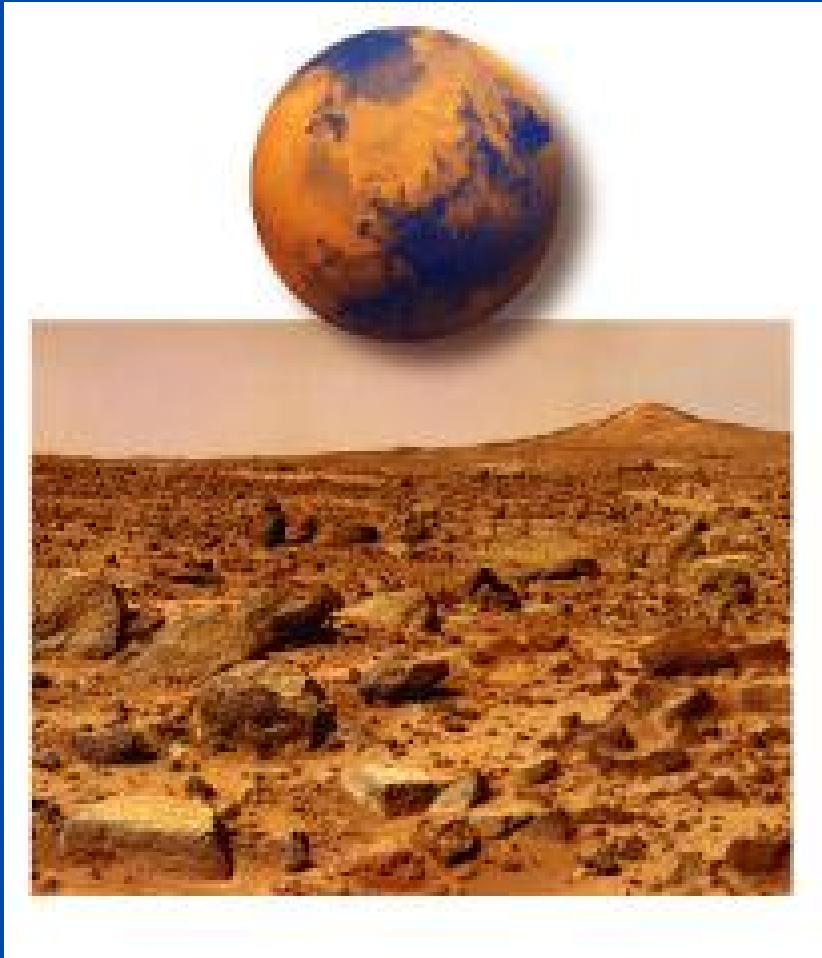
- Seasonal winds can drive dust storms on Mars.
- Dust in the atmosphere absorbs blue light, sometimes making the sky look brownish-pink.

Mars today has polar ice caps (though different from Earth's)



- **Residual ice of the south polar cap remaining during summer is primarily water ice.**
- **Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole.**

Why did Mars' climate change?

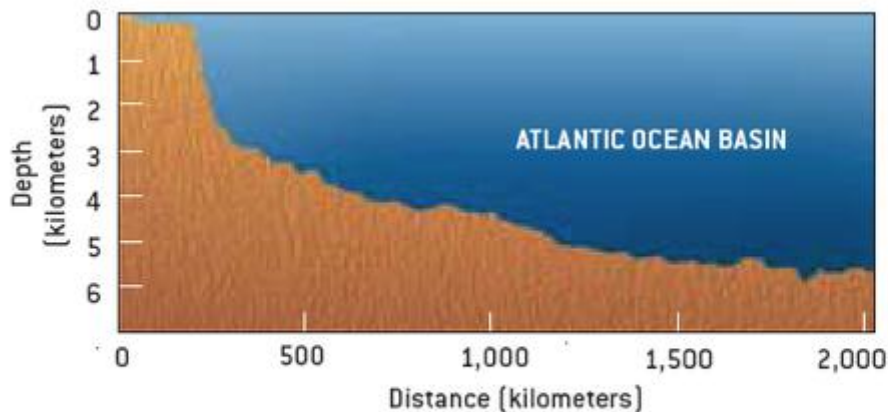


- Evidence of previous era when liquid water was plentiful
- Today: Evidence for ice mixed with soil in top meter of ground

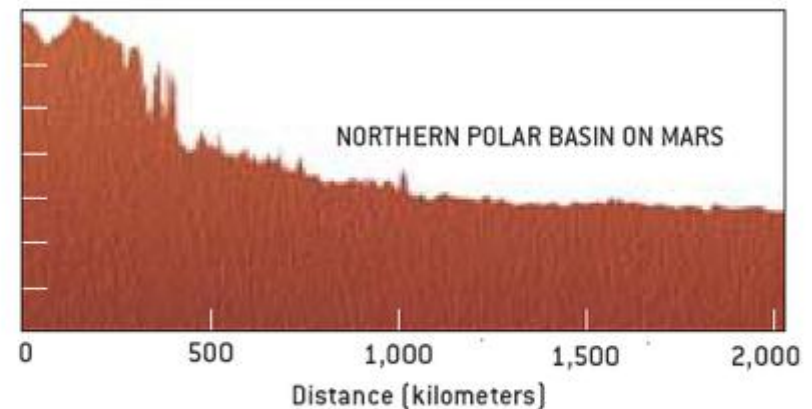
There was once liquid water on Mars



- **Geomorphological evidence (*lots* of it)**
 - River and flood channels, alluvial fans, slumps, canyons, ...
- **One more piece of evidence: shape of ocean basins**

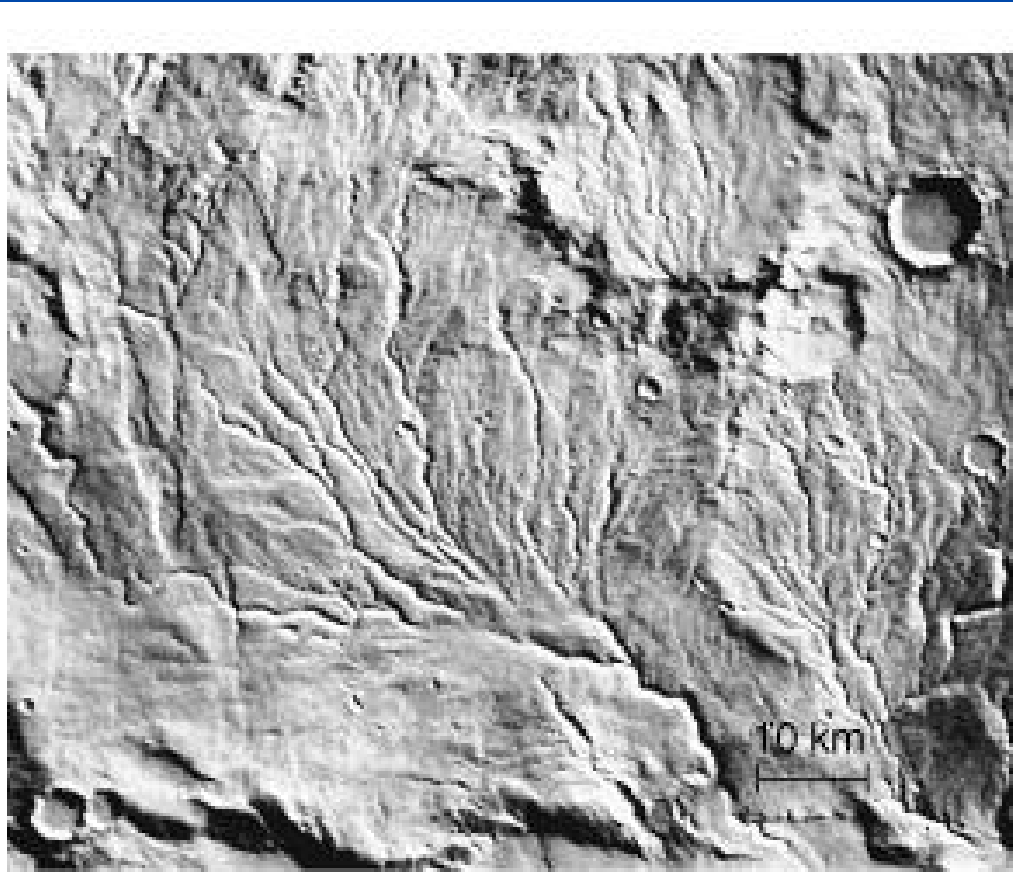


TOPOGRAPHIC MAPPING of Mars has recently revealed remarkable similarities to the ocean basins on Earth. For example, the western



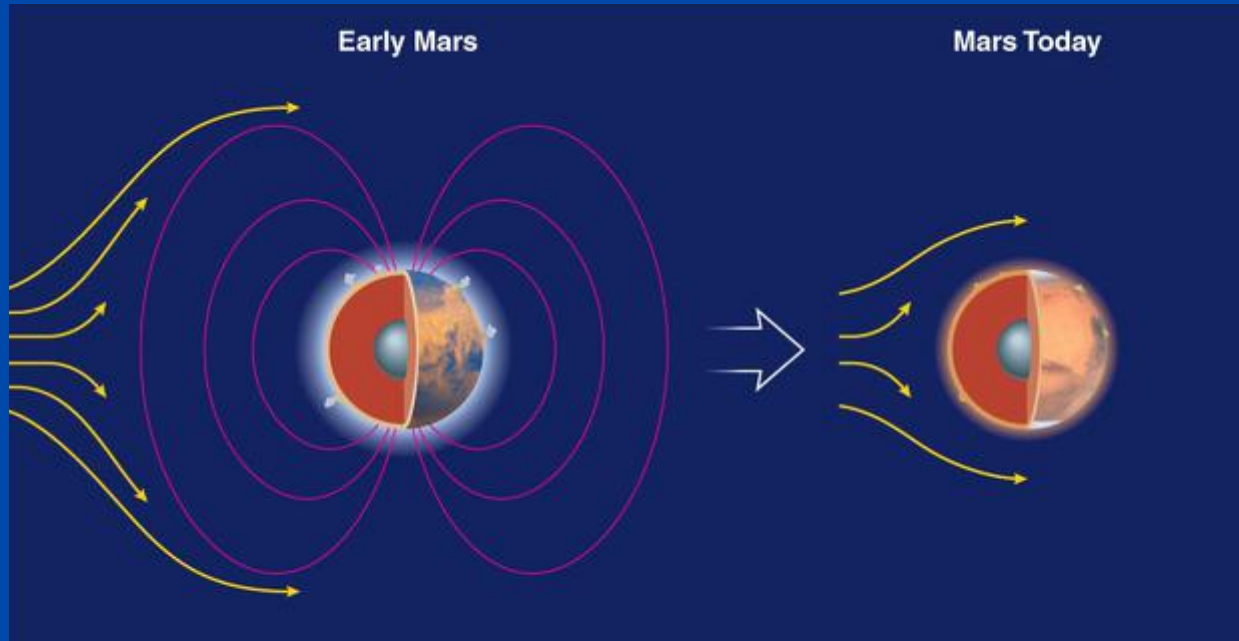
Atlantic near Rio de Janeiro (*left*) presents a similar profile to that of the northern polar basin on Mars (*right*).

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 (no more Greenhouse)**

Climate Change on Mars: Role of magnetic field



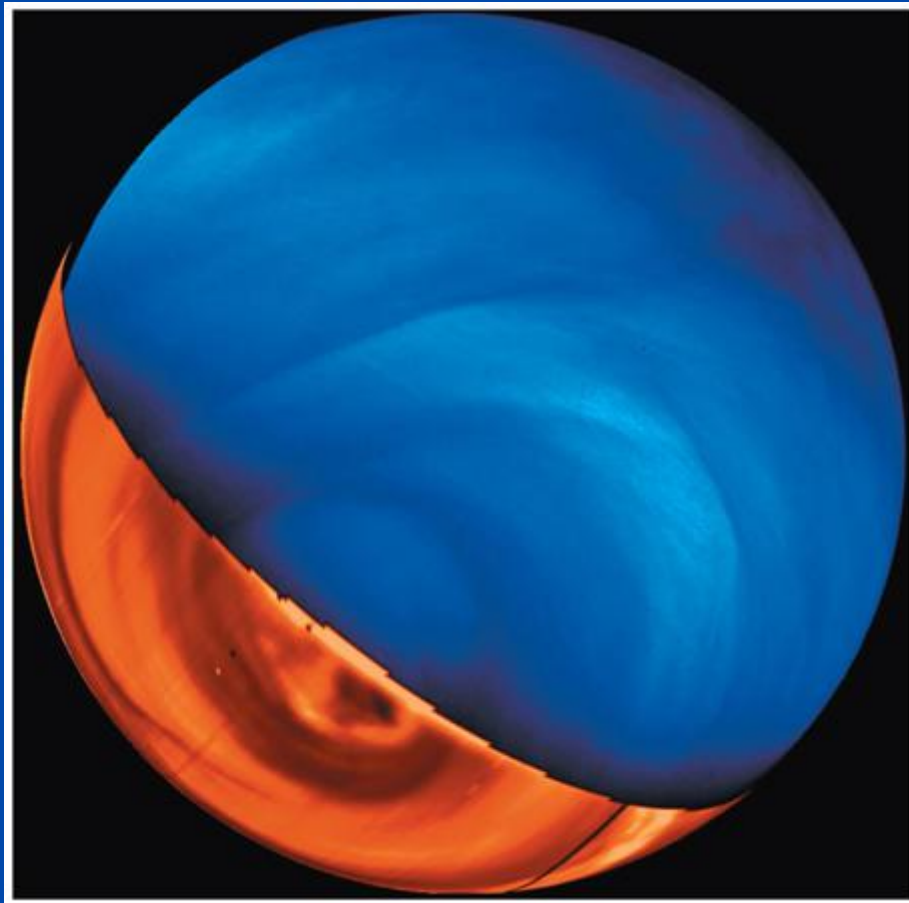
- Magnetic field may have helped protect early Martian atmosphere from solar wind.
- Solar wind could have stripped atmosphere after field decreased because of interior cooling.

Mars' atmosphere affected by both volcanoes and B fields?



- Shortly after Mars formed, its surface temperature was ~ equal to its blackbody temperature (around -55 C).
- As volcanoes dumped CO₂ and H₂O vapor into atmosphere, greenhouse effect increased temperature above 0 C (freezing) so liquid water could exist.
- Two competing effects determined amount of CO₂ in atmosphere: volcanoes adding CO₂, and rocks absorbing CO₂. Result: moderate level of CO₂ .
- Greenhouse effect could keep surface T > 0 C, as long as volcanoes kept erupting.
- Eventually Mars' core cooled and solidified (Mars is small). Volcanic activity subsided. Magnetic field went away, solar wind particles eroded atmosphere.
- Once rate of eruptions tapered off, CO₂ in the atmosphere started to fall.
- As the atmosphere thinned out, the greenhouse effect weakened. Eventually the average surface temperature dropped, and surface water froze.

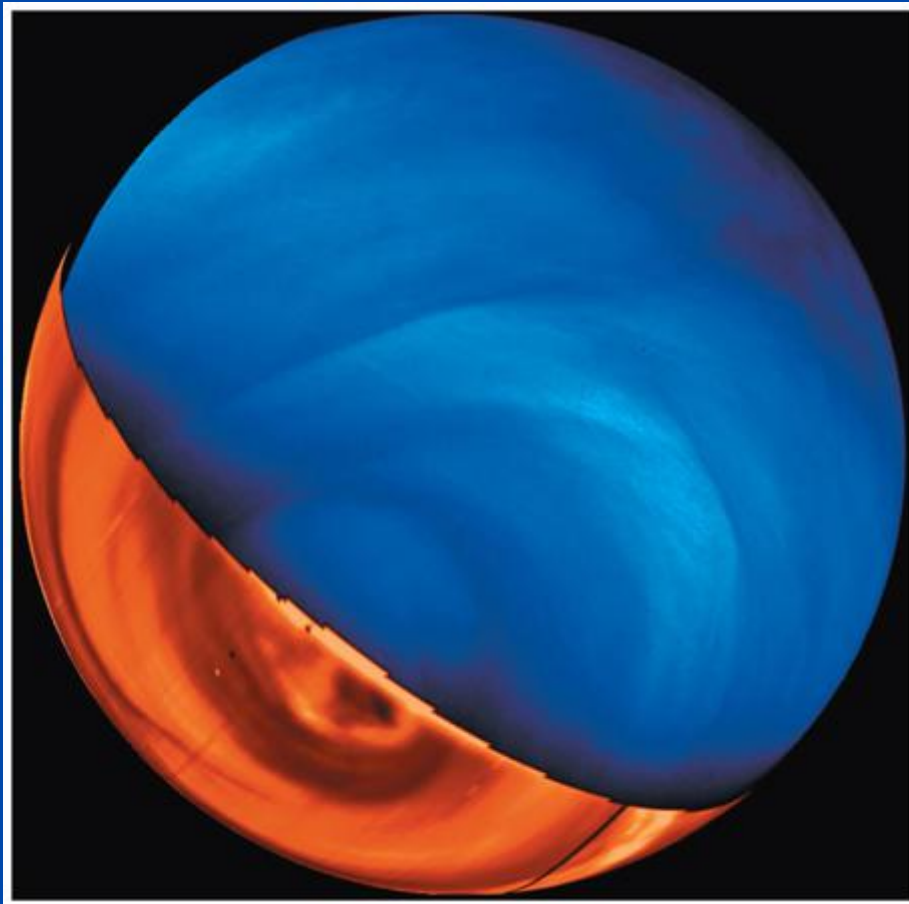
Atmosphere of Venus Today



- **Venus has a very thick carbon dioxide atmosphere with a surface pressure 90 times that of Earth.**
- **Surface temperature very high.**
- **Slow rotation produces little weather.**

**Visible wavelength image of day side (red-orange);
infrared image of night side (blue)**

Greenhouse Effect on Venus



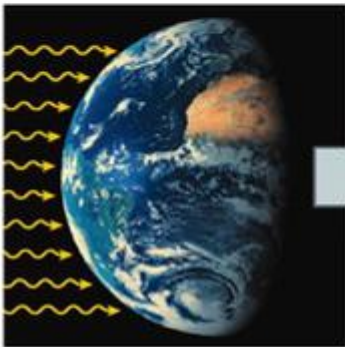
- **Thick carbon dioxide atmosphere produces an extremely strong greenhouse effect.**
- **Earth escapes this fate because most of its carbon and water is in rocks and oceans.**

Venus Climate Today: Due to runaway greenhouse effect

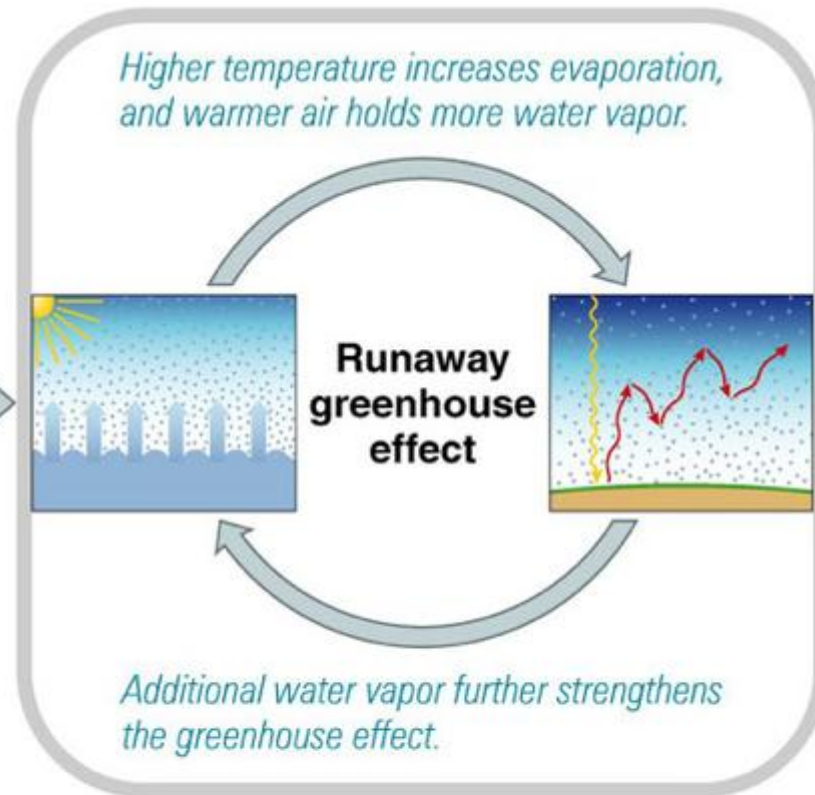


If Earth moved to Venus's orbit

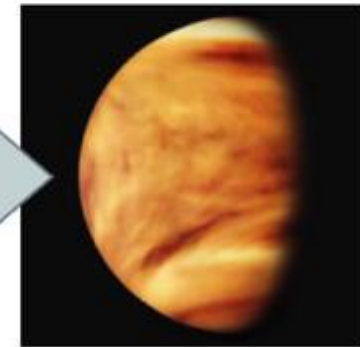
More intense sunlight...



...would raise surface temperature by about 30°C.



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

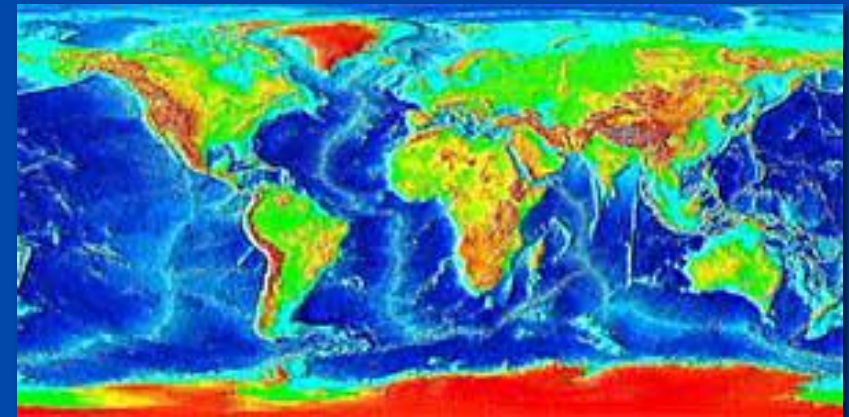
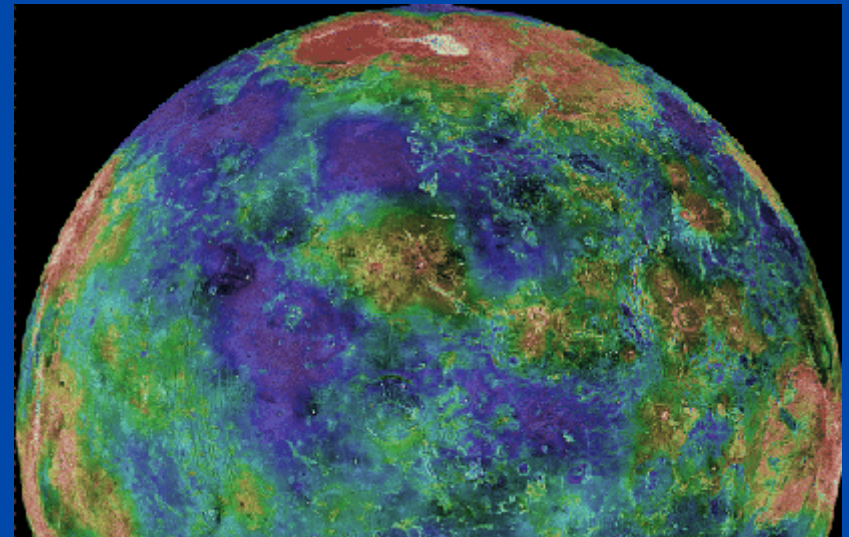


...making Earth hotter than Venus.

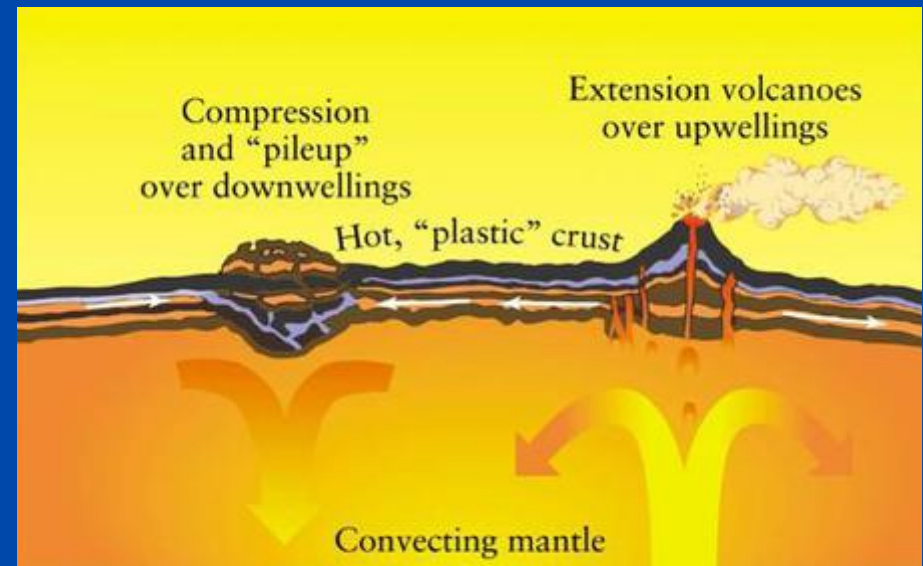
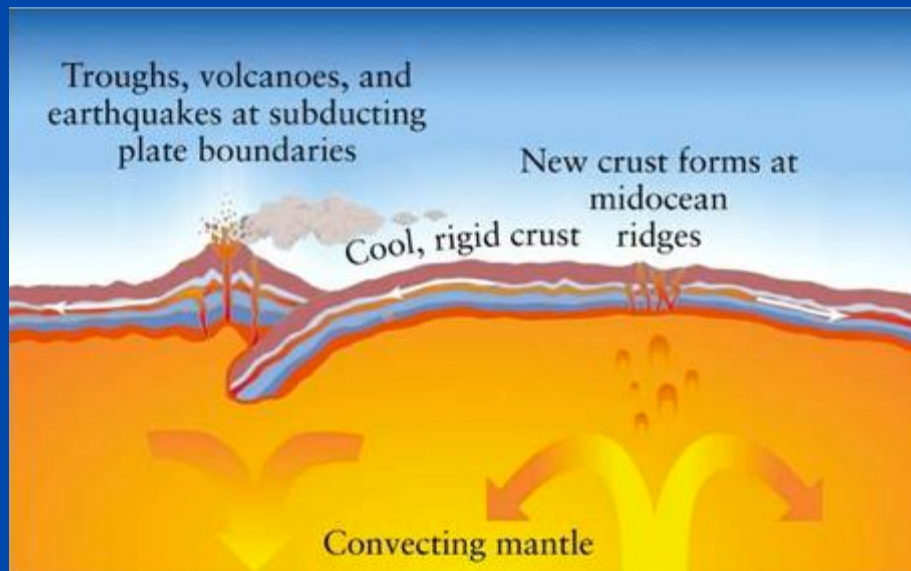
Venus plate tectonics?



- No evidence for **plate tectonics** on Venus
 - No mid-ocean rifts
 - No subduction trenches
- **Volcanos** spread **evenly** across surface instead of at plate boundaries, as on Earth.
- Lithosphere not broken into plates; probably because heat at surface slightly softens the lithosphere.



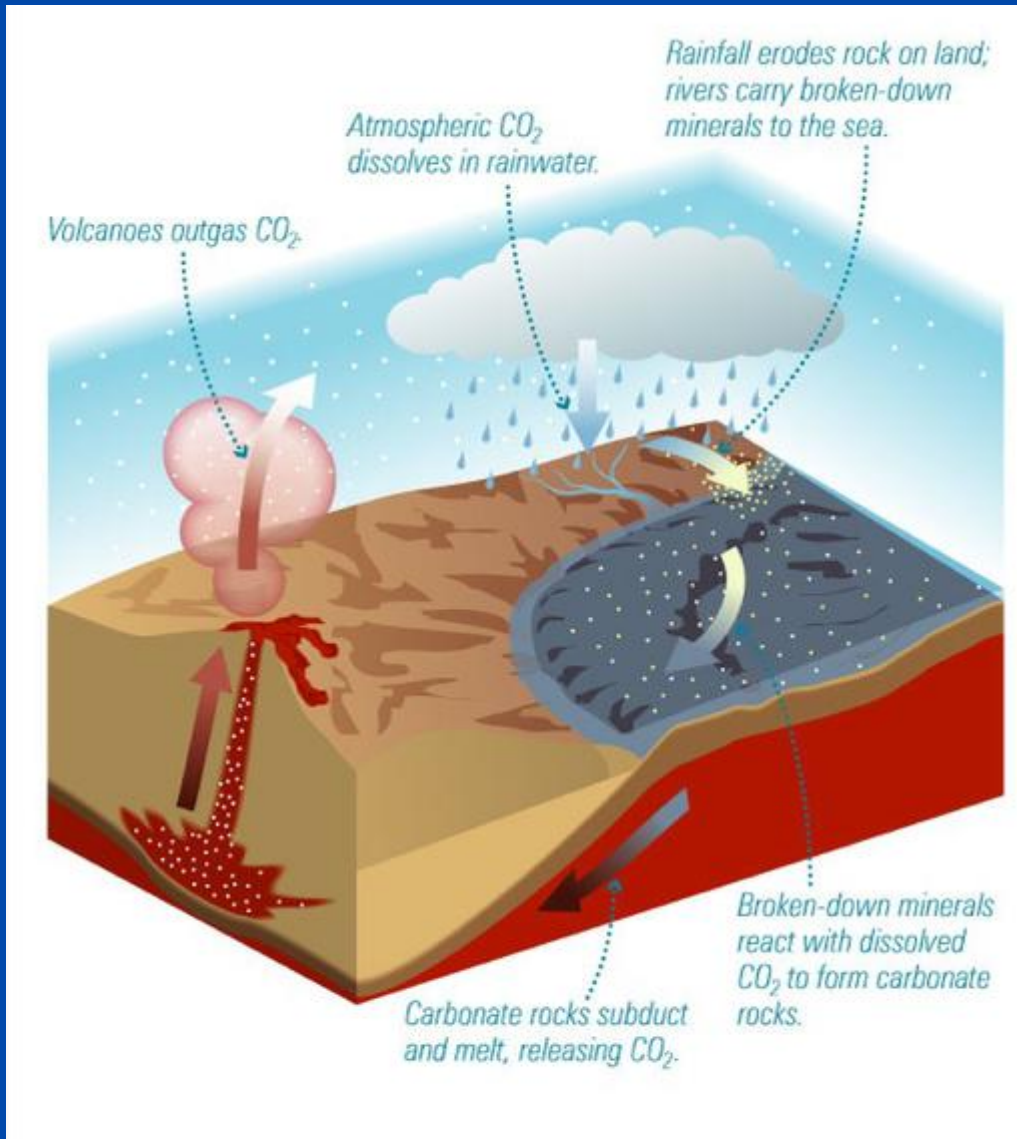
Subduction of Earth's crust takes carbon out of atmosphere



Credit: The New Solar System, Sky Publishing Corporation

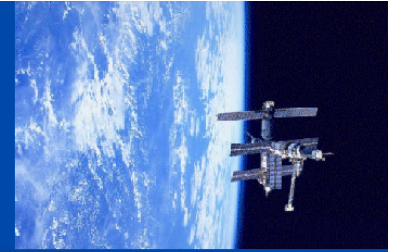
- Carbonates on rock surfaces and from shells of sea life are subducted along with crust on Earth
- Takes Carbon out of atmosphere, so it can't form CO₂
- Doesn't happen on Venus (any more ...)

No carbon-silicate cycle on Venus



Earth's carbon-silicate cycle

Resurfacing on Venus



- **Venus has far fewer impact craters than Moon & Mercury**
 - Dense atmosphere protects it
 - Volcanic resurfacing has erased most small craters
- **Surface age is < a billion years.**
 - Venus was "resurfaced" by lava flows during relatively short period
- **This differs profoundly from Earth's crustal history. What is it telling us?**
 - Could Venus' present crust only have formed that recently?
 - Could there have been a growing crust before 1 billion years ago that "turned over" as heat built up underneath, to lead to a new era of major lava flows?
- **Is this event correlated with the end of plate tectonics due to "bake-out" of water from surface rocks?**

The Main Points



- **Planetary atmospheres are a balancing act:**
 - Gravity vs. thermal motions of air molecules
 - Heating by Sun vs. heat radiated back into space
 - Weather as a way to equalize pressures at different places on Earth's surface
- **Atmospheres of terrestrial planets are very different now from the way they were born**
 - Formation: volcanoes, comets
 - Destruction: escape, incorporation into rocks, oceans
 - Huge changes over a billion years or less
- **Prospect of human-induced global warming on Earth needs to be taken seriously**