Our solar system

Contains one star, major planets and their moons, dwarf planets, asteroids, comets, and interplanetary dust

Officially, how many planets are there in our solar system?

a) 8

b) 9

c) dozens

Officially, how many planets are there in our solar system?

a) 8 (post-2006 answer)

b) 9 (1930 to 2006 answer)

c) dozens (dwarf planets included)

The Doppler formula is: $v = (\Delta\lambda/\lambda) * 300{,}000$ km/sec for light waves.

A particular spectral feature is seen at 5000 Angstroms in the laboratory, but we observe it at 5020 A in the spectrum of a galaxy. What is $\Delta\lambda$?
a. +20A
b. -20 A
c. 5000 A
d. 5020 A

To continue the previous example, what is the correct means of calculating the radial velocity of the galaxy?
a.   v = (20/5000) * 300,000 km/sec away from us
b.   v = (20/5000) * 300,000 km/sec towards us
c.   v = (20/5020) * 300,000 km/sec away from us
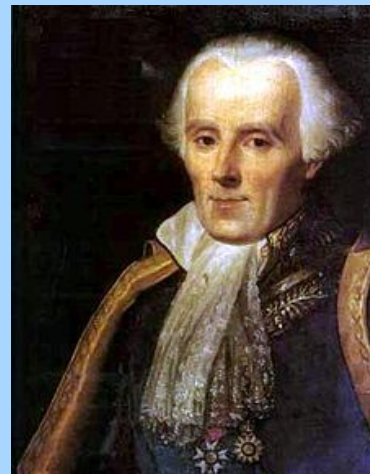d.   v = (20/5020) * 300,000 km/sec towards us

An atom of the most common isotope of the most common element in the universe (hydrogen) consists of:

a. Two neutrons, two protons and two electrons
b. Two neutrons, one proton, and one electron
c. One neutron, one proton, and one electron
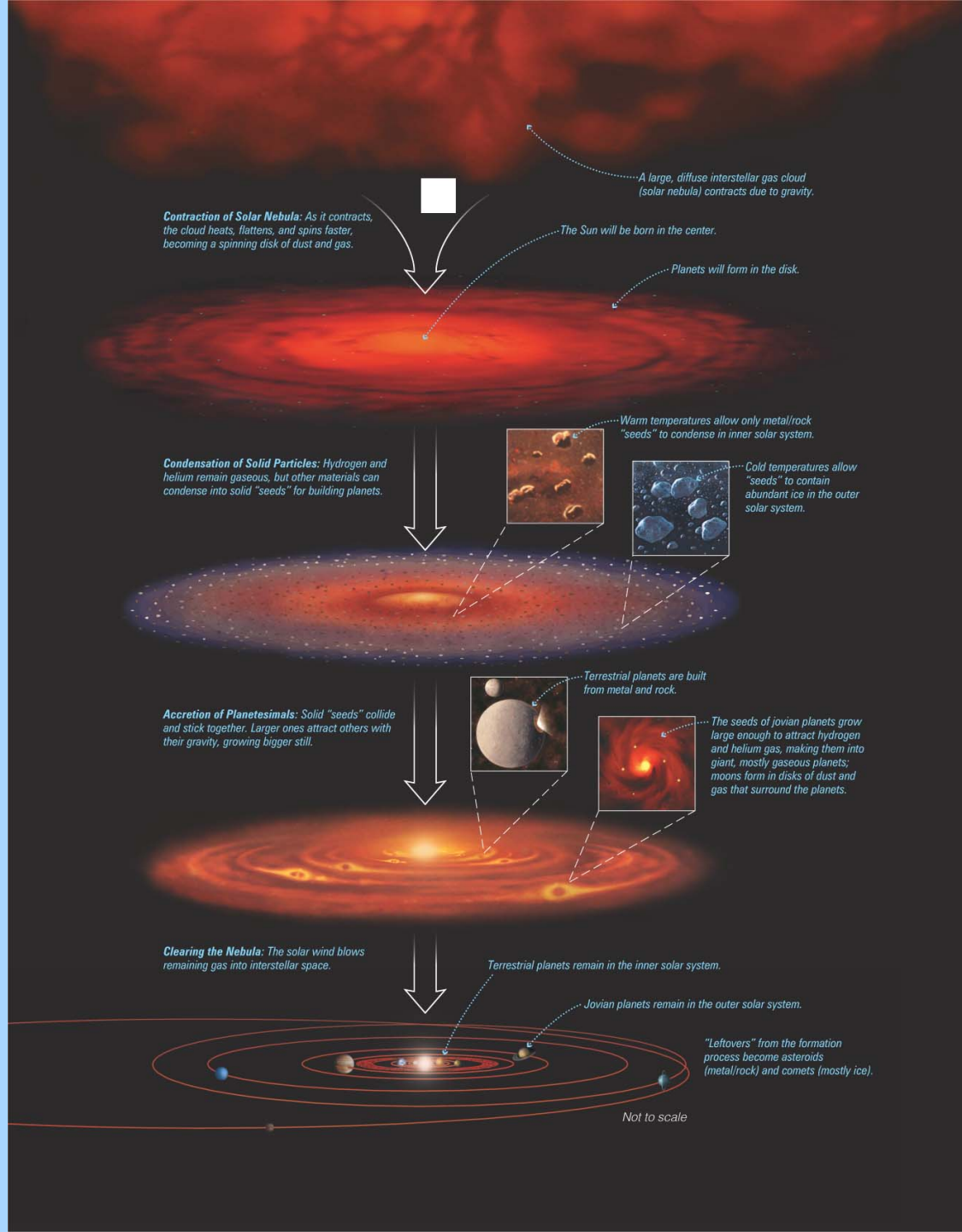d. One proton and one electron

After the publication of Newton's *Principia* in 1687, we had a working idea concerning what held the universe together – universal gravitation. In 1755 the German philosopher Immanuel Kant published his *Allgemeine Naturgeschichte und Theorie des Himmels*, which explained in Newtonian terms the formation of the Milky Way galaxy. The same ideas apply to the formation of the solar system and were independently developed by Pierre-Simon Laplace in 1796. This was the *nebular hypothesis*.

Kant

Laplace

Contraction of Solar Nebula: As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas.

A large, diffuse interstellar gas cloud (solar nebula) contracts due to gravity.

The Sun will be born in the center.

Planets will form in the disk.

Condensation of Solid Particles: Hydrogen and helium remain gaseous, but other materials can condense into solid "seeds" for building planets.

Warm temperatures allow only metal/rock "seeds" to condense in inner solar system.

Cold temperatures allow "seeds" to contain abundant ice in the outer solar system.

Accretion of Planetesimals: Solid "seeds" collide and stick together. Larger ones attract others with their gravity, growing bigger still.

Terrestrial planets are built from metal and rock.

The seeds of jovian planets grow large enough to attract hydrogen and helium gas, making them into giant, mostly gaseous planets; moons form in disks of dust and gas that surround the planets.

Clearing the Nebula: The solar wind blows remaining gas into interstellar space.

Terrestrial planets remain in the inner solar system.

Jovian planets remain in the outer solar system.

"Leftovers" from the formation process become asteroids (metal/rock) and comets (mostly ice).

Not to scale

The solar system was formed from the collapse of a cloud of dust and gas, roughly 5 billion years ago. As the cloud contracted, it heated up and rotated faster. H and He stayed gaseous, but other elements condensed into solid building blocks.

The proto-planets each swept up the smaller planetesimals in an annulus surrounding the Sun. That's why there is only one planet at a particular distance from the Sun.

Well, actually, there's one exception to that rule.....

In 1766 the German astronomer Johann Daniel Titius noticed a particular pattern in the distances of the planets from the Sun. This pattern was published in 1772 without attribution by the director of the Berlin Observatory, Johann Elert Bode. It is known as the Titius-Bode Law, or more commonly as Bode's Law.

Consider the following set of numbers:

0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
0.0	0.3	0.6	1.2	2.4	4.8	9.6	19.2
0.4	0.7	1.0	1.6	2.8	5.2	10.0	19.6

The mean distances of the planets from the Sun (in AU) are:

0.39 Mercury, 0.72 Venus, 1.00 Earth, 1.52 Mars, 5.2 Jupiter, 9.54 Saturn, and 19.2 Uranus. Those were all the planets known by the end of the 18th century. Where was the planet at 2.8 AU from the Sun?

On New Year's Day, 1801, the first day of the 19th century, the Italian astronomer Piazzi discovered Ceres, the largest asteroid. Other asteroids were discovered in 1802, 1804, 1807, plus any others since. Many of these objects are situated between the orbits of Mars and Jupiter. If we could put all of them together, they would not make a planet as big as our Moon. Still, their existence was "predicted" by the Titius-Bode Law.

It is owing to the strong gravitational effect of Jupiter that the material between Mars and Jupiter did not congeal into a proper planet.
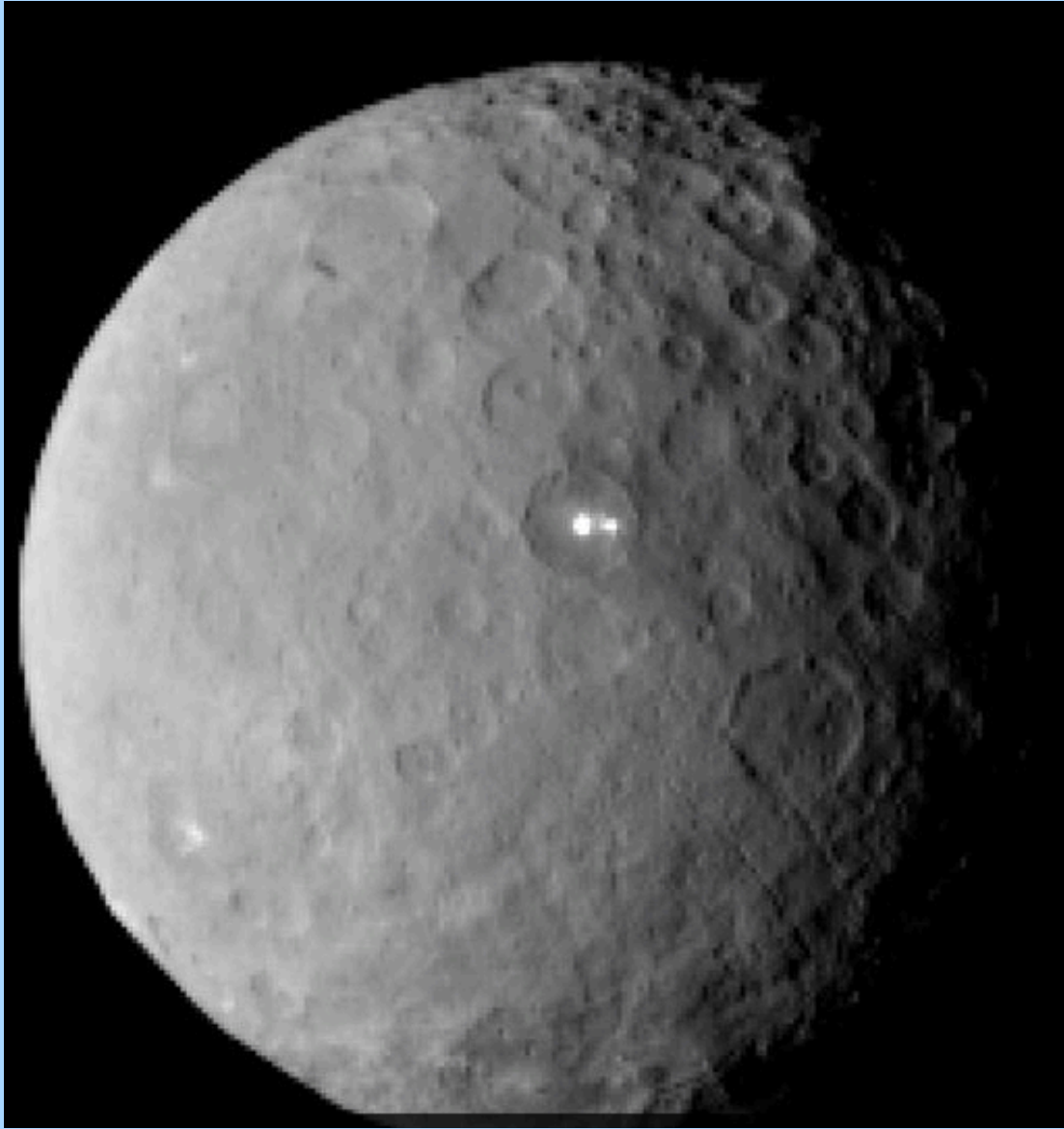
A satellite named Dawn went into orbit around Ceres on March 6, 2015. It previously visited Vesta.

For an object to be a planet it must satisfy these 3 criteria:

1) It must orbit a star.

2) It must be approximately spherical in shape.

3) It must have cleared out the doughnut-shaped ring of volume around its parent star.

Otherwise, it would be classified a dwarf planet, like Ceres or Pluto.

Jupiter in Ultraviolet
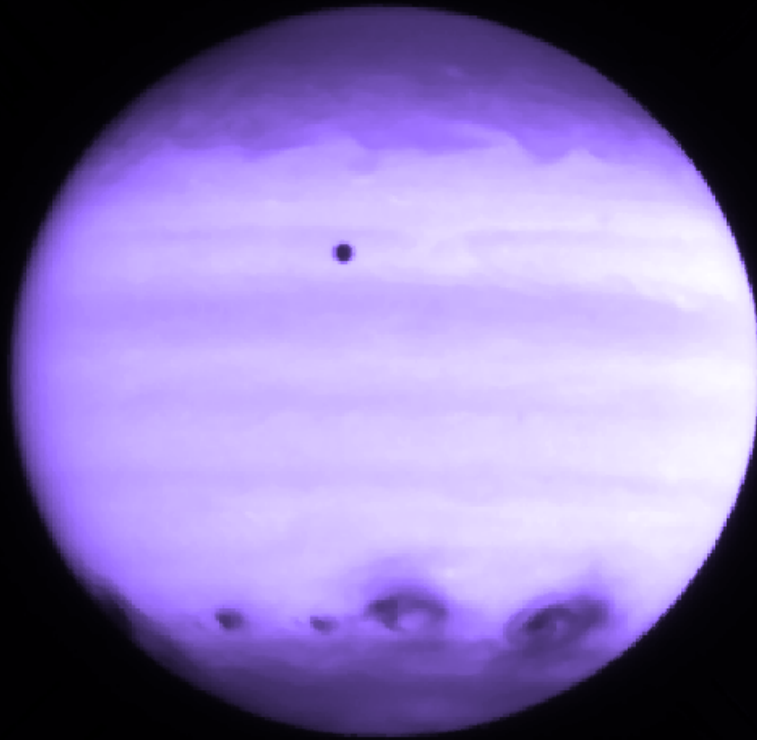
H N Q₂ D/G

B Q₁ R L

Hubble Space Telescope
Wide Field Planetary Camera 2

Even now Jupiter can capture asteroids and comets. In 1994 it ripped apart Comet Shoemaker-Levy 9 prior to its collision with Jupiter. The various pieces hit Jupiter at a series of longitudes near the bottom of the planet in this view. (The spot above is one of Jupiter's moons.)

Evolution of D/G Comet Impact Sites on Jupiter
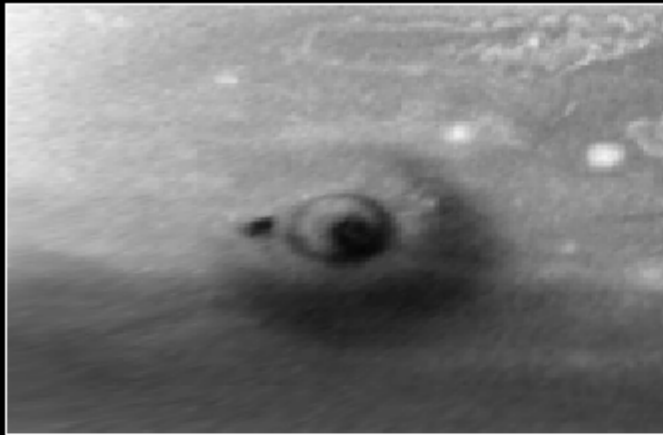
July 18, 1994
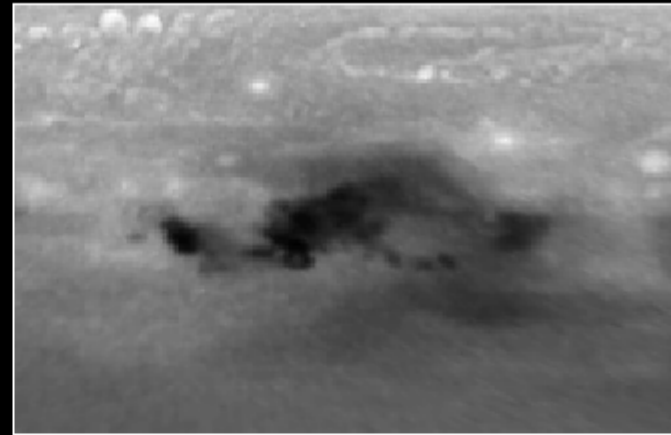
July 23, 1994
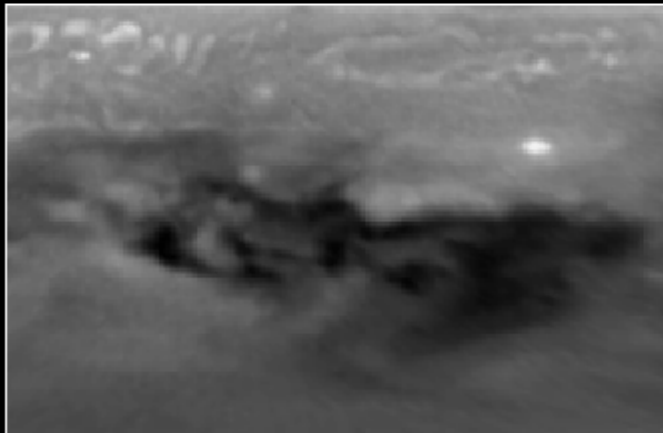
July 30, 1994
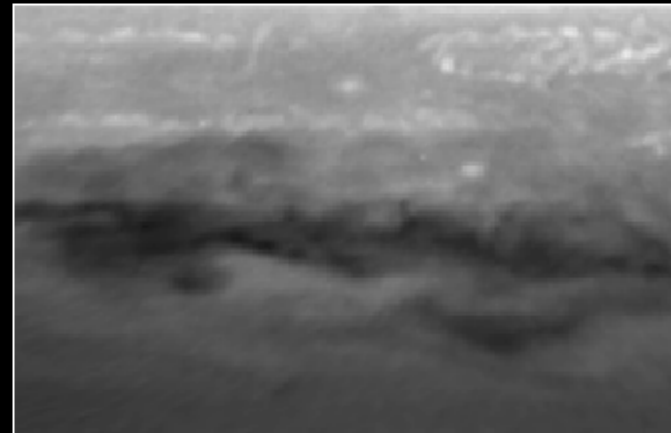
August 24, 1994

Hubble Space Telescope • Wide Field Planetary Camera 2

The planets are as follows:

Terrestrial (Earth-like) planets: Mercury, Venus, Earth, Mars. Rocky, with relatively thin atmospheres (compared to the size of the planet). Much remaining evidence of bombardment by asteroids and meteors. Contain live volcanoes or evidence of past lava flows. Few moons.

Jovian (Jupiter-like) planets: Jupiter, Saturn, Uranus, Neptune. Gas giants. Low average density compared to terrestrial planets. All have ring systems and many moons.

All of the planets revolve around the Sun in the same direction (counterclockwise as you view the solar system from the direction that allows you to see the Earth's north pole).

The orbital inclinations of the other planets are very small compared to the plane of the Earth's orbit. This is why the planets are found at most a couple degrees north or south of the ecliptic.

The planets do *not* all rotate on their axes the same direction, however. Venus rotates very slowly in the opposite direction in 243 days. Uranus rolls around on its side like a car tire.

Mercury 0.1°

Venus 177°

Earth 23°

Mars 25°

Jupiter 3°
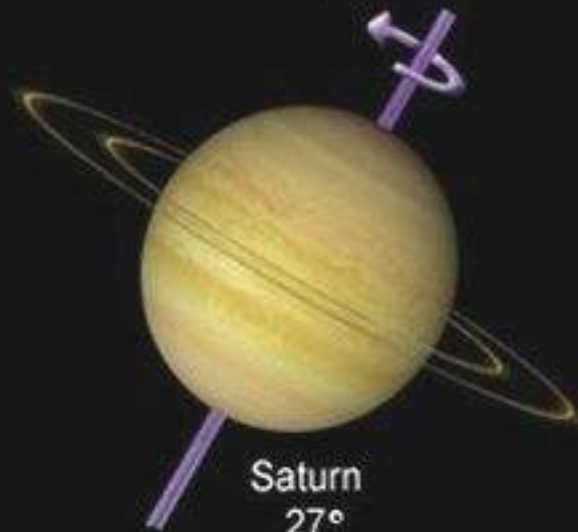
Saturn 27°

Uranus 98°

Neptune 30°

Mercury, Venus, Mars, Jupiter, and Saturn have been known since ancient times.

Uranus was discovered in 1781 by the German-English astronomer William Herschel during a systematic survey of the sky. He was the first astronomer to use almost exclusively reflecting telescopes for his observations. His largest telescope had a 48-inch mirror made of metal.

Neptune was first seen in 1846 after it was predicted to exist by the French astronomer U. J. J. LeVerrier and the English astronomer John Couch Adams. Because the positions of Uranus were not "behaving" properly, Adams and LeVerrier surmised that another large planet existed, which was perturbing the motion of Uranus.

Pluto was discovered in 1930 by the American astronomer Clyde Tombaugh. It was the culmination of a many-year search at Lowell Observatory in Flagstaff, Arizona. It was regarded as an official planet until 2006. Now it is considered a **dwarf planet**.

Pluto's orbit is inclined (tilted) 17 degrees from the plane of the Earth's orbit, much more than the other planets. Pluto's orbital eccentricity is 0.248. From 1979 to 1999 it was closer to the Sun than Neptune. It orbits the Sun every 248 years.

Pluto orbits the Sun in resonance with Neptune. Three orbits of Neptune take the same amount of time as two orbits of Pluto. This is to say that Neptune has captured Pluto in a way, though they are not very close to each other very often.

Another planetary resonance is the rotational period of Mercury. It rotates on its axis in 59 days, or 2/3 of the time it takes to orbit the Sun once.

Pluto's largest moon, Charon, was discovered in 1978. Two other moons (Kerberos and Styx) were imaged in 2005, so five moons are known now.
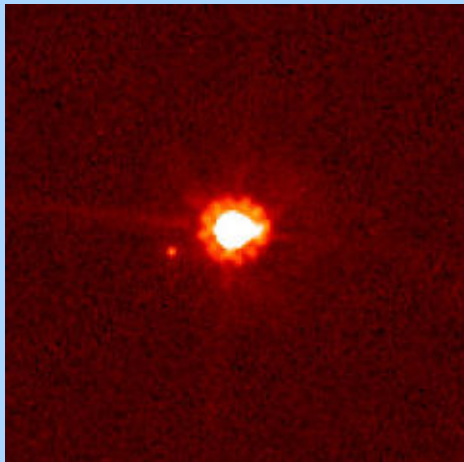
The largest known dwarf planet is Eris, shown here with its moon Dysnomia, named after the Greek goddesses of discord and lawlessness. Discovered in 2005, they orbit the Sun with a period of 560 years.

A spherical body that orbits a star but has not cleared out the doughnut-shaped volume around the star that it occupies is called a

a) red dwarf
b) white dwarf
c) dwarf planet
d) brown dwarf

Amazingly enough, we have found a number of meteorites on the Earth that came from Mars. One fell in Nakhla, Egypt, in 1911. It weighed 10 kg. The most famous one (ALH84001) was discovered in the Allan Hills of Antarctica. It is dated to be 4.5 billion years old. In a remarkable paper published in 1996, geologists claimed that this meteorite had evidence of fossilized bacteria, but upon further study most scientists do not accept this claim.

How can a meteorite found on Earth be from Mars? An asteroid can collide with Mars, and a chunk of Mars can be ejected from its surface, orbit the Sun for a time and collide with the Earth. From the composition of the rock and our knowledge of Martian rocks, we can determine *for certain* that some of these meteorites are from Mars.

The Role of Planetary Size

Small Terrestrial Planets

Interior cools rapidly...

...so that tectonic and volcanic activity cease after a billion years or so. Many ancient craters therefore remain.

Lack of volcanism means little outgassing, and low gravity allows gas to escape more easily; no atmosphere means no erosion.
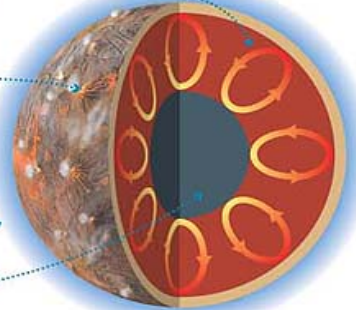
Large Terrestrial Planets

Warm interior causes mantle convection...

...leading to ongoing tectonic and volcanic activity; most ancient craters have been erased.

Outgassing produces an atmosphere and strong gravity holds it, so that erosion is possible.

Core may be molten, producing a magnetic field if rotation is fast enough.

The Role of Distance from the Sun

Sun

Planets Close to the Sun

Surface is too hot for rain, snow, or ice, so little erosion occurs.

High atmospheric temperature allows gas to escape more easily.
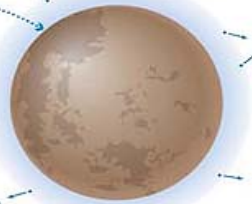
Planets at Intermediate Distances from the Sun

Moderate surface temperatures can allow for oceans, rain, snow, and ice, leading to substantial erosion.

Gravity can more easily hold atmospheric gases.

Planets Far from the Sun

Low surface temperatures can allow for ice and snow, but no rain or oceans, limiting erosion.

Atmosphere may exist, but gases can more easily condense to make surface ice.

The Role of Planetary Rotation

Slow Rotation

Less wind and weather means less erosion, even with a substantial atmosphere.
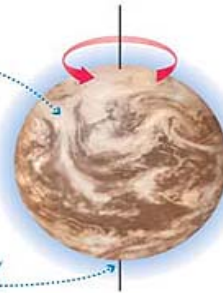
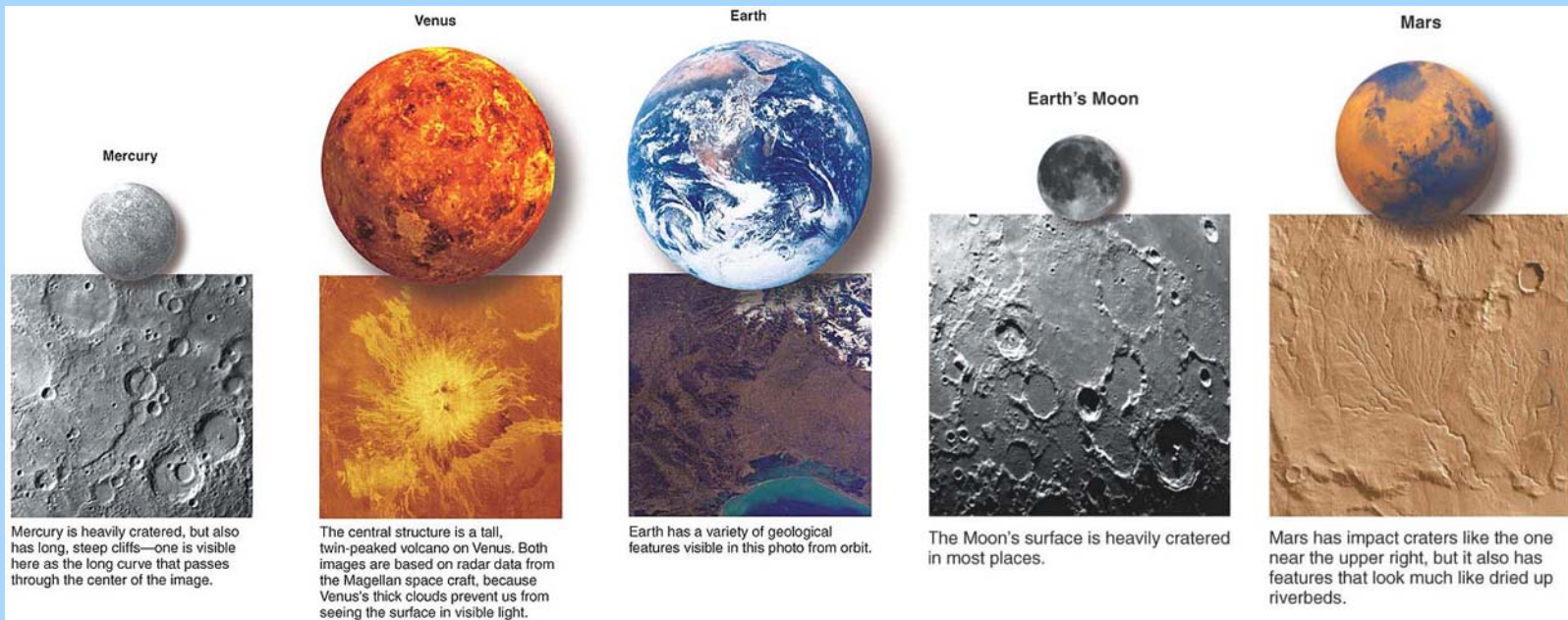*Slow rotation means weak magnetic field, even with a molten core.*

Rapid Rotation

More wind and weather means more erosion.

Rapid rotation is necessary for a global magnetic field.

Mercury

Venus

Earth

Earth's Moon

Mars

Mercury is heavily cratered, but also has long, steep cliffs—one is visible here as the long curve that passes through the center of the image.

The central structure is a tall, twin-peaked volcano on Venus. Both images are based on radar data from the Magellan space craft, because Venus's thick clouds prevent us from seeing the surface in visible light.

Earth has a variety of geological features visible in this photo from orbit.

The Moon's surface is heavily cratered in most places.

Mars has impact craters like the one near the upper right, but it also has features that look much like dried up riverbeds.

Ancient and very recent collisions of asteroids and meteorites with Mercury, our Moon, and Mars are easily visible. Due to volcanism on Venus, Earth, and Mars, plus erosion, many craters have been worn down or paved over with lava.

The Barringer meteor crater near Winslow, Arizona, was formed 50,000 years ago when a meteorite approximately 50 meters in diameter crashed into the Earth at a speed of 12 km/sec.

The bomb that was dropped on Hiroshima on August 6, 1945, had the destructive power of 15.5 thousand tons of dynamite. If a 5 km diameter asteroid hits the Earth, what is its equivalent destructive power?

A. About the same as the Hiroshima bomb
B. About 65 "Hiroshimas" (1 Megaton of TNT)
C. About 3000 "Hiroshimas" (50 Megatons of TNT)
D. About 1 billion times the power of the Hiroshima bomb (15 million Megatons of TNT)

How much destructive energy does a 5 km diameter asteroid have, if it collides with the Earth at 30 km/sec?

$$\text{Kinetic Energy} = \tfrac{1}{2}\, m\, v^2$$

radius r = 2.5 km = 2500 meters

volume = 4/3 π r^3 = 6.55 X 10^{10} cubic meters

perhaps density = 2 times that of water, or 2 gm/cm^3 =
  2000 kg/m^3 so mass ~ 1.31 X 10^{14} kg

let impact velocity = 30 km/sec = 3 X 10^4 m/sec

K.E. of collision is 5.89 X 10^{22} Joules

Since 1 megaton of dynamite explodes with the energy of 4 X 10^{15} J, our hypothetical asteroid collision has the destructive power of a 15 **million megaton** nuclear bomb!!

The biggest nuclear bomb ever exploded was the Tsar Bomba, set off by the Soviet Union on October 30, 1961. It had a yield of 58 megatons.

Meteorites and asteroids are still colliding with the Earth from time to time.

Something exploded over Siberia in 1908 at a place called Tunguska.
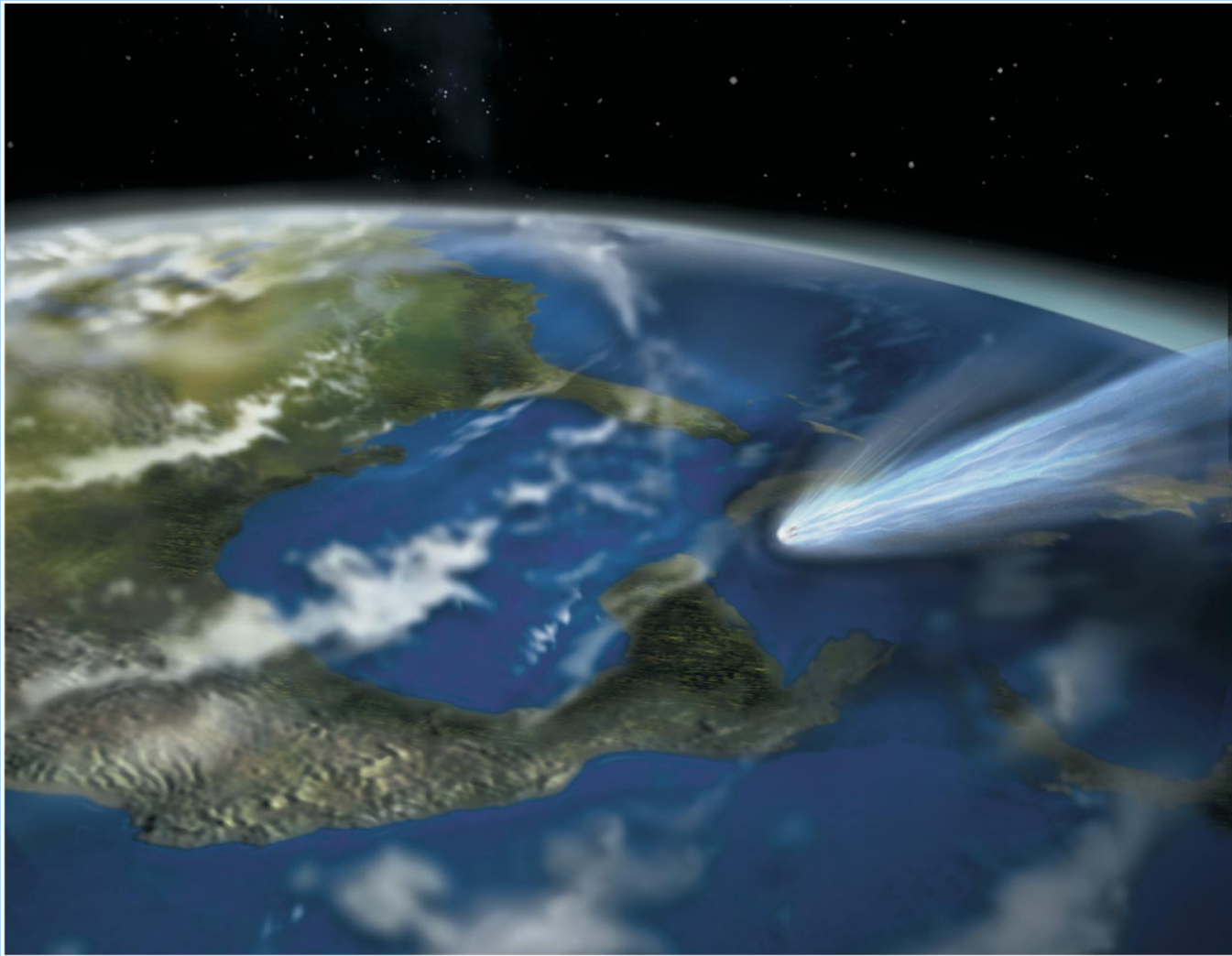
The collision of an asteroid or comet with the Earth 65 million years ago could have led to the dinosaurs' extinction.

What is the evidence for this suggestion?
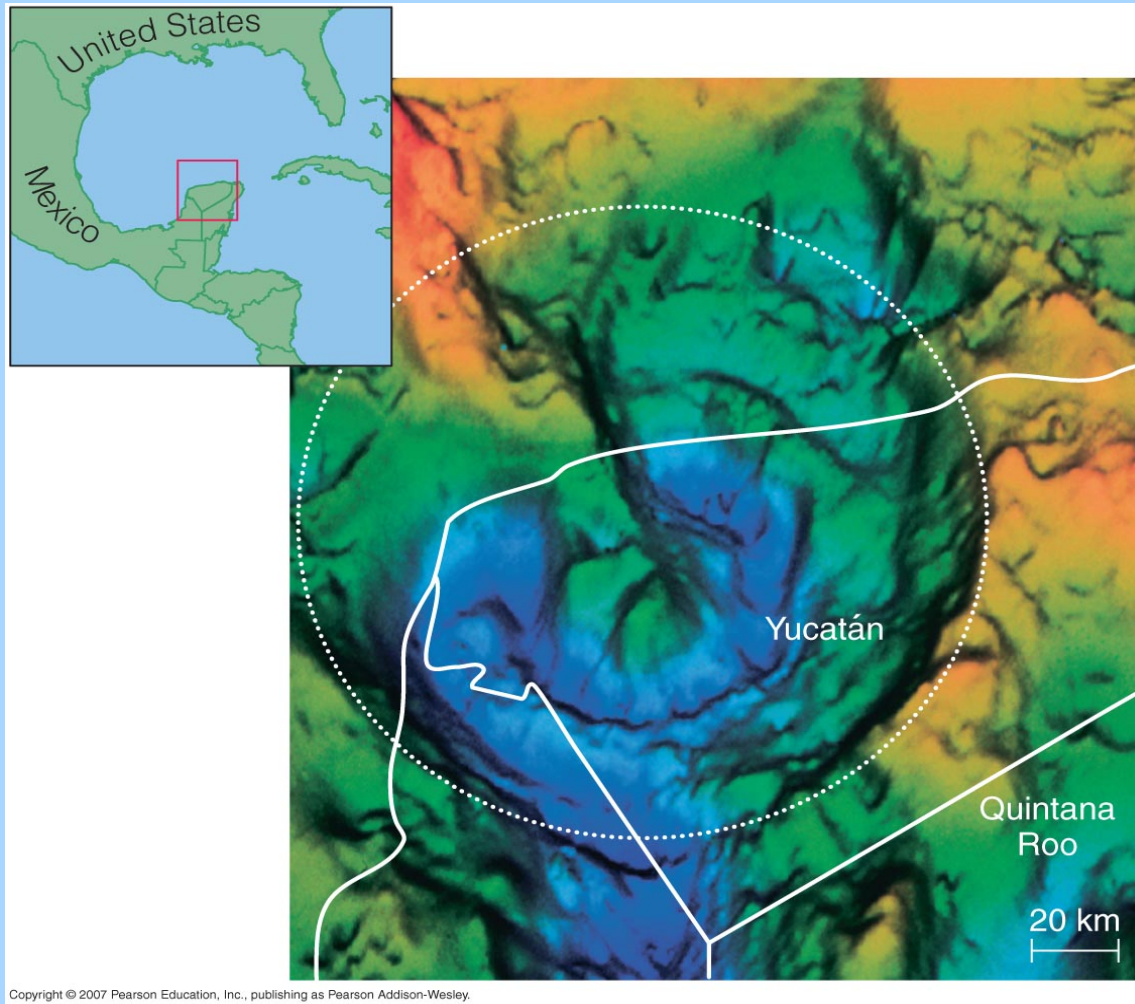
An iridium-rich sediment layer and an impact crater on the Mexican coast show that a large impact occurred at the time the dinosaurs died out about 65 million years ago.
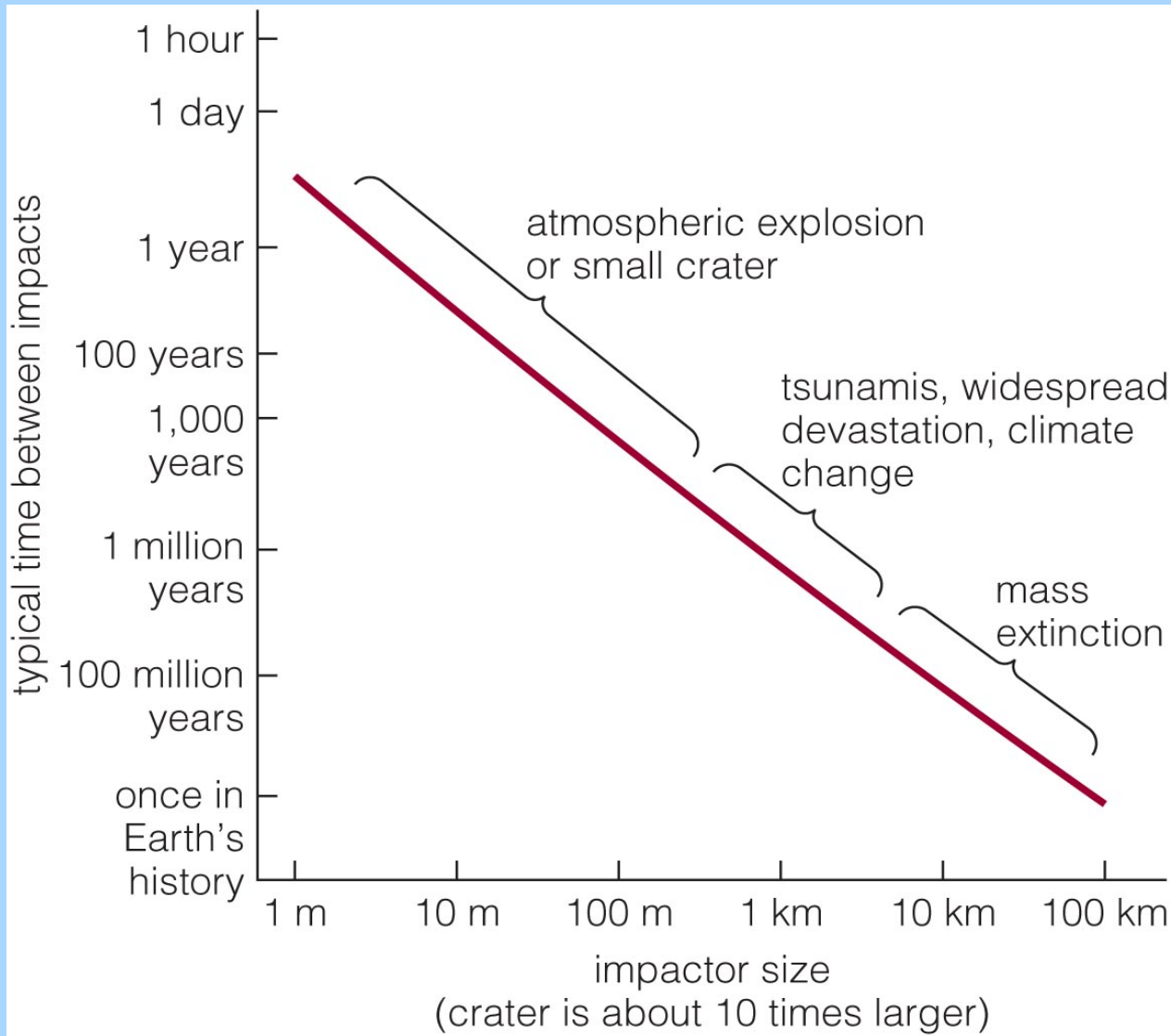
More destructive explosions occur less often, but they do occur!

There are probably something like 400,000 to 1 million asteroids in the solar system with sizes greater than 1 km. One of the most biggest national security threat comes from the potential collision of a Near Earth Object (NEO) with the Earth.

We estimate that there are 20,000 Potentially Hazardous Objects with size greater than 140 m that might hit the Earth.

The Earth as a planet; the CO_2 cycle

The Earth's crust is mostly SiO_2 and its core is mostly iron and nickel. By mass the Earth is 34.6% Fe, 29.5% O, 15.2% Si, 12.7% Mg, 2.4% Ni, 1.9% S, 0.05% Ti, and 3.65% everything else. If we consider the different atomic weights of the elements, the most common atom in the Earth's crust is O, followed by Fe, then Si.

The Earth is the densest large body in the solar system.

Whole Earth

Oxygen 30%

Iron 35%

Other <1%
Aluminum 1%
Calcium 1.1%
Sulfur 2%
Nickel 2.4%

Magnesium 13%

Silicon 15%

Crust

Oxygen 46%

Silicon 28%

Other 3.2%
Potassium 2.3
Calcium 2.5%
Magnesium 4%

Iron 6%

Aluminum 8%

http://www.indiana.edu/~geol116/week2/mineral.htm
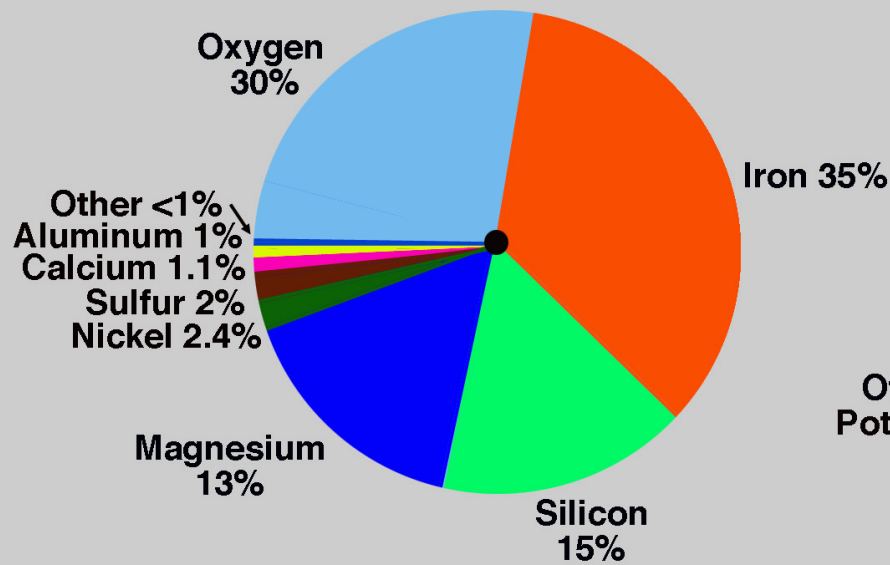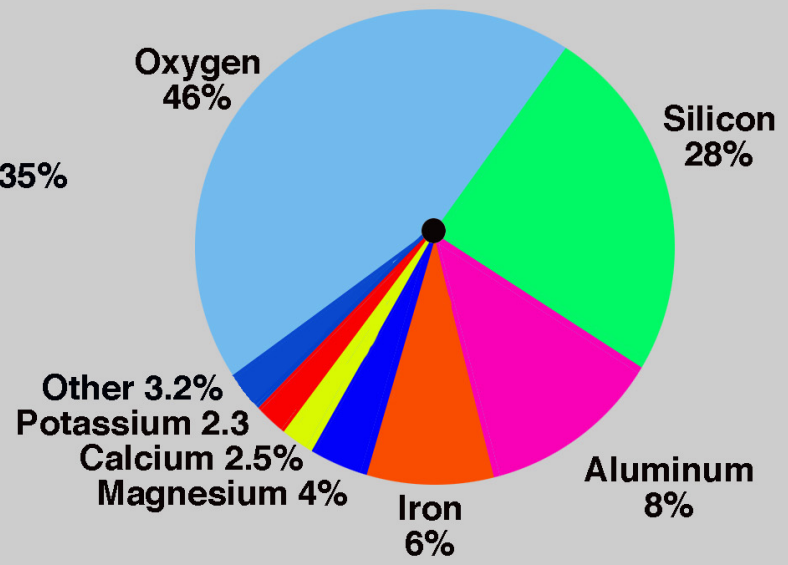
When the Earth was forming and was young, the interior was hot for a number of reasons:
a) the Earth was contracting (conversion of grav. potential energy into heat)
b) pressure
c) convection
d) radioactive decay of long-lived unstable atoms such as uranium and thorium

Nowadays, it is only radioactive decay that is significant to keep the outer core molten.

Alfred Wegener (1880-1930) proposed the idea of continental drift. His ideas were not taken seriously until the 1960's.

Note how nicely South America could have fit into west Africa.

It turns out that plate tectonics plays a crucial role in the carbon dioxide cycle of the Earth.

Atmospheric CO_2 dissolves in rainwater, creating mild acid.

The mildly acidic rainwater erodes rocks on Earth's continents. Rivers carry the minerals to the oceans.

In the oceans the eroded minerals combined with dissolved CO_2 and fall to the ocean floor, making rocks such as limestone.

On time scales of millions of years plate tectonics carries the carbonate rocks to *subduction zones*, and subduction pushes them down into the Earth's mantle.

As they are pushed into the mantle, some of the carbonate rocks melts, releasing CO_2, which then outgasses back into the atmosphere through volcanoes.

The CO_2 cycle acts as a thermostat for the Earth, because the rate at which CO_2 is extracted from the atmosphere is very sensitive to temperature. A small change in the Earth's can be offset by a change in the CO_2 cycle.

Volcanoes outgas CO_2.

Atmospheric CO_2 dissolves in rainwater.

Rainfall erodes rock on land; rivers carry broken-down minerals to the sea.

Broken-down minerals react with dissolved CO_2 to form carbonate rocks.

Carbonate rocks subduct and melt, releasing CO_2.

Copyright © 2007 Pearson Education, Inc., publishing as Pearson Addison-Wesley.
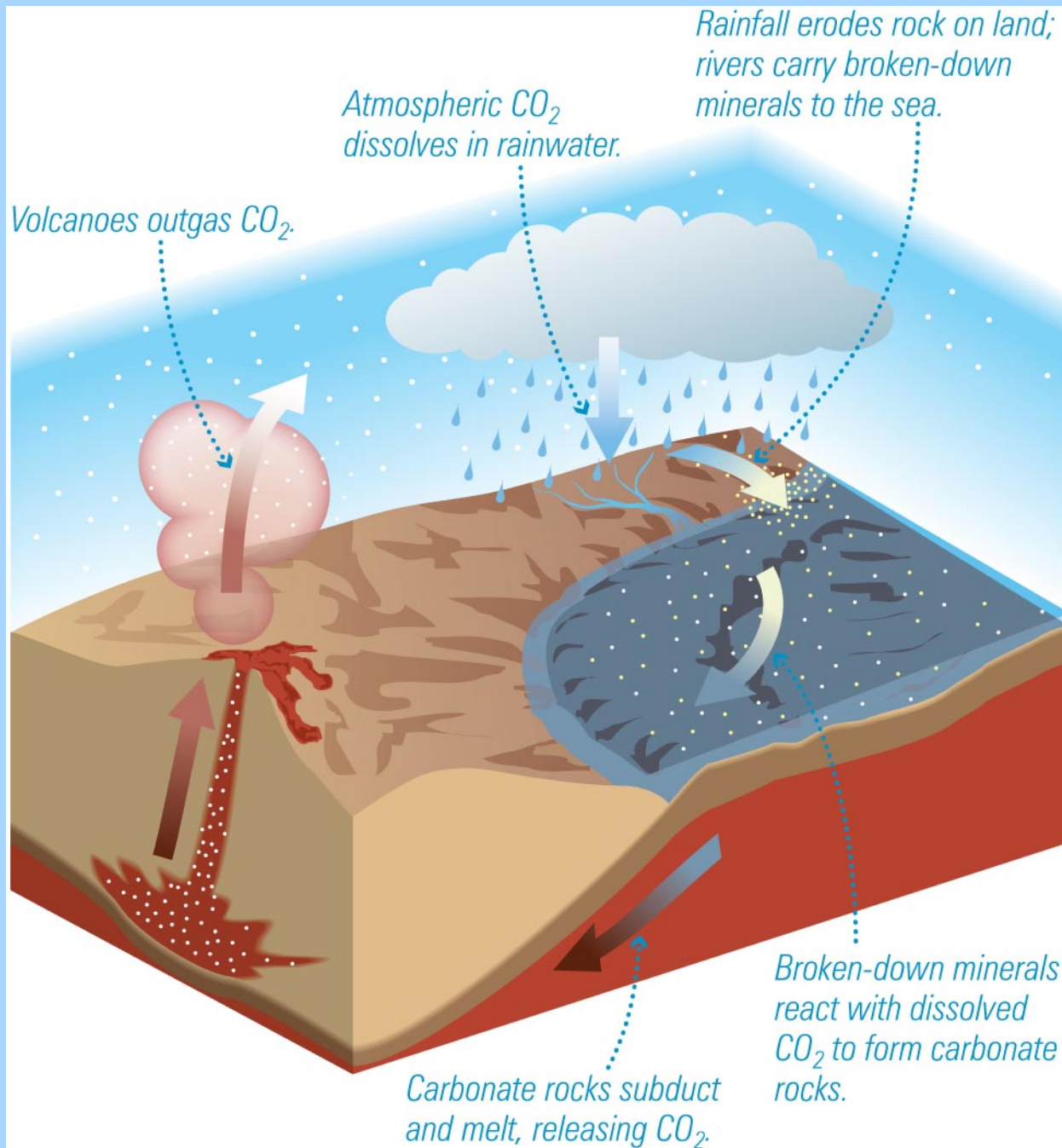
Without plate tectonics CO_2 would remain locked up in the seafloor rocks rather than being recycled through outgassing from volcanoes.

The CO_2 cycle can make a warm Earth cooler or a cool Earth warmer, as follows:

A warmer Earth will have more evaporation and heavier rainfall, pulling more CO_2 out of the atmosphere. The reduced CO_2 of the atmosphere weakens the greenhouse effect, which counteracts the initial warming, and the planet cools down.

If the Earth gets too cool, precipitation decreases and less CO_2 is dissolved in rainwater. Allowing CO_2 released by volcanism to build back up in the atmosphere. The increased CO_2 strengthens the greenhouse effect and warms the planet back up.

It is important to note that the CO_2 cycle operates on a time scale of a few hundred thousand years, which means it has no effect on short-term changes. If humans pump a lot of CO_2 into the atmosphere, it might not be able to adjust.

Also, without plate tectonics, the CO_2 cycle would not operate. Mars and Mercury no longer have tectonic activity. This is related to the planet size. Both of these planets have effectively lost their atmospheres.
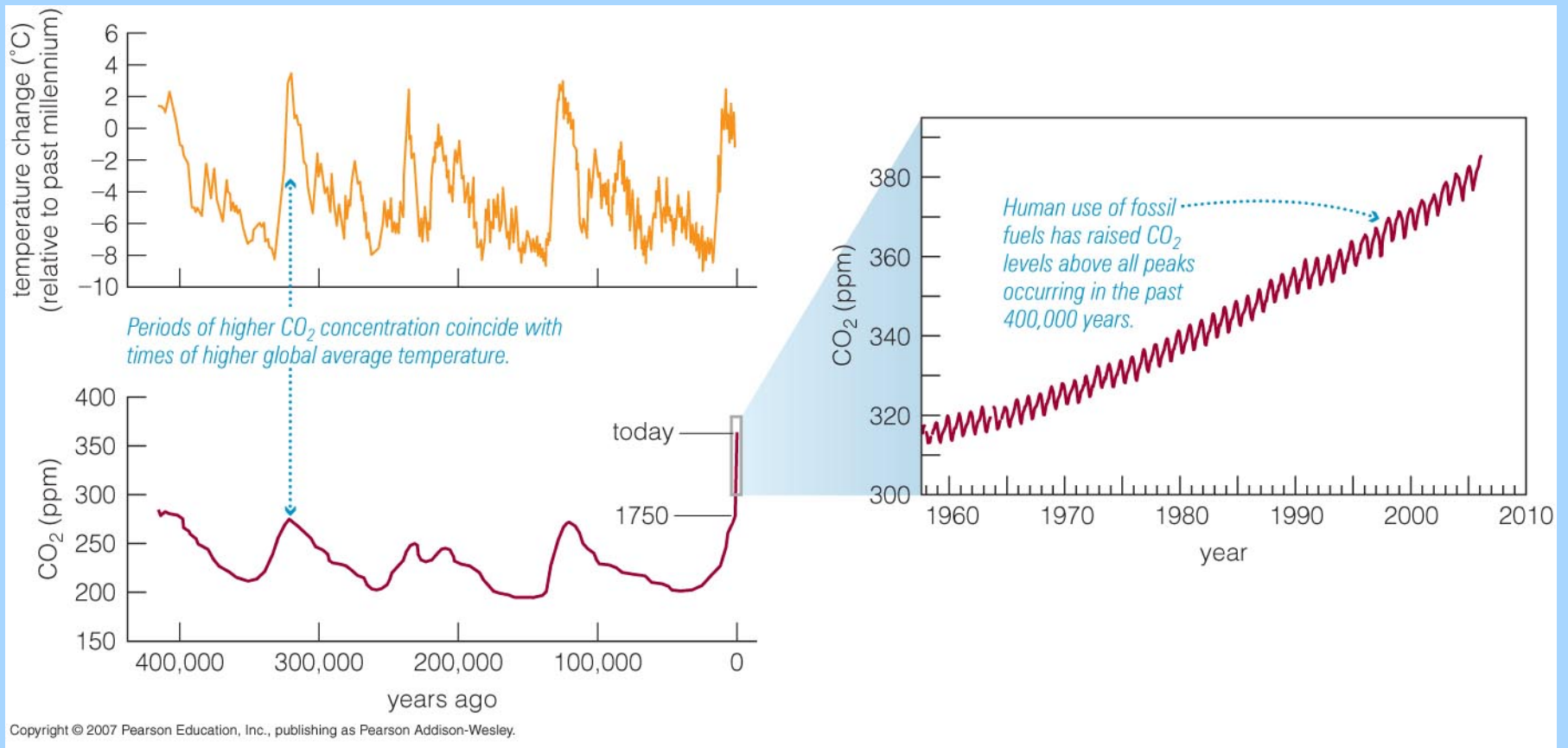
Note how global temperature over the past 400,000 years correlates with CO_2 content of the atmosphere. The data from Mauna Loa (above, right) show how CO_2 content has changed over the past 50 years.
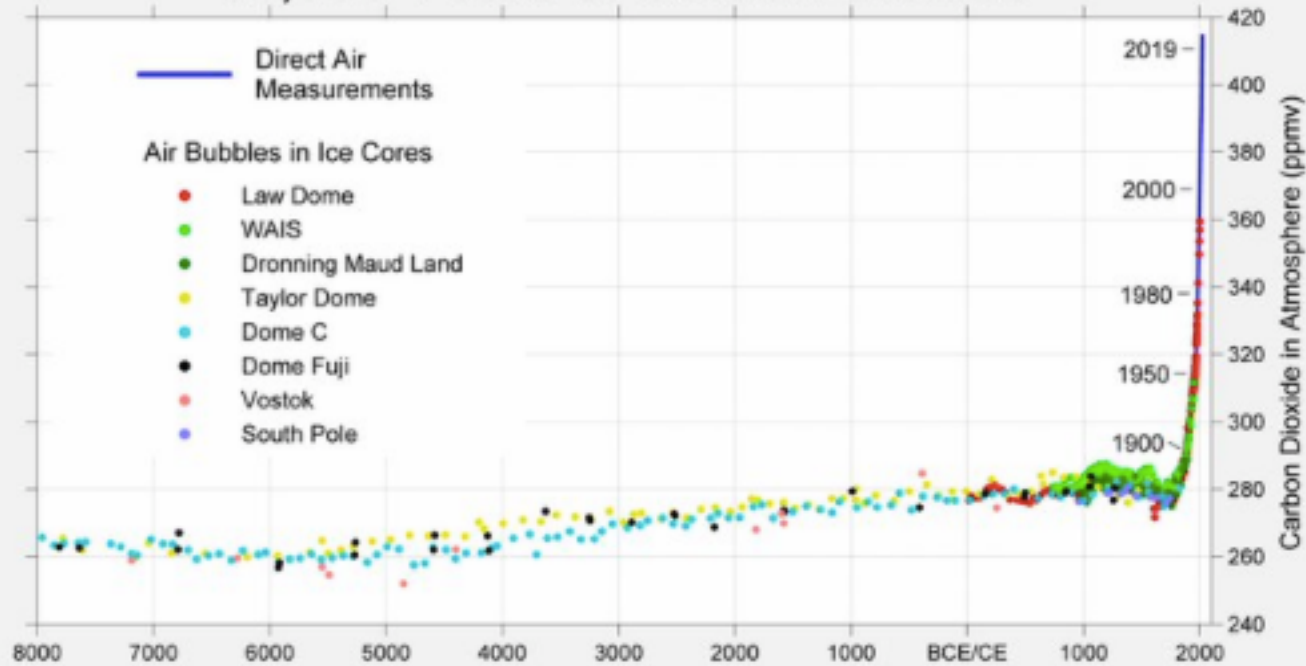
On an annual basis, when it is spring and summer in the northern hemisphere the green plants are absorbing CO_2 and producing oxygen. So the CO_2 content diminishes. This leads to one-year variations of the CO_2 content.
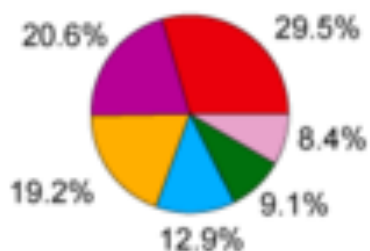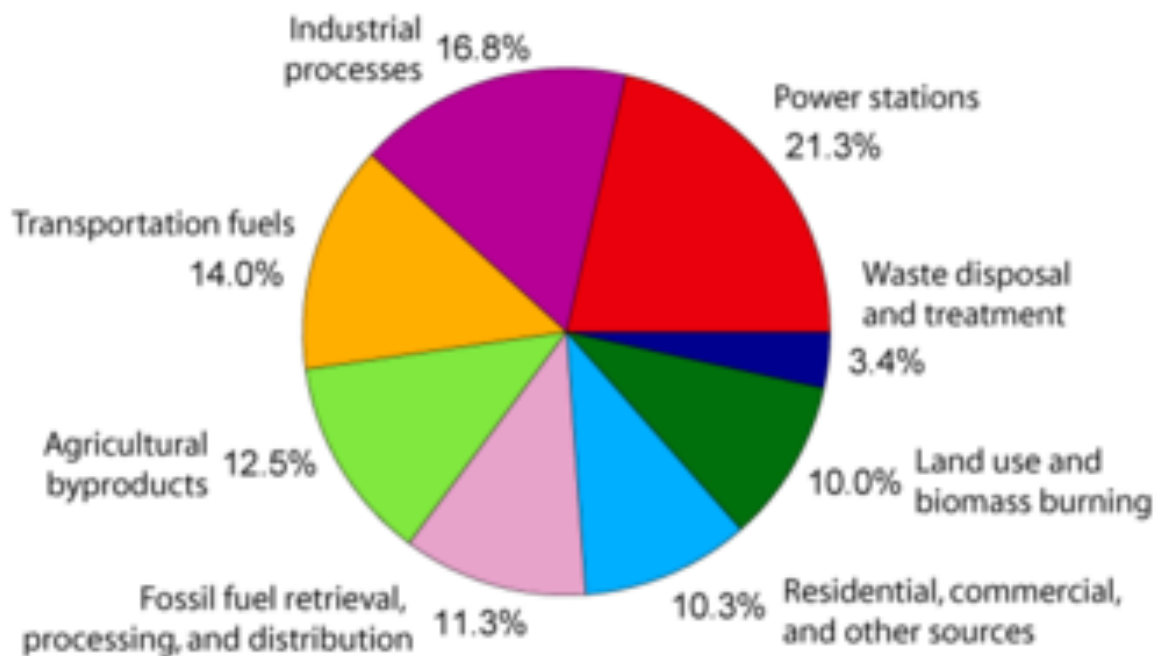
But as you can see, over the past 50 years there has been a 20 percent increase in atmospheric CO_2. The rainfall and outgassing by volcanoes cannot adjust on this kind of time scale. There is a strong possibility that this is related to the burning of fossil fuels and deforestation worldwide. It behooves us to diminish our dependence on fossil fuels.
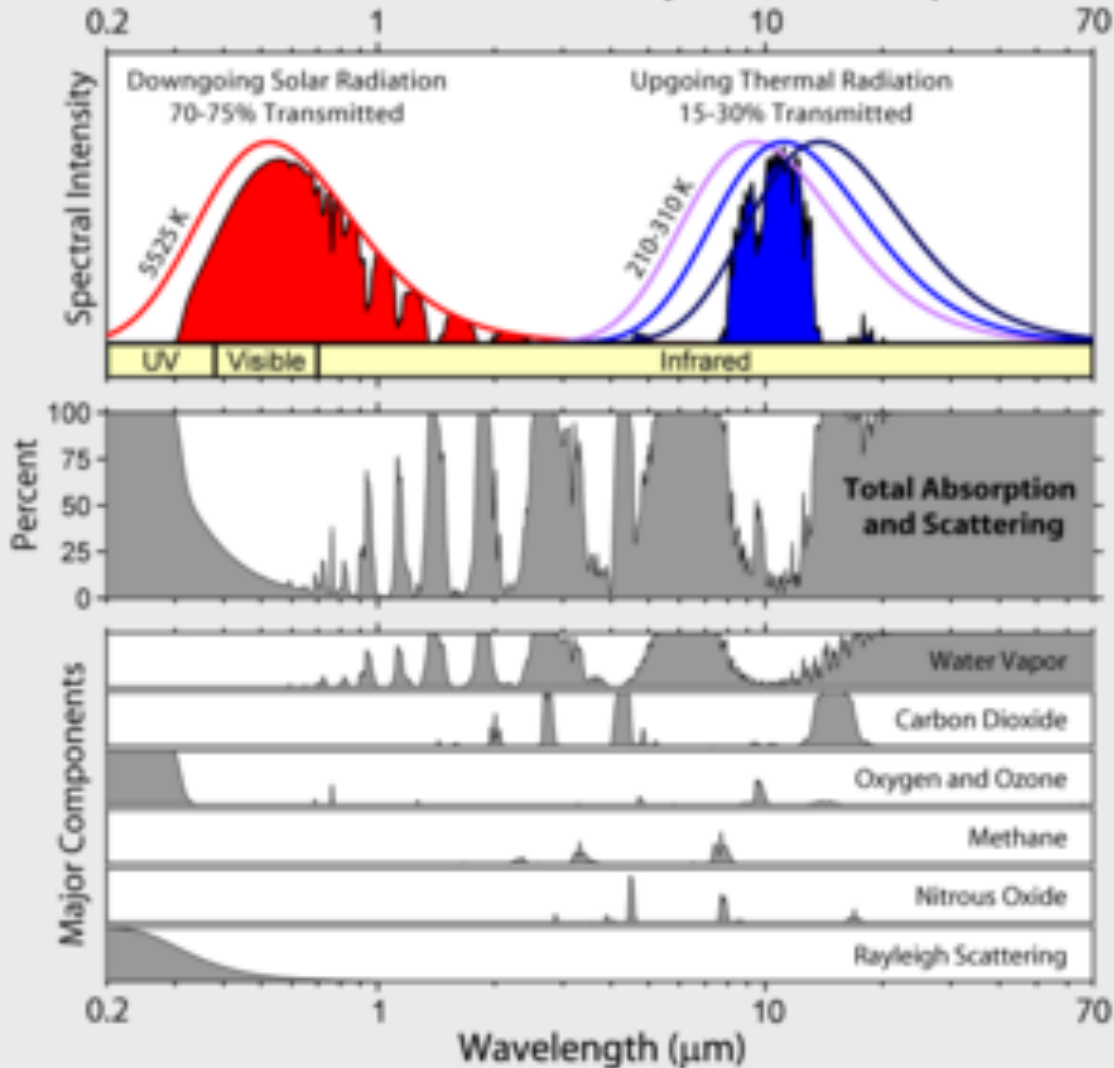
The greenhouse effect happens b/c the radiation that comes in from the Sun gets trapped by molecules in the atmosphere.
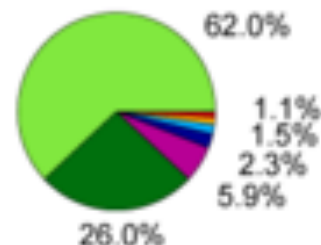
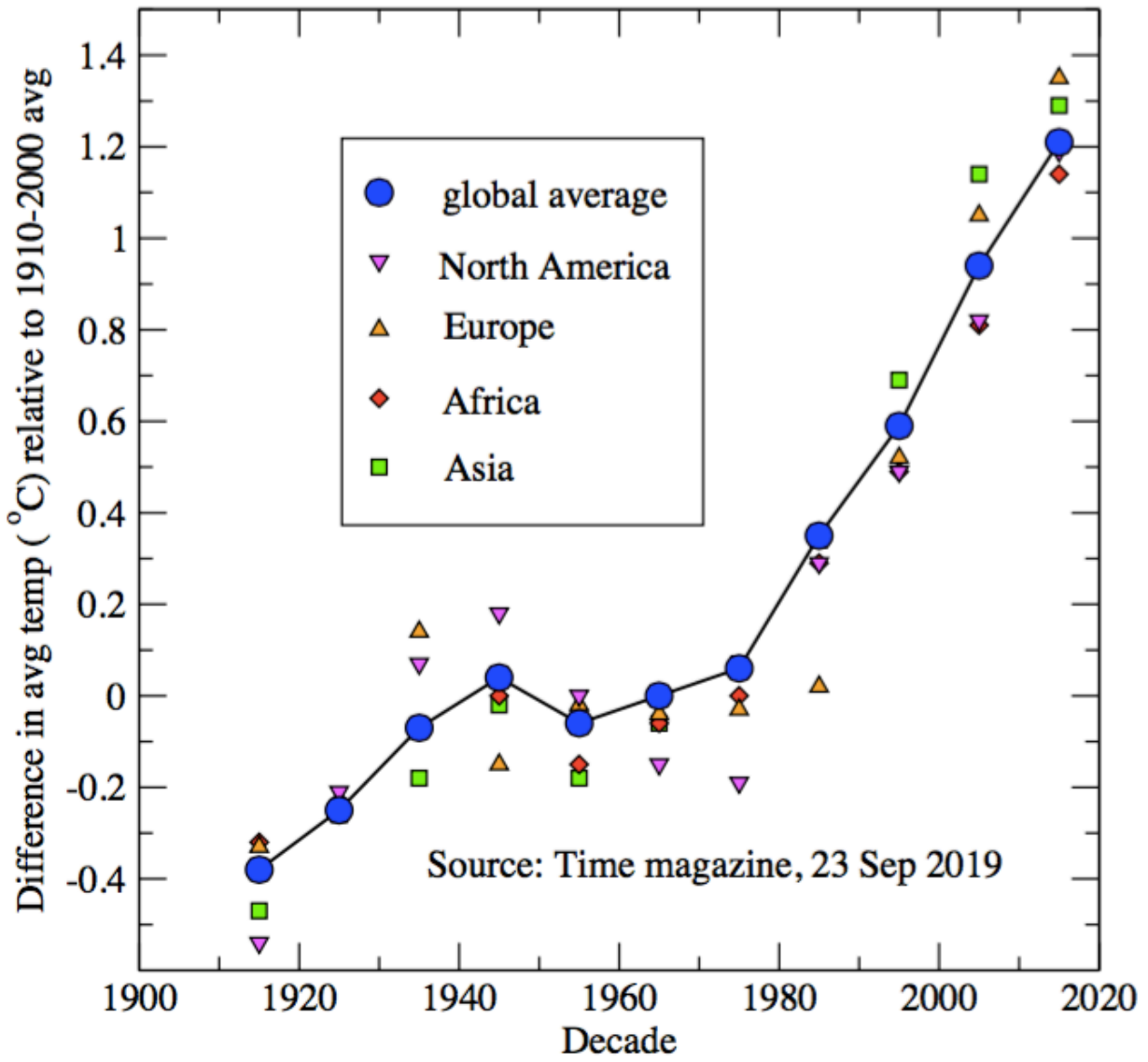# Annual Greenhouse Gas Emissions by Sector

Industrial processes 16.8%

Power stations 21.3%

Transportation fuels 14.0%

Waste disposal and treatment 3.4%

Agricultural byproducts 12.5%

Land use and biomass burning 10.0%

Fossil fuel retrieval, processing, and distribution 11.3%

Residential, commercial, and other sources 10.3%

Carbon Dioxide (72% of total)
29.5% 20.6% 19.2% 12.9% 9.1% 8.4%
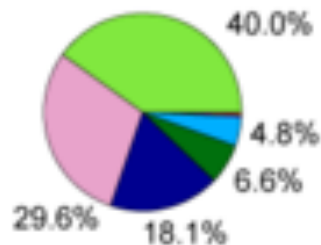
Methane (18% of total)
40.0% 29.6% 18.1% 6.6% 4.8%

Nitrous Oxide (9% of total)
62.0% 26.0% 5.9% 2.3% 1.5% 1.1%

Source: Time magazine, 23 Sep 2019

The principal greenhouse gases:

CO_2 (carbon dioxide)

CH_4 (methane)

N_2O (nitrous oxide)

H_2O (water vapor)

If there are no greenhouse gases, the equilibrium average temperature of a planet can be shown to be:

$$T = 279 \, (1-a)^{1/4} \left(\frac{L_*}{L_\odot}\right)^{1/4} / d_{AU}^{1/2}$$

Here T is in degrees Kelvin, a is the reflectivity (aka albedo) of the planet, L_*/L_{sun} is the luminosity of a star in solar luminosities, and d is the distance of the planet from its parent star (in Astronomical Units).

For the Earth $d_{AU} = 1$ and $L_* / L_{\_Sun} = 1$. The albedo of The Earth is in the range of 28 to 30%, so a = 0.28 to 0.30.

For $a = 0.28$, the mean temperature of the Earth would be 257 deg K = -16 deg C = +3.2 deg F.

For a = 0.30, T = 255 deg K = -18 deg C = -0.4 deg F.

This means that with no greenhouse gases the Earth's mean temperature is well below the freezing point of water. Agriculture would be impossible and we'd all starve. Thus, *some* greenhouse gases are necessary. The problem is that the CO_2 level is now higher than it's been in half a million years, and global temperatures are rising.

According to the web article "Which emits more carbon dioxide: volcanoes or human activities?" (climate.gov) how does the amount of CO_2 outgassed by volcanoes compared to the amount produced by human activities?
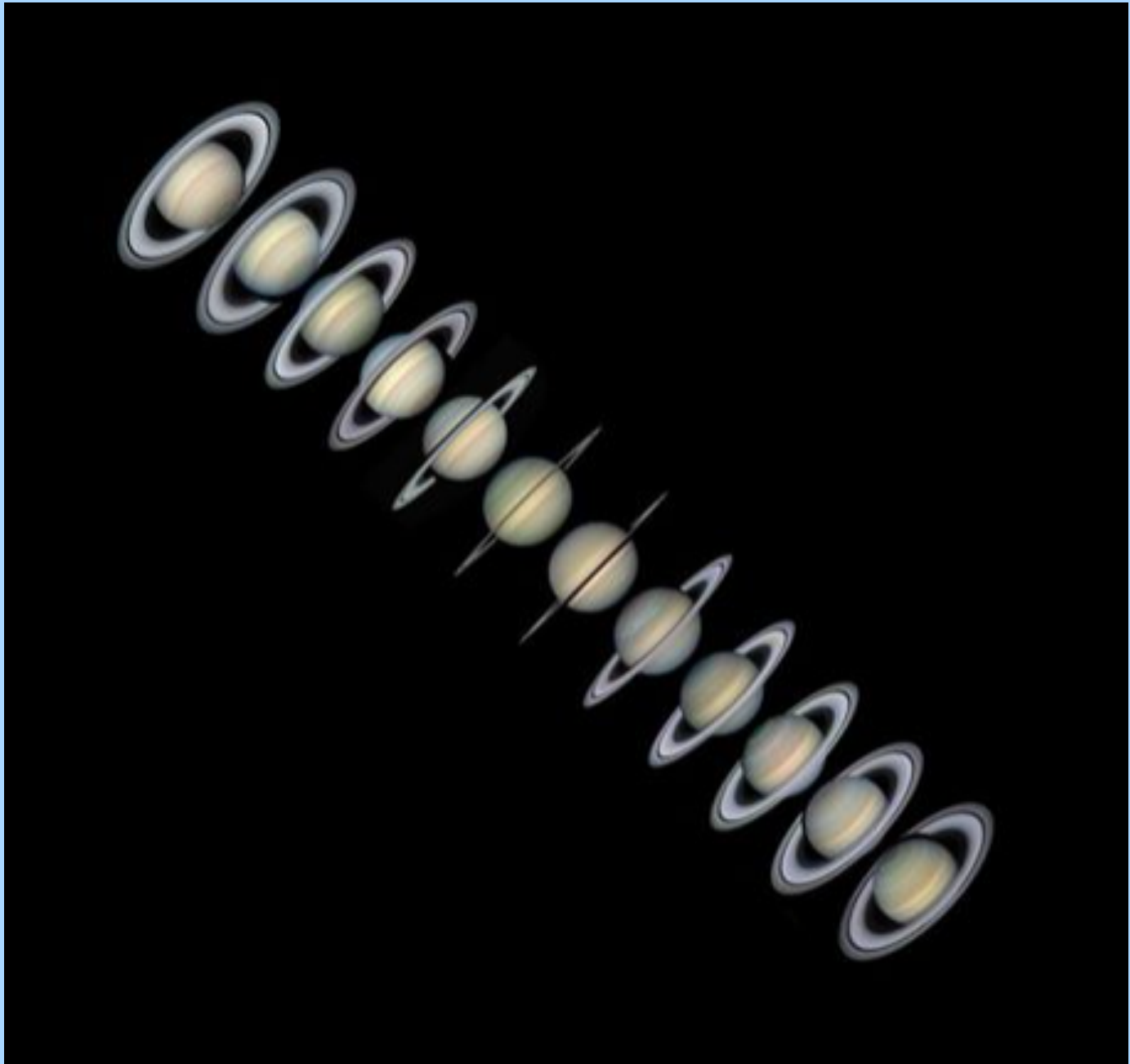
a) about 2%

b) 10%

c) 50%

d) Volcanoes put out way more CO_2 (so we don't really have to worry about car emissions and other such production of greenhouse gases)

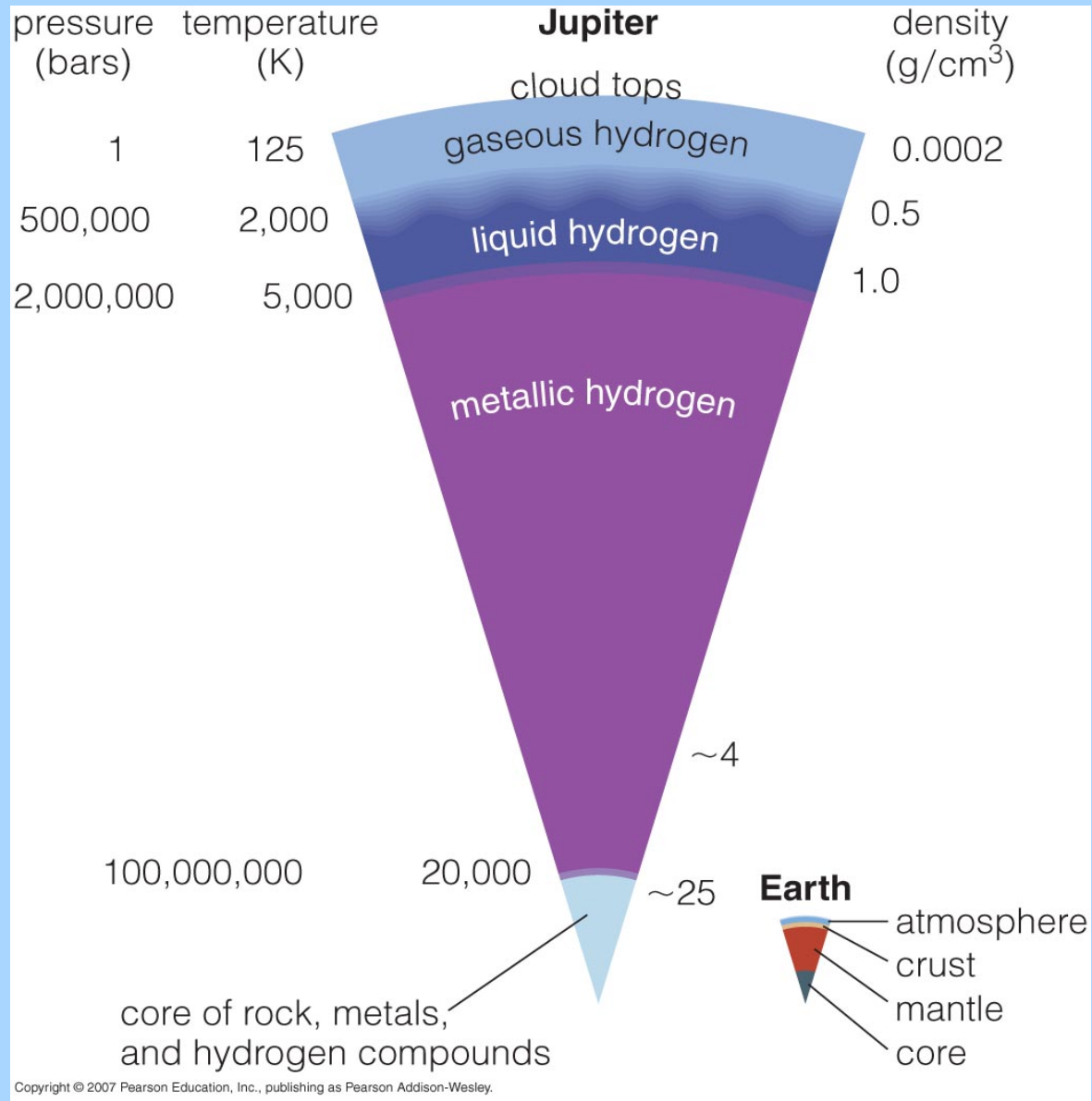Which of the following is *not* a greenhouse gas?
a. ammonia
b. methane
c. carbon dioxide
d. nitrous oxide

The Jovian planets

Earth

Jupiter
Distance from Sun = 5.20 AU
Mass = 318 M_{Earth}
Density = 1.33 g/cm^3
Composition: mostly H, He

Saturn
Distance from Sun = 9.54 AU
Mass = 95 M_{Earth}
Density = 0.71g/cm^3
Composition: mostly H, He

Uranus
Distance from Sun = 19.2 AU
Mass = 14 M_{Earth}
Density = 1.24 g/cm^3
Composition: H compounds,
  rock, H and He

Neptune
Distance from Sun = 30.1AU
Mass = 17 M_{Earth}
Density = 1.67 g/cm^3
Composition: H compounds,
  rock, H and He

Already in the 17th century it would have been possible to determine that Jupiter has a mass of roughly 300 Earth masses and a density roughly 1/5 that of the Earth. From its rapid rotation (just under 10 hours) and its flattened appearance, one could conclude that Jupiter has an extensive atmosphere. It is a gas giant.

Jupiter

pressure (bars)	temperature (K)		density (g/cm³)
		cloud tops	
1	125	gaseous hydrogen	0.0002
500,000	2,000	liquid hydrogen	0.5
2,000,000	5,000		1.0
		metallic hydrogen	
			~4
100,000,000	20,000		~25

core of rock, metals, and hydrogen compounds

Earth
- atmosphere
- crust
- mantle
- core

The Jovian planets have *very* different internal structure compared to the terrestrial planets!

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The Coriolis force diverts winds.

to equator

N

H

5,000 km

high pressure
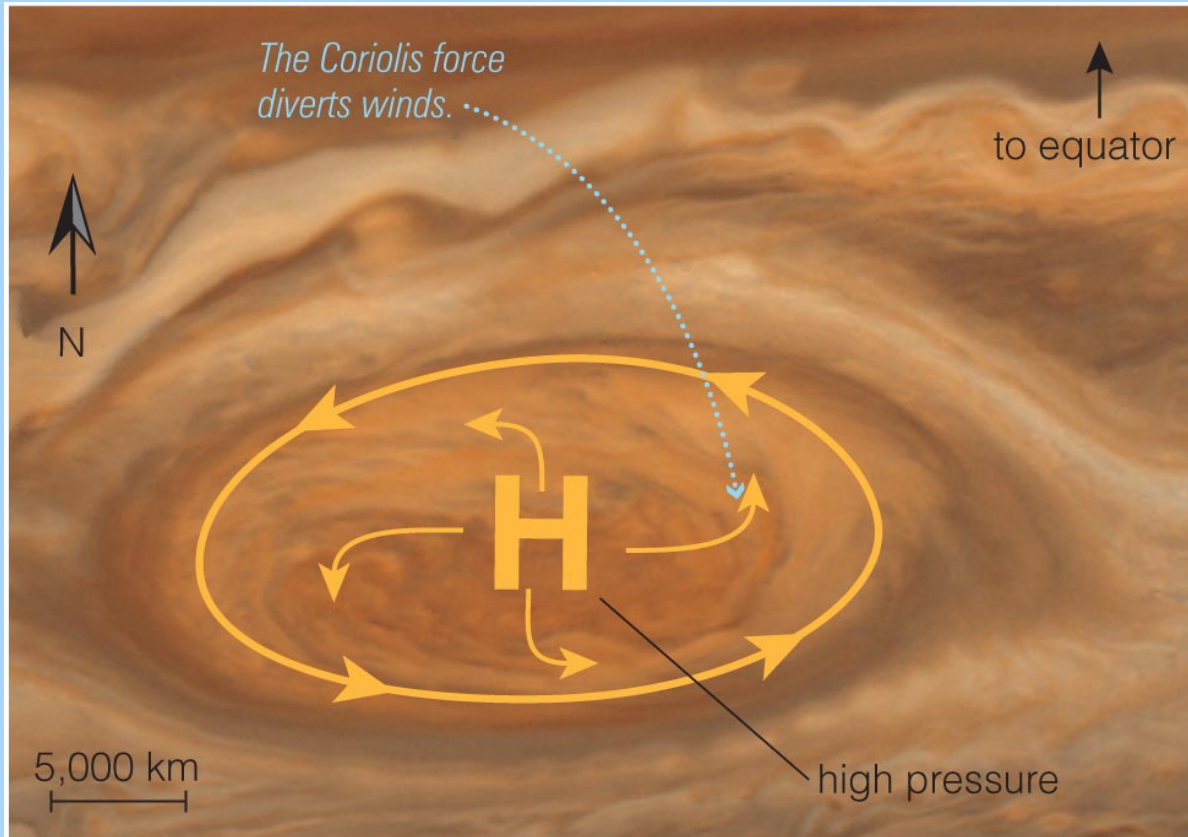
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Jupiter's Great Red Spot was seen perhaps as early
as the 1660's by the Italian-French astronomer Cassini.
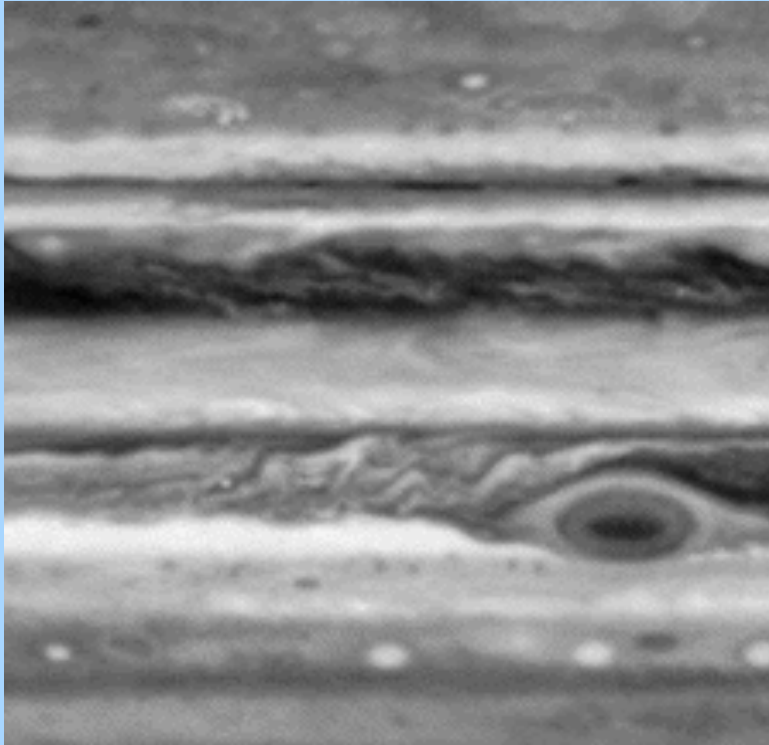
Note the counter-clockwise motion within the Great Red Spot.

Jupiter

Saturn

Uranus

Neptune
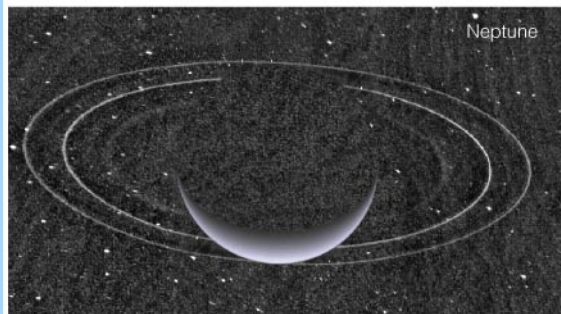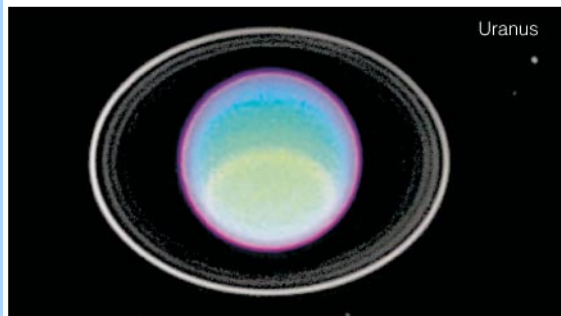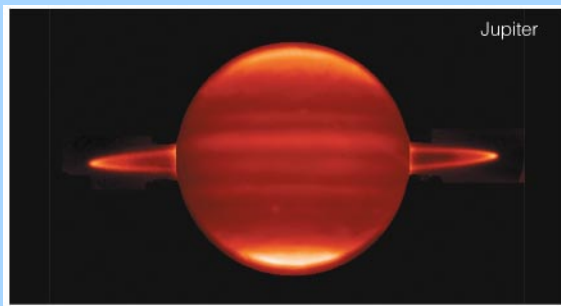
The rings of Saturn were discovered by the Dutch astronomer C. Huyghens in 1655. Galileo had seen two "knobs" on each side of the planet, but could not discern their true nature. Uranus' rings were discovered in 1977, from the Kuiper Airborne Observatory. Jupiter's rings were discovered by Voyager 1 in 1979. Neptune's rings were discovered in 1983.

Medium and Large Moons of the Jovian Planets

Jupiter: Io, Europa, Ganymede, Callisto

Saturn: Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Iapetus
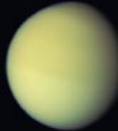
Uranus: Miranda, Ariel, Umbriel, Titania, Oberon

Neptune: Triton, Nereid

Other objects for comparison: Mercury, Moon, Pluto, 3,000 km
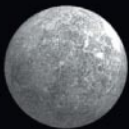
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Many moons of the Jovian planets are comparable in size to the the smaller planets.

Giant impact formation of our Moon

The Moon is too massive to have been captured by the Earth.

If the Earth and Moon both formed from the accretion of planetesimals, they should have the same composition and density. The Moon's mean density is considerably lower.

The going hypothesis today is that a Mars-sized planetesimal struck the proto-Earth. Some of the Earth's outer layers were blasted into space, and that material could have congealed into the Moon.

This hypothesis is by no means certain. (What happened to that Mars-sized object that hit the Earth?)

jets of SO₂ gas

SO₂ frost

Basalt lava flow

20 km
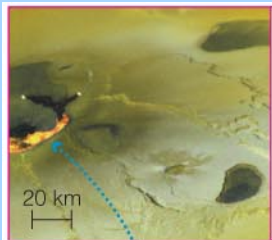
This close-up shows the glow of intensely hot lava from a volcanic eruption.

10 km
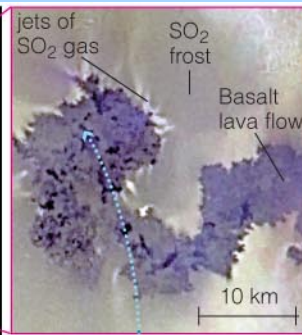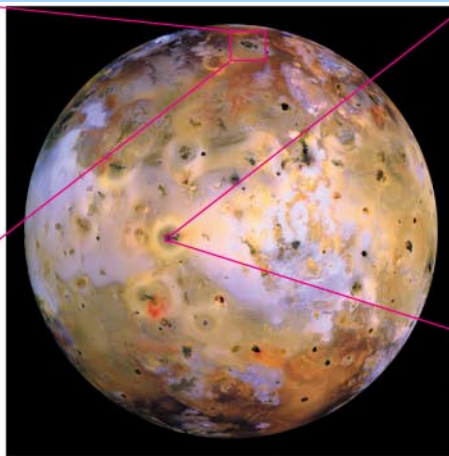
This 80-km-high gas plume was created when hot lava flowed over sulfur dioxide frost, causing it to sublimate explosively into gas.

200 km

Some sulfur-rich volcanoes deposit red, orange, or yellow fallout.
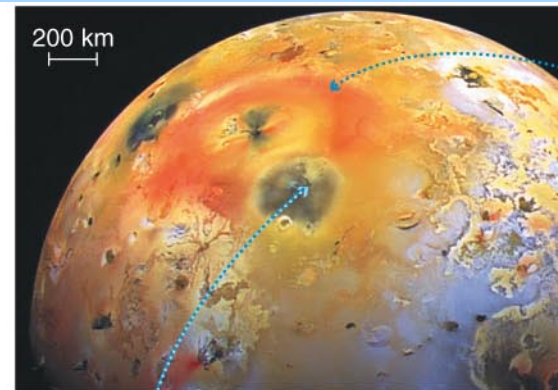
An eruption during the Galileo mission produced dusty fallout that covered an area larger than Arizona in a matter of months.
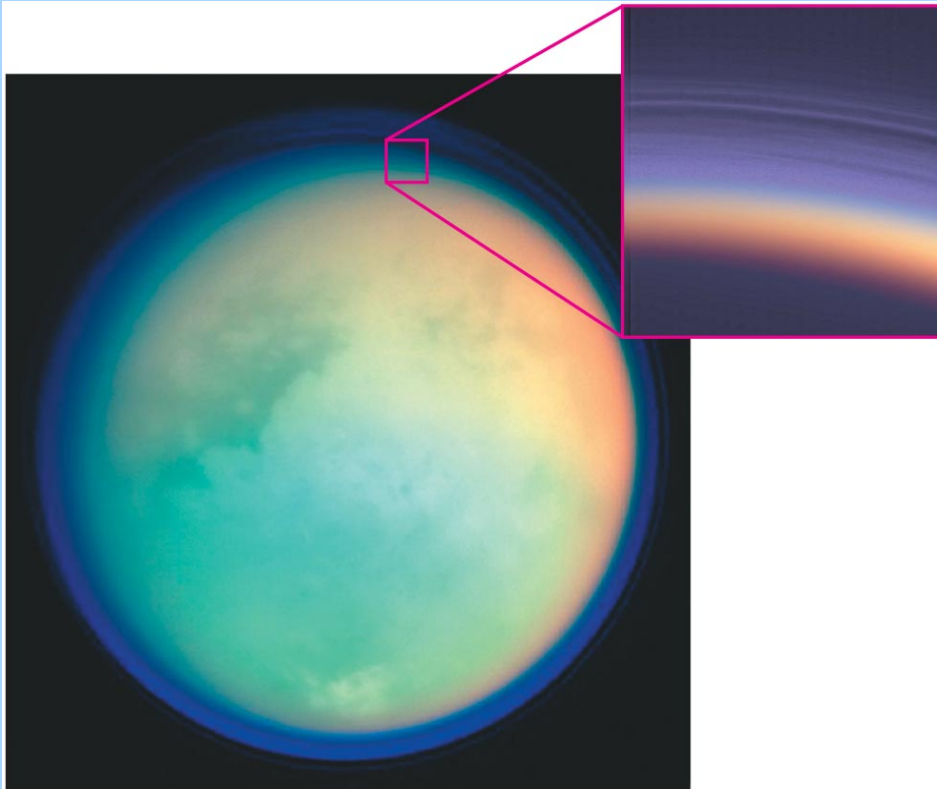
Jupiter's moon Io is the most volcanically active body in the solar system. Due to its varying distance from Jupiter, the tidal forces vary. The result is that the satellite is flexed in different directions. The volcanic activity results from **tidal heating**.
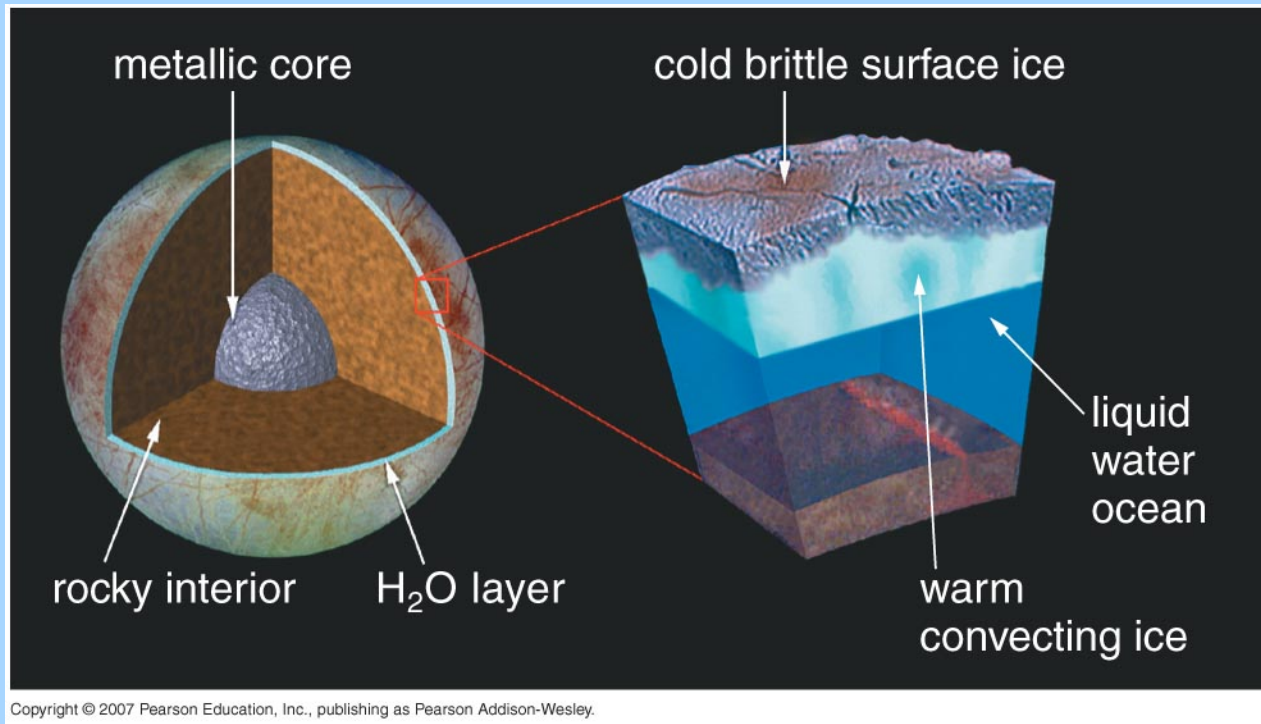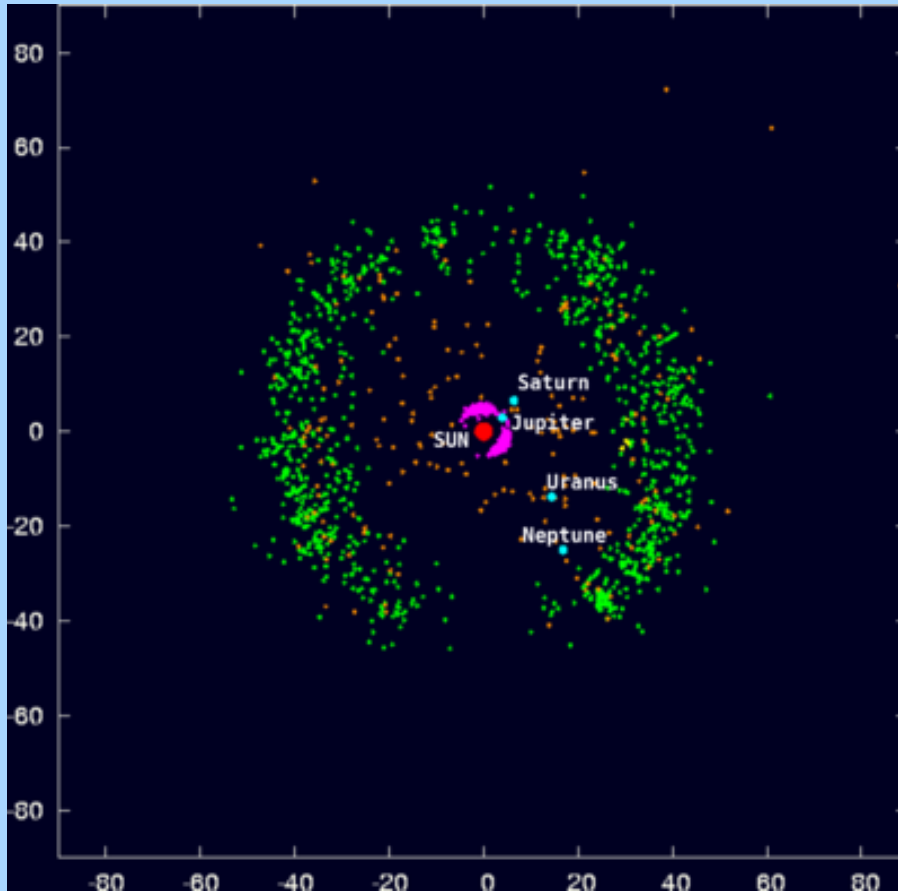
Jupiter's moon Europa has layer of *water*, but it is not known if it is liquid water, or convecting ice.

Saturn's moon Titan has a thick atmosphere mostly made of methane (CH_4).

The Kuiper belt extends from the orbit of Neptune (30 AU) out to roughly 55 AU. It consists of many km-sized objects and a number of dwarf planets. There might be 70,000 Kuiper belt objects. The Kuiper belt is the repository of long-period comets, those with periods > 200 yrs.

How to find Trans-Neptunian objects

Take images opposite to the direction of the Sun (objects transitting celestial meridian at local midnight).
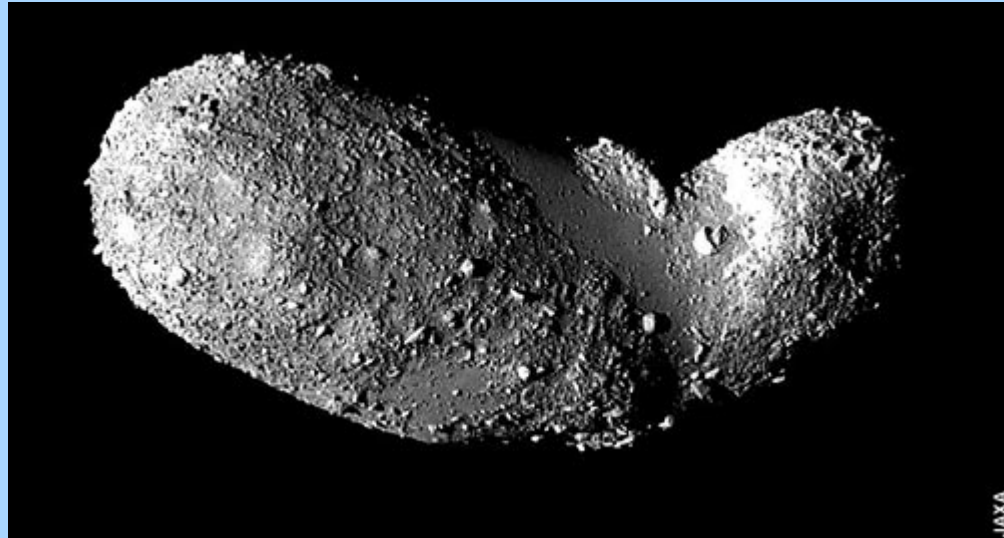
These objects will be undergoing retrograde motion.

If at the distance of Neptune (29 AU beyond Earth), daily retrograde motion will be 100 arc seconds.

If orbit size = 55 AU, daily retrograde motion will be 57".

These objects will be faint (fainter than 20th magnitude).
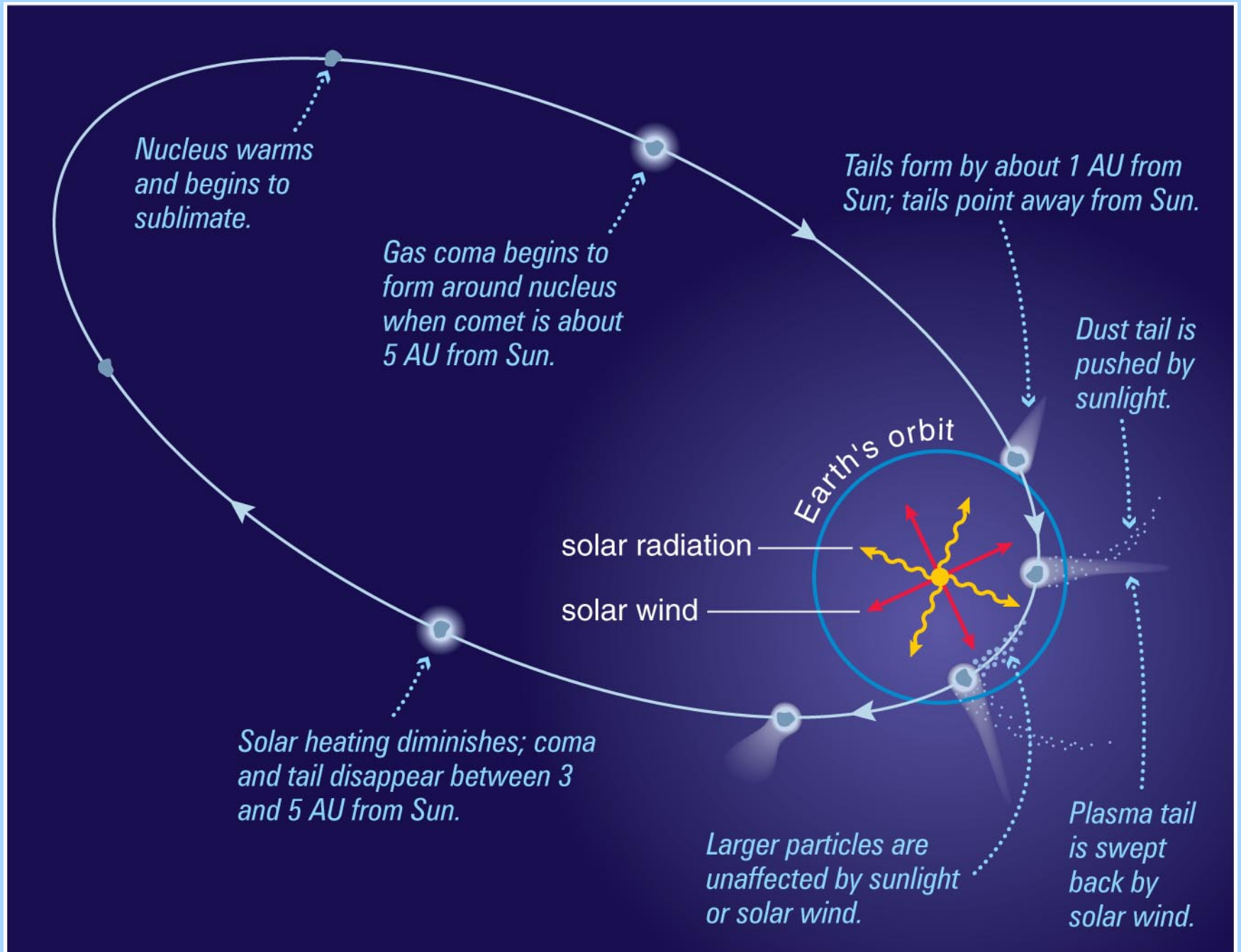
Most asteroids
are solid bodies,
but.....

Asteroid Itokawa is apparently *not* a solid body.
Rather, it is what they call a **rubble pile**. It is
a bunch of boulders, gravel, and sand held
together by weak gravity and static electricity.
This image was obtained by the Japanese
probe Hayabusa in November, 2005.

A **comet** is bunch of rocks and gravel all frozen together with ice. It's like a dirty snowball. As it orbits the Sun, when it comes close to the Sun the ices boil off, leading to a gas+dust tail.

Nucleus warms and begins to sublimate.

Gas coma begins to form around nucleus when comet is about 5 AU from Sun.

Tails form by about 1 AU from Sun; tails point away from Sun.

Dust tail is pushed by sunlight.

Earth's orbit

solar radiation

solar wind

Solar heating diminishes; coma and tail disappear between 3 and 5 AU from Sun.

Larger particles are unaffected by sunlight or solar wind.

Plasma tail is swept back by solar wind.

If the Earth intersects the orbit of a former comet or an existing one, the gravel that was once part of the comet collides with the Earth from a very particular direction. This is the origin of **meteor showers**. A meteor is not a "falling star". Rather, it is a piece of sand that vaporizes in the Earth's atmosphere due to friction.

Review question:

At the present epoch what source of energy causes
much of the outer core of the Earth to be hot, molten lava?

A. The pressure
B. The infrared emission of the Earth
C. Radioactive decay of various unstable elements
D. Tidal action of the Sun and Moon

The search for extra-solar planets

There are a number of ways to detect planets orbiting other stars:

1) periodic variations in the radial velocity of a star

2) transits of a large planet in front of a star – you measure a decrease in the light of the star
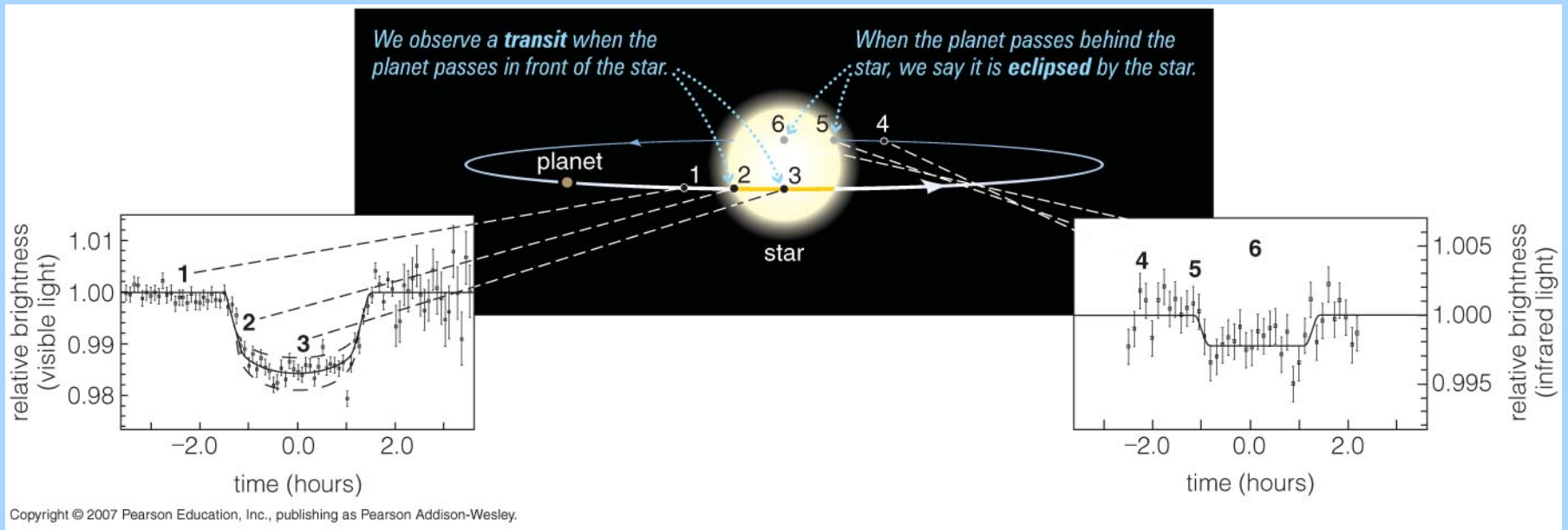
3) direct imaging
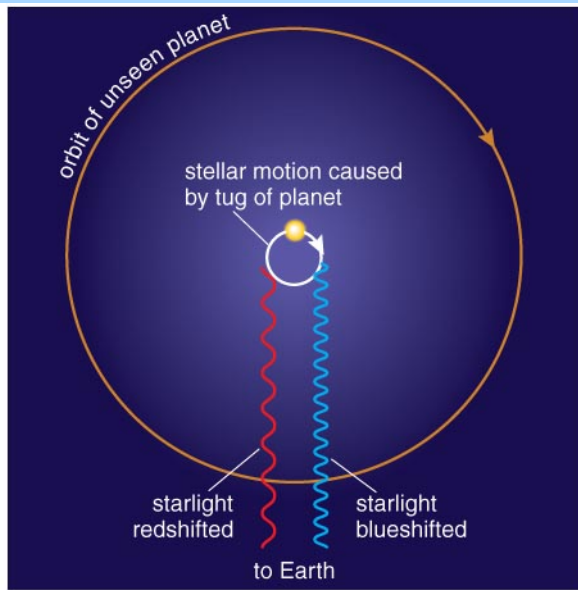
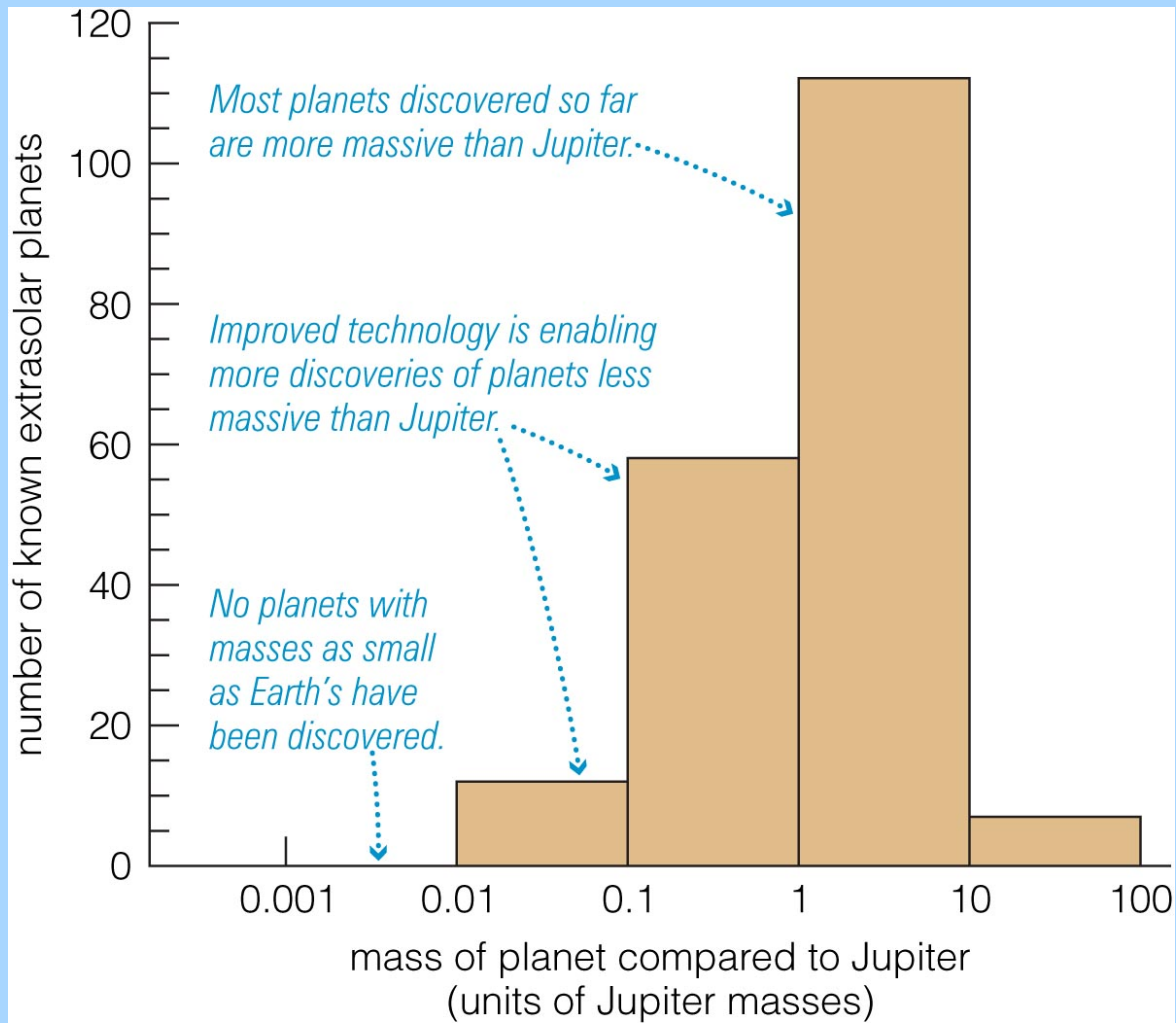**a** Doppler shifts allow us to detect the slight motion of a star caused by an orbiting planet.
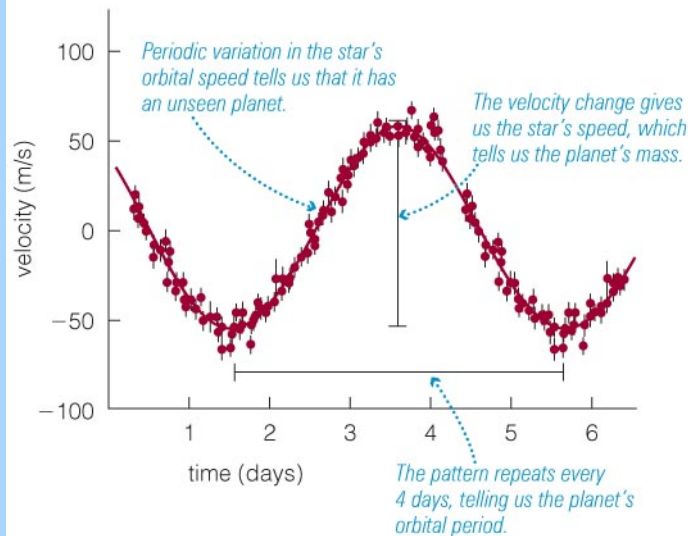
b A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

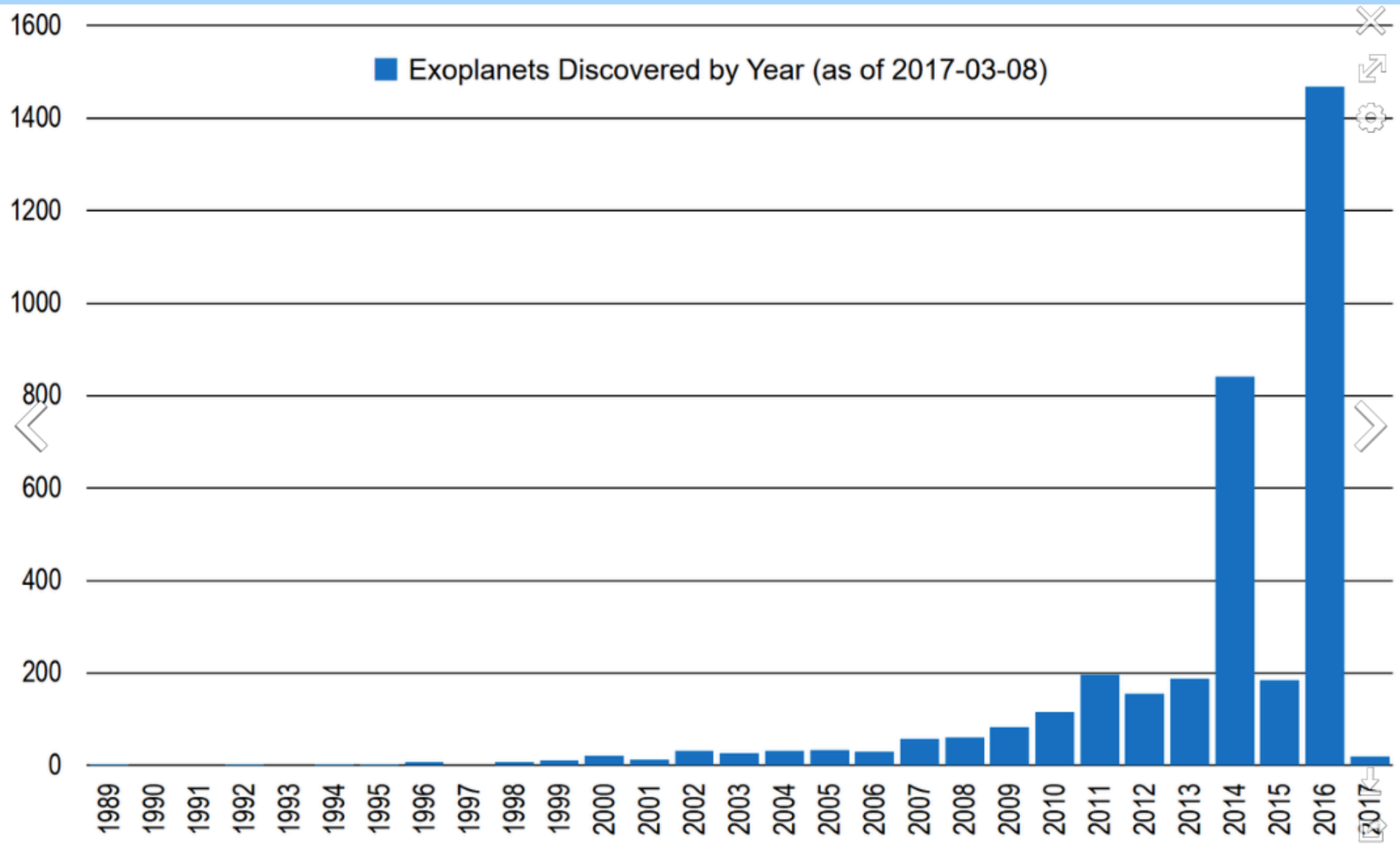Copyright © 2007 Pearson Education, Inc., publishing as Pearson Addison-Wesley.

Most extra-solar planets have been discovered by means of very accurate radial velocities of solar-type stars. From variations in the radial velocity of a star we can deduce that a massive planet is orbiting it (if the orbit is being viewed side-on to some degree).

We observe a **transit** when the planet passes in front of the star.

When the planet passes behind the star, we say it is **eclipsed** by the star.

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Another way to detect an extra-solar planet is to measure a slight dimming of a star. The transit of a large planet across the star's disk may cause a 1-2 percent change in the light of the star.
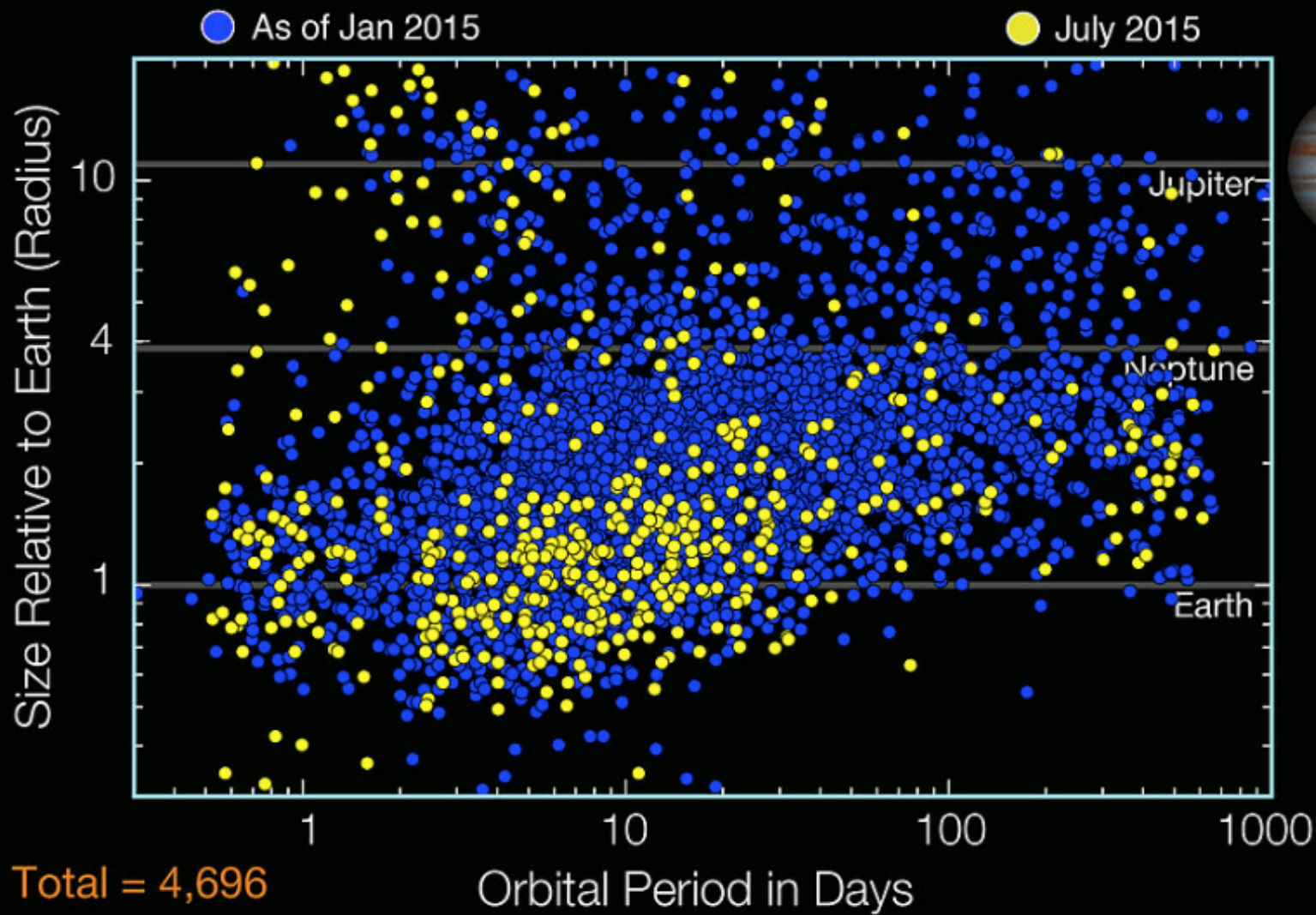
(data through 2006)

Exoplanets Discovered by Year (as of 2017-03-08)

New Kepler Planet Candidates
As of July 23, 2015

● As of Jan 2015   ○ July 2015

Size Relative to Earth (Radius)

Jupiter

Neptune

Earth

Total = 4,696

Orbital Period in Days

Approximately how many advanced technological civilizations are there in our Galaxy? What is your opinion?

a. 1
b. 1000
c. one million
d. one billion
e. other

The search for extraterrestrial life

or

The search for extraterrestrial intelligence (SETI)

The Drake Equation

Number of civilizations = $N_{HP} \times f_{life} \times f_{civ} \times f_{now}$

where

N_{HP} = number of habitable planets in the Galaxy

f_{life} = fraction of those that actually *have* life

f_{civ} = fraction of those on which civilizations capable of interstellar communication have arisen at some time

f_{now} = fraction of those that happen to have civilizations at the present time

There are roughly 200 billion stars in our Galaxy.
Perhaps 20 billion of them have planets at distances
that allow there to be liquid water.

Microbial life may be common on these planets,
but what fraction develop advanced life forms
and civilizations with the capability of communicating
with other civilizations in the Galaxy.

There could be thousands and thousands of them
in our Galaxy alone, or maybe only a few.

Given that there are billions of galaxies, the odds are
that we are not alone......