Announcements

- Today: review for midterm 3
- **Midterm 3: Wednesday April 23**
  - Neutron stars and black holes (Ch 13)
  - The solar system (Chs 4, 6, 7, + bits of Ch 5 [Earth] and 8 [moons of Jupiter, Saturn])
  - The Milky Way Galaxy (Ch 14)
- Review problem sets and quizzes for practice
- 45 questions
- No books, notes or calculator
- Bring a #2 pencil!

Information provided on midterm:

- 1 AU = 3×10^8 km
- speed of light = 3×10^8 m/s
- Kepler's 3rd law:

  $$a^3 = P^2$$

  with the period P in years and semi-major axis a in AU.
- Newton's law of gravity:

  $$F = \frac{GMm}{r^2}$$

- Peak wavelength and temperature of blackbody radiation:

  $$\lambda = \frac{3 \times 10^6}{T}\ \text{nm}$$

  with wavelength λ in nm (1 nm = 10^{-9} m) and temperature T in Kelvin.
- Conversion of mass into energy: $E = mc^2$
- Relationship between brightness B and distance d:

  $$B_2 = B_1 \times \frac{d_1^2}{d_2^2}$$

- Relationship between luminosity L, temperature T and radius R of stars:

  $$L = 4\pi\sigma T^4 R^2$$

  where $4\pi\sigma$ are constants.

Neutron Stars

Collapsed remnants of massive stars

- **Mass and size – neutron stars are 10-20 km in radius and have approximately the mass of the sun, so they are extremely dense**

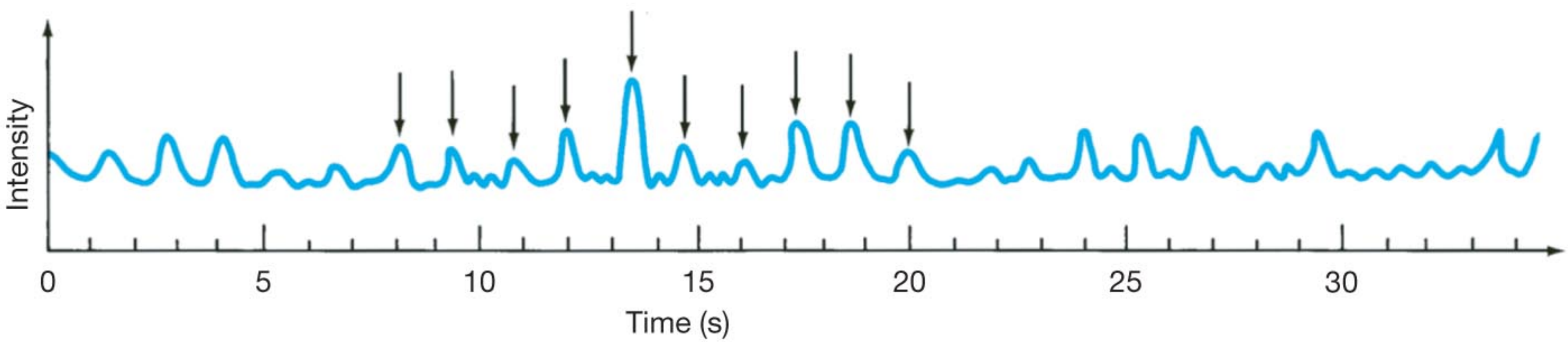
- **Rotation – as the parent star collapses, the neutron core spins very rapidly, conserving angular momentum. Typical periods are fractions of a second.**

- **Magnetic field – again as a result of the collapse, the neutron star's magnetic field becomes enormously strong.**

Pulsars

The first pulsar was discovered in 1967. It emitted extraordinarily regular pulses; nothing like it had ever been seen before.

After some initial confusion, it was realized that this was a neutron star, spinning very rapidly.

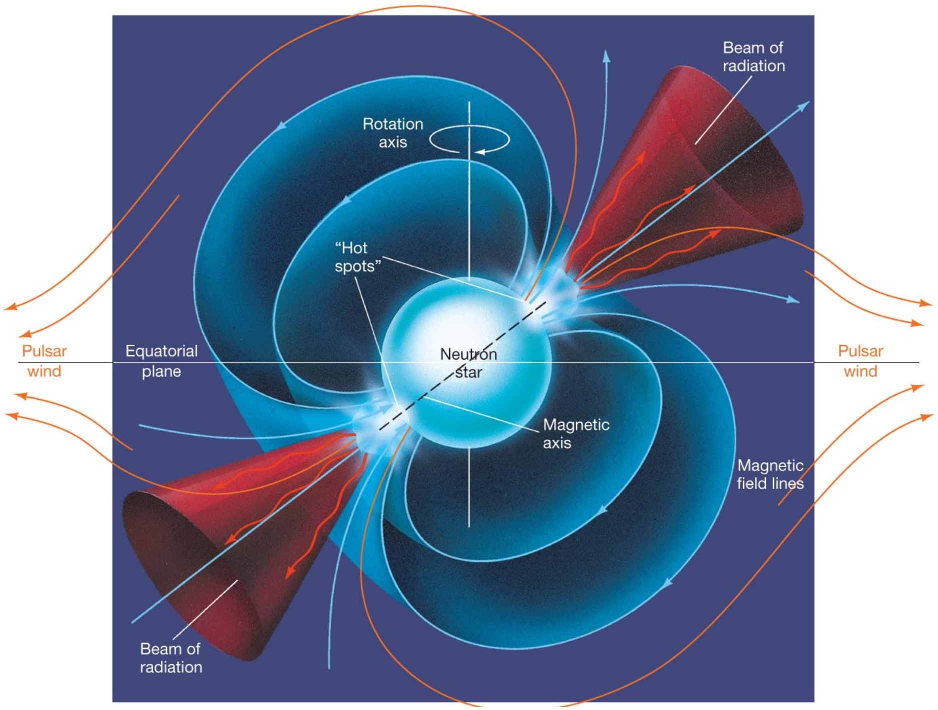


Pulsars

But why would a neutron star flash on and off?

This figure illustrates the lighthouse effect responsible.

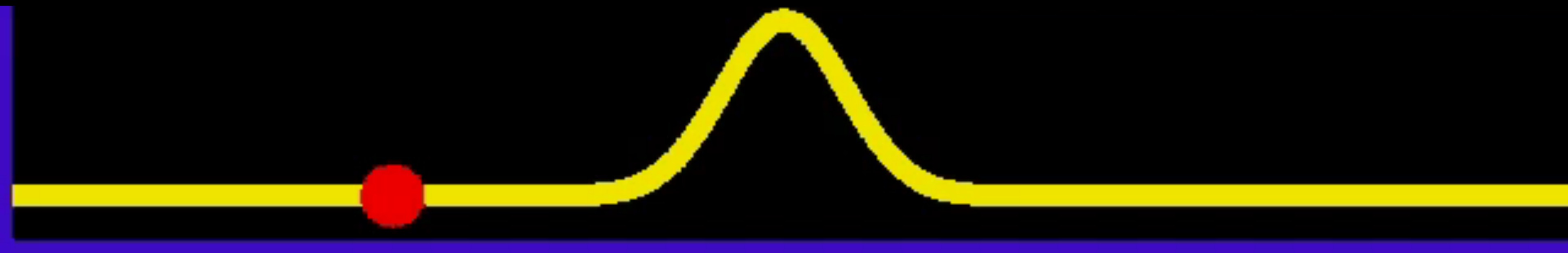
Strong jets of matter are emitted at the magnetic poles, as that is where they can escape. If the rotation axis is not the same as the magnetic axis, the two beams will sweep out circular paths. If Earth lies in one of those paths, we will see the star blinking on and off.



Neutron Star Fun Facts

- $R \approx 15$ km and $M \approx 1.5\ M_{Sun}$
- Central density 2-10 times that of atomic nucleus
  - 1 teaspoon is about 10^{12} kg
  - a cube 300 meters on a side has the same mass as the Earth

- Magnetic field $>10^{12}$ times that on Earth
  - erase credit cards from 30,000 km & kill from 200 km
- Spin frequencies from 0.1 Hz to 716 Hz → **pulsars**
  - faster than a kitchen blender!



Pulsars

Pulsars radiate their energy away quite rapidly; the radiation weakens and stops in a few tens of millions of years, making the neutron star virtually undetectable.

Pulsars also will not be visible on Earth if their jets are not pointing our way.

However, some pulsars – millisecond pulsars – have been *spun up*; their rotation rate has increased to nearly 1000 times per second. This is believe to happen because of accretion from a binary companion.

Black holes and an upper limit on the mass of neutron stars

The pressure from nuclear forces in a neutron star keep the star from collapsing.

But there is a maximum pressure that nuclear forces can exert and beyond 3 times the mass of the Sun, gravity must win.

At this point, the neutron star will collapse to a **black hole**, an object whose gravity is so strong that not even light can escape.

Nothing can escape from a black hole. How does this work?

Black Holes

The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.

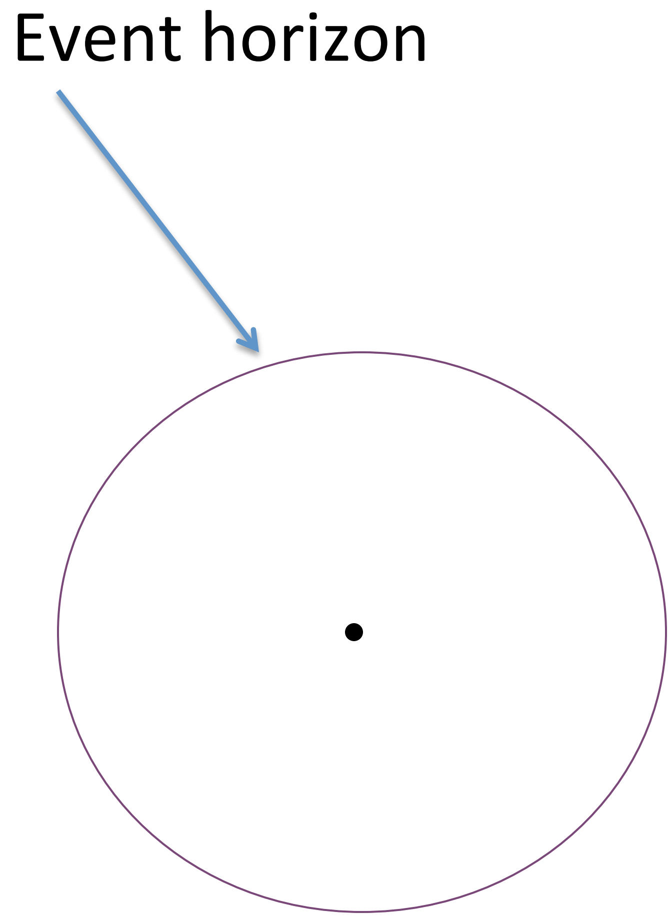
Eventually the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.

The radius at which the escape speed from the black hole equals the speed of light is called the event horizon.

An Earth-mass black hole has an event horizon of about a centimeter; for the Sun it is about 3 km.

A **black hole** is an object in which the gravitational field is so intense that **the escape velocity is greater than the speed of light**, the upper limit on speed in our universe. Because nothing can travel faster than this, nothing can escape.

The region from which nothing can escape is the *black hole*.
Its boundary is called an *event horizon* because no one outside can see events that occur inside: You can't see anything inside of the horizon.



OBSERVING BLACK HOLES

Black holes are black, so how do we see them?

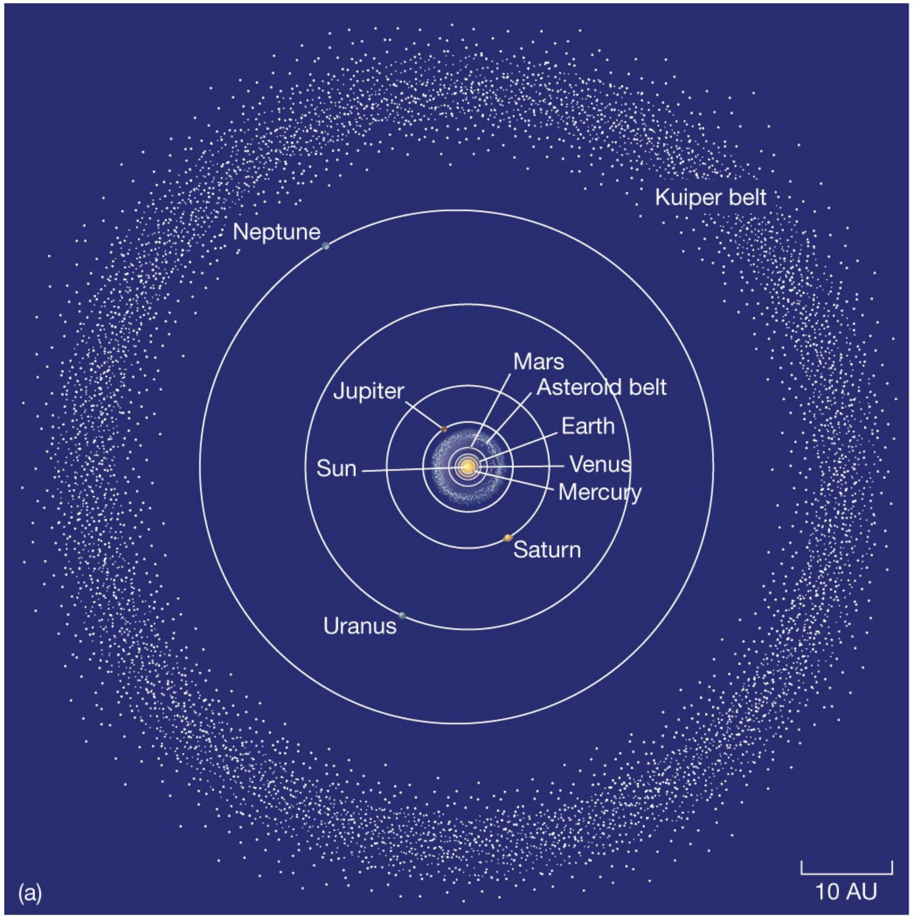
If a black hole is in a binary system with a companion star that is close enough for some of its matter to be caught by the black hole, the matter spirals in at speeds close to the speed of light, heats up by its own enormous friction, and emits energetic x-rays.

But matter spiraling in to neutron stars also emits x-rays. How do we know we're looking at a black hole and not a neutron star? We measure the mass, and if it's too massive to be a neutron star it must be a black hole.

An Inventory of the Solar System

Early astronomers knew Moon, stars, Mercury, Venus, Mars, Jupiter, Saturn, comets, and meteors.

Now known: Solar system has 166 moons, one star, eight planets (added Uranus and Neptune), asteroids, comets, meteoroids, dwarf planets, and Kuiper Belt objects.



An Inventory of the Solar System

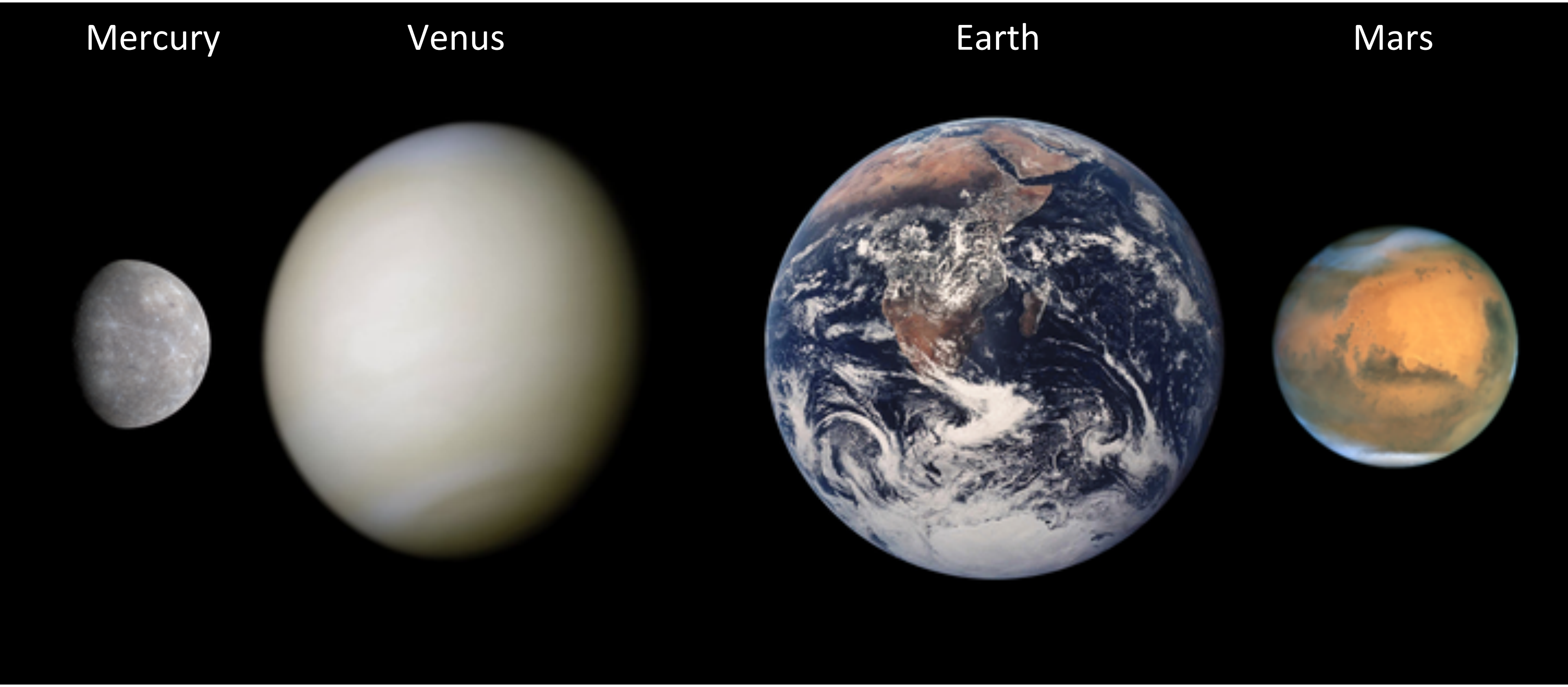
- The Solar System consists of the sun and everything in orbit around it.
  - Nearly all the mass is in the Sun (~ 99.8%)
  - Nearly all the rest is in the planets and moons
  - The rest are
    - Plutoids – balls of ice and rock in the Kuiper belt
    - Asteroids – rocky piles mostly between Mars and Jupiter
    - Comets – Piles of ice and rocks
    - Meteoroids – pebbles from comets that got ejected when comets came close to the Sun and fragments of asteroids

An Inventory of the Solar System

- The planets orbit the sun from W to E along the plane of the ecliptic – looking down from Earth's North pole, planets orbit counterclockwise.
- Orbits are nearly circular – yes, Kepler says that they are ellipses, and they are, but they are nearly perfectly circular ellipses
- Nearly all in the same plane – without Pluto, they are perfect to 1%
- Inner planets are called terrestrial planets
- Outer planets are called Jovian planets

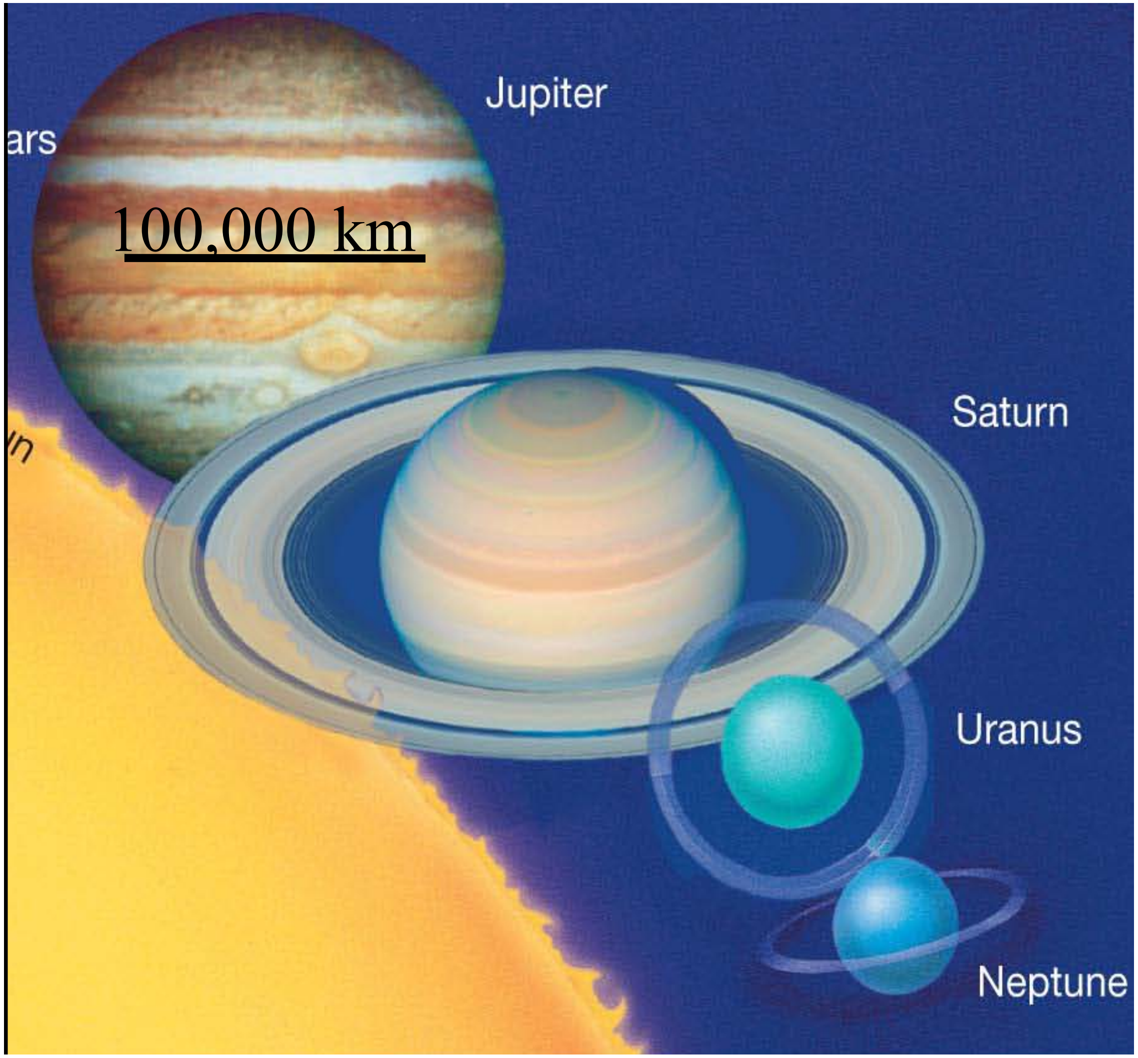
Terrestrial Planets

- Close to the Sun
- Made of rocks (silicon) and iron
- High density
- Small (~10000 km in diameter)



Jovian Planets

- Farther from the Sun
- Made of gases (hydrogen, helium, methane, water, ammonia)
- lower density
- large (~100,000 km in diameter)



Comparison of Terrestrial and Jovian Planets

	Distance from Sun	Composition	Mass	Radius	Density	Spin	Number of moons
Terrestrial	close	rock and iron	Earth or less	Earth or less	high (rock)	slow	few or none
Jovian	far	Gas: H, He, H_20, NH_4, CH_4	larger	larger	low	fast	many

History of the Solar System

- We want to understand the history of the solar system
- However, large bodies like planets evolve
  - Volcanism, erosion, plate tectonics…
- So it is important to look at things that hold a better record of the past: small bodies that don't change much
- The small bodies that have the best clues are **asteroids, comets, meteoroids** (coming from asteroids and comets) and **plutoids**
- The age and chemical composition of these things can tell us about the early solar system

Asteroids

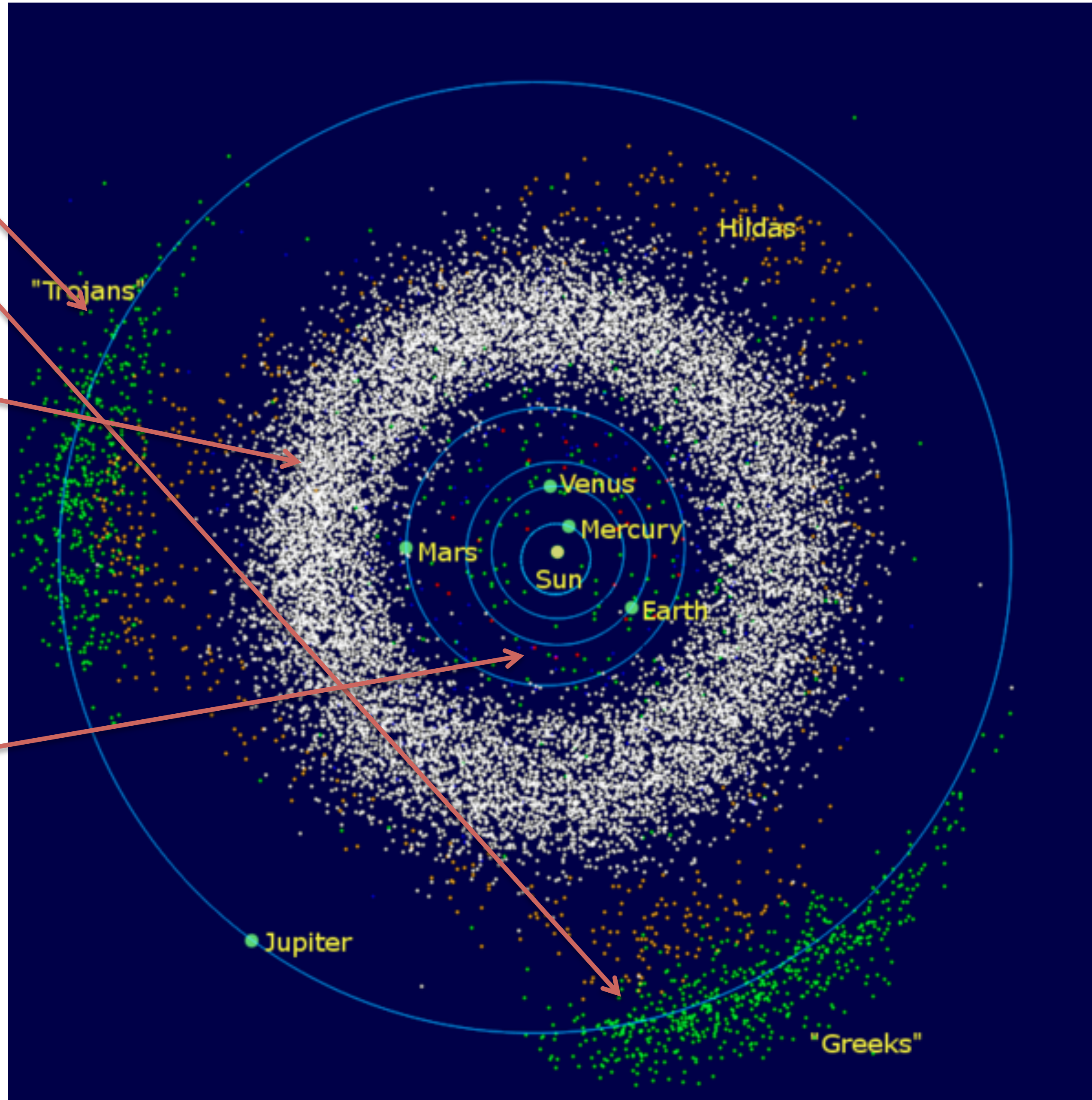
- Rocky bodies that are held together by gravity
- Most live in a belt between Mars and Jupiter at 2.8 A.U. called the asteroid belt
  - about 100,000 rocky objects bigger than 1km exist
- Ceres is the largest asteroid with a diameter of ~1000 km
- A few thousand have orbits that cross Earth's orbit – called near-Earth asteroids (NEAs)
- Some are near Jupiter (60 degrees ahead and behind) and are called Trojans

Asteroids

Trojans

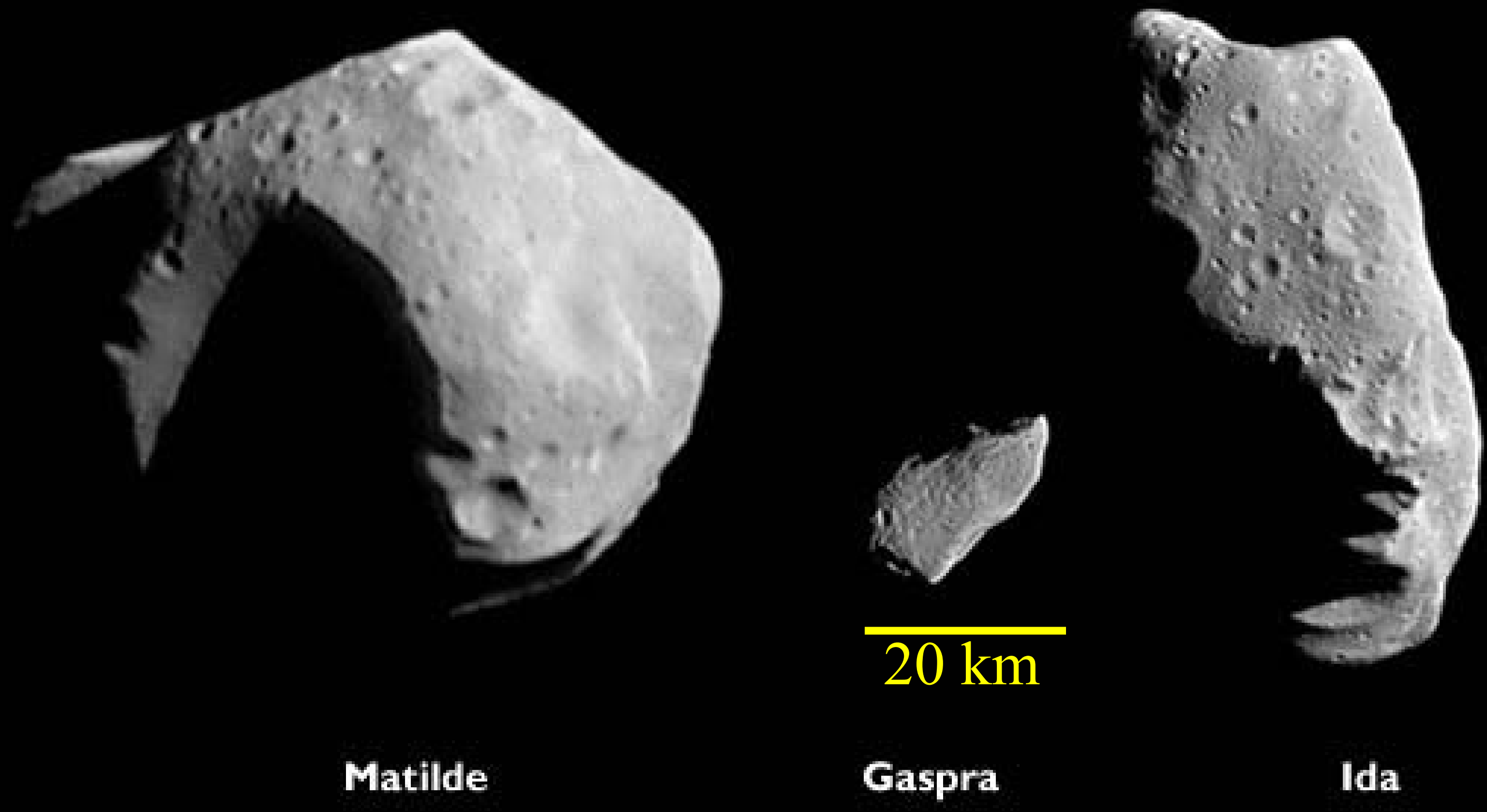
Asteroid Belt

Near Earth Asteroids



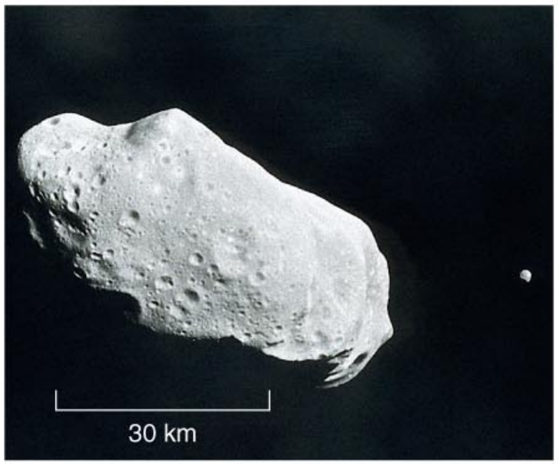
The first close-up photos of asteroids

(photos taken by Galileo in ‘91, NEAR in ‘97)



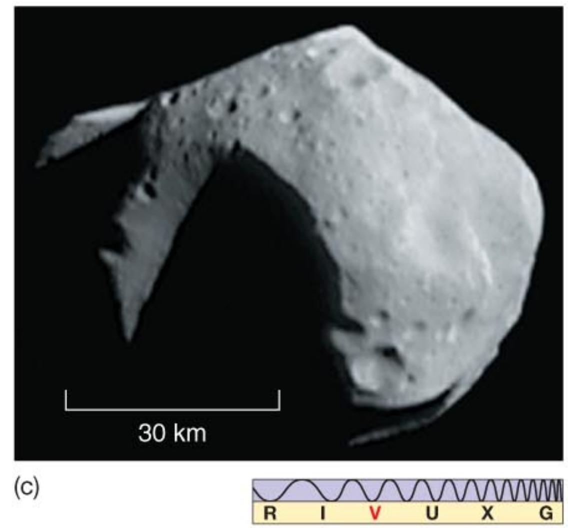
Asteroids and Meteoroids

Asteroids and meteoroids have rocky composition; asteroids are bigger.



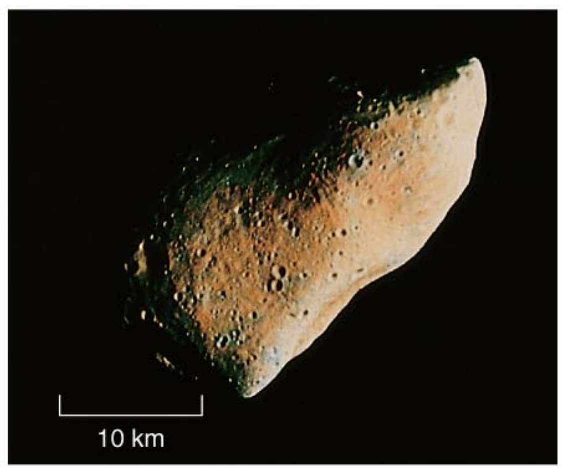
(b)

(below) Asteroid Gaspra



(c)

(above) Asteroid Ida with its moon, Dactyl



(a)

(above) Asteroid Mathilde

Meteoroids

- Small rocks in the solar system
- **Asteroid: >100 m in size**
- **Meteroid: <100 m in size**
- If they enter the Earth’s atmosphere and burn up they are called **meteors**
- **Meteorites** are meteors that penetrate though the atmosphere to hit the ground

Comets

- Icy bodies – called “dirty snowballs” – made of rocks, water ice, frozen methane, frozen ammonia, and frozen carbon dioxide
- ~1 – 10 km in size.
- When they pass close to the sun, the ices sublimate: solid -> gas. Blows out a halo of gas and rocks (pebbles), which is called a **coma**
- Sunlight and the solar wind push on the gas and dust blowing the tail away from the sun
- Comet tails point away from the sun, NOT opposite of direction of motion

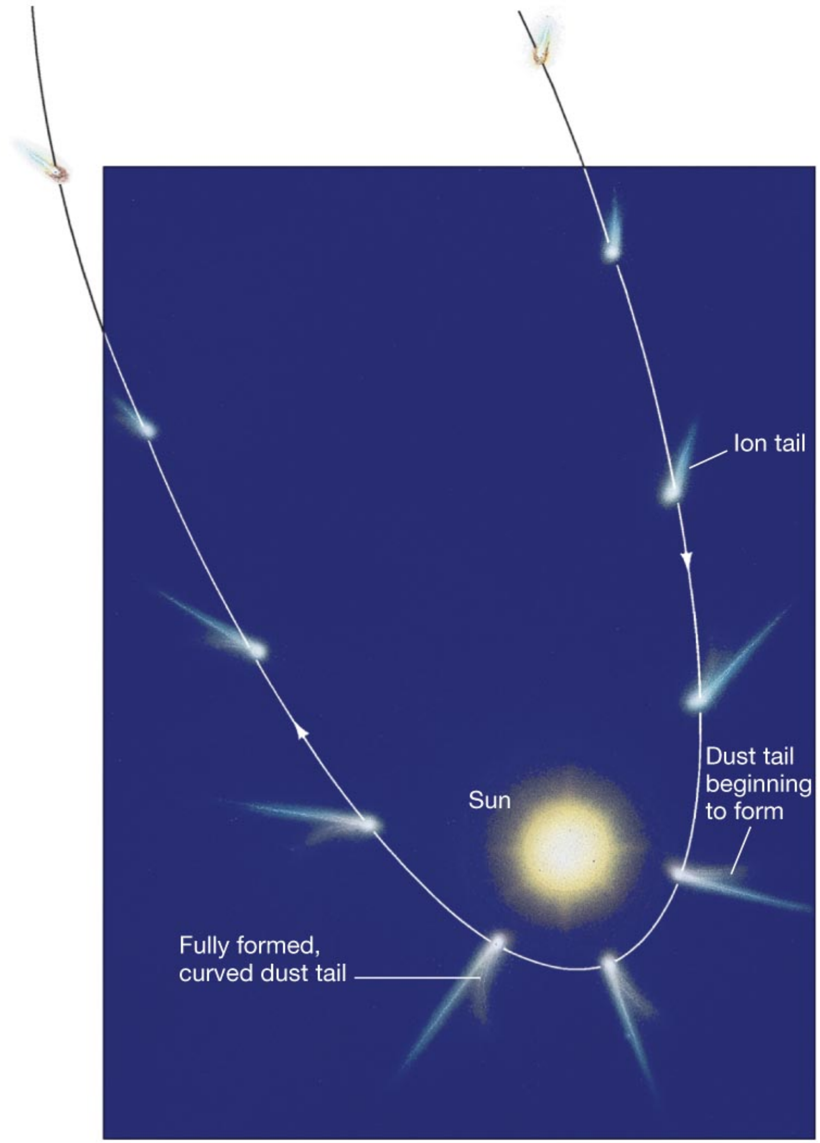
Comets

- Consist of the **nucleus** – main solid body of the comet
- And the **coma** – diffuse halo of gas and dust around it
- Very low density ~ 100 kg/m^3 << water ice (1000 kg/m^3), so they are loosely packed *snowballs*
- Orbits are typically 1000s of years and originate far beyond the orbit of Pluto in the Oort cloud.
- Short period comets (<200 years) originate in the region near Pluto known as the Kuiper belt

Comets

The solar wind means the ion tail always points away from the Sun.

The dust tail also tends to point away from the Sun, but the dust particles are more massive and lag somewhat, forming a curved tail.



Features of the solar system

- Planets are all (nearly) in a plane to about 1%
- All orbit in a counterclockwise direction (as viewed from Earth's N pole) and nearly all rotate in the same direction as well
- Orbits are nearly circular
- Planets are relatively isolated – far away from their neighbors
- Space between the planets is relatively empty

	Distance from Sun	Composition	Mass	Radius	Density	Spin	Number of moons
Terrestrial	close	rock and iron	Earth or less	Earth or less	high (rock)	slow	few or none
Jovian	far	Gas: H, He, H_20, NH_4, CH_4	larger	larger	low	fast	many

Can we develop a model for the formation of the solar system that explains these properties?

The **nebular hypothesis** suggests that the planets formed from a gas cloud which collapsed into a disk.

This gas cloud has roughly the same composition as the Sun (mostly hydrogen, helium, + a trace of carbon, oxygen, nitrogen, iron etc)

Small bits of dust in the cloud condense into larger objects, becoming planets. Beyond the **snow line** where ice can form, planets can grow larger and become gas giants.

The Nebular Hypothesis and the Solar System

- Planets form in a rotating disk
    - Planets are all (nearly) in a plane to about 1%
    - All orbit in a counterclockwise direction and nearly all rotate in the same direction as well.
    - Orbits are nearly circular
- Planets are relatively isolated – far away from their neighbors
    - Planets accrete all the material in their neighboring orbits
- The composition of the planets differ
    - The presence of the snow line allows different materials to condense onto forming protoplanets.
- Space between planets is relatively empty
    - Planets scatter small bodies

Earth

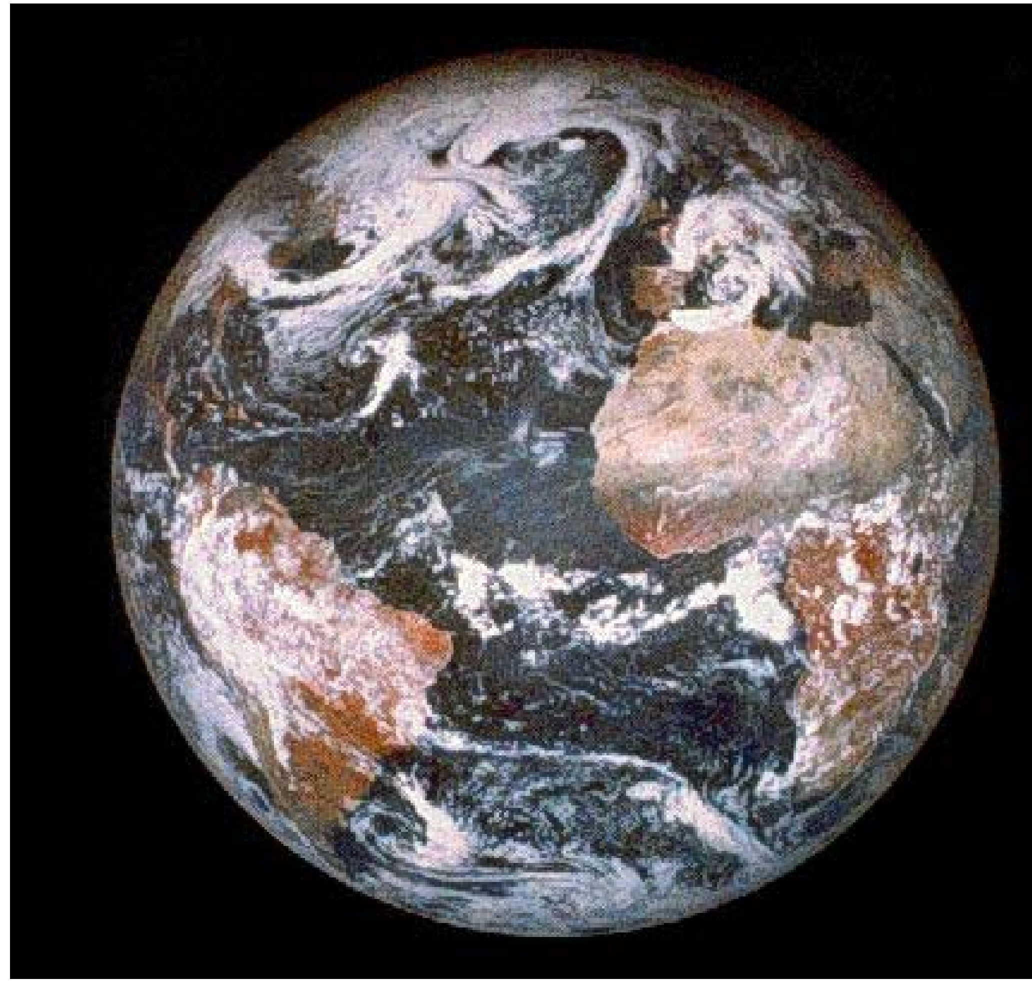
Radius ~ 6400 km

Density ~ 5000 kg/m^3 – five times density of water

Has a thick **atmosphere** of mostly nitrogen and oxygen

Has active **volcanoes**

Has a **magnetic field**



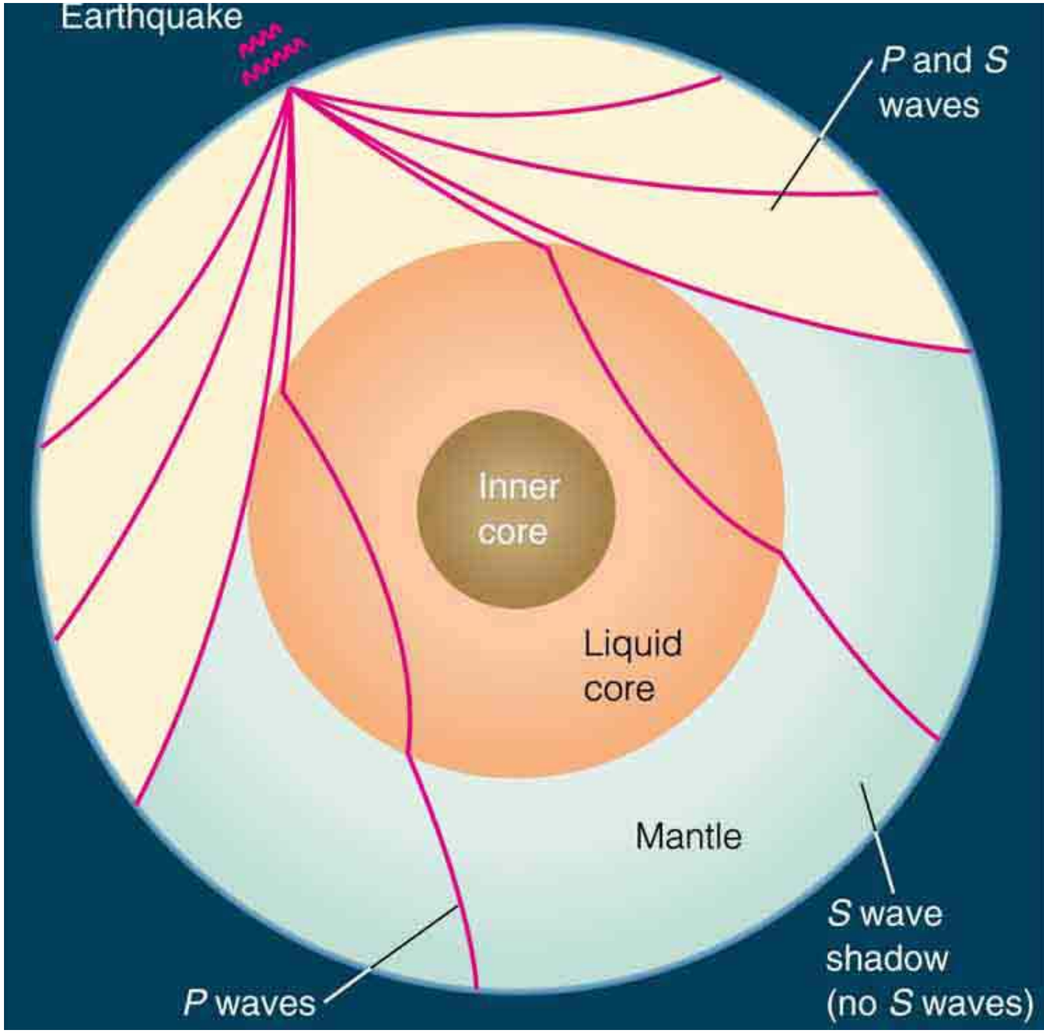
Structure of the Earth

Inner core is solid iron

Outer core is liquid iron and nickel.

Mantle is mostly molten rock (silicon and oxygen)

Crust (30 km thick) is solid rock.



Know this structure from looking at **earthquake waves**.

Mercury

Radius ~ 2400 km

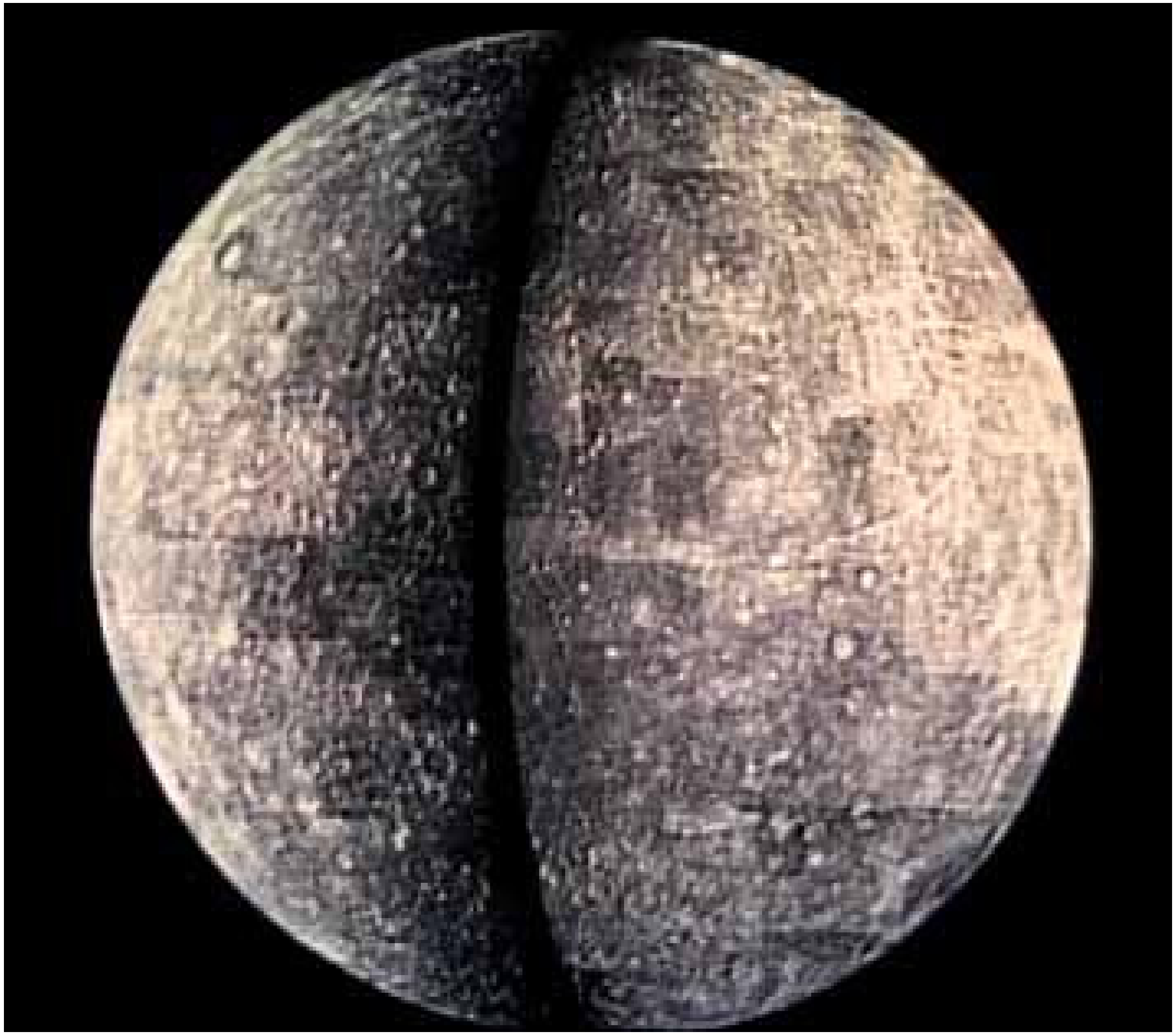
Mass ~ 5% of Earth

Density 5400 kg/m^3 – about the same as Earth

No atmosphere

No volcanoes

Has a magnetic field



Mercury

- Temperature on Mercury varies drastically! On the day side it is hot, 700K, but on the night side it is cold, 100 K (-200 F)

- Wide variation in temperature because there is no atmosphere to trap heat and moderate temperatures

- Because Mercury has no atmosphere and no water, there is no erosion, so the surface is heavily cratered like the Moon

Venus

Radius ~ 6100 km

Mass ~ 82% of Earth

Density ~ 5300 kg/m^3 – about the same as Earth

Very thick atmosphere

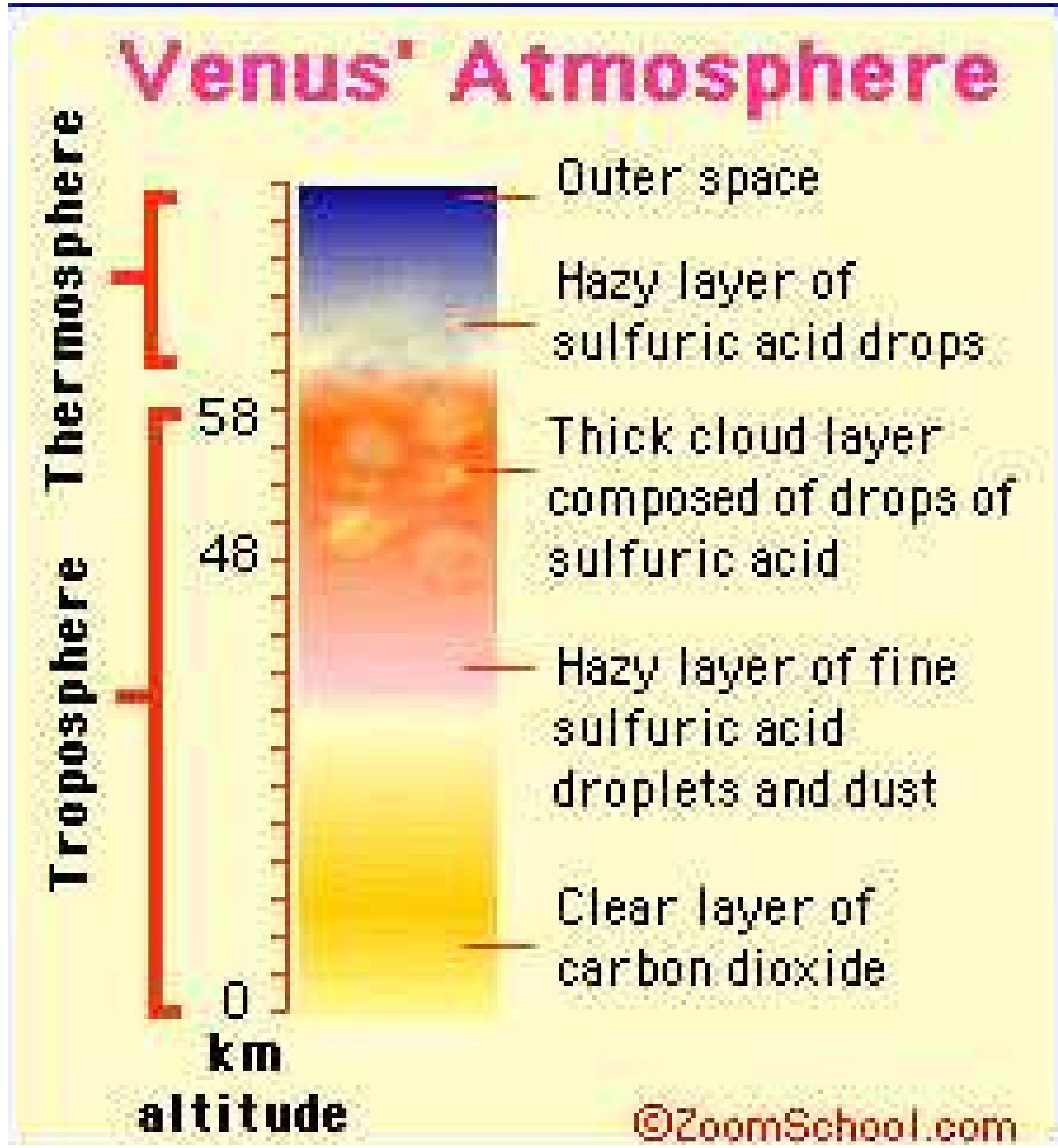
Volcanic features, indirect evidence of current volcanic activity

No magnetic field

Venus

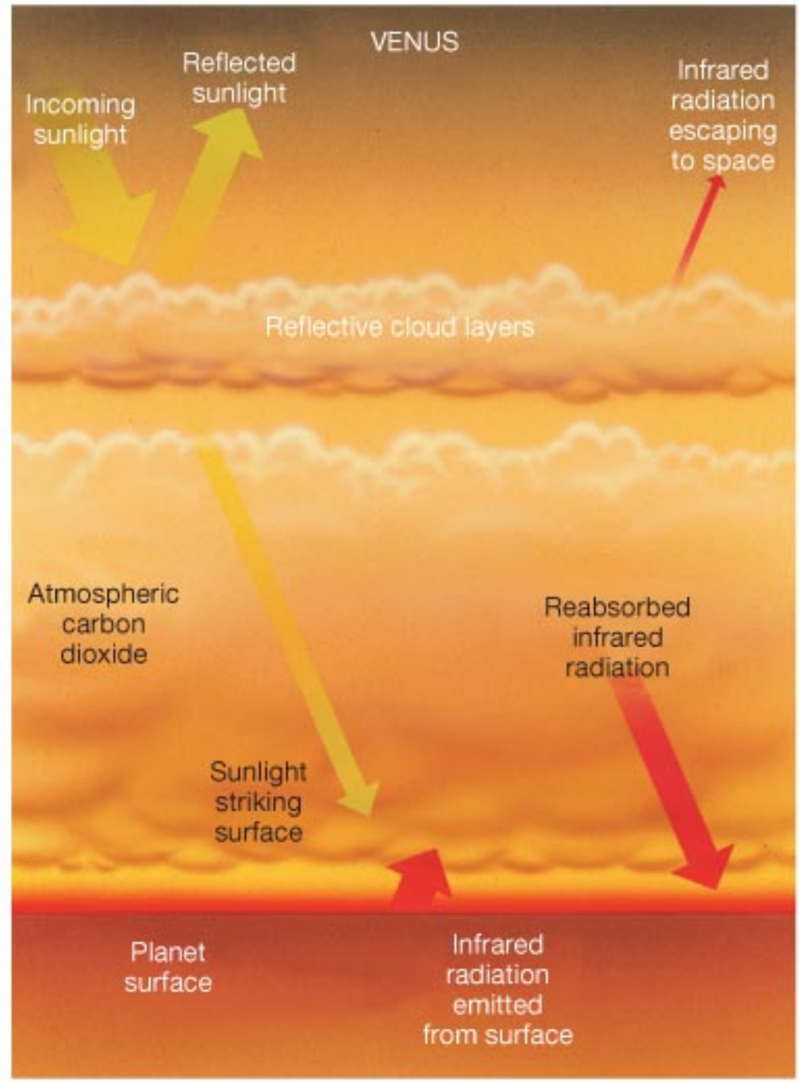
Venus has a large, thick atmosphere which covers the entire surface with clouds of sulfuric acid.

Its atmosphere is 90x thicker than the Earth's: pressure on the surface is 90 times higher than on Earth



Venus

- Venus is HOT! Its average temperature is 730 K – hotter than Mercury and hot enough to melt lead
- This is because the atmosphere traps heat via the greenhouse effect
- Sunlight strikes surface and is converted to heat, which is absorbed and re-radiated by carbon dioxide in the atmosphere instead of radiating out into space
- Also operates on Earth



Mars

Radius ~ 3400 km – ½ radius of earth

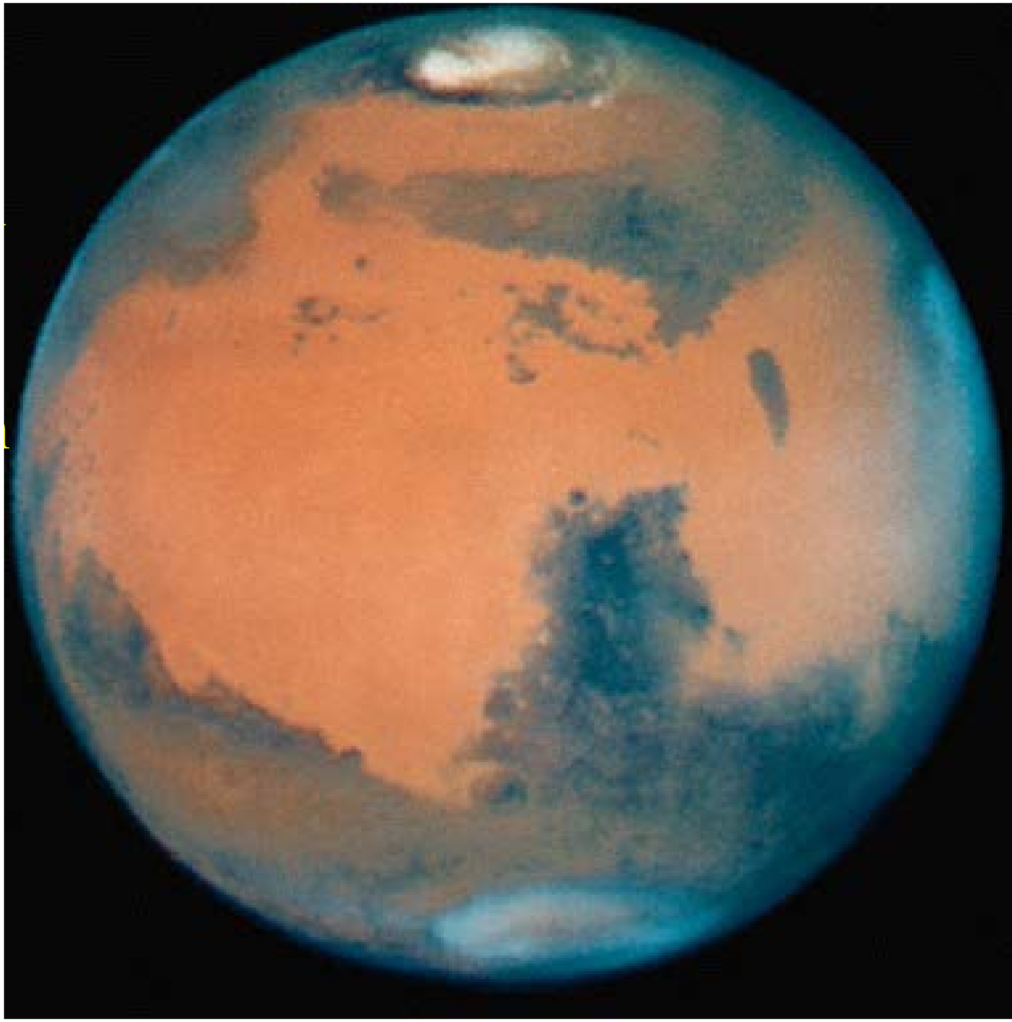
Mass ~ 10% of Earth

Density ~ 3900 kg/m^3 – smaller than Earth – density of rock.

Thin atmosphere

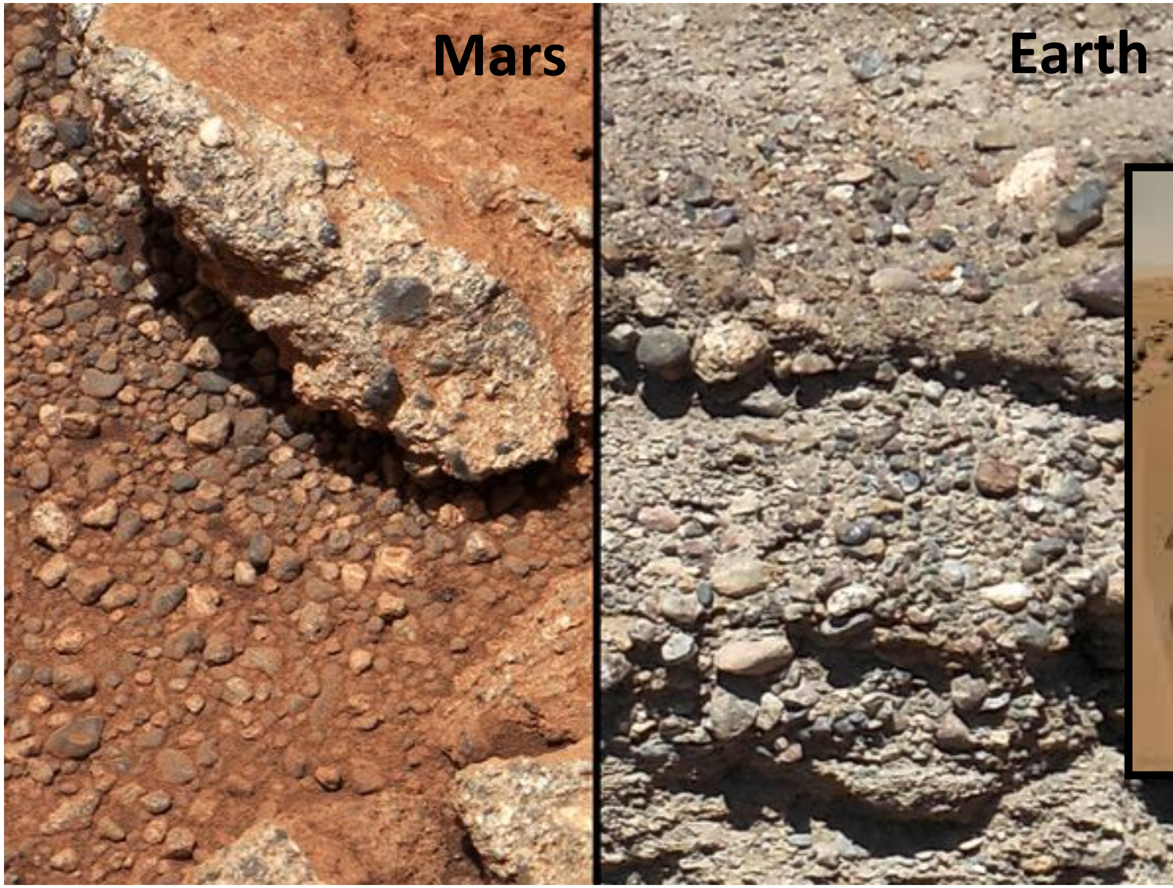
Extinct volcanoes

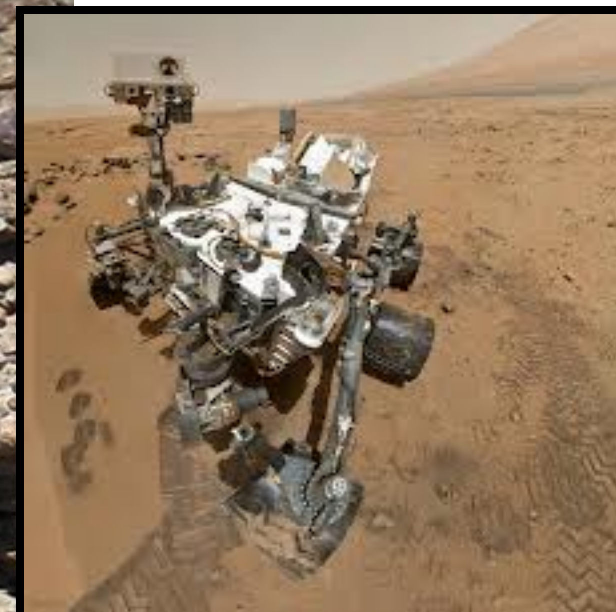
No magnetic field



Seasons on Mars: Changing CO2 ice caps

Evidence for water on Mars





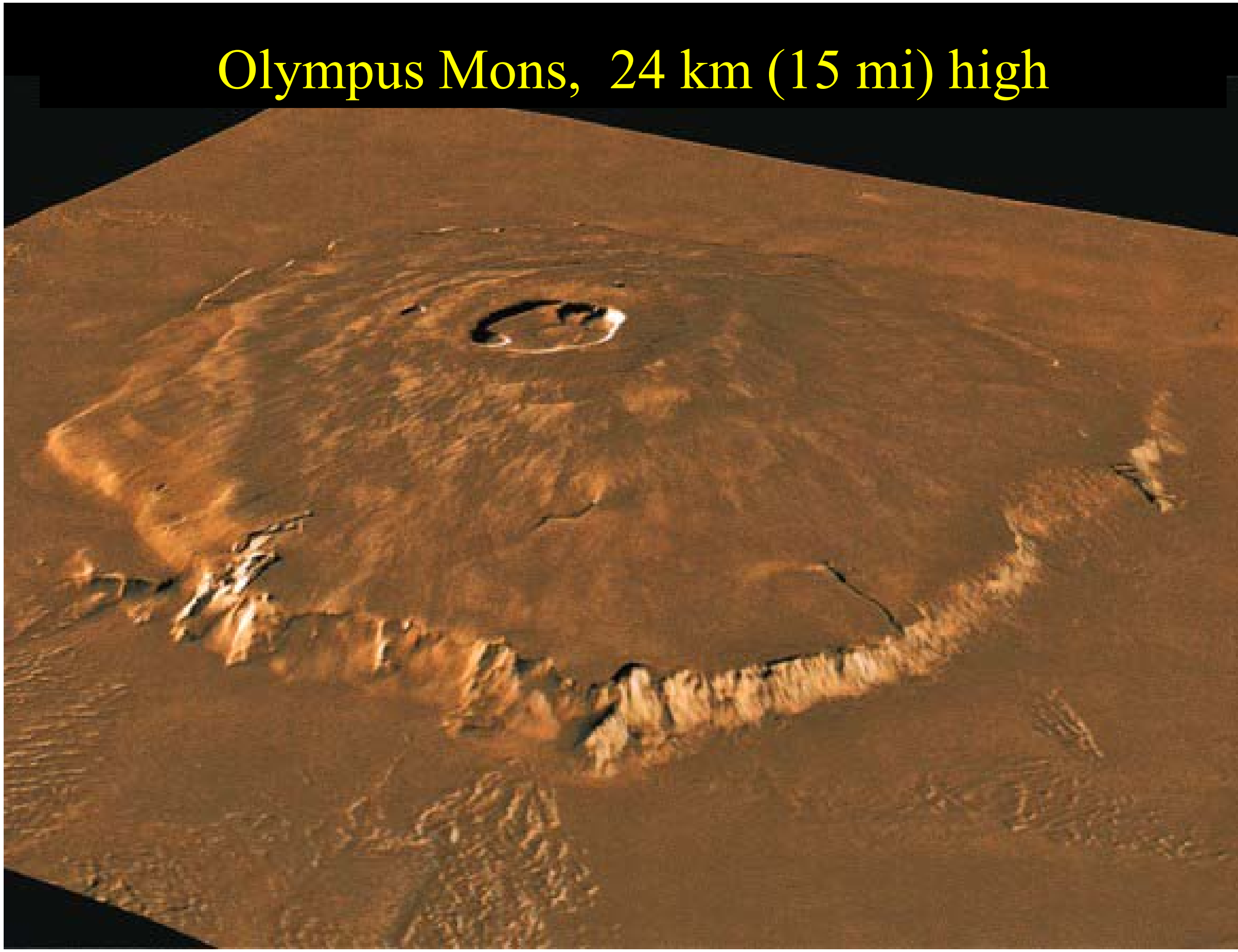
September 2012: Curiosity rover finds ancient streambed, pebbles moved and smoothed by water, present for thousands to millions of years

Mars

- Has huge volcanoes – now extinct. Olympus Mons is the largest volcano in the solar system.

3 x the size of Mount Everest!

These are also shield volcanoes. They are much larger than ones on earth and Venus because of lower gravity.



Jupiter

Radius ~ 10 x Earth's
Mass ~ 300 x Earth's

Density ~ 1300 kg/m^3 – about same as water

Compose of mainly hydrogen and helium

No surface

Strong magnetic field

Rapid rotation ~ 10 hrs

Weather of Jupiter

Multicolored bands in atmosphere

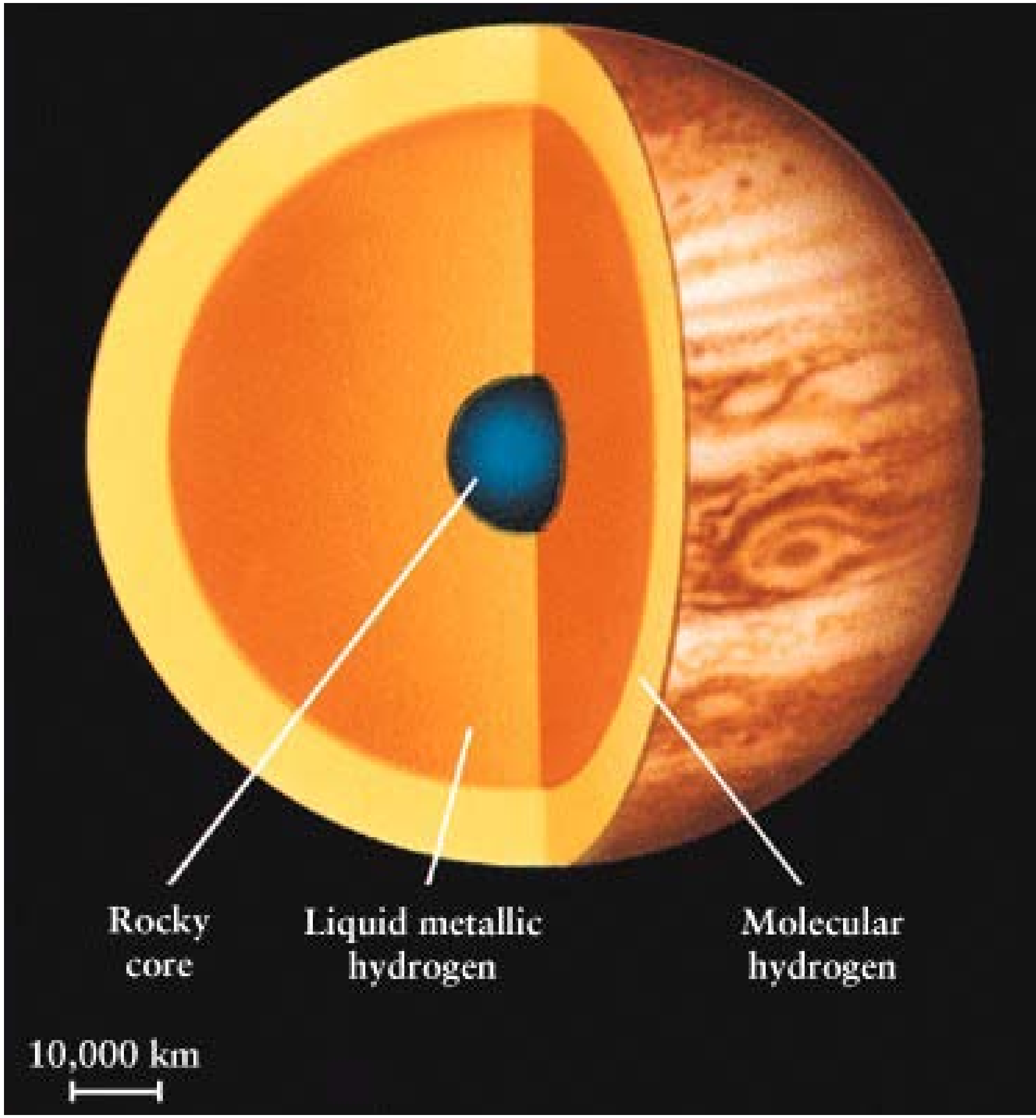
Bands are caused by convective cells that are stretched by rotation

Most prominent feature is the Great Red Spot – a hurricane that has persisted for at least 300 years

Jupiter's Great Red Spot

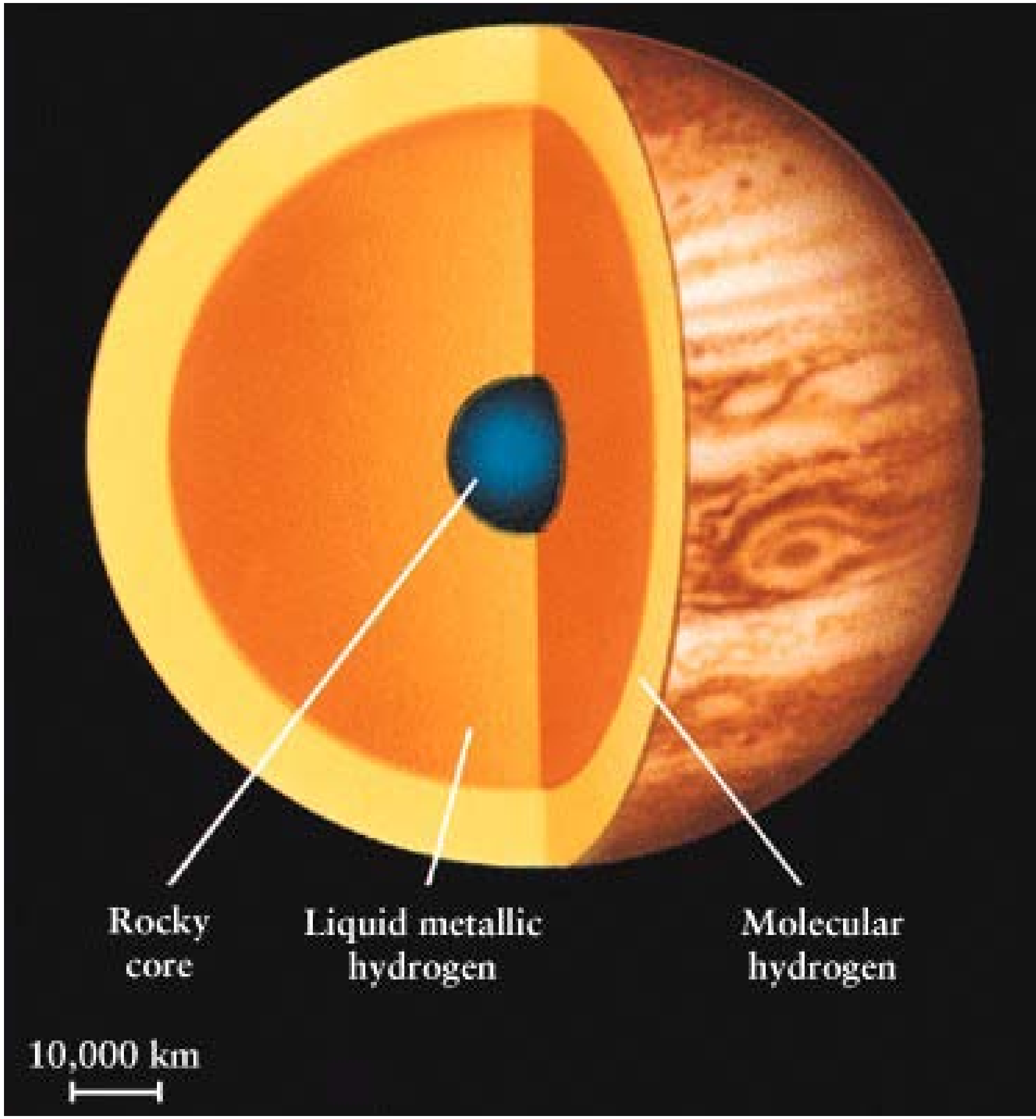
Structure of Jupiter

- Inner core rocky, like Earth
- Mantle is **liquid metallic hydrogen**: under very high pressures, hydrogen becomes liquid and acts like a metal – able to conduct electricity
- Outer mantle is molecular hydrogen
- Atmosphere very convective with large, persistent weather features



Internal Heating

- Jupiter gives off 2 times the heat it receives from the Sun.
- This heat is from its formation 4.5 billion years ago – it is still cooling!
- Transport of this heat drives convection in the metallic hydrogen mantle – produces a strong magnetic field



Moons of Jupiter

Jupiter has at least 67 moons!

The 4 largest are the ones first observed by Galileo – they are called the Galilean satellites.

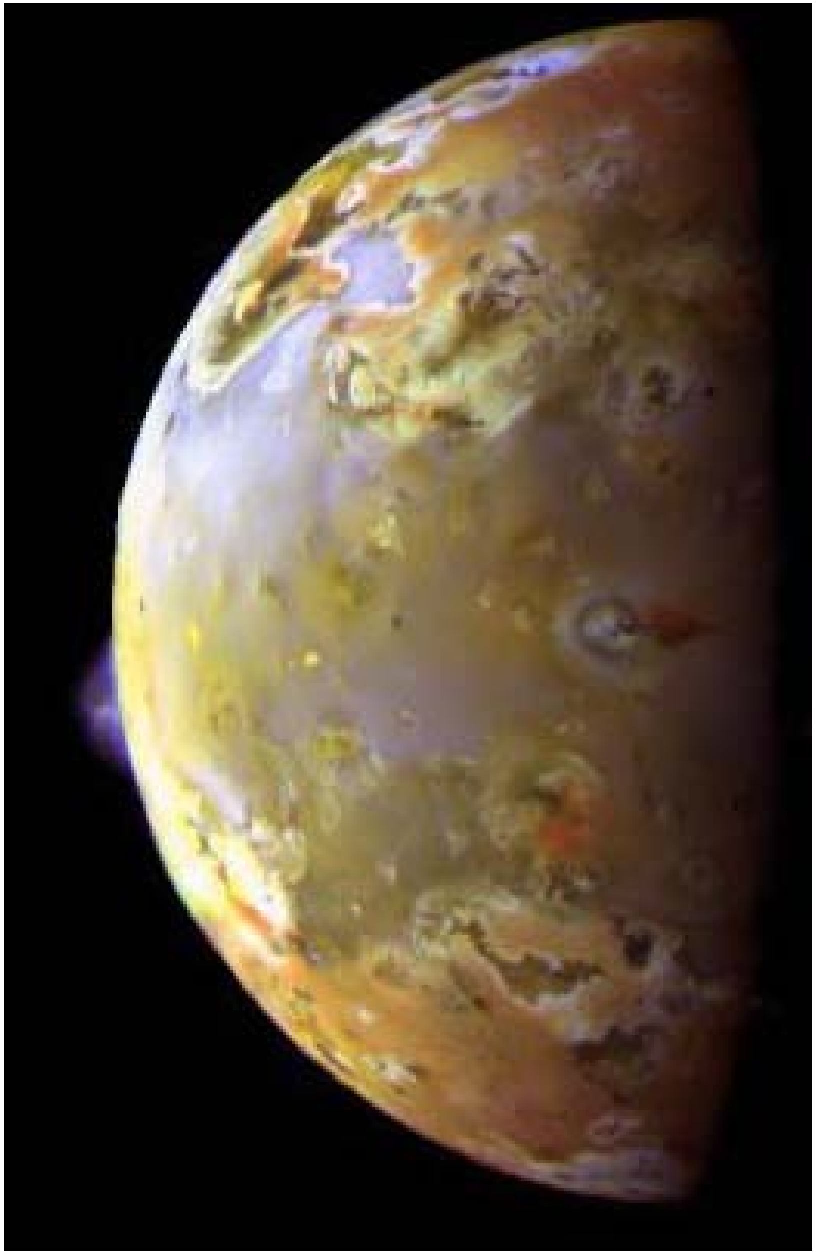
They are from closest to farthest from Jupiter: **Io, Europa, Ganymede**, and **Callisto**

Io

Io is the closest of Jupiter's large moons and is the most volcanically active body in the solar system.

The volcanoes are powered by **tides** between Europa and Jupiter that trap Io in a tug-of-war. The heating melts the interior and drives the vulcanism.

Io's surface is very new – no craters!



Europa

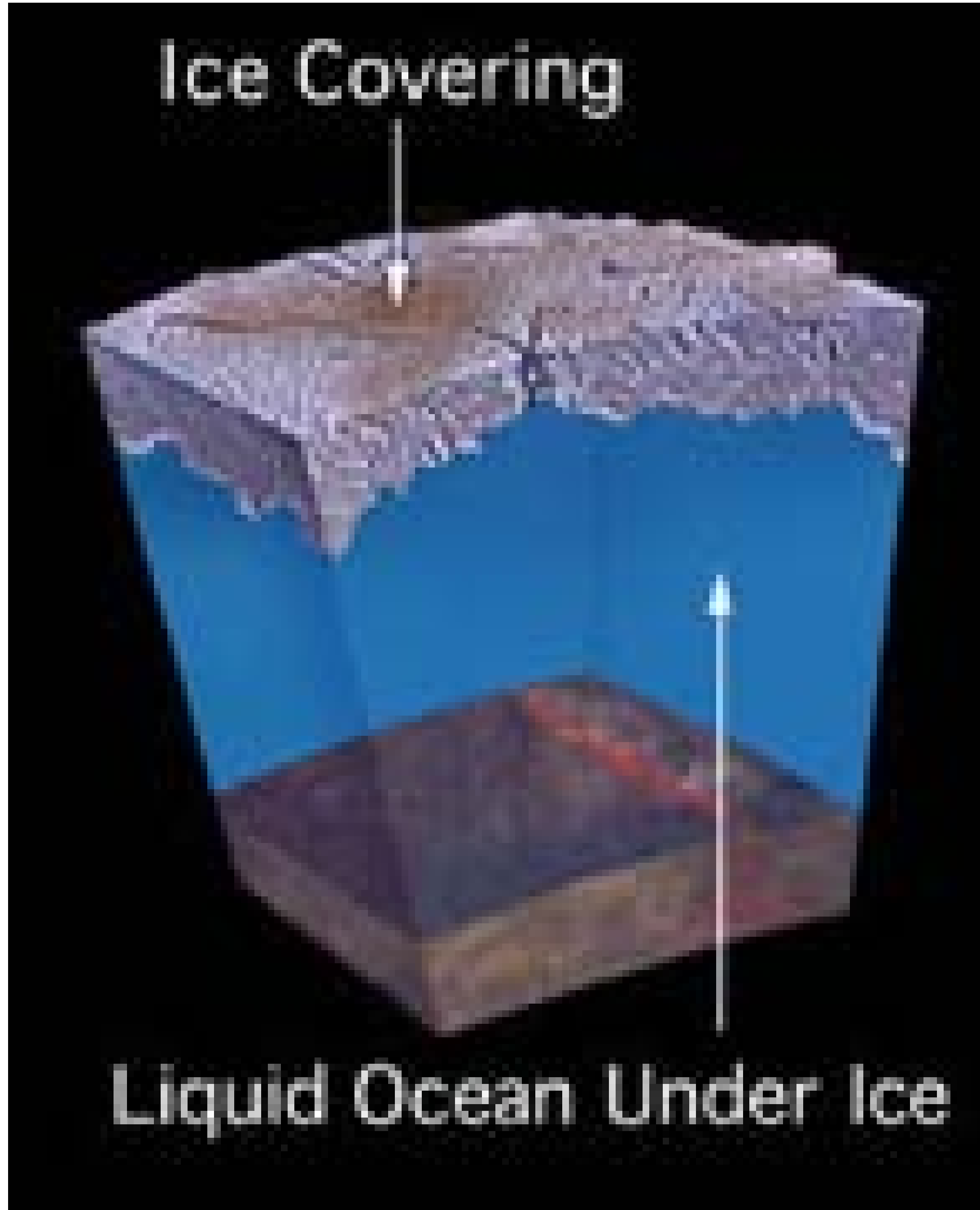
Europa is the next closest moon.

It has an icy surface with large cracks and no craters! This means that craters are filled in somehow.

This suggests liquid (probably water) under the icy surface.

For there to be an ocean under the surface, there must be some heat source – maybe tides from Jupiter.

This suggests that Europa could harbor life like that on the ocean's floor on Earth



Saturn

Radius ~ 10 times Earth, mass ~ 100 times Earth

Density ~ 700 kg/m^3 – less than water, Saturn would float!

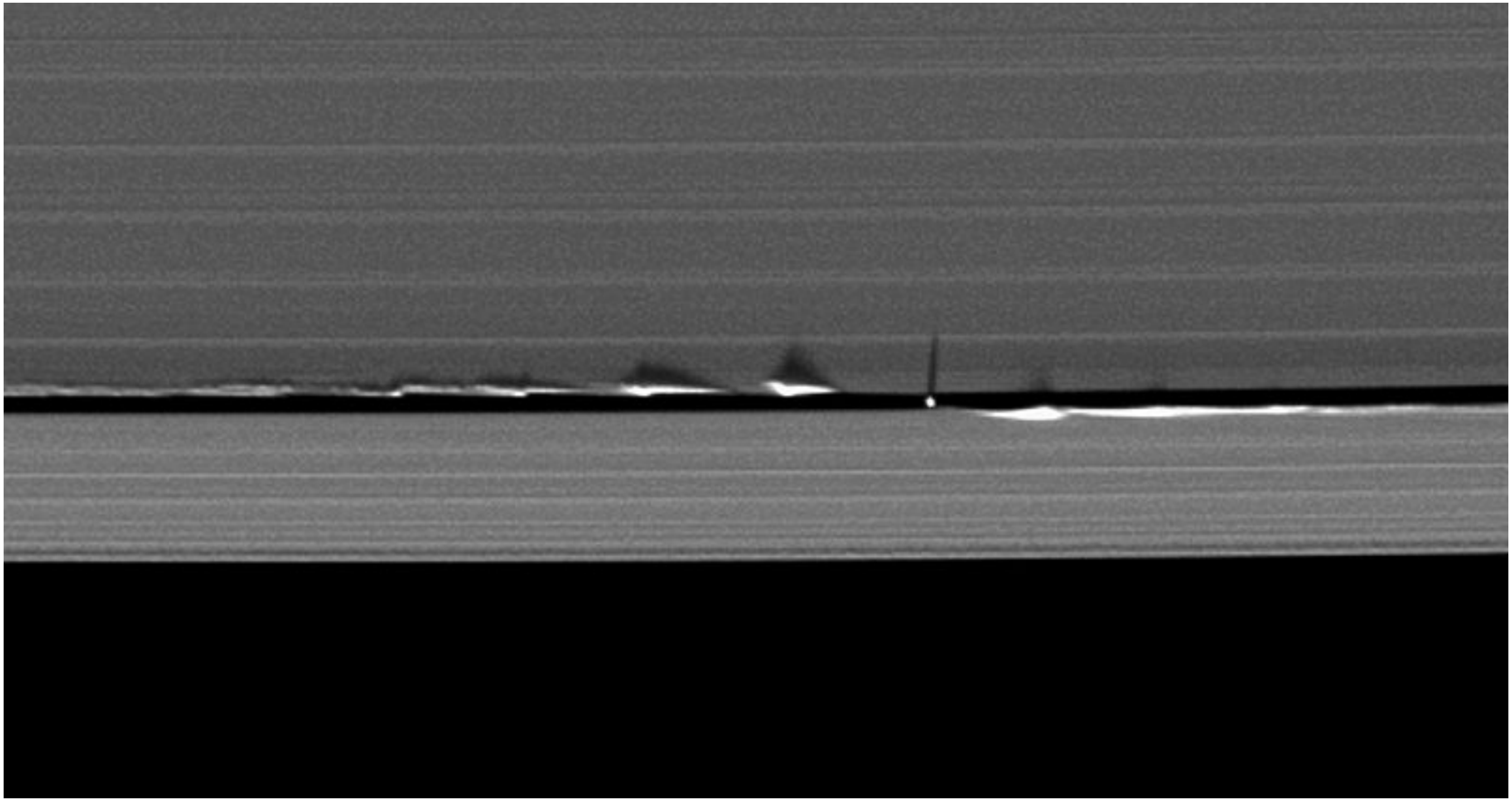
Composed of mainly hydrogen and helium

No surface

Strong magnetic field

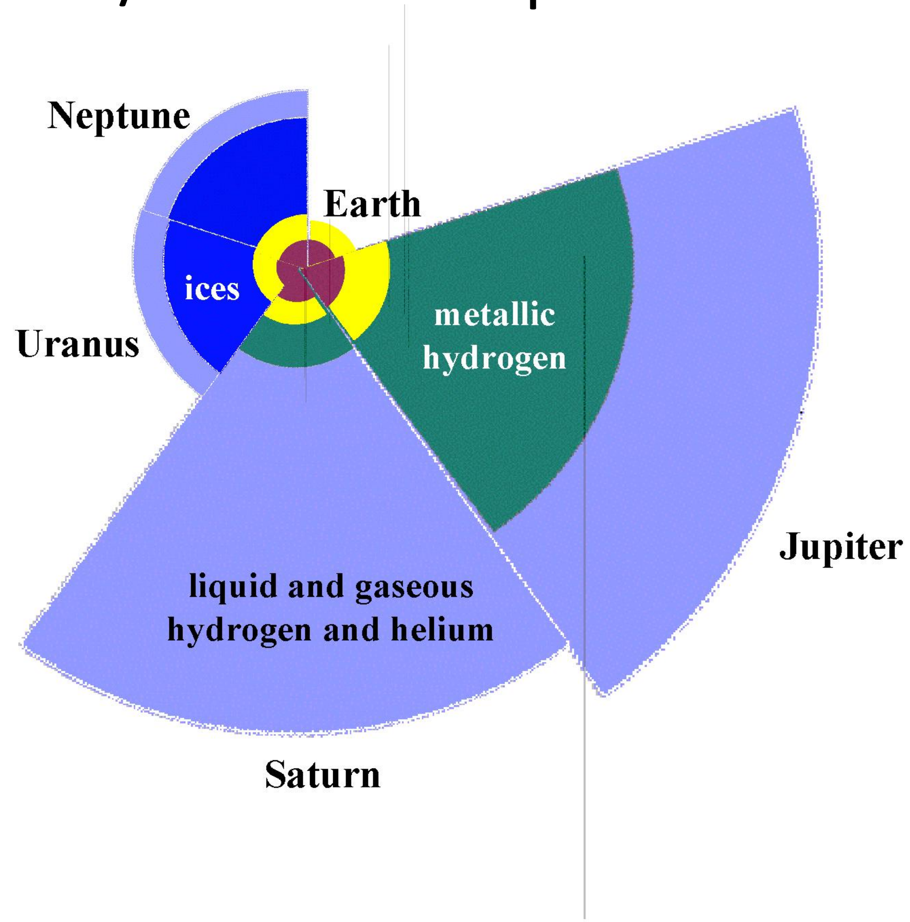
Saturn's Rings

- Made of icy particles from 1 cm to a few meters in size
- The many divisions in the rings are due to tiny moons between the divisions known as shepherd moons



Structure of Saturn

The internal structure of Saturn is similar to Jupiter, but the amount of metallic hydrogen is much smaller. Because there is less conducting material, Saturn has a weaker magnetic field – 1/20 that of Jupiter.



Cross-sections of the Jovian planets, with Earth for comparison

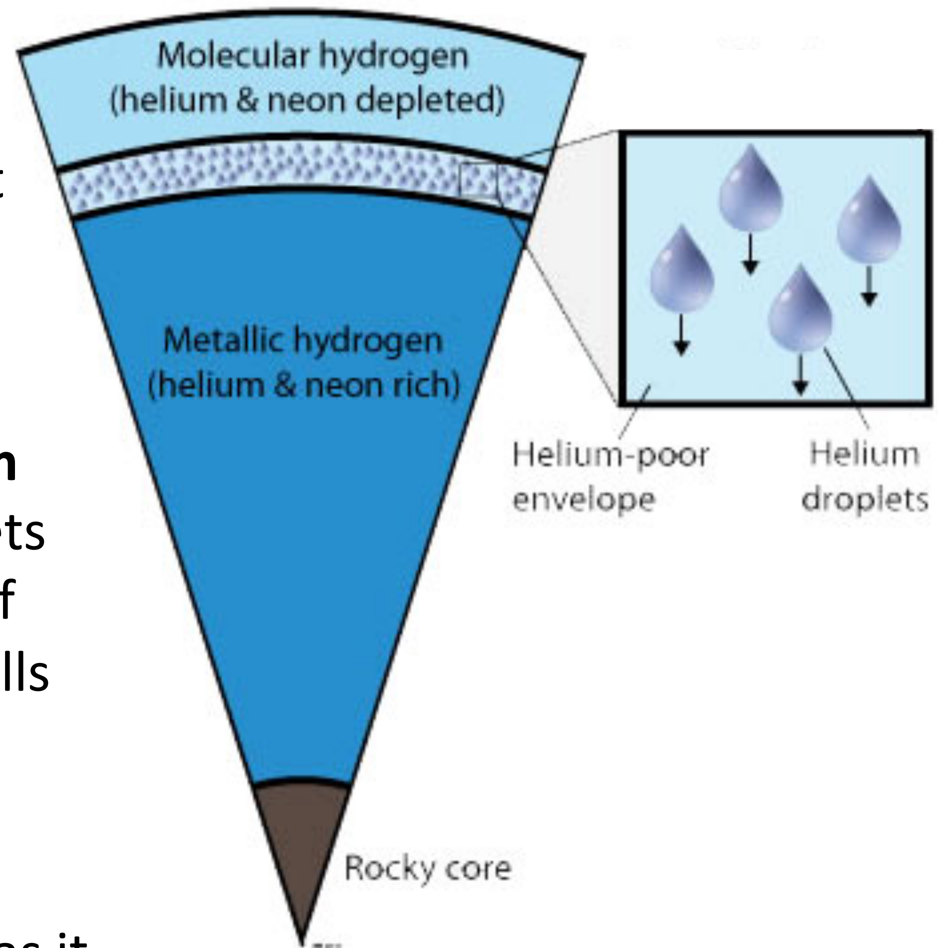
Internal Heating

Saturn gives off 3x more heat than it receives from the Sun – more than Jupiter

Can't be explained by leftover heat from formation – Saturn is smaller than Jupiter, cooled quickly

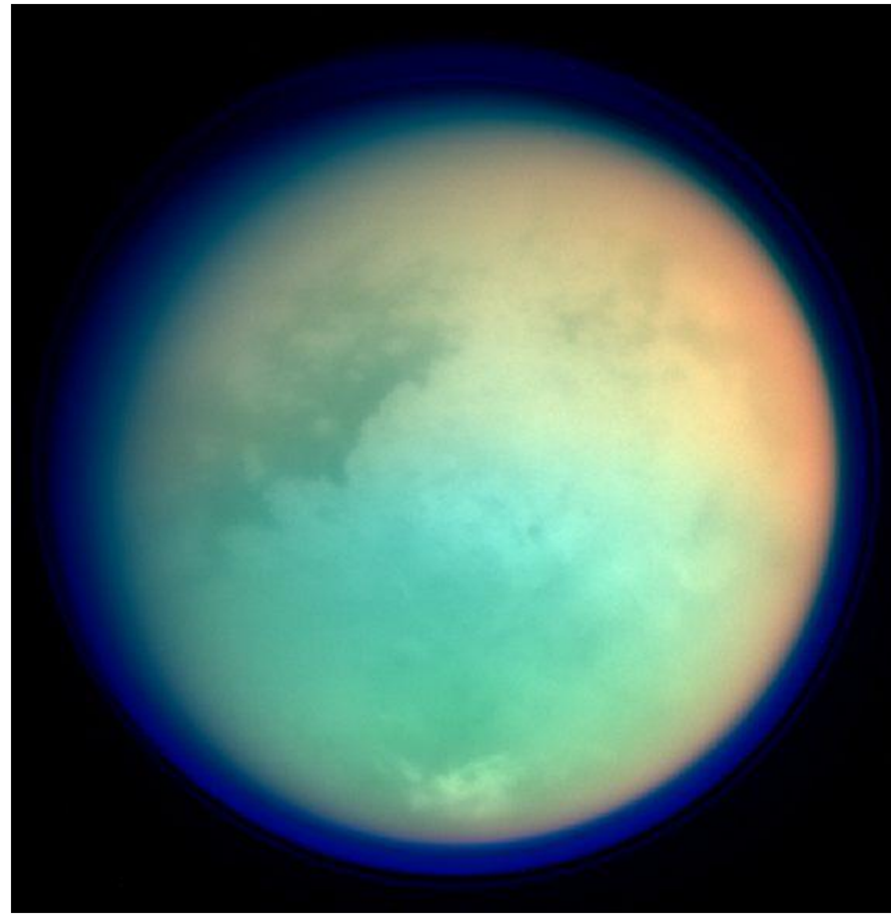
It is thought that Saturn has **helium rain**: helium condenses into droplets at the temperature and pressure of Saturn's upper atmosphere, and falls as rain – upper atmosphere is depleted in helium

Helium is compressed and heated as it falls, providing Saturn's internal heat source



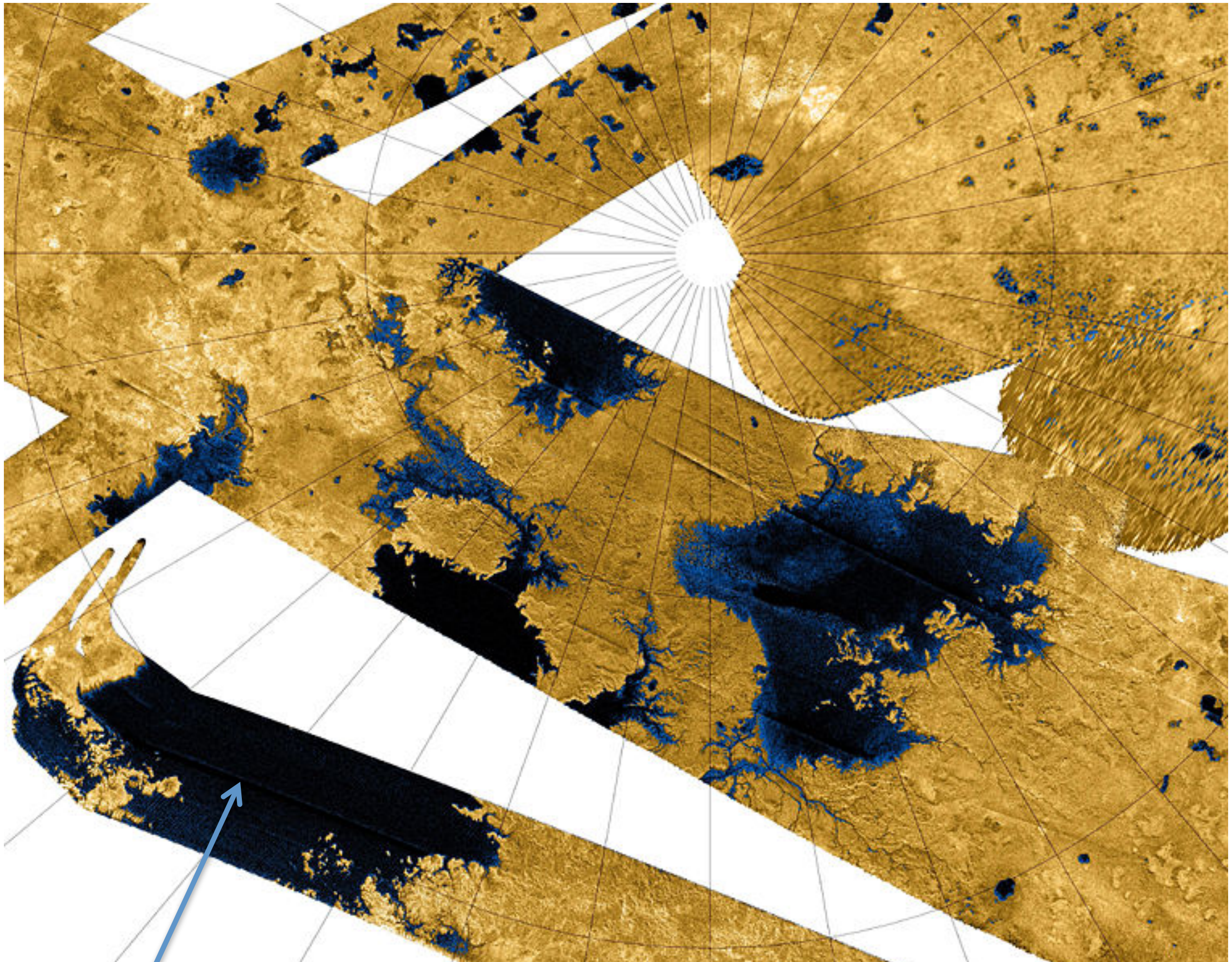
Titan

- Saturn's largest moon – 2nd largest in solar system (Jupiter's Ganymede is largest)
- Only other body in solar system with **stable surface liquid**: seas and lakes of methane
- Nitrogen-rich (98%)atmosphere, thicker and denser than Earth's
- Evidence for methane rain



False color image of Titan

The Lakes of Titan



Titan is cold – methane becomes liquid

Kraken Mare

Radar mosaic of Titan's north polar region. Blue coloring shows areas of low reflectivity caused by lakes of liquid ethane and methane.

Uranus

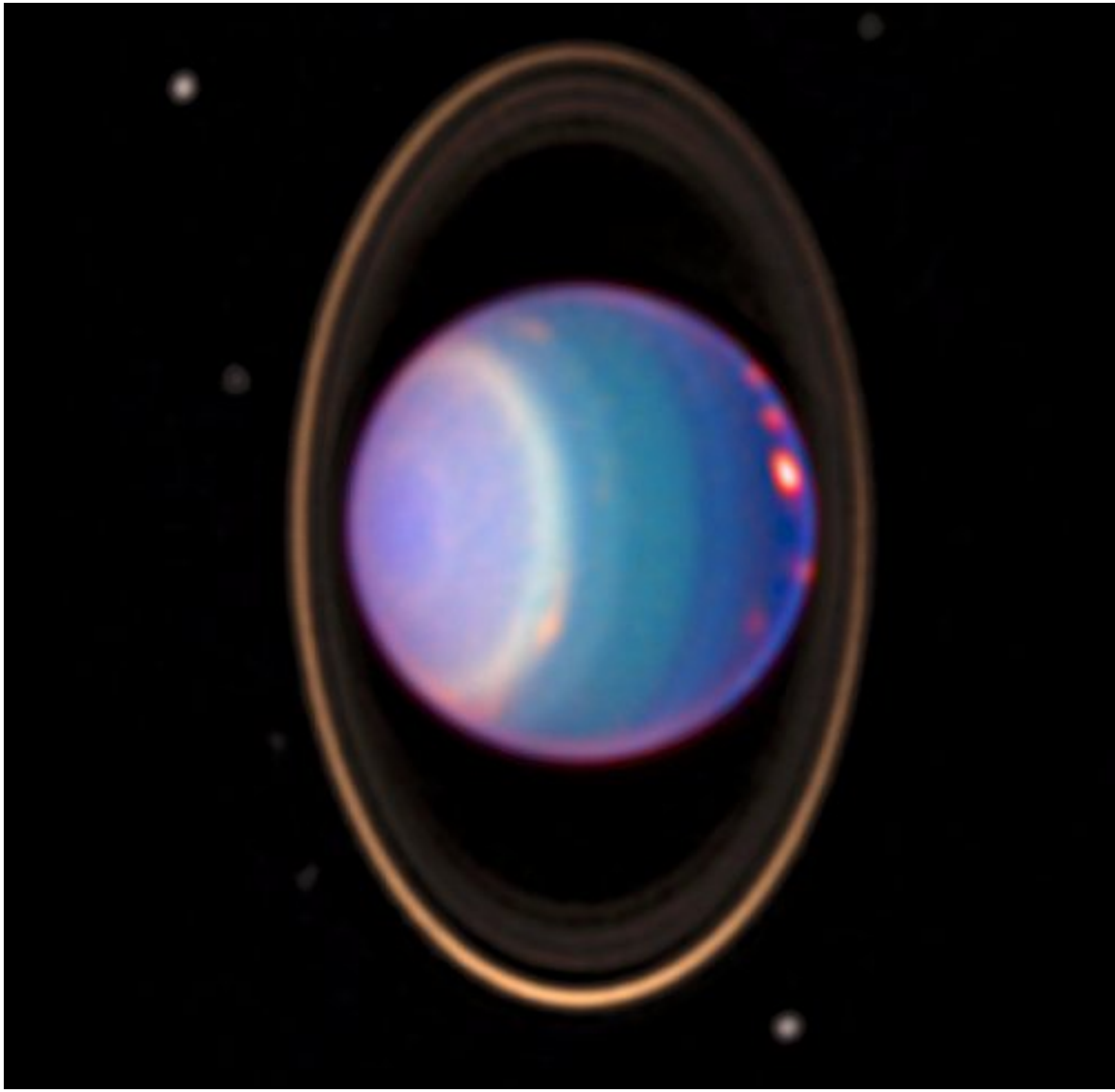
Radius ~ 4 times Earth

Mass ~ 15 times Earth

Nearly featureless – image at right is a false color image.

Rotation axis is tilted 98 degrees!

The tilt may be result of a giant impact (?)



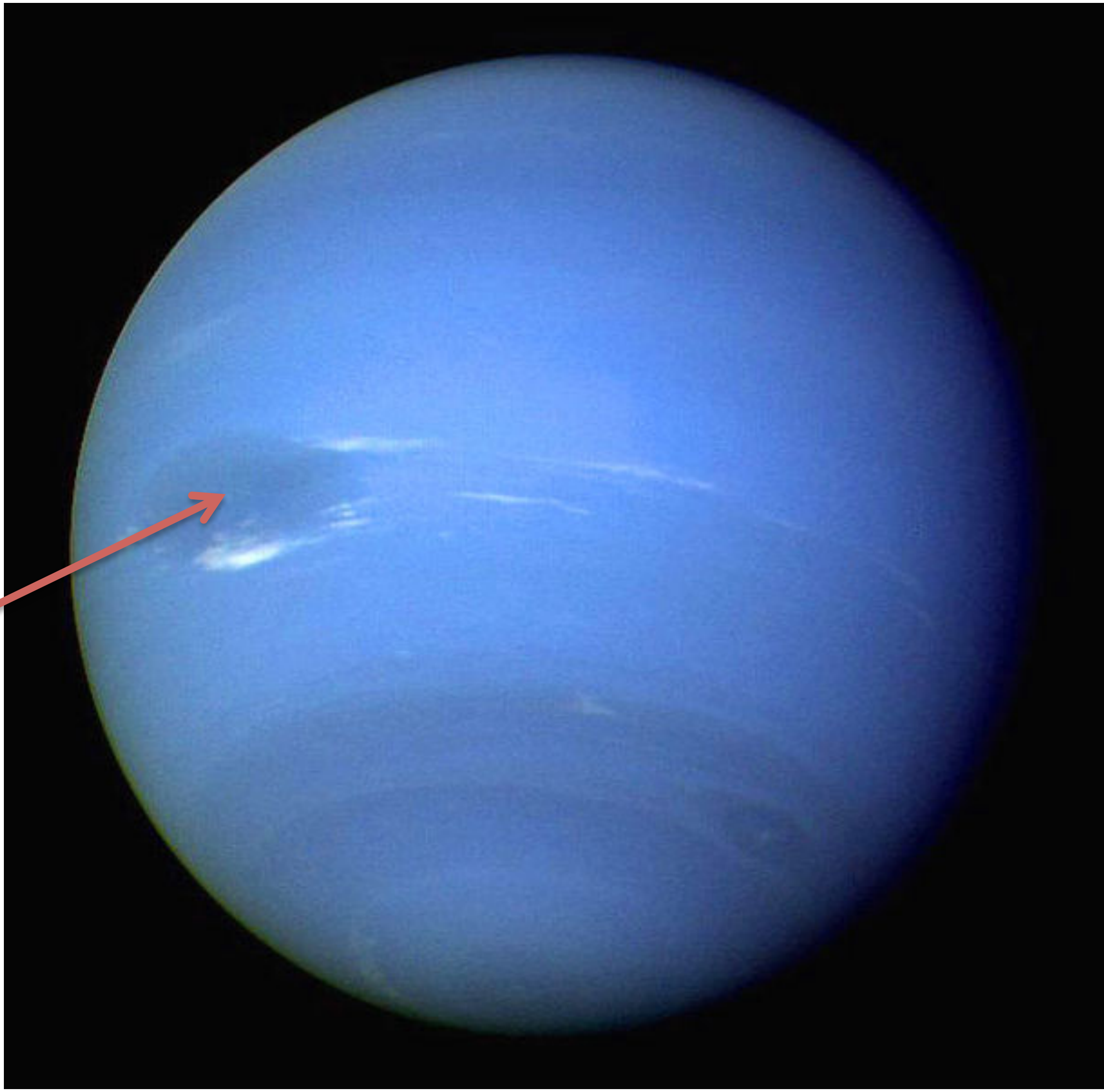
Neptune

Radius ~ 4x bigger than Earth.

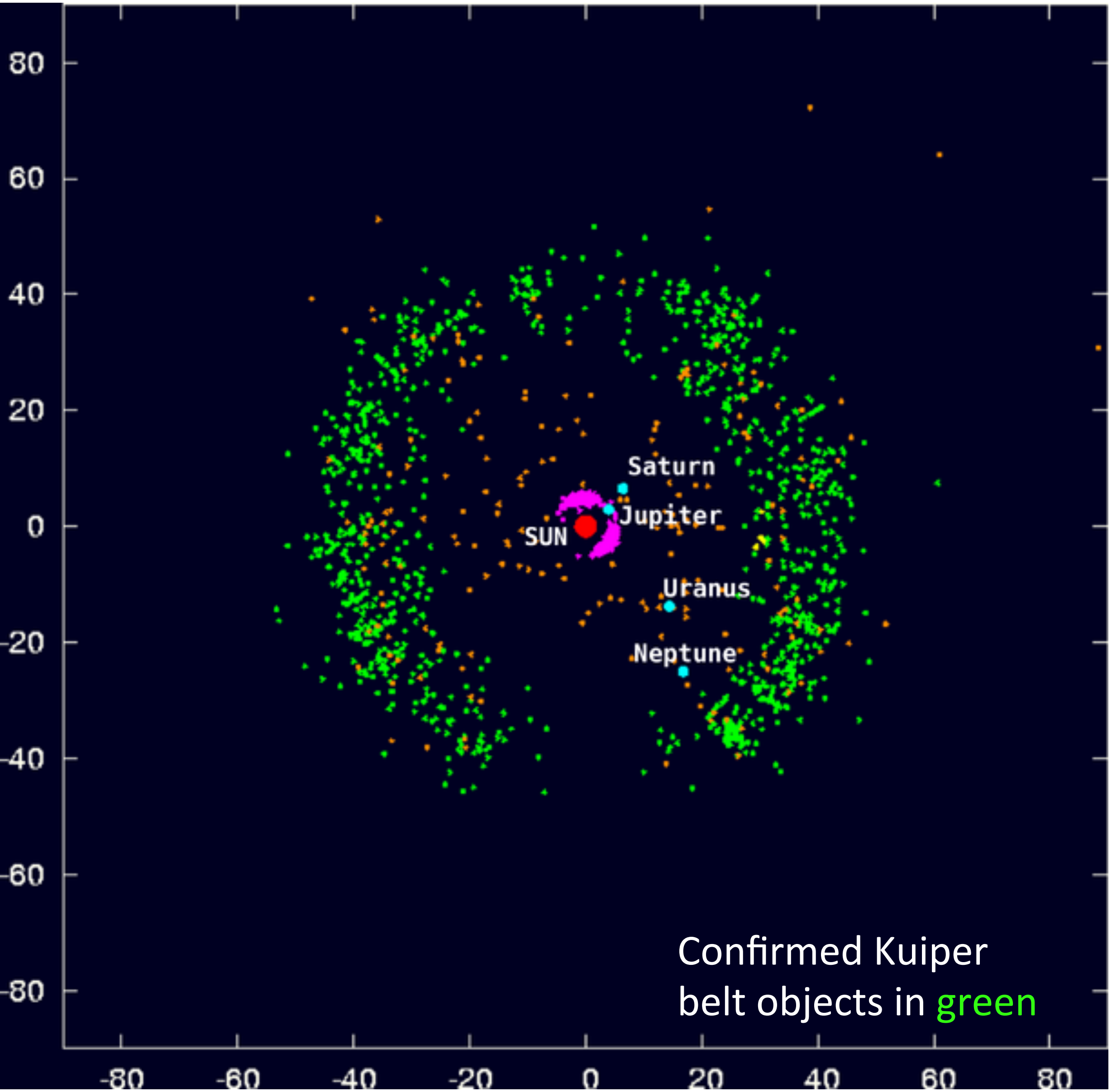
Mass ~ 17x Earth

Has bands of clouds unlike Uranus

Has a large storm on it called the Great Dark Spot.



Pluto and the Kuiper Belt

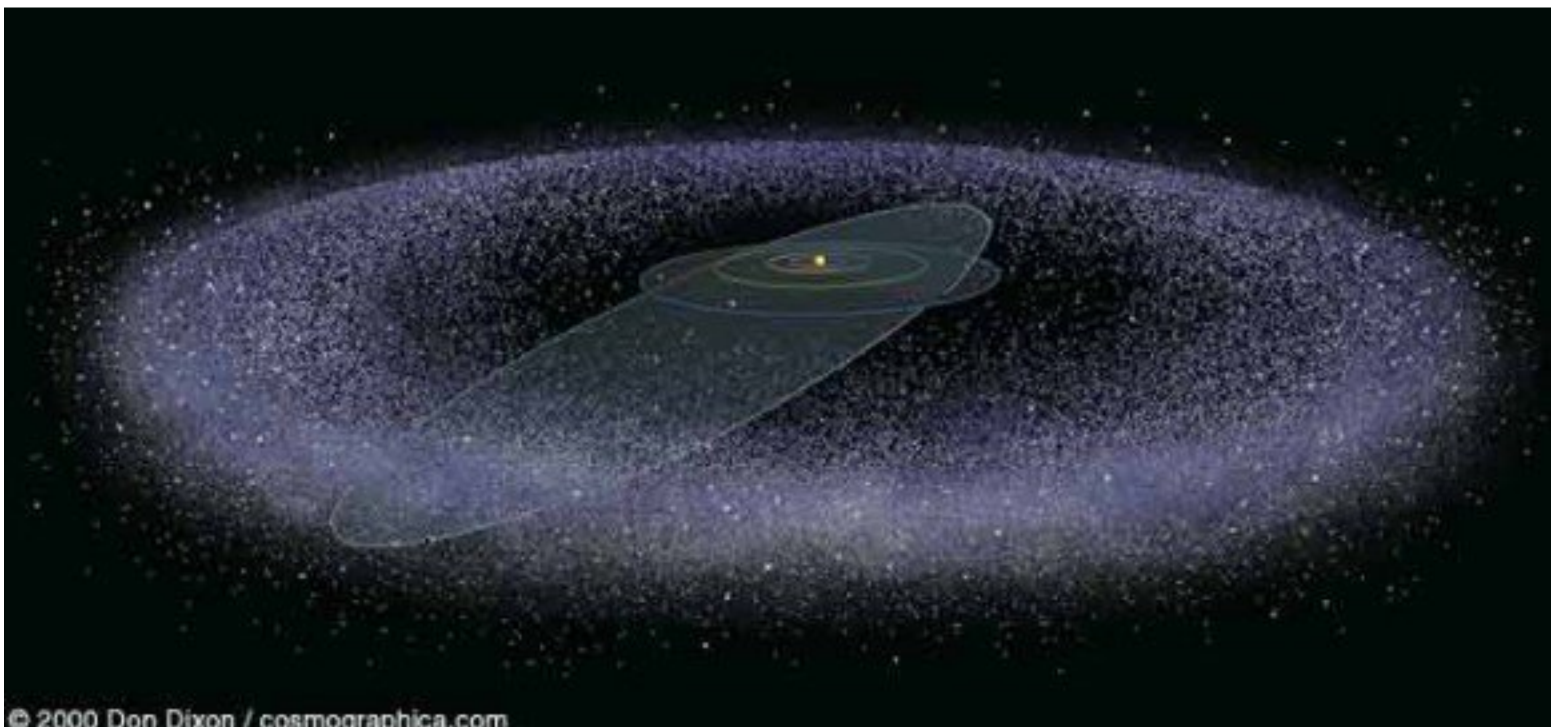


Recall: Kuiper belt extends from orbit of Neptune (20 AU) to 50 AU from Sun

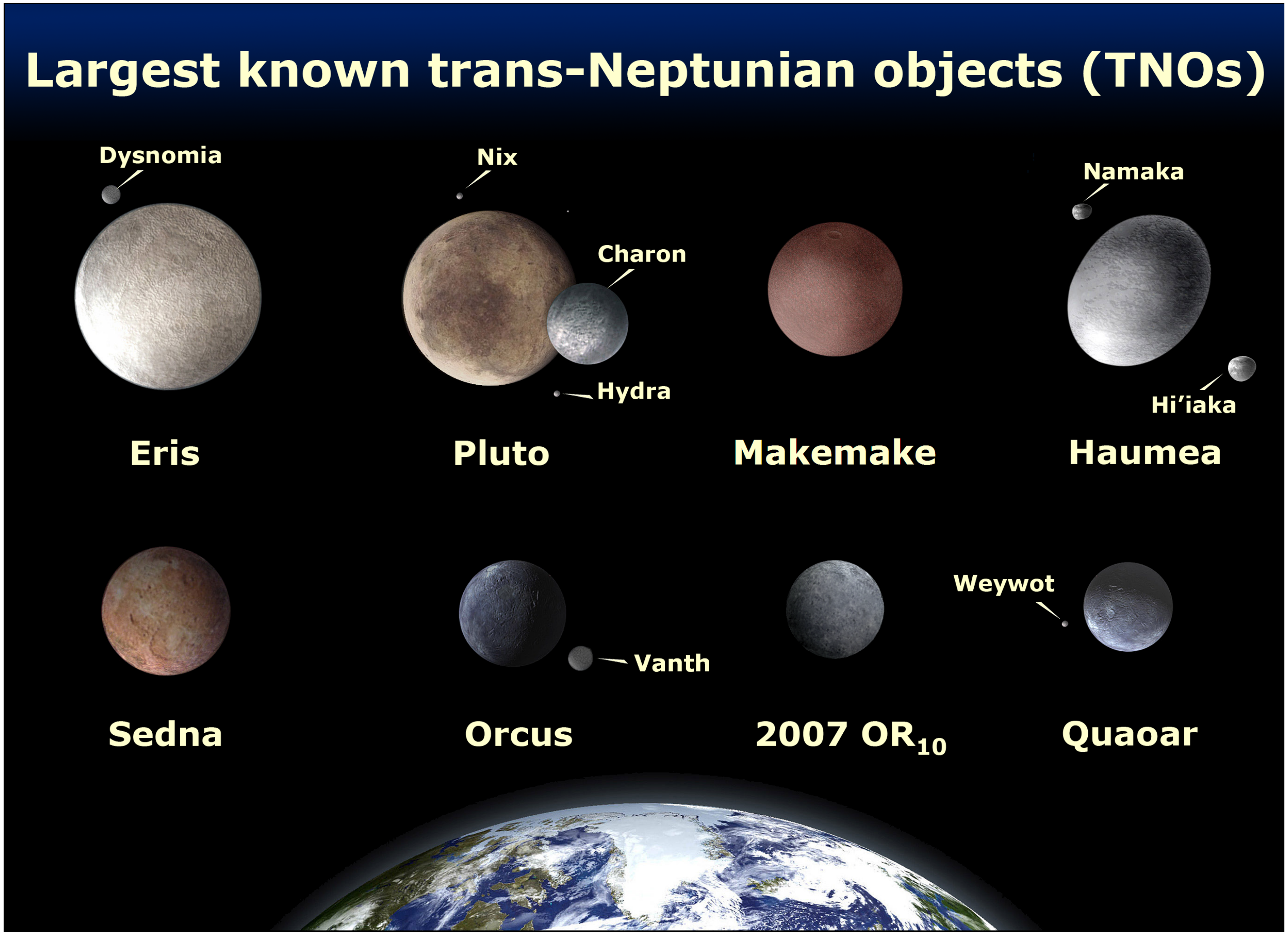
Contains many small, icy bodies

Pluto and the Kuiper Belt

- Pluto is just one member of the Kuiper Belt
- Consists of a large number of icy bodies that are not in a plane – more like a thick disk.
- Contrast this with the 8 planets which are in a plane to an accuracy of 1%

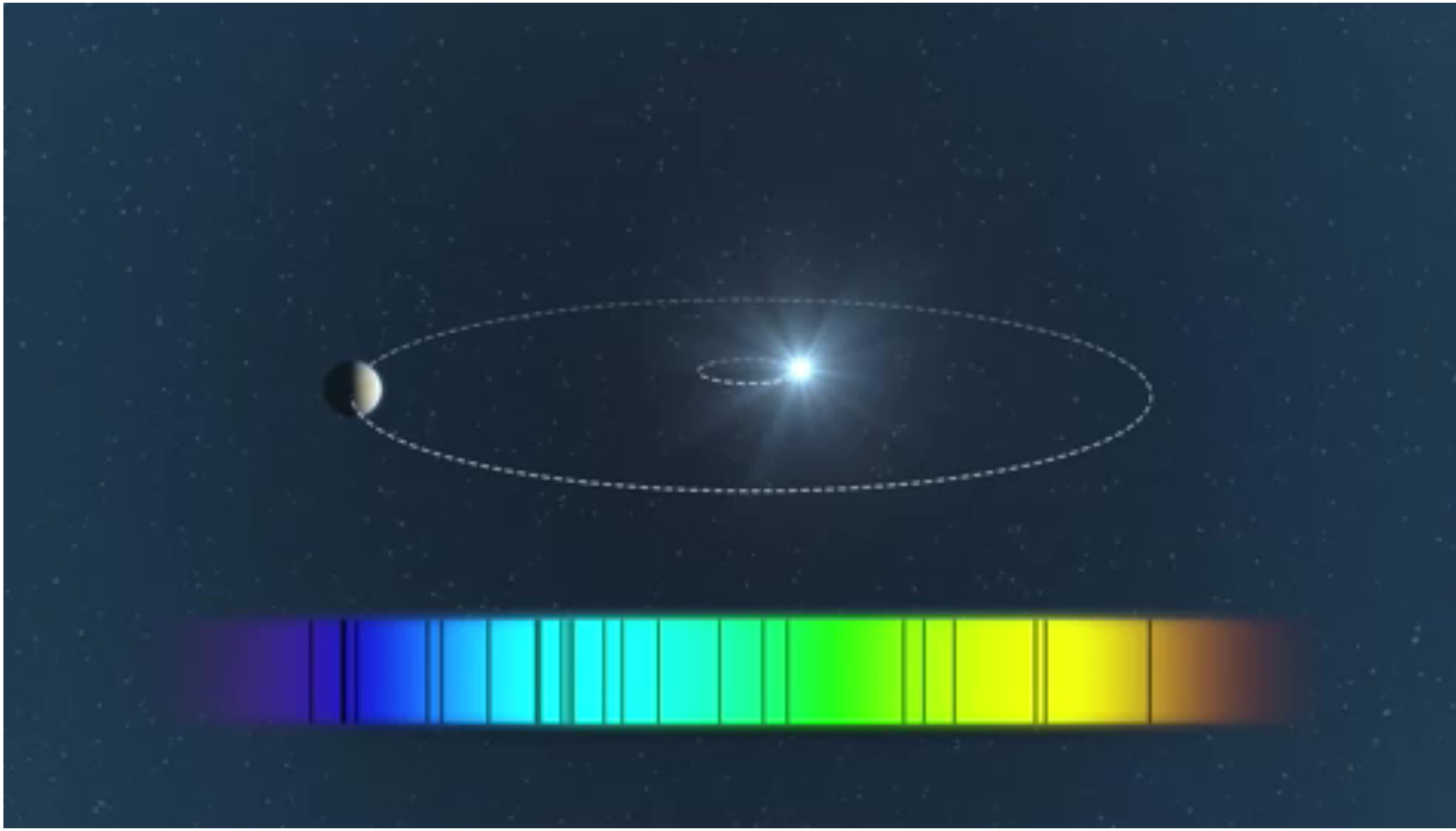


Pluto and the Kuiper Belt



Pluto is only the second largest of the Kuiper Belt objects – the largest is Eris

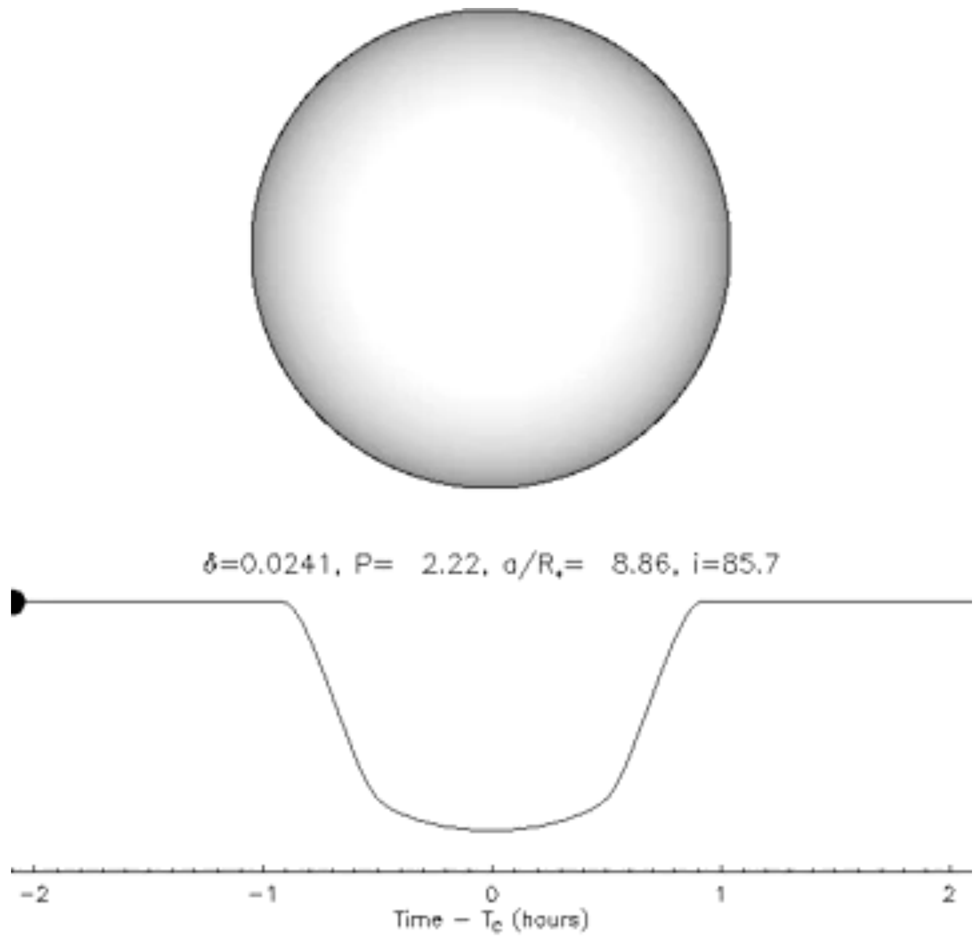
Finding Extrasolar Planets
Technique 1: Radial Velocity

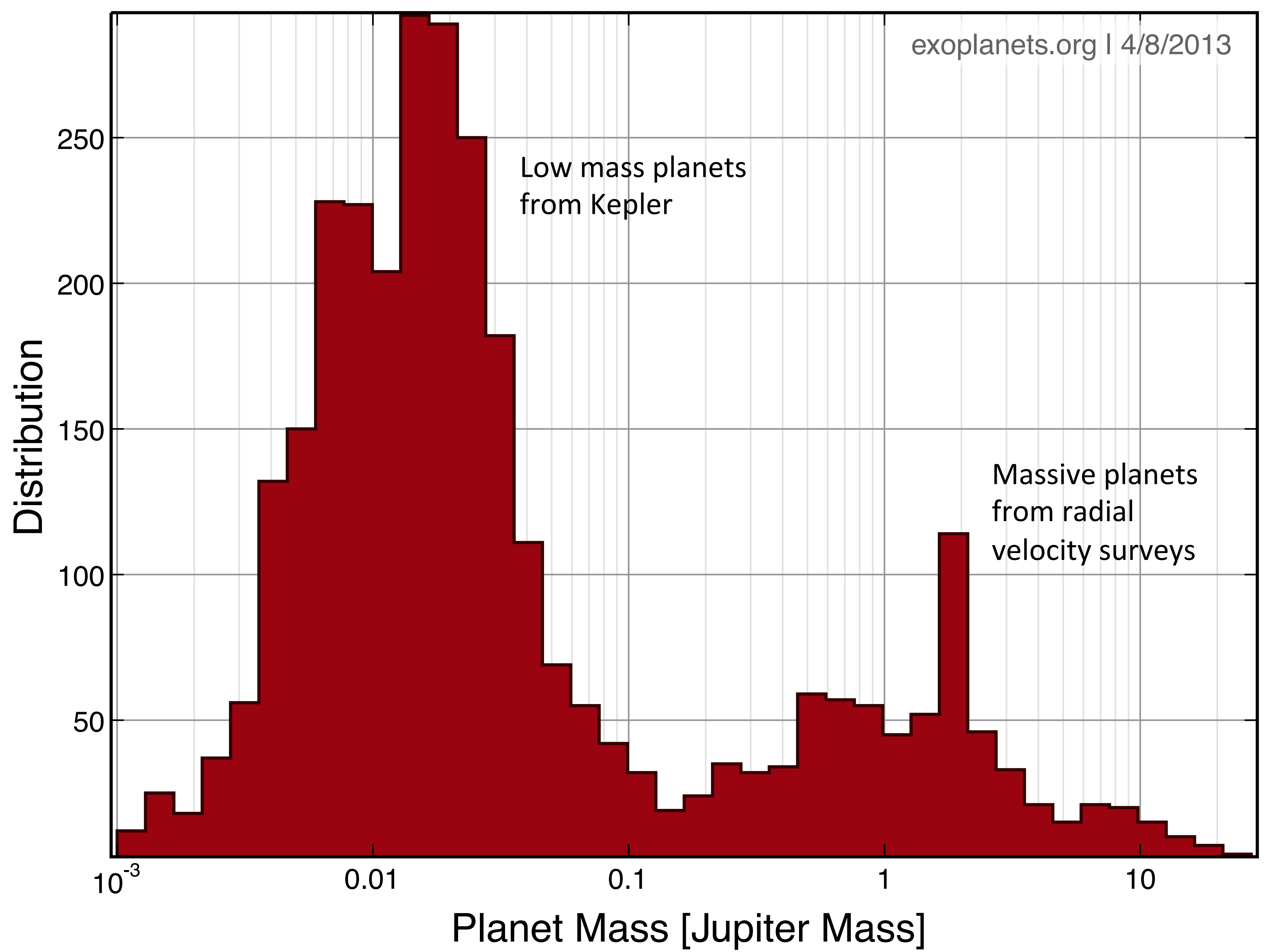


Spectral lines of stars with planets have a Doppler shift due to planet tugging on star

Finding Extrasolar Planets
Technique 2: Transits

- Another way to find planets is to watch for eclipses, when planets pass in front of their parent star
- Look for a very small drop in the amount of light received
- This can tell us the radius of the planet, since we know how much of the light of the star is blocked

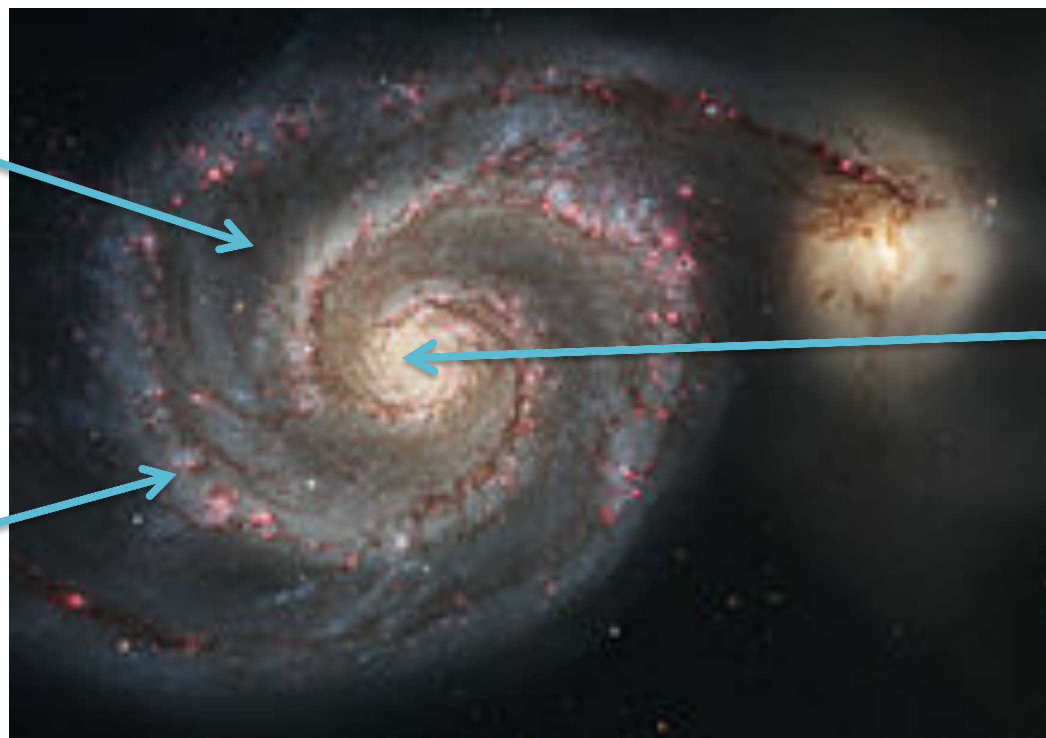



exoplanets.org | 4/8/2013
Low mass planets from Kepler
Massive planets from radial velocity surveys
Distribution
250
200
150
100
50
10^{-3}
0.01
0.1
1
10
Planet Mass [Jupiter Mass]

A galaxy is a huge collection of stars that is isolated in space and held together by gravity.

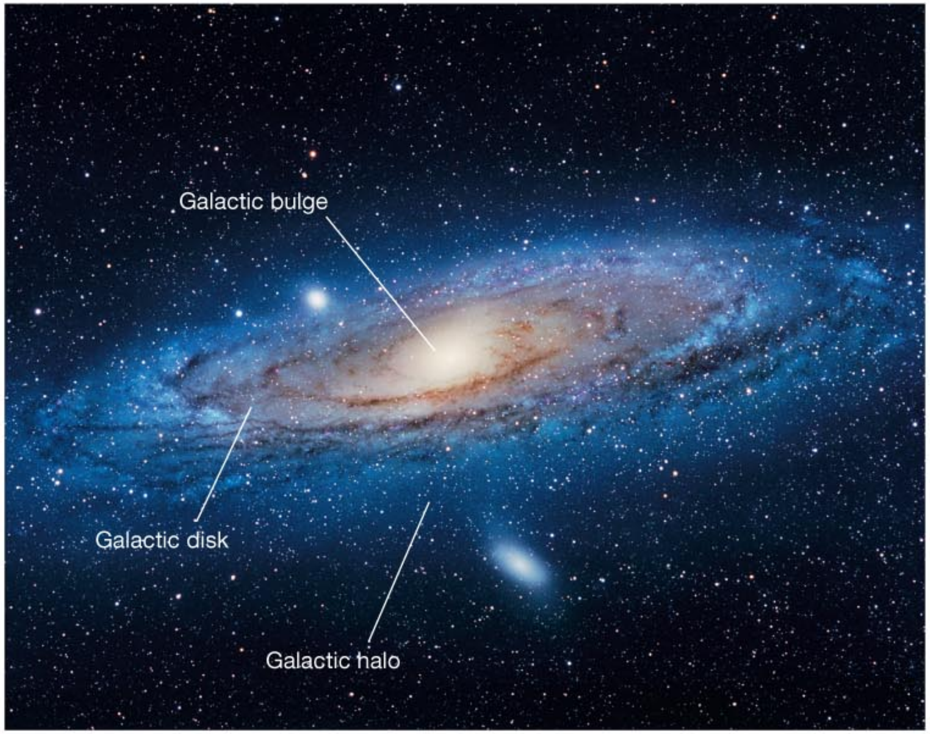
We happen to live in one called the Milky Way Galaxy or just the Galaxy (with a capital ``G'')

The structure of the Galaxy looks like this:



This is a picture of the Whirlpool galaxy – not the Milky Way

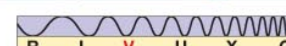
The Milky Way



(a)

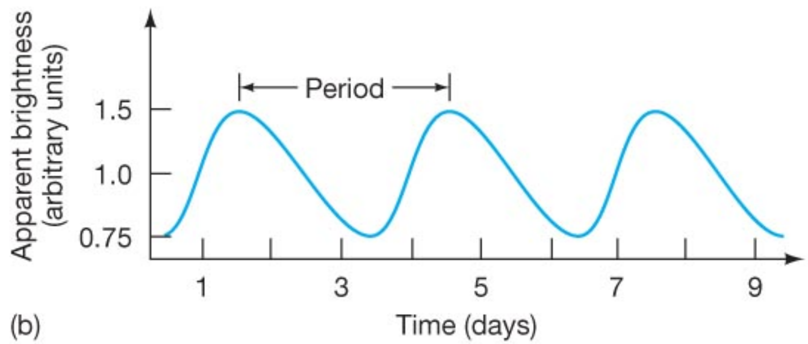

(b)


(c)

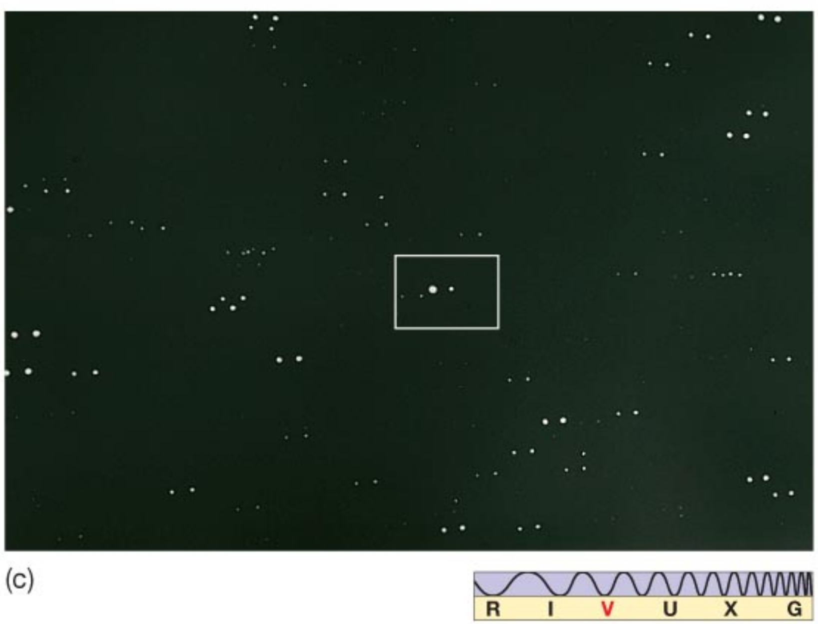


Our Galaxy is a spiral galaxy. Here are three similar galaxies.

Cepheid variables: pulsating stars with period proportional to luminosity: distance indicator!



Cepheid light curve



Cepheid—two displaced images taken at different times

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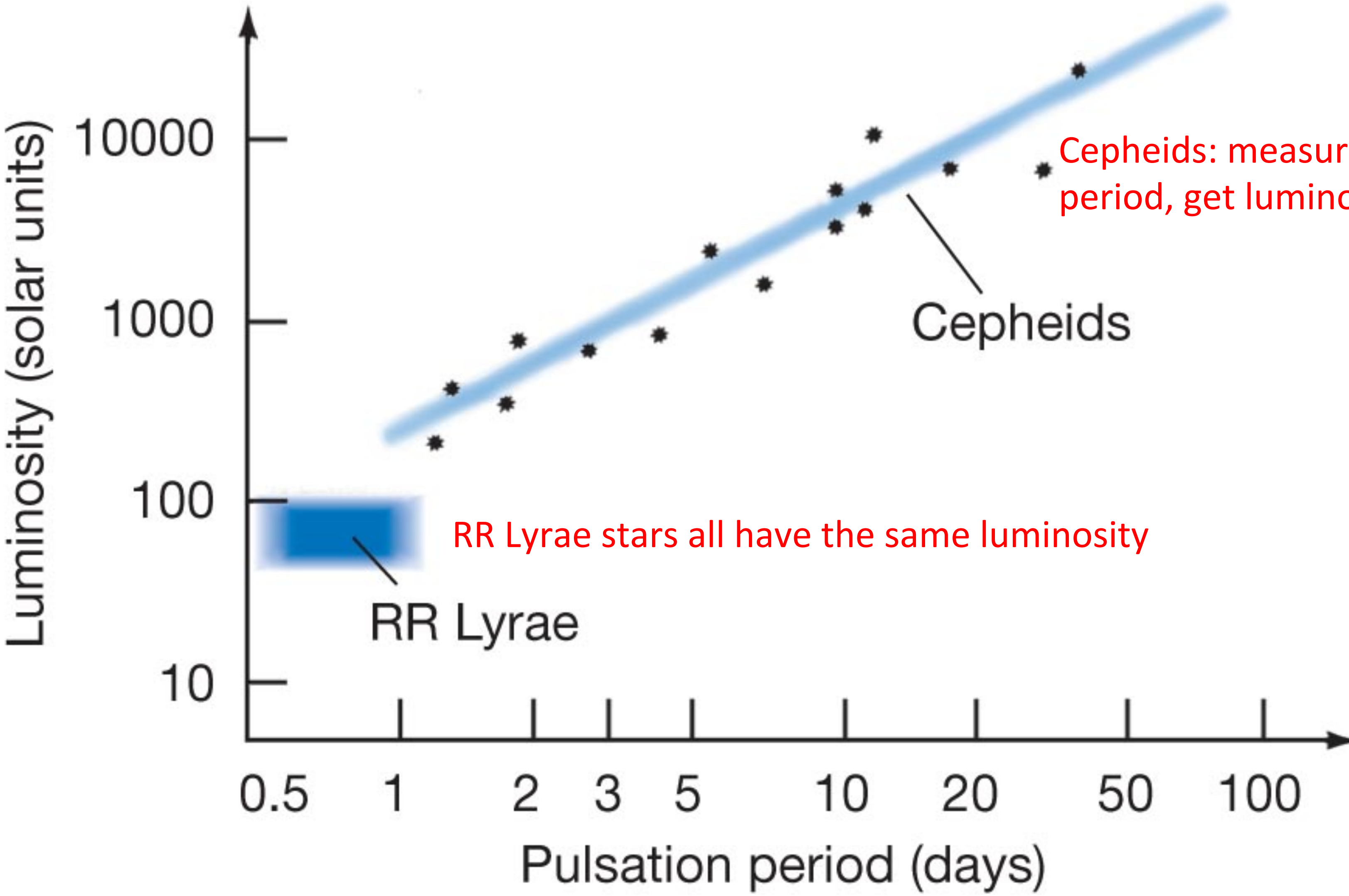
Leavitt's Period-Luminosity Relation for Cepheid Variable Stars



Cepheids: measure period, get luminosity

RR Lyrae stars all have the same luminosity

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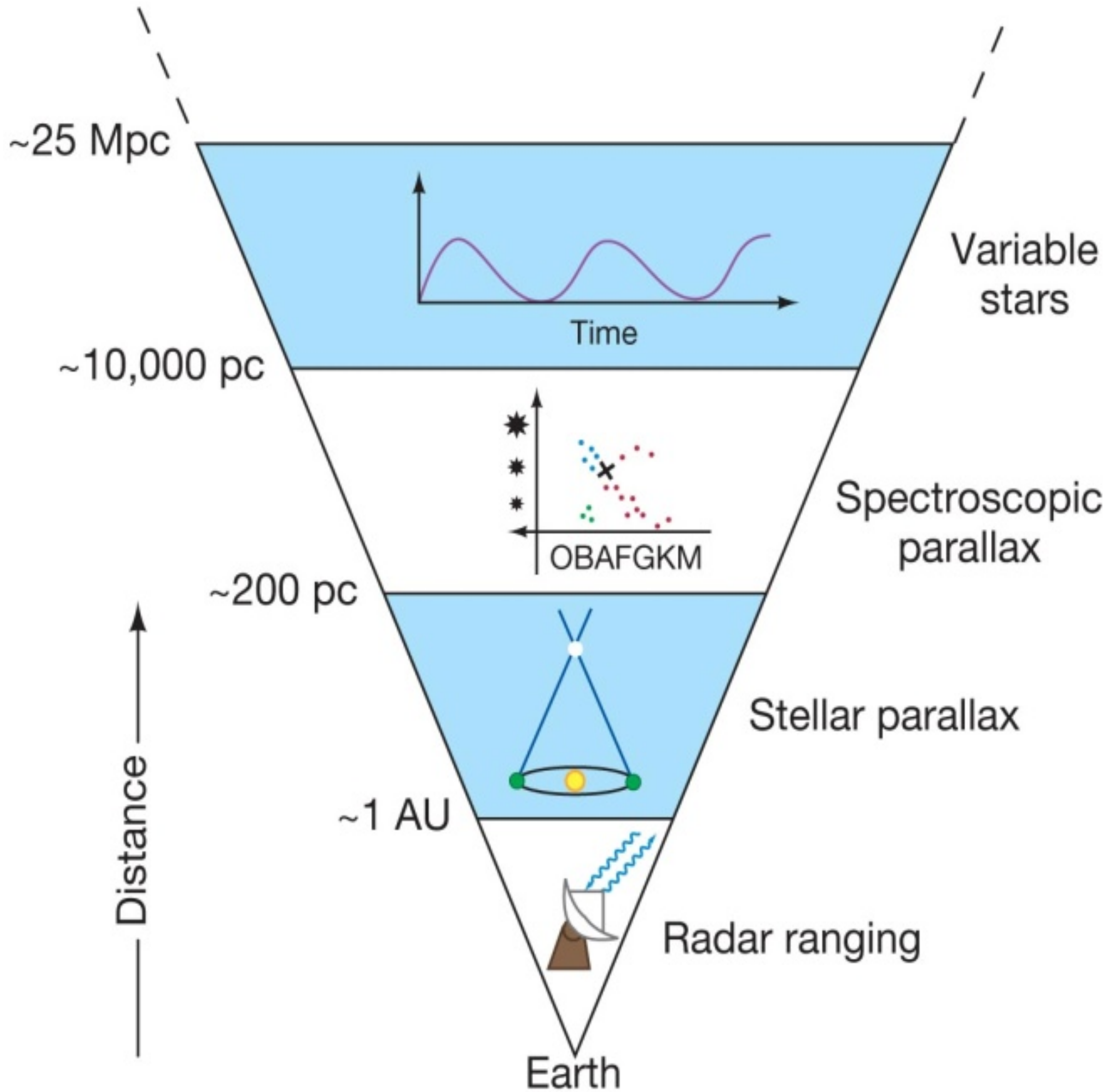
As a result:

A Cepheid variable can be used as a standard candle:

1) Find its luminosity by measuring its period

2) Measure its apparent brightness and deduce its distance from the $1/r^2$ formula

$$r = \sqrt{\frac{\text{luminosity}}{4\pi \times \text{apparent brightness}}}$$



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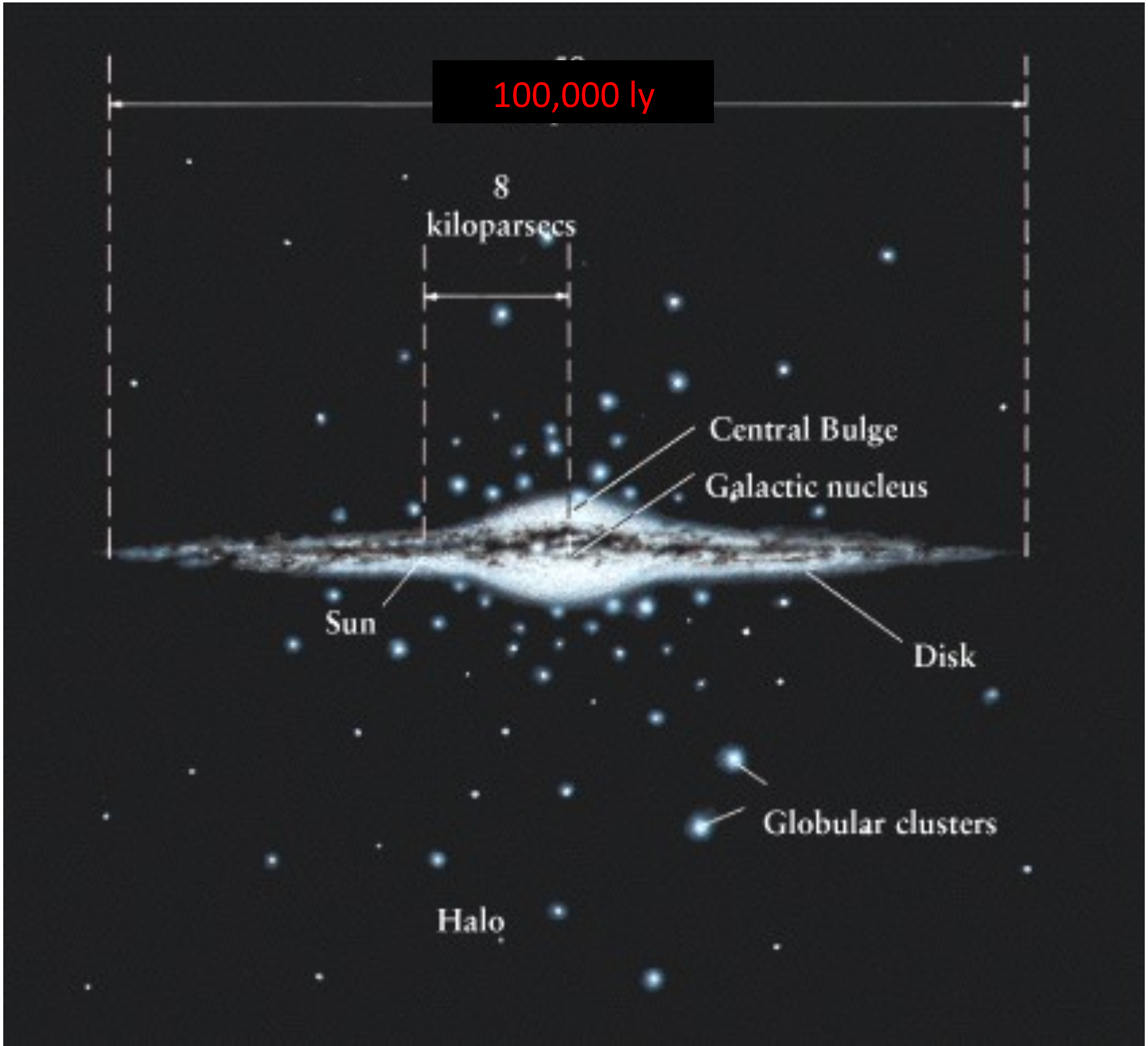
Structure of the Milky Way



Structure of the Milky Way

- The Milky Way Galaxy consists of several parts
  - The Galactic disk
  - The Galactic bulge
  - The Galactic halo
  - And the Galactic Center

- The Galactic Disk is home to most of the young stars in the Galaxy
- The Galactic Bulge contains a mix of old and young stars
- The Galactic Halo has mainly old stars and is home to many globular clusters
- And the Galactic Center contains a supermassive black hole

Galactic Structure

The galactic halo and globular clusters formed very early; the halo is essentially spherical. All the stars in the halo are very old, and there is no gas and dust.

The galactic disk is where the youngest stars are, as well as star formation regions – emission nebulae, large clouds of gas and dust.

Surrounding the galactic center is the galactic bulge, which contains a mix of older and younger stars.

Stellar populations: Old and new stars

• Stars formed at the time the Galaxy formed are called Population II stars. They are almost entirely hydrogen and helium with few heavier elements, because the matter in them had not previously been in another star. They lie in all parts of the galaxy, the halo (globular clusters), disk, and bulge.

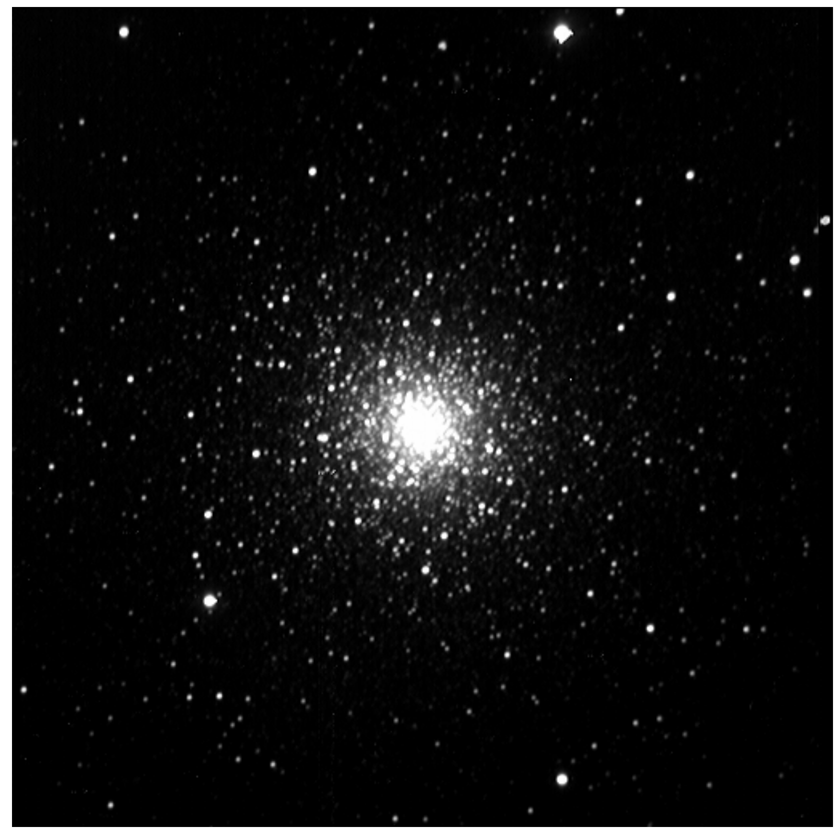
• Younger stars, formed from matter in the disk of the galaxy, are called Population I stars. They are made from reprocessed material, matter that was once in other stars and was redistributed to the galaxy when the star died.

Population I stars are thus younger and begin their lives with a larger fraction of heavier elements than Population II stars.

Both Population I and Population II stars are made mainly of hydrogen and helium. Even in Population I stars, like the Sun, heavier elements are a small fraction of the total mass.

- Globular clusters formed at the time the galaxy formed. They are dense clusters of up to 1 million stars, all Population II.

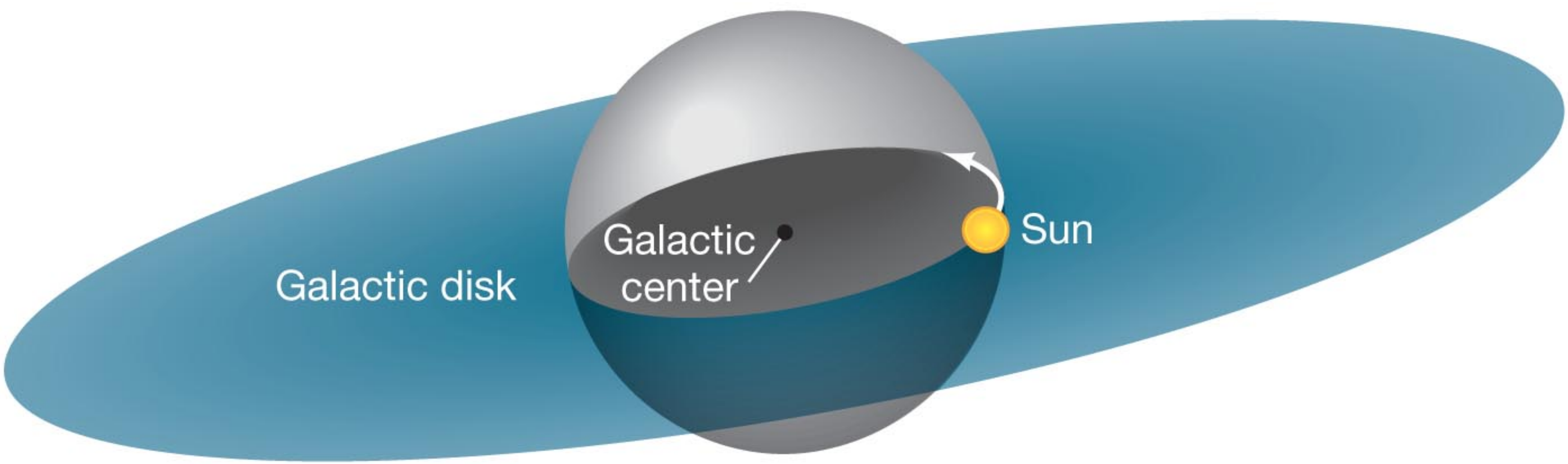
- An example of a typical globular cluster is M3



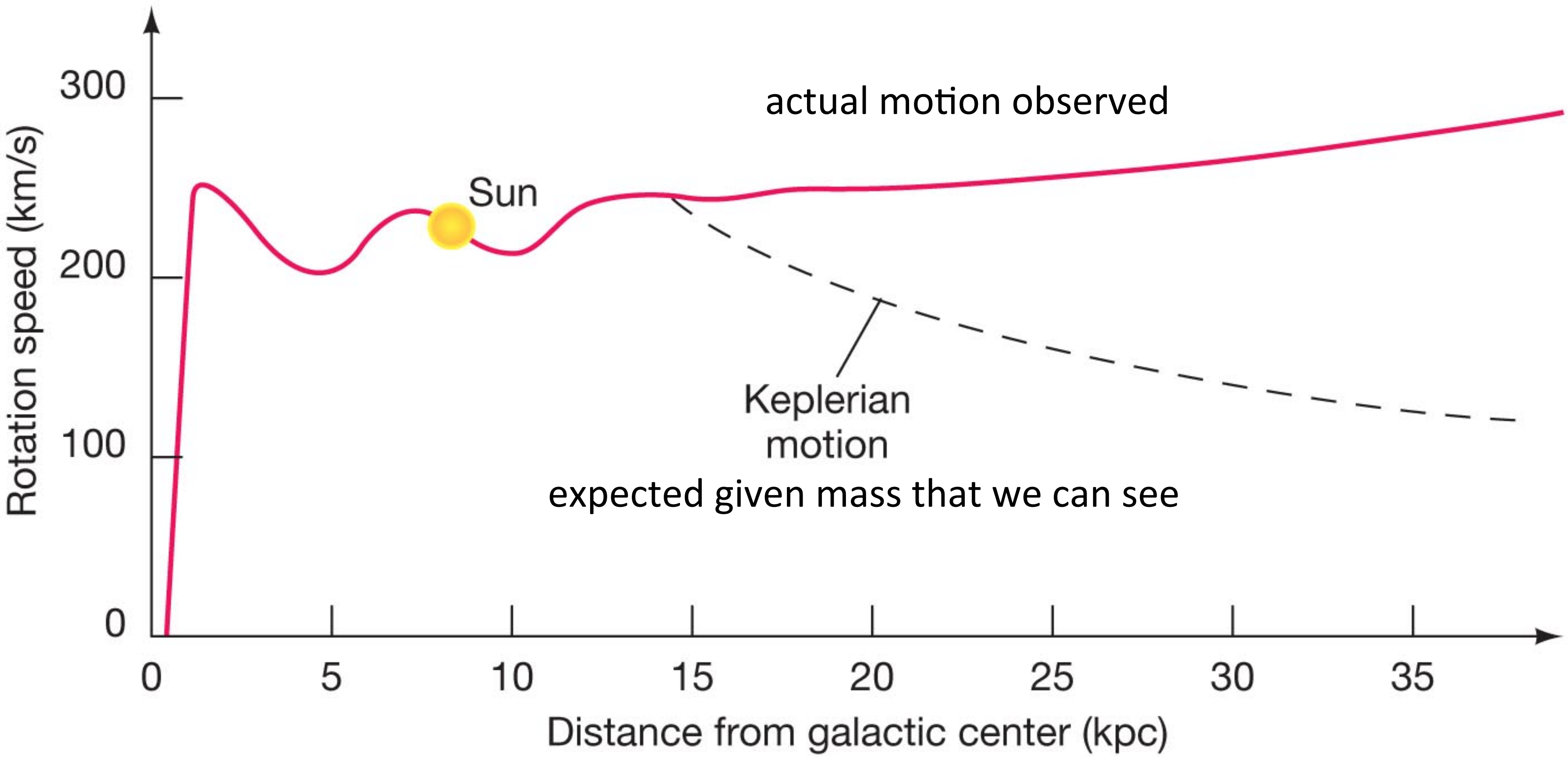
- Globular clusters are among the oldest objects in the universe.

The Mass of the Milky Way Galaxy

The orbital speed of an object depends only on the amount of mass between it and the galactic center.



Rotation curve of the Galaxy: How fast objects move as a function of the distance to the galactic center.



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Instead, the speed at which stars, globular clusters and gas clouds orbit the galaxy implies a much larger mass than is visible:

- **Most of the Galaxy's mass is dark matter, matter too dim to see at any wavelength, that lies in the halo.** **We do not yet know what it is.**

This is true of all other large galaxies whose mass we have measured. What constitutes most of the universe's mass is one of the most fundamental mysteries of current astronomy.

Dark Matter Summary

How fast a star orbits the galaxy tells us how much mass is inside the radius of the star's orbit

The faster the star moves, the more mass must be pulling it to keep it from flying out of the galaxy

Stars far from the center of the galaxy move unexpectedly fast: **Therefore there is much more mass in the galaxy than we can see**

At least 90% of the Galaxy's mass is "dark matter," matter that we cannot see at any wavelength

We know where it is (mostly in the halo) but
we don't yet know what it is

The Galactic Center

The galactic center appears to have

- **a stellar density a million times higher than near Earth**
- **a ring of molecular gas 400 pc across**
- **strong magnetic fields**
- **a rotating ring or disk of matter a few parsecs across**
- **a strong X-ray source at the center**

- Observations of orbiting stars near the Galaxy's center show that about 4 million solar masses lie within 6 light-hours of the center.

From the stars’ distance from the center and the very short time it takes them to complete their orbits, one finds that they are orbiting something whose mass is 3.7 million times the mass of the Sun! All of that mass is squeezed into something smaller than a few light-days across – about the size of the solar system.

- This strongly suggests that there is a 4-million solar mass black hole in the center of the Galaxy.

With 16 years of data, here's what the orbits look like

Recently the star S0-2 completed an orbit that we observed from start to finish

It comes very close to the center and moves very quickly

This is evidence that something very massive and dense lives in the center