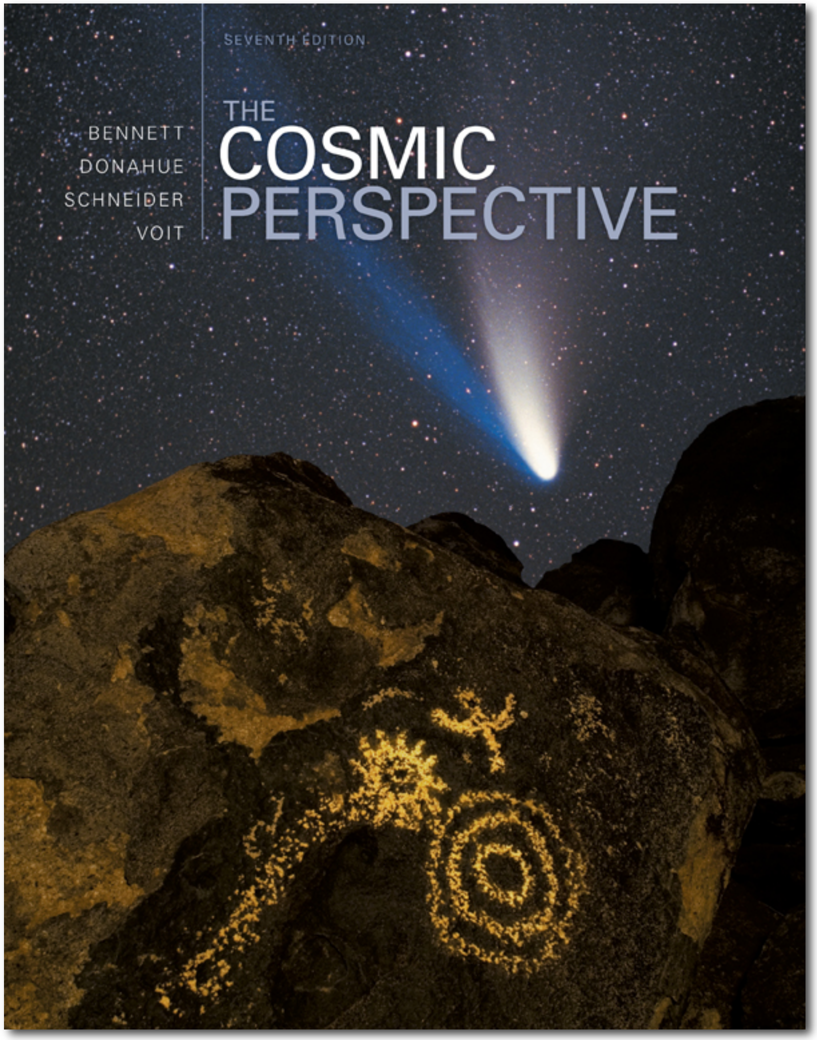
Chapter 11 Lecture

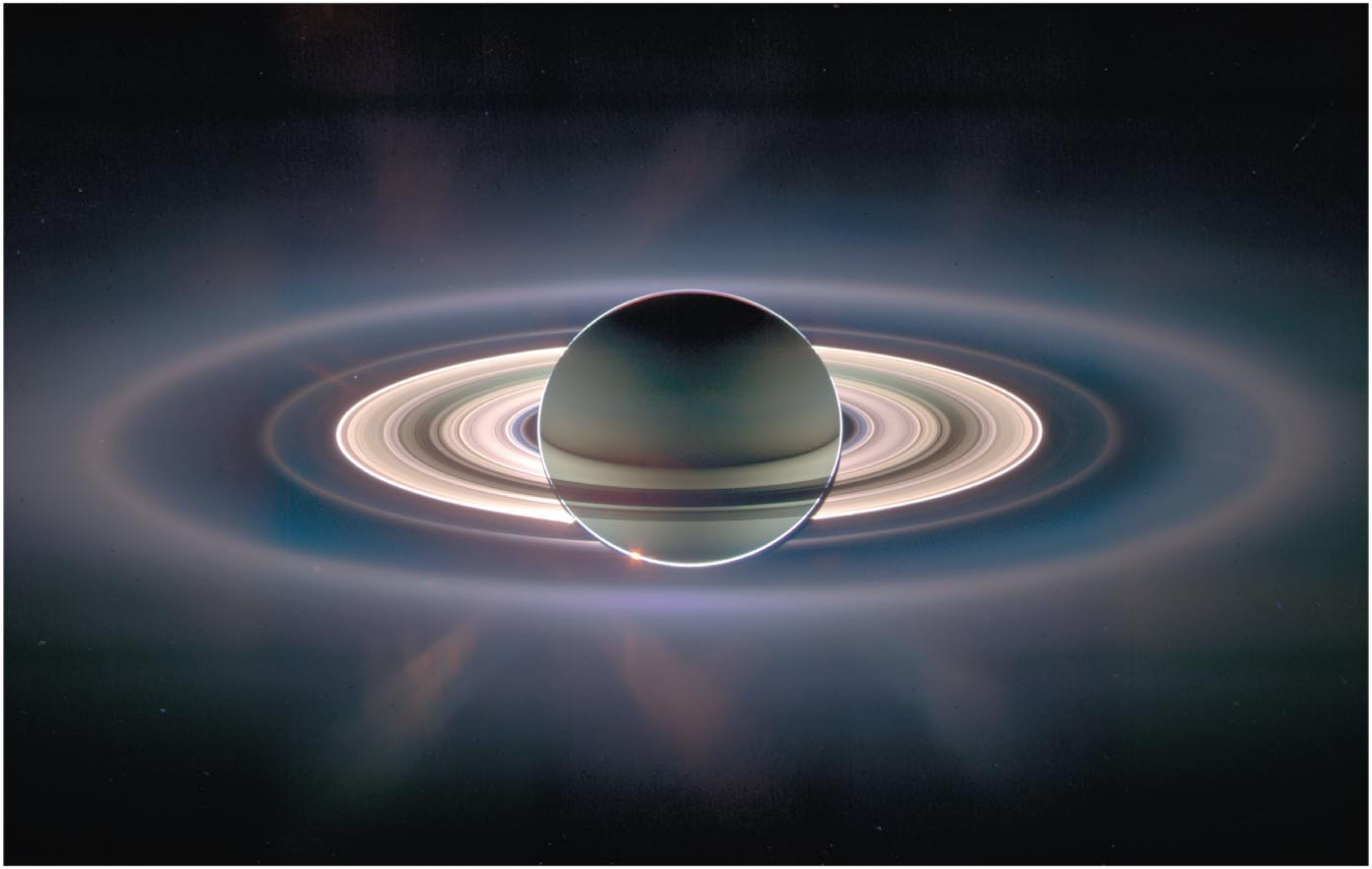
The Cosmic Perspective

Seventh Edition

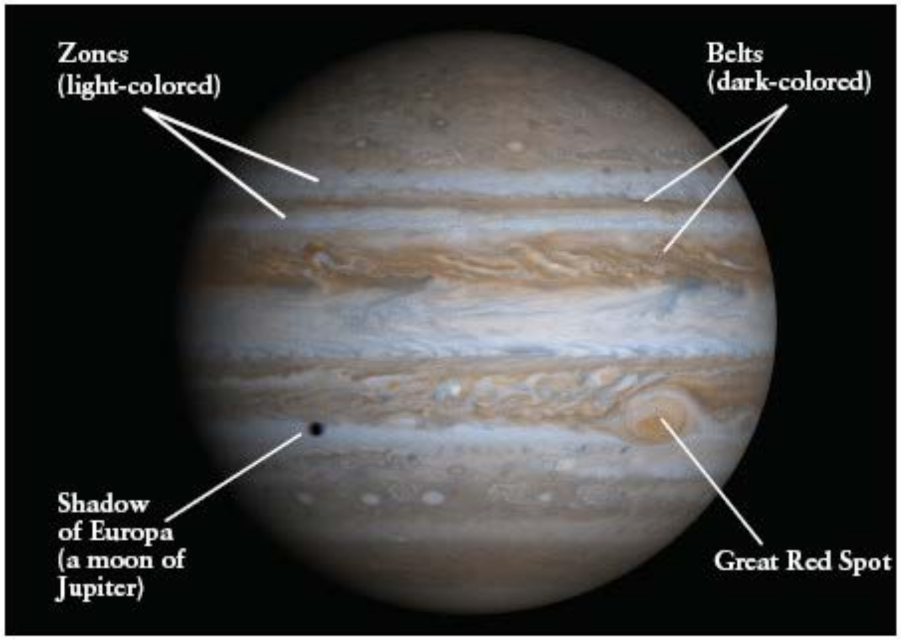


Jovian Planet Systems

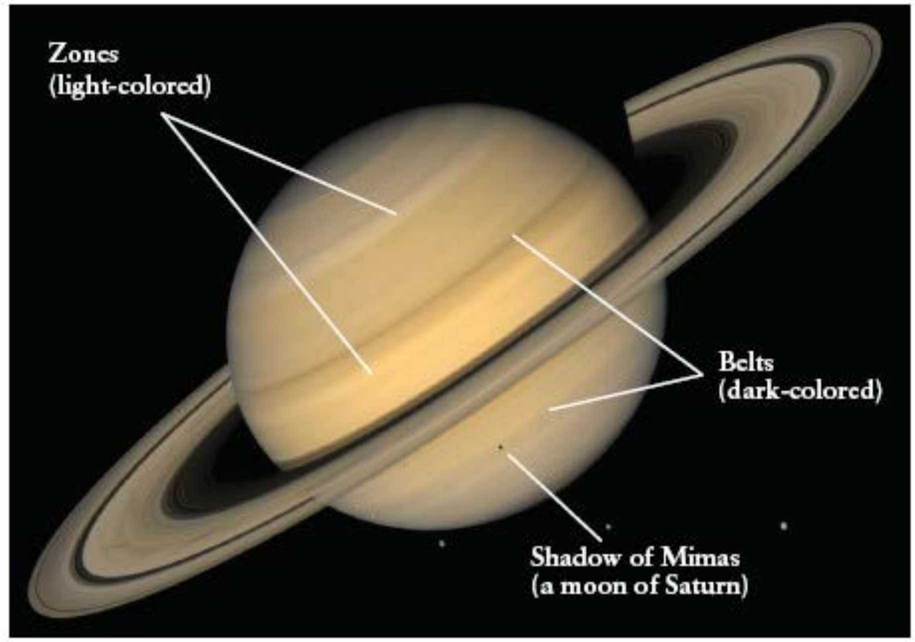
Jovian Planet Systems



Belts and Zones



(a) Jupiter



(b) Saturn

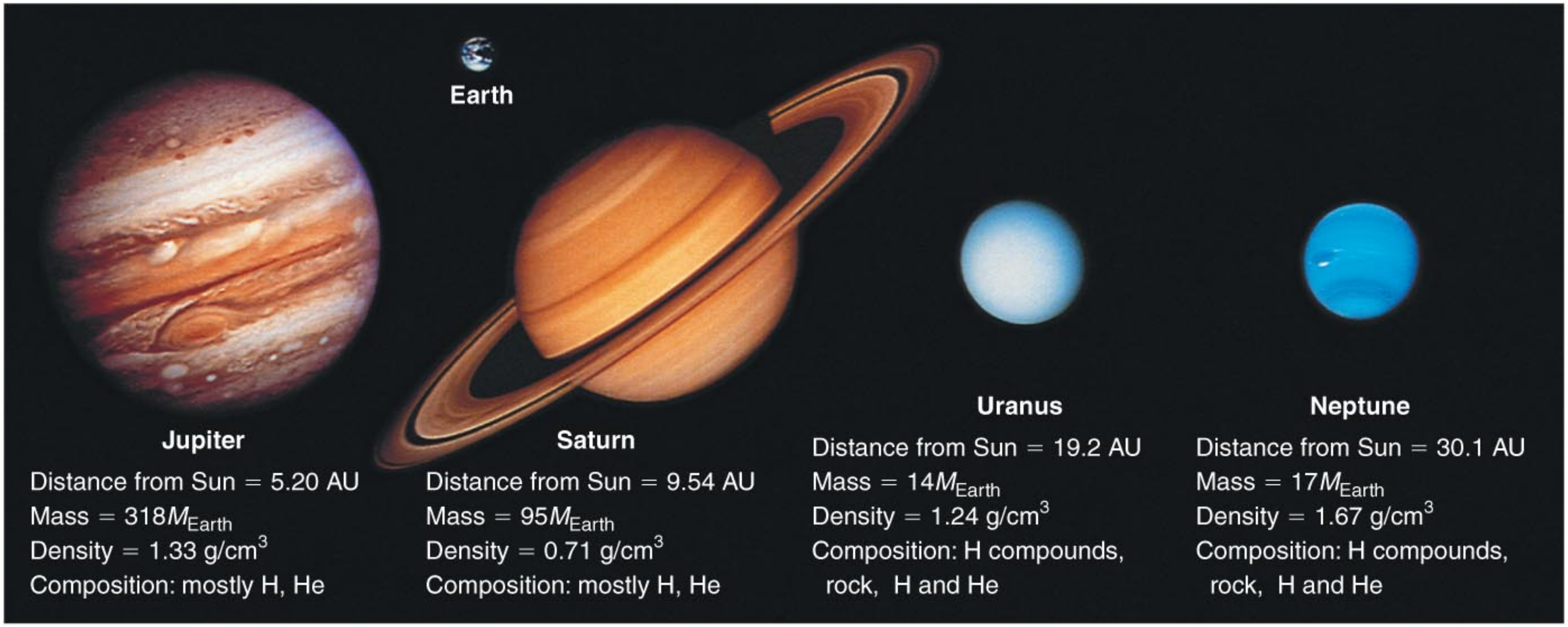
Rapid rotation of these planets stretch weather systems into colorful bands **(belts and zones)**.

The rings of Saturn are made of icy fragments that have a high reflectivity. The rings of Jupiter are made of dustlike particles that reflect little light.

11.1 A Different Kind of Planet

- Our goals for learning:
  - **Are jovian planets all alike?**
  - **What are jovian planets like on the inside?**
  - **What is the weather like on jovian planets?**
  - **Do jovian planets have magnetospheres like Earth's?**

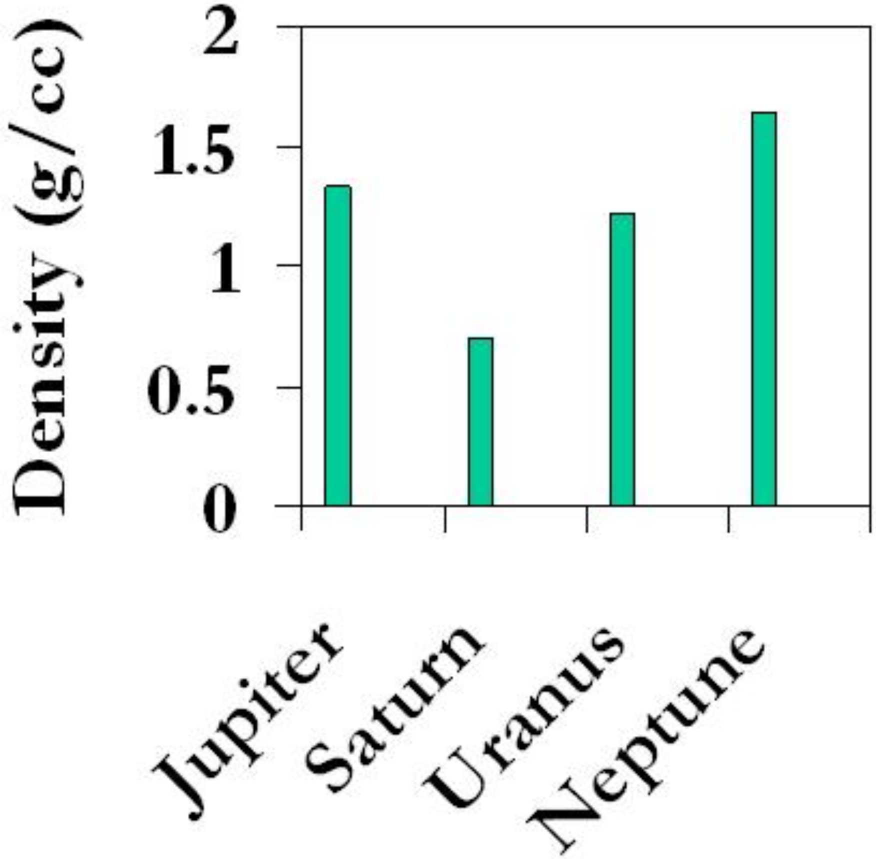
Are jovian planets all alike?



Jovian Planet Composition

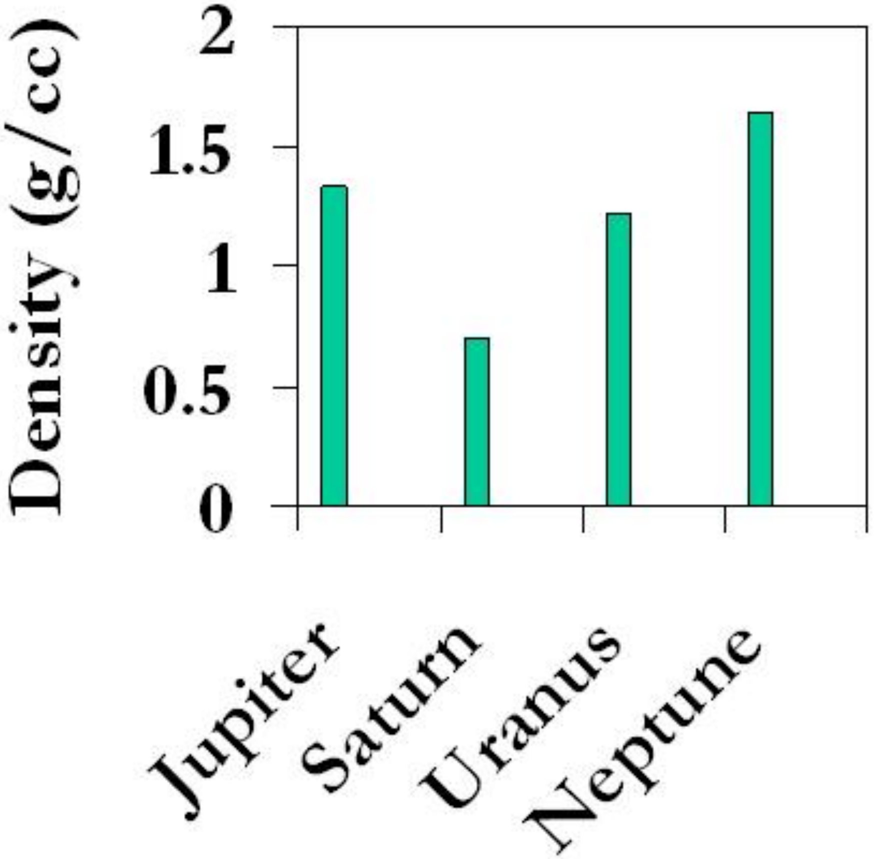
- Jupiter and Saturn
  - Mostly H and He gas (plus core of rocks metals and hydrogen compounds)
- Uranus and Neptune
  - Mostly hydrogen compounds: water (H_2O), methane (CH_4), ammonia (NH_3)
  - Some H, He, and rock

Density Differences



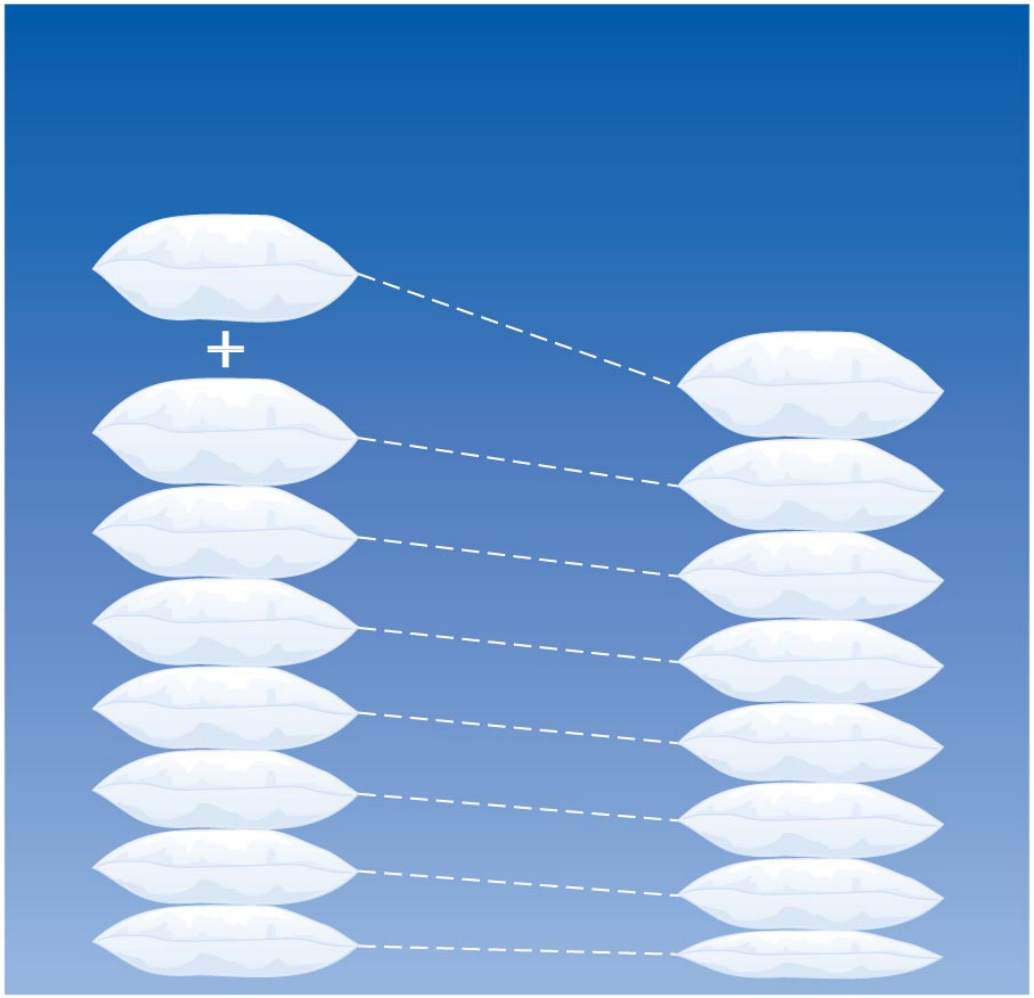
- Uranus and Neptune are denser than Saturn because they have less H/He, proportionately.

Density Differences



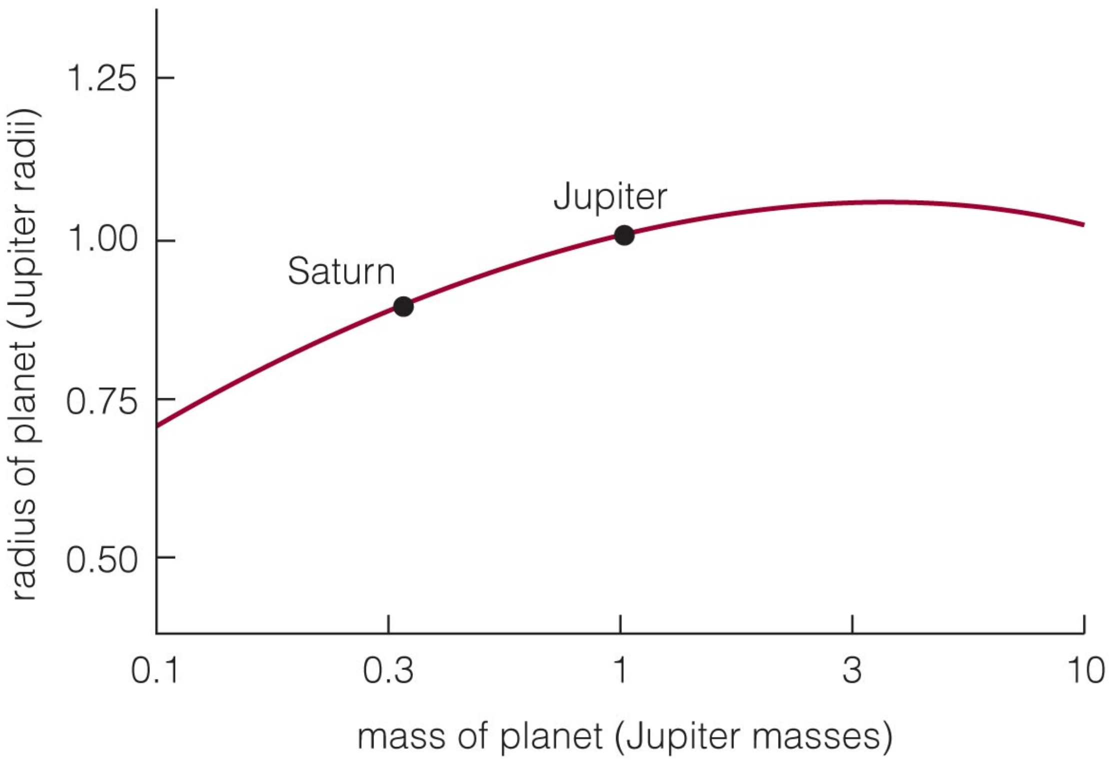
- But that explanation doesn't work for Jupiter….

Sizes of Jovian Planets



- Question: Why is Jupiter more dense than Saturn even though their abundances by mass of H and He are similar?
- Answer: Since Jupiter is significantly more massive than Saturn one expects greater compression (larger pressure) of the hydrogen and helium within Jupiter resulting in Jupiter having a larger density than Saturn.

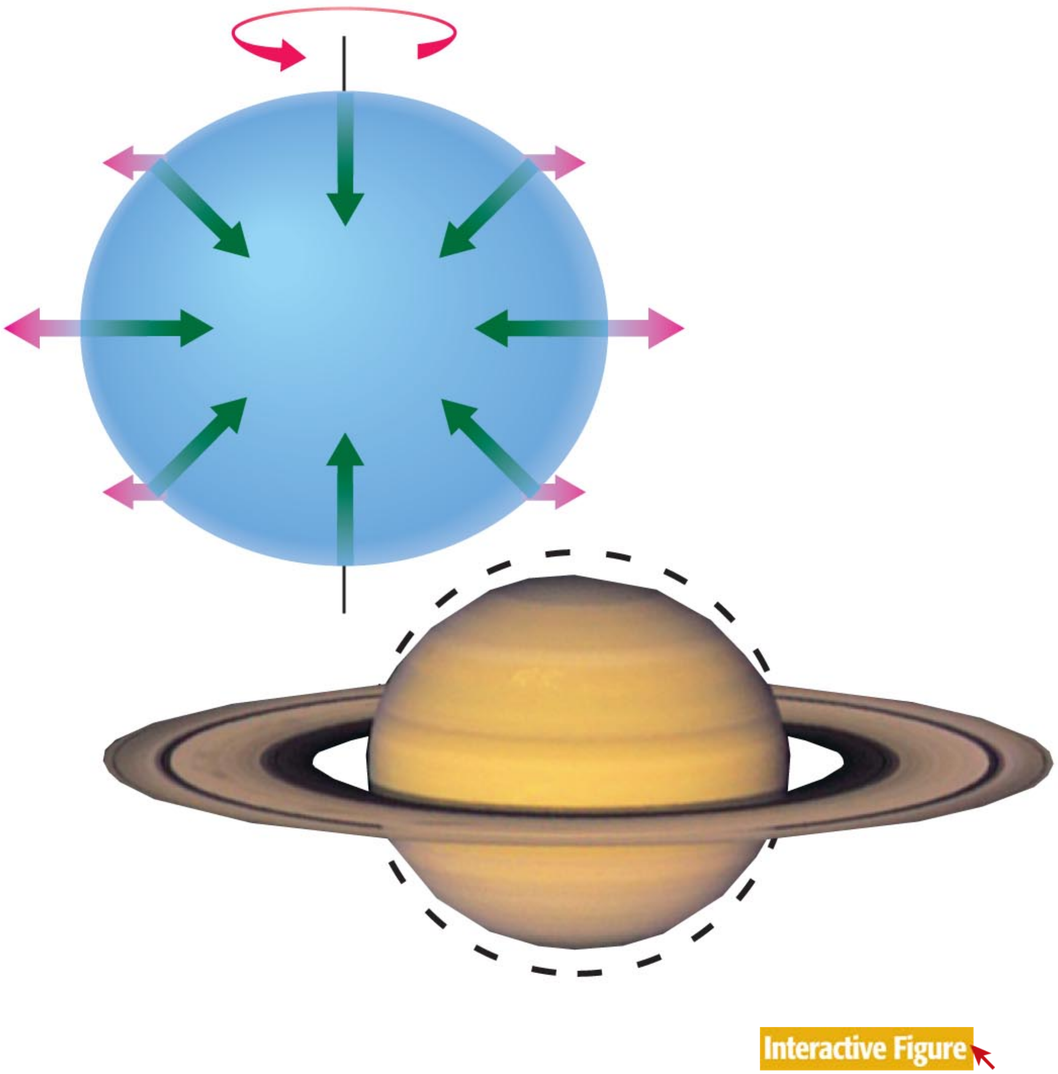
Sizes of Jovian Planets



- Greater compression is why Jupiter is not much larger than Saturn even though it is three times more massive.

- Jovian planets with even more mass can be smaller than Jupiter.

Rotation and Shape

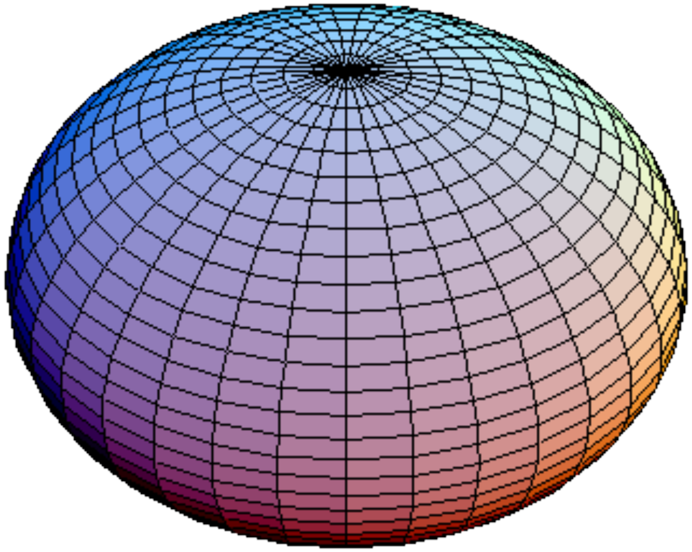


- Jovian planets are not quite spherical because of their rapid rotation.

Oblateness of Jupiter and Saturn

Flattening or oblateness *f* is defined as:

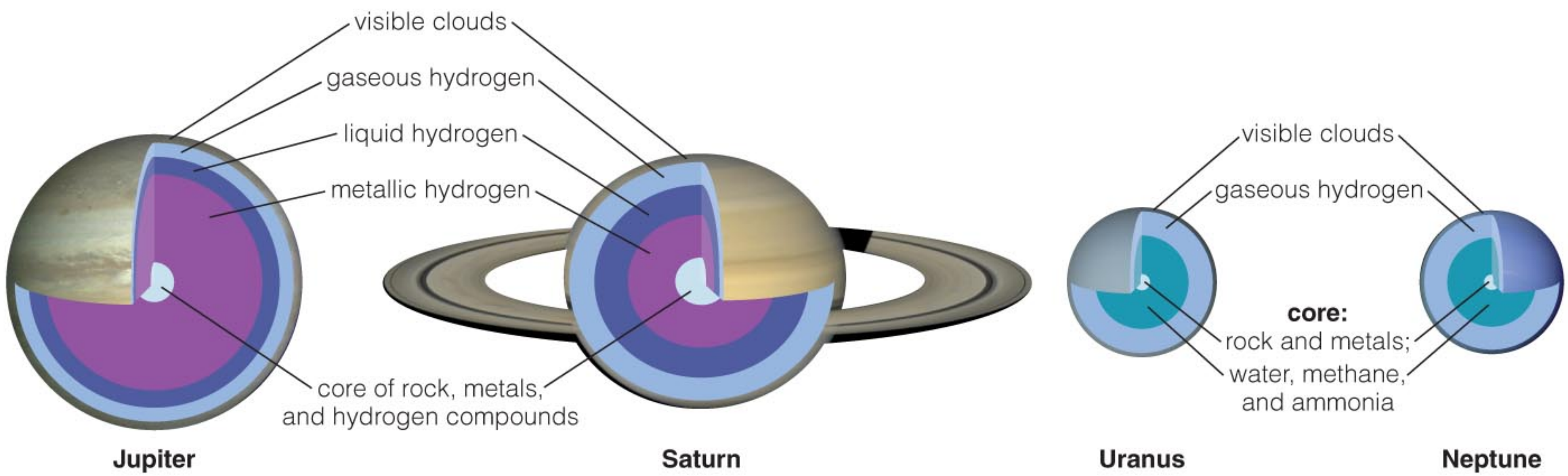
$$f = \frac{D_E - D_P}{D_E}$$



Where:
D_E = diameter across equator
D_P = diameter from pole to pole

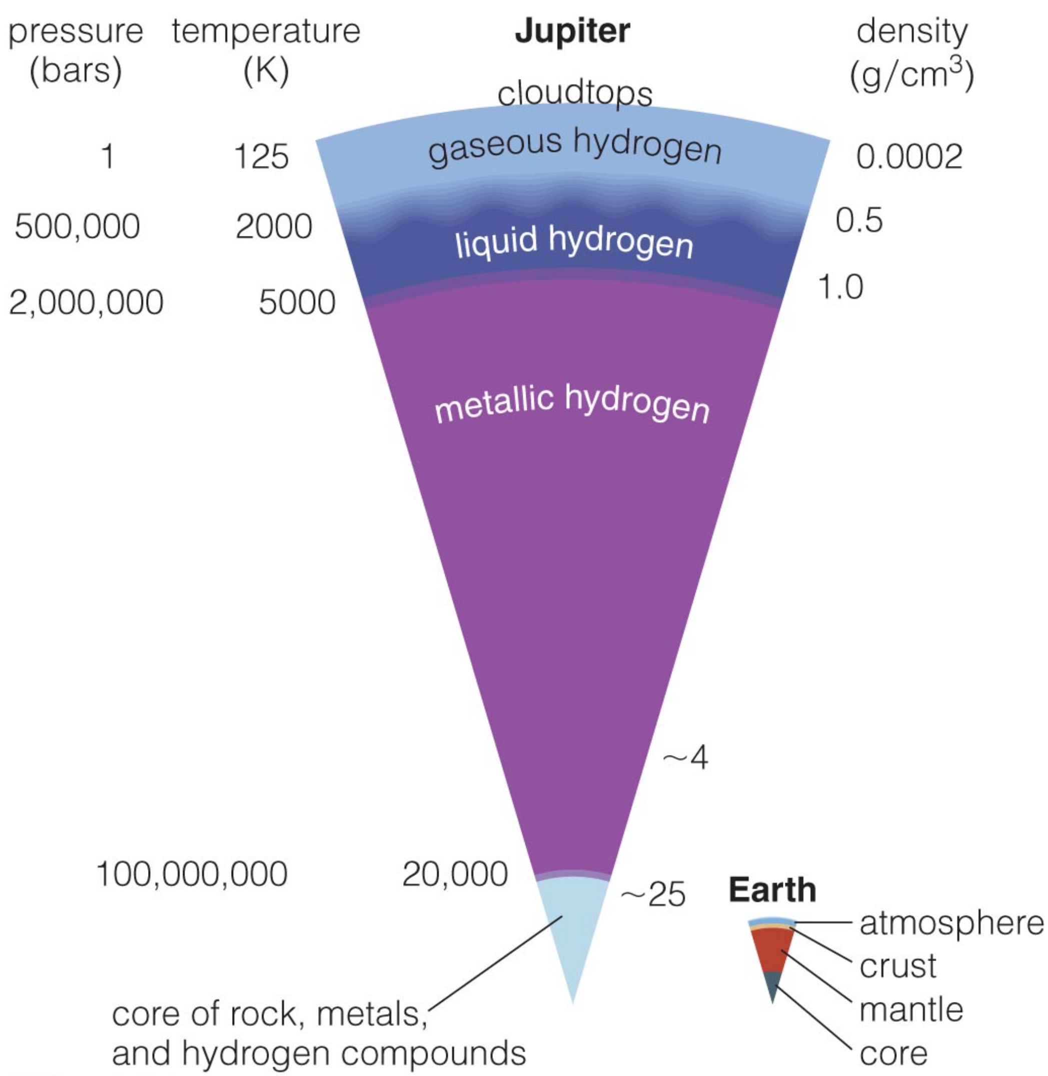
Jupiter's oblateness = 6.5%
Saturn's oblateness = 9.8%
Earth's oblateness = 0.34%

What are jovian planets like on the inside?



- No solid surface
- Layers under high pressure and temperatures
- Cores (~10 Earth masses) made of hydrogen compounds, metals, and rock
- The layers are different for the different planets. WHY?

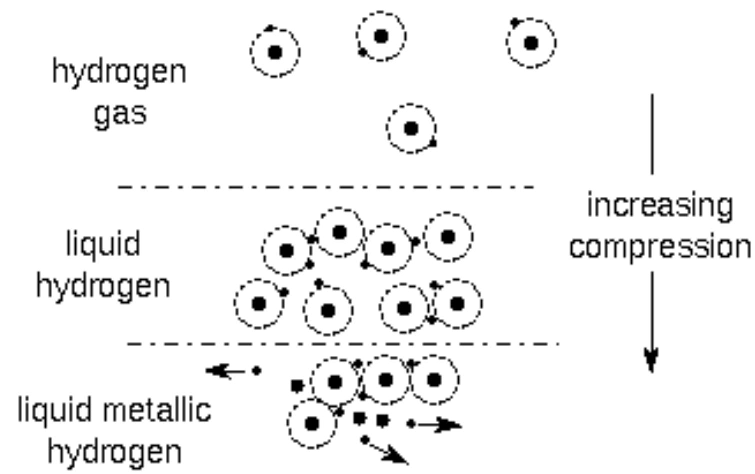
Inside Jupiter



- High pressures inside Jupiter cause phase of hydrogen to change with depth.
- Hydrogen acts like a metal at great depths because its electrons move freely.

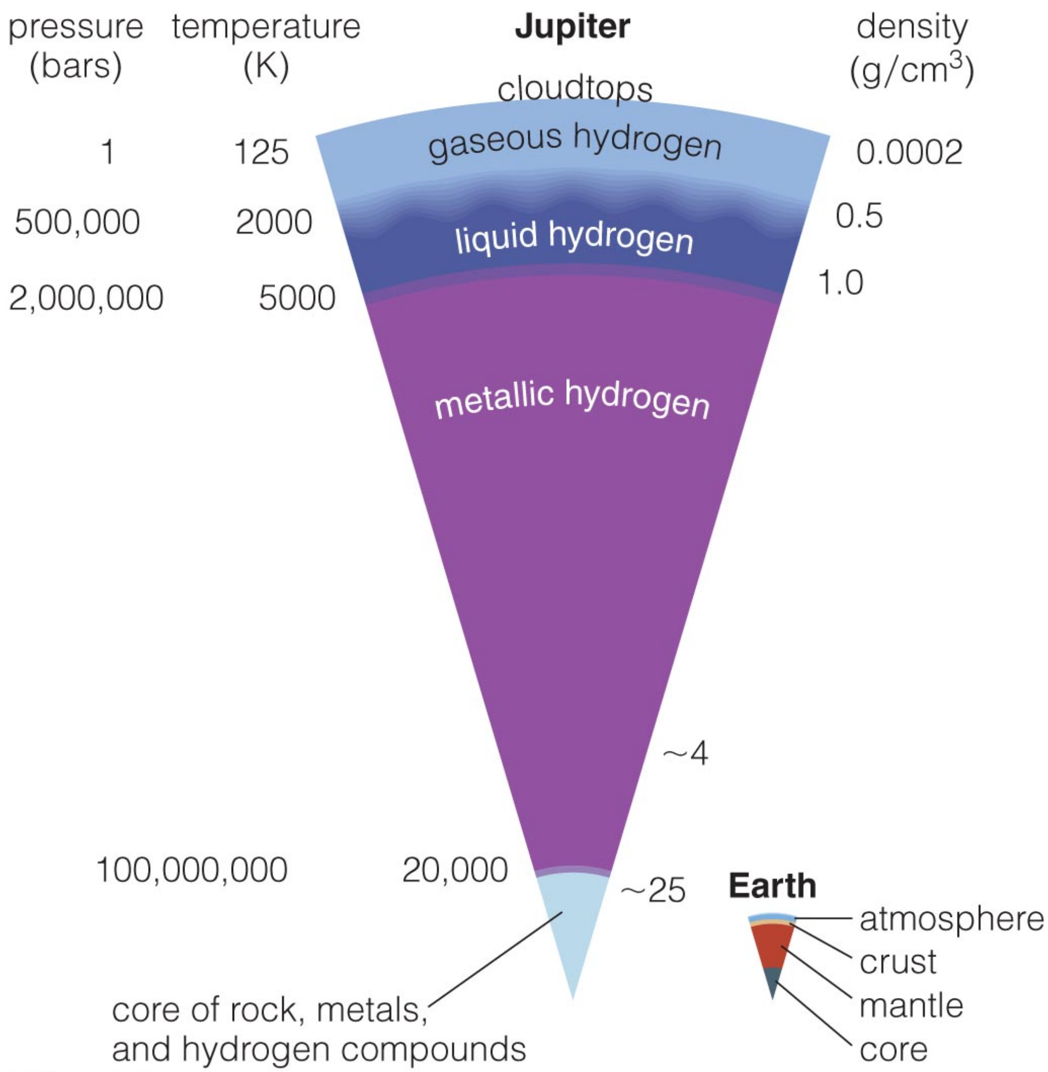
Inside Jupiter: Liquid Metallic Hydrogen

Laboratory experiments show that hydrogen becomes a liquid metal when the pressure is more than about 1.4 million times ordinary atmospheric pressure on Earth. Recent calculations suggest that this transition occurs about 7000 km below Jupiter's cloudtops.



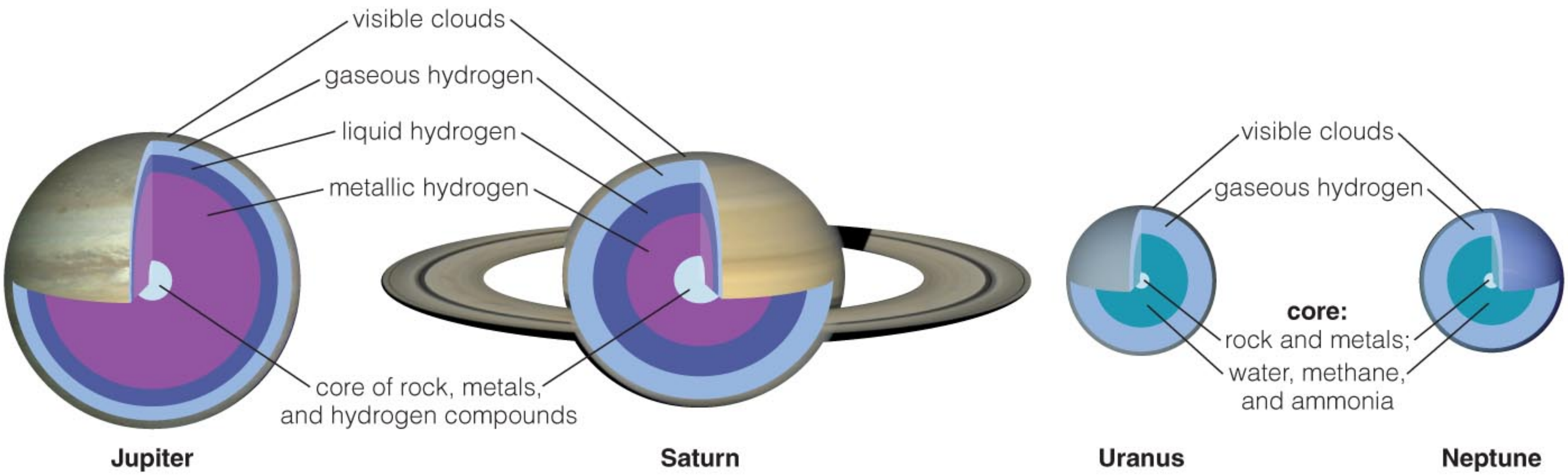
In Jupiter and Saturn the gravitational compression is great enough to squeeze electrons out of the hydrogen atoms so they move easily in the liquid and conduct electricity—liquid ''metallic'' hydrogen.

Inside Jupiter



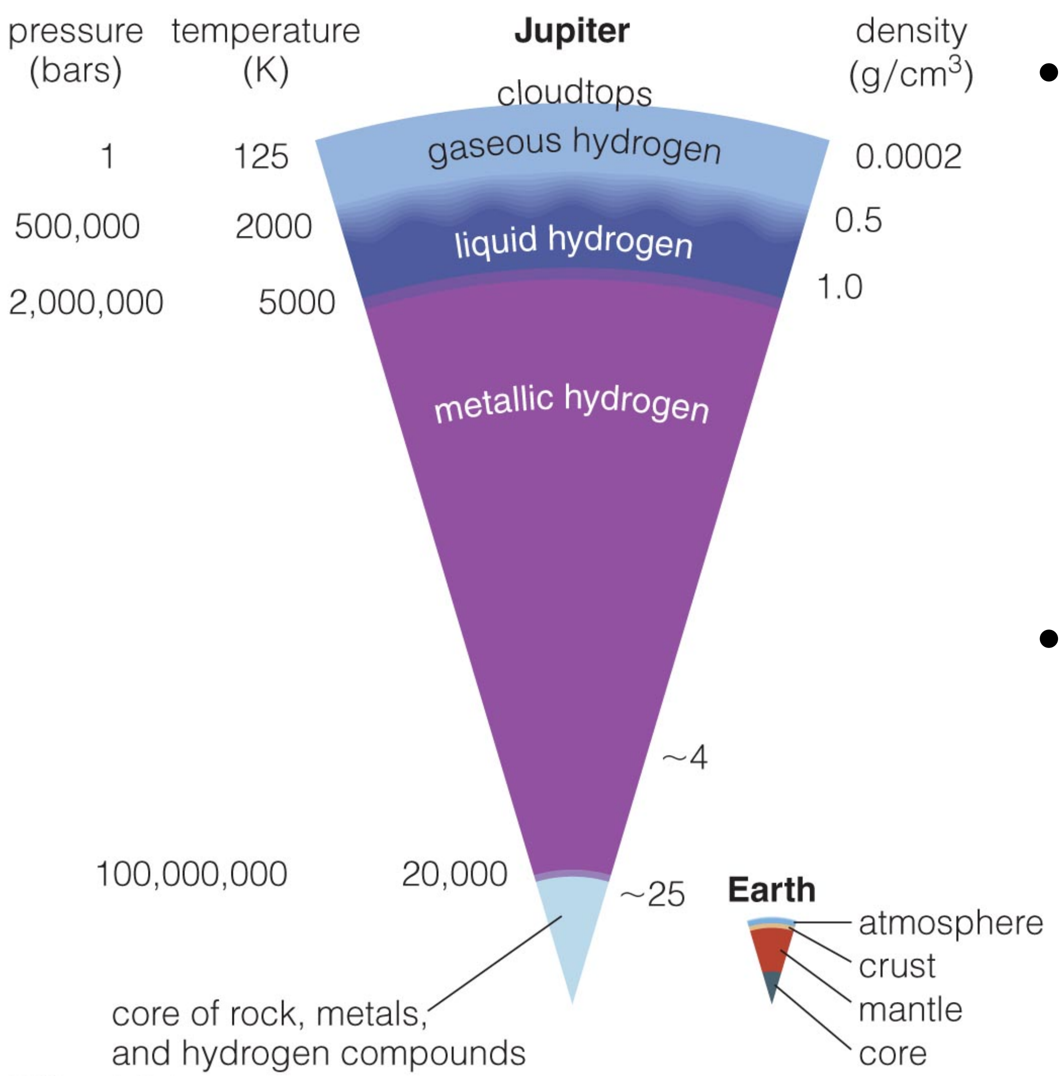
- Core is thought to be made of rock, metals, and hydrogen compounds.
- Core is about same size as Earth but 10 times as massive.

Comparing Jovian Interiors



- Models suggest cores of jovian planets have similar composition.
- Lower pressures inside Uranus and Neptune mean no metallic hydrogen.

Jupiter's Internal Heat

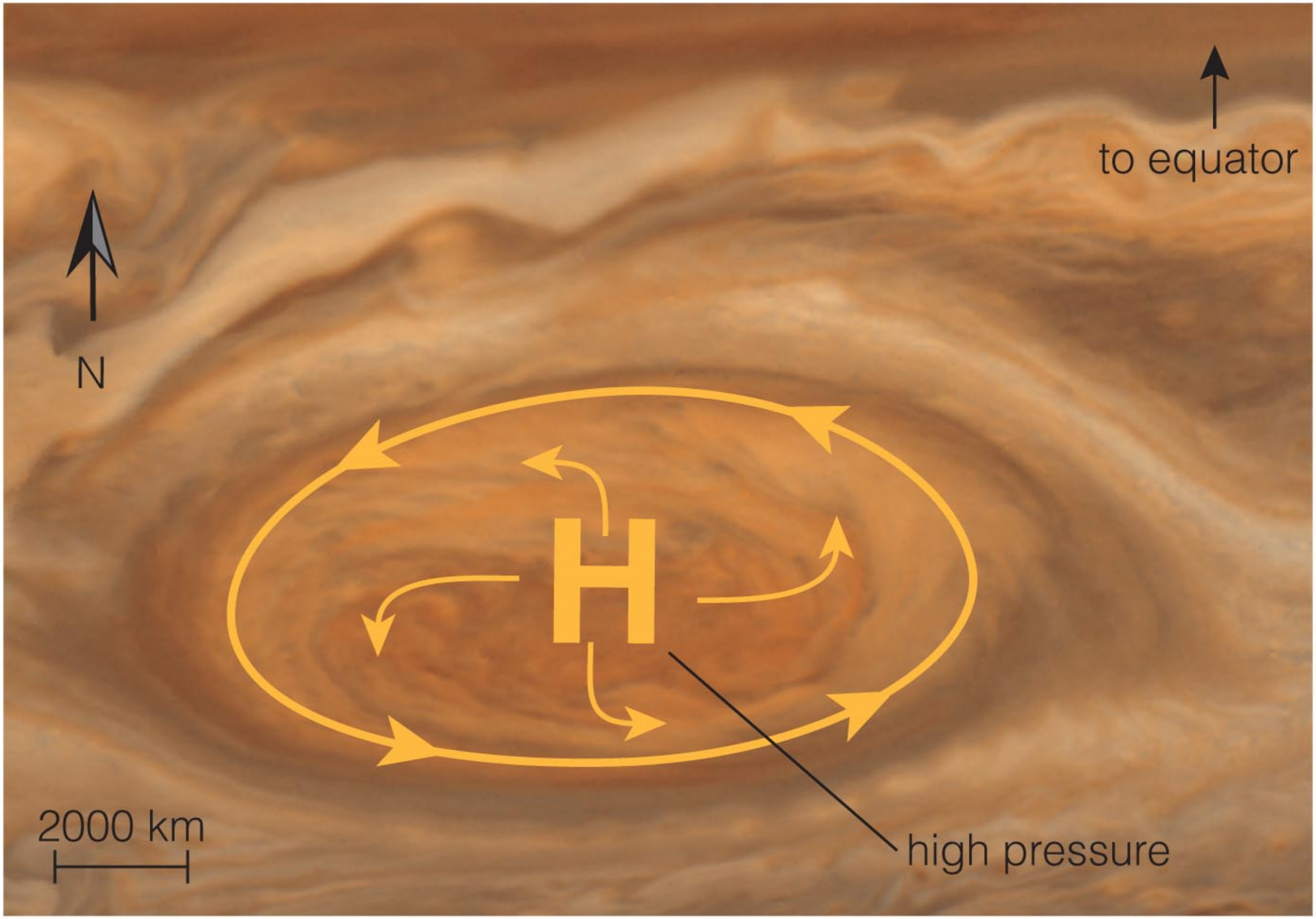


- Jupiter radiates twice as much energy as it receives from the Sun.
- Energy probably comes from slow contraction of interior (releasing potential energy).

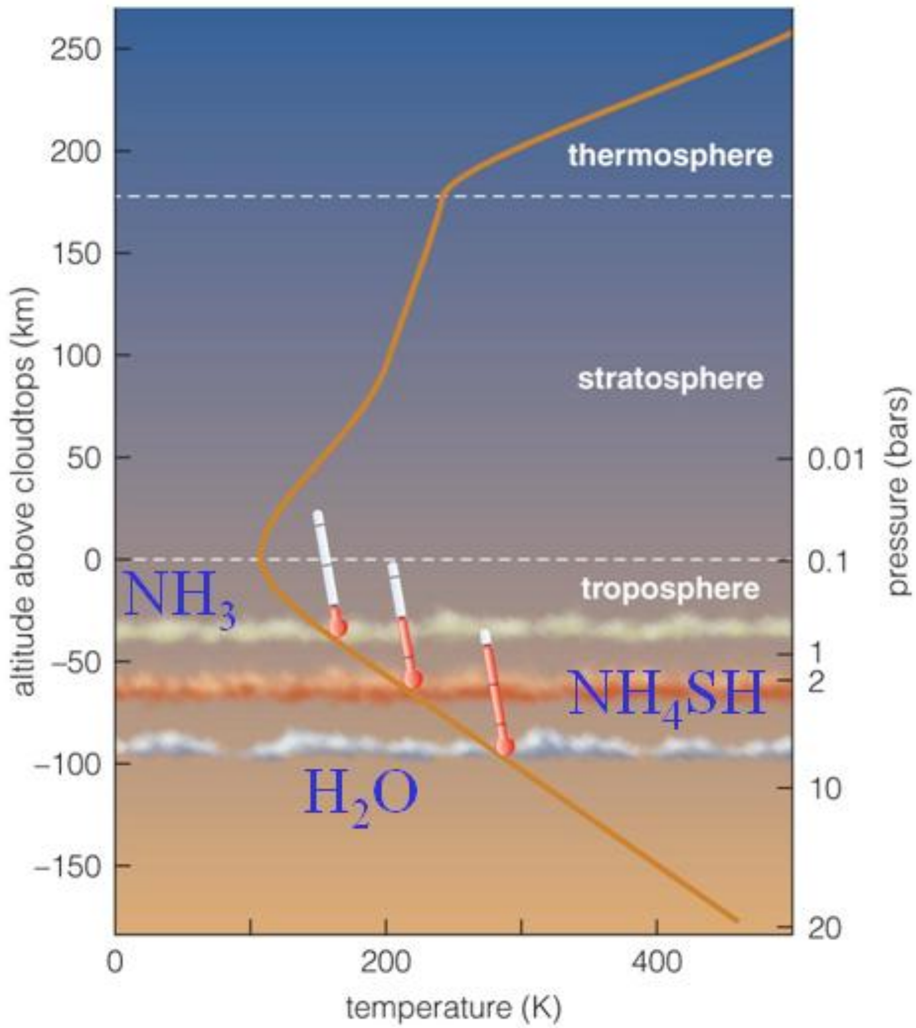
Internal Heat of Other Planets

- Saturn also radiates twice as much energy as it receives from the Sun.
- Energy probably comes from differentiation (helium rain).
- Neptune emits nearly twice as much energy as it receives, but the source of that energy remains mysterious.

What is the weather like on jovian planets?

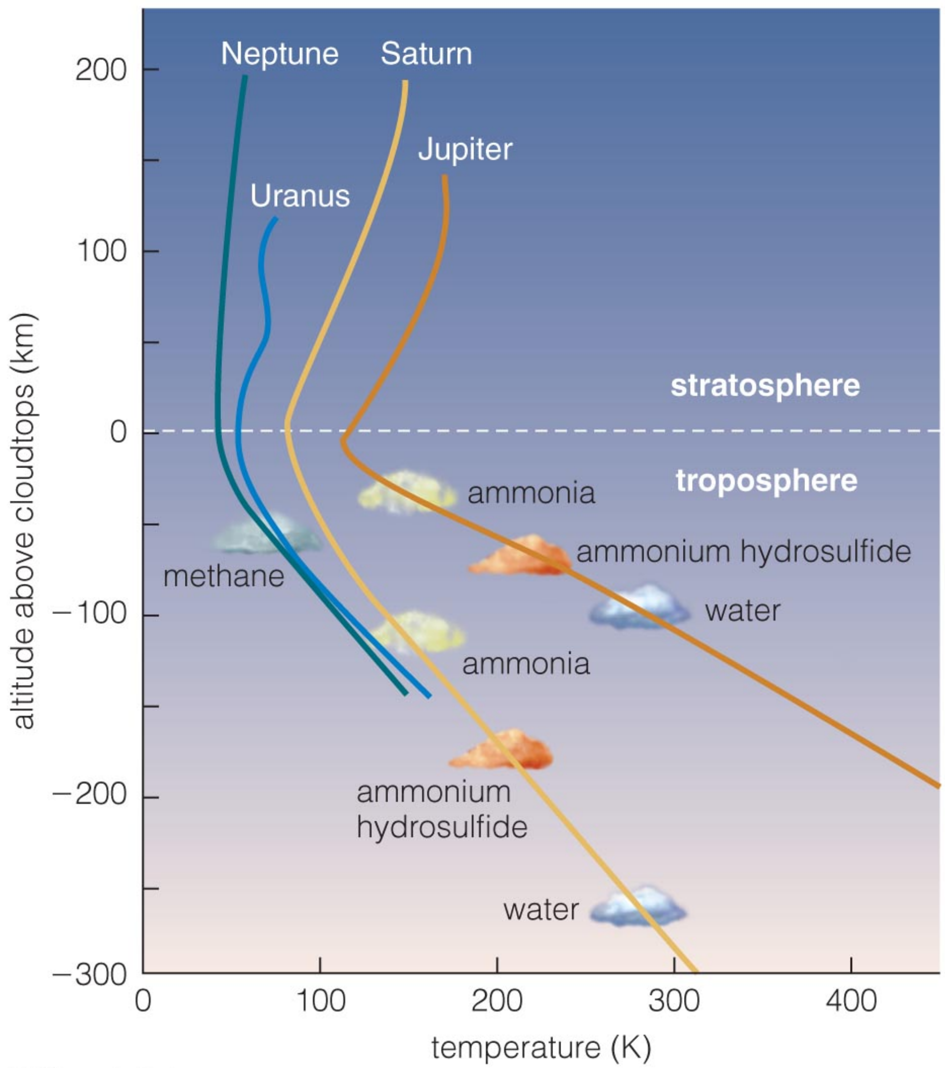


Jupiter's Atmosphere



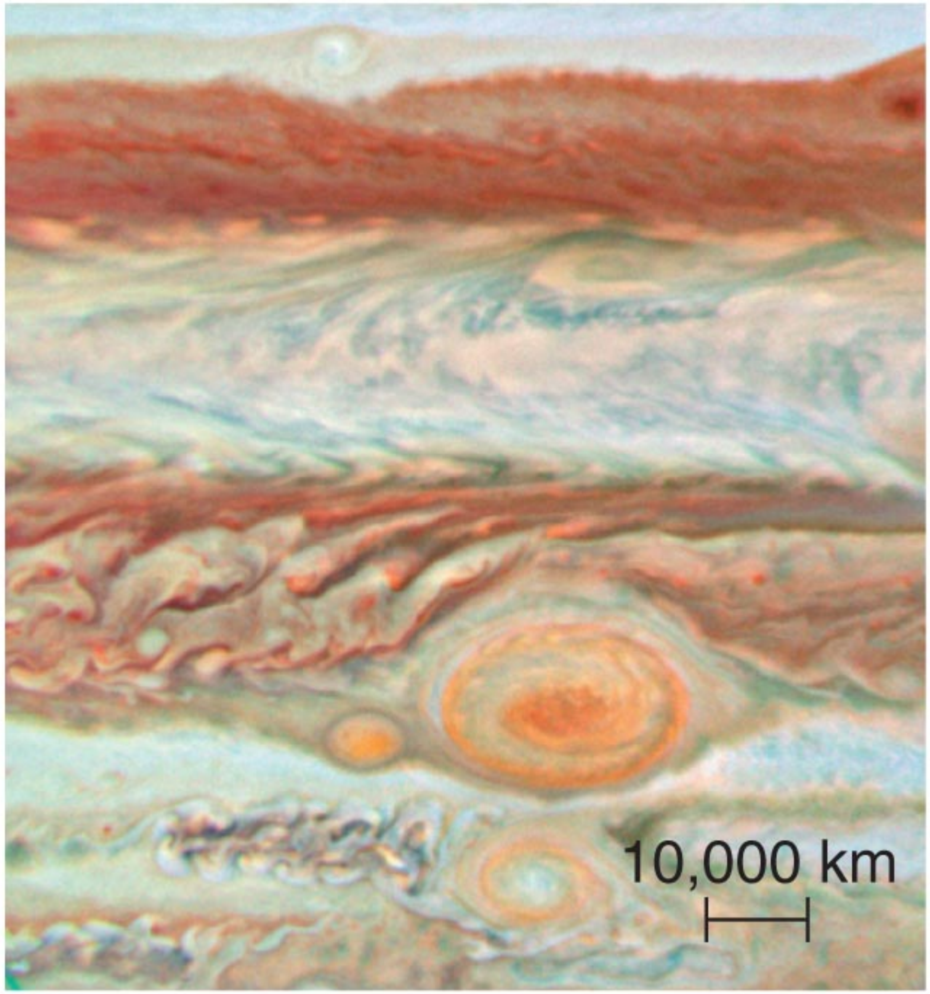
- Ammonia, ammonium hydrosulfide, and water in Jupiter form clouds.
- Different cloud layers correspond to freezing points of different hydrogen compounds.

Jovian Planet Atmospheres



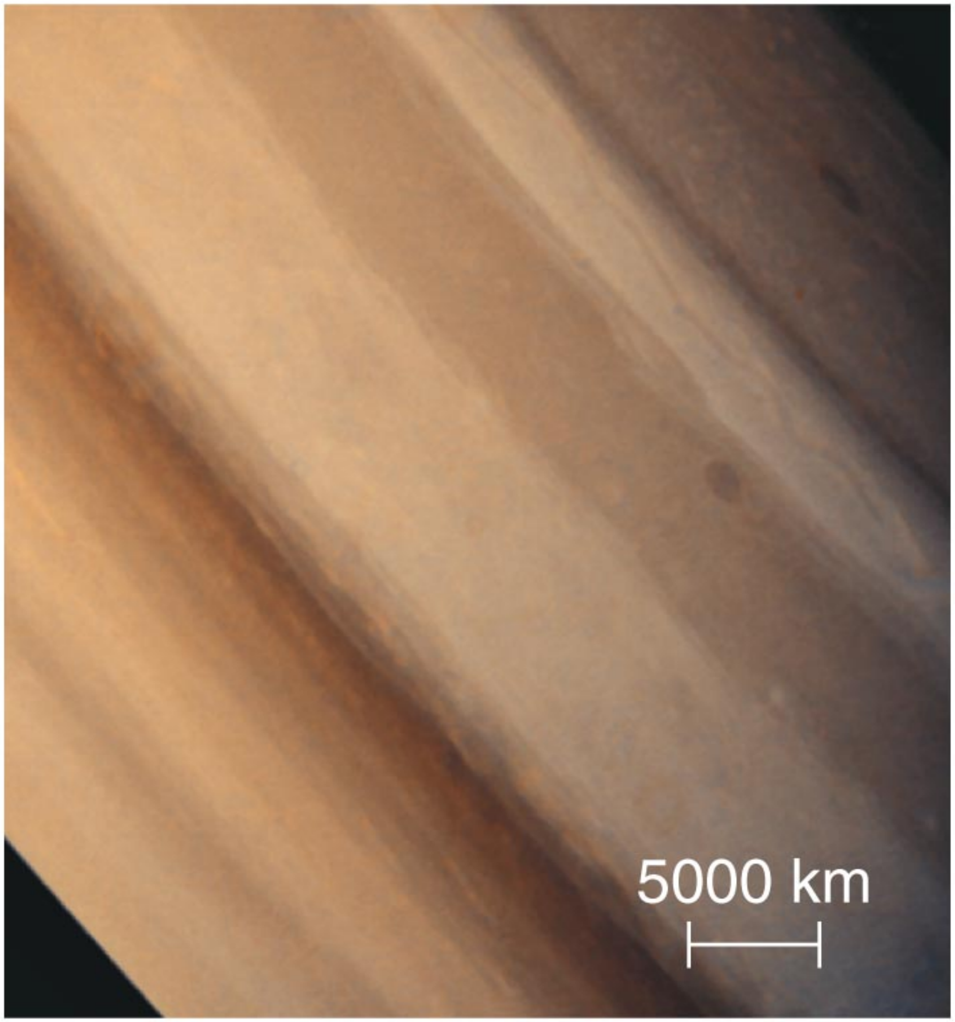
- Other jovian planets have cloud layers similar to Jupiter's.
- Different compounds make clouds of different colors.
- Saturn has weaker surface gravity than Jupiter so its clouds are more spread out.

Jupiter's Colors



- Ammonium sulfide clouds (NH_4SH) reflect red/brown.
- Ammonia, the highest, coldest layer, reflects white.

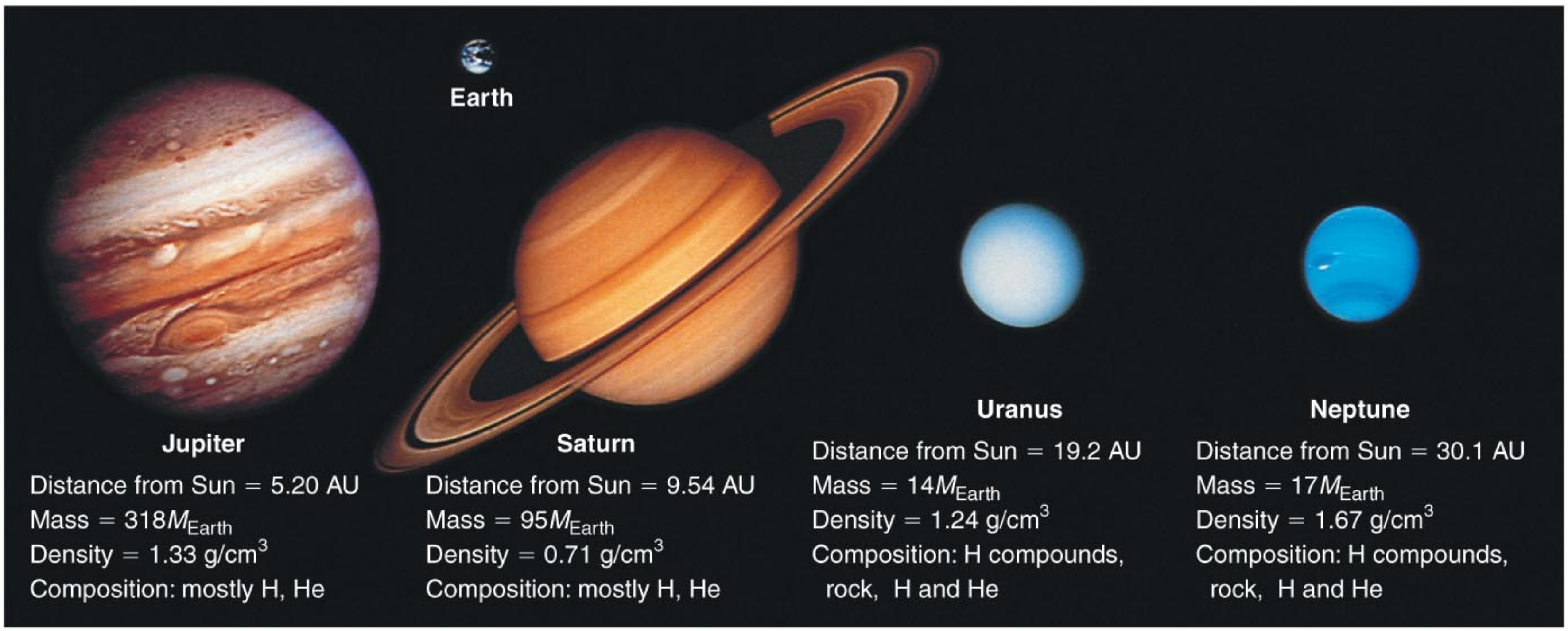
Saturn's Colors



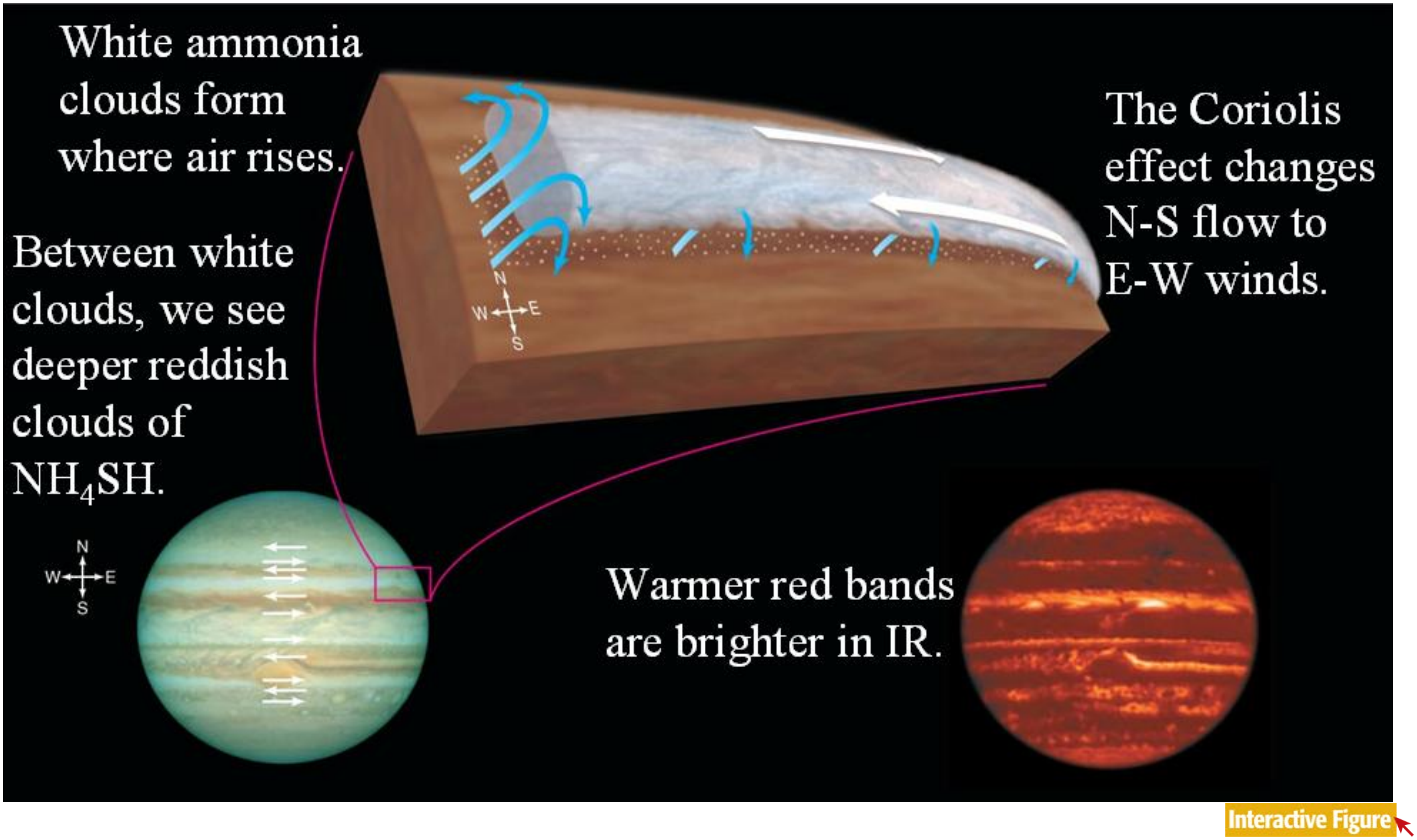
- Saturn's layers are similar, but deeper in and farther from the Sun (more subdued).

Methane on Uranus and Neptune

- Methane gas of Neptune and Uranus absorbs red light but transmits blue light.
- Blue light reflects off methane clouds, making those planes look blue.

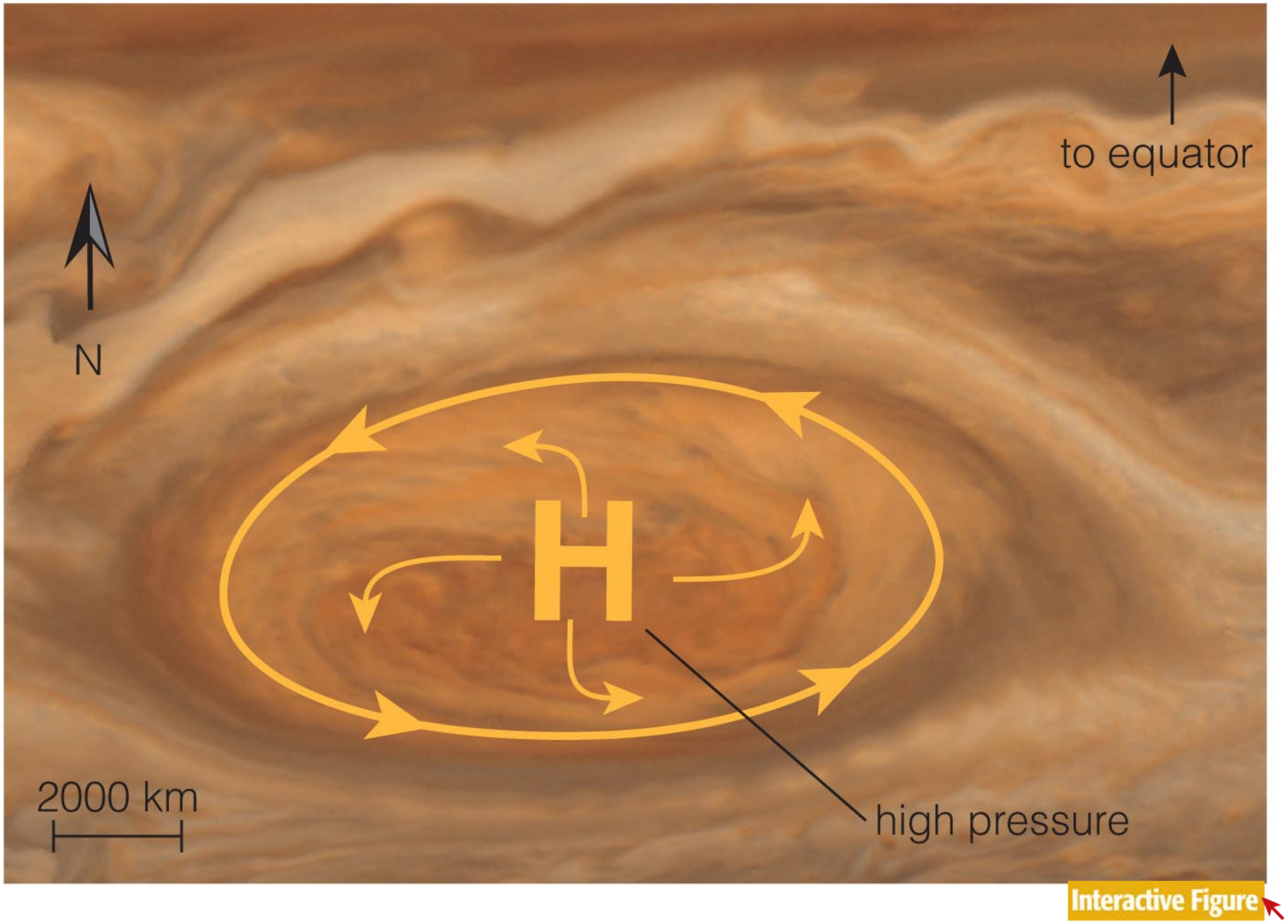


Jupiter's Bands



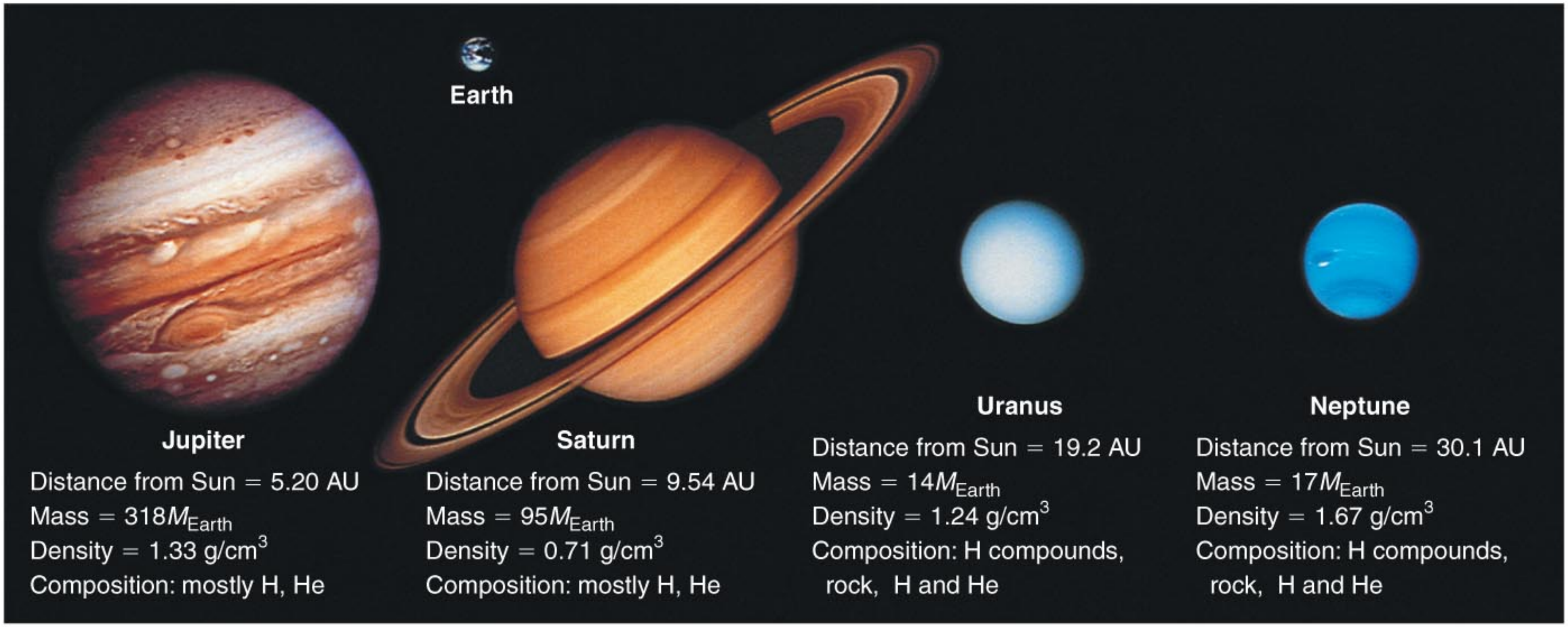
Zones are light-colored (white ammonia) and belts are dark-colored (deeper reddish clouds of NH_4SH)

Jupiter's Great Red Spot



- Is a storm twice as wide as Earth
- Has existed for at least three centuries

Weather on Jovian Planets



- All the jovian planets have strong winds and storms.
- **the winds on these planets are powered by solar energy and internal heat.**

Winds of Jupiter and Saturn

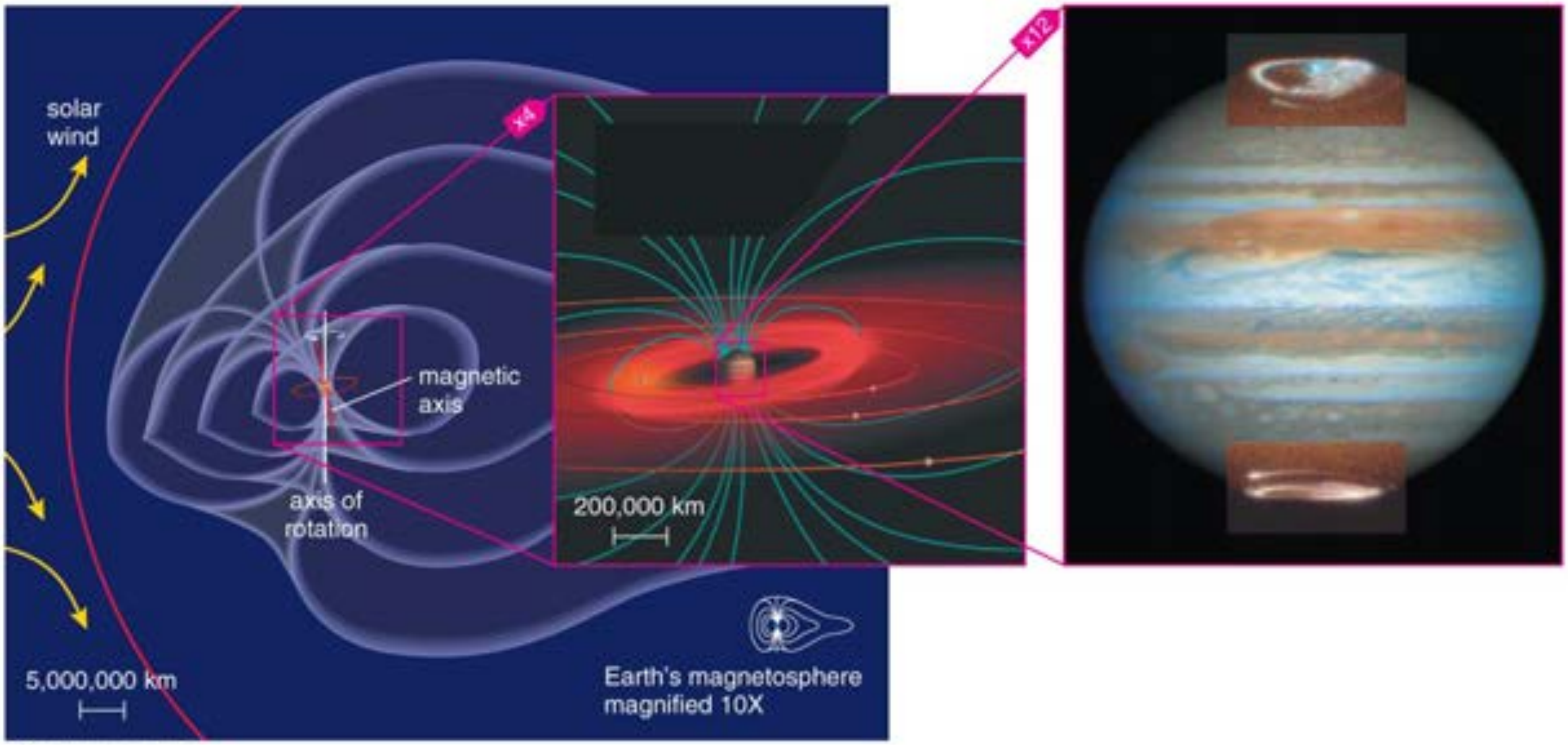
The very rapid rotation of both Jupiter and Saturn create a global pattern of eastward and westward zonal winds.

Within a given zone or belt these winds reverse direction between the northern and southern boundaries.

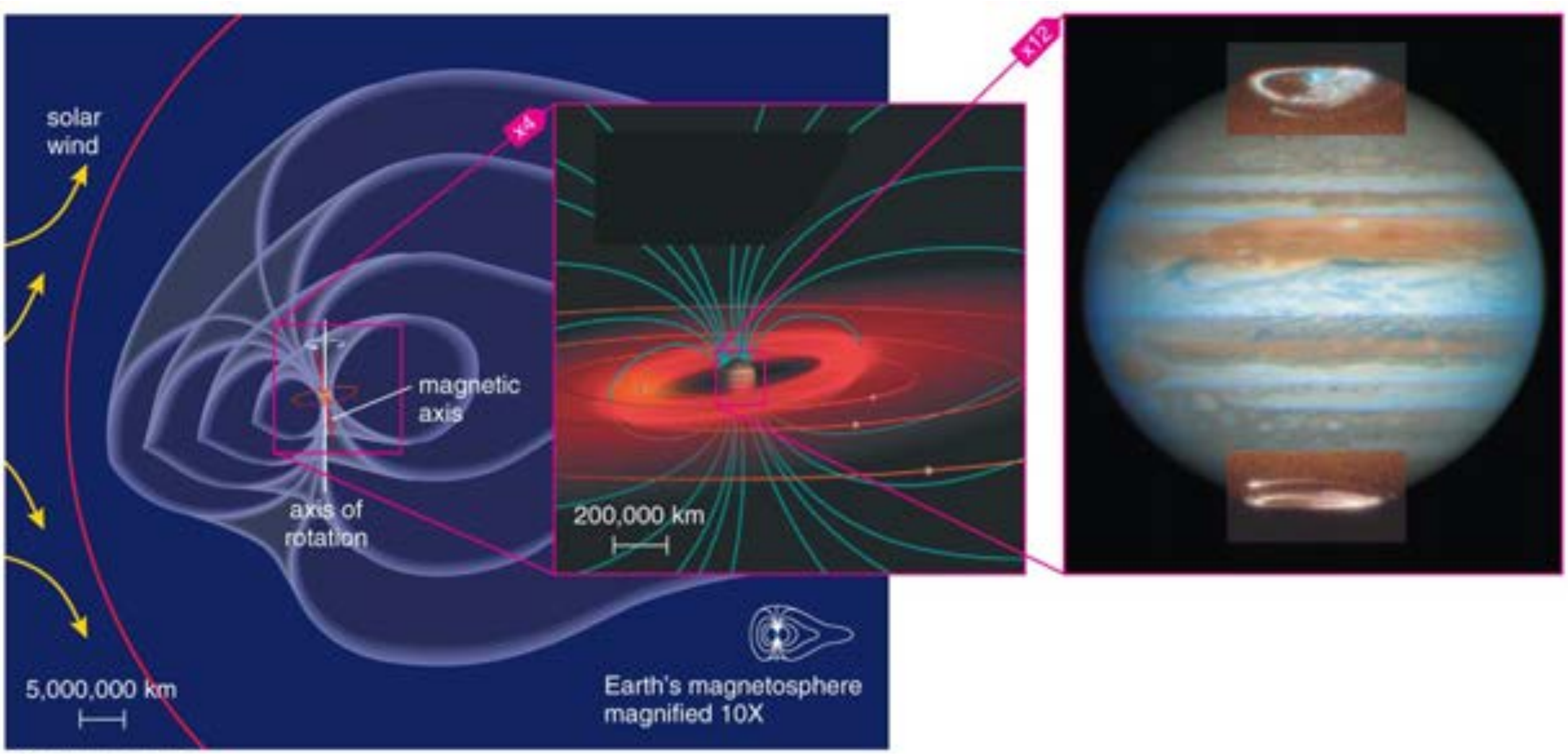
These winds can reach speeds of up to 500 km/h on Jupiter.

Saturn has surprisingly faster winds with speeds as fast as 1,800 km/h.

Do jovian planets have magnetospheres like Earth's?

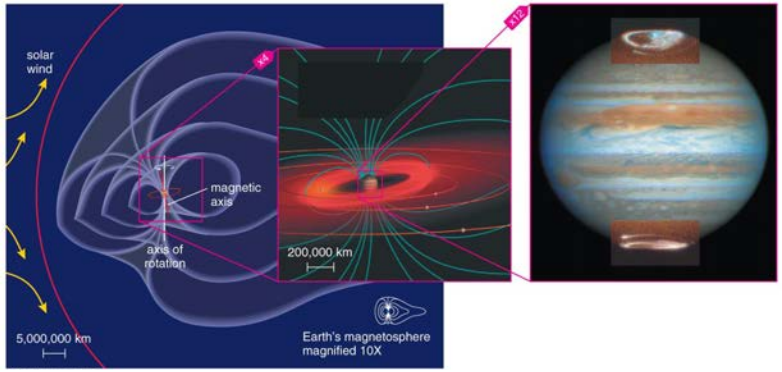


Jupiter's Magnetosphere



- Jupiter's strong magnetic field gives it an enormous magnetosphere.
- Gases escaping Io feed the donut-shaped Io torus.

Jupiter's Magnetosphere



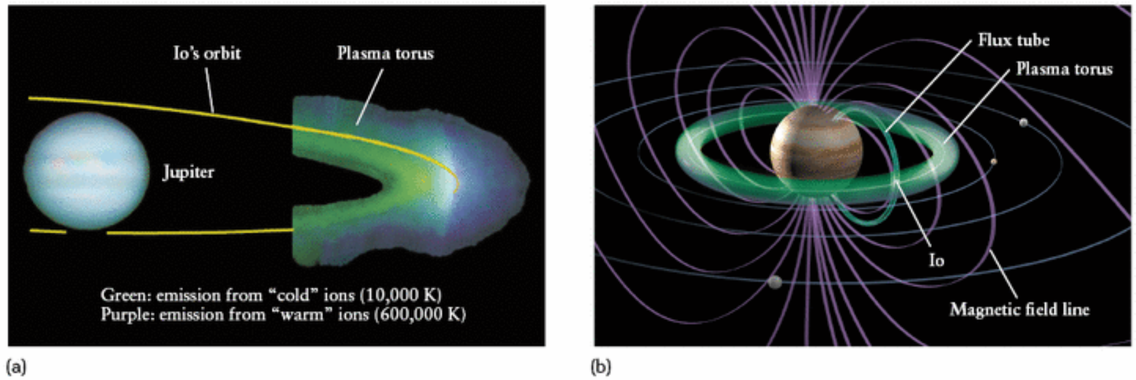
The bulk of Jupiter's magnetic field is produced by the circulation of a **liquid metallic hydrogen in its outer core**.

Hydrogen becomes a liquid metal only when the pressure exceeds about **1.4 million atmospheres**. This occurs at depths larger than 7000 km below Jupiter’s cloud-tops.

Jupiter’s rapid rotation sets the liquid metallic hydrogen into motion, giving rise to an **intense magnetic field**.

Jupiter's magnetosphere is filled with a **plasma made up of electrons, protons, and ions of He, S and O** (partly originating from its moon Io).

Jupiter's Magnetosphere



Io feeds Jupiter's magnetosphere: As Jupiter rotates, ionized gas in it's magnetosphere interacts with particles emitted from Io's volcanoes. Some of these particles get trapped in Jupiter's magnetosphere.

Io's Torus: Some of the material ejected from Io's volcanoes forms a torus (donut-shaped ring) of ionized material tracing the orbit of Io around Jupiter.

Keep Out High Voltage: As Jupiter's magnetic field sweeps by Io it generates a large electric field across it with an estimated voltage of 400,000 volts. This high voltage produces a current through Io of about 5 million amps.

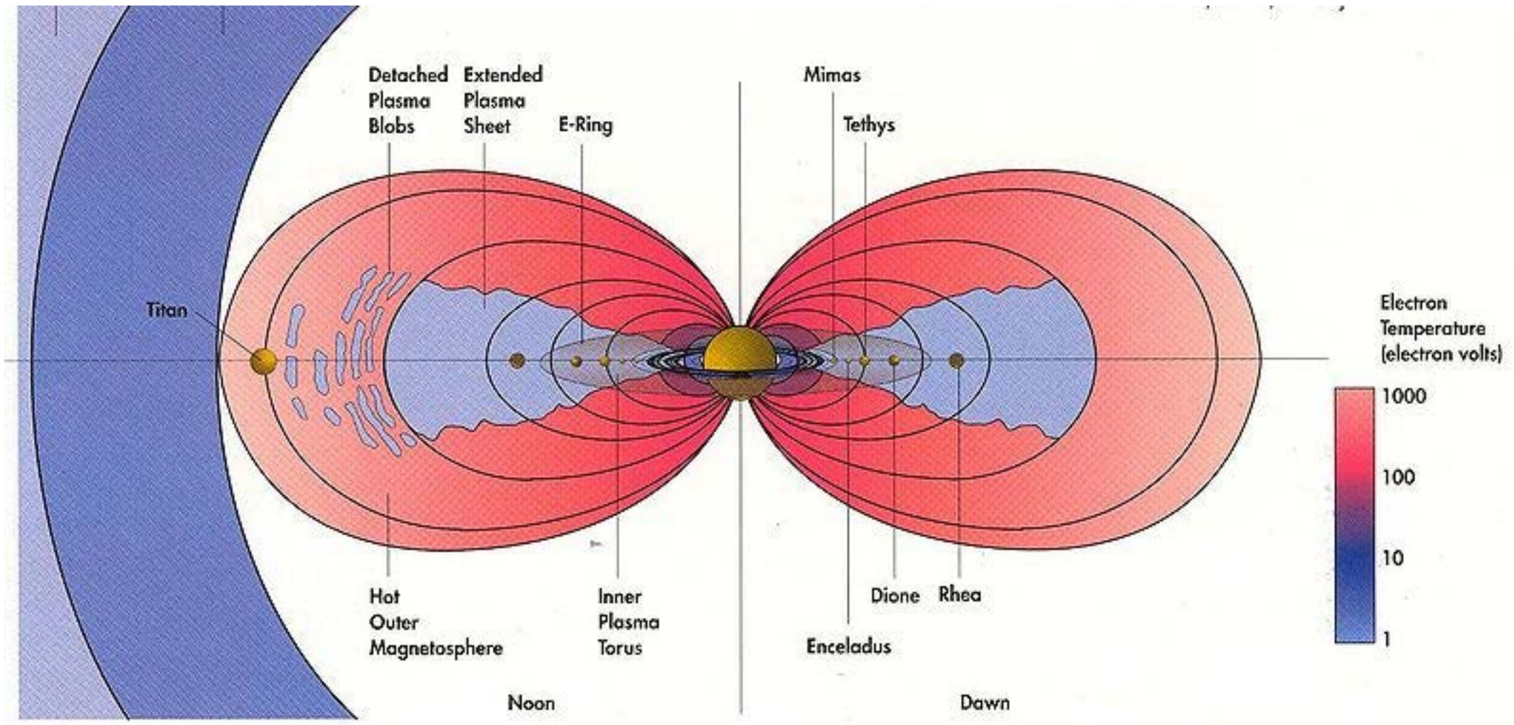
Jupiter's Radio Emission

Source of radio emission in Jupiter:

(1) Sporadic bursts of radio waves at wavelengths of a few meters. This **decametric** (10-meter) radiation are thought to be produced by electrical discharges triggered by electromagnetic interactions between Io and Jupiter.

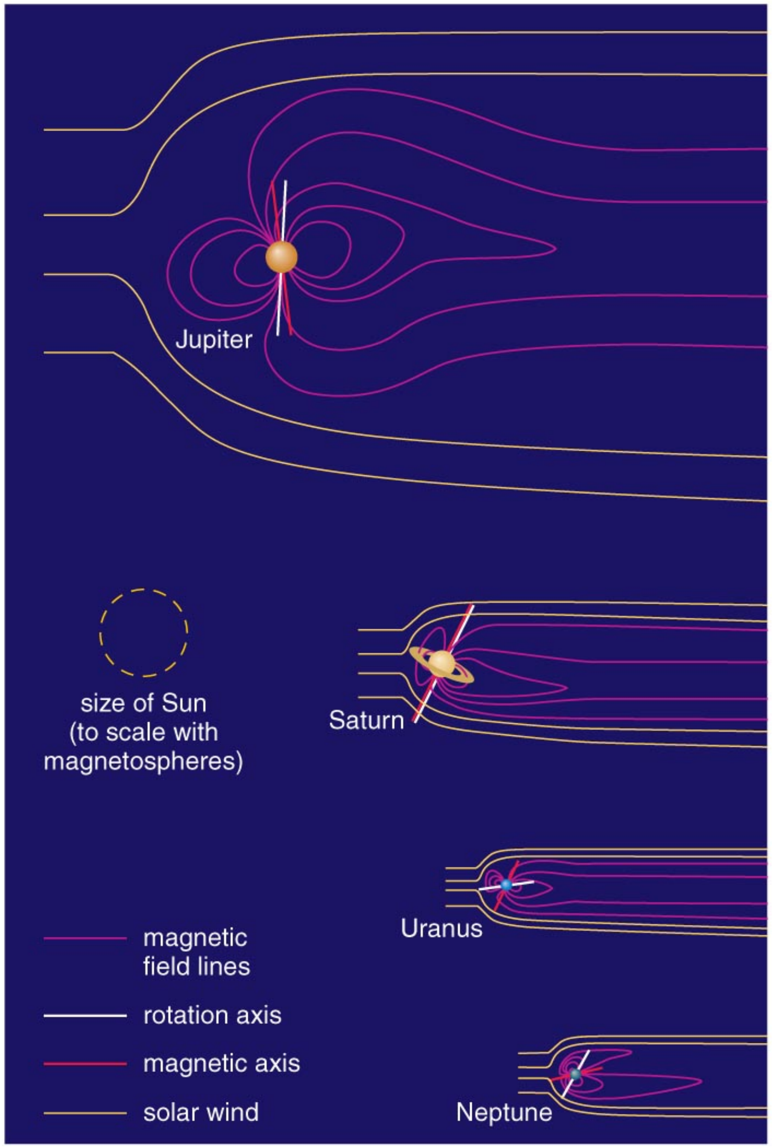
(2) Synchrotron emission at wavelengths of a few tenths of a meter (**decimetric**) produced by electrons spiraling in Jupiter's strong magnetic field.

Saturn's Magnetosphere



Saturn's magnetosphere is filled with plasmas originating from both the planet and its moons. The main source is the small moon Enceladus, which ejects as much as 1,000 kg/s of water vapor from the geysers on its south pole.

Other Magnetospheres



- All jovian planets have substantial magnetospheres, but Jupiter's is the largest by far.
- Saturn rotates nearly as rapidly as Jupiter but has a weaker magnetic field. This implies Saturn has less liquid metallic hydrogen than Jupiter to be stirred up by the rotation and thereby generate a magnetic field.
- This makes sense: Compared to Jupiter, Saturn has less mass, less gravity, and less internal pressure to compress ordinary hydrogen into liquid metallic hydrogen.

Thought Question

Jupiter does *not* have a large metal core like the Earth. How can it have a magnetic field?

a) The magnetic field is left over from when Jupiter accreted.
b) Its magnetic field comes from the Sun.
c) It has metallic hydrogen inside, which circulates and makes a magnetic field.
d) Its core creates a magnetic field, but it is very weak.

Thought Question

Jupiter does *not* have a large metal core like the Earth. How can it have a magnetic field?

a) The magnetic field is left over from when Jupiter accreted.
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c) **It has metallic hydrogen inside, which circulates and makes a magnetic field.**
d) Its core creates a magnetic field, but it is very weak.

What have we learned?

- **Are jovian planets all alike?**
  - Jupiter and Saturn are mostly H and He gas.
  - Uranus and Neptune are mostly H compounds.
- **What are jovian planets like on the inside?**
  - Layered interiors with very high pressure and cores made of rock, metals, and hydrogen compounds
  - Very high pressure in Jupiter and Saturn can produce metallic hydrogen.

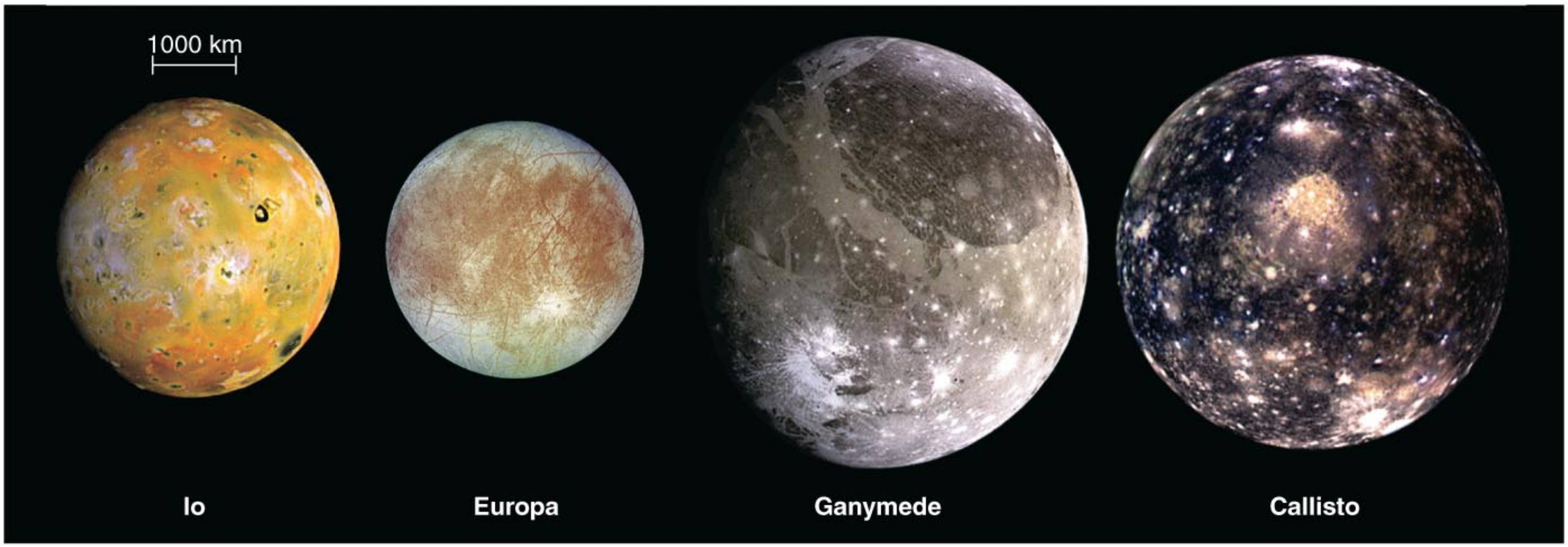
What have we learned?

- **What is the weather like on jovian planets?**
  - Multiple cloud layers determine colors of jovian planets.
  - All have strong storms and winds.
- **Do jovian planets have magnetospheres like Earth's?**
  - All have substantial magnetospheres.
  - Jupiter's is the largest by far.

11.2 A Wealth of Worlds: Satellites of Ice and Rock

- Our goals for learning:
  - **What kinds of moons orbit the jovian planets?**
  - **How did the Galilean moons form?**
  - **Why are Jupiter's Galilean moons so geologically active?**
  - **What is remarkable about Titan and other major moons of the outer solar system?**
  - **Why are small icy moons more geologically active than small rocky planets?**

What kinds of moons orbit the jovian planets?

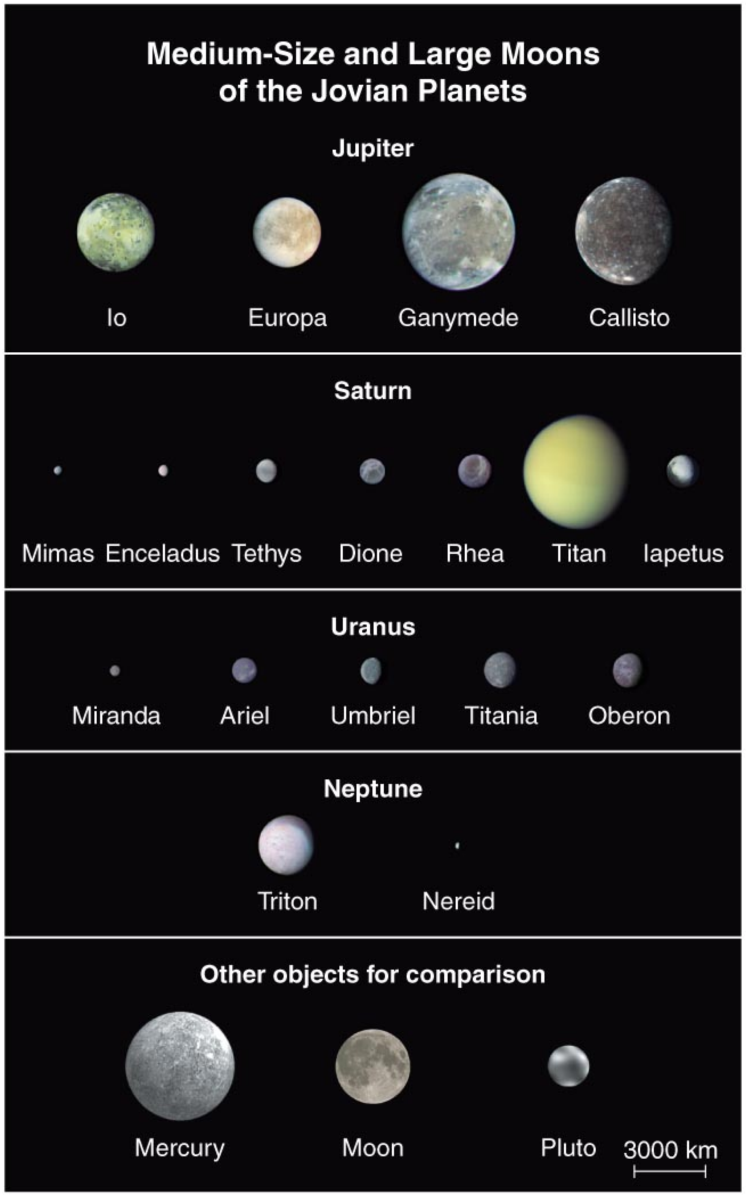


sizes, shapes and origin

Sizes of Moons

- Small moons (< 300 km)
  - No geological activity
- Medium-sized moons (300–1500 km)
  - Geological activity in past
- Large moons (> 1500 km)
  - Ongoing geological activity

Medium and Large Moons



- Enough self-gravity to be spherical
- Have substantial amounts of ice
- Formed in orbit around jovian planets
- Circular orbits in same direction as planet rotation

Small Moons

- These are far more numerous than the medium and large moons.
- They do not have enough gravity to be spherical: Most are "potato-shaped."

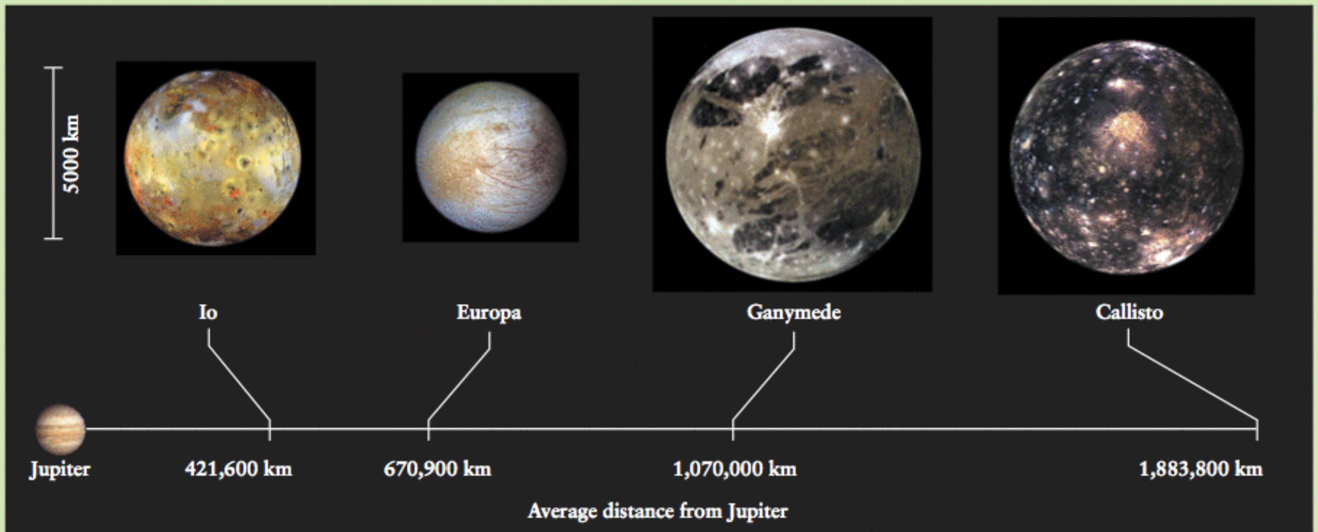
Small Moons

- They are captured asteroids or comets, so their orbits do not follow usual patterns.

The Formation of the Moons of Jupiter

Table 13-1 Jupiter's Galilean Satellites Compared with the Moon, Mercury, and Mars

	Average distance from Jupiter (km)	Orbital period (days)	Diameter (km)	Mass (kg)	Mass (Moon = 1)	Average density (kg/m^3)	Albedo
Io	421,600	1.769	3642	8.932×10^{22}	1.22	3529	0.63
Europa	670,900	3.551	3120	4.791×10^{22}	0.65	3018	0.64
Ganymede	1,070,000	7.155	5268	1.482×10^{23}	2.02	1936	0.43
Callisto	1,883,000	16.689	4800	1.077×10^{23}	1.47	1851	0.17
Moon	—	—	3476	7.349×10^{22}	1.00	3344	0.11
Mercury	—	—	4880	3.302×10^{23}	4.49	5430	0.12
Mars	—	—	6794	6.419×10^{23}	8.73	3934	0.15



Note: Jupiter is shown to the same scale as the distances of the satellites from Jupiter. Compared to this scale, the images of the satellites themselves have been enlarged 74×.

WEBLINK 13.2

R I V U X G

(NASA/JPL)

The Formation of the Moons of Jupiter

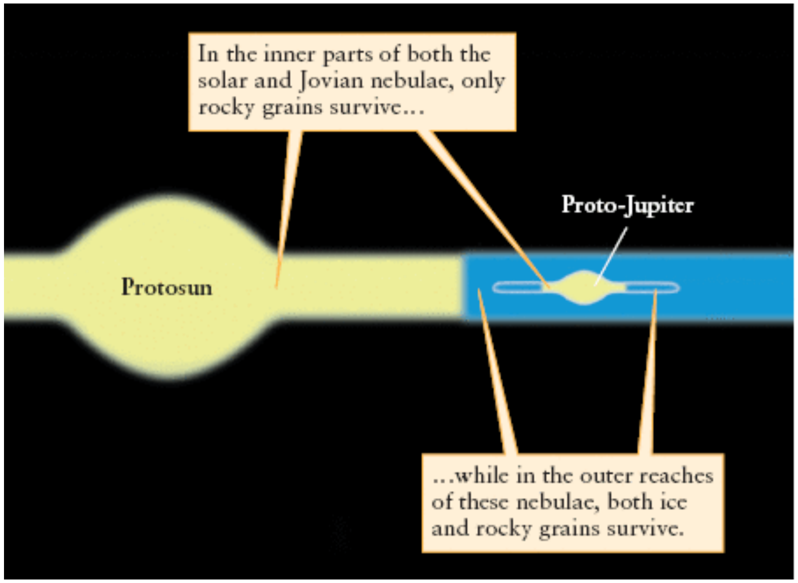
Ganymede and Callisto have relatively low densities compared to Earth and are therefore mostly composed of a combination of rocks and water ice.

Io and Europa are most likely composed of rocky material with less water ice. The reflection spectrum from Europa's surface implies the presence of water ice. Since Europa has a relatively large density the water ice must be limited to the surface of the satellite's outer layers.

The Formation of the Moons of Jupiter

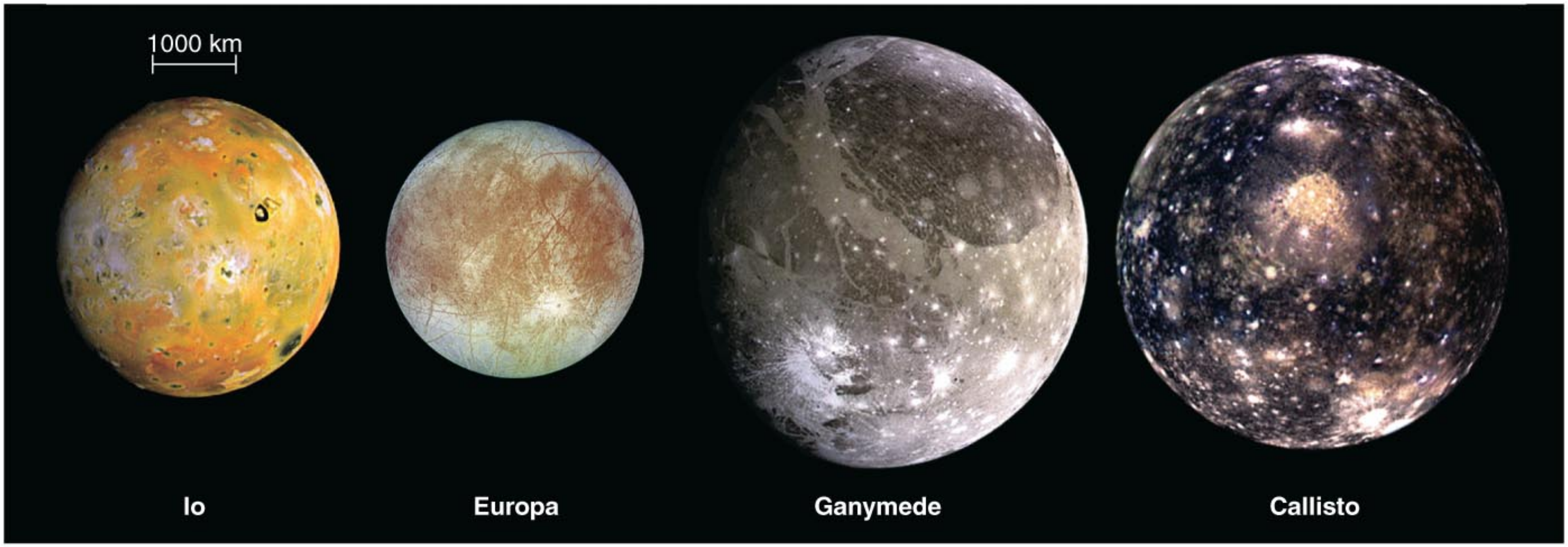
The more distant a moon is from Jupiter the lower its density. The planets in our solar system follow a similar trend with the terrestrial planets having larger densities than the Jovian ones.

The best explanation for this similarity is that the Galilean satellites formed around Jupiter in much the same way that the planets formed around the Sun, although on a much smaller scale.

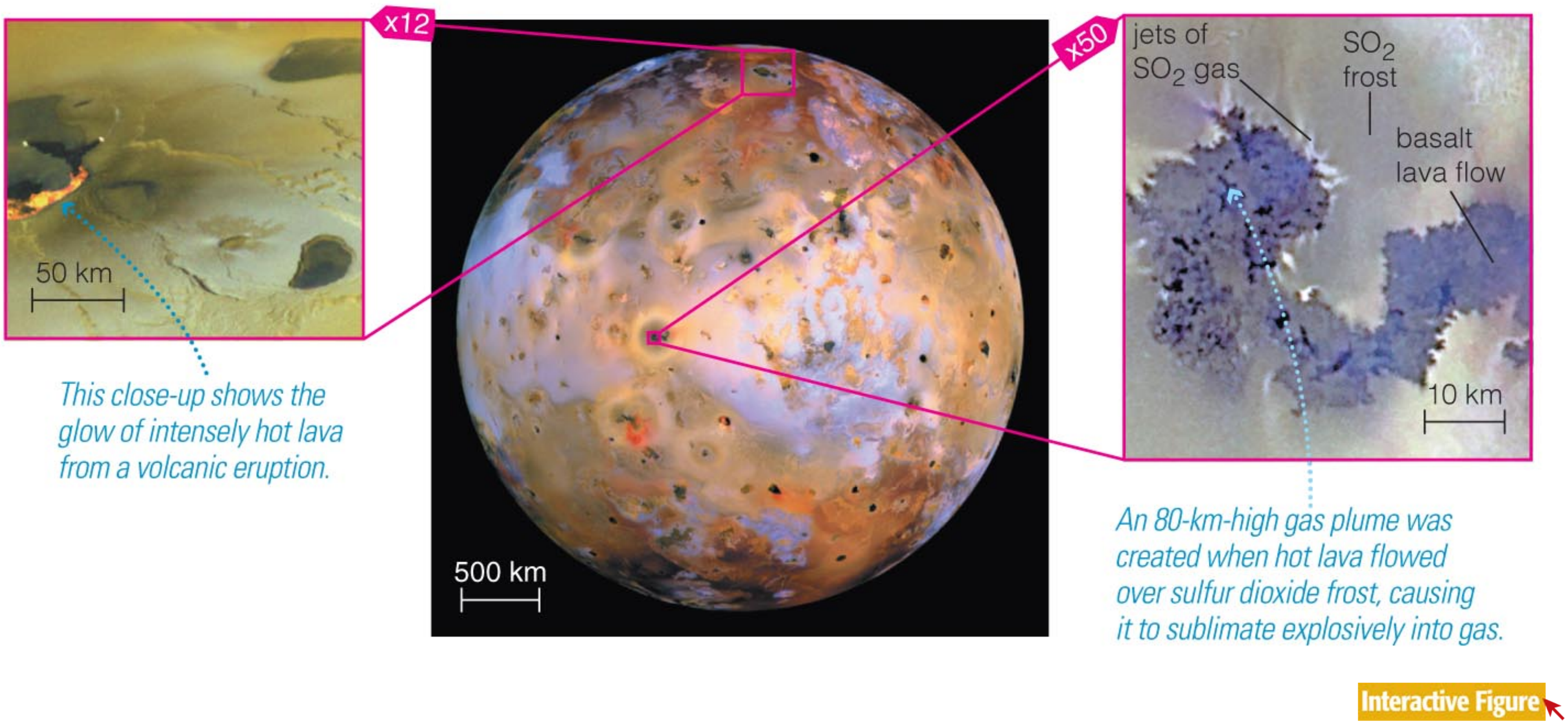


Jupiter's heat evaporated any icy grains that were too close to the center of the "Jovian nebula." Hence, the two inner Galilean satellites were formed primarily from rock, while the outer two incorporated both rock and ice.

Why are Jupiter's Galilean moons so geologically active?

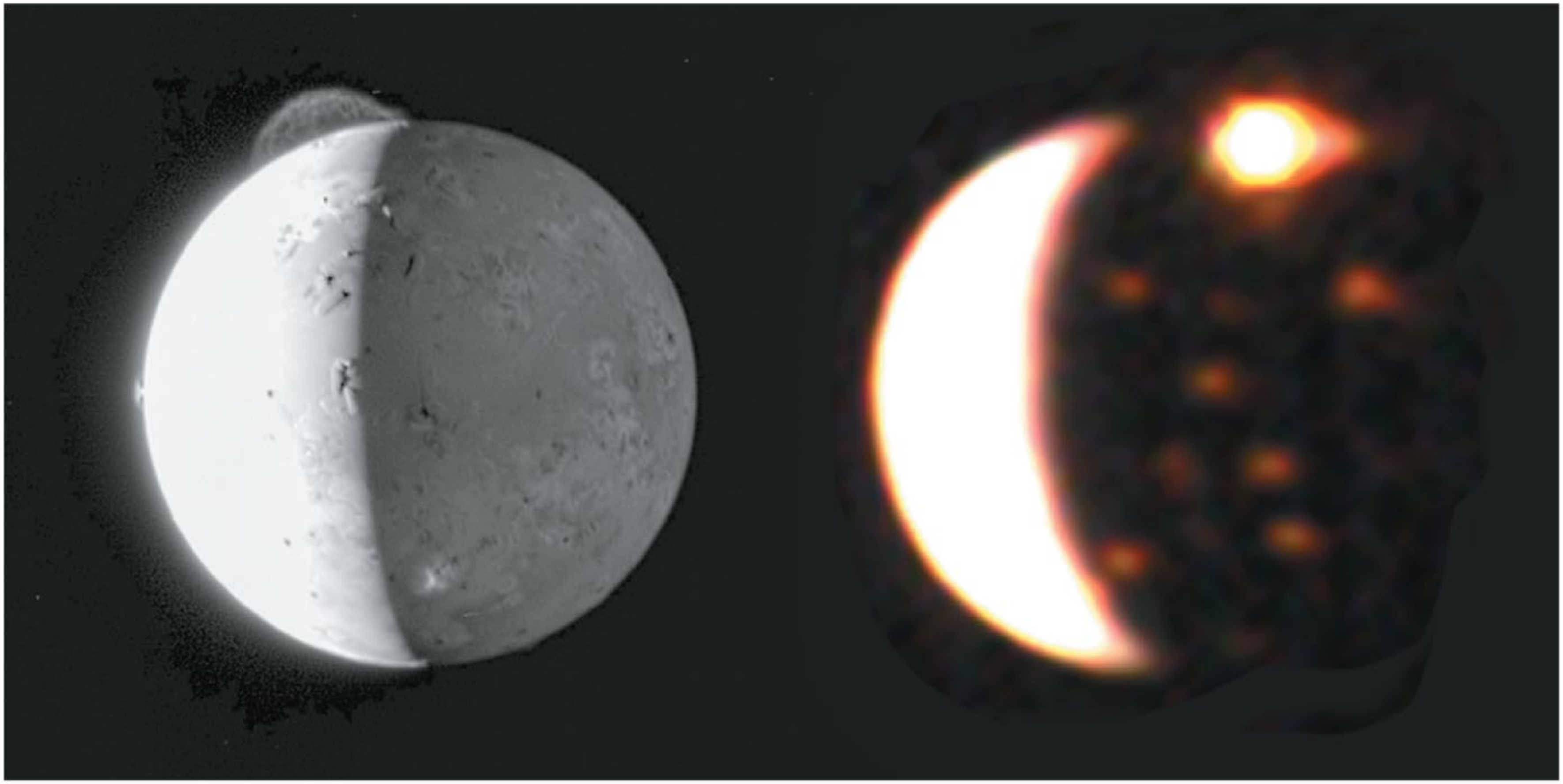


Io's Volcanic Activity



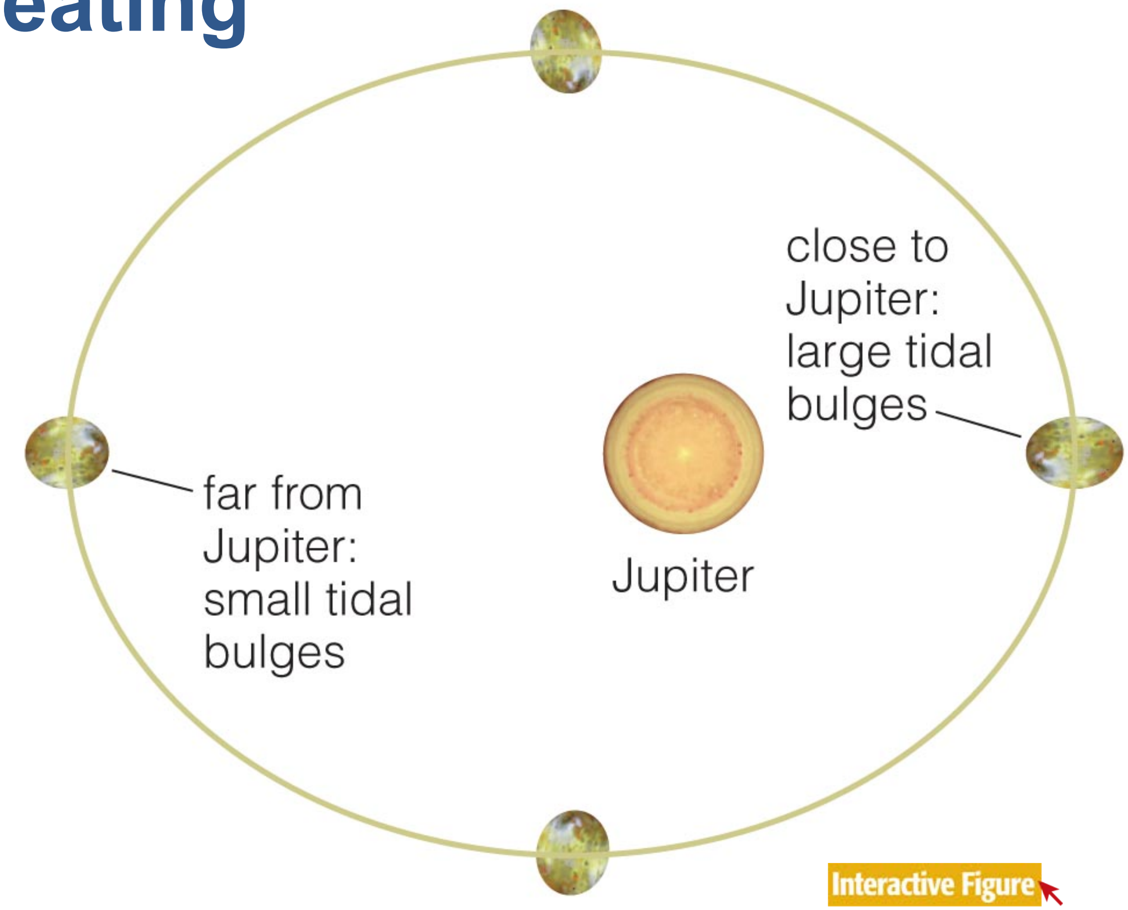
- Hot lava flows and sulfur dioxide plumes
- Io is the most volcanically active body in the solar system, but why?

Io's Volcanoes



- Volcanic eruptions continue to change Io's surface.

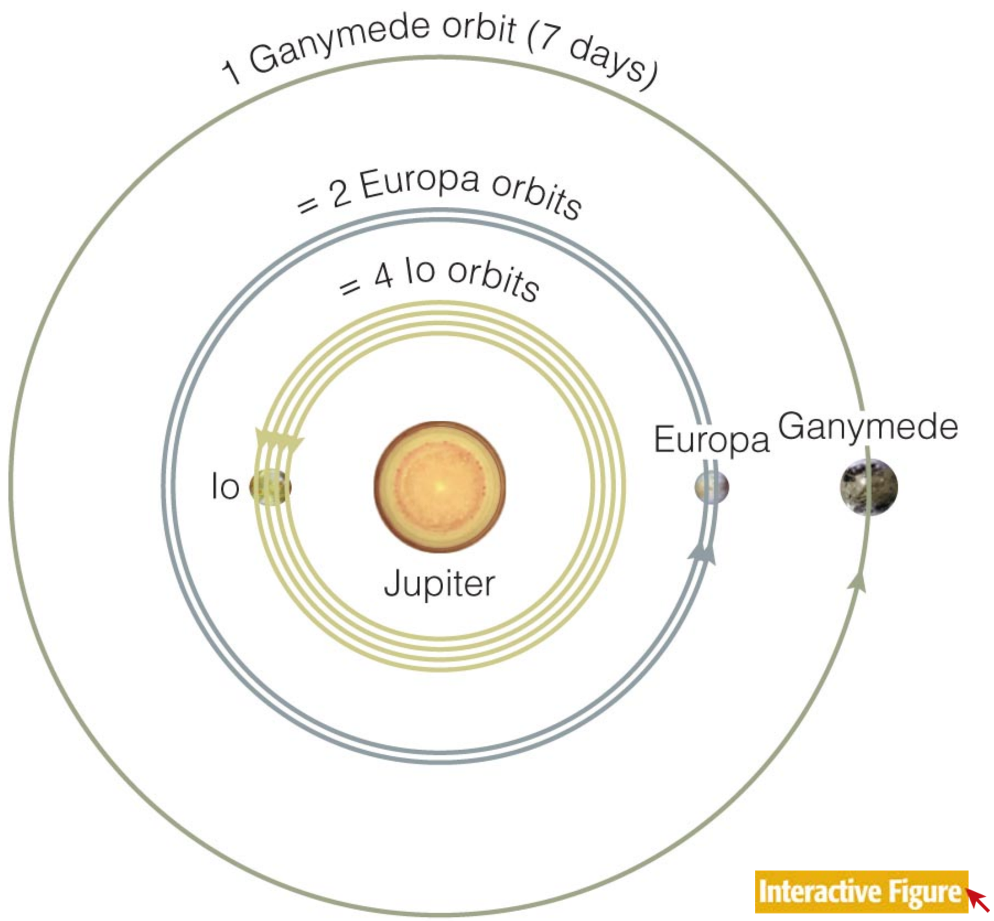
Tidal Heating



Io is squished and stretched as it orbits Jupiter.

But why is its orbit so elliptical?

Orbital Resonances



- Every 7 days, these three moons line up.
- The tugs add up over time, making all three orbits elliptical.

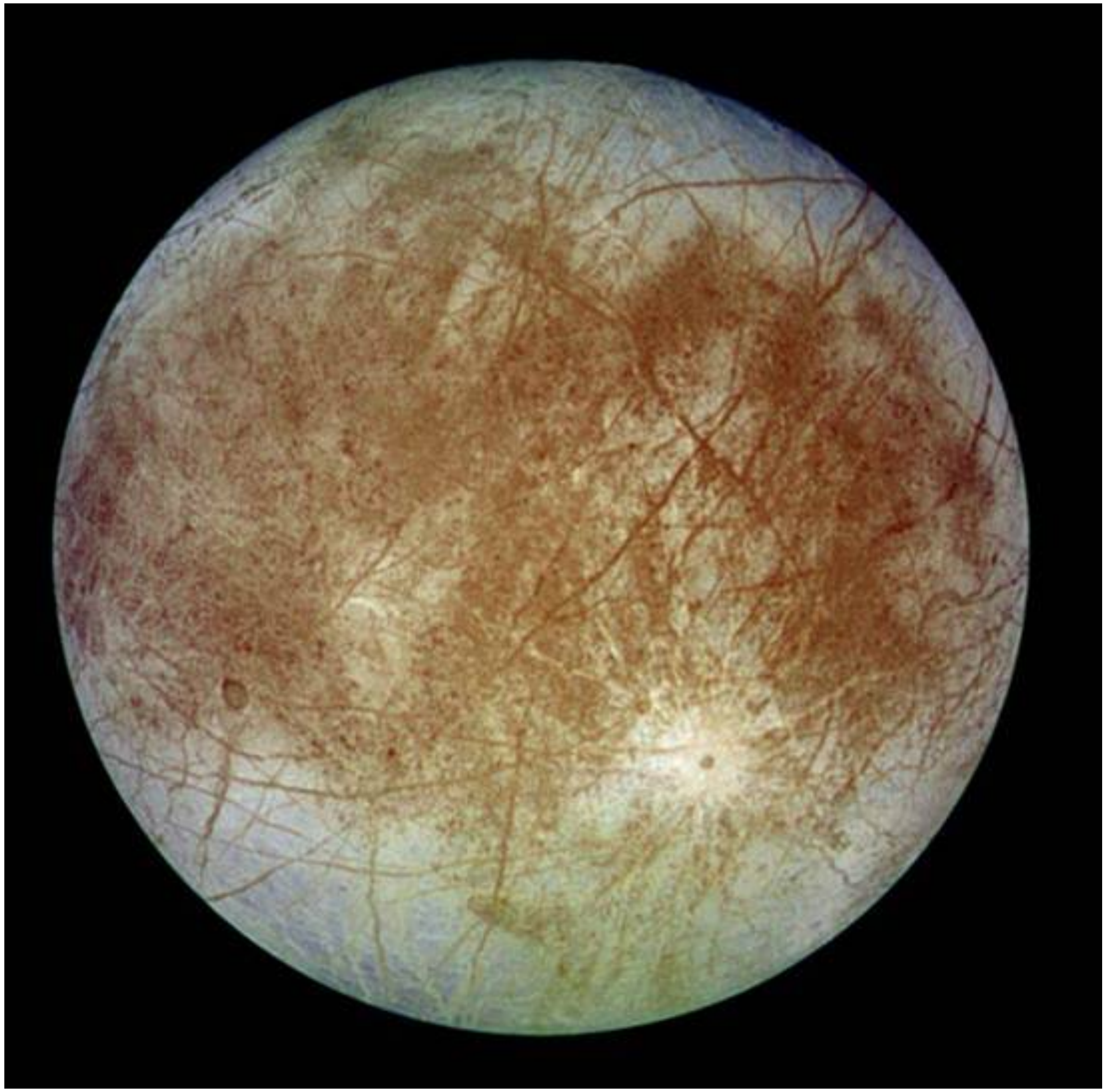
Orbital Resonances

Orbital resonance occurs when two orbiting bodies exert a regular, **periodic gravitational influence** on each other, usually due to their orbital periods being related by a ratio of two small integers.

Unstable resonances with Saturn's inner moons give rise to gaps in the rings of Saturn. Example the 2:1 resonance between the the Cassini Division (P=11.3 h) and the moon Mimas (P=22.6 h).

Stable resonances are the 4:2:1 resonances of Jupiter's moons Io, Europa and Ganymede.

Europa's Ocean: Waterworld?



NASA/JPL/DLR

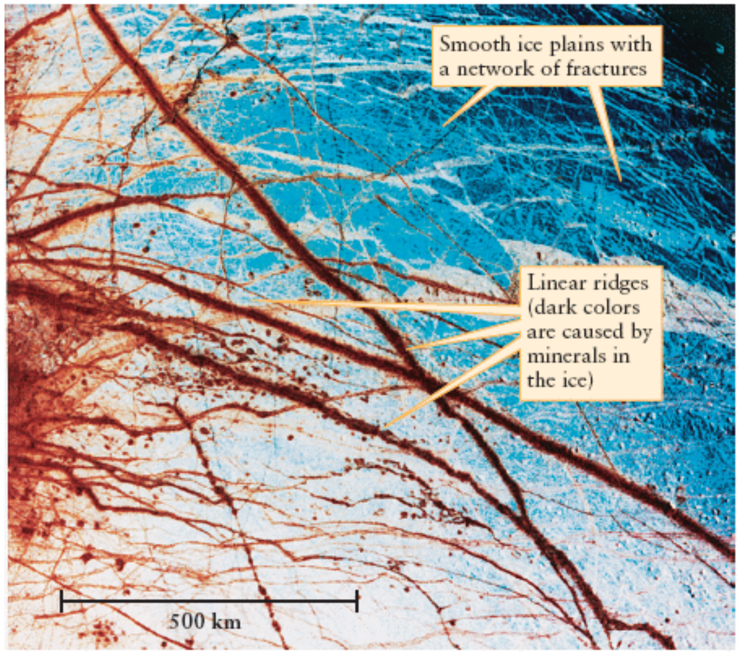
Europa

There are almost no craters on Europa indicating **recent and ongoing geological activity.**

The infrared spectrum of Europa's surface is similar to that of water ice.

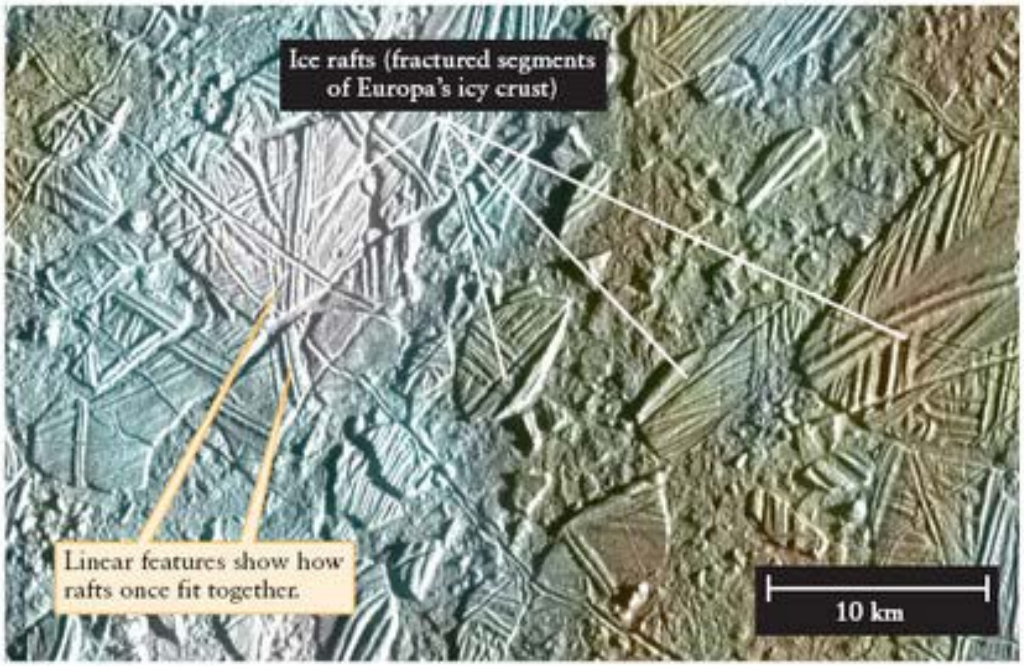
The purity of the water ice on the surface implies that liquid water from the interior is brought upward where it solidifies.

The source of Europa's internal heat is thought to be tidal forces from Jupiter that squeeze and stretch it.

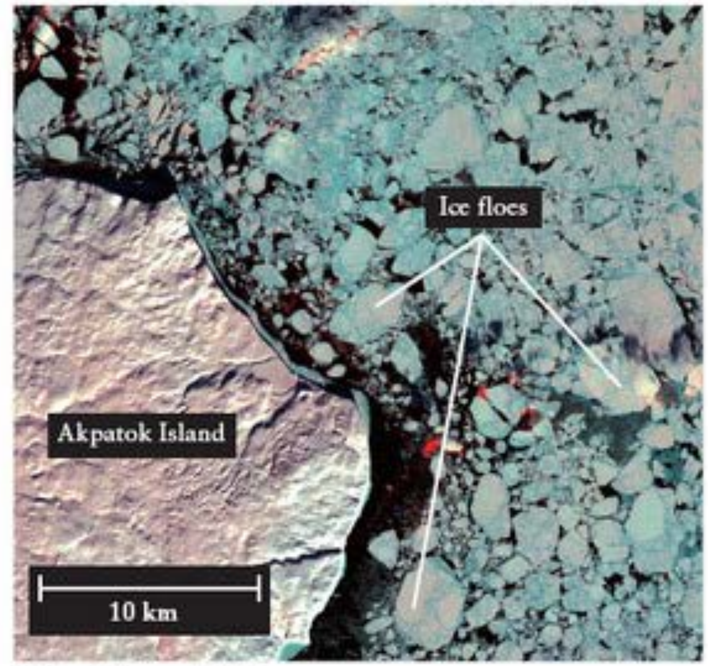


Galileo image of Europa's surface showing brown linear ridges containing minerals and smooth water ice plains.

Tidal stresses crack Europa's surface ice.



(a) Ice rafts on Europa



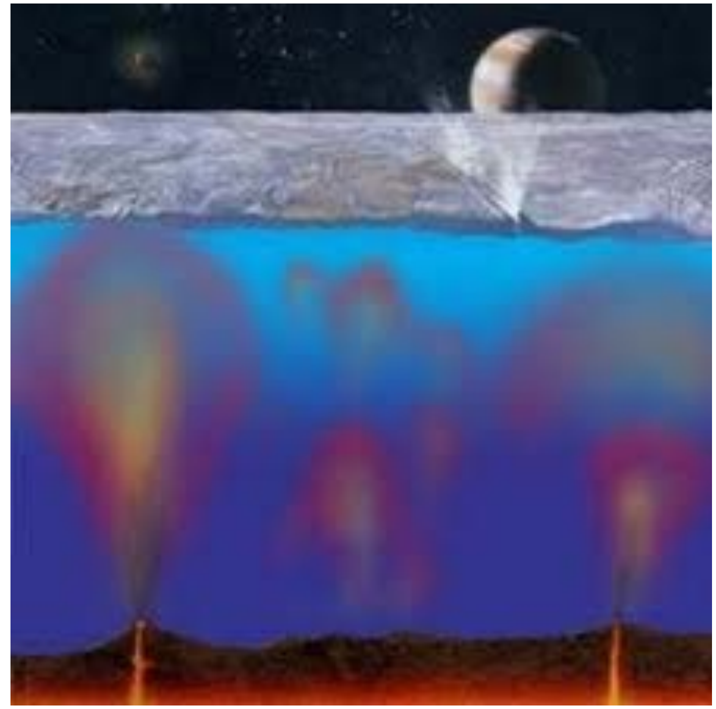
(b) Ice floes on Earth

(left) Tidal stresses brake the surface into small chunks of crust a few kilometers across, which then move around (raft) by an underlying liquid or plastic layer. (right) Europa's ice rafts are analogous to ice floes created when pack ice breaks up, as in this spacecraft view of part of the Canadian arctic.

Europa's interior also warmed by tidal heating.

Measurements of induced electric fields in Europa imply the presence of an electrically conducting fluid (**liquid water with minerals**) beneath Europa's crust.

The presence of a warm underground ocean raises the possibility of life in this environment. Single-celled organisms may have evolved in the water beneath Europa's crust, where they would use dissolved minerals and organic compounds as food sources.

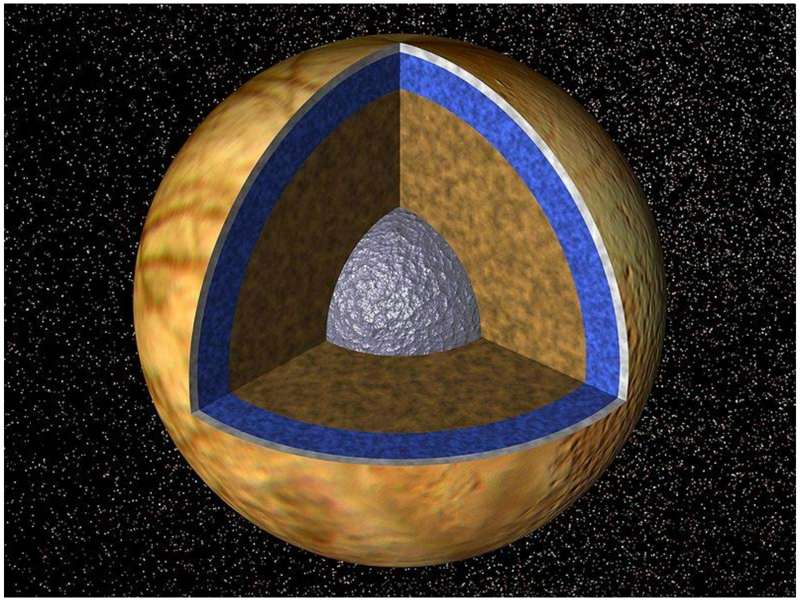


The presence of ridges and rafts implies that Europa has substantial internal heat to form an underground ocean of water.

Europa's interior and Atmosphere

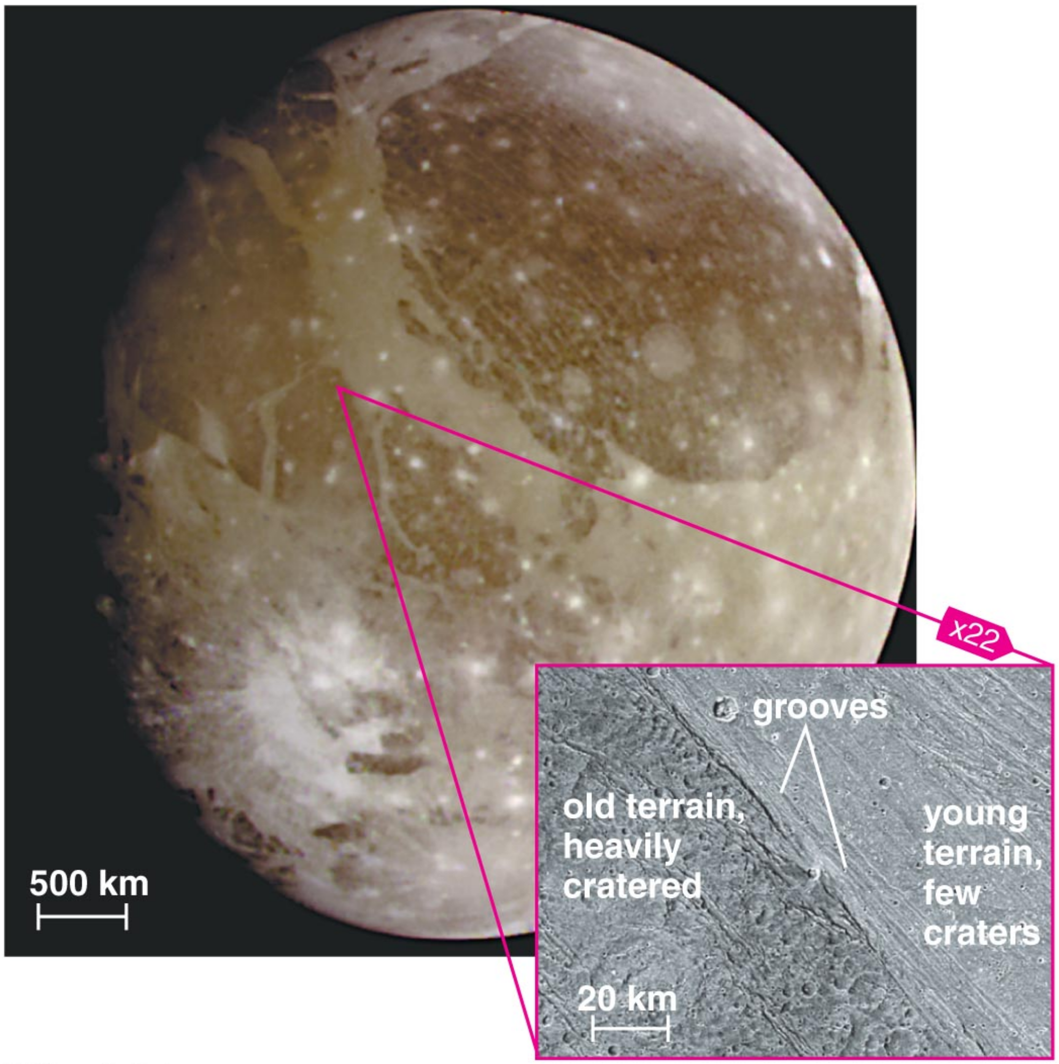
Europa has a tenuous atmosphere containing **traces of oxygen.**

This oxygen is thought to be formed when **solar UV photons and charged particles** in Jupiter's magnetosphere **break up water molecules** on Europa's surface into hydrogen and oxygen. The hydrogen escapes but O_2 remains bound to Europa.



Europa's interior is thought to consist of a rocky metallic core surrounded by a rocky silicate mantle and a outer shell of liquid water and a solid water ice surface.

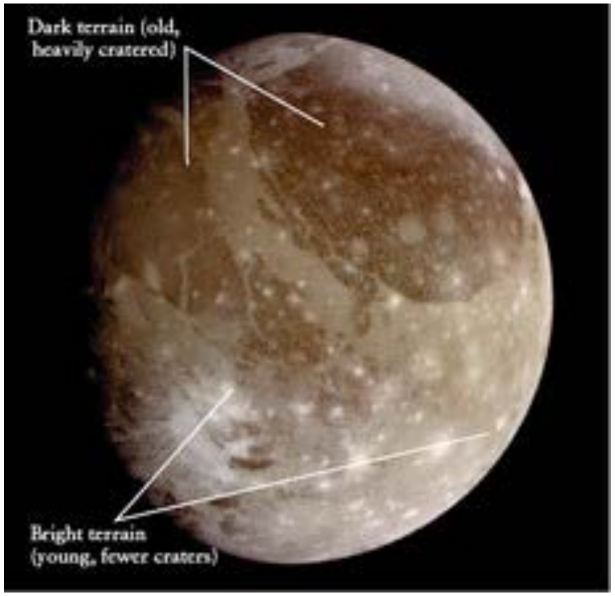
Ganymede



- Largest moon in the solar system
- Clear evidence of geological activity
- Tidal heating plus heat from radio-active decay?

Ganymede

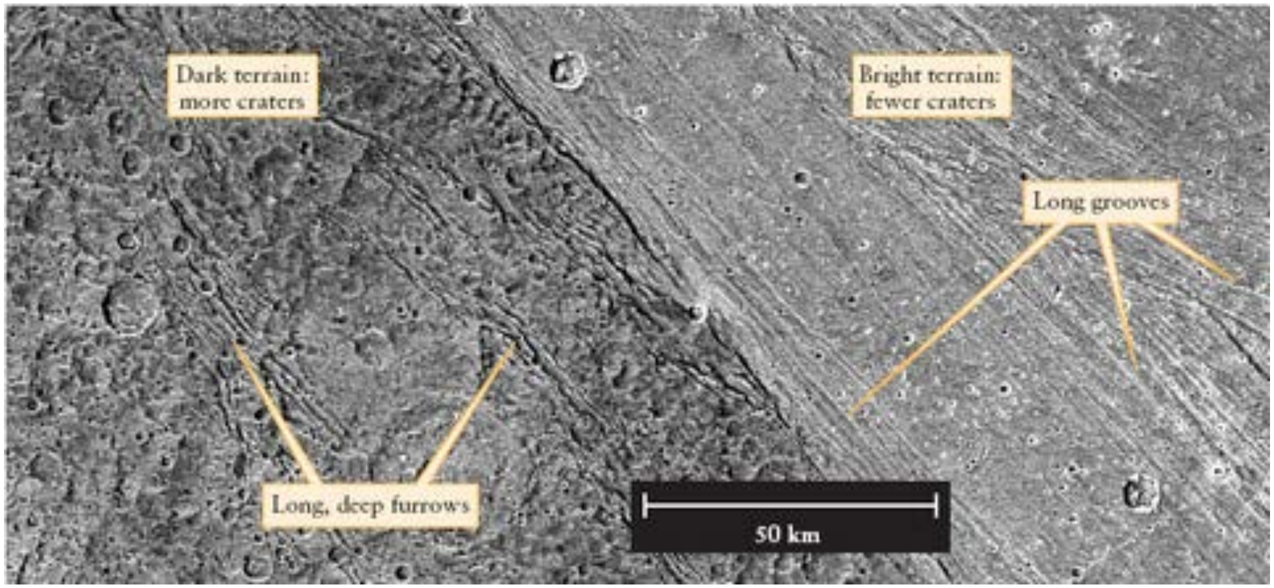
Ganymede's surface has two distinct types of terrain—one dark, heavily cratered, and hence old, the other bright, less cratered, and hence younger. These **craters are primarily made of ice.**



The older craters are darker because of chemical reactions of light with compounds in the icy craters.

Tidal stresses in Ganymede's crust have **produced long deep furrows** that extend for hundreds of kilometers across both the dark and bright terrain.

Geological Activity on Ganymede



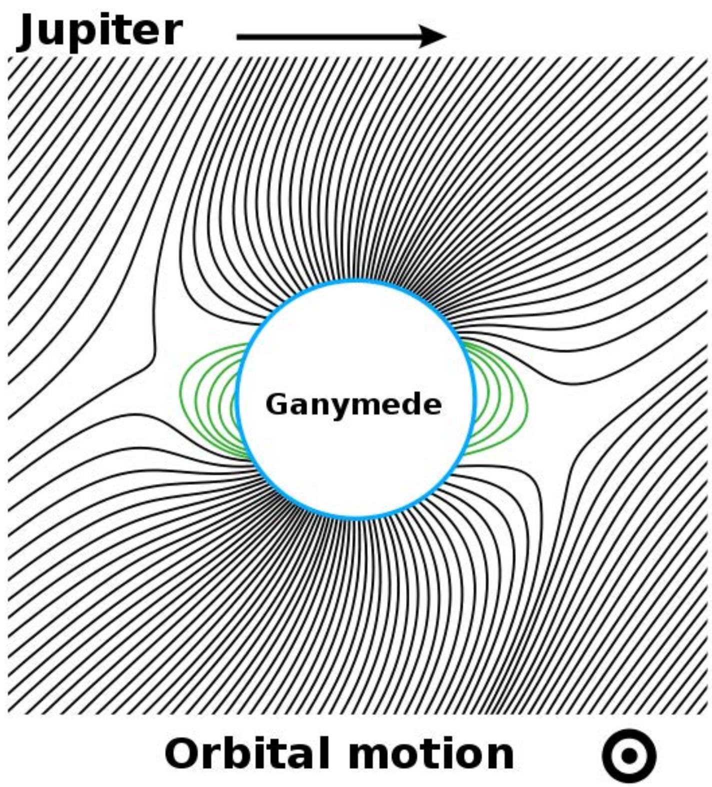
It is thought that **the bright terrain** was formed in areas where the crust was pulled apart (**rift valleys**) and underground water flooded these valleys.

The presence of rift valleys is evidence that Ganymede must have had a warm interior in the past, and that this internal warmth persisted at least until the era when the bright terrain formed a billion years ago.

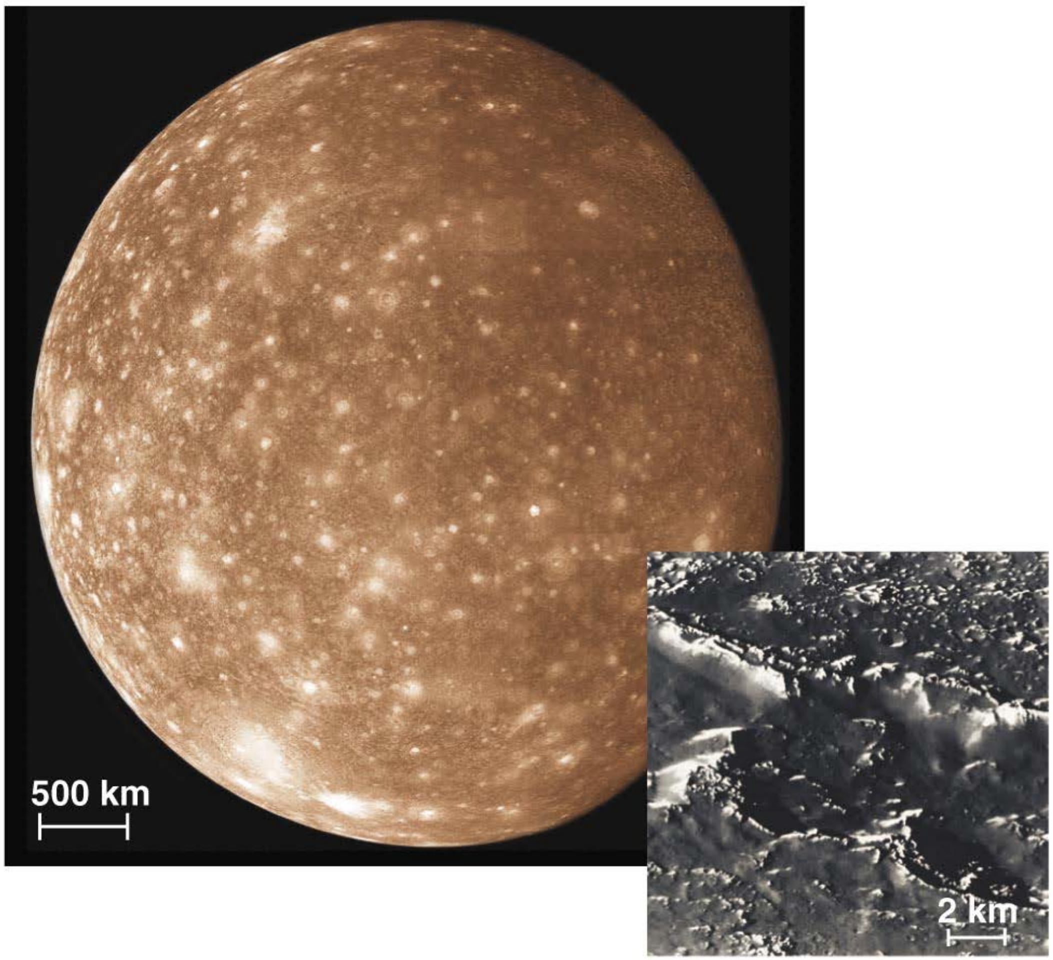
Ganamede’s Magnetic Field

a) **Ganymede’s Internal Magnetic field**. The presence of a magnetic field shows that electrically conducting material must be in motion within Ganymede, which means that the satellite must have **substantial internal heat even today**.

b) **Ganymede also has an induced magnetic field** from moving through Jupiter’s magnetosphere. This suggests that under the solid crust lies a conducting liquid ocean of **salty liquid water**.

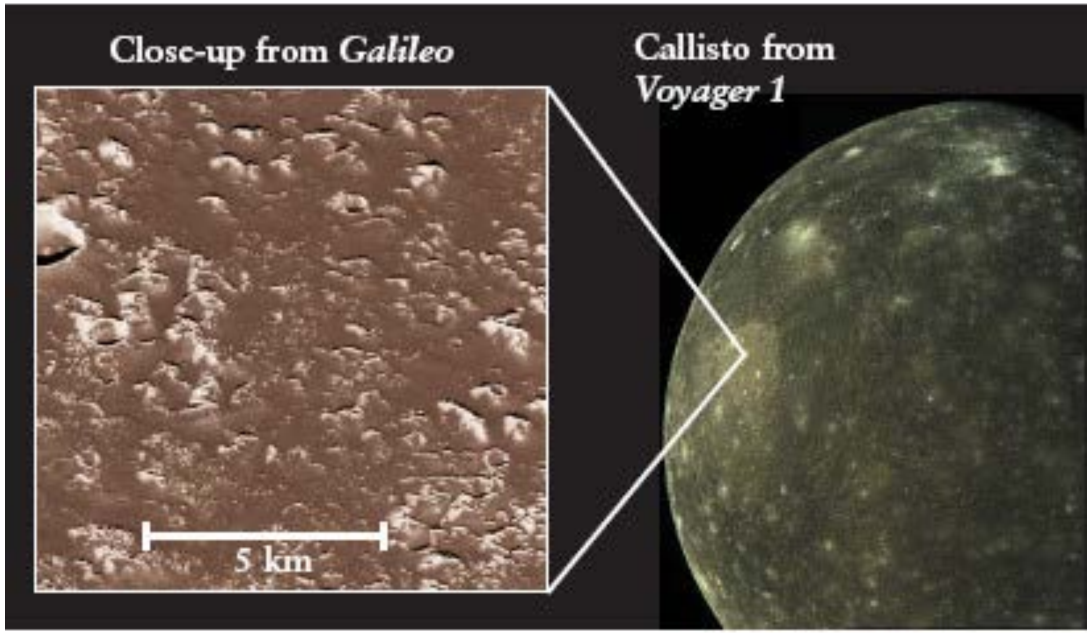


Callisto



- "Classic" cratered iceball
- No tidal heating, no orbital resonances
- But it has a magnetic field!?

Callisto



Callisto has numerous large impact craters scattered over an icy crust. The surface is covered with dark mineral deposits.

Some unknown mechanism has led to the erosion of very small craters.

Callisto's Magnetic Field and Atmosphere

Callisto has an **induced magnetic field** produced from its motion through Jupiter's magnetosphere. Callisto must have a layer of electrically conducting material in order to generate such a field.

One model posits that under the solid crust lies a conducting liquid ocean made up of **a mixture of water and ammonia** about 10 km deep.

Callisto has an atmosphere composed of carbon dioxide (CO_2).

Thought Question

How does Io get heated by Jupiter?

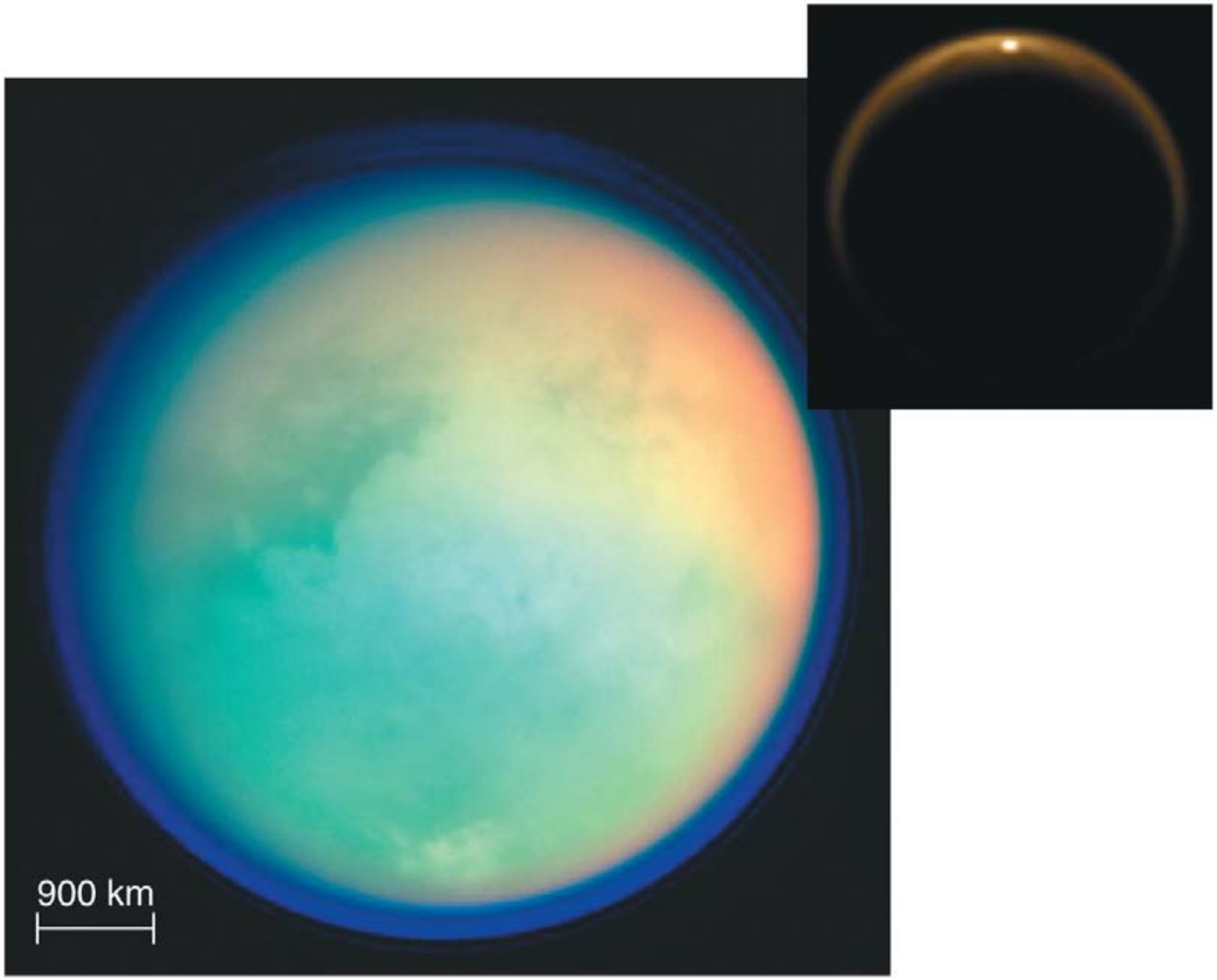
a) auroras
b) infrared light
c) tidal resonance
d) volcanoes

Thought Question

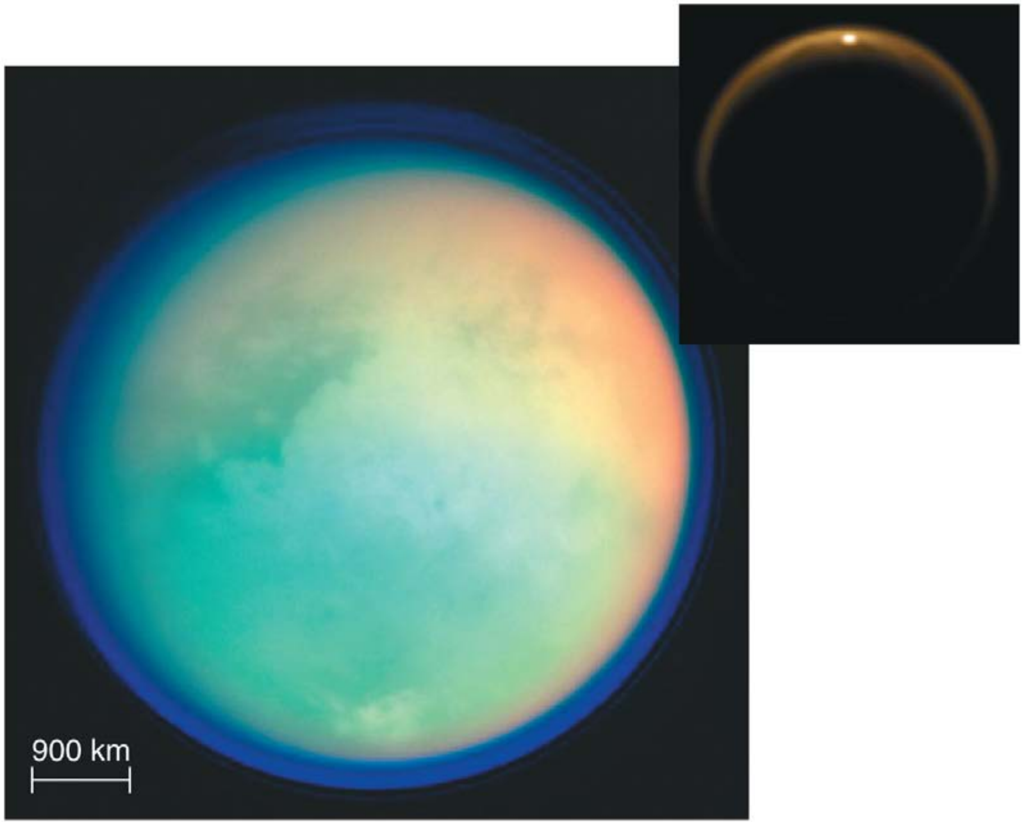
How does Io get heated by Jupiter?

a) auroras
b) infrared light
c) **tidal resonance**
d) volcanoes

What is remarkable about Titan and other major moons of the outer solar system?



Titan's Atmosphere



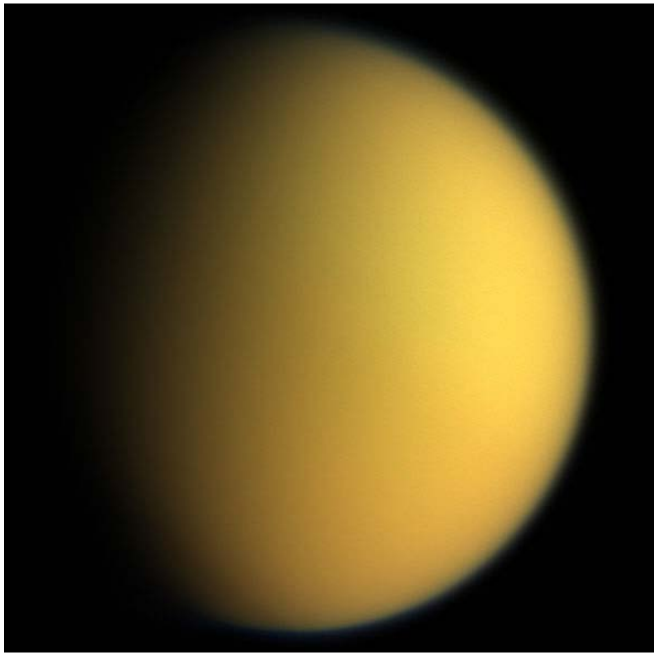
- Titan is the only moon in the solar system to have a thick atmosphere.
- It consists mostly of nitrogen with some argon, methane, and ethane.

Saturn's Moon Titan

Titan, was discovered by Christian Huygens in 1665. It has a low density that suggests it is made of a mixture and ice and rock and a thick atmosphere with a unique chemical composition.

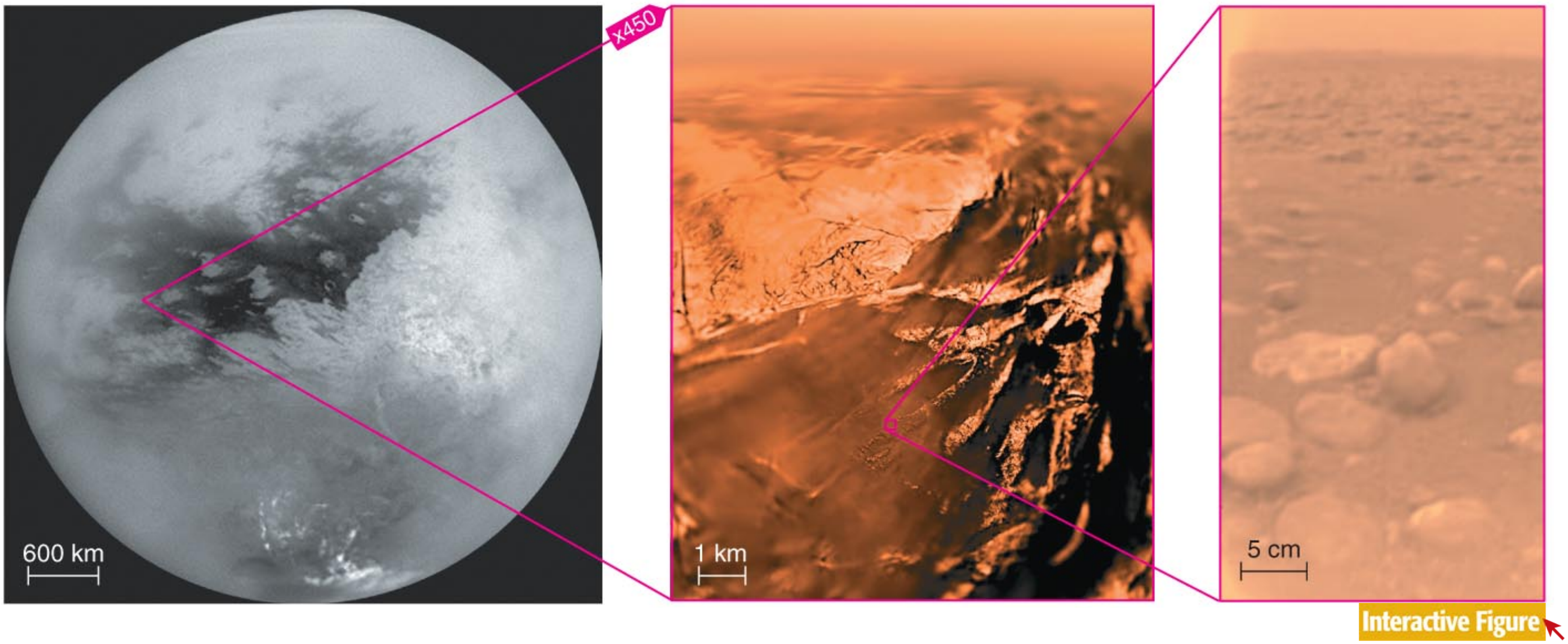
Atmosphere consists of 95% nitrogen that probably came from NH_3 broken up by UV sunlight.

Most of the remaining gas is argon, methane(CH_4) and hydrocarbons produced from the interaction of CH_4 with UV from the sun.



Titan as seen from the *Cassini* spacecraft. The orange color is due to the hydrocarbon particles in the atmosphere.

Titan's Surface



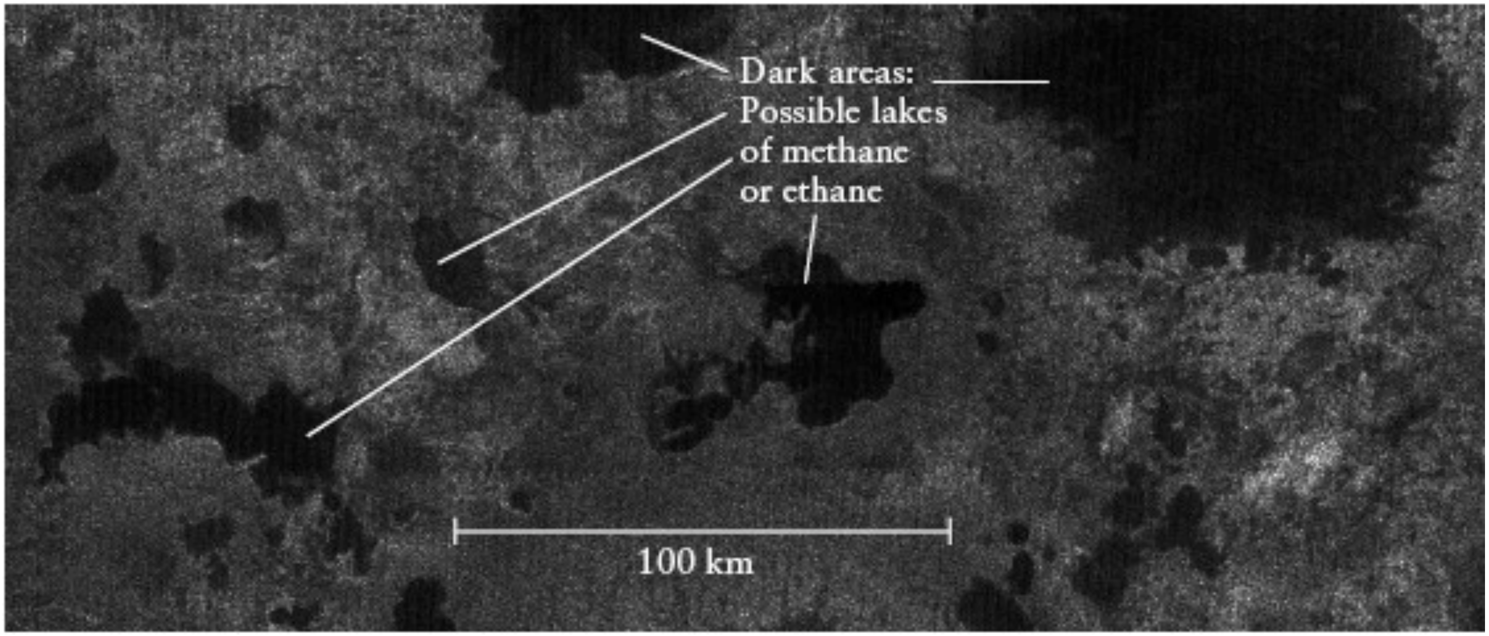
- *Huygens* probe provided first look at Titan's surface in early 2005.
- It found liquid methane and "rocks" made of ice.

Titan's Surface

Cassini used IR imaging and radar to penetrate through Titan's dense atmosphere. Most of the surface is bright with long parallel lines of **dark sand dunes** presumably formed by winds. The **sand dunes are likely made of water ice and polymers** that give it the dark color.

The infrared telescope on *Cassini* also detected a volcano that explains the presence of methane in the atmosphere. (CH_4 is broken up by solar UV and needs to be replenished)

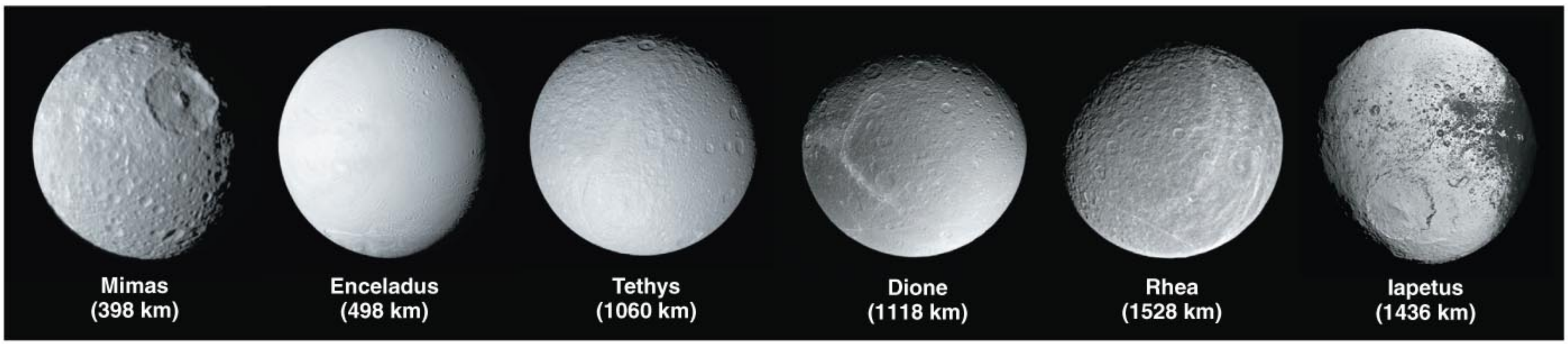
Titan's Surface



Cassini's radar image indicates **lakes of ethane** (C_2H_6) near Titan's north (shown) and south poles, with fewer lakes in the south.

Scientists also found **extensive clouds of ethane** in Titan's atmosphere especially near the north pole.

Medium Moons of Saturn

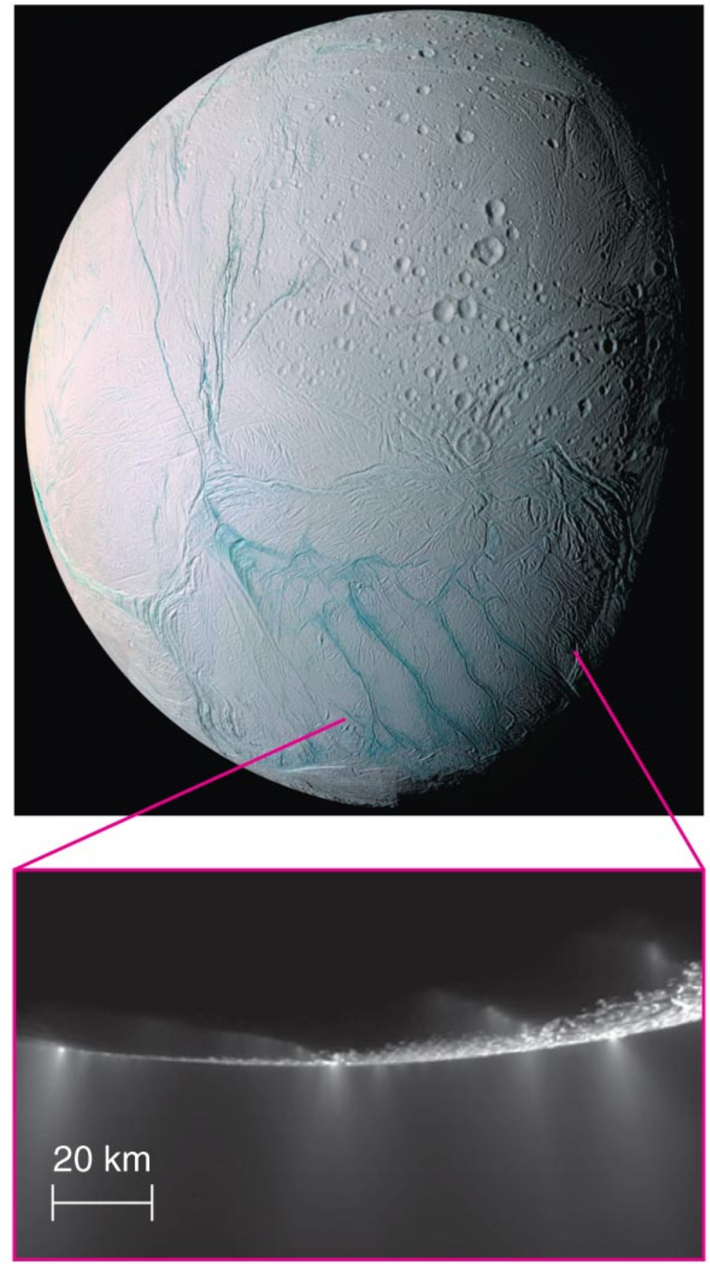


- Almost all of them show evidence of past impacts, volcanism and/or tectonics.

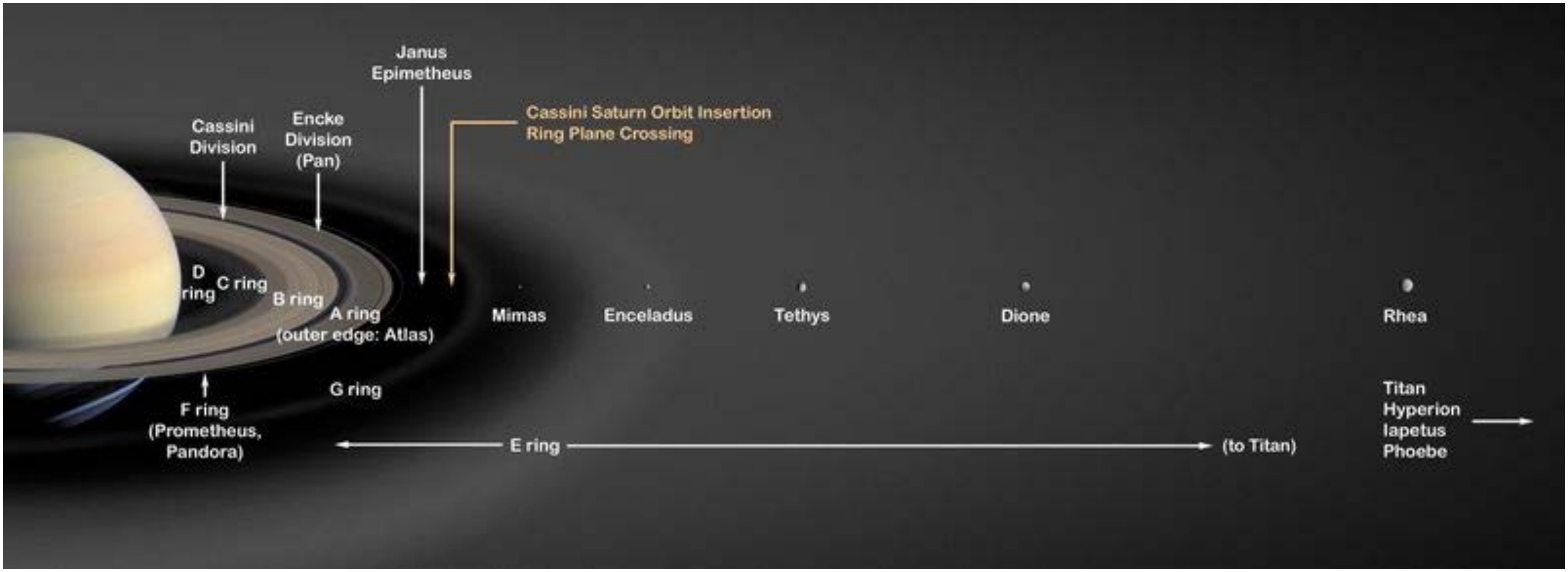
Medium Moons of Saturn

- Ice fountains of **Enceladus** suggest it may have a subsurface ocean.

- **Enceladus** has very few craters indicating geologic activity in the last 100 million years. Enceladus surface is mainly ices and has an albedo of 0.95, the highest of any large object in the solar system.

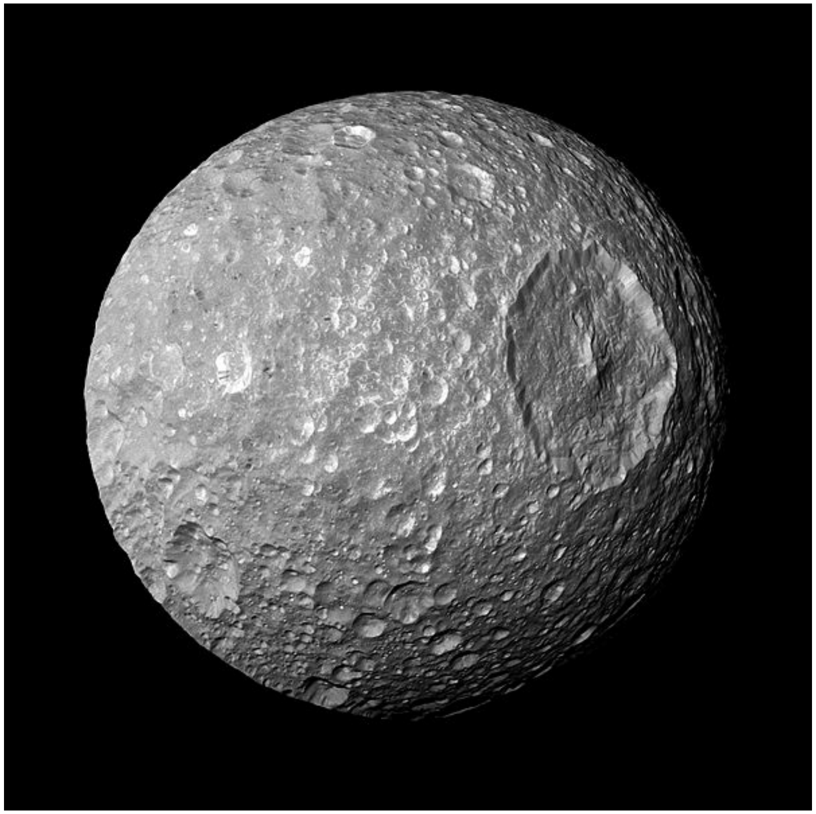


Orbital Resonance between Enceladus and Dione



Tidal Heating of Enceladus? Enceladus (P = 32.9h) and Dione(P=65.7h) are in a 2:1 orbital resonance that may enhance tidal heating. Enceladus has water geysers that inject water ice and hydrocarbons that feed Saturns E ring.

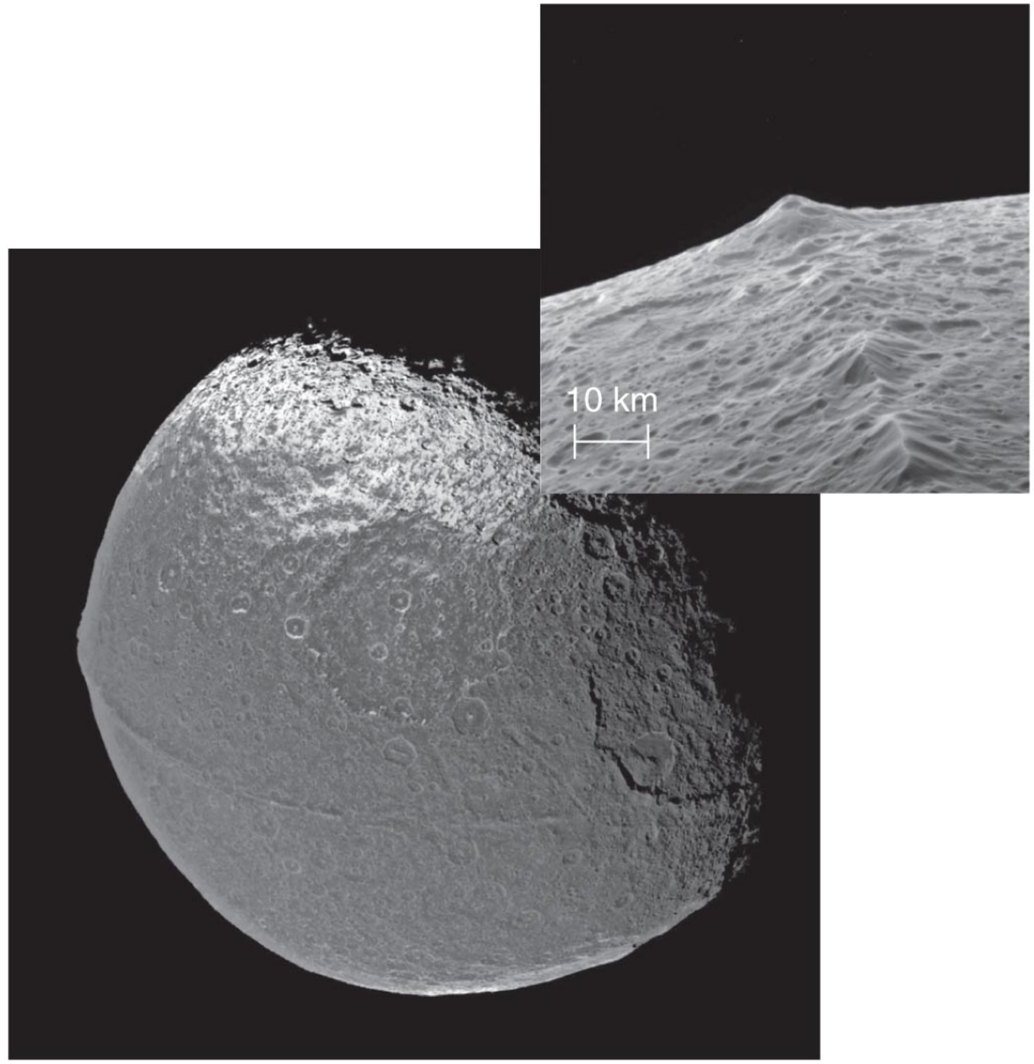
Saturn’s Moon Mimas



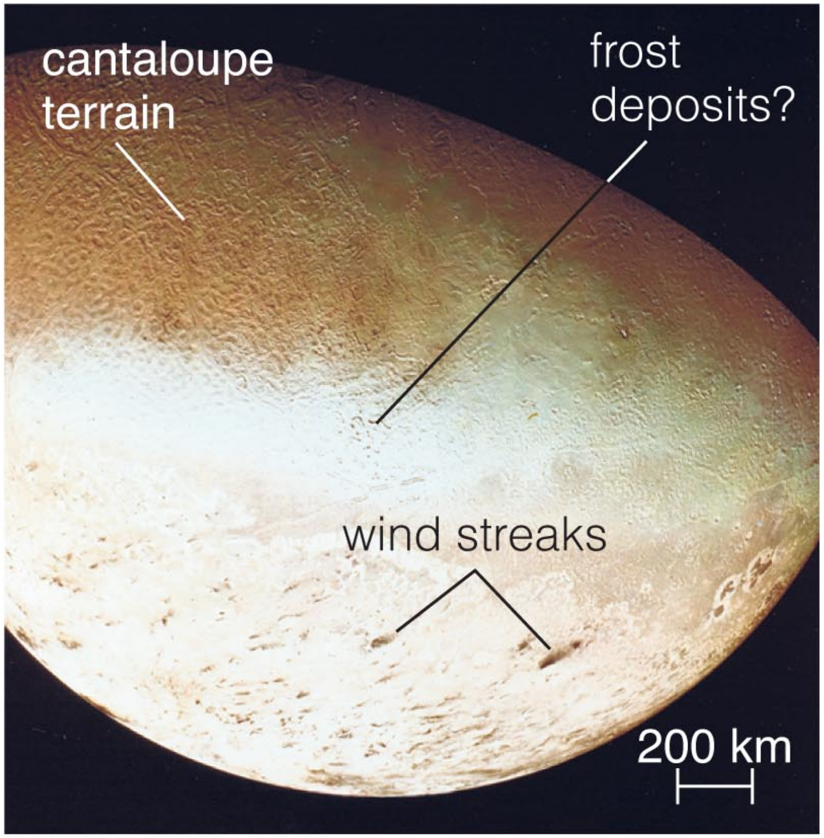
Mimas is heavily cratered with one crater that is so large that the impact that formed it might have come close to shattering this moon. The (2:1) orbital resonance of Mimas (P=22.6h) is responsible for the Cassini Division (P=11.3h) between the A and B rings of Saturn.

Medium Moons of Saturn

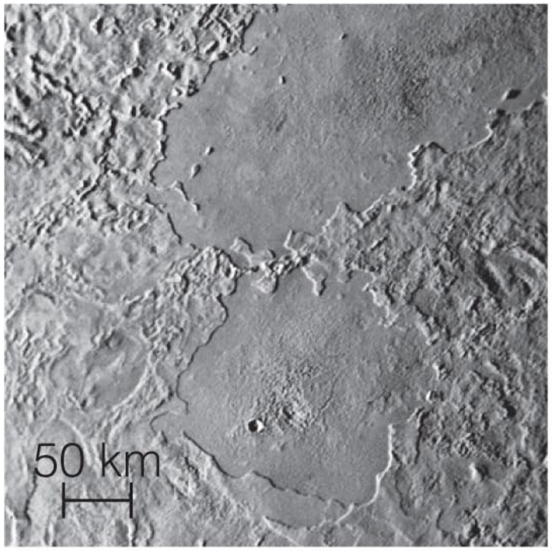
- Iapetus has a curious ridge around much of its equator



Neptune's Moon Triton



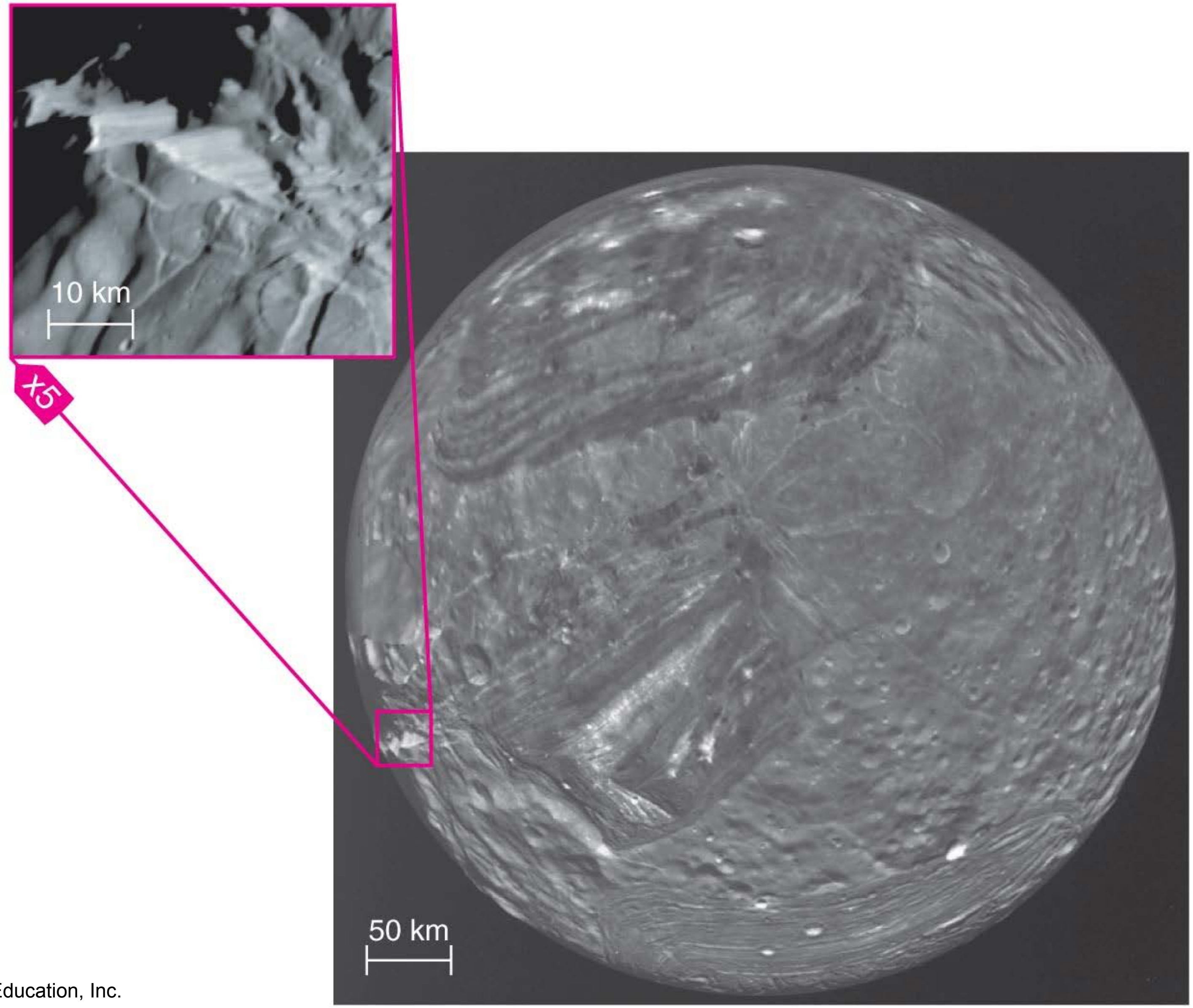
Triton's southern hemisphere as seen by *Voyager 2.*



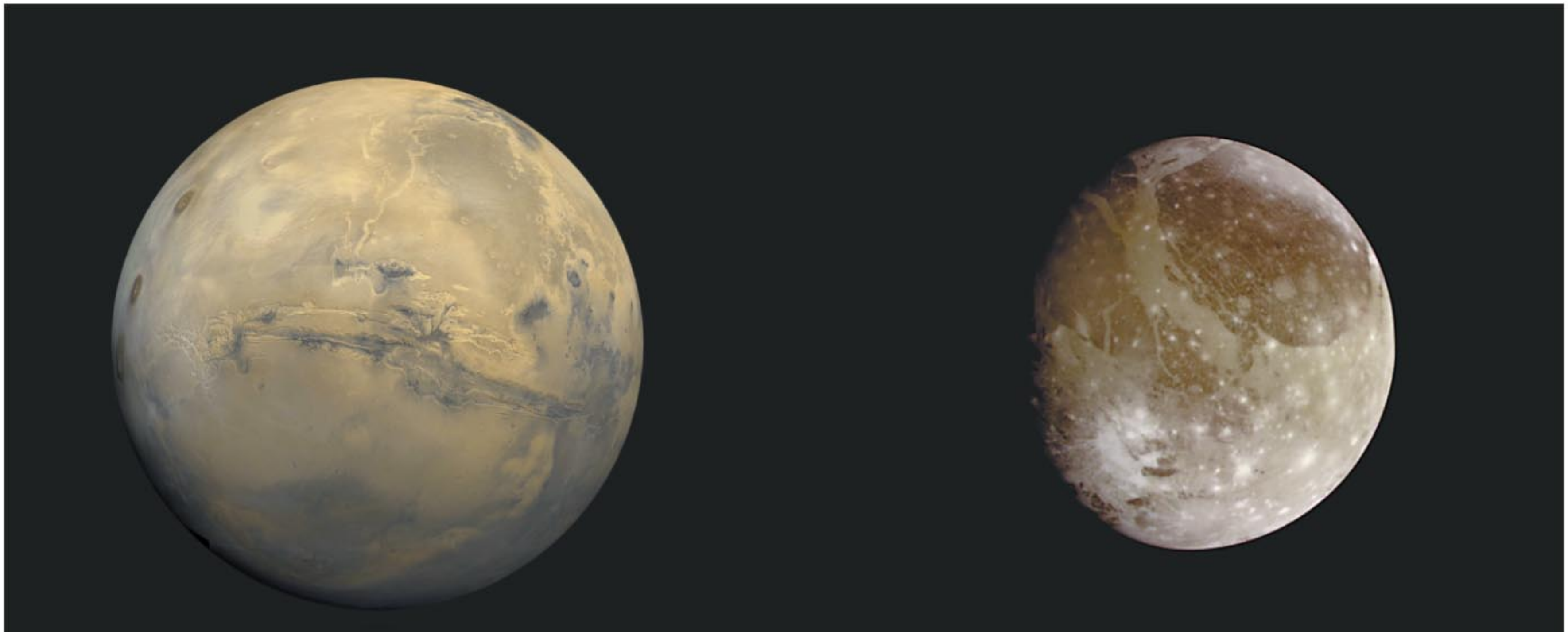
This close-up shows lava-filled impact basins similar to the lunar maria, but the lava was water or slush rather than molten rock.

- Similar to Pluto, but larger
- Evidence of past geological activity

Why are small icy moons more geologically active than small rocky planets?



Rocky Planets versus Icy Moons



- Rock melts at higher temperatures.
- Only large rocky planets have enough heat for activity.
- Ice melts at lower temperatures.
- Tidal heating can melt internal ice, driving activity.

What have we learned?

- **What kinds of moons orbit the jovian planets?**
  – Moons come in many sizes.
  – The level of geological activity depends on a moon's size.
- **Why are Jupiter's Galilean moons so geologically active?**
  – Tidal heating drives geological activity, leading to Io's volcanoes and ice geology on other moons.

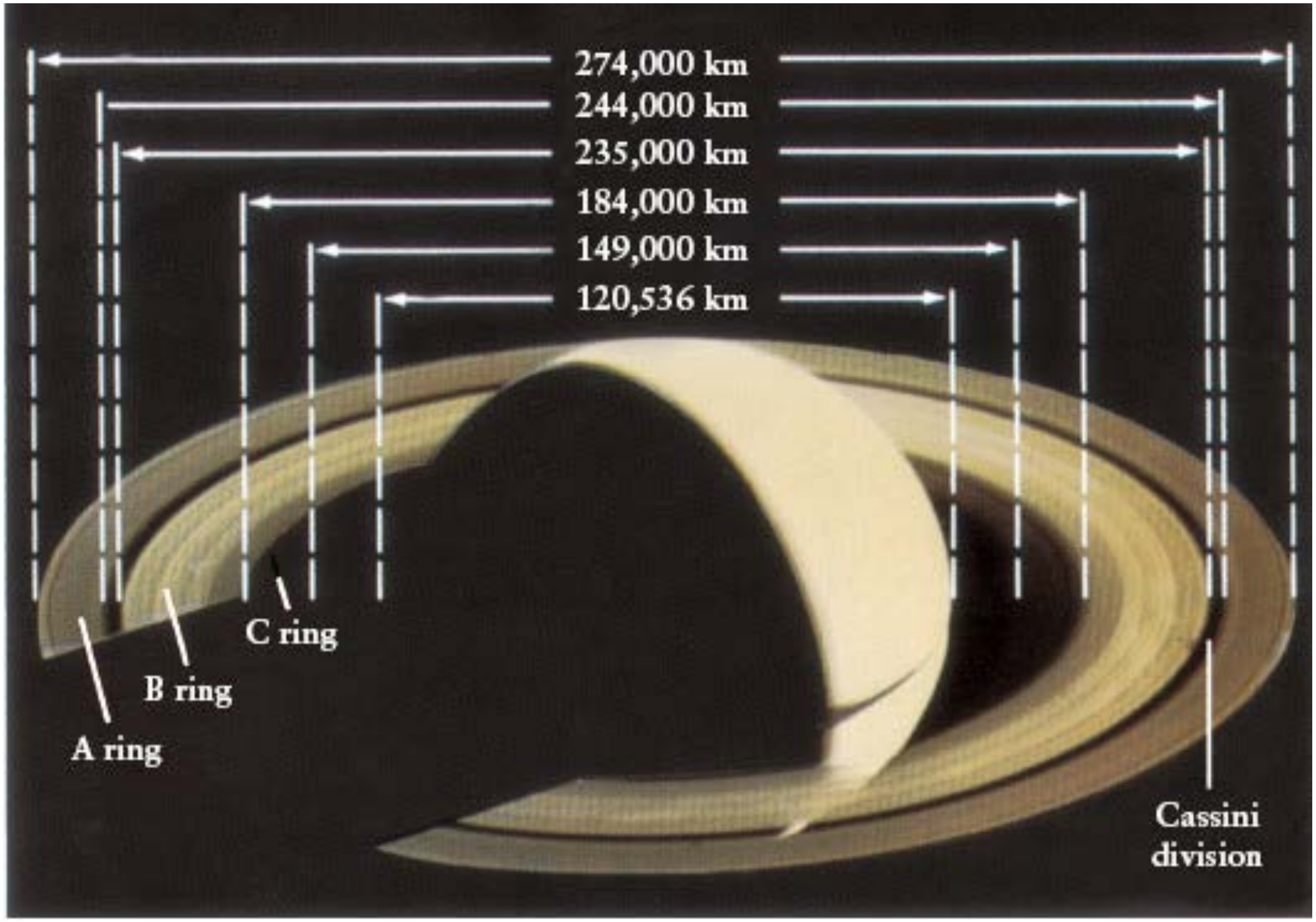
What have we learned?

- **What is special about Titan and other major moons of the solar system?**
  – Titan is only moon with thick atmosphere.
  – Many other major moons show signs of geological activity.
- **Why are small icy moons more geologically active than small rocky planets?**
  – Ice melts and deforms at lower temperatures, enabling tidal heating to drive activity.

11.3 Jovian Planet Rings

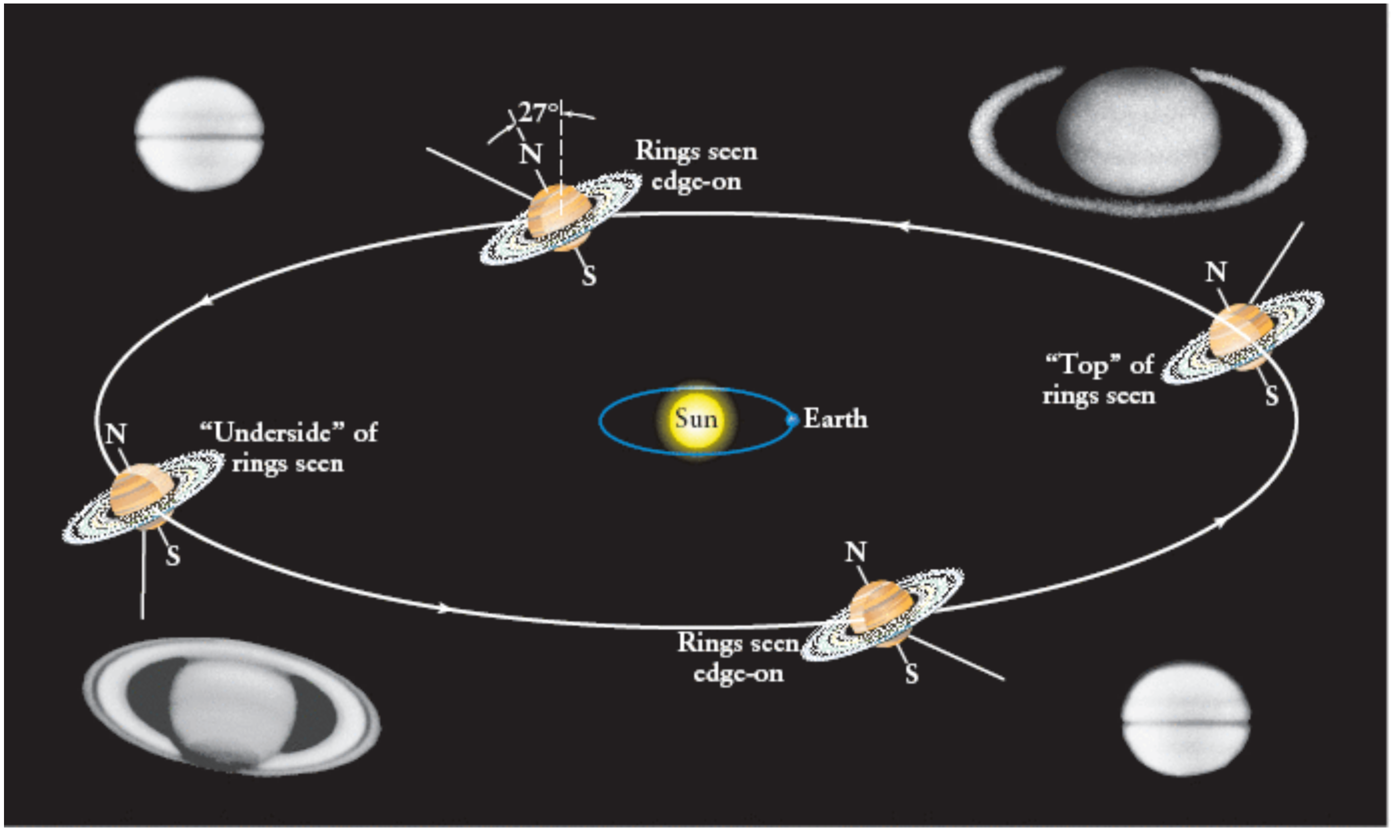
- Our goals for learning:
  - **What are Saturn's rings like?**
  - **How do other jovian ring systems compare to Saturn's?**
  - **Why do the jovian planets have rings?**

What are Saturn's rings like?



This *Voyager 1* image shows many details of Saturn’s rings.

Appearance of Saturn’s Rings



Saturn’s rings are aligned with its equator, which is tilted 27° from Saturn’s orbital plane. As Saturn moves around its orbit, the rings maintain the same orientation in space, so observers on Earth see the rings at various angles.

Saturn's Rings are Composed of Icy Fragments

James Clerk Maxwell calculated that the **rings of Saturn could not be solid** because they would be torn apart by tidal forces.

James Keeler measured the spectral lines reflected from the rings and found that the size of the wavelength Doppler shift increased inward across the rings - **the closer to the planet, the greater the shift**.

Keeler's observations showed **that the rings of Saturn are made of individual fragments** that rotate around Saturn obeying Kepler's 3rd law.

Properties of Saturn's Rings

Saturn's rings **reflect about 80% of sunlight** that falls on them.

Near infrared observations show absorption lines from frozen water in the rings. This confirms that **Saturn's ring particles are made of ice and ice-coated rock.**

Voyager and *Cassini* measured the temperature of the rings to range from –180°C in the sunshine to less than –200°C in Saturn's shadow.

By measuring the radio signals transmitted by spacecraft through the rings scientists estimate the sizes of the **ring fragments to range from a ~1 cm to ~5 m.**

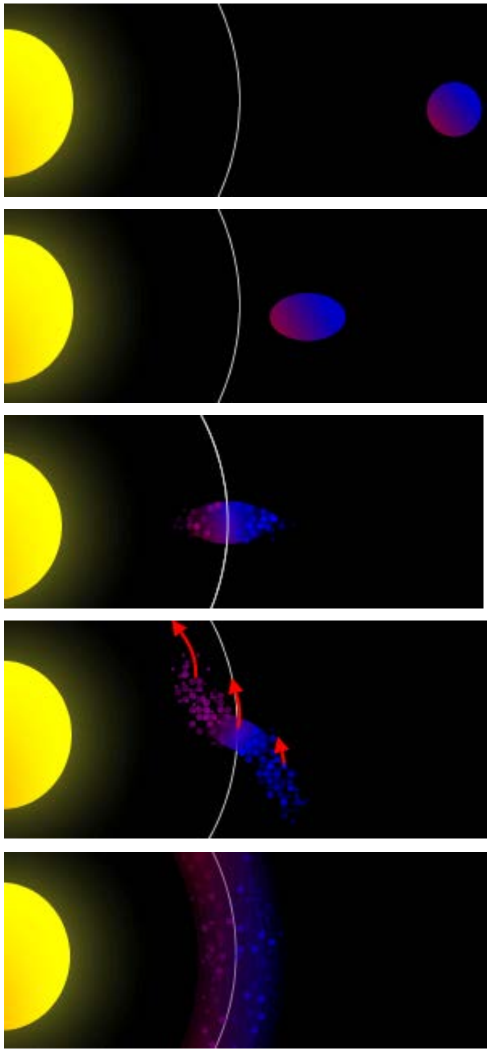
Roche Limit

The Roche limit is the smallest distance from a planet where a second object can be held together by gravitational forces alone.

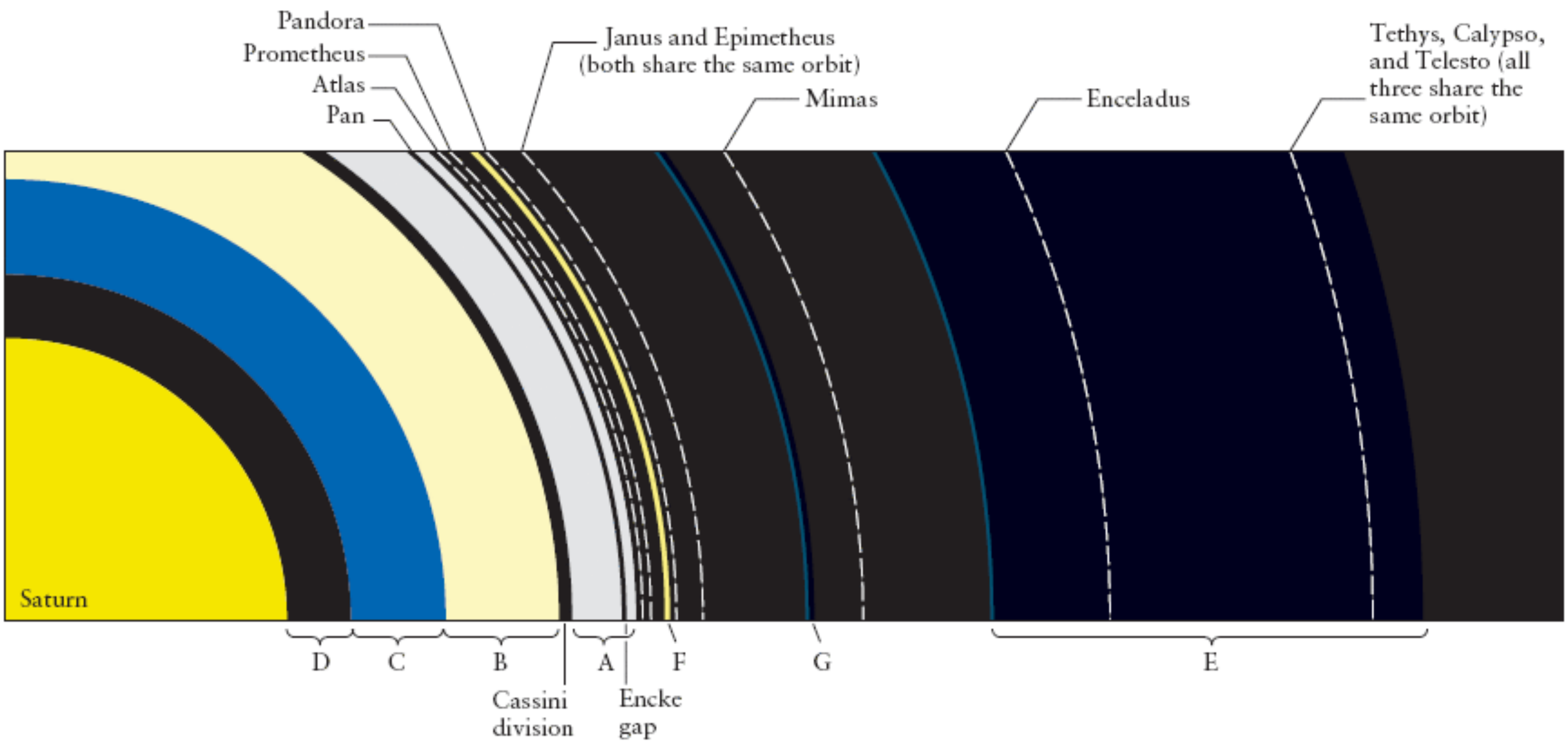
If the second object moved closer in than the Roche limit the tidal forces would overwhelm the gravitational pull between neighboring particles.

Saturn's ring particles are within the *Roche limit* and therefore cannot accrete and form a moon.

Why don't Saturn's ring particles break up?

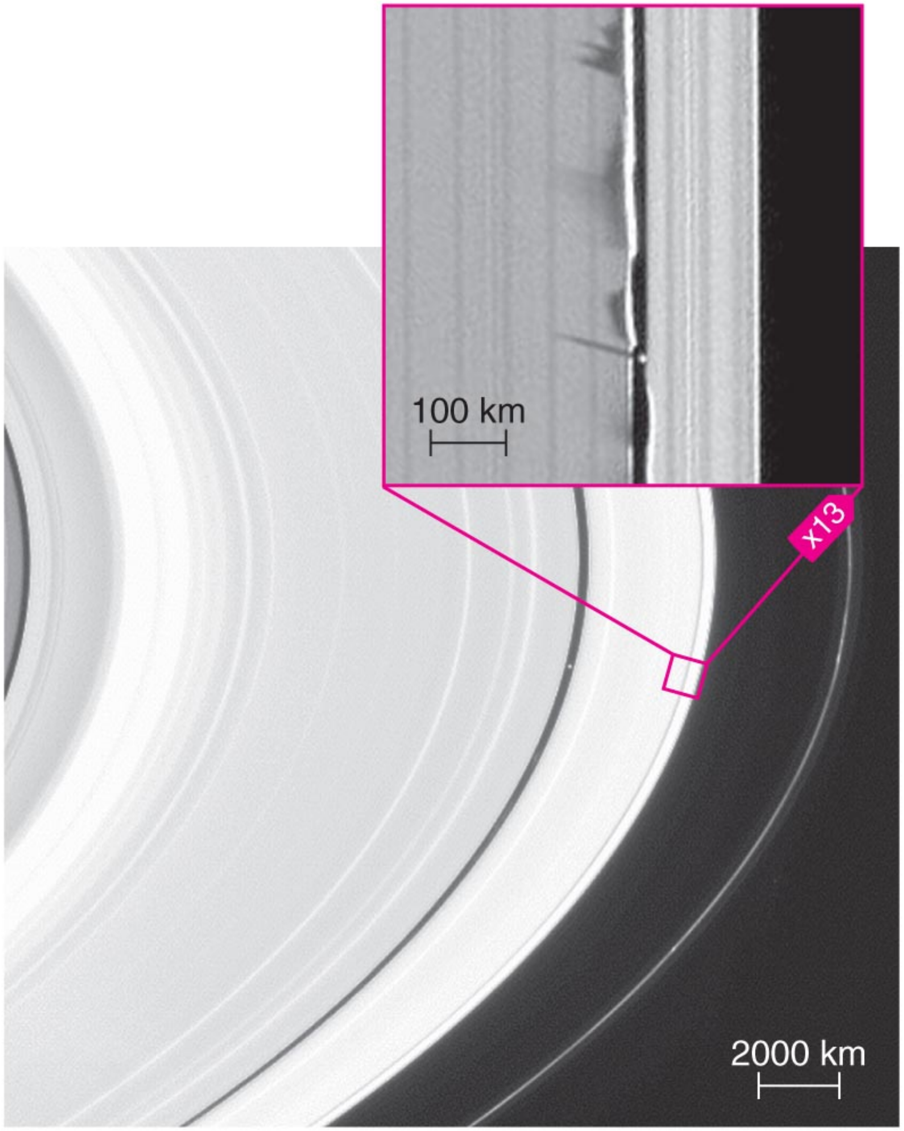


Saturn's Rings



The faint rings D, G and E were discovered by spacecraft flybys. The E ring encloses the orbit of Enceladus, one of Saturn's icy satellites. Some scientists suspect that water geysers on Enceladus are the source of ice particles in the E ring.

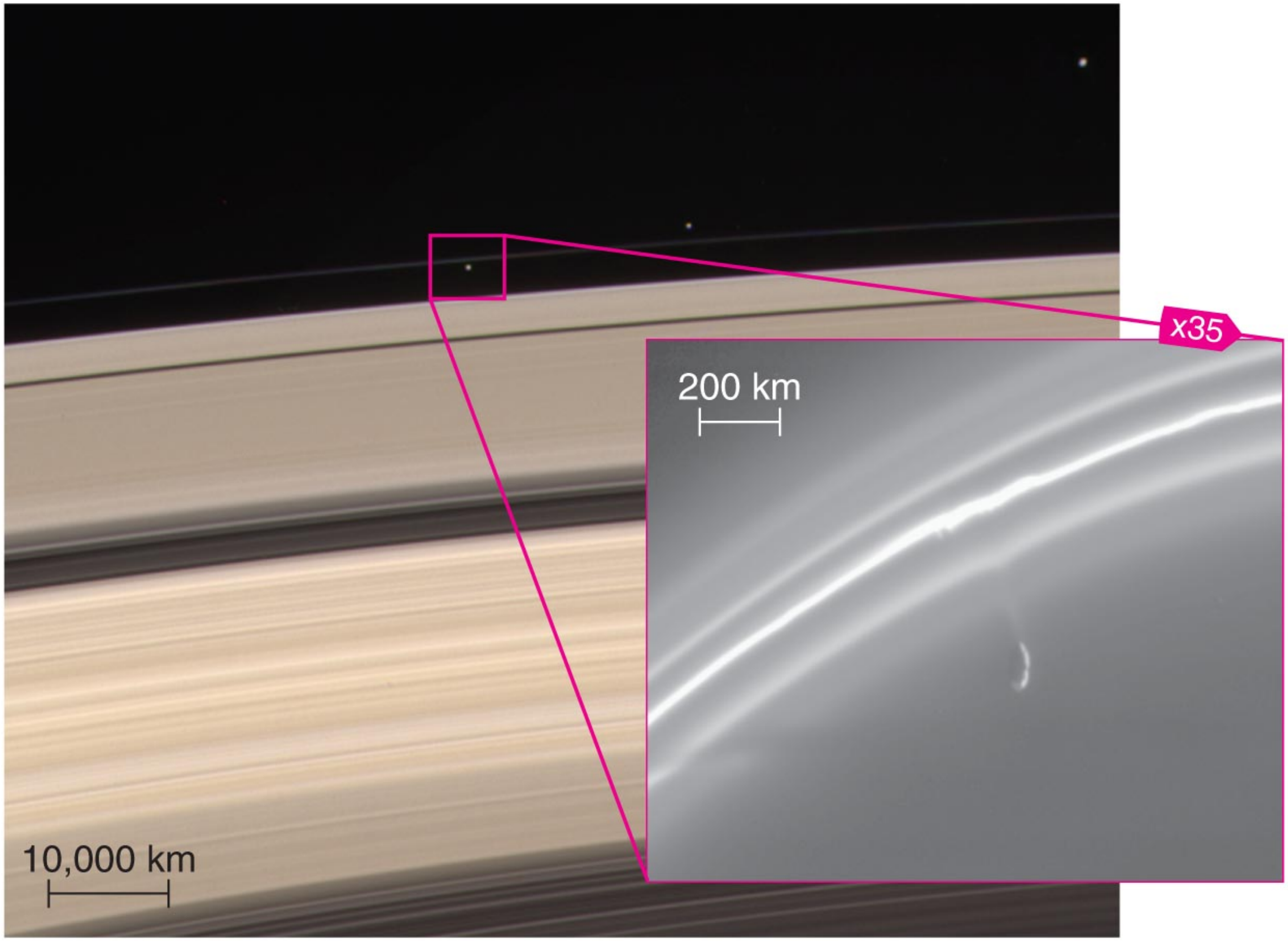
Gap Moons



a Some small moons create gaps within the rings.

- Some small moons create gaps within rings.

Shepherd Moons



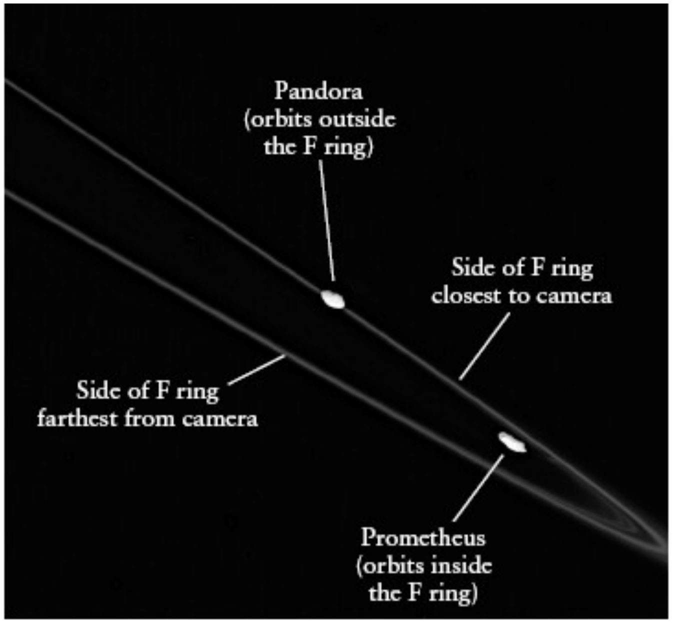
- A pair of small moons can force particles into a narrow ring.

Shepherd Moons

Following Kepler's law *Prometheus* moves faster than the particles in the F ring and it's gravitational effect on them is to increase their orbital energy and move them to a higher orbit.

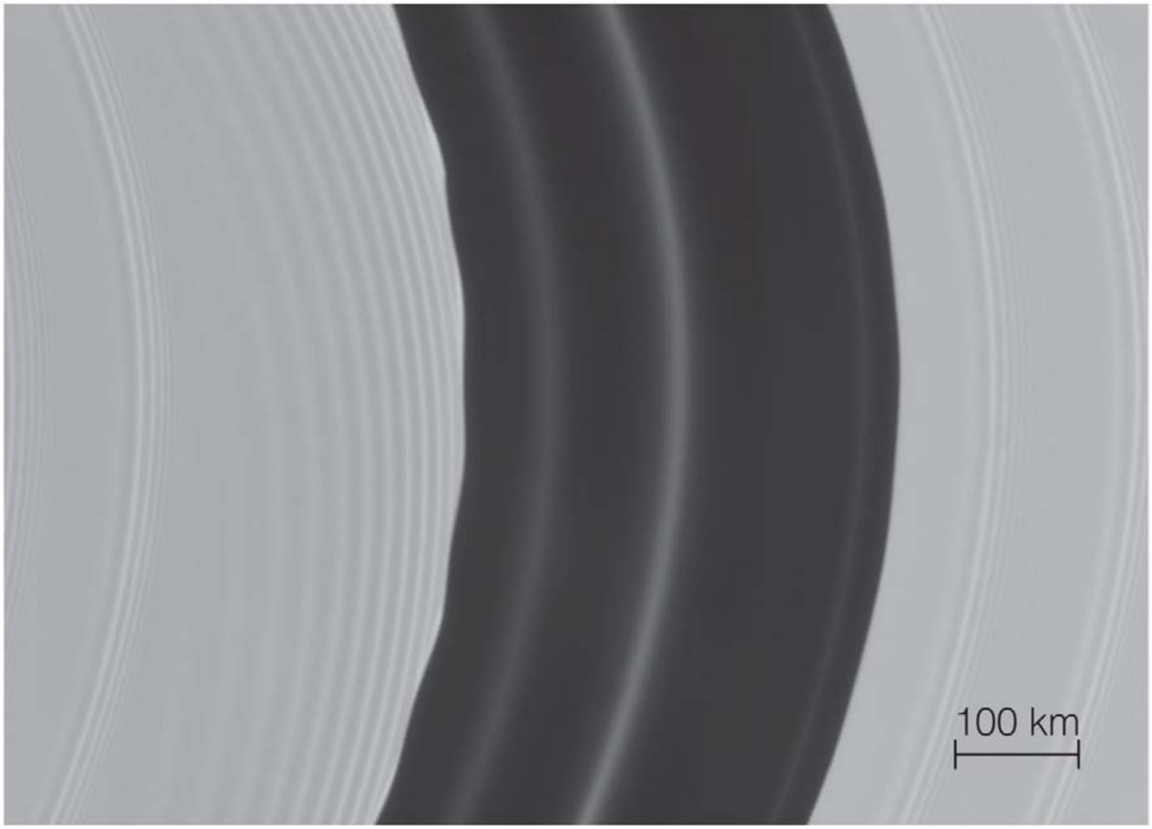
Pandora being outside of the F ring moves slower and its gravitational effect on the F ring particles is to reduce their orbital energy and move them into a lower orbit.

The combined gravitational effects of *Prometheus* and *Pandora* on the F ring particles is to focus (shepherd) the particles in a narrow band.



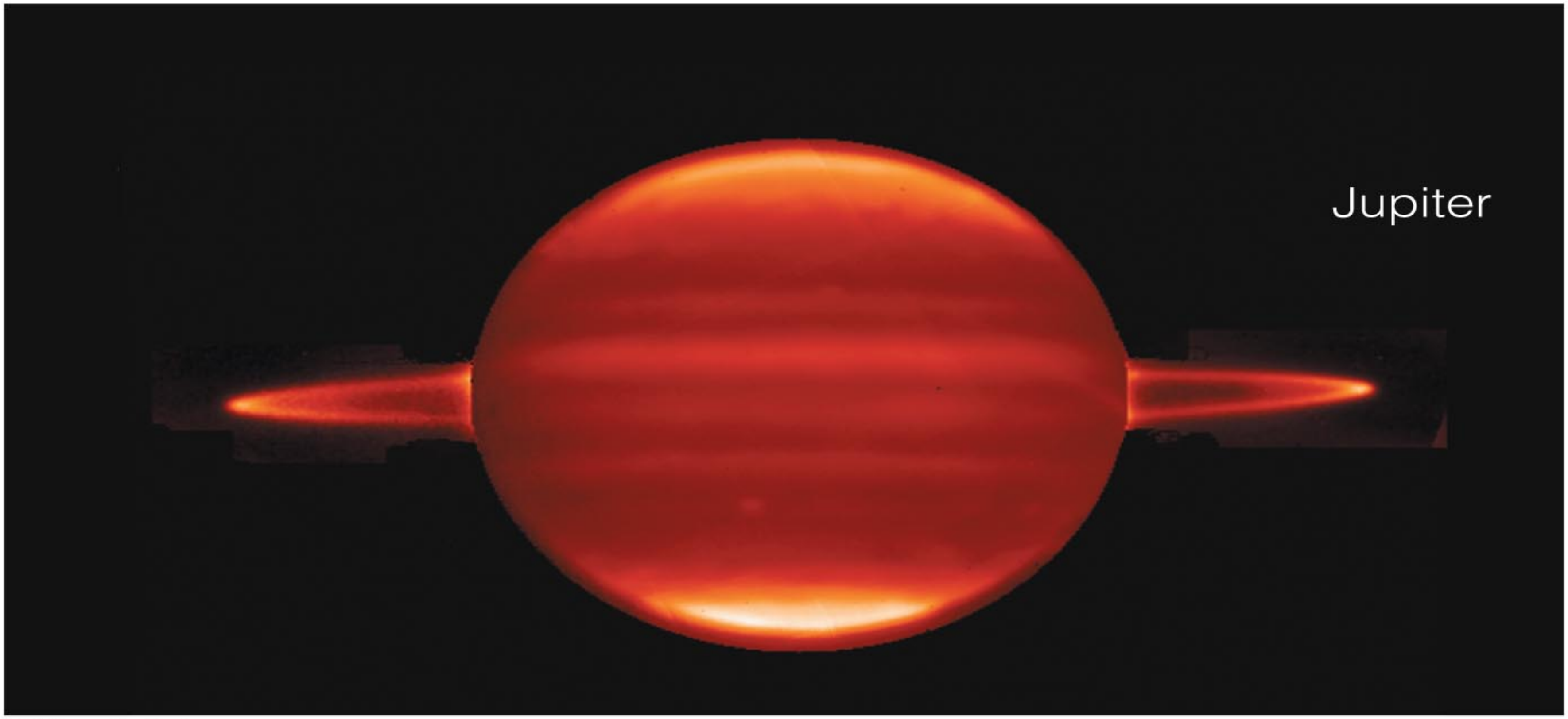
Pandora and *Prometheus* orbit Saturn on either side of its F ring, shepherding the ring particles into a narrow band.

Resonance Gaps

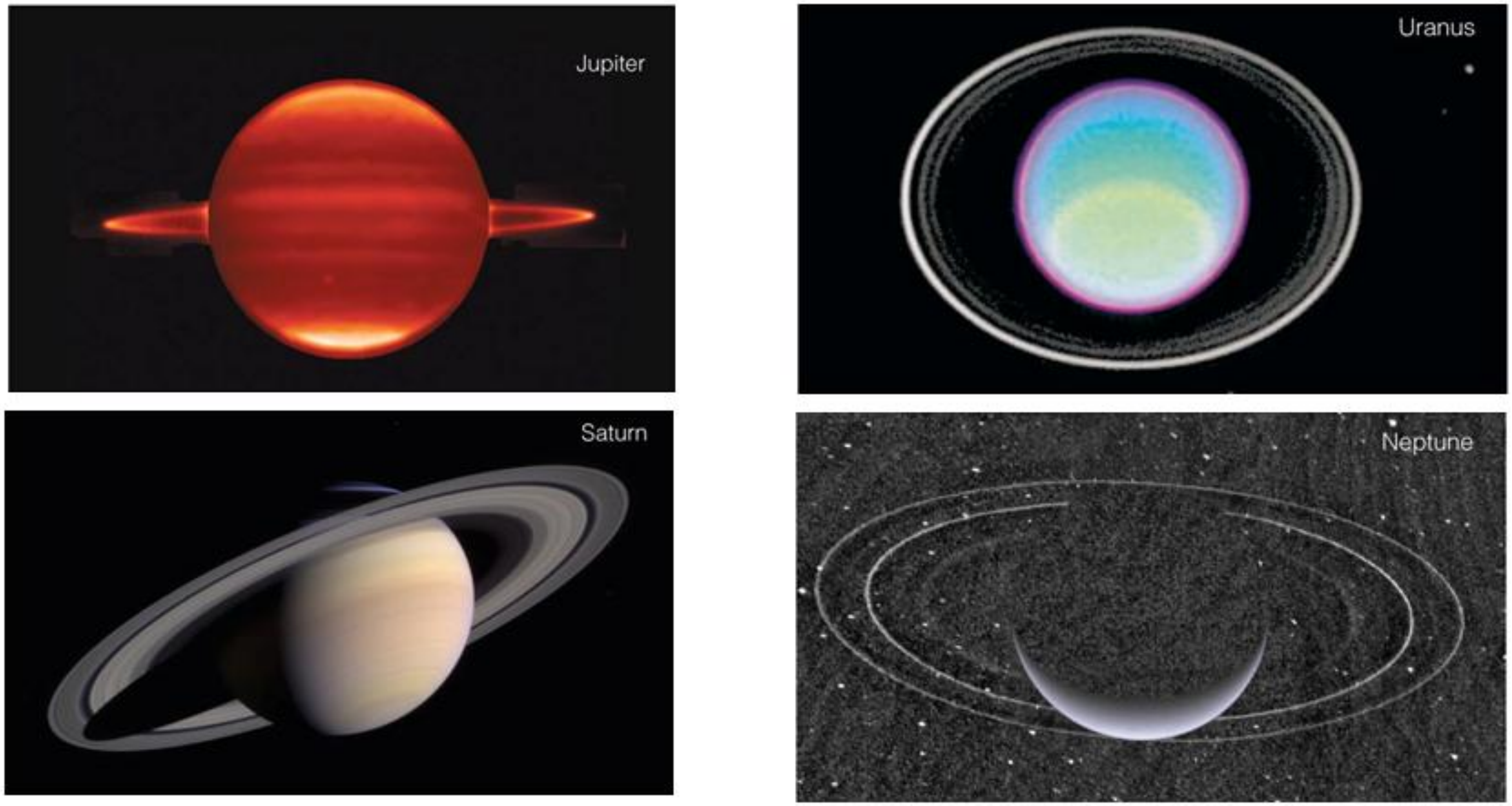


- Orbital resonance with a larger moon can also produce a gap.

How do other jovian ring systems compare to Saturn's?

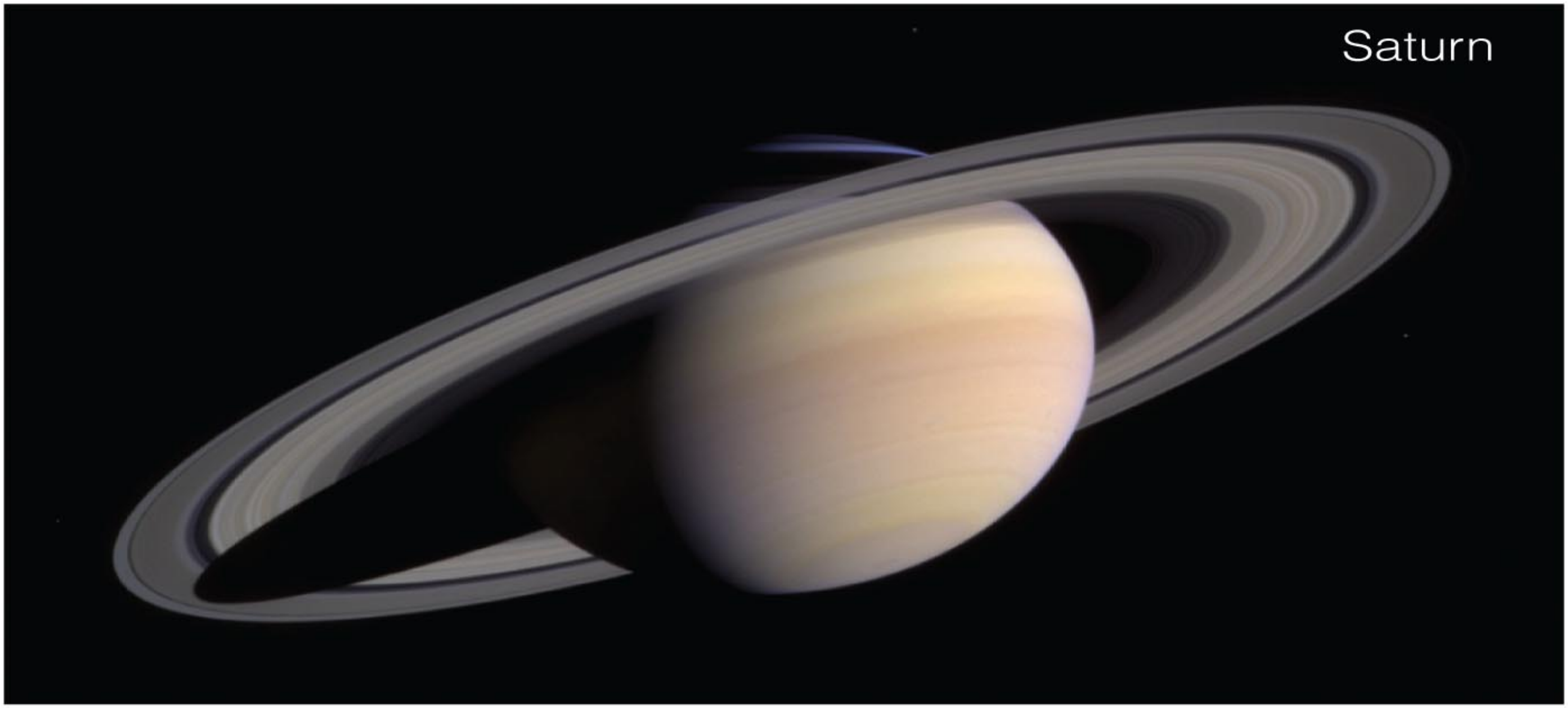


Jovian Ring Systems



- All four jovian planets have ring systems.
- Others have smaller, darker ring particles than Saturn.

Why do the jovian planets have rings?



Why do the jovian planets have rings?

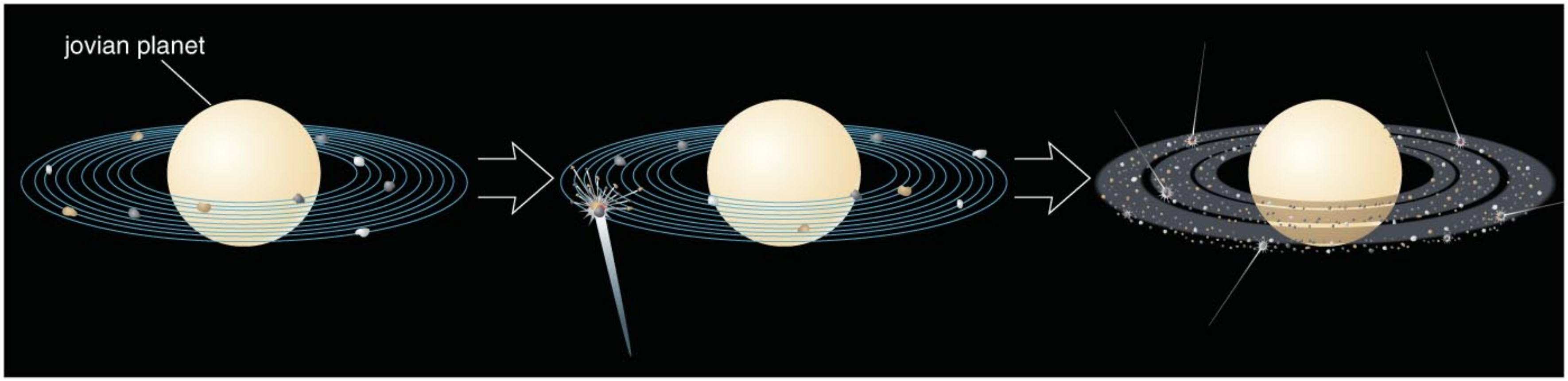
- They formed from dust created in impacts on moons orbiting those planets.

How do we know?

How do we know?

- Rings aren't leftover from planet formation because the particles are too small to have survived for so long.
- There must be a continuous replacement of tiny particles.
- The most likely source is impacts with jovian moons.

Ring Formation



- Jovian planets all have rings because they possess many small moons close in.
- Impacts on these moons are random.
- Saturn's incredible rings may be an "accident" of our time.

What have we learned?

- **What are Saturn's rings like?**
  - They are made up of countless individual ice particles.
  - They are extremely thin with many gaps.
- **How do other jovian ring systems compare to Saturn's?**
  - The other jovian planets have much fainter ring systems with smaller, darker, less numerous particles.
- **Why do the jovian planets have rings?**
  - Ring particles are probably debris from moons.