Chapter 10
Planetary Atmospheres
Earth and the Other Terrestrial Worlds

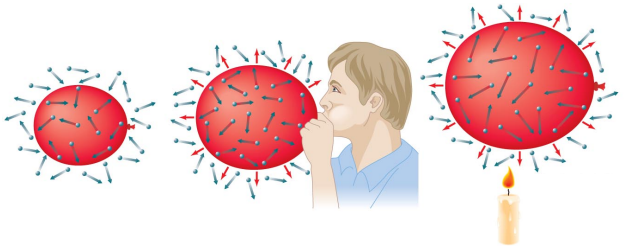
What is an atmosphere?

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 - 78%) and oxygen (O_2 - 21%)

Atmospheric Pressure

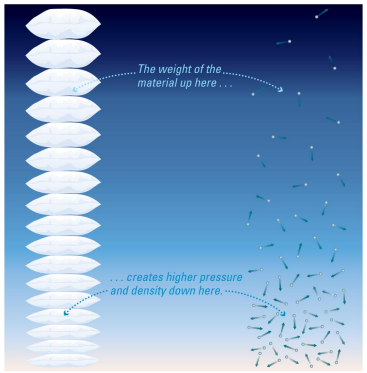


Gas pressure depends on both density and temperature.

Adding air molecules increases the pressure in a balloon.

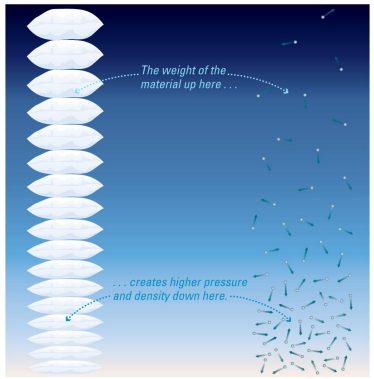
Heating the air also increases the pressure.

Atmospheric Pressure



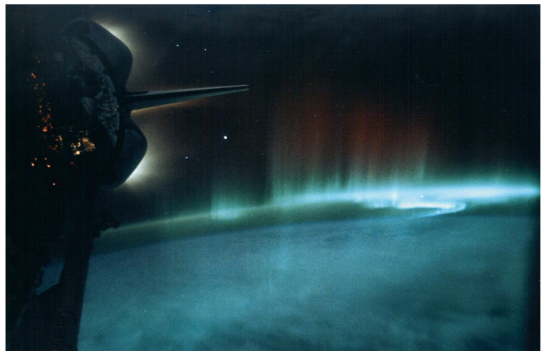
- Pressure and density decrease with altitude because the weight of overlying layers is less
- Earth's pressure at sea level is
  - 1.03 kg per sq. meter
  - 14.7 lbs per sq. inch
  - 1 bar

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?

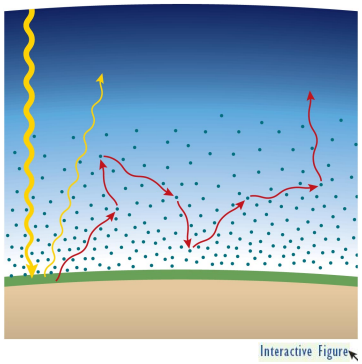


- Small amounts of gas are present even at > 300 km

Effects of Atmospheres

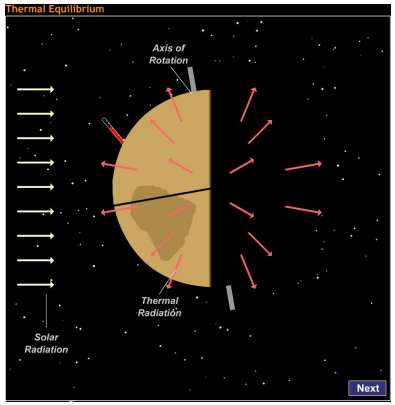
- Create pressure that determines whether liquid water can exist on surface
- Absorb and scatter light
- Create wind, weather, and climate
- Interact with solar wind to create a magnetosphere
- Can make planetary surfaces warmer through greenhouse effect

Greenhouse Effect



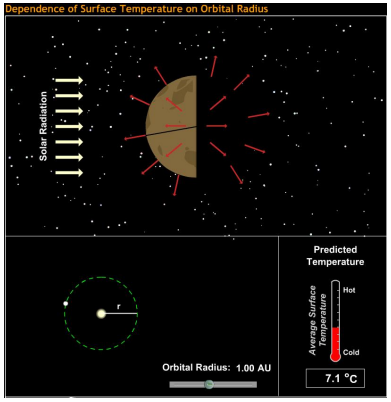
- Visible light passes through atmosphere and warms planet's surface
- Atmosphere absorbs infrared light from surface, trapping heat

Planetary Temperature



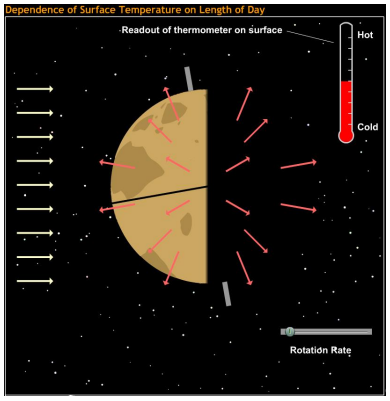
- A planet's surface temperature is determined by the balance between sunlight it absorbs and outgoing thermal radiation.
- Surface temperature depends on: distance from Sun, rotation rate, albedo, and atmosphere

Temperature and Distance



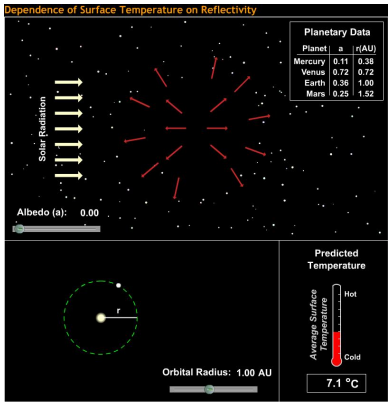
- A planet's distance from the Sun determines the total amount of incoming sunlight

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

Atmosphere: "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. For example, Venus has 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.

- Venus would be 510°C colder without greenhouse effect
- Earth would be 31°C colder (below freezing on average)

Thought Question

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

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

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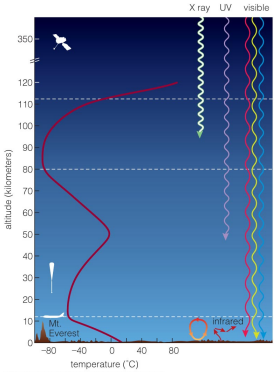
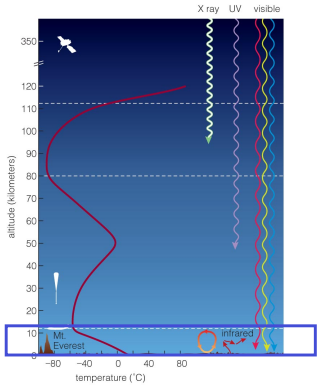
Why do atmospheric properties vary with altitude?

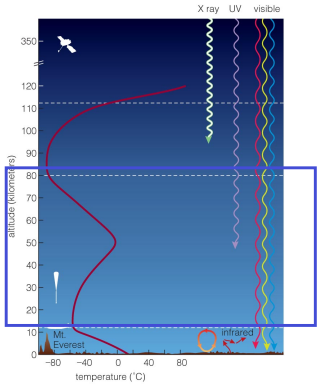


Earth's Atmospheric Structure



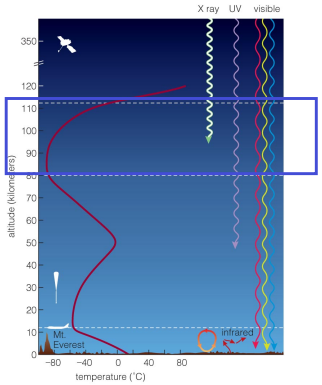
- **Troposphere:** lowest layer of Earth's atmosphere
- Temperature drops with altitude
- Warmed by infrared light from surface (heated by visible light) and convection

Earth's Atmospheric Structure



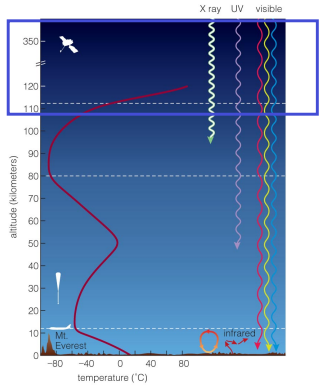
- **Stratosphere:** Layer above the troposphere
- Temperature rises with altitude in lower part, drops with altitude in upper part
- Warmed by absorption of ultraviolet sunlight

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

Thought Question

Why is the sky blue?

a) The sky reflects light from the oceans.
b) Oxygen atoms are blue.
c) Nitrogen atoms are blue.
d) Air molecules scatter blue light more than red light.
e) Air molecules absorb red light.

Thought Question

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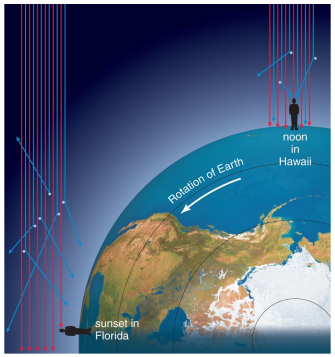
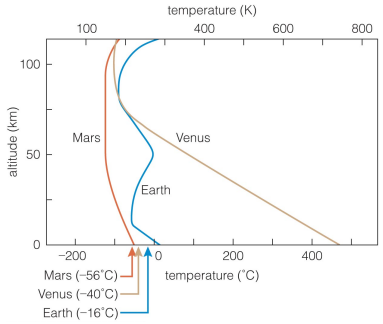
Why the sky is blue



- Atmosphere scatters blue light from Sun, making it appear to come from different directions
- Sunsets are red because red light scatters less

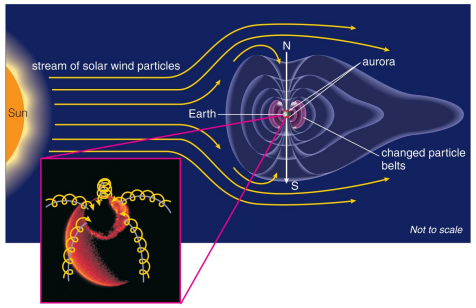
Atmospheres of Other Planets



- 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.

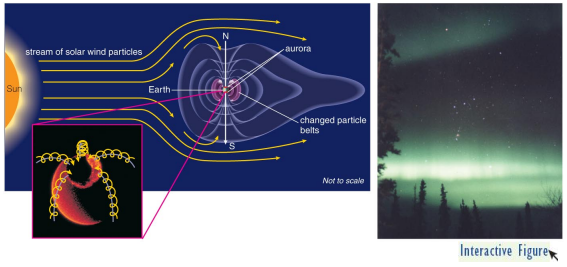
No greenhouse temperatures

Earth's Magnetosphere



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

Aurora



Interactive Figure

- Charged particles can enter atmosphere at magnetic poles, causing an aurora

What creates wind and weather?

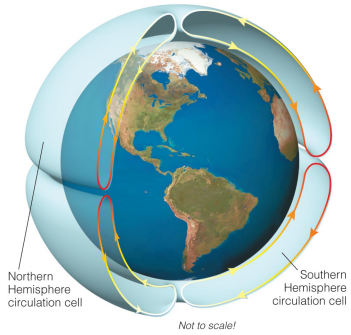
Weather and Climate

- **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

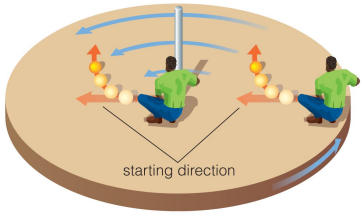
- Global winds blow in distinctive patterns
  - Equatorial: E to W
  - Mid-latitudes: W to E
  - High-latitudes: E to W

Circulation Cells: No Rotation



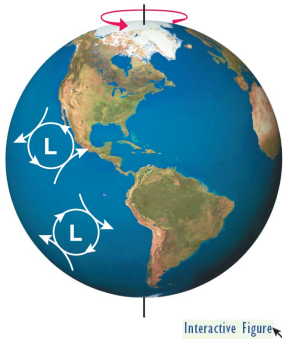
- Heated air rises at equator
- Cooler air descends at poles
- Without rotation, these motions would produce two large circulation cells

Coriolis Effect



- Conservation of angular momentum causes a ball's apparent path on a spinning platform to change direction

Coriolis Effect on Earth

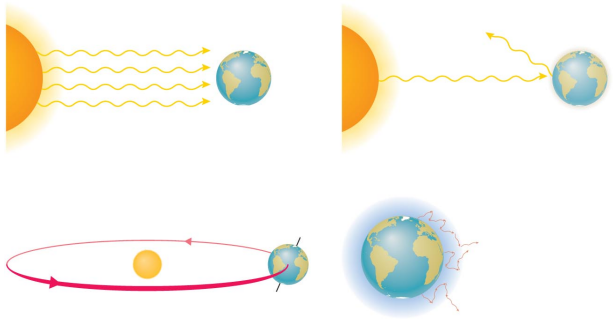


- Air moving from pole to equator is going farther from axis and begins to lag Earth's rotation
- Air moving from equator to pole goes closer to axis and moves ahead of Earth's rotation

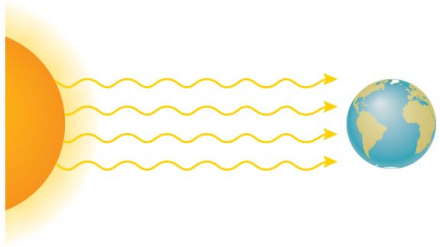
Coriolis Effect on Earth

- Conservation of angular momentum causes large storms to swirl
- Direction of circulation depends on hemisphere
  - N: counterclockwise
  - S: clockwise

What factors can cause long-term climate change?

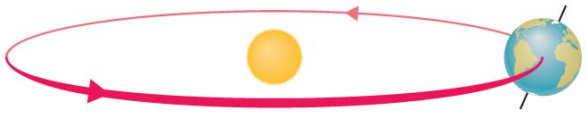


Solar Brightening



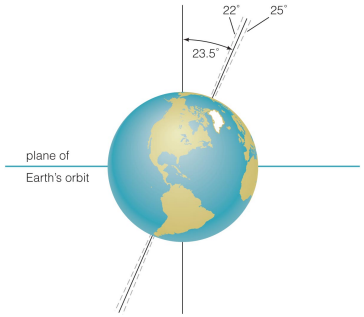
- Sun very gradually grows brighter with time, increasing the amount of sunlight warming planets

Changes in Axis Tilt



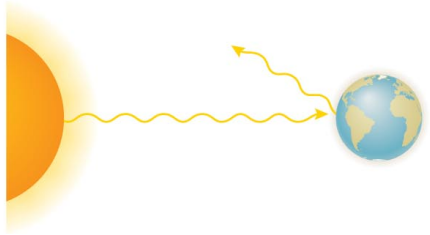
- Greater tilt makes more extreme seasons, while smaller tilt keeps polar regions colder

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

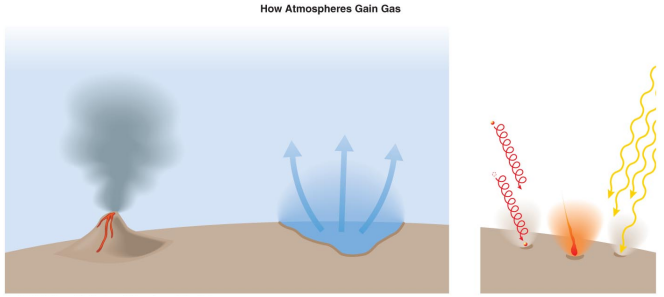


- Higher reflectivity tends to cool a planet, while lower reflectivity leads to warming

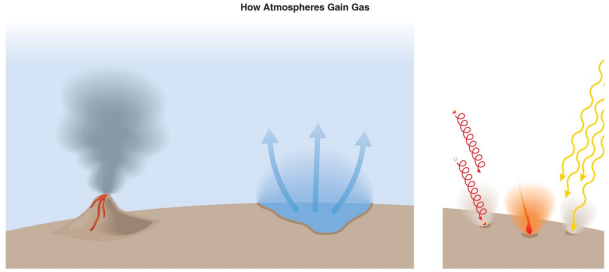
Changes in Greenhouse Gases

- 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

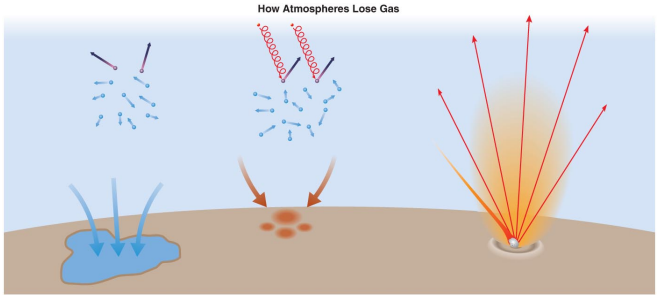


Outgassing from volcanoes

Evaporation of surface liquid; sublimation of surface ice

Impacts of particles and photons eject small amounts

Losses of Gas

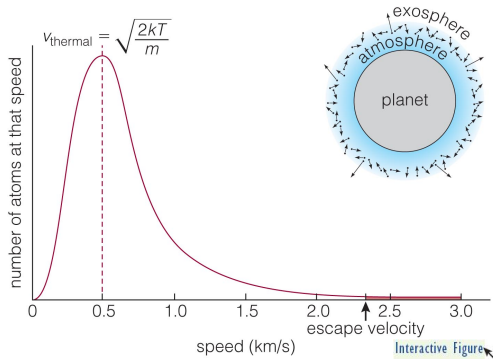


Condensation onto surface

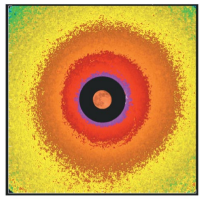
Chemical reactions with surface

Large impacts blast gas into space

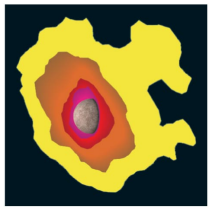
Thermal Escape



Exospheres of Moon and Mercury



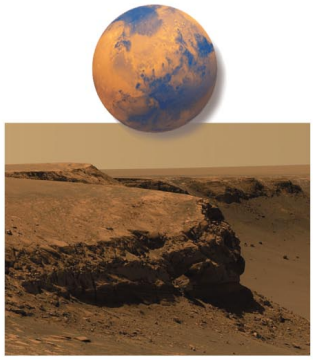
Moon



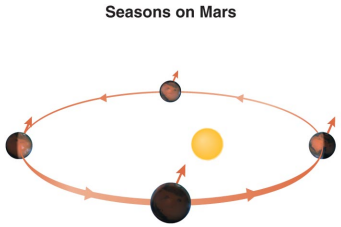
Mercury

- Sensitive measurements show Moon and Mercury have extremely thin, temporary "atmospheres"
- Gas comes from impacts that eject surface atoms

What is Mars like today?

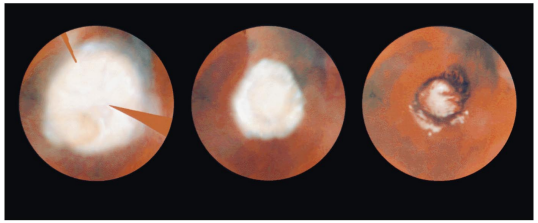


Seasons on Mars



- The ellipticity of Mars's orbit makes seasons more extreme in the southern hemisphere

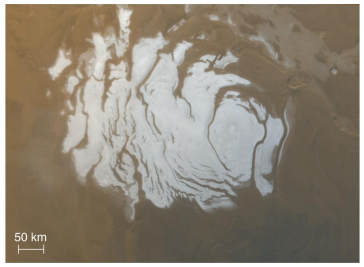
Polar Ice Caps of Mars



Late winter Midspring Early summer

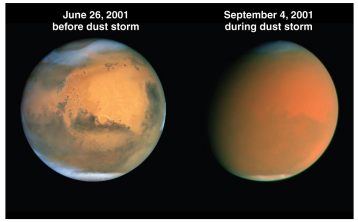
- Carbon dioxide ice of polar cap sublimates as summer approaches and condenses at opposite pole

Polar Ice Caps of Mars



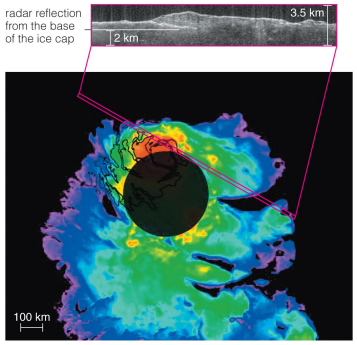
- Residual ice of polar cap during summer is primarily water ice

Dust Storms on Mars



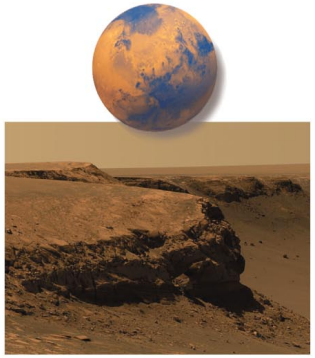
- Seasonal winds can drive dust storms on Mars
- Dust in the atmosphere absorbs blue light, sometimes making the sky look brownish-pink

Changing Axis Tilt

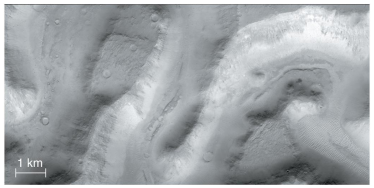


- Calculations suggest Mars's axis tilt ranges from 0° to 60° over long time periods
- Such extreme variations cause dramatic climate changes
- These climate changes can produce layers of ice and dust

Why did Mars change?

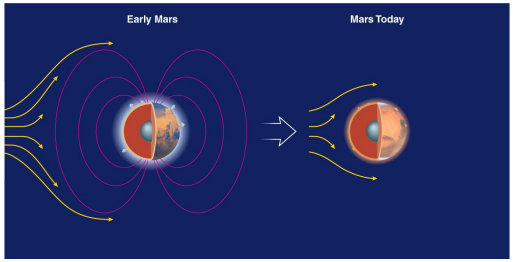


Climate Change on Mars



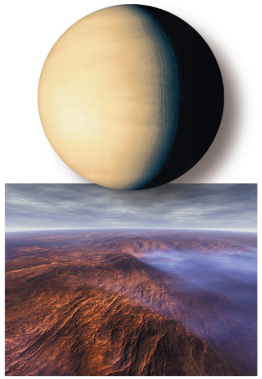
- Mars has not had widespread surface water for 3 billion years
- Greenhouse effect probably kept surface warmer before that
- Somehow Mars lost most of its atmosphere

Climate Change on Mars

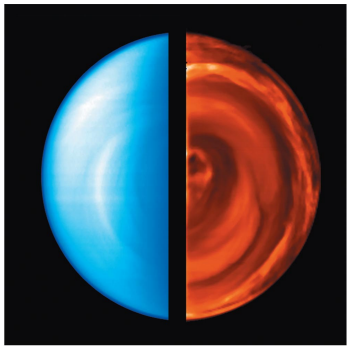


- Magnetic field may have preserved early Martian atmosphere
- Solar wind may have stripped atmosphere after field decreased because of interior cooling

What is Venus like today?

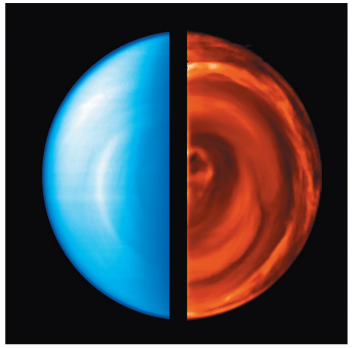


Atmosphere of Venus



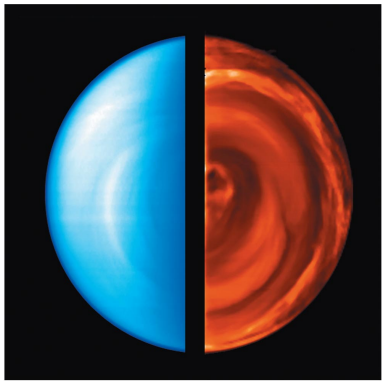
- Venus has a very thick carbon dioxide atmosphere with a surface pressure ~100 times Earth's
- Slow rotation produces very weak Coriolis effect and little weather

Greenhouse Effect on Venus

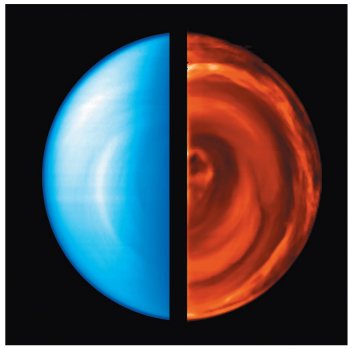


- Thick carbon dioxide atmosphere produces an extremely strong greenhouse effect
- Earth escapes this fate because most of its carbon and water is in rocks and oceans

How did Venus get so hot?

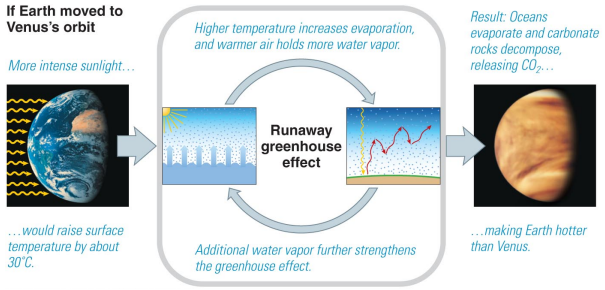


Atmosphere of Venus



- 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

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

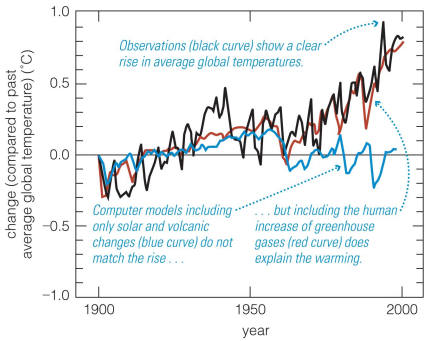
Nitrogen and Oxygen

- 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

How is human activity changing our planet?



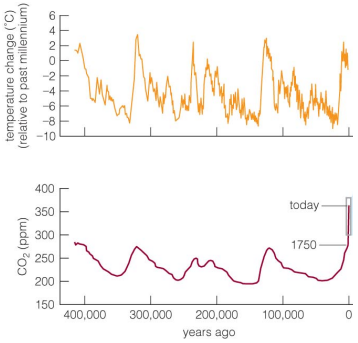
Dangers of Human Activity

- 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

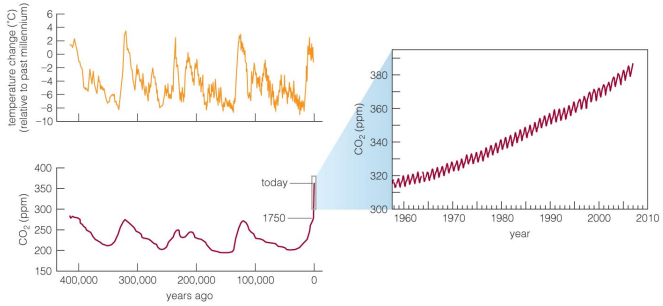
- Earth's average temperature has increased by 0.5°C in past 50 years
- Concentration of CO_2 is rising rapidly
- An unchecked rise in greenhouse gases will eventually lead to global warming

CO_2 Concentration



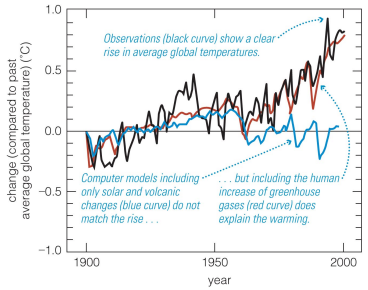
- Global temperatures have tracked CO_2 concentration for last 500,000 years
- Antarctic air bubbles indicate current CO_2 concentration is highest in at least 500,000 years

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