



# ASTRONOMY TODAY

CHAISSON  
McMILLAN

SEVENTH EDITION

Lecture Outlines

Chapter 11-13

*Astronomy Today*

*7th Edition*

Chaisson/McMillan



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# Units of Chapter 11-13

1. Portraits and cloud top temperatures
2. Orbital and Physical Properties skip
3. Compare internal structures light
4. Compare Atmospheres Mostly Jup
5. Compare the Moons Mostly Saturn
6. Compare the Rings Mostly Saturn

# Chapter 11-13

## Comparing the Jovians

$T_{min}=125\text{ K}$

$T_{expect}=105\text{ K}$



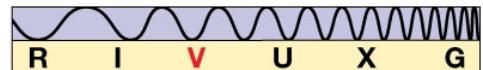
# Chapter 11-13

## Comparing the Jovians

T<sub>min</sub>=97 K



T<sub>expect</sub>=74K

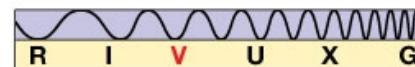


# Chapter 11-13

## Comparing the Jovians

$T_{\min} = 58 \text{ K}$

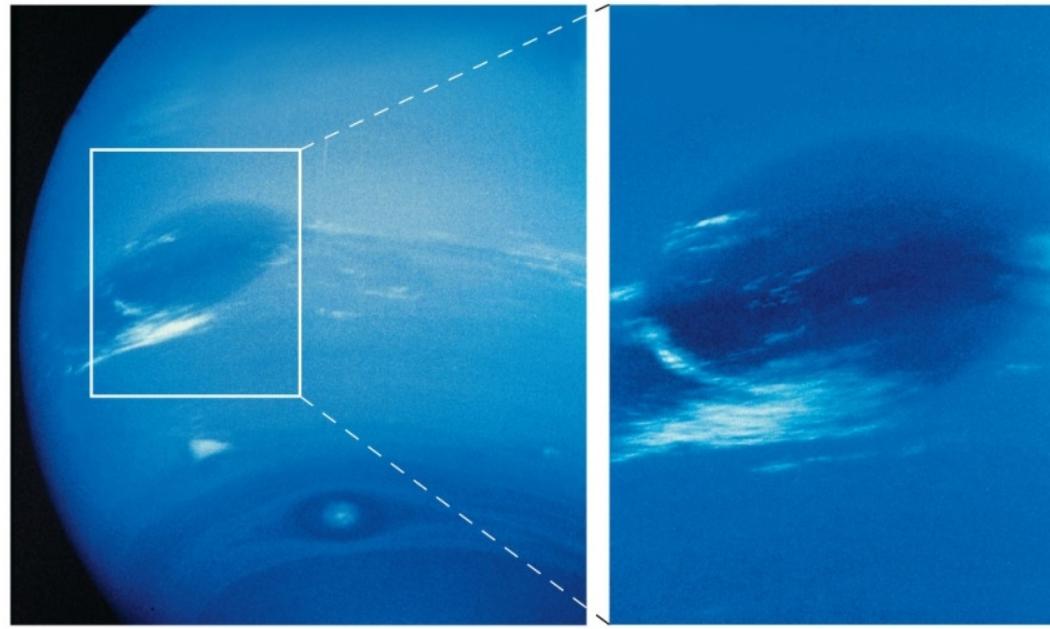
$T_{\text{expect}} = 58 \text{ K}$



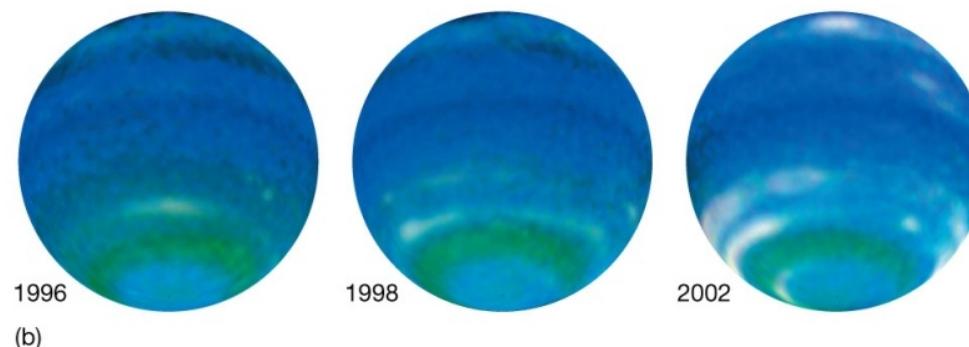
# Chapter 11-13

## Comparing the Jovians

$T_{\min} = 59 \text{ K}$



$T_{\text{expect}} = 46 \text{ K}$



# Condensation and freezing points of gases

$T_{BP} = T_{boiling} = T_{condensation}$ . Gas $\leftrightarrow$ liquid.

$T_{FP} = T_{freezing} = T_{sublimation/evaporation}$ . Gas $\leftrightarrow$ Solid.

These temperatures assume  $P=1\text{ atm}$

Gas	Gas, name	$T_{BP}$ K	$T_{BP}$ °C	$T_{FP}$ K	$T_{FP}$ °C	$T_{FP}$ °F
	$H_2O$ Water vapor	373 K	100 °C	273 K	0 °C	32 °F
86%	$H_2$ Hydrogen	20	-253	14	-259	-434
13.8%	He Helium	4	-269	1	-272	-458
Jupiter	$N_2$ Nitrogen	77	-196	63	-210	-346
	$O_2$ Oxygen	90	-183	55	-218	-360
	$NH_3$ Ammonia	240	-33	195	-78	-126
	$CH_4$ Methane	113	-161	91	-182	-296
	$NH_4SH$ Am.Hydrosulfide	330	57 <195?	?	?	?

# Cloud layers of Jupiter

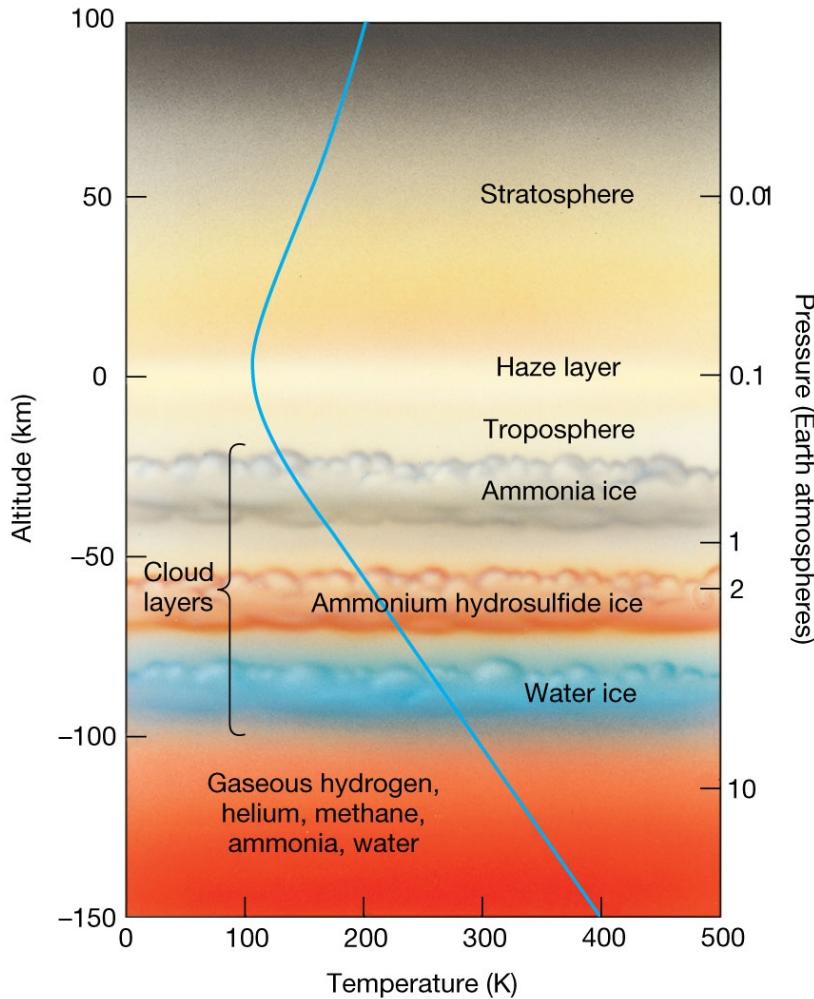
No clouds of H or He.

Methane could form drops ( $T_{BP} = 113K$ ), but  $P < 1$  atm.  $\text{CH}_4$  more important on other Jovians.

White  $\rightarrow$  ammonia ice  $T_{FP} = 195K$

Orange  $\rightarrow$   $(\text{NH}_4)\text{HS}$   $T_{FP} < 330K$

Blue  $\rightarrow \text{H}_2\text{O}$  ice  $T_{FP} = 273 K$



# Cloud layers of Saturn

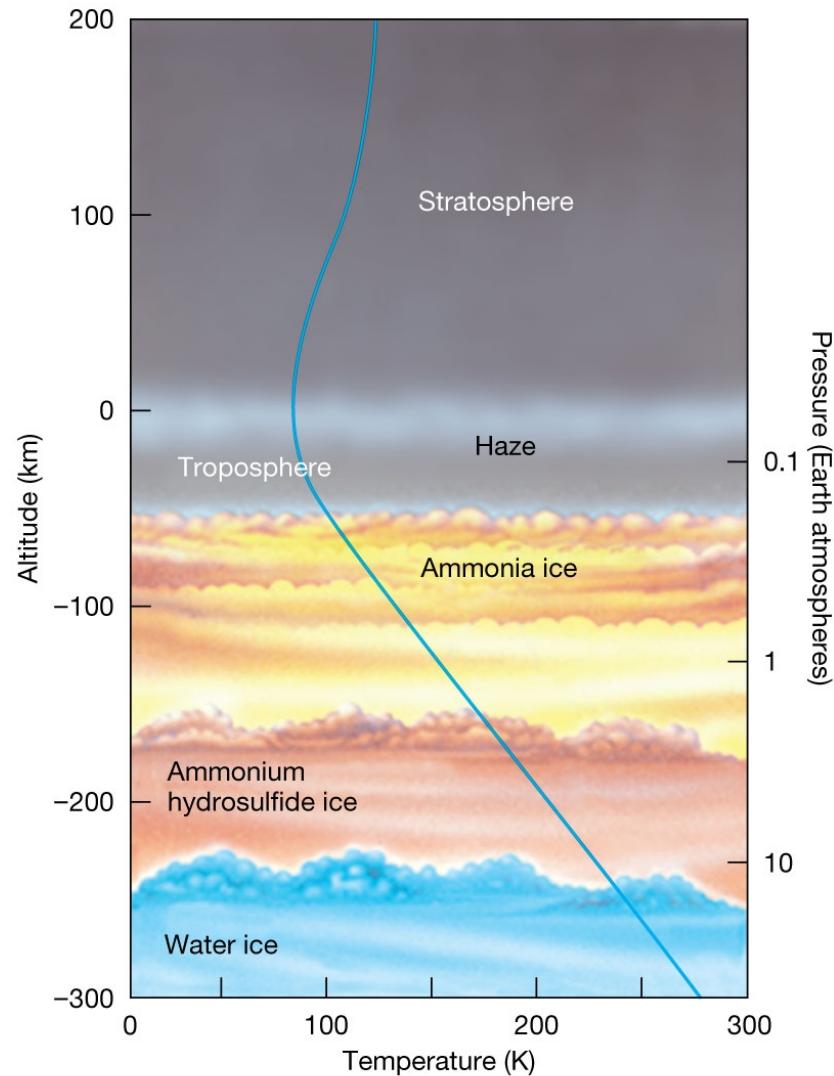
The same types of clouds seen on Jupiter exist on Saturn, but they are more spread out vertically. Why?

Scale height,  $H=kT/mg$ , so it's because  $g$  is smaller on Saturn.

$$H_{\text{Jup}} = 27 \text{ km} \quad g = 26 \text{ m/s}^2$$

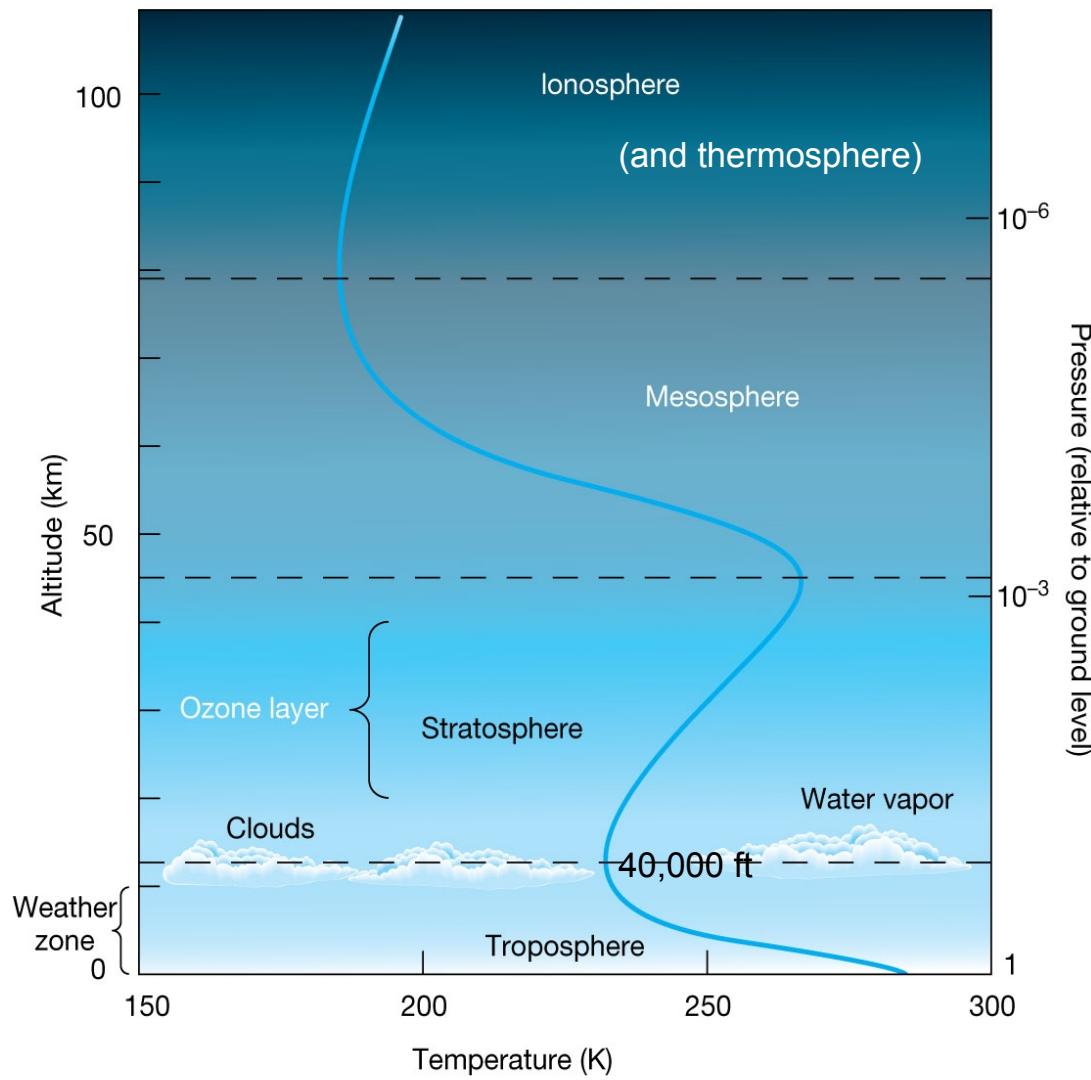
$$H_{\text{Sat}} = 60 \text{ km} \quad g = 11 \text{ m/s}^2$$

$$H_{\text{Earth}} = 8.5 \text{ km} \quad g = 9.8 \text{ m/s}^2$$



# 7.2 Earth's Atmosphere

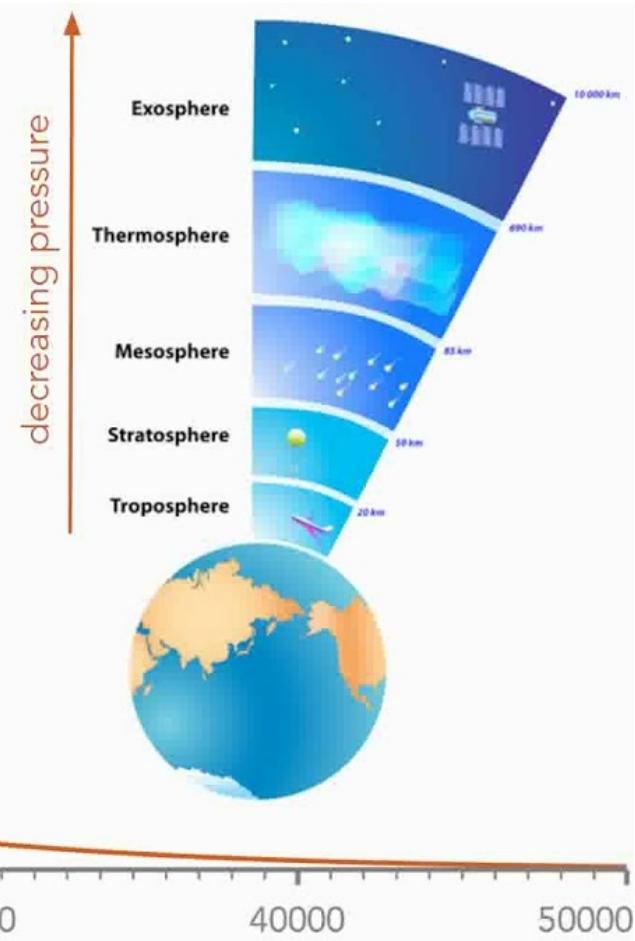
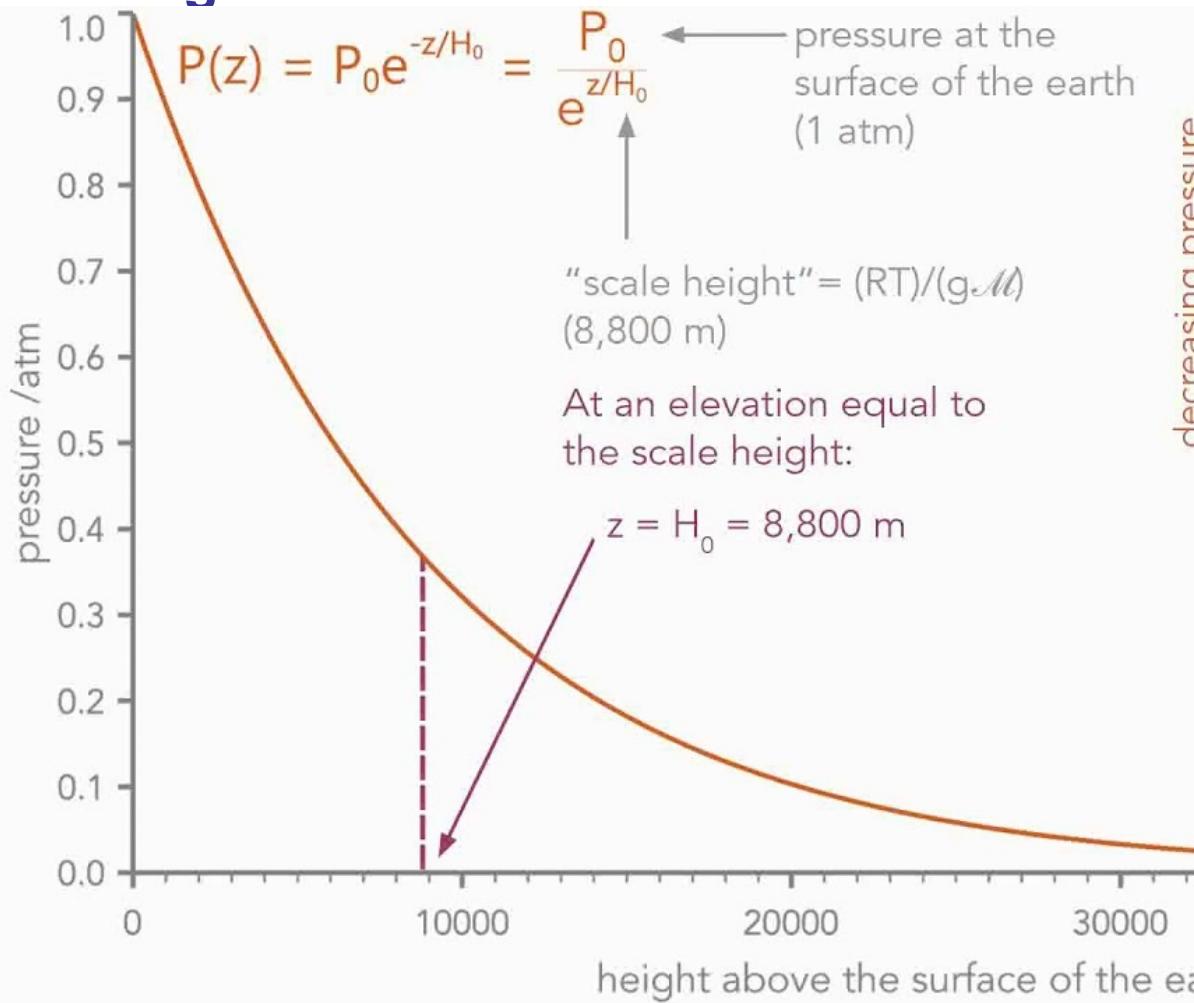
- Only 12 km tropopause.
- Scale height of Earth's atmosphere is ~8.5 km.



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# 7.2 Earth's Atmosphere

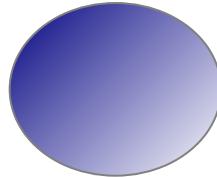
- **Scale height** is the increase in height in an atmosphere that causes the pressure (and density) to decrease to 36.8% of the starting value.



### 3. Internal Structures

Although we can't see through the atmospheres of the Jovians, we can use the orbits of our spacecraft to figure out the internal mass density distribution.

They are *oblate spheroids* because of rapid rotation.

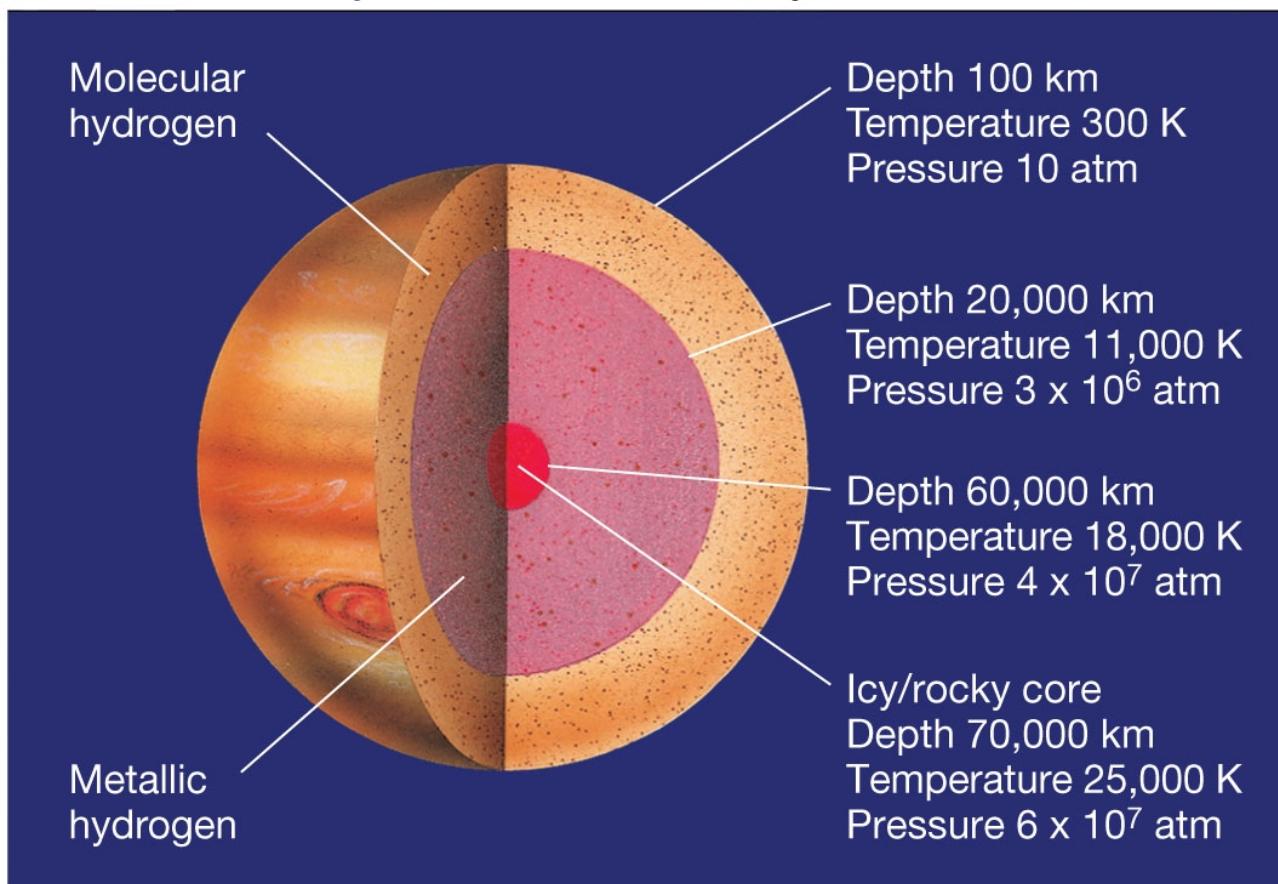


They are generally azimuthally symmetric, but not spherically symmetric. Degree of oblateness suggests denser cores than if made of only H and He.

### 3. Internal Structures

The internal layers are based on changes in phase and molecular form of hydrogen and helium. (Behavior of H and He known from lab and atomic theory.)  
The center is probably a dense “rocky” core.

Jupiter



### 3. Internal Structure - Jupiter

Jupiter radiates more energy than it receives from the Sun:

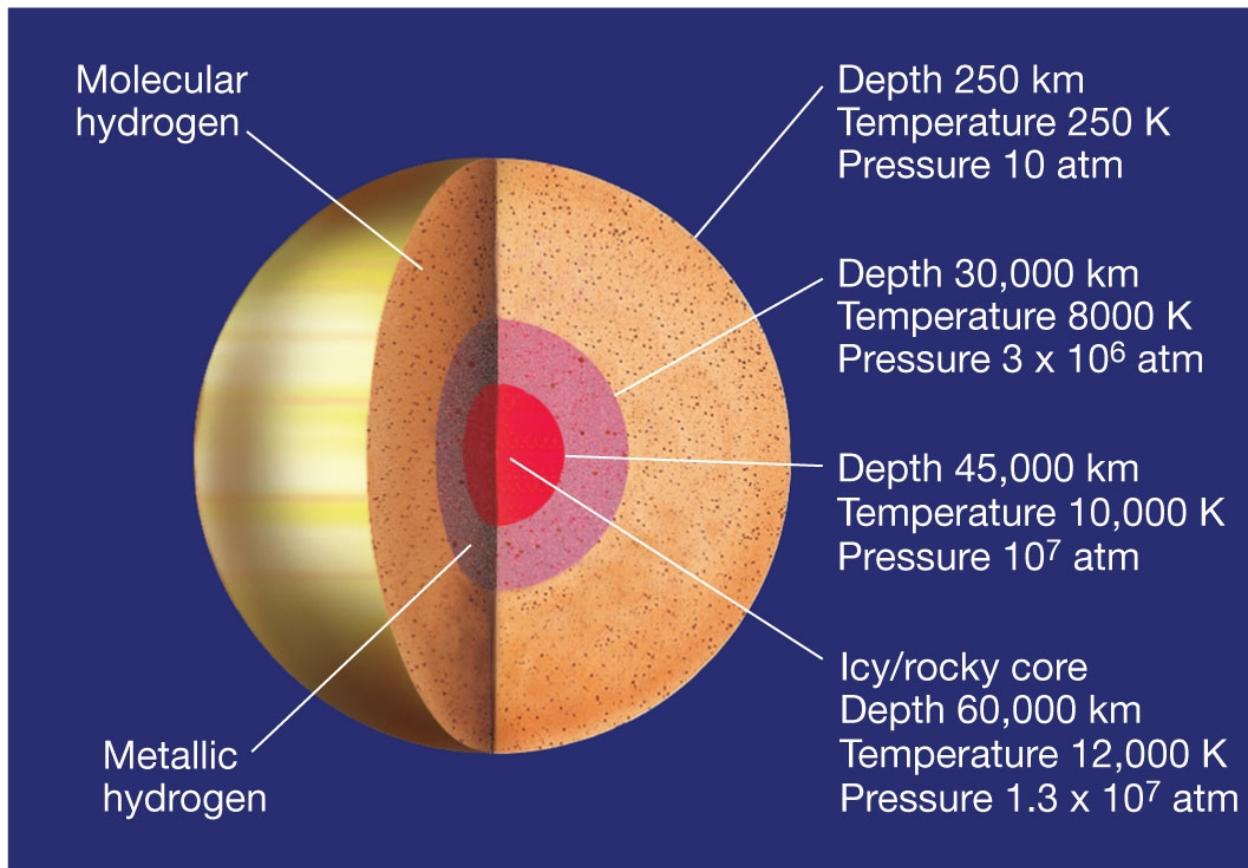
- Core is still cooling off from heat of gravitational contraction

Q: Could Jupiter have been a star?

- No; not dense and hot enough at the core for H fusion. It would need to be about 80 times more massive to be even a very faint star.
- Brown dwarfs have  $M < \sim 0.08 M_{\odot}$  - below fusion limit.
- Jupiter has  $M \sim 0.001 M_{\odot}$

# 3. Internal Structures - Saturn

Interior structure similar to Jupiter's



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### 3. Internal Structure - Saturn

Saturn also radiates more energy than it gets from the Sun, but it's not just the residual heat of collapse. It is ...

Helium rain: helium tends to condense into droplets and then fall.

- Gravitational energy converts into thermal energy as the mass descends and collides with other matter.
- Atmosphere is now noticeably depleted of He.

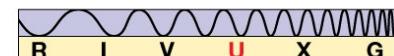
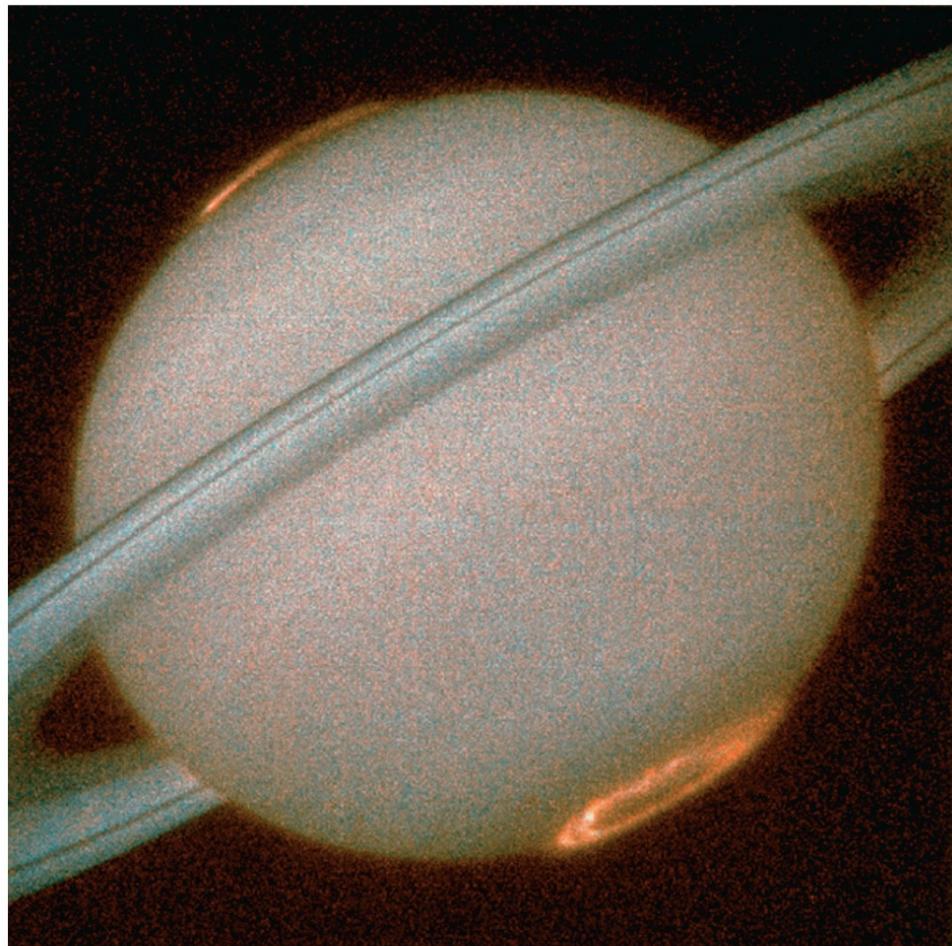
# 3 Internal Structures - Saturn

Saturn also has a strong magnetic field, but only 5% as strong as Jupiter's.

Suggests interior rotation of  $10^{\text{h}}46^{\text{m}}$ .

Almost no tilt relative to spin axis.

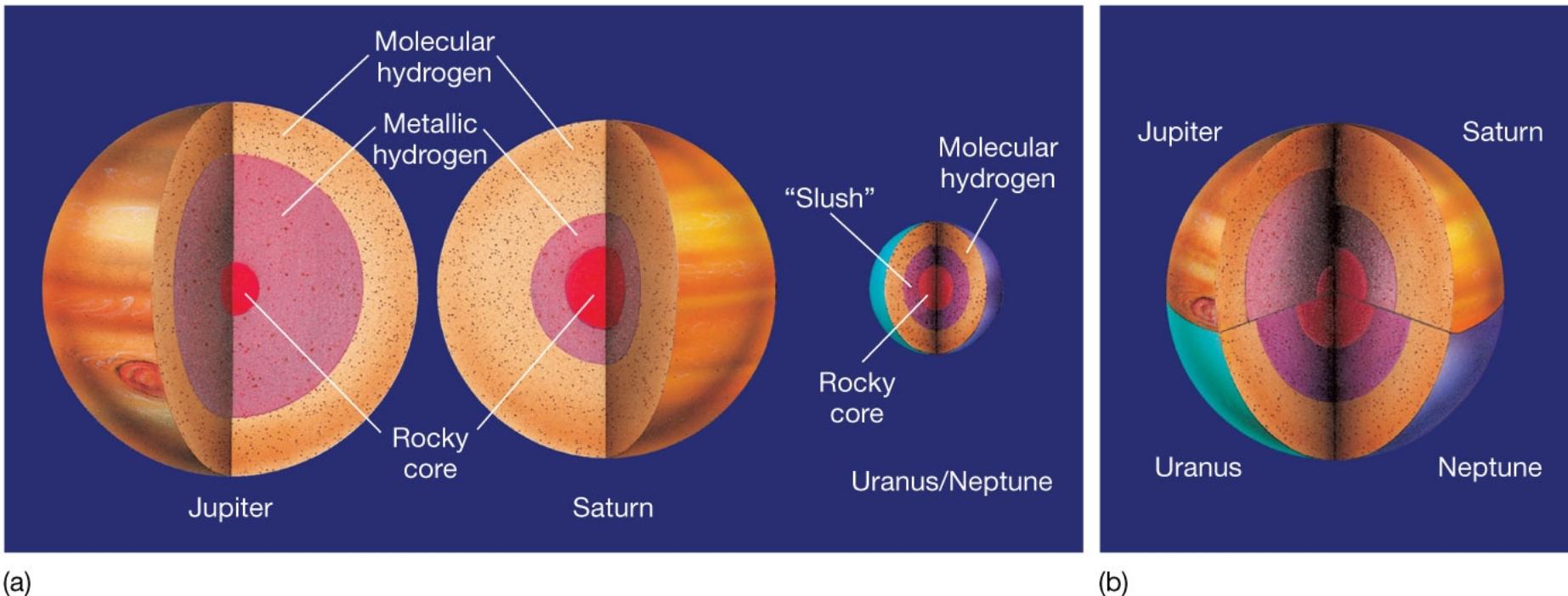
Creates aurorae.



### 3. Internal Structures - Uranus/Neptune

Magnetic fields of Uranus and Neptune may be produced by dynamos, in the outer slushy layers, not metallic H.

Interior structure of Uranus and Neptune, compared to that of Jupiter and Saturn



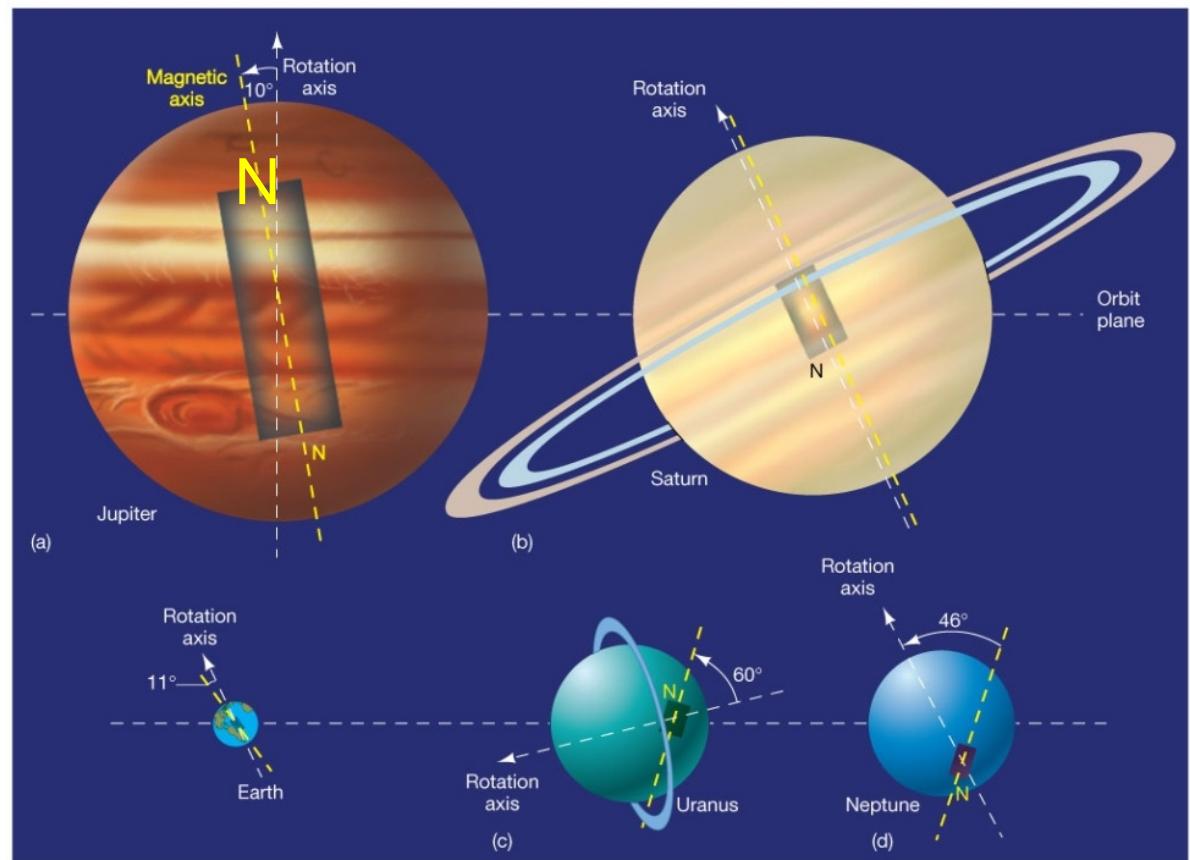
(a)

(b)

### 3. Internal Structures (Uranus & Neptune)

Uranus and Neptune both have substantial magnetic fields, but at a large angle to their rotation axes.

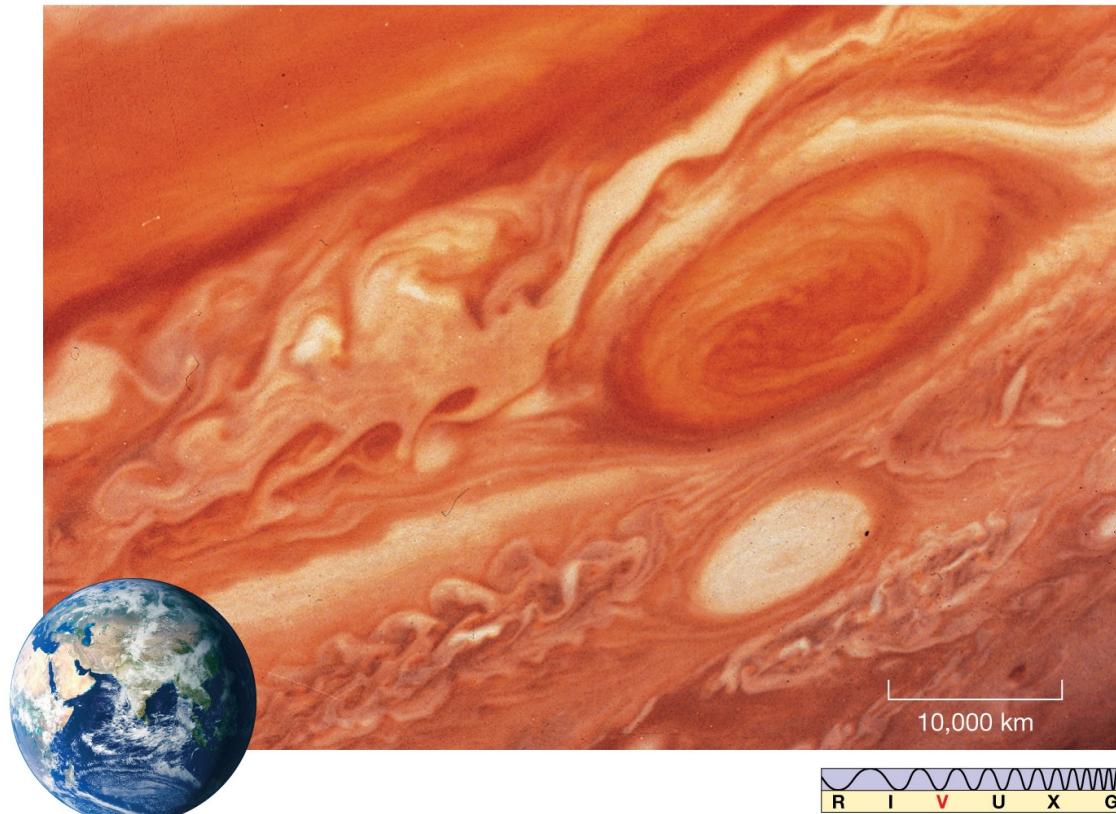
The rectangle within each planet shows a bar magnet that would produce a similar field. Both Uranus' and Neptune's are significantly off center.



# 4. Atmospheres - Jupiter

Major visible features:

white ovals, brown ovals, Great Red Spot

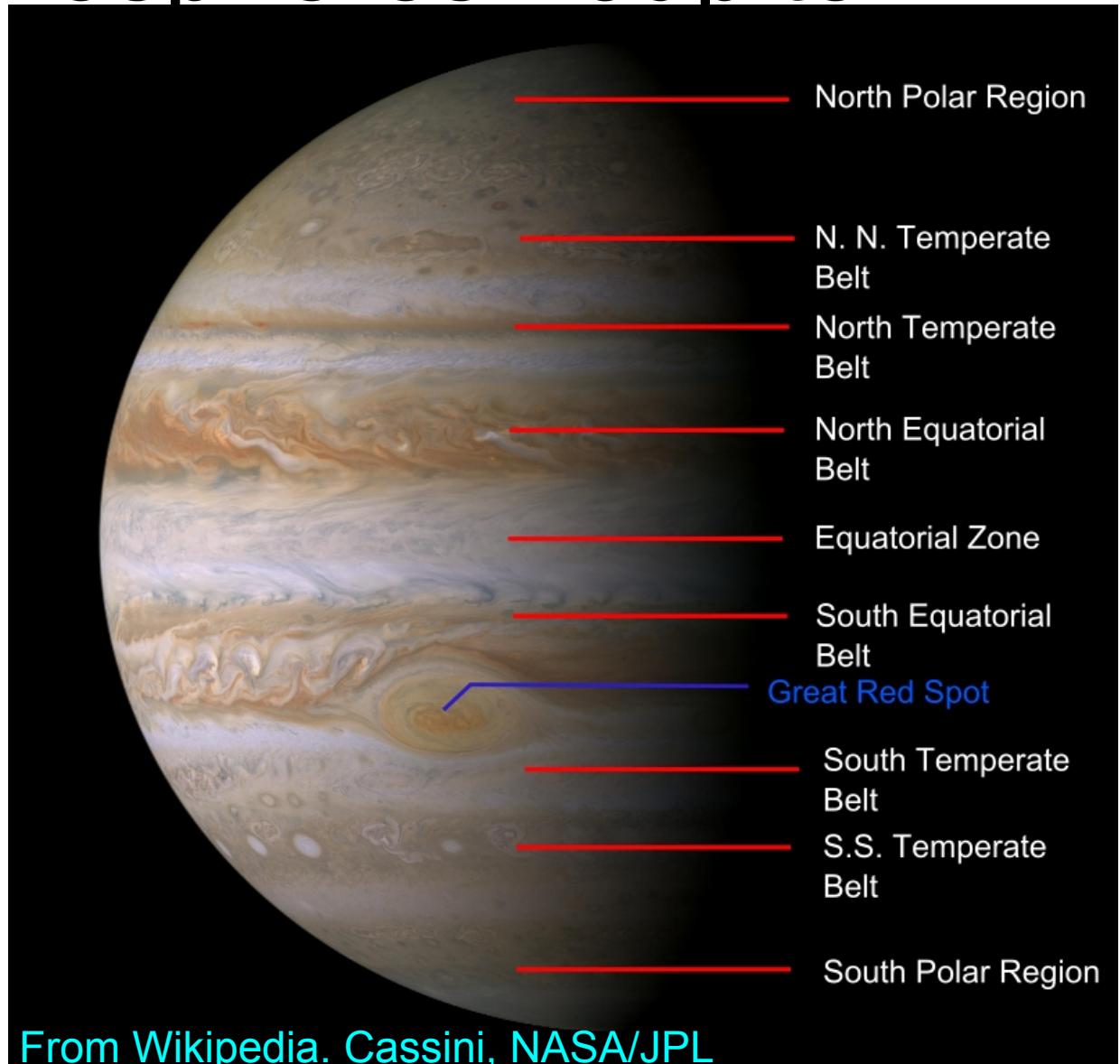


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# 4. Atmospheres - Jupiter

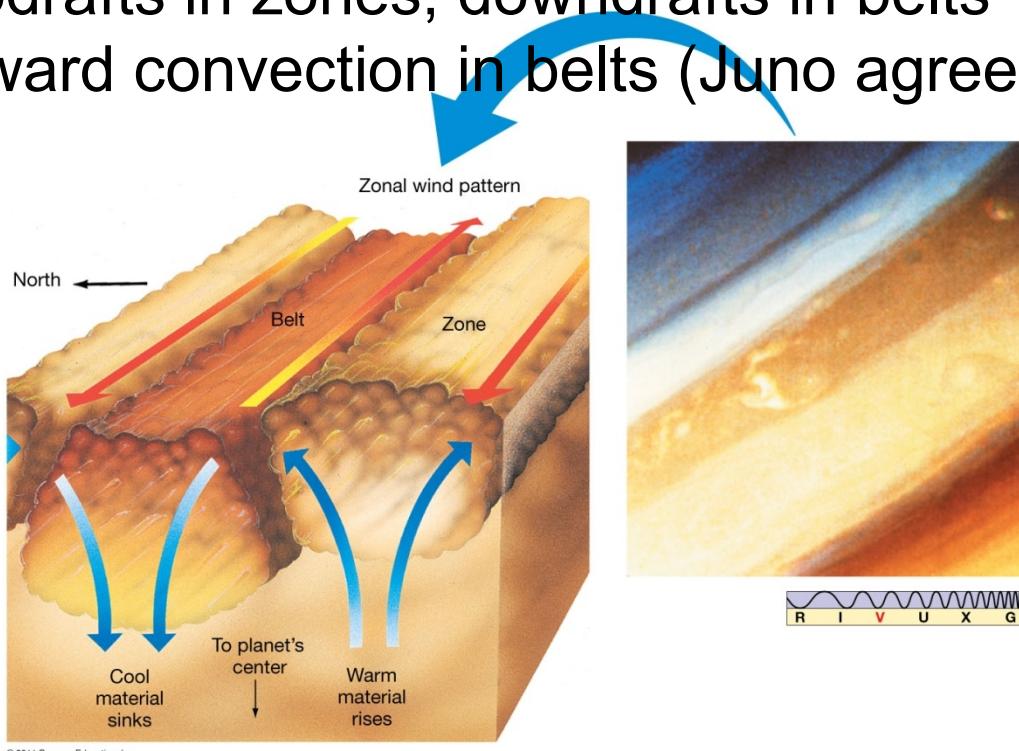
Belts: dark

Zones: light



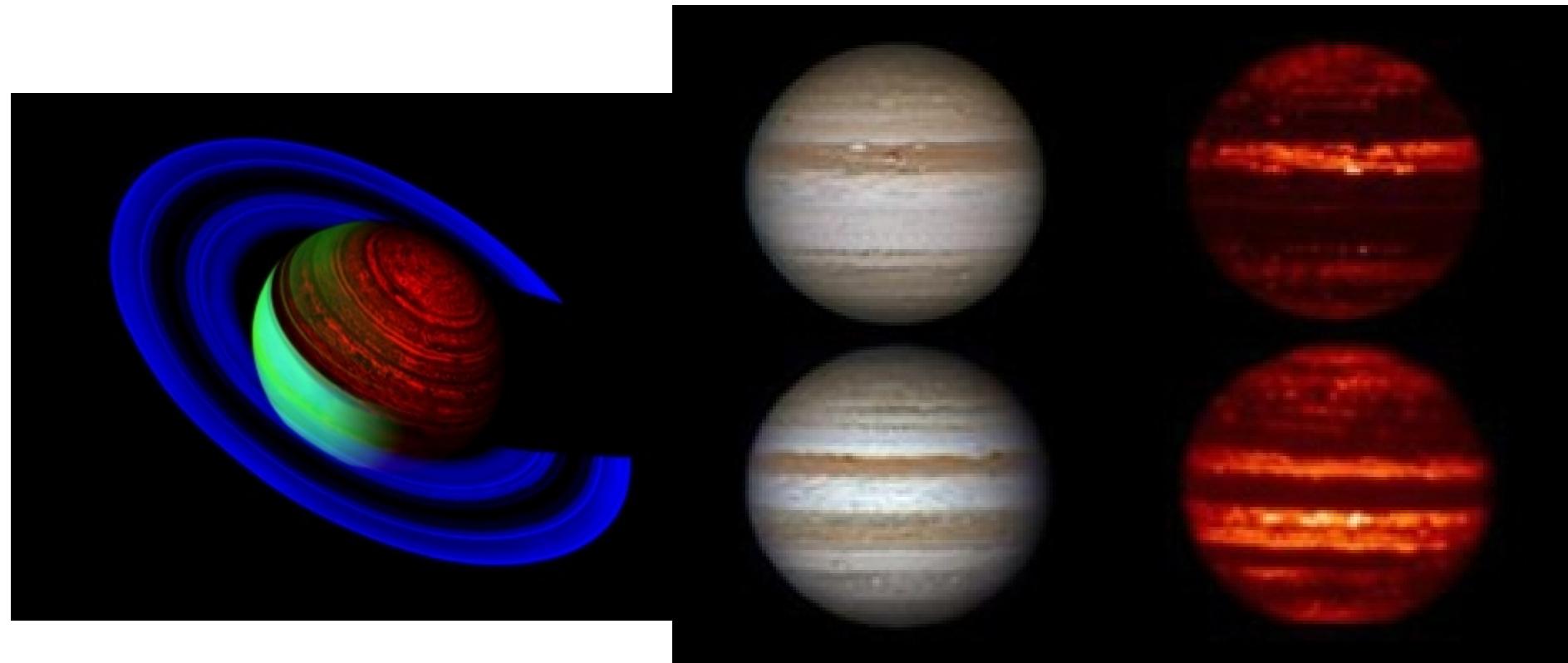
# 4. Atmospheres - Jupiter

- Atmosphere has bright **zones** and dark **belts**
- **Zones** are cooler, and are higher than **belts**
- A stable, **zonal flow**, underlies zones and belts
- **Voyager** model: updrafts in zones, downdrafts in belts
- **Cassini** model: upward convection in belts (Juno agrees)



# 4. Atmospheres – belts & zones

- Zones are cooler, and are higher **than** belts
- Infrared images are brighter where we have direct sight of deeper, hot regions
- Visible images: bright=upper cloud decks



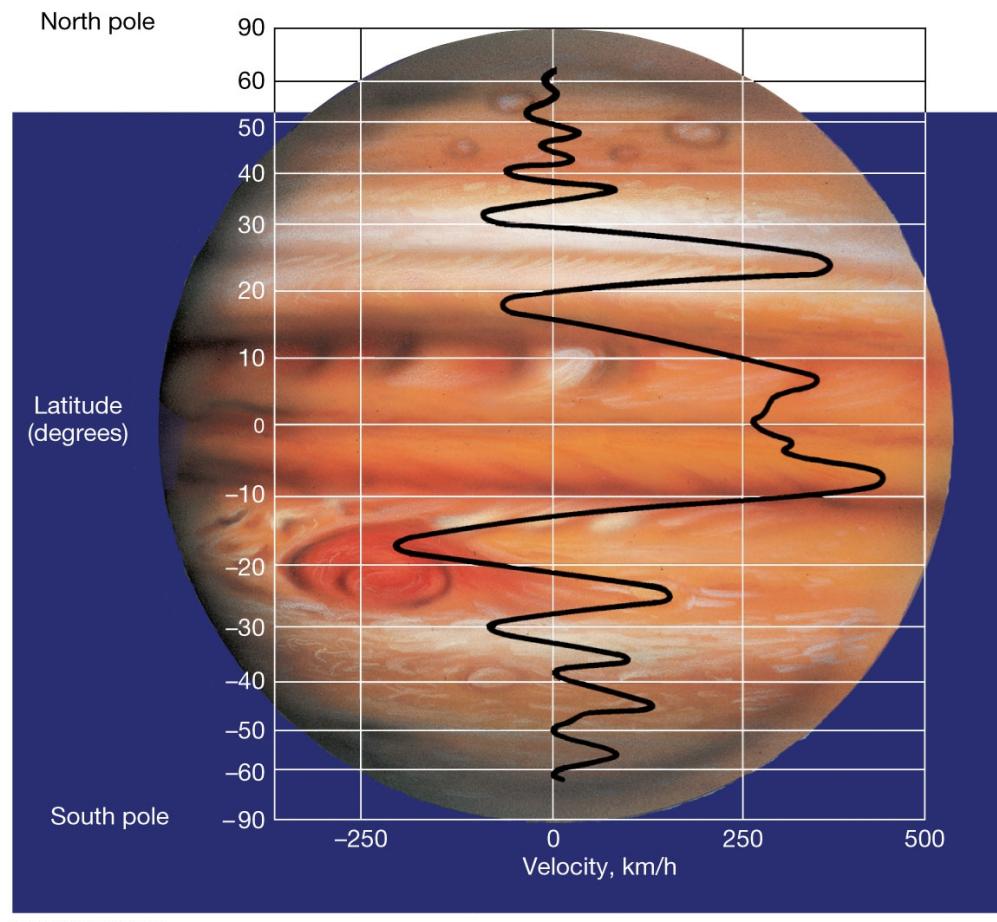
Q: what is strangely missing above?

# 4. Atmospheres - Jupiter

**Zonal Flow:** Wind speed with respect to internal rotation rate.

Fast winds to E at equatorial zone and other zones.

Fast winds to W at S equatorial belt and N equatorial belt.

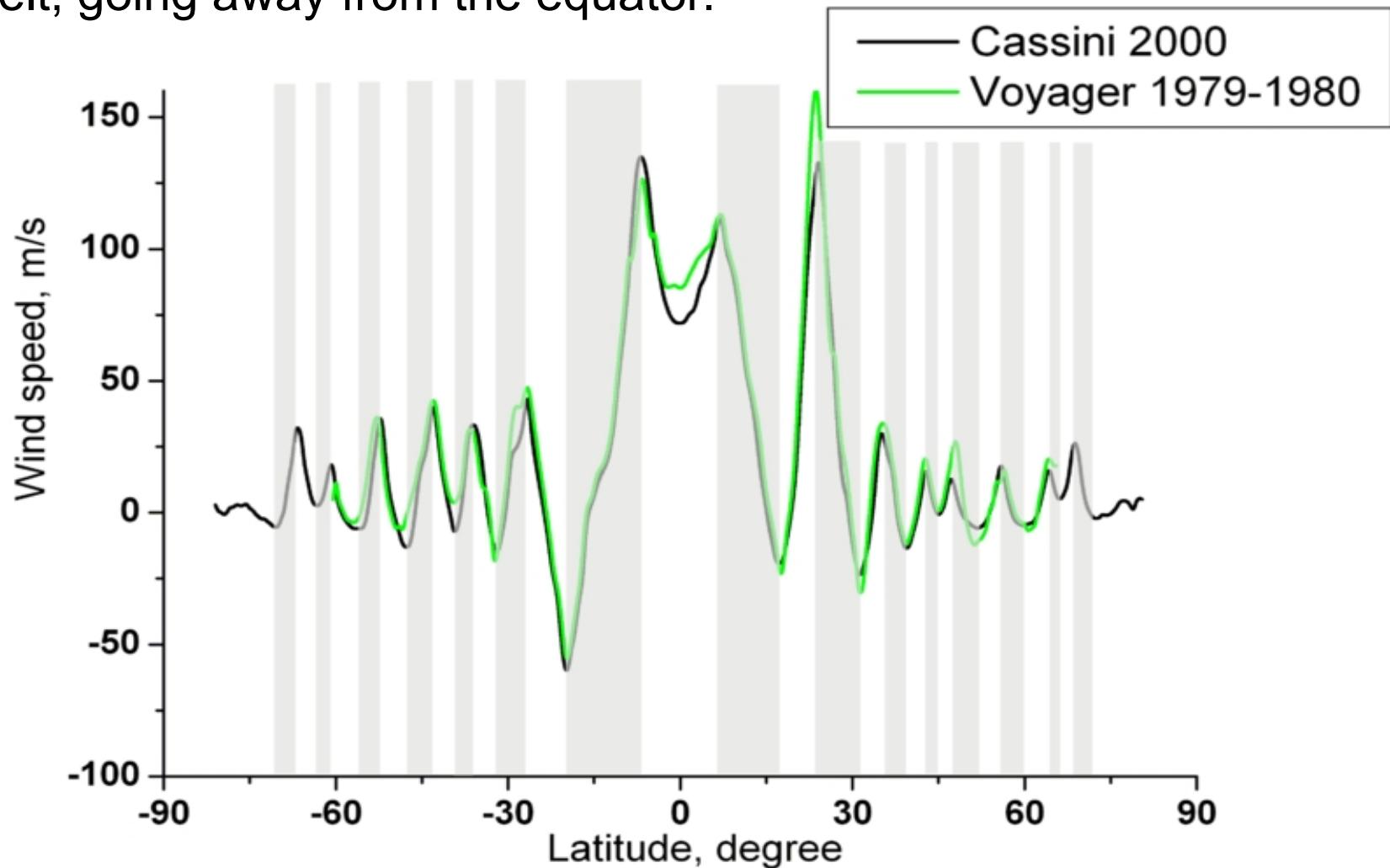


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See animated zonal flow in Wikipedia

## 4. Atmospheres - Jupiter

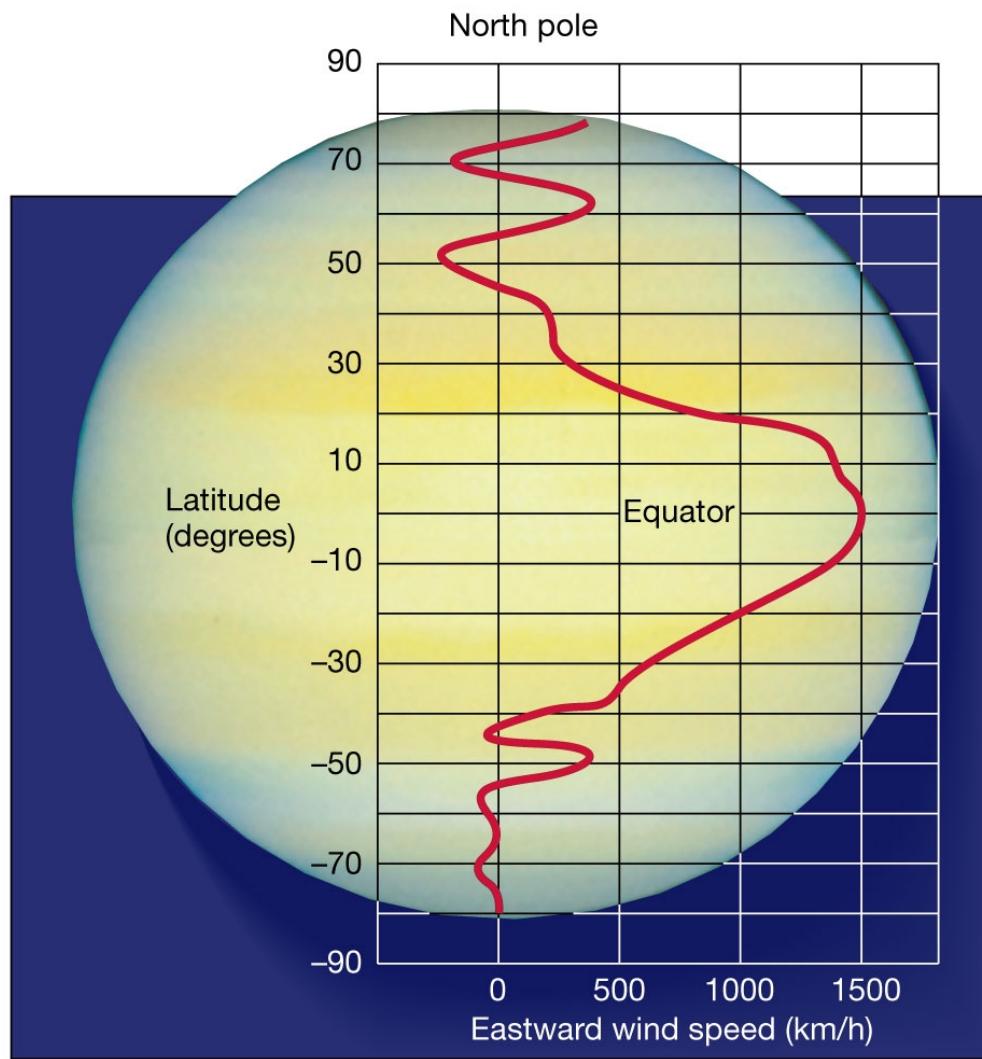
Actually, the peak Eastward flows are at transitions from zone to belt, going away from the equator.



# 4. Atmospheres - Saturn

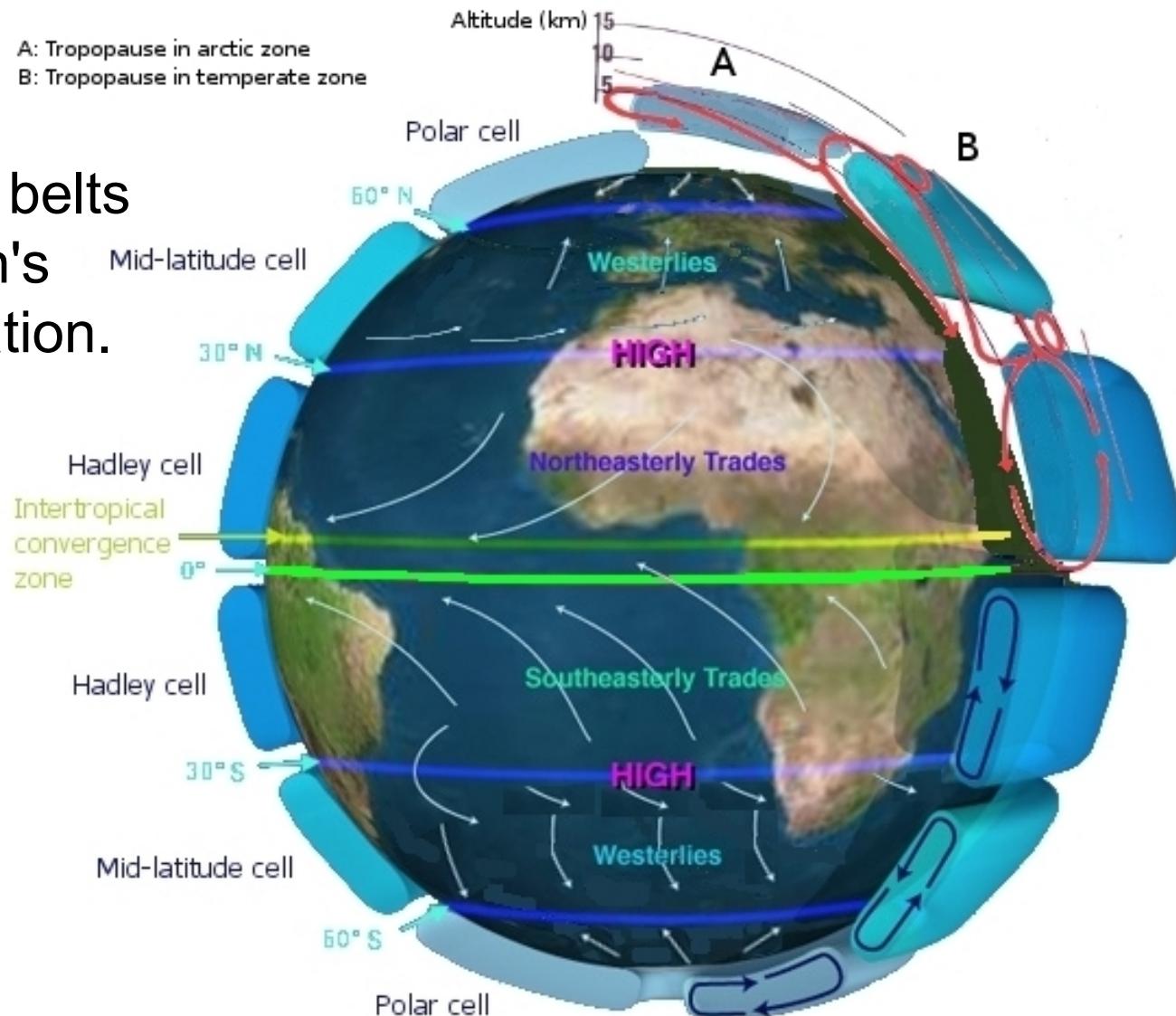
Zonal Flow: Wind speed with respect to internal rotation rate.

Up to 1500 km/s.  
Broader range of latitudes per zone.



# 4. Atmospheres - Earth

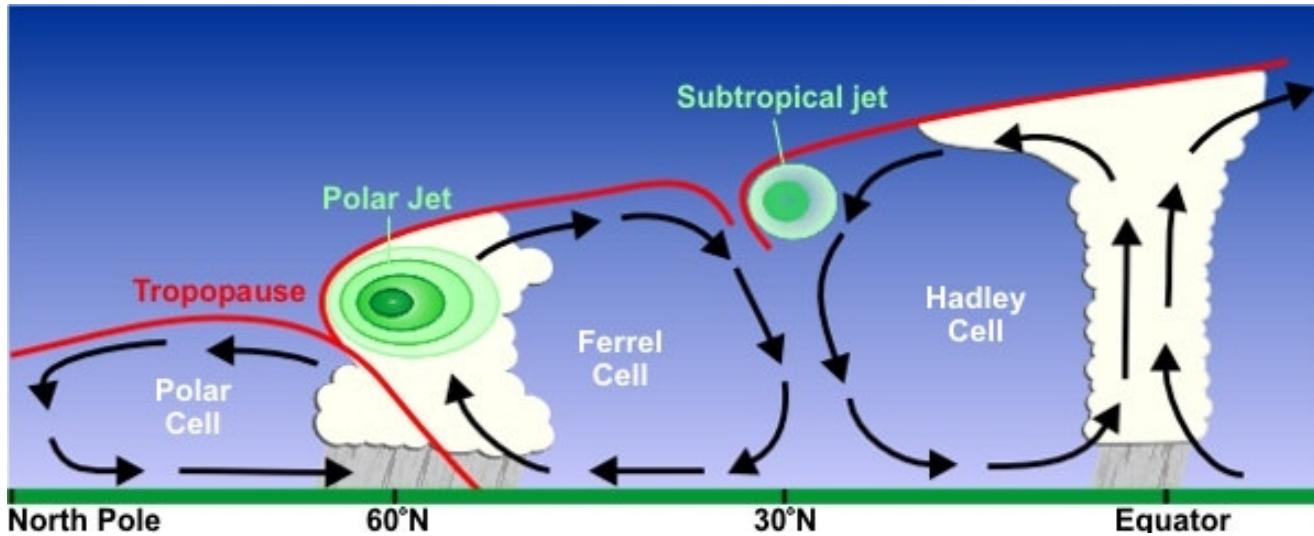
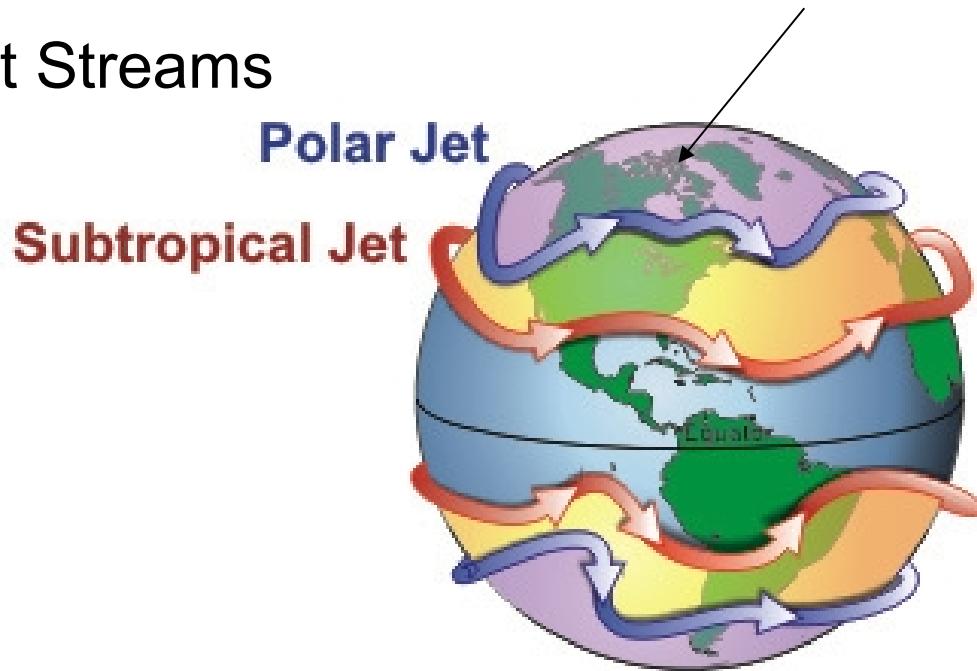
Compare Jupiter's belts  
and zones to Earth's  
**Hadley Cell** circulation.



## 4. Atmospheres - Earth

“polar vortex”

Compare to Earth: Jet Streams



## 4. Atmospheres - Jupiter

Composition of atmosphere: mostly molecular hydrogen (86%) and helium (14%); small amounts of methane, ammonia, and water vapor

The colors in visible images are probably due to complex chemical interactions, like photolysis.  $\text{NH}_3$ ,  $\text{CH}_4$ , and  $\text{C}_2\text{H}_2$  exposed to UV can produce chromophores<sup>†</sup> (coloring agents). Sulfur compounds, phosphine ( $\text{PH}_3$ ), and organic compounds may also make up some of the chromophores.

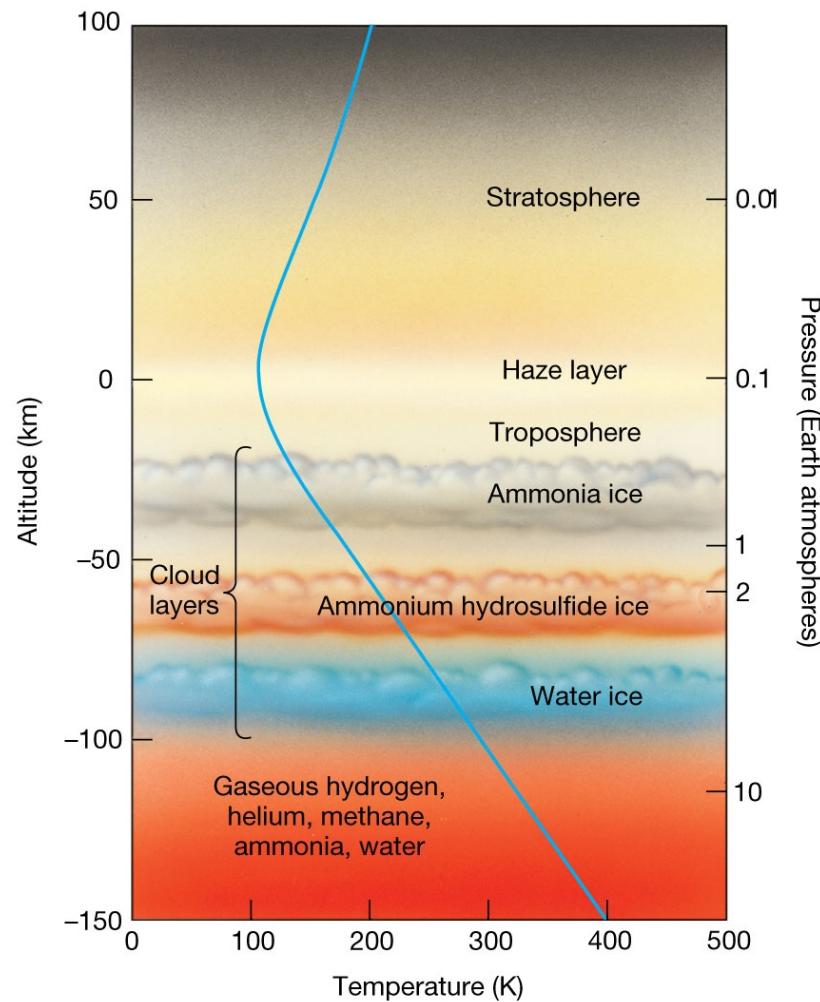
<sup>†</sup>like aliphatic imines, amines, and nitriles – R. Carlson JPL 2006.

## 4. Atmospheres - Jupiter

No solid surface; take top of troposphere to be at 0 km

Lowest cloud layer cannot be seen by optical telescopes

Measurements by Galileo probe show high wind speeds even at great depth—probably due to heating from planet, not from Sun



## 4. Atmospheres - Saturn

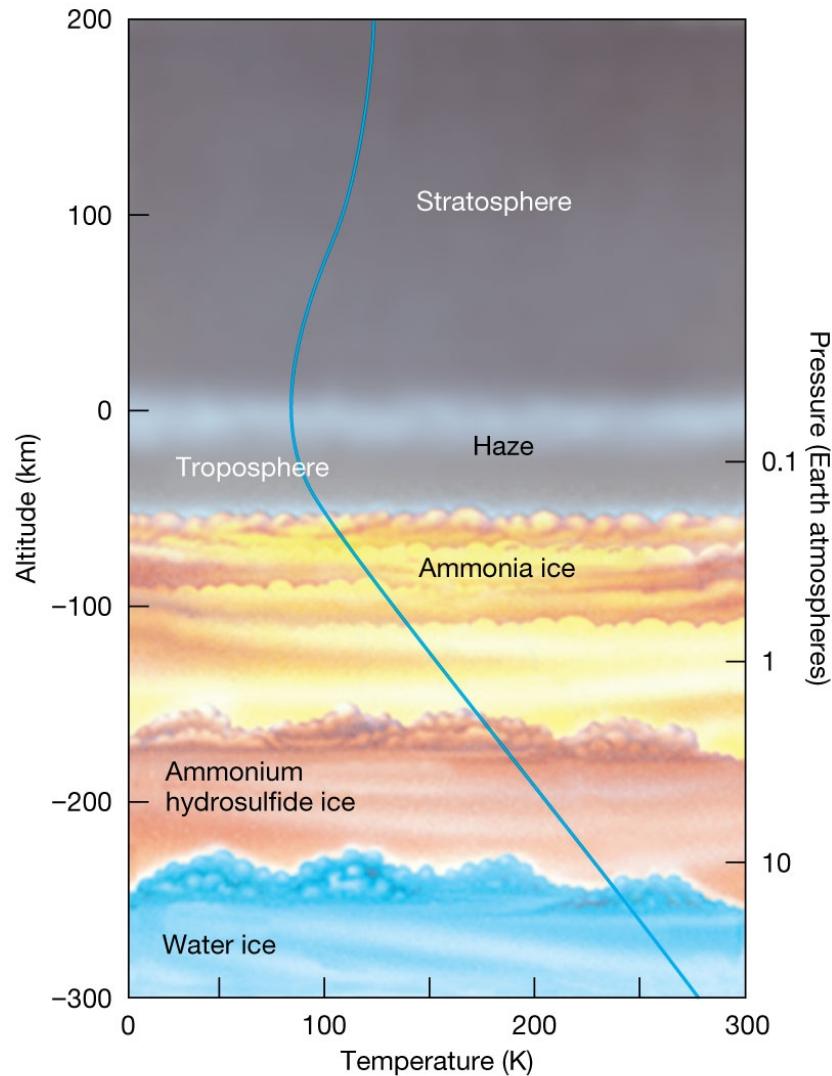
The same types of clouds seen on Jupiter exist on Saturn, but they are more spread out vertically. Why?

Scale height,  $H=kT/mg$ , so it's because  $g$  is smaller on Saturn.

$$H_{\text{Earth}} = 8.5 \text{ km}$$

$$H_{\text{Jup}} = 27 \text{ km}$$

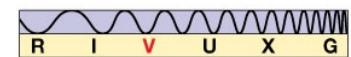
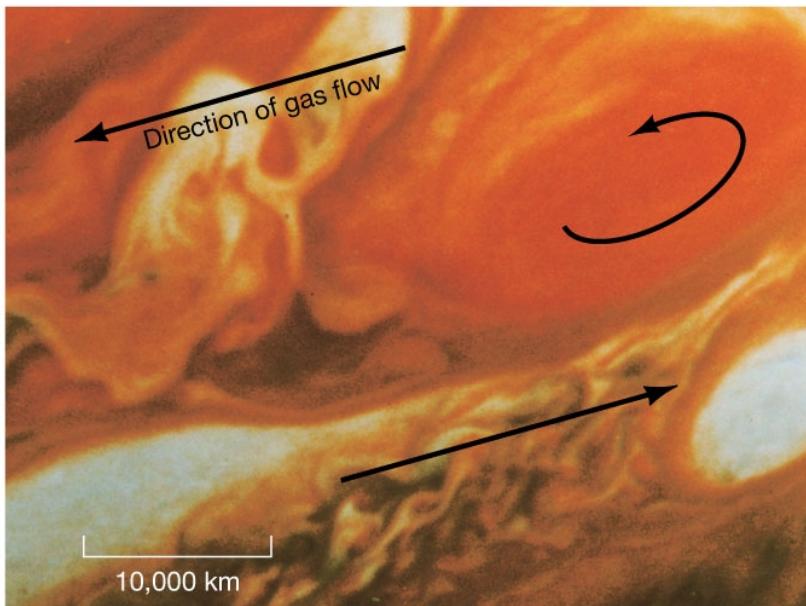
$$H_{\text{Sat}} = 60 \text{ km}$$



## 4. Atmospheres - Jupiter

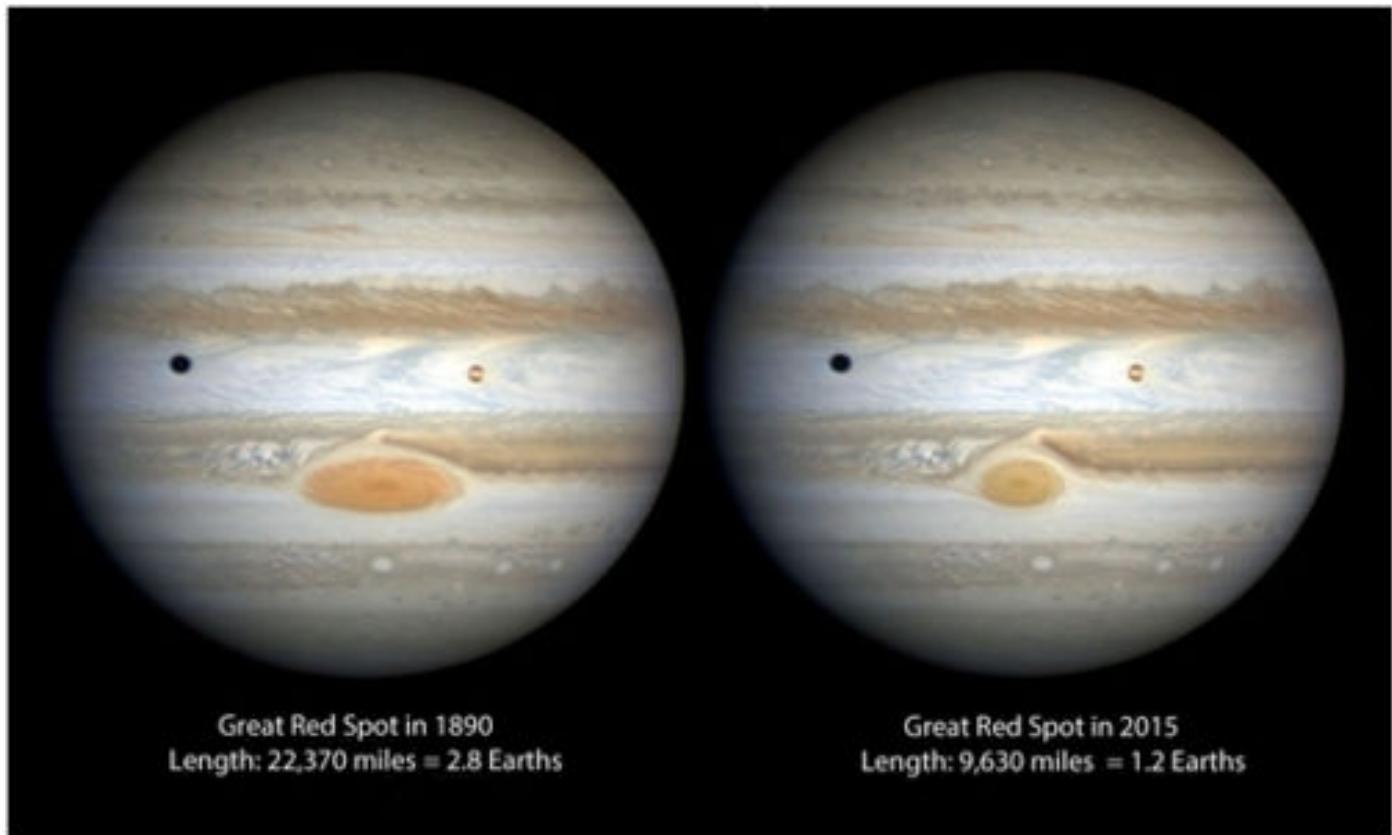
Great Red Spot has existed for at least 120 years, possibly much longer.

Color and energy source still not understood



## 4. Atmospheres - Jupiter

Great Red Spot has been shrinking over the last 120 years or so. It has varied in contrast as well.

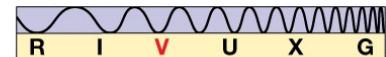
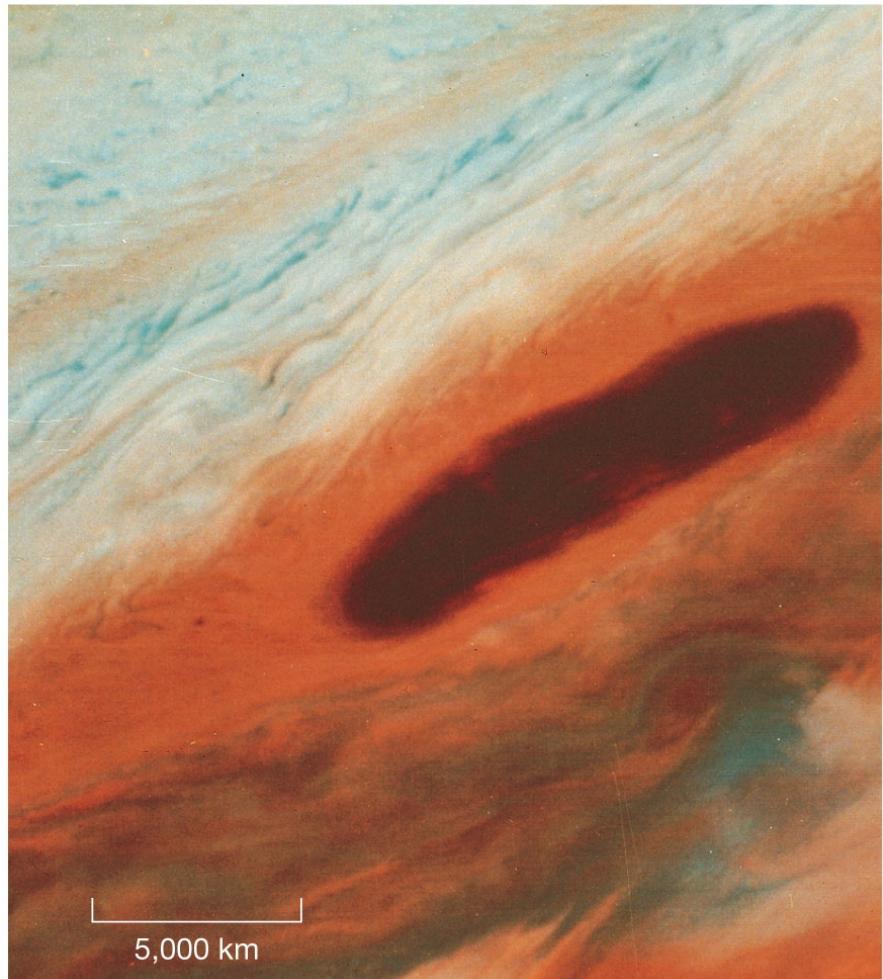


# 4. Atmospheres - Jupiter

Lightning-like flashes have been seen; also shorter-lived rotating storms

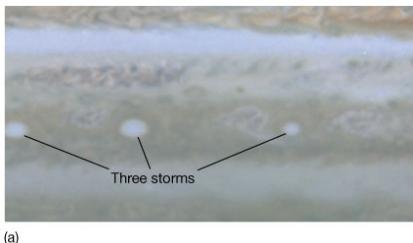
One example: Brown Oval, really a large gap in clouds.

These have only been seen around 20° N latitude, and have cyclonic rotation (CCW in Northern Hem.)

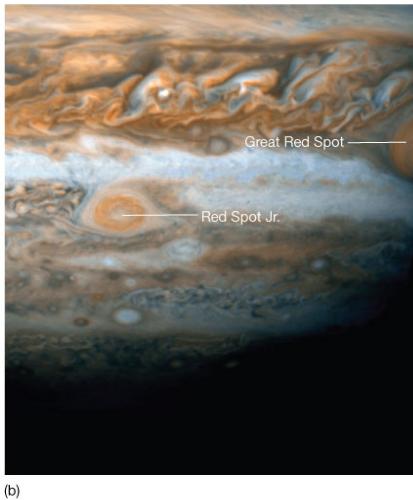


# 4. Atmospheres - Jupiter

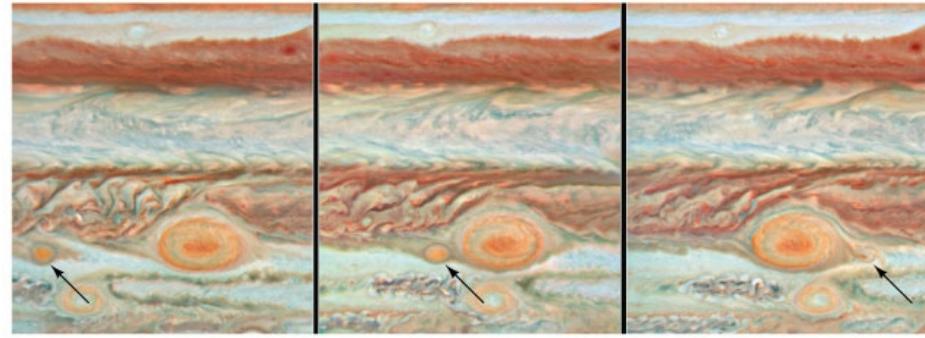
In 2000, three white storms were observed to merge into a single storm, which then turned red. Called “Oval BA” or “Red Spot Jr.”.



(a)



(b)



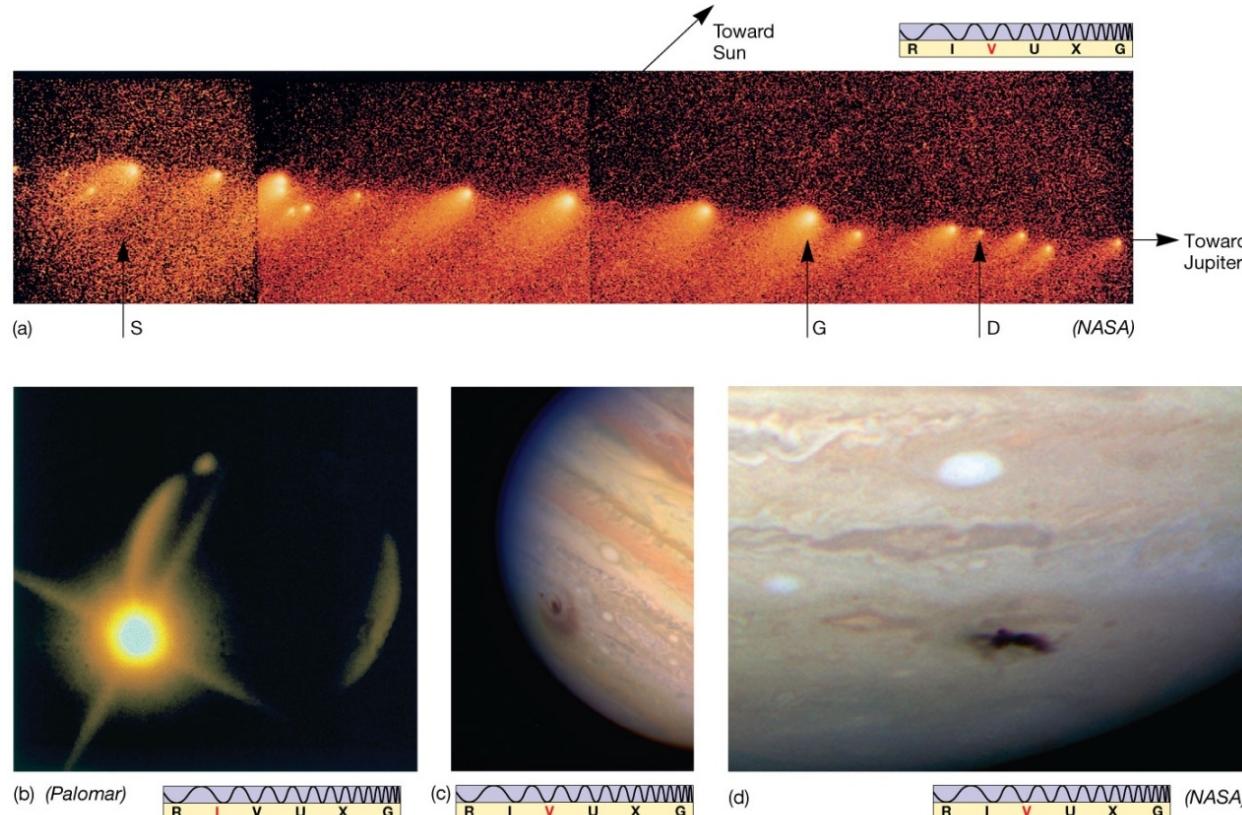
(c)

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See video of Jupiter's zonal flow.

# Discovery 11-1: A Cometary Impact

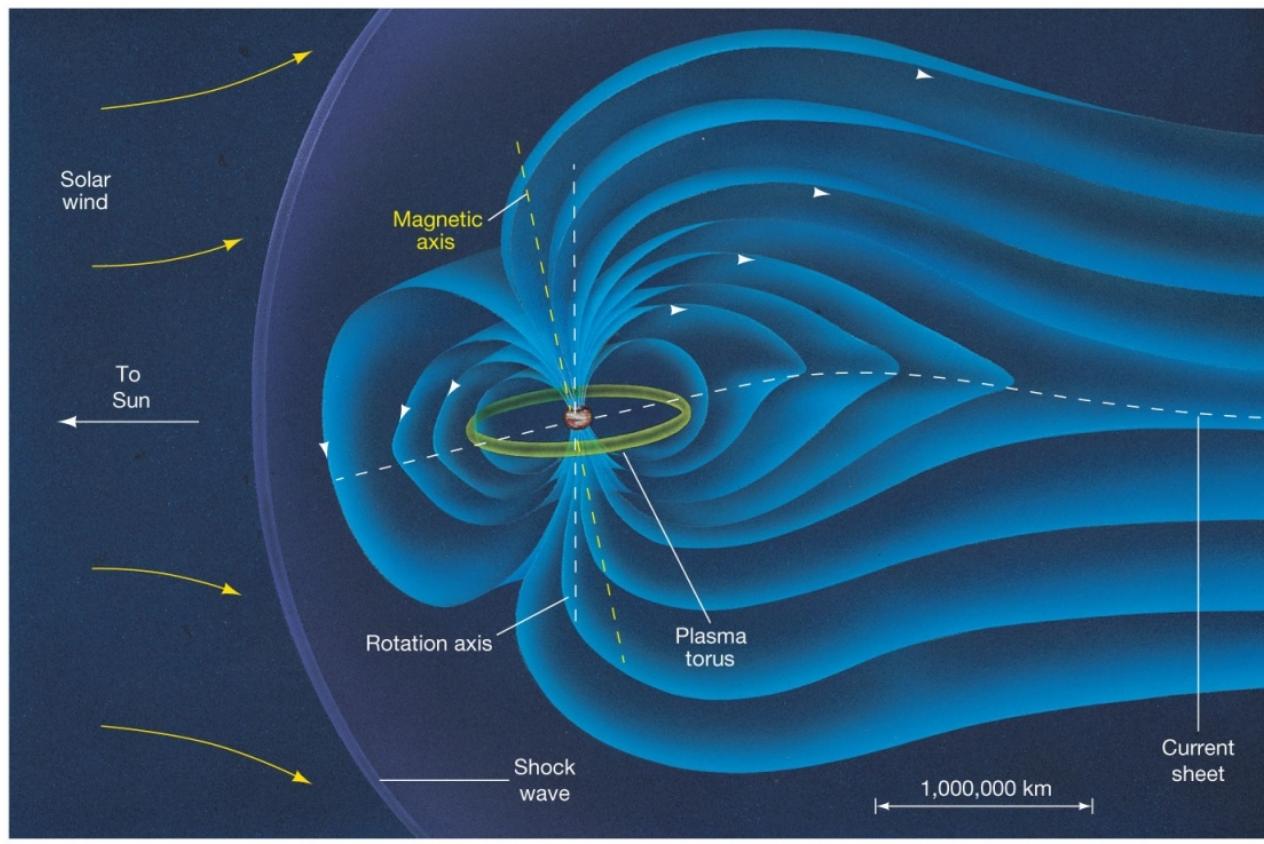
July 1994: Comet Shoemaker-Levy 9, in fragments, struck Jupiter, providing information about high-level winds, and composition.



# 11.4 Jupiter's Magnetosphere

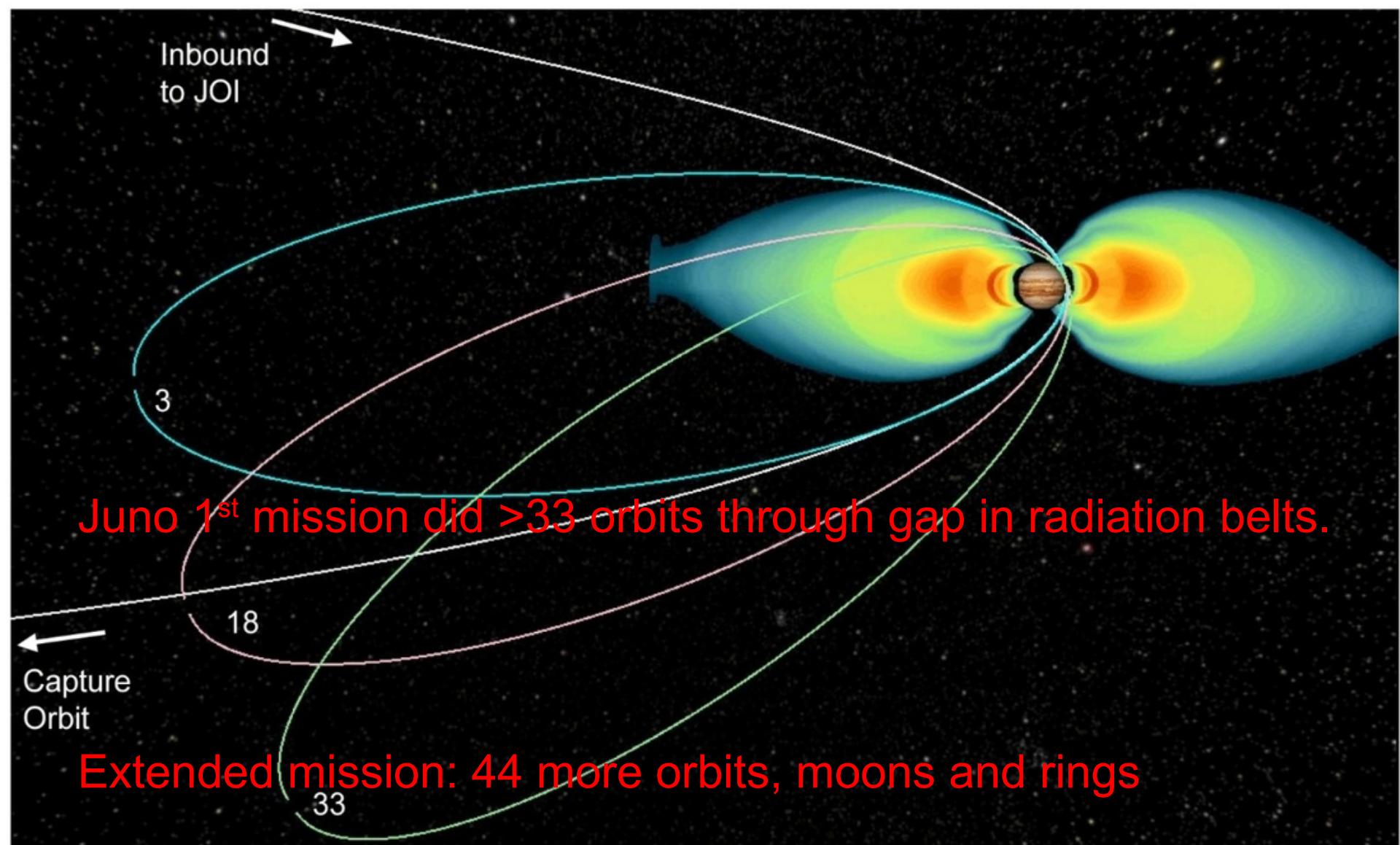
Jupiter is surrounded by belts of charged particles, much like the Van Allen belts but vastly larger

Magnetosphere is 30 million km across



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# 11.4 Jupiter's Magnetosphere

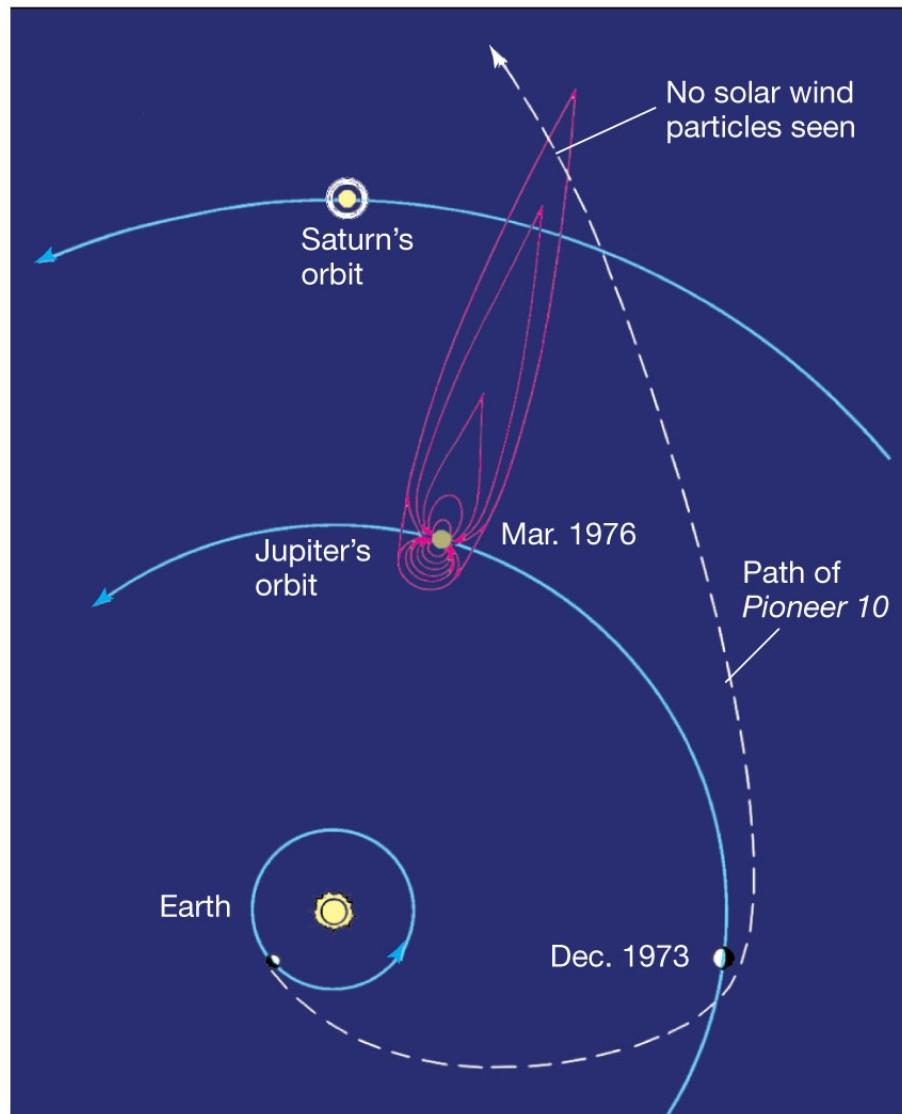


# 11.4 Jupiter's Magnetosphere

Intrinsic field strength is 20,000 times that of Earth.

Volume of magnetosphere is a million times the Earth's.

Magnetosphere tail extends beyond the orbit of Saturn



# 11.5 The Moons of Jupiter

80\* moons have now been found orbiting Jupiter, but most are very small.

The four largest are the Galilean moons, so called because they were first observed by Galileo:

- Io, Europa, Ganymede, Callisto.

Galilean moons have similarities to terrestrial planets:

All orbit in same direction, in same plane

Rotate CCW (tidally interlocked like our Moon)

Made of less dense materials as distance increases

Sizes are comparable to the Moon and Mercury

\* As of 2022.

**Table 2:**

Moon	Distance from Jupiter (km)	Radius (km)	Mass (Earth)	Density (gm/cm <sup>3</sup> )	Orbital Period (days)
Io	422,000	1,815	0.0145	3.53	1.77
Europa	671,000	1,569	0.0080	3.03	3.55
Ganymede	1,070,000	2,631	0.0242	1.93	7.16
Callisto	1,883,000	2,400	0.0176	1.79	16.69

Check the ratios of Orbital periods ...



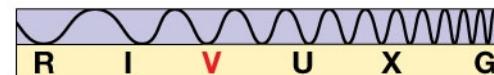
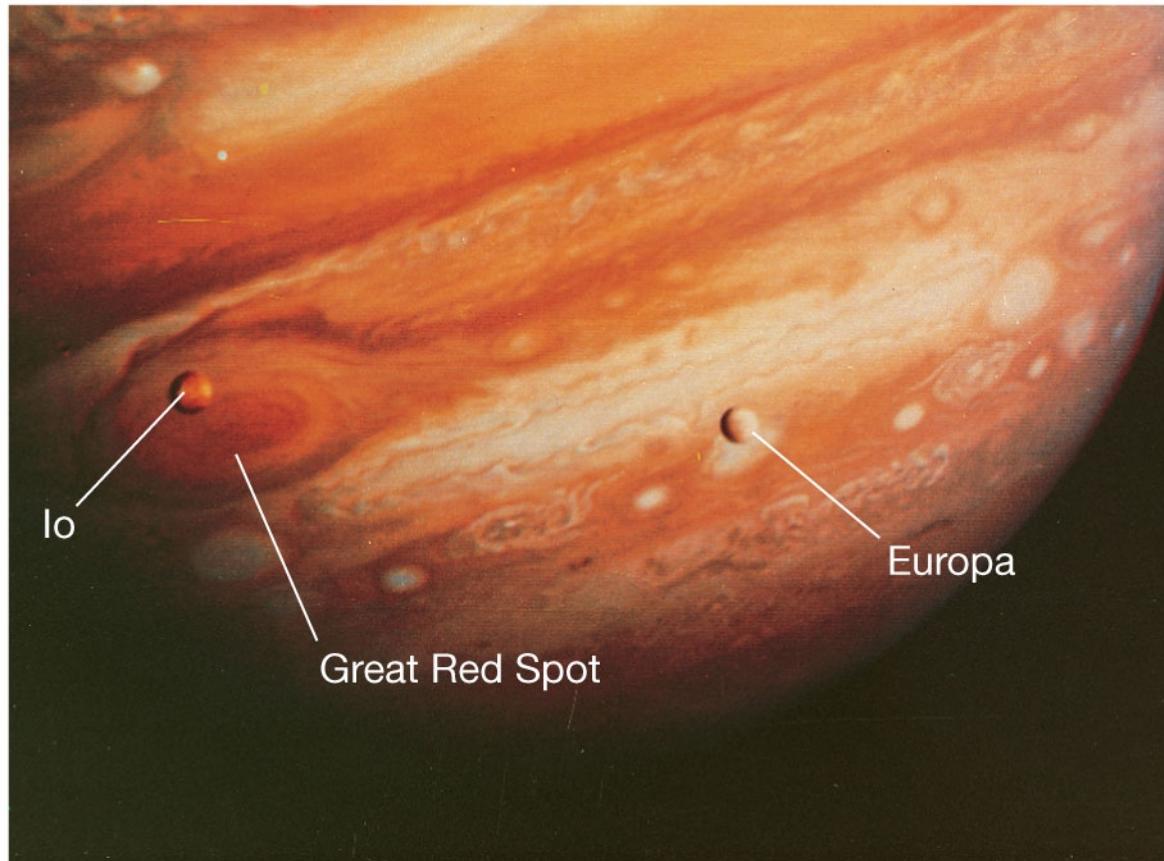
# 11.5 The Moons of Jupiter

*Celestia Gaia Sky animation of the Moon's of Jupiter shows ...*

- 1) 4 small moon's closer to Jupiter than Io:  
Adrastea, Amalthea, Metis, Thebe.
- 2) Adrastea and Metis almost share an orbit.
- 3) All moons revolve CCW (seen from N)
- 4) Zooming in on a Moon often shows it to keep one side facing Jupiter (gravitational interlocking or 1-1 spin:orbit resonance)

# 11.5 The Moons of Jupiter

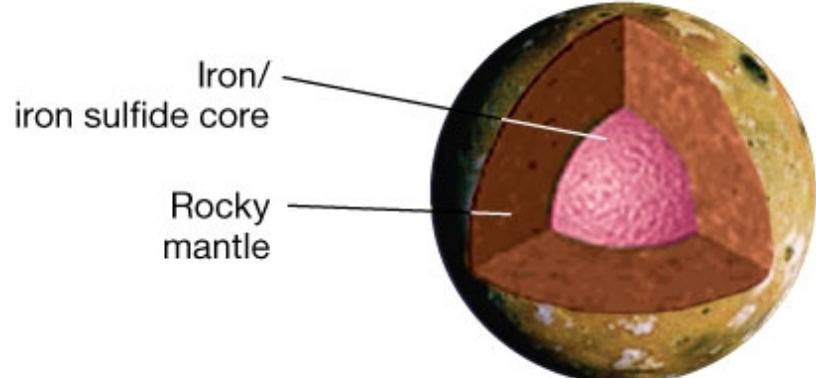
Jupiter with Io and Europa. Note the relative sizes!



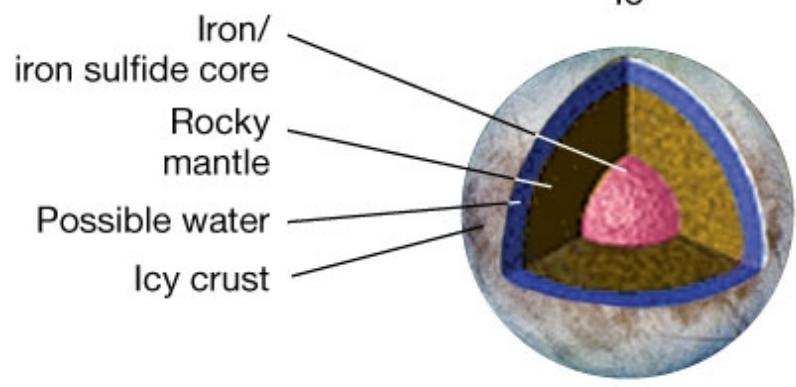
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# 11.5 The Moons of Jupiter

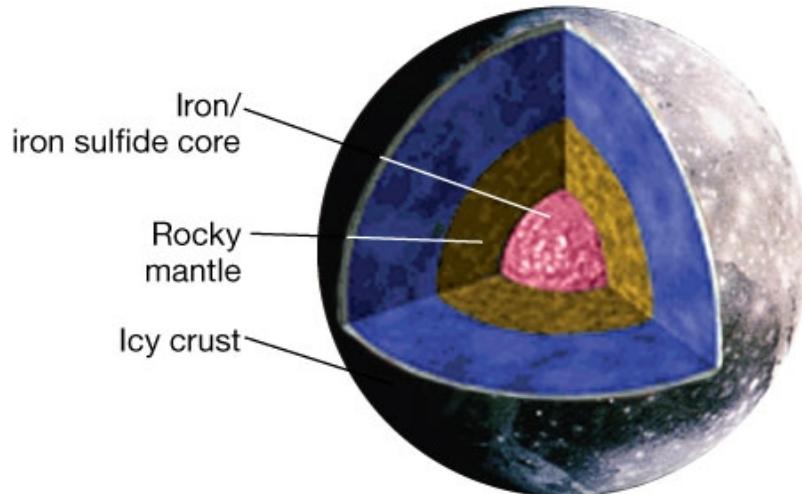
## Interiors of the Galilean moons



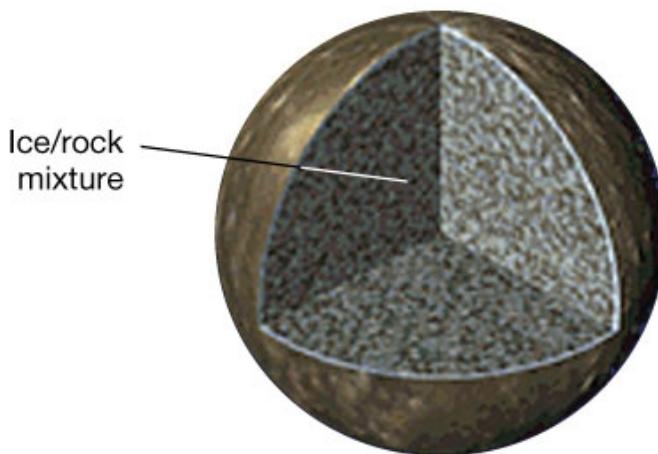
Io



Europa



Ganymede



Callisto

# 11.5 The Moons of Jupiter

Io is the densest of Jupiter's moons, and the most geologically active object in the solar system:

- Many **active** volcanoes, some quite large
- Can change surface features in a few weeks
- No craters; they fill in too fast—Io has the youngest surface of any solar system object

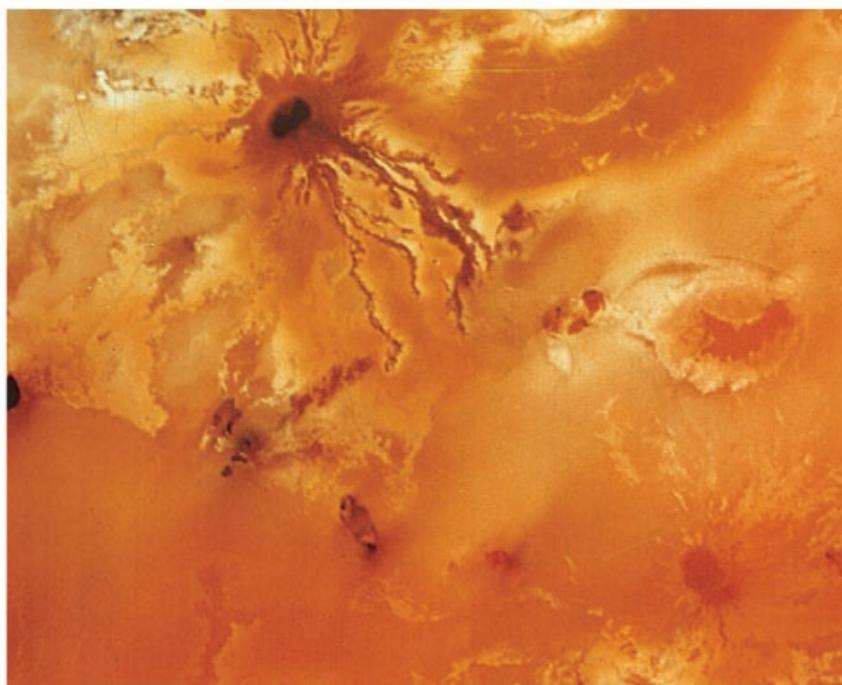
# 11.5 The Moons of Jupiter

Orange color is probably from sulfur compounds in the ejecta



(a)

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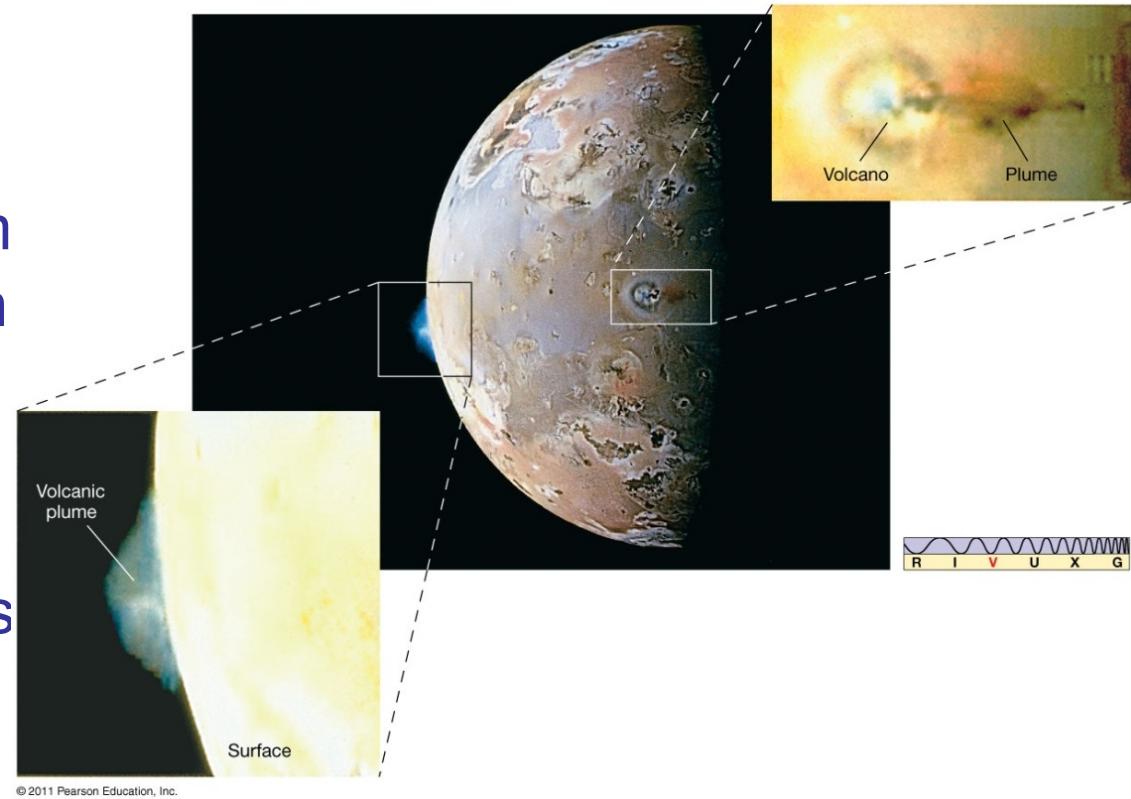
(b)



# 11.5 The Moons of Jupiter

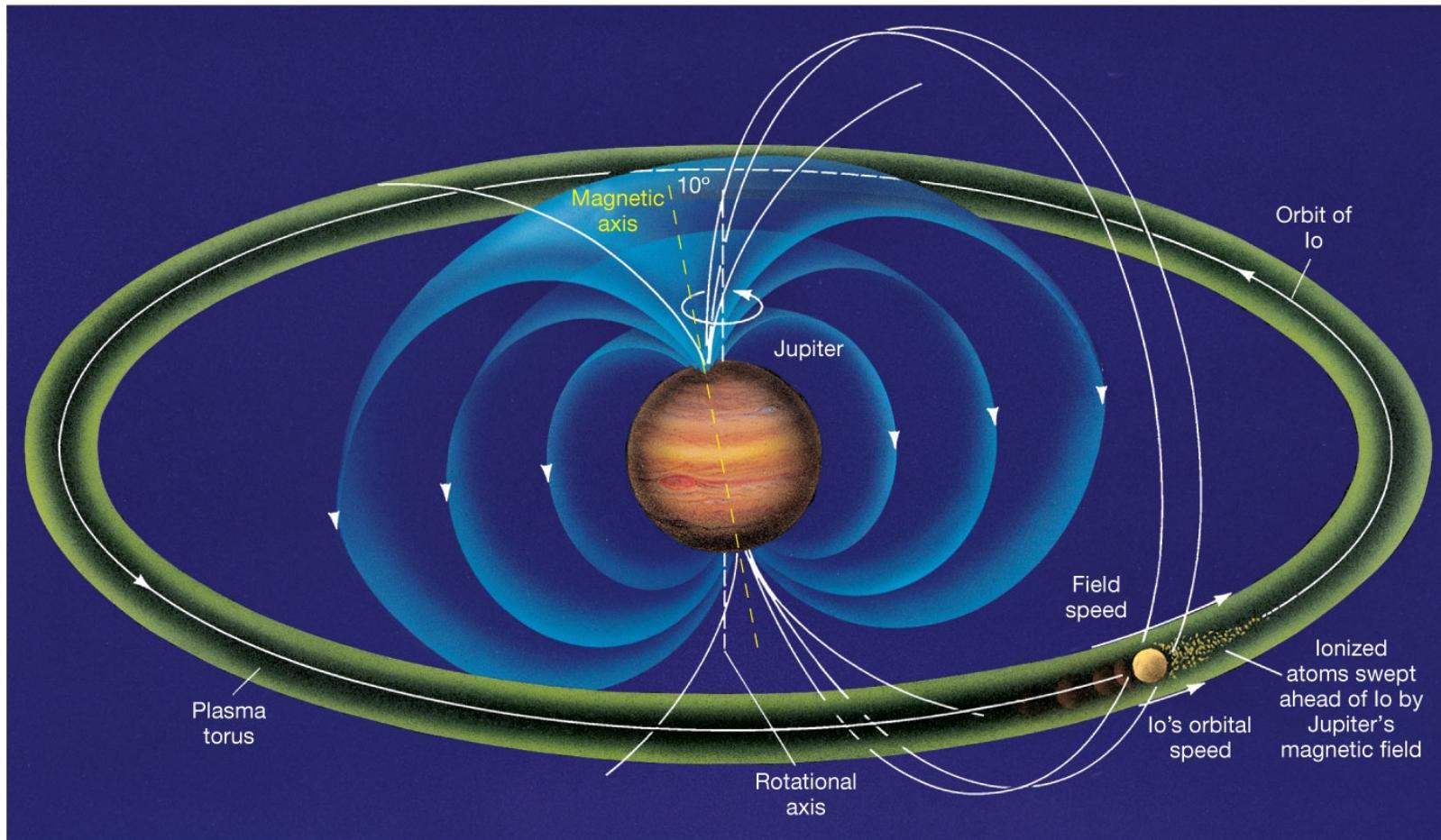
Cause of volcanism: Gravity!

Io is very close to Jupiter so the tidal force is huge. Io passes Europa every 3.6 days and the tug from Europa makes Io quicken and then slow in its orbit. This makes Io librate back and forth relative to Jupiter, so the tidal forces knead Io like bread dough and provide the energy for the volcanoes.



# 11.5 The Moons of Jupiter

Volcanic eruptions also eject charged particles; these interact with Jupiter's magnetosphere and form a plasma torus

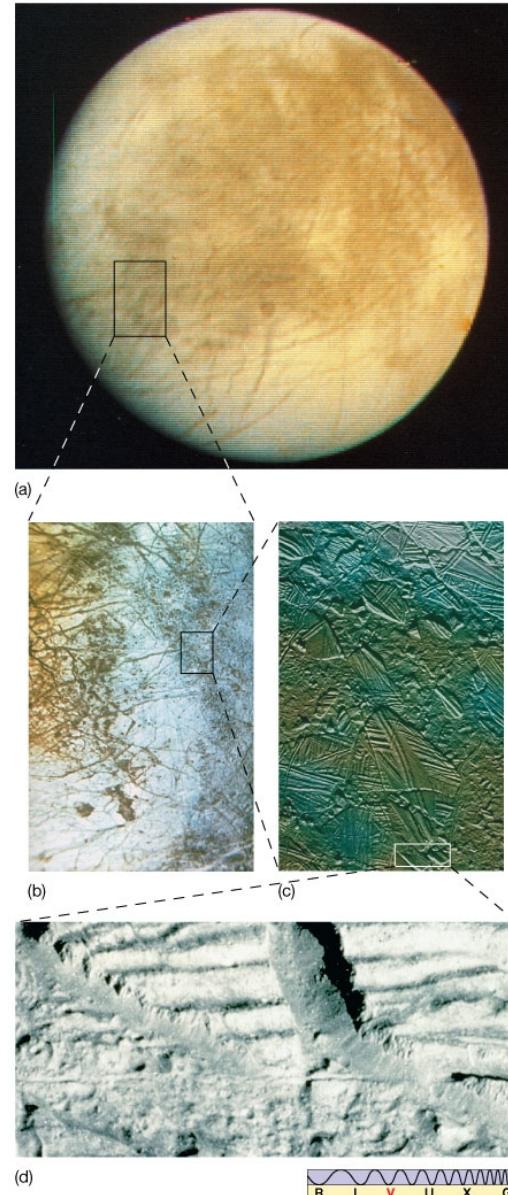


# 11.5 The Moons of Jupiter

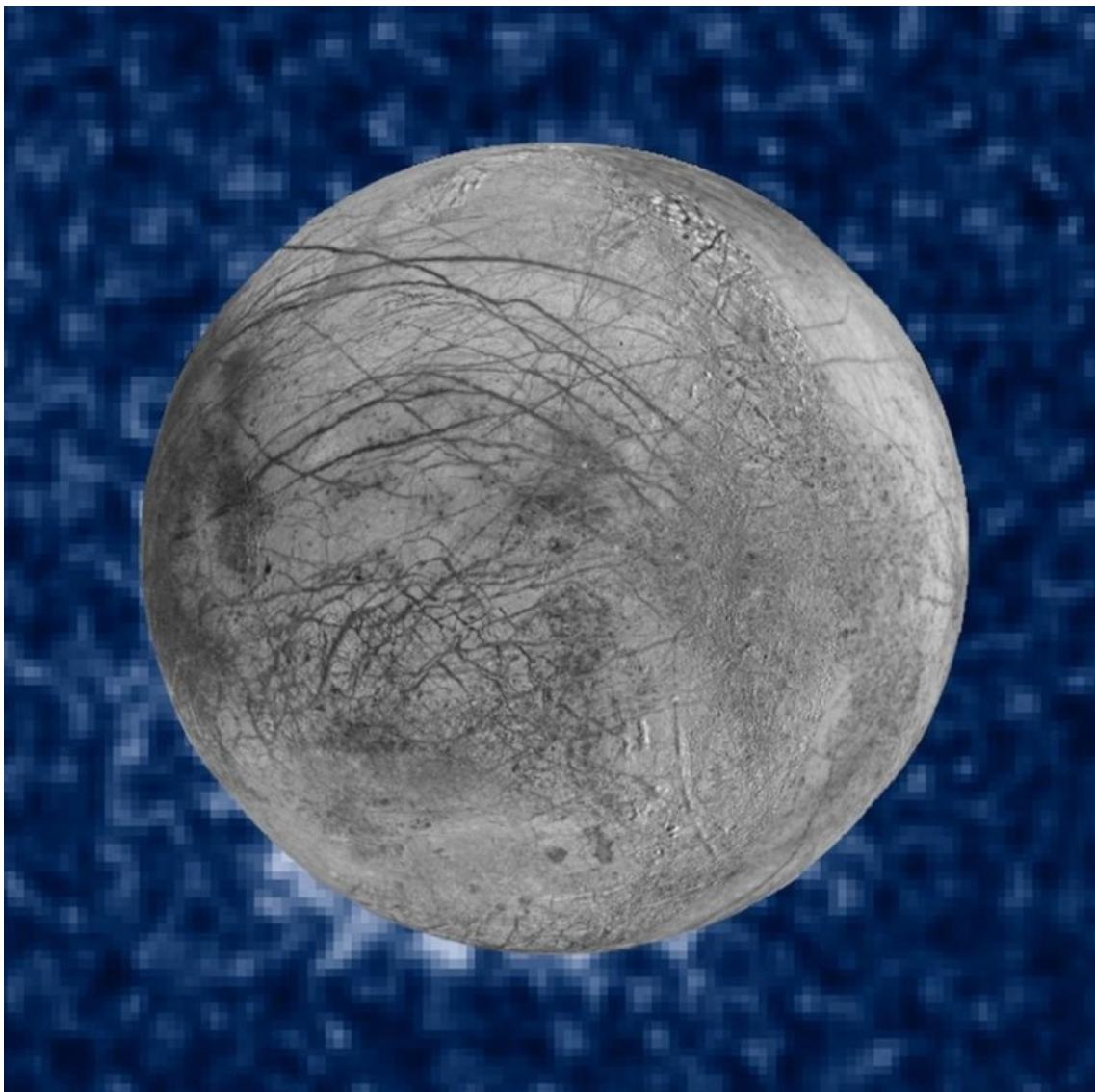
Europa shows few craters; surface is water ice, possibly with liquid water below.

Tidal forces stress and crack ice; water flows, keeping surface relatively flat.

See sci-fi movie “Europa Report”.



# 11.5 The Moons of Jupiter



Europa: water geysers were detected by HST in 2016 as it passed in front of Jupiter.

ESA and NASA plan a “Europa flyby” mission in 2020’s.

# 11.5 The Moons of Jupiter

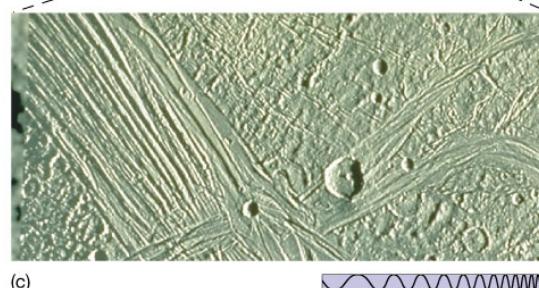
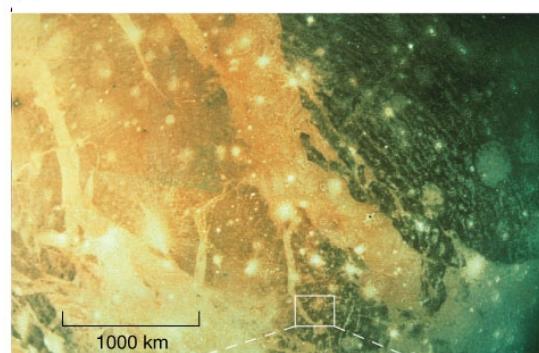
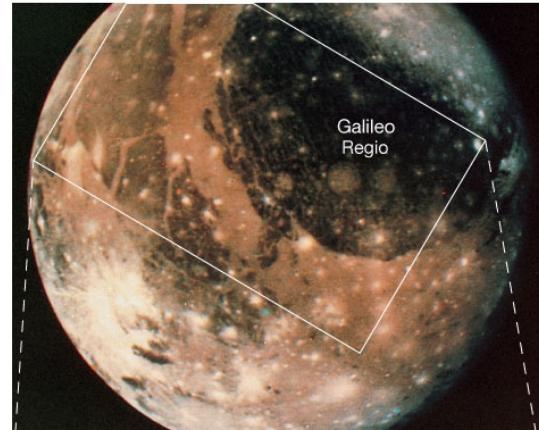
Ganymede is the largest moon in the solar system—larger than Pluto and Mercury

Surface is mostly water ice and a sub-surface ocean is likely.

Dark regions slightly older.

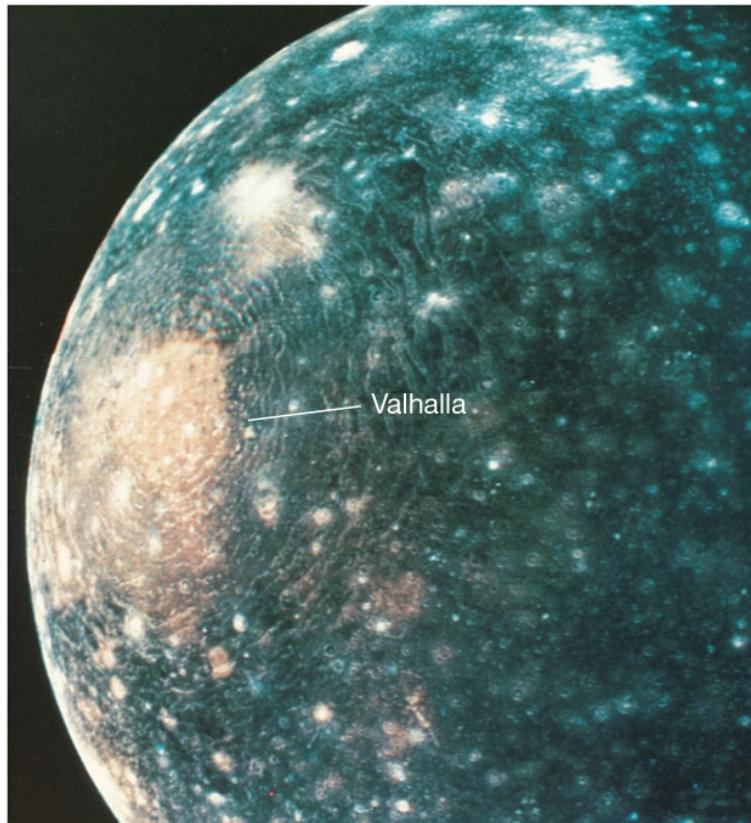
Galileo Regio like maria, but old.

Possible plate tectonics.

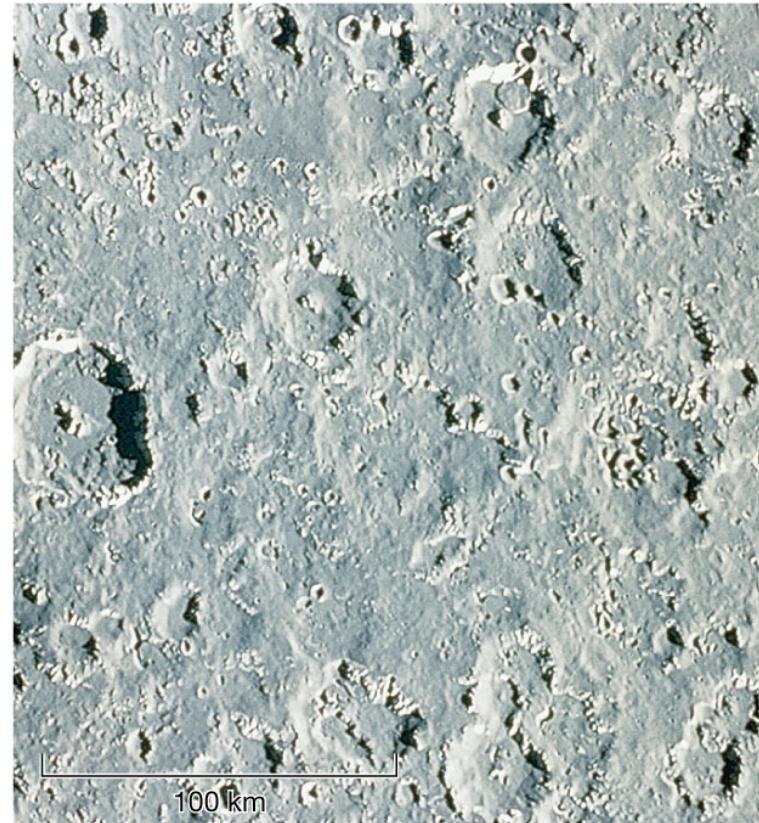


# 11.5 The Moons of Jupiter

Callisto is similar to Ganymede. No evidence of plate activity; highest crater density; leading edge darker.



(a)



(b)

# 12.5 The Moons of Saturn

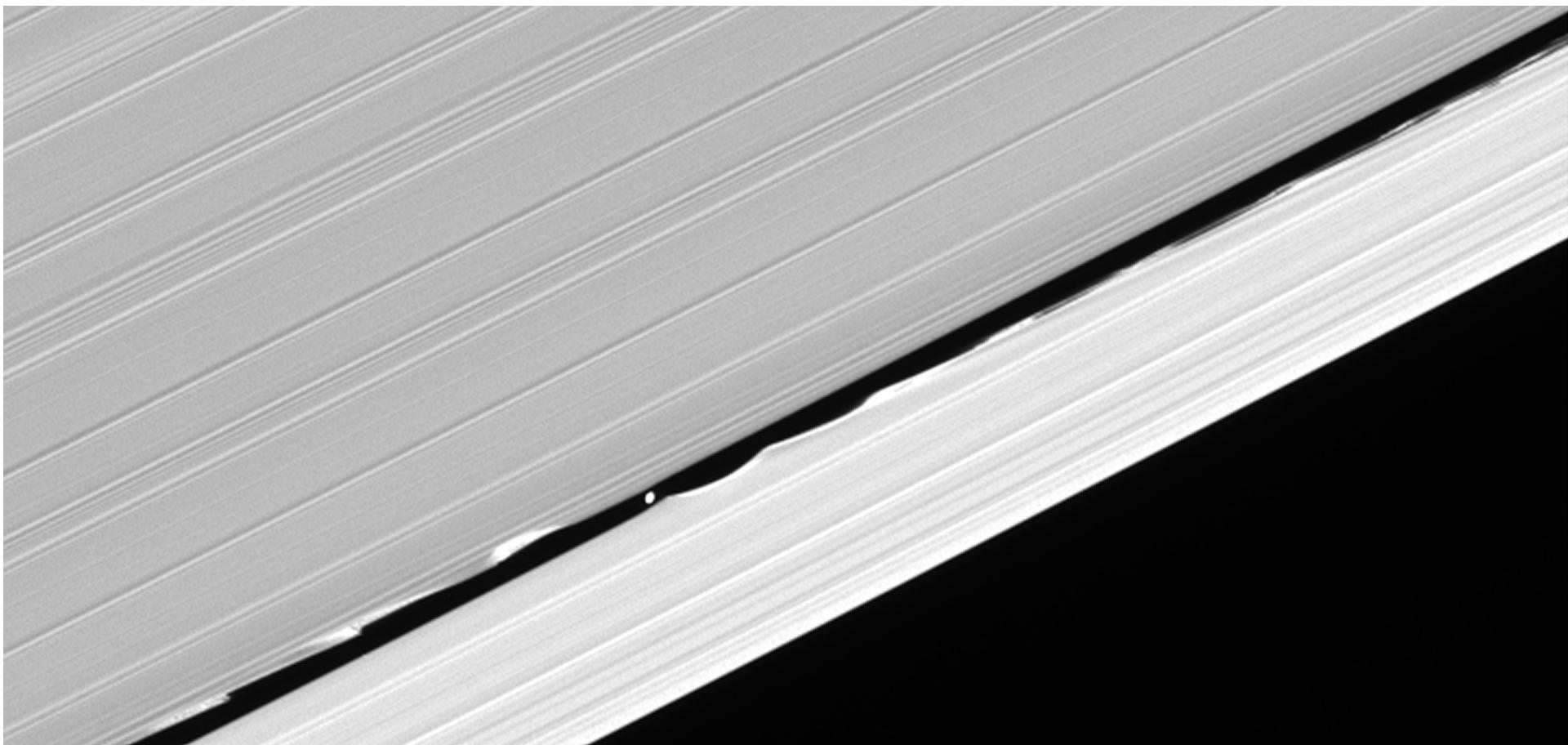
Mnemonic for the larger (>300 km) Moons of Saturn, in order of distance from Saturn:

MET DR THIP

Inspection of orbits of Saturn's moons with *Celestia* reveals:

- Many small (<100 km) moons among rings
- Some *shepherd* moons: Pandora, Prometheus
- “*Moonlets*” in gaps: Daphnis in Keeler Gap, Pan in Encke Gap
- Co-orbital moons: Janus and Epimetheus
- Calypso and Telesto are in Lagrange points ((L4, L5) of Tethys' orbit
- Most big moons tidally locked and orbit CCW in the same plane
- Outer moons (Phoebe) have more eccentric orbits.

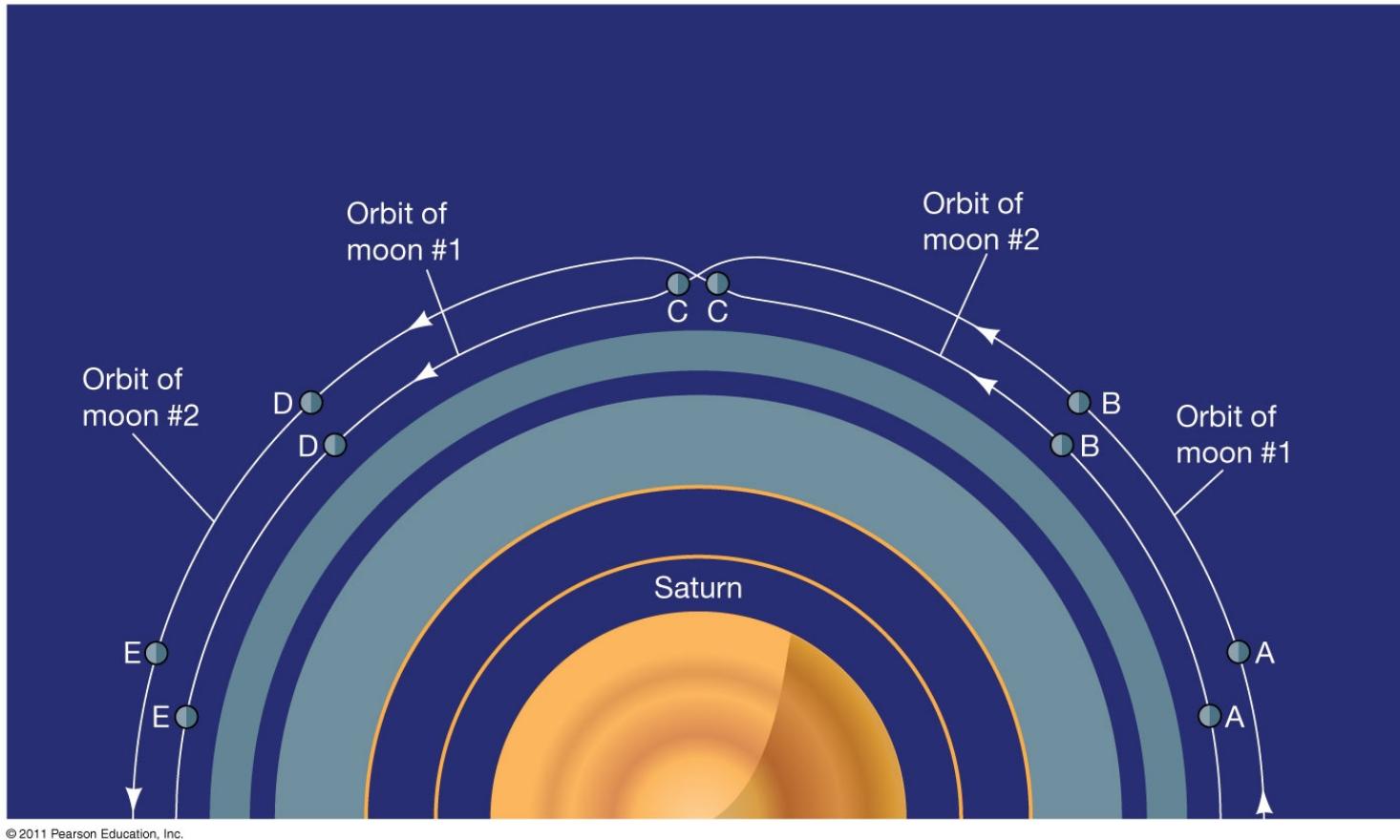
# 12.5 The Moons of Saturn



Daphnis in the Keeler Gap.

# 11.5 The Moons of Saturn

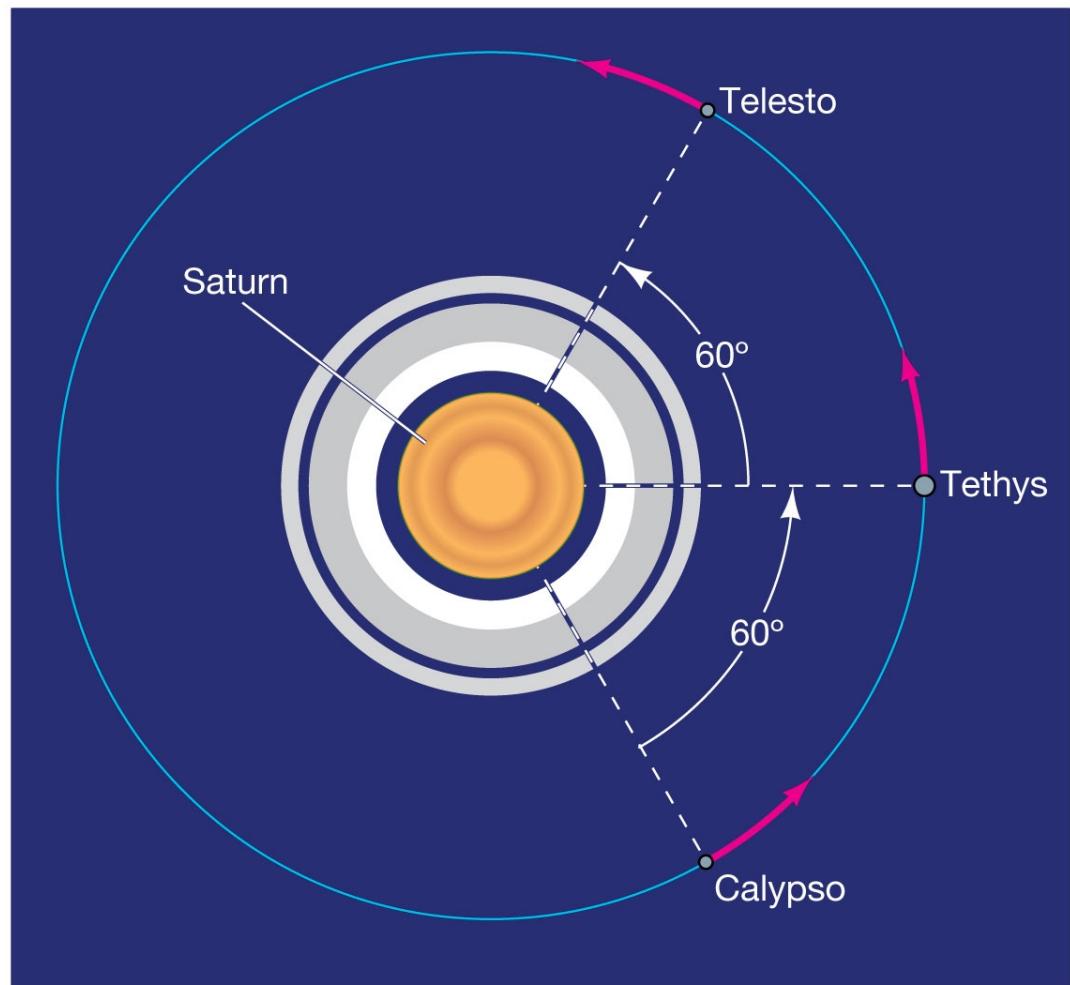
## Janus and Epimetheus



Orbital exchange occurs every  $\sim 4$  yrs.

# 12.5 The Moons of Saturn

Two more moons are at the Lagrangian points of Tethys



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# 12.5 The Moons of Saturn

This image shows Saturn's mid-sized moons

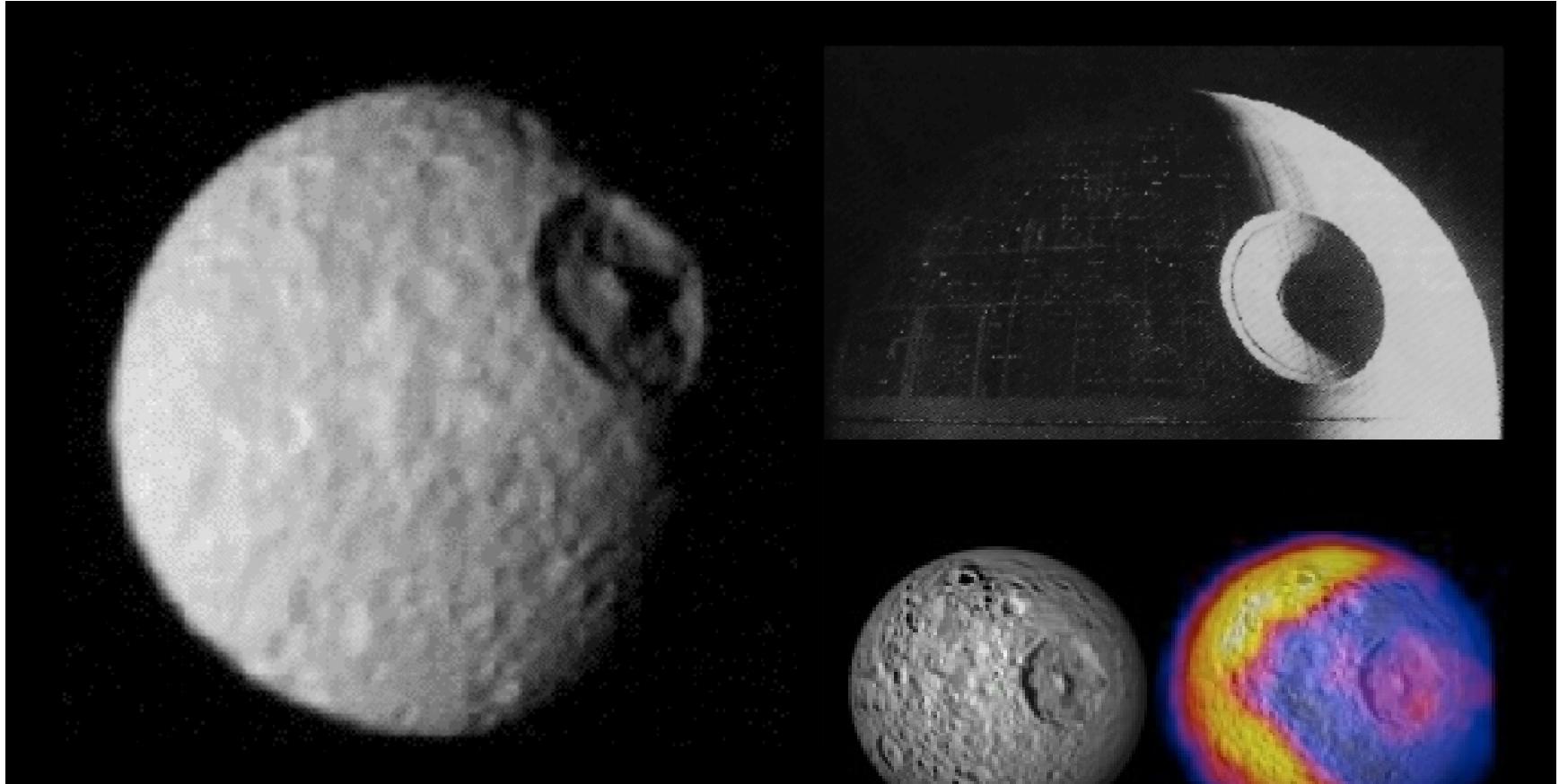


# 12.5 The Moons of Saturn

- Mimas, Enceladus, Tethys, Dione, and Rhea all orbit between 3 and 9 planetary radii from Saturn, and all are tidally locked—this means they have “leading” and “trailing” surfaces
- Iapetus (the “walnut”) orbits 59 radii away and is also tidally locked.
- Mimas = the “death star”
- Tethys = has two “tagalong” moons

# 12.5 The Moons of Saturn

Mimas – stranger than fiction?



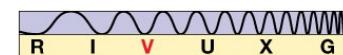
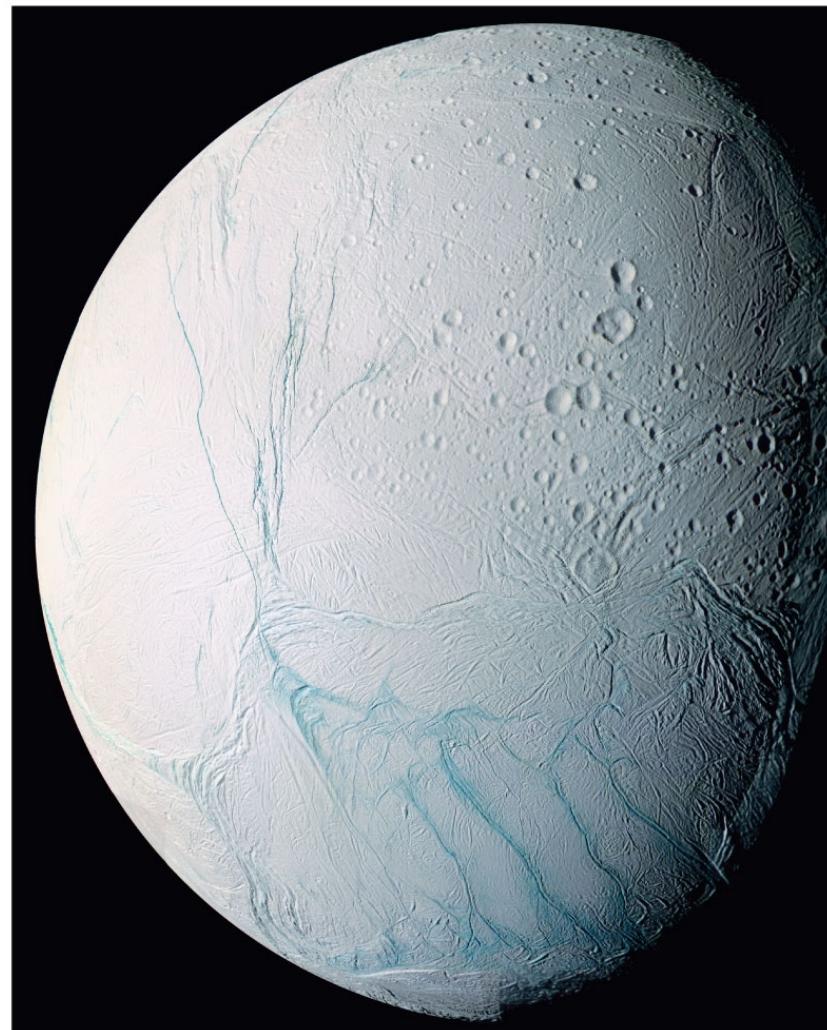
Source: [www.nightsky.ie/2009](http://www.nightsky.ie/2009)

# 12.5 The Moons of Saturn

Surface of Enceladus is young  
near the “Tiger Stripes”.

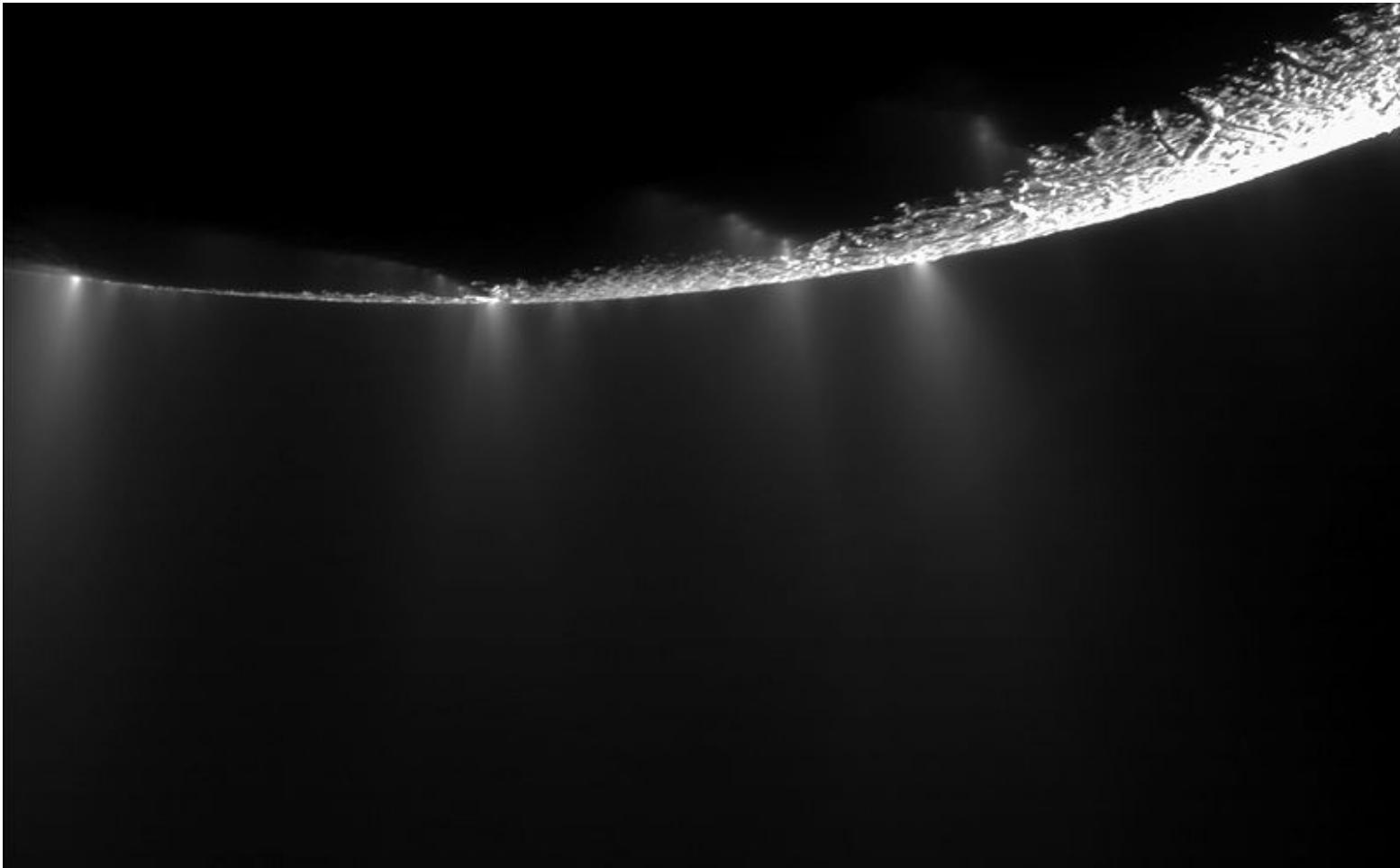
Highest albedo in solar system  
at 99%.

(Previous collage makes it look  
more tan colored.)



# 12.5 The Moons of Saturn

The “Tiger striped” region of Enceladus also produces jets or water geysers. (Likely source of E ring.)



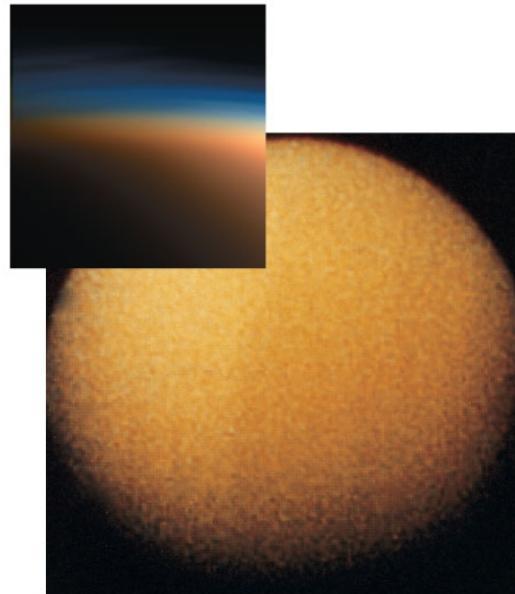
(Image from Wikipedia. A JPL/ NASA news release of Cassini data.)

# 12.5 The Moons of Saturn

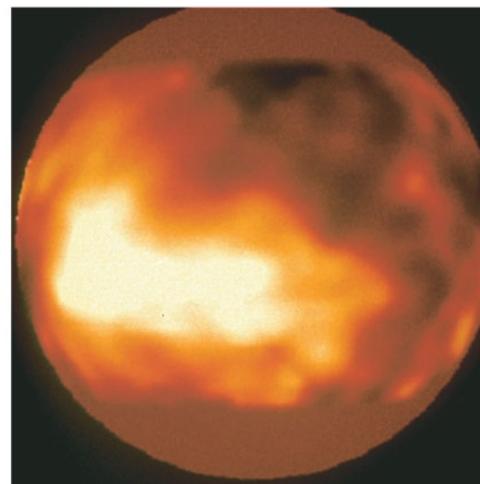
Titan is almost as big as Ganymede.

Its atmosphere is thicker and denser than Earth's; mostly nitrogen (96% N<sub>2</sub>) and methane (3.5% CH<sub>4</sub>)

Need Radio or IR to see deeper details.



(a)

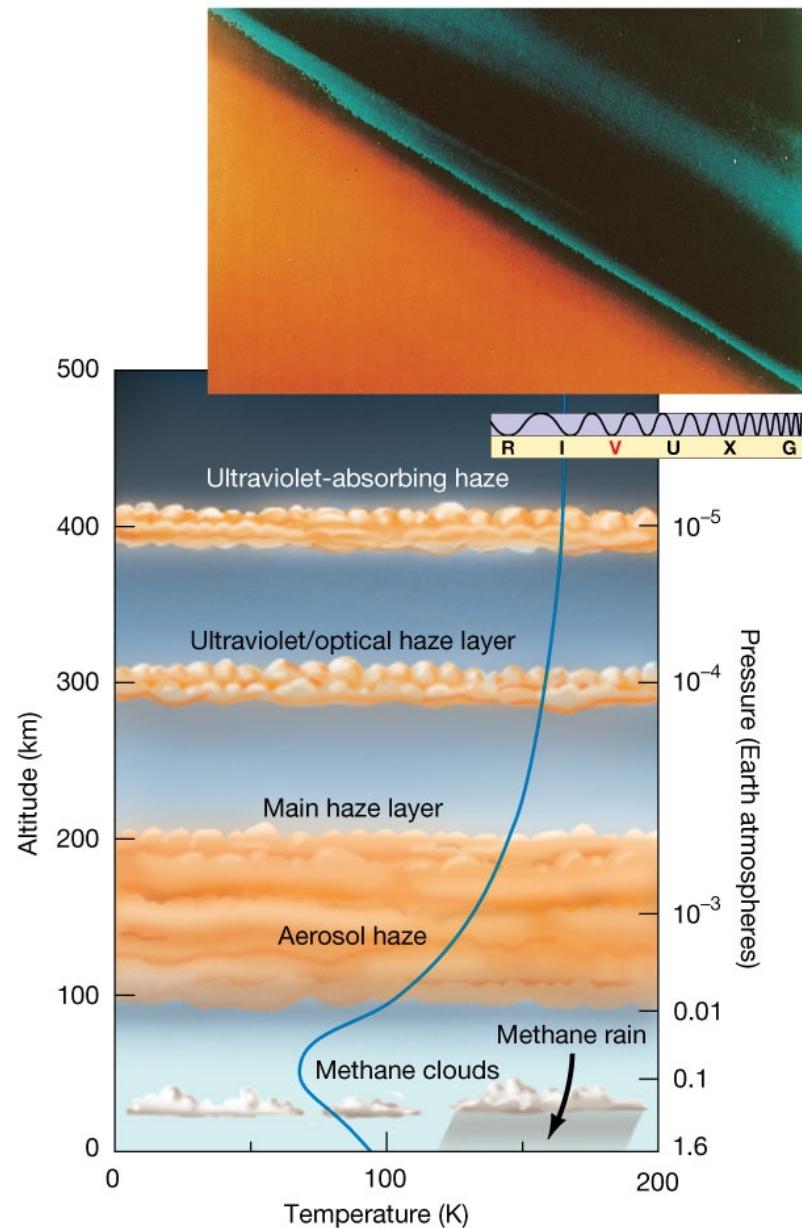


(b)



# 12.5 The Moons of Saturn

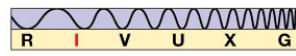
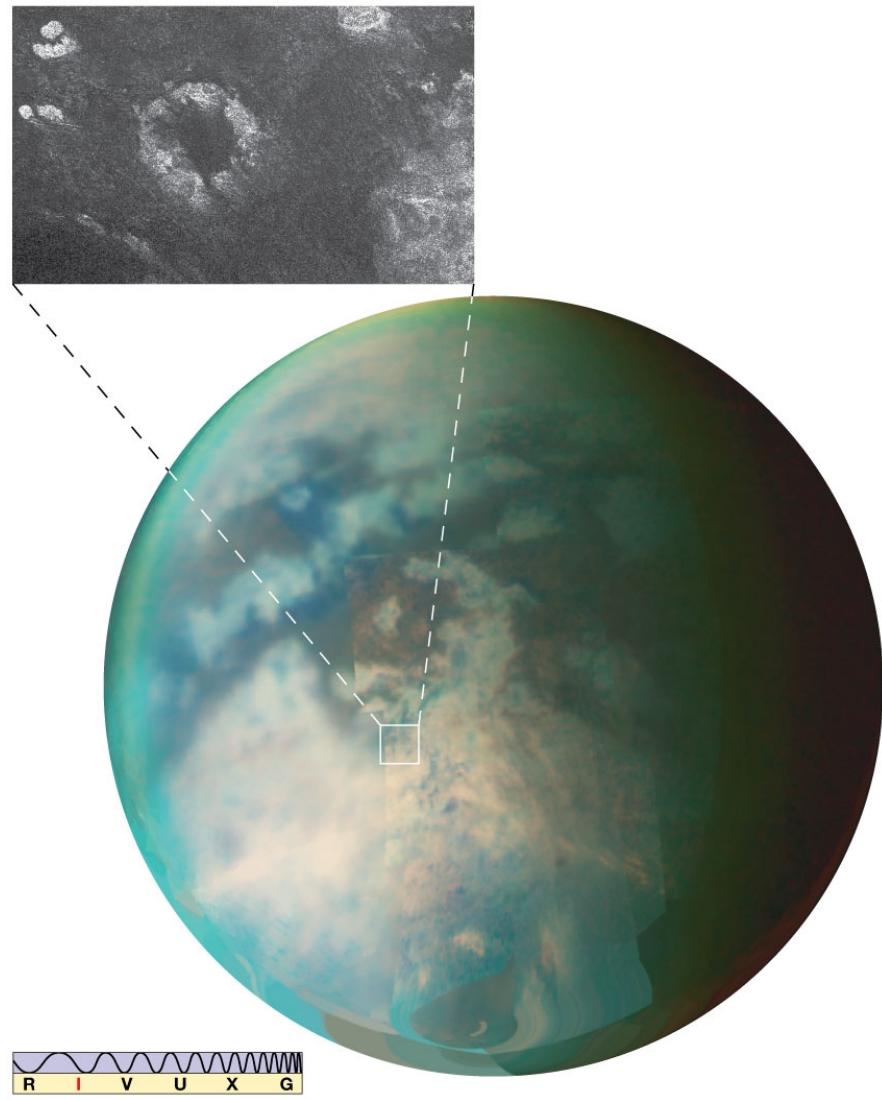
Trace chemicals in Titan's atmosphere make it chemically complex



# 12.5 The Moons of Saturn

Some surface features on Titan are visible in this *Cassini* infrared image.

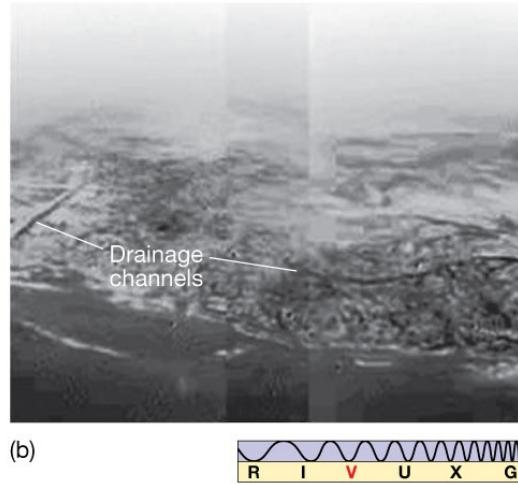
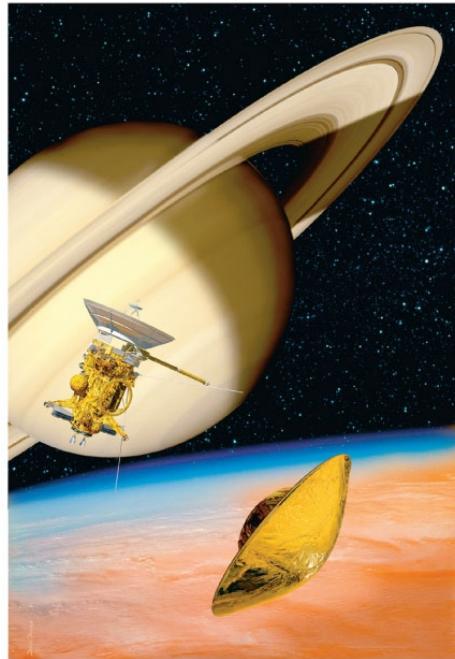
Titan has lakes of liquid hydrocarbons like methane, ethane, propane, and carbon monoxide – organic chemistry!



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# 12.5 The Moons of Saturn

The *Huygens* spacecraft has landed on Titan and returned images directly from the surface

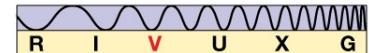


# The Moons of Uranus and Neptune

Uranus (discovered by Herschel in 1781) has 4 moons visible in small telescopes.)

It has about 23 other Moons discovered between 1948 and 2008.

Named after characters in literature of Shakespeare and Pope.

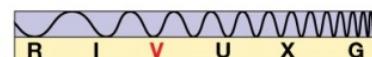


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# The Moons of Uranus and Neptune

Neptune was discovered in 1846, after analysis of Uranus's orbit indicated its presence

Arrows point to Triton and Nereid.

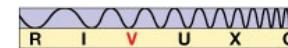


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# 13.5 The Moon Systems of Uranus and Neptune



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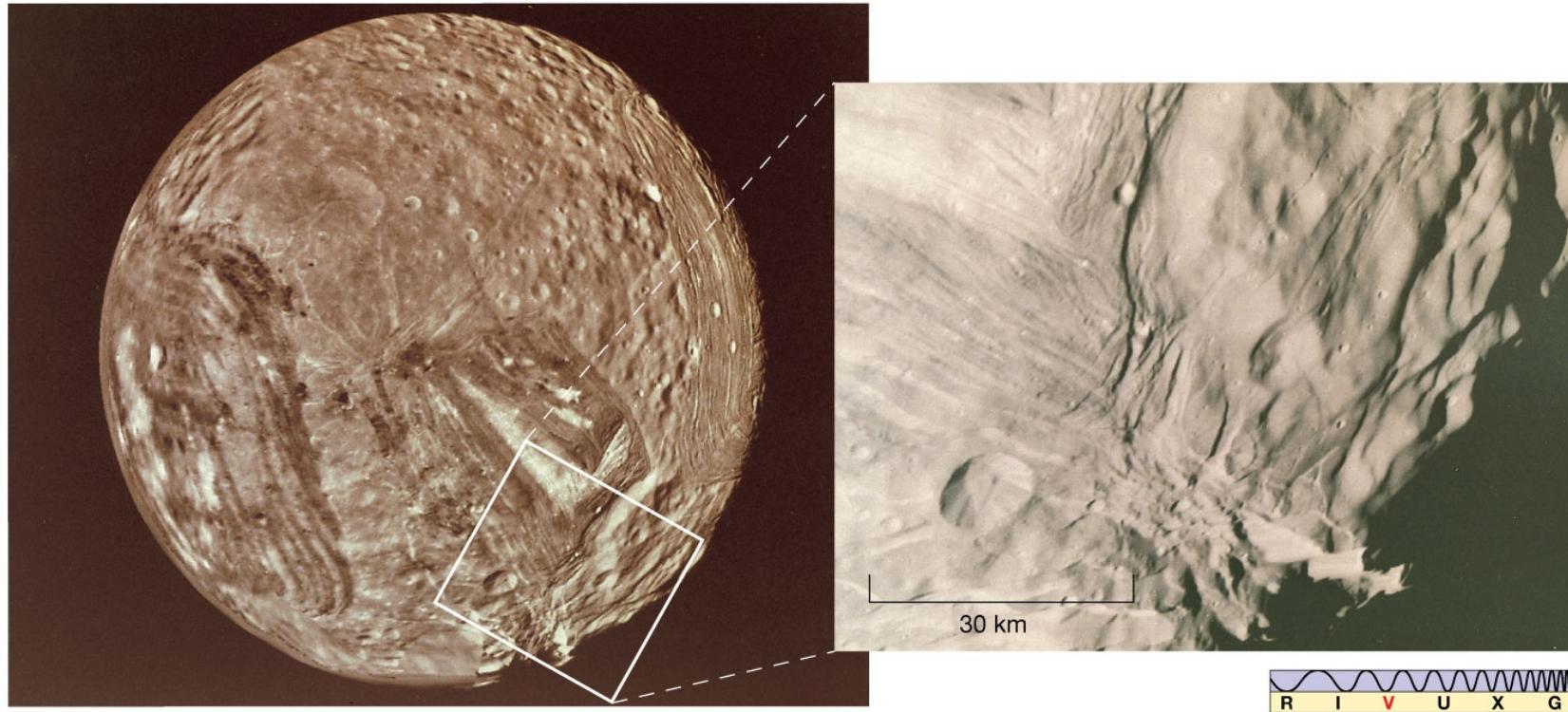


# 13.5 The Moon Systems of Uranus

- Uranus has 27 moons, five of which are major: Miranda, Ariel, Umbriel, Titania, and Oberon
- Similar to Saturn's medium-sized moons, except that all are much less reflective (Umbriel is the darkest)
- About 9 irregular moons were probably captured
- Orbital resonances, tidal locking, and tidal “kneading” probably occurred with major moons and inner moons.

# 13.5 The Moon Systems of Uranus and Neptune

Miranda is the most unusual moon of Uranus; origin of the cracks and grooves is uncertain, however ...



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Miranda has the most inclined and eccentric orbit of the large Uranian moons. Collision?

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# 13.5 The Moons of Neptune

Neptune has 14 moons, but only two can be seen from Earth: Triton and Nereid

Triton is in a retrograde orbit and is destined to crash onto Neptune (in  $\sim 10^8$  yrs)

Nereid's orbit is highly eccentric

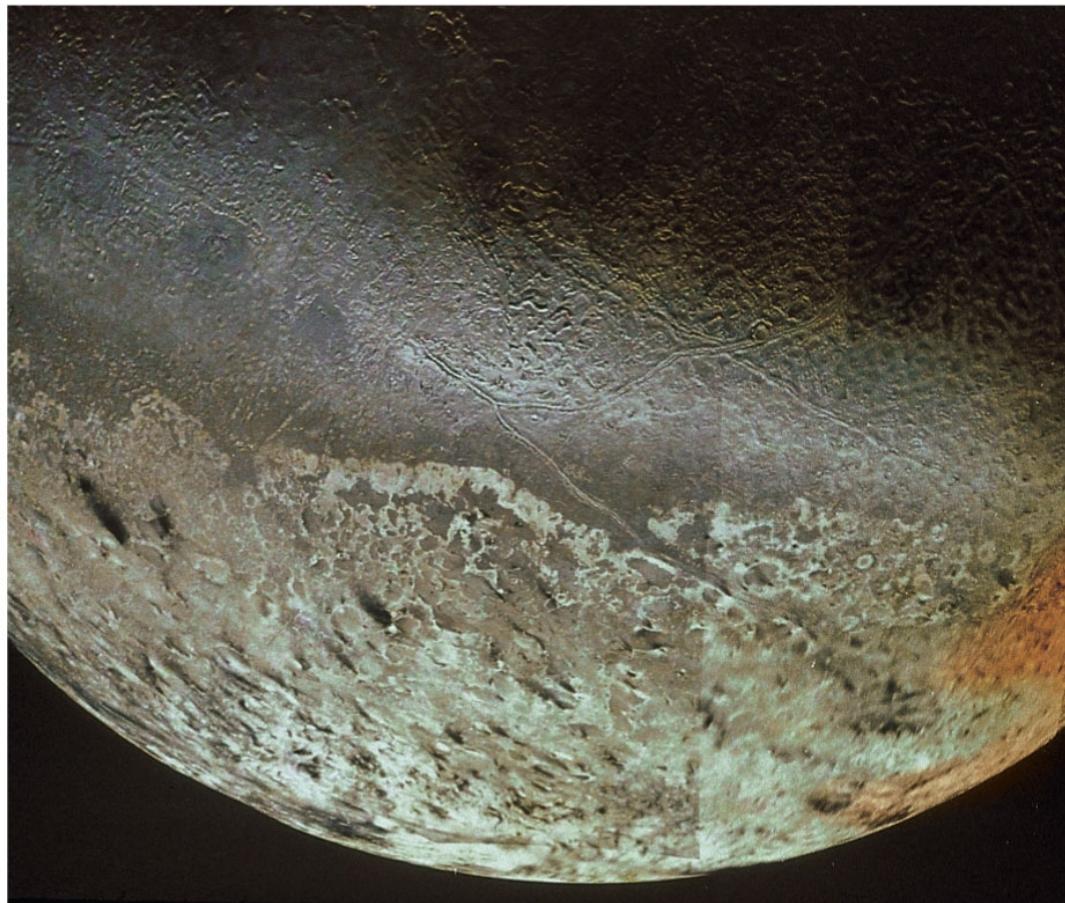
Text: “No dynamically regular moons around Neptune” (Actually, there are 7!)

Triton's surface has few craters, indicating an active surface. T $\sim$ 37 K! So Nitrogen ice is present (esp. near poles) along with dry ice, methane ice, etc.

# 13.5 The Moons of Neptune

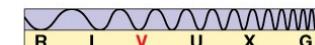
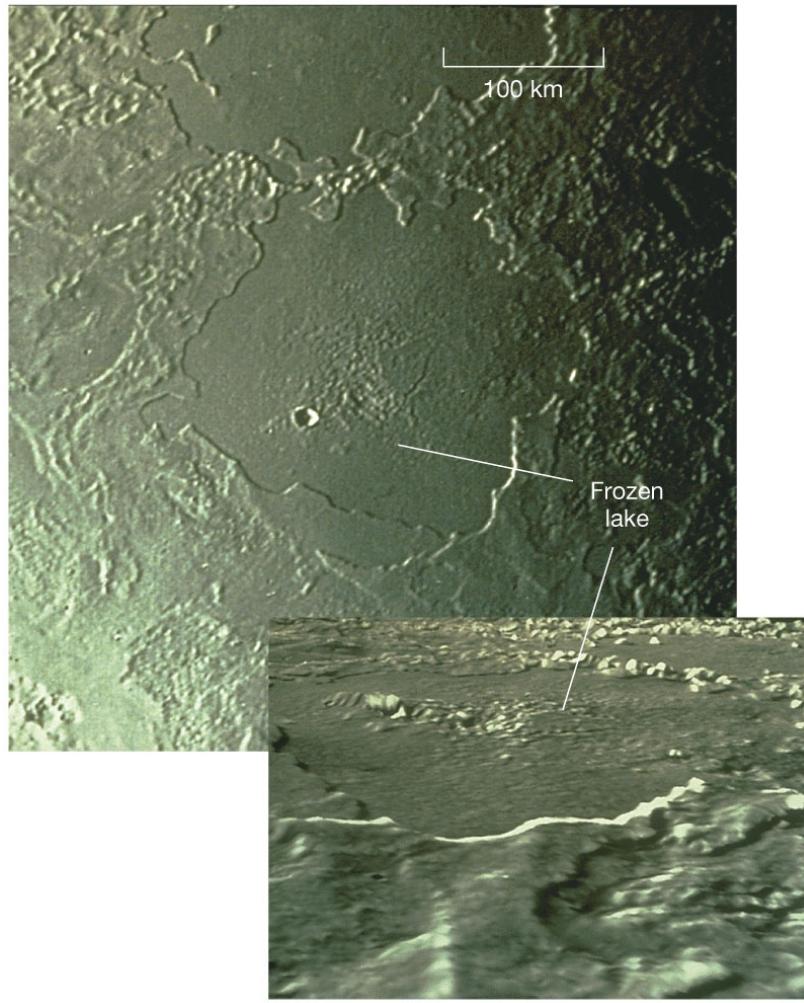
Triton – the  
musk-melon moon.

Nitrogen geysers  
have been observed  
on Triton,  
contributing to the  
surface features



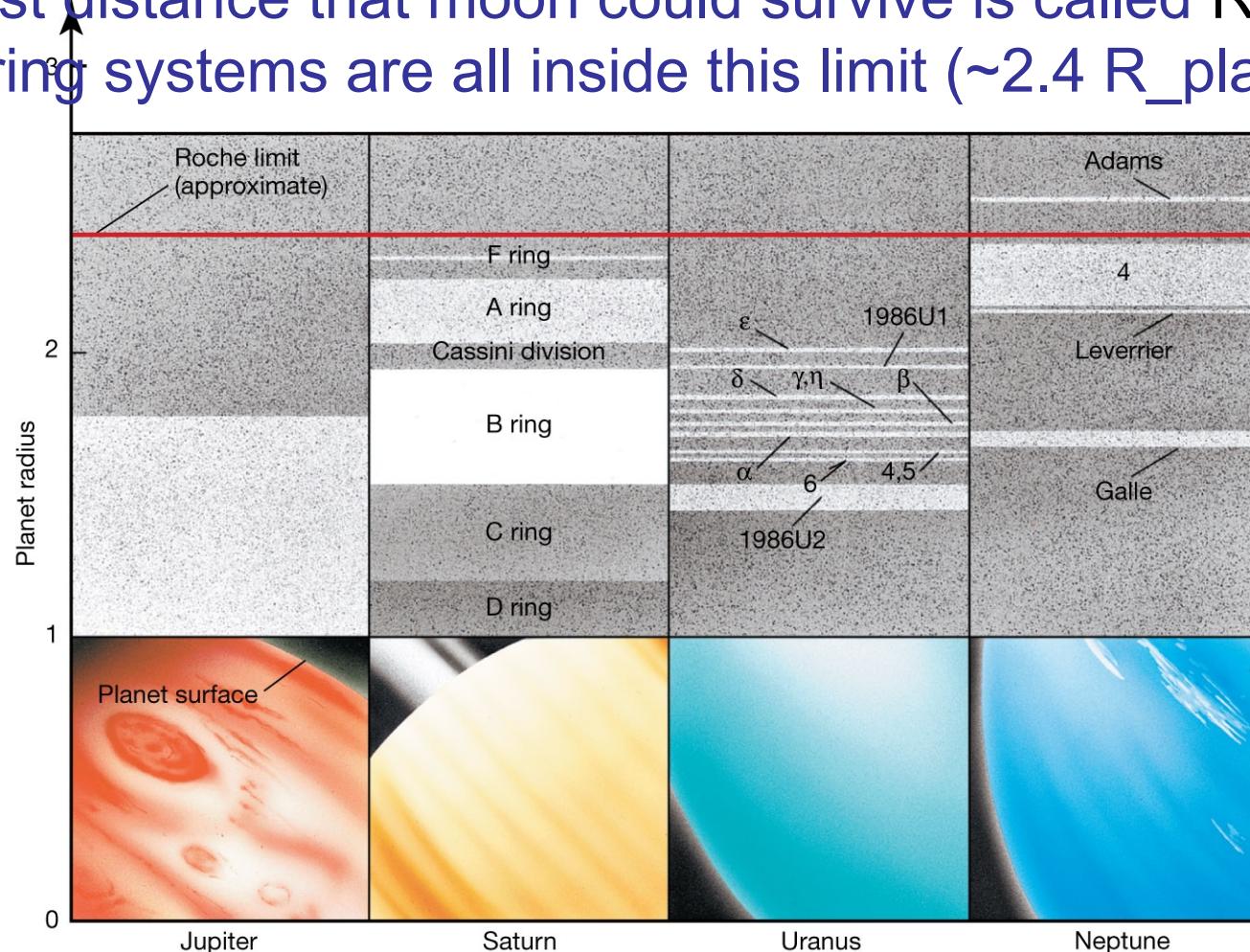
# 13.5 The Moon Systems of Uranus and Neptune

Also, there appear to be ice volcanoes



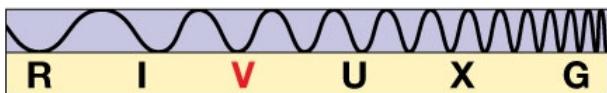
# 12.4 Saturn's Spectacular Ring System

Closest distance that moon could survive is called Roche limit; ring systems are all inside this limit ( $\sim 2.4 R_{\text{planet}}$ )



# 11.6 Jupiter's Ring

Jupiter was found to have a close-in, diffuse ring

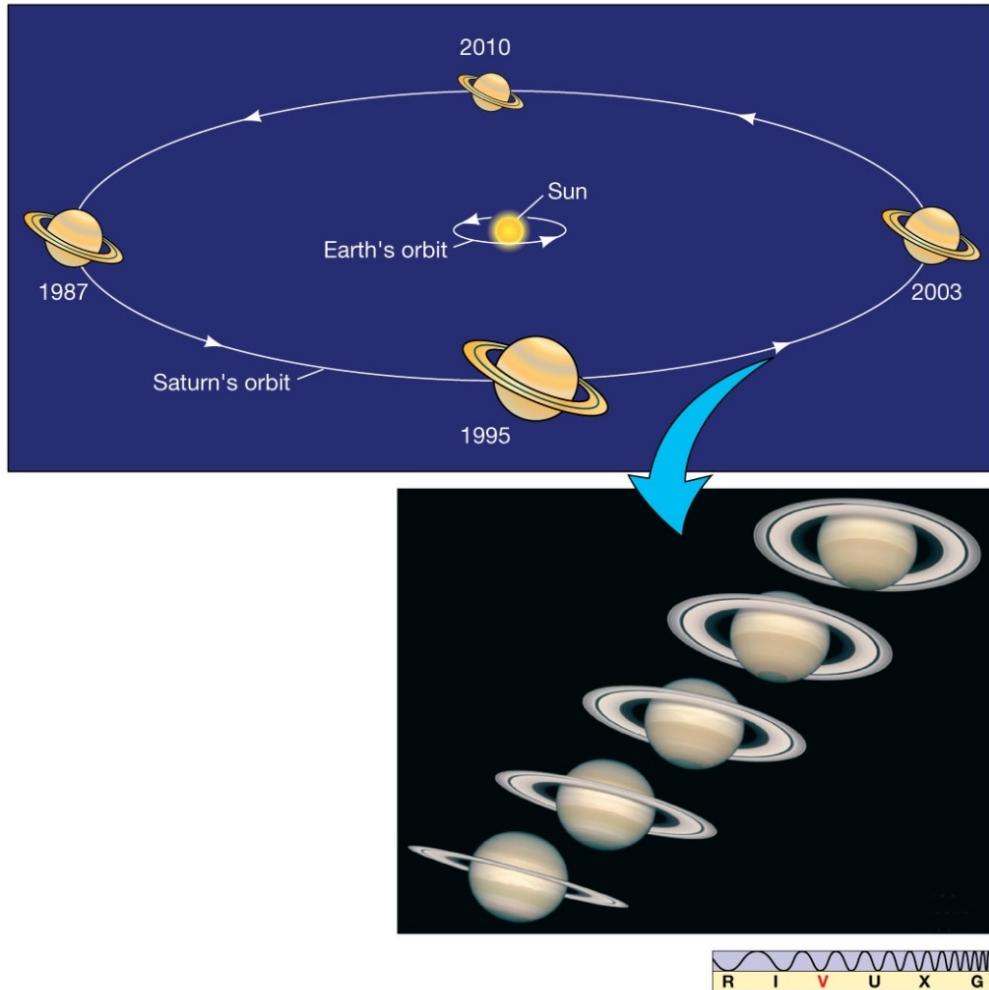


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# 12.4 Saturn's Spectacular Ring System

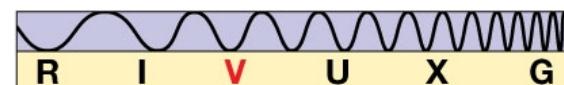
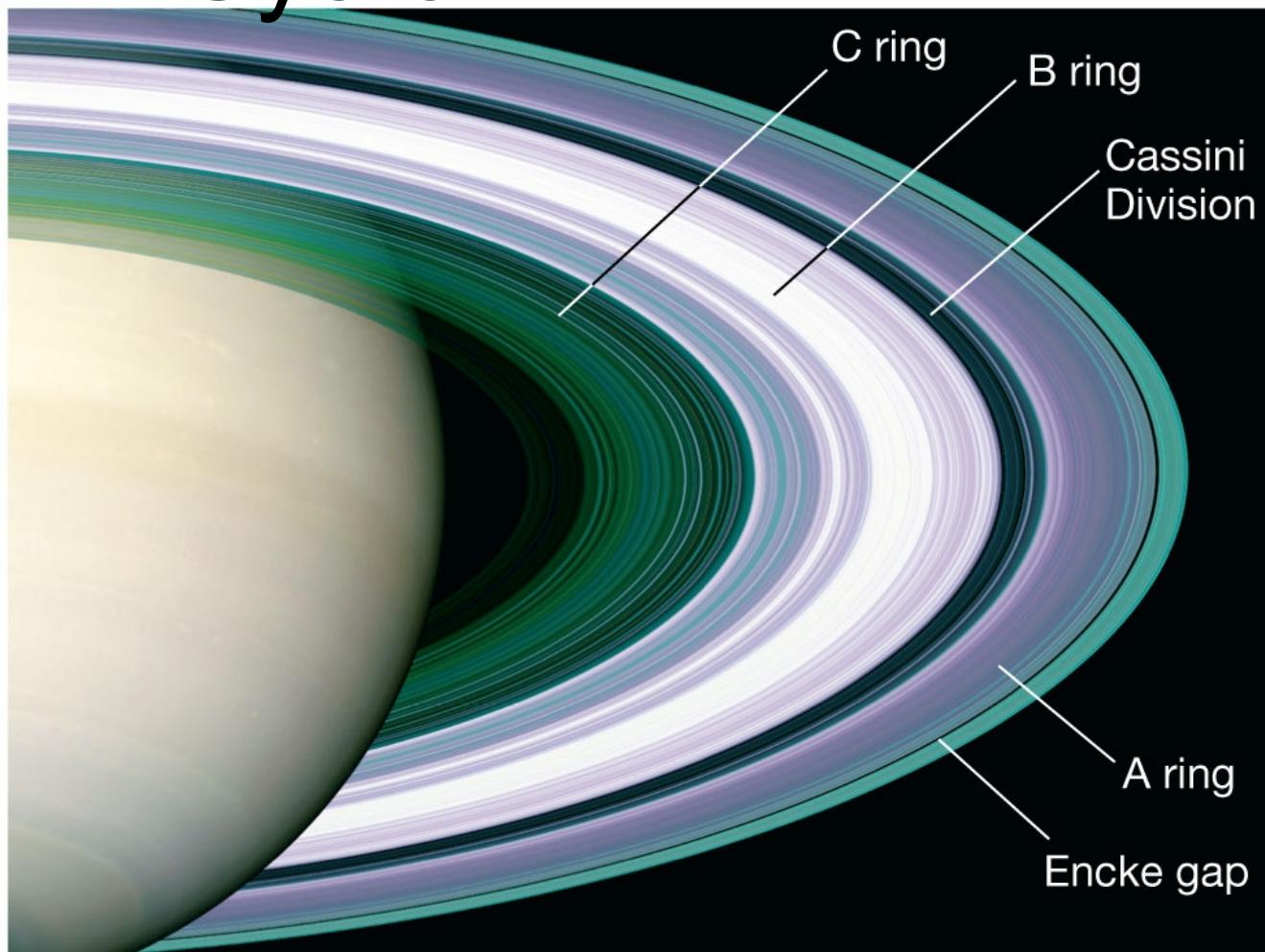
Saturn has an extraordinarily large and complex ring system, which was visible even to the first telescopes.

Ring-plane crossings occur every ~15 years.



# 12.4 Saturn's Spectacular Ring System

Overview of the ring system



# 12.4 Saturn's Spectacular Ring System

Ring particles range in size from fractions of a millimeter to tens of meters

Composition: Water ice—similar to snowballs

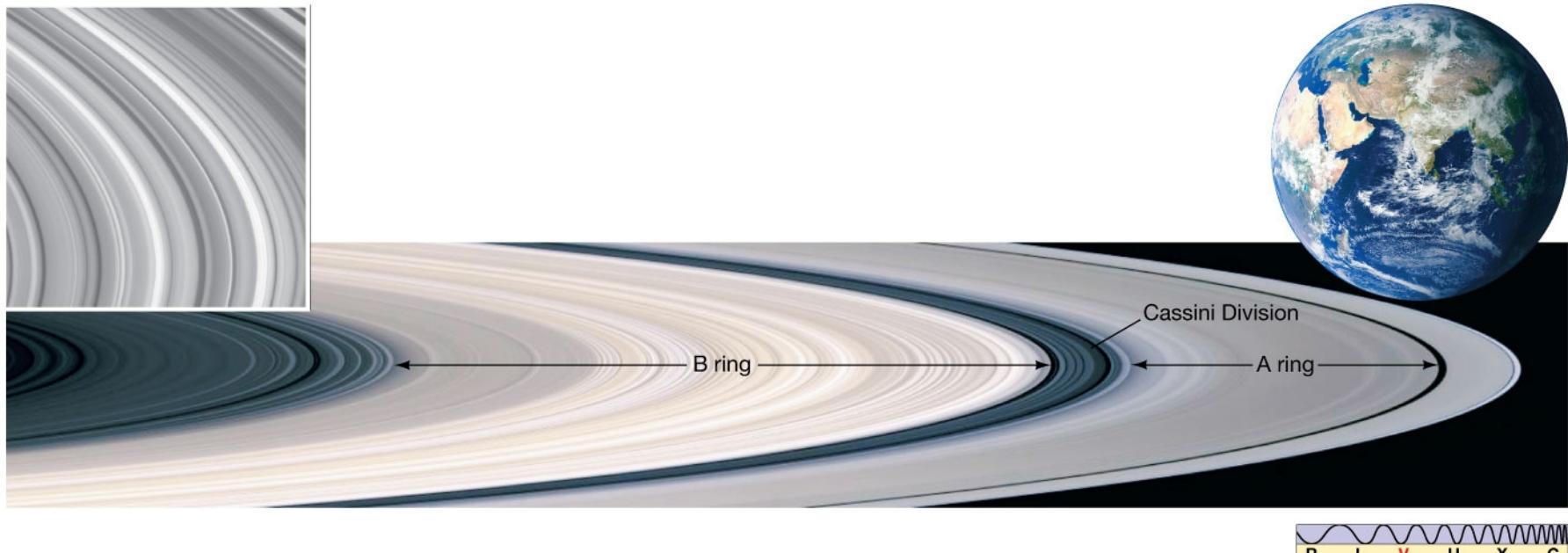
Why rings?

- Too close to planet for moon to form—tidal forces would tear it apart

# 12.4 Saturn's Spectacular Ring System

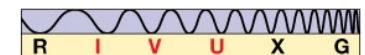
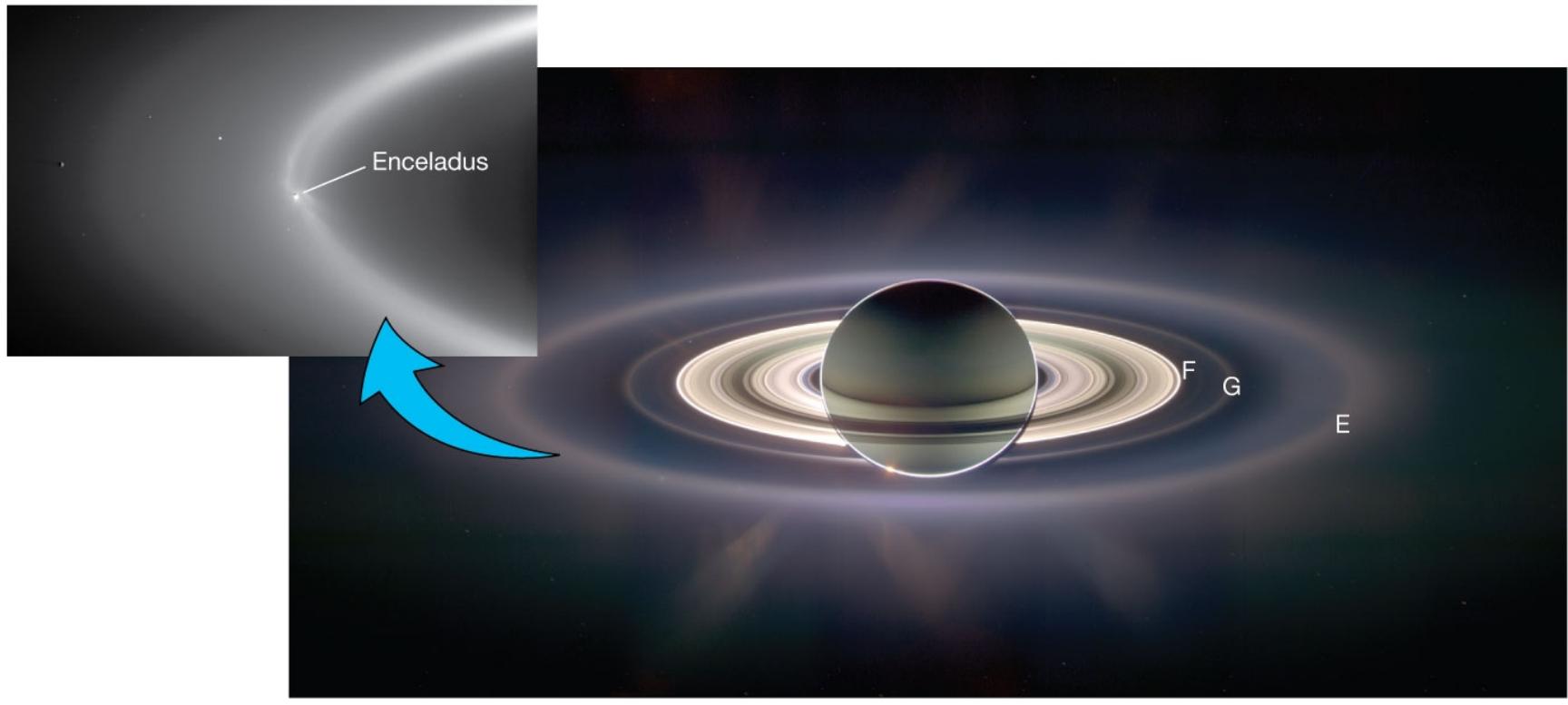
*Voyager* probes showed Saturn's rings to be much more complex than originally thought

(Earth is shown on the same scale as the rings)

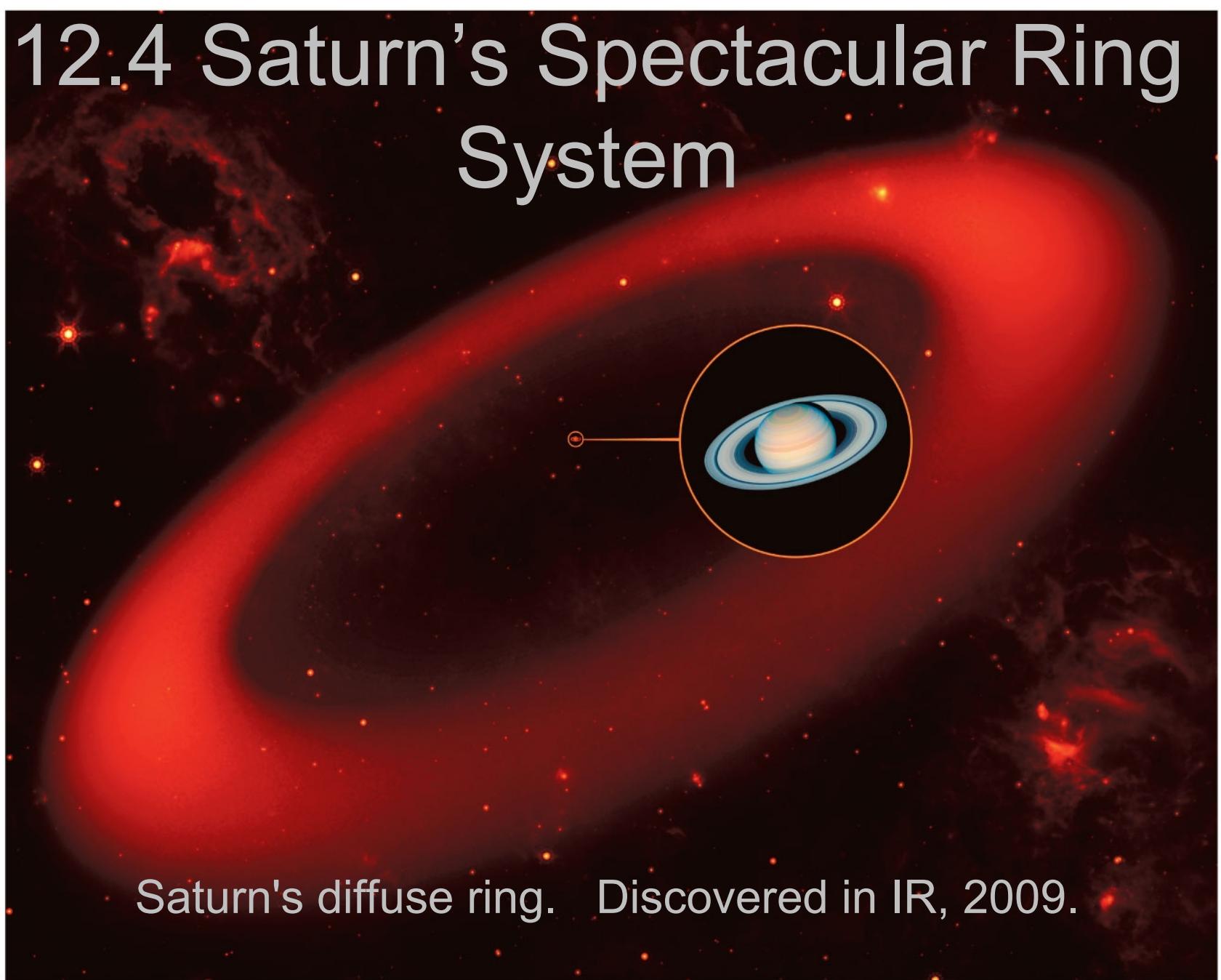


# 12.4 Saturn's Spectacular Ring System

This backlit view shows the fainter F, G, and E rings



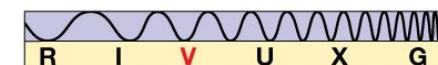
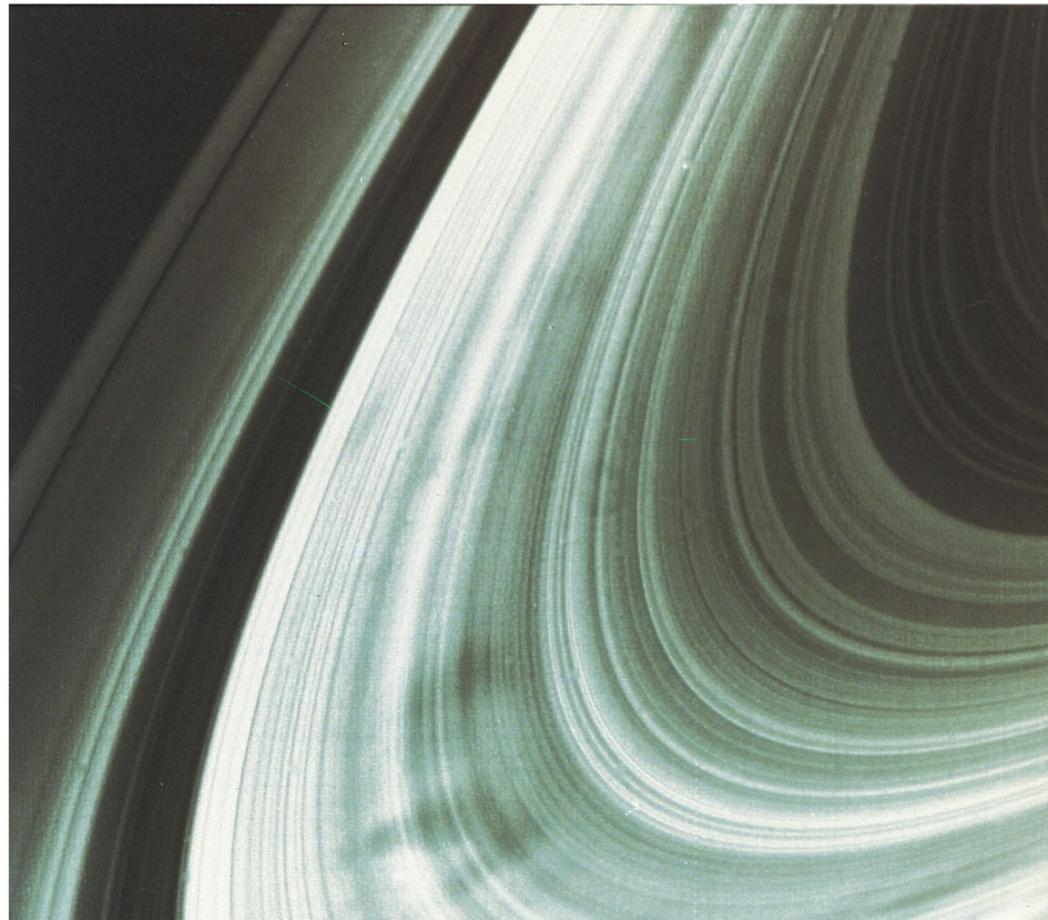
# 12.4 Saturn's Spectacular Ring System



Saturn's diffuse ring. Discovered in IR, 2009.

# 12.4 Saturn's Spectacular Ring System

Voyager also found radial “spokes” that formed and then dissipated; this probably happens frequently.

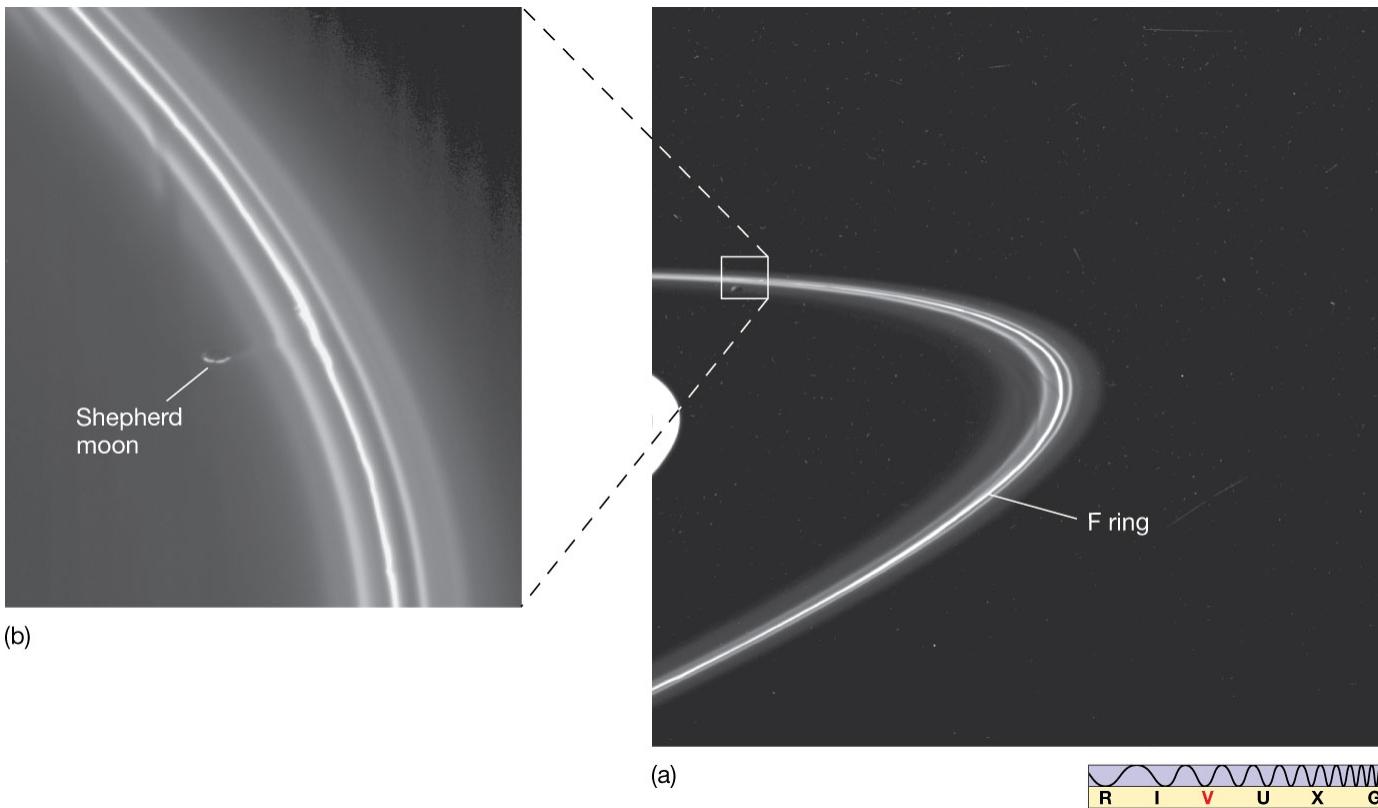


# 12.4 Saturn's Spectacular Ring System

- Other edges and divisions in rings are also the result of shepherd moons or resonance
- “Shepherd” moon Atlas defines outer edge of A ring through gravitational interactions

# 12.4 Saturn's Spectacular Ring System

Strangest ring is the F ring; it appears to have braids and kinks. It is just beyond the A ring.



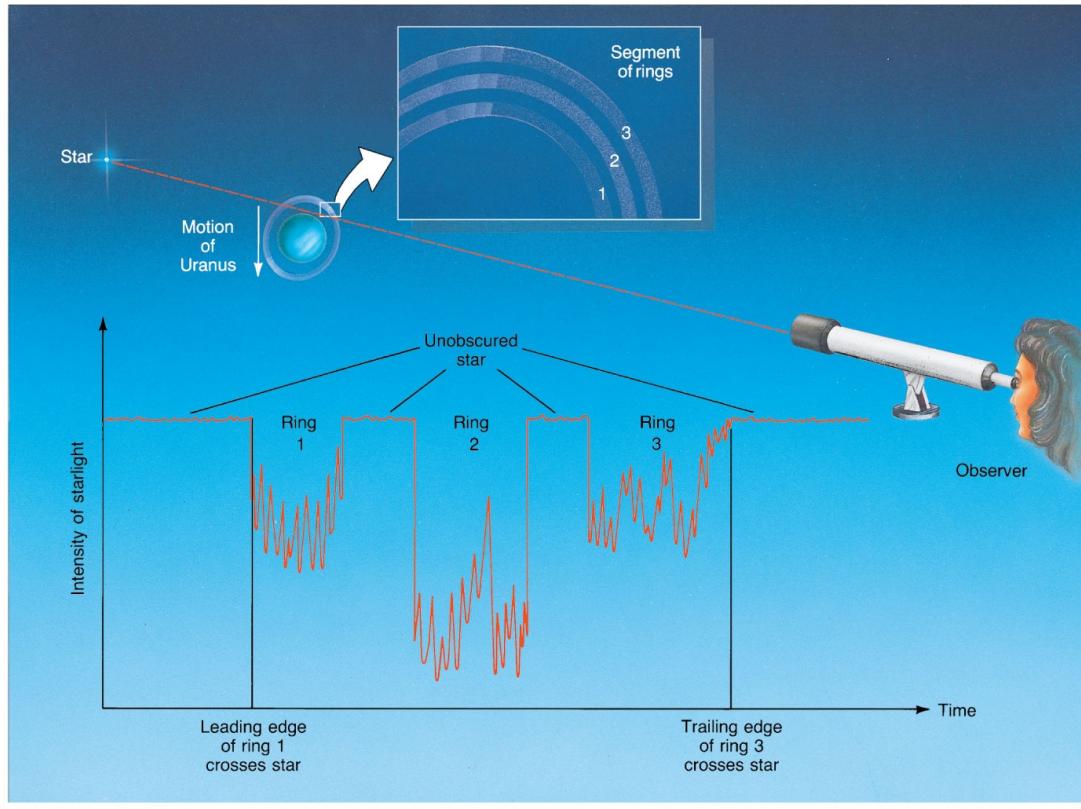
# 12.4 Saturn's Rings

How and when did they form?

- Probably too active to have lasted since birth of solar system.
- Not all rings may be the same age. B may be very old.
- Either must be continually replenished, or are the result of a catastrophic event.
  - Can you think of a time when a comet or asteroid flew close in to a Jovian planet? What if it hit a moon?

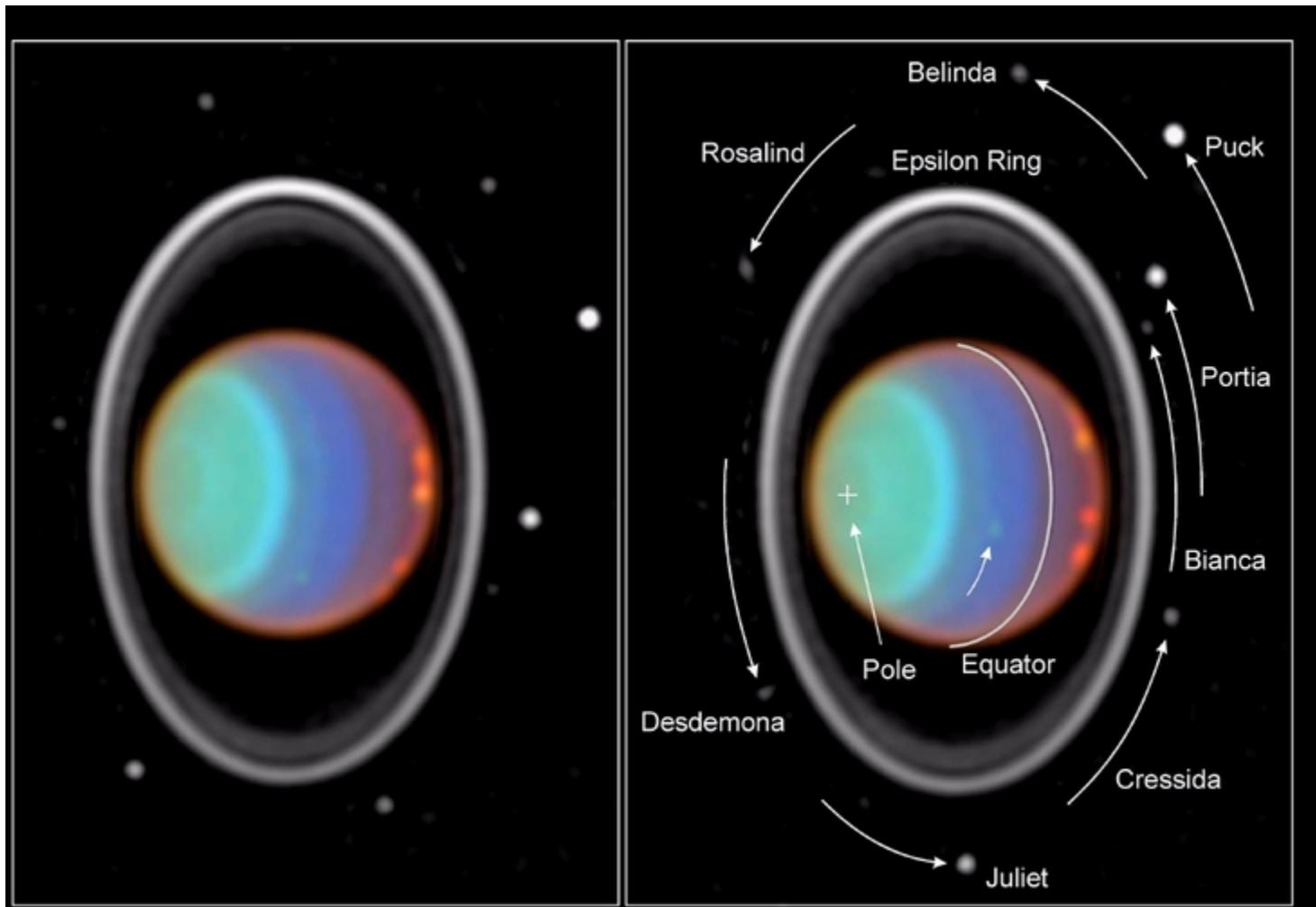
# 13.6 The Rings of the Outermost Jovian Planets

Uranus and Neptune have faint ring systems, detected during stellar occultations



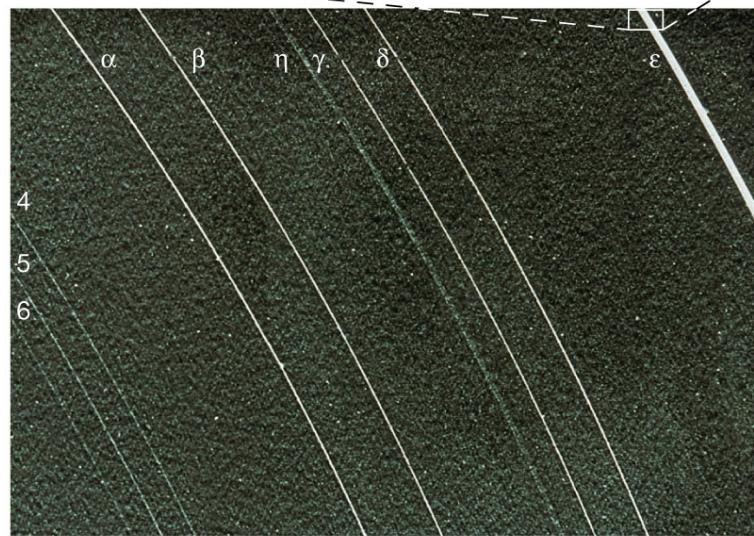
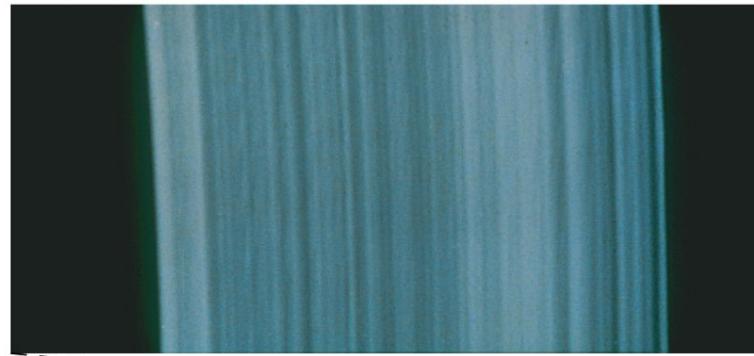
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# Uranus' Rings (and inner moons)



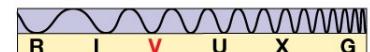
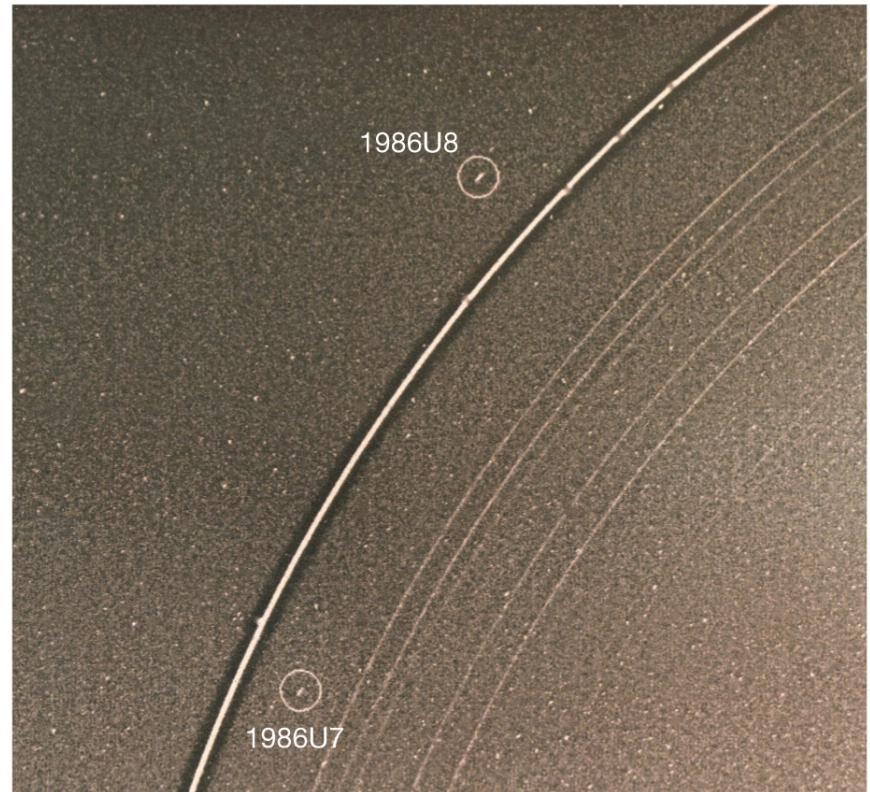
# 13.6 The Rings of the Outermost Jovian Planets

Uranus's rings are narrow



# 13.6 The Rings of the Outermost Jovian Planets

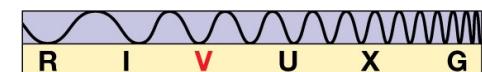
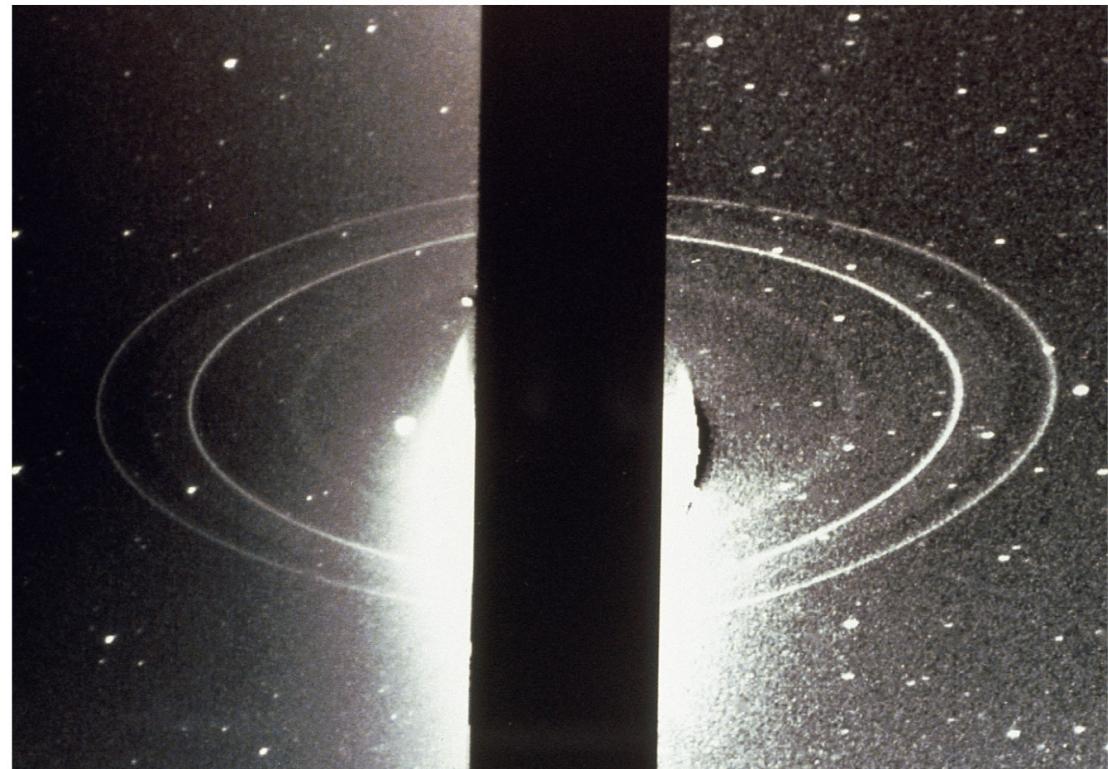
Two shepherd moons keep the epsilon ring from diffusing



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# 13.6 The Rings of the Outermost Jovian Planets

Neptune has five rings:  
three narrow and two wide



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# Summary of Chapter 11

- Jupiter is the largest planet in the solar system
- Rotates rapidly
- Cloud cover has three main layers, forms zone and belt pattern
- Great Red Spot is a very stable storm
- Pressure and density of atmosphere increase with depth; atmosphere becomes liquid and then “metallic”

# Summary of Chapter 11 (cont.)

- Relatively small rocky core (but still about 10x size of Earth)
- Still radiating energy from original formation
- 79+ moons, four very large
- Io: active volcanoes, due to tidal forces
- Europa: cracked, icy surface; may be liquid water underneath
- Ganymede and Callisto: similar; rock and ice