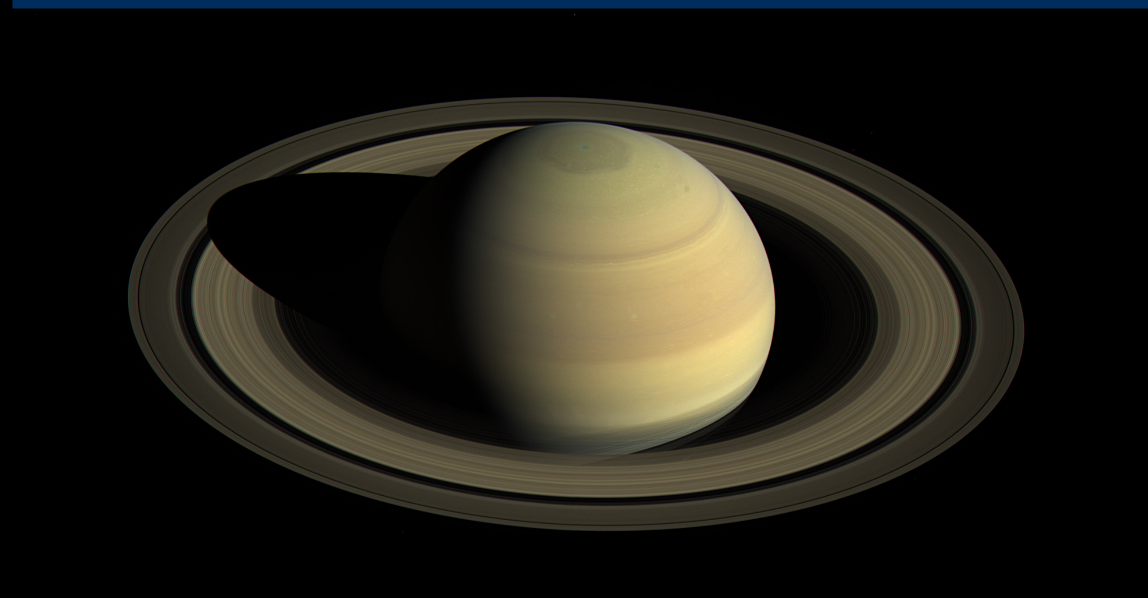
Announcements

- Extra Credit: Take a photo of yourself with the eclipse on Monday and e-mail it to me. Evidence of the eclipse could be from shadows, a pin-hole camera, an image through a telescope, etc
- Physics Day is April 13, student talks, free lunch

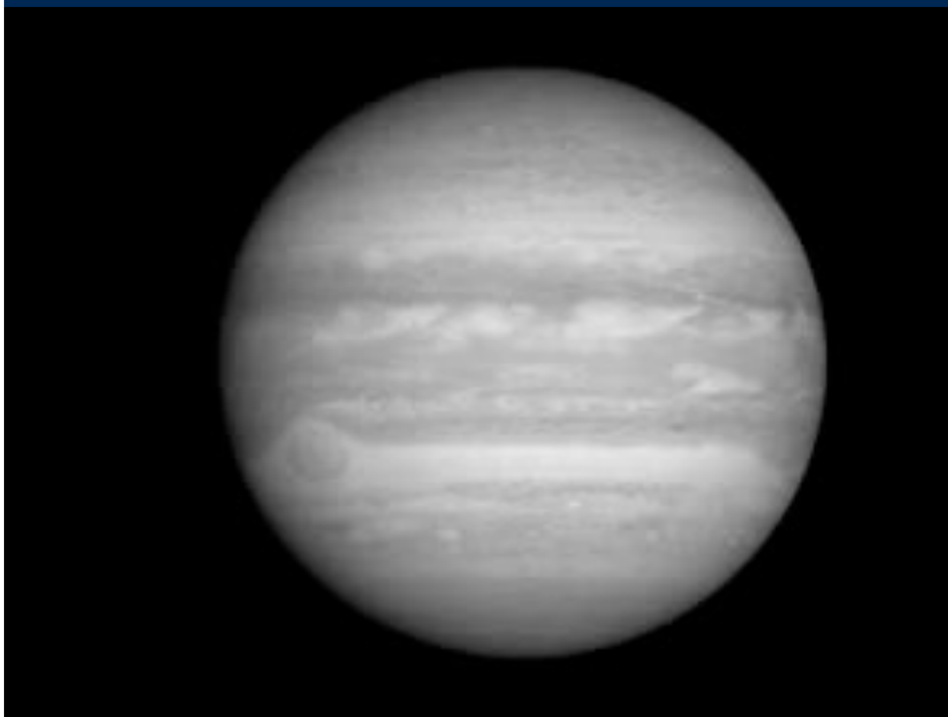
Register before April 9:
https://physics.unm.edu/pandaweb/undergraduate/day2024/index.php

Jupiter and Saturn



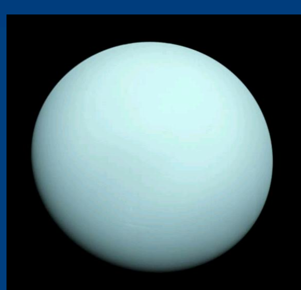
The Jovian Planets (Gas Giants)

Jupiter



Saturn

Uranus



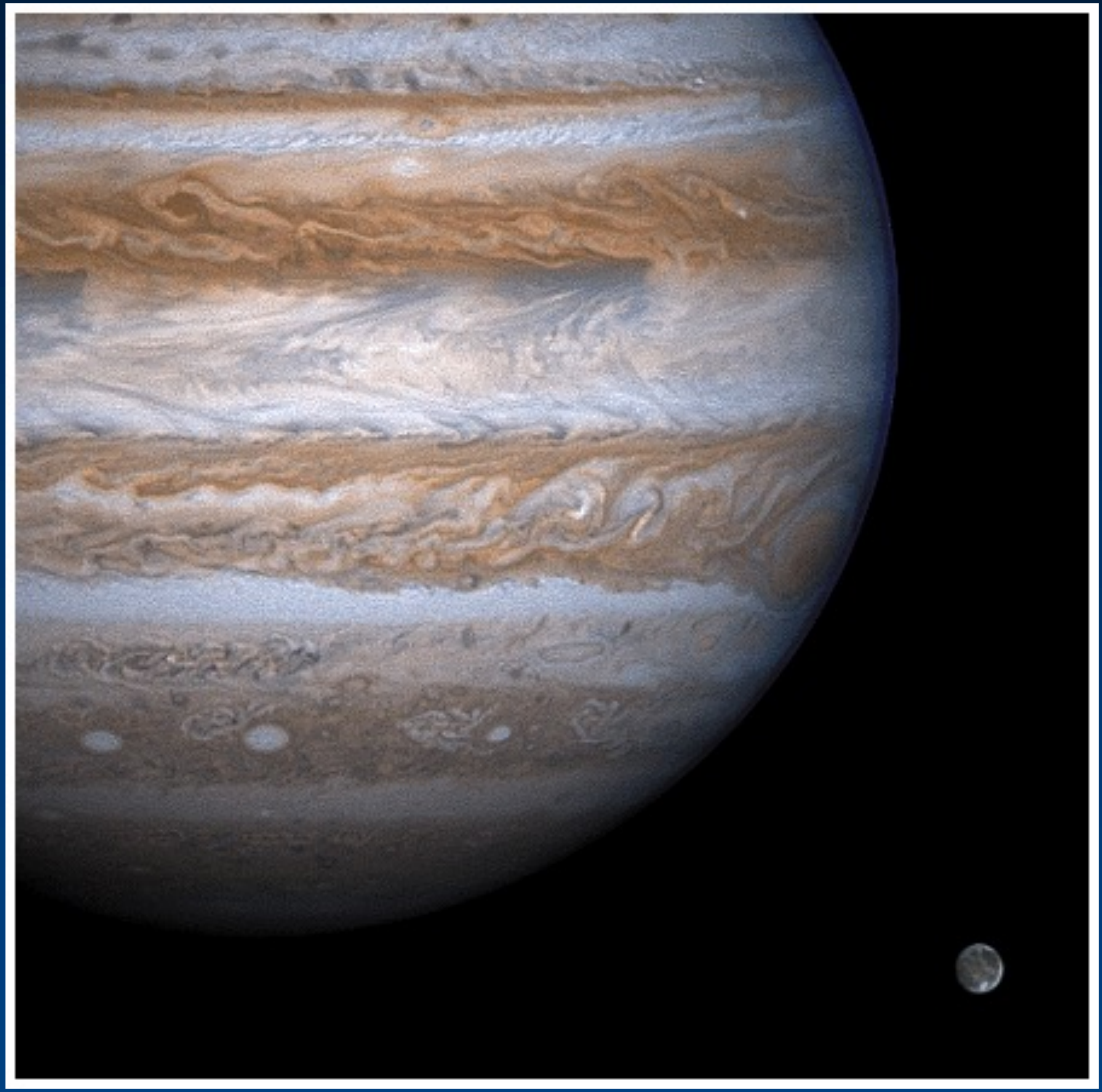
Neptune

(roughly to scale)

Reminder - Terrestrial and Jovian Planets

- The four inner planets are the terrestrial planets
  - Small diameters (5000 to 13,000 km)
  - High average densities (3.9-5.5 g/cm^3)
  - Composed primarily of rocky materials

- The four giant outer planets are the Jovian planets
  - Large diameters (50,000 to 143,000 km)
  - Low average densities (0.7-1.7 g/cm^3)
  - Composed primarily of hydrogen and helium



Jupiter and moon Ganymede (Cassini spacecraft image)

Jupiter basic data

Semi-major axis	5.2 AU
Orbital period	11.9 Earth years
Rotation period	$9^h\ 50^m$ (equatorial)
	$9^h\ 56^m$ (polar)
Diameter	11.2 times Earth's
Mass	318 times Earth's
Density	1326 kg/m^3 = 1.3 g/cm^3
V_{esc}	60 km/s
Surface gravity	2.36 times Earth's
Temp	(cloud top) 165 K
Albedo	0.44

Jupiter - a gas giant

- Deep hydrogen/helium gas and liquid atmosphere
- Small core of rock and iron?
- Rotates rapidly which creates large equatorial bulge:
  - Equatorial radius 71,492 km
  - Polar radius 66,854 km (7% smaller)

Spacecrafts to Jupiter

- Fly-bys:
  - Pioneer 10 & 11 (1973,1974)
  - Voyager 1& 2 (1979)
  - Cassini (2000) on its way to Saturn

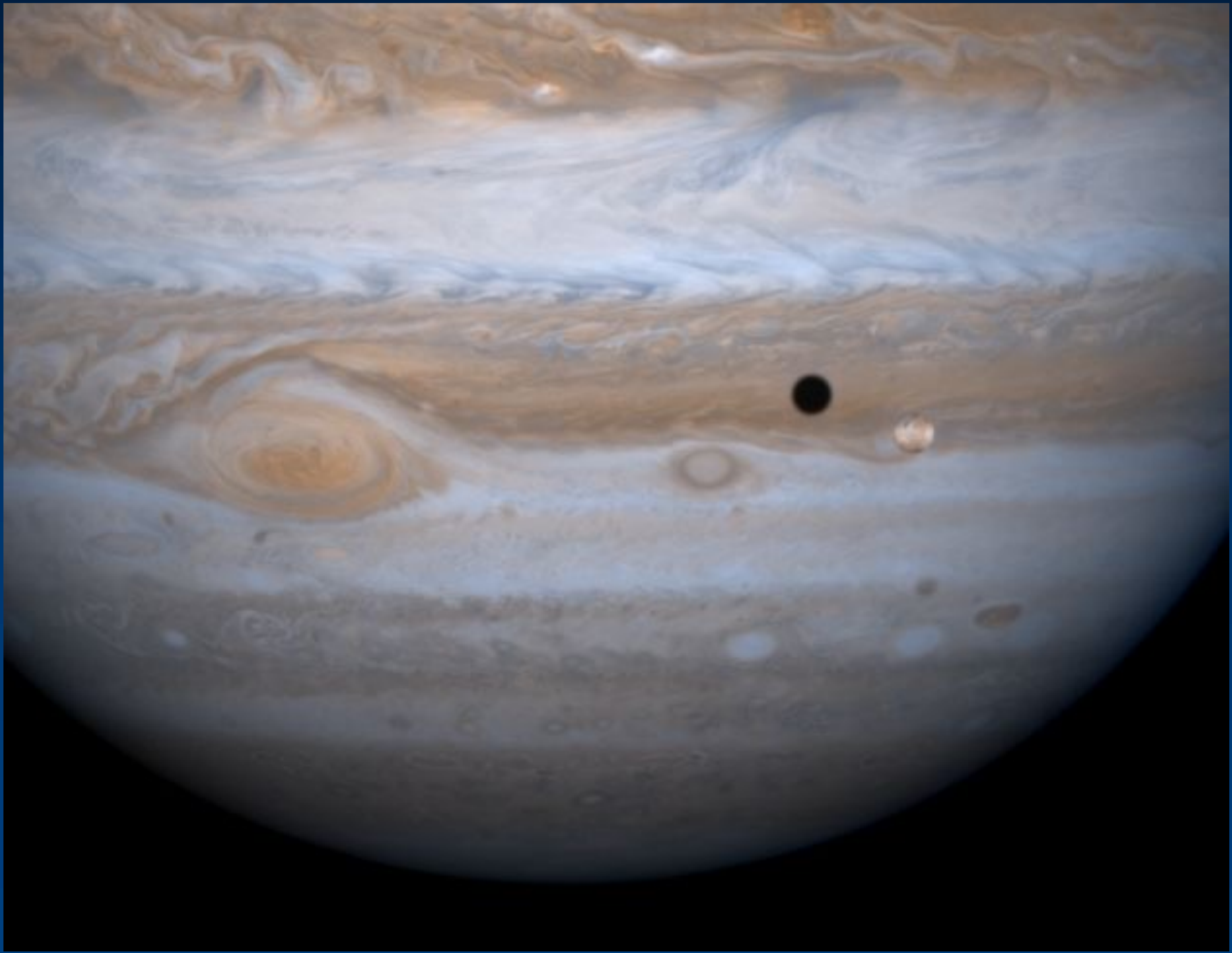
- Orbiting satellites:
  - Galileo (1995-2003), dropped an atmospheric probe
  - Juno (2016 - now)

Earth-based images:

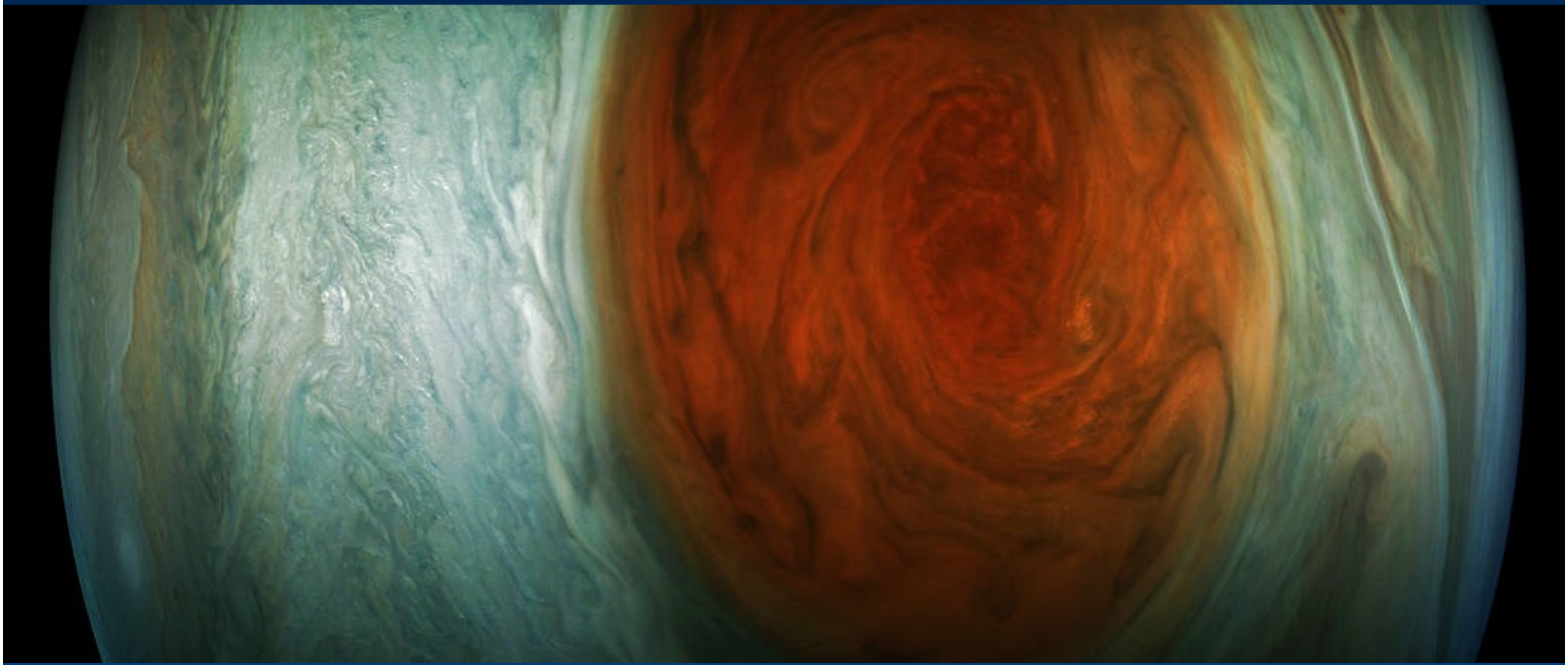
Oblate, cloud bands, zones (white), belts (brown), white spots, brown spots, red spot, 4 Galilean satellites

Space-based images: Pioneer 10, 11; Voyager 1,2; Cassini has given much more detail, discovered many more moons

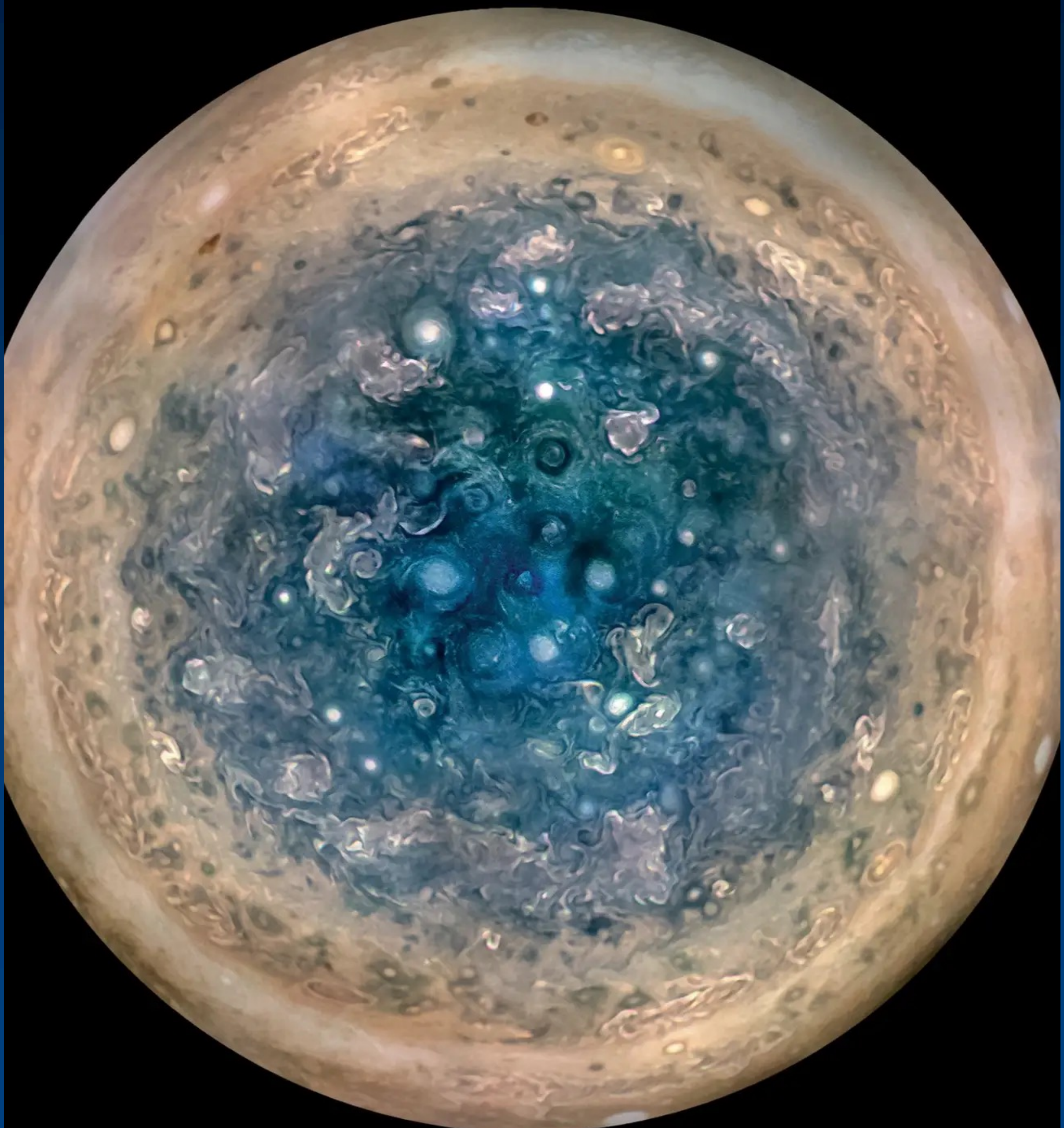
Voyager 1 (1979) image from 30 million km.
Resolution ~600 km.



Jupiter and Io from Cassini

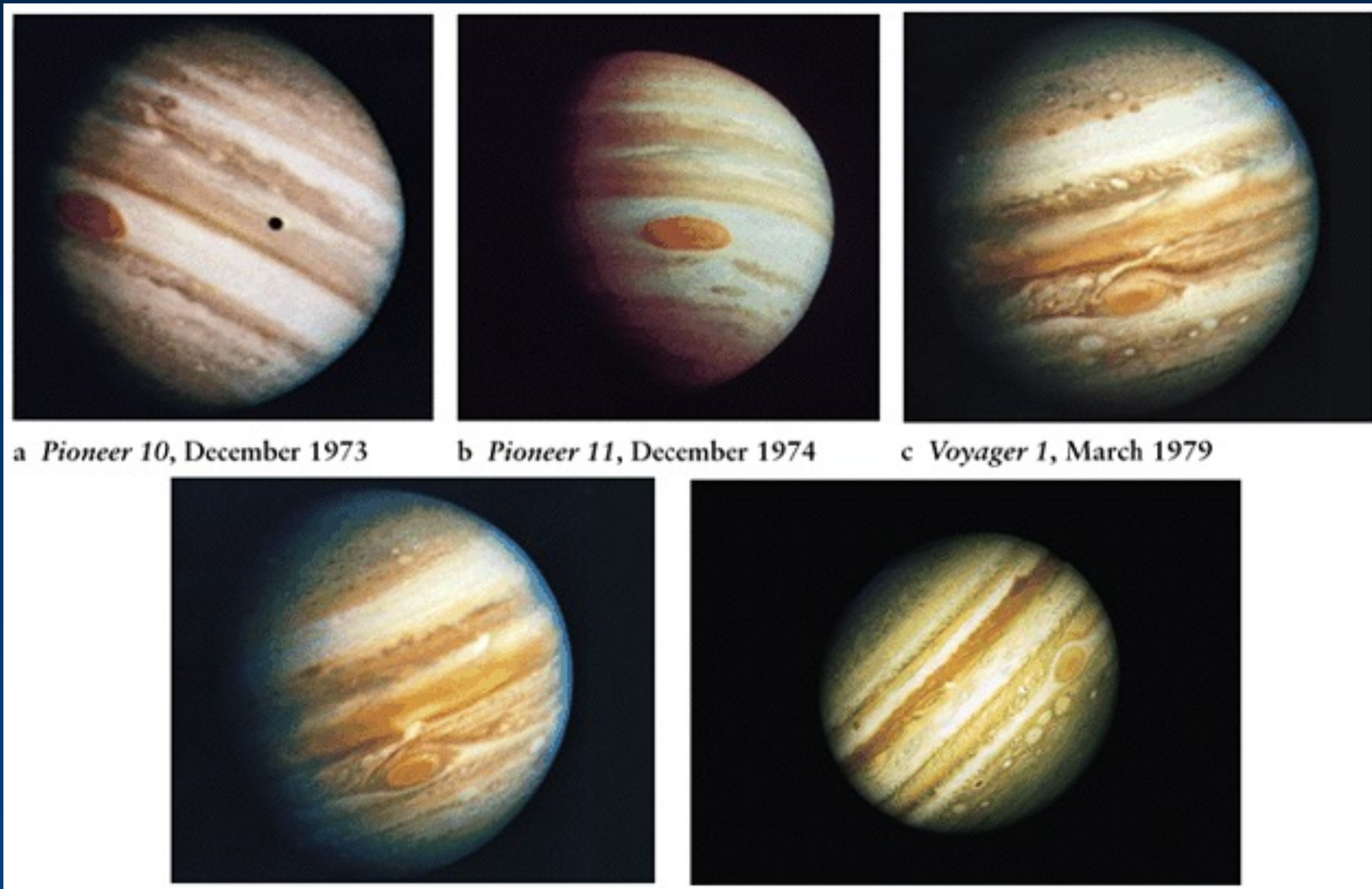


Jupiter’s great red spot seen by Juno



South pole of Jupiter as seen by Juno

The bands change with time



a *Pioneer 10*, December 1973

b *Pioneer 11*, December 1974

c *Voyager 1*, March 1979

d *Voyager 2*, July 1979

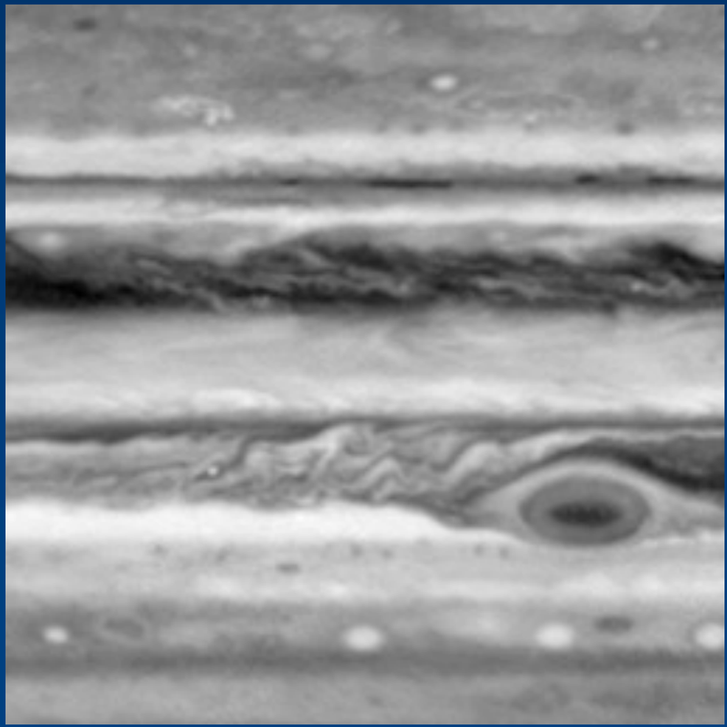
e HST, February 1995

Jupiter's rotation

- Differential rotation: Cassini (1690) realized that rotation rate at the poles was slower than at equator

Near poles	At equator
$9^h\ 56^m$	$9^h\ 50^m$

- Different bands rotate at different speeds as well



Rotation and interior

- Rotation plus oblateness allows us to model interior structure: constrains how Jupiter's mass is distributed over its volume
- Model suggests dense, rocky core of roughly 8 M_{earth}.
- Remaining mass is H and He.
- Most of the interior H is in the form of *liquid metal.*

  At high temperatures and pressures (millions of atmospheres) electrons can jump between H_2 molecules as in electrically conducting metals.

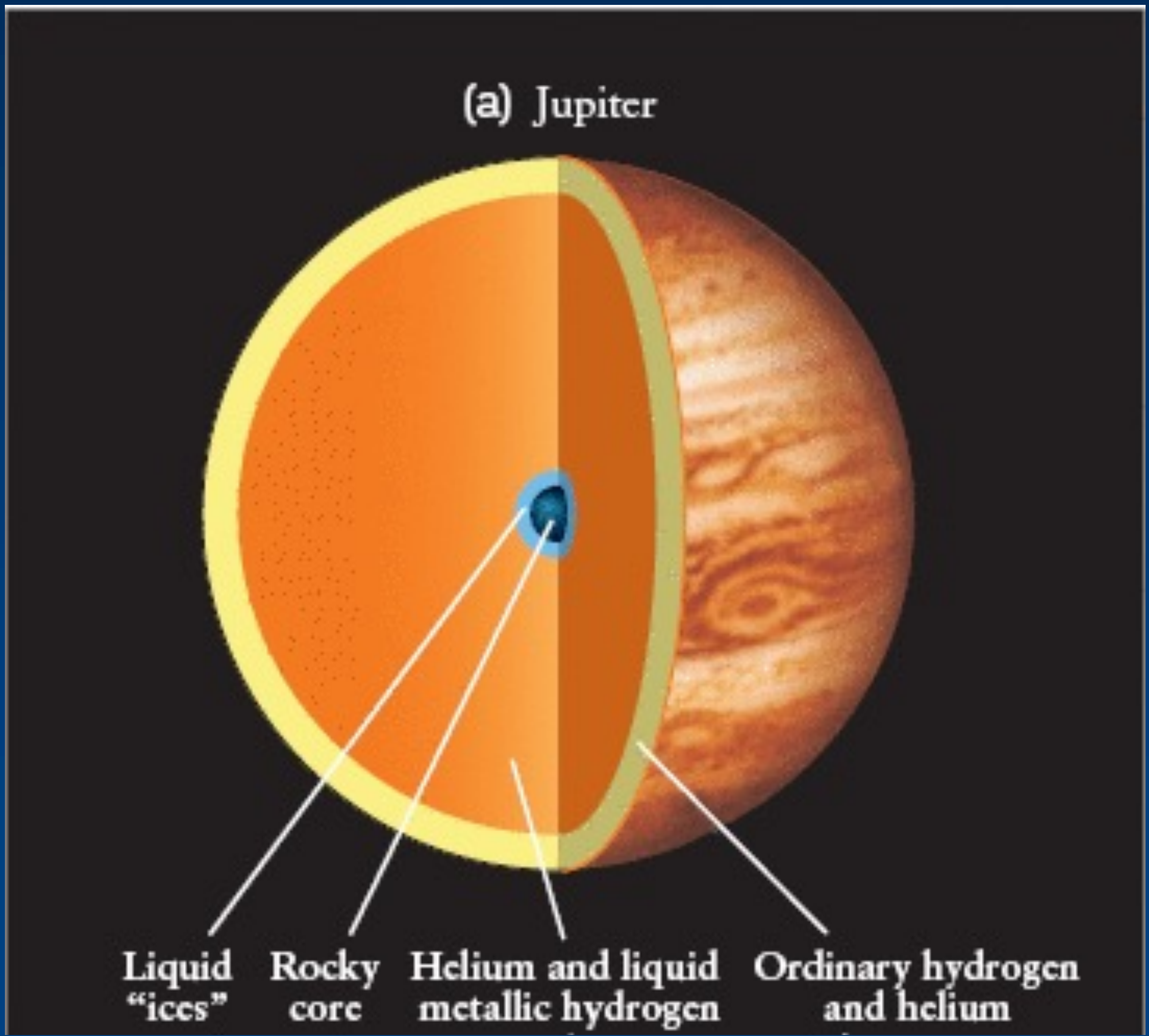
Layers:

rocky core

hot liquid water, methane, ammonia and related compounds

liquid metallic hydrogen dominates

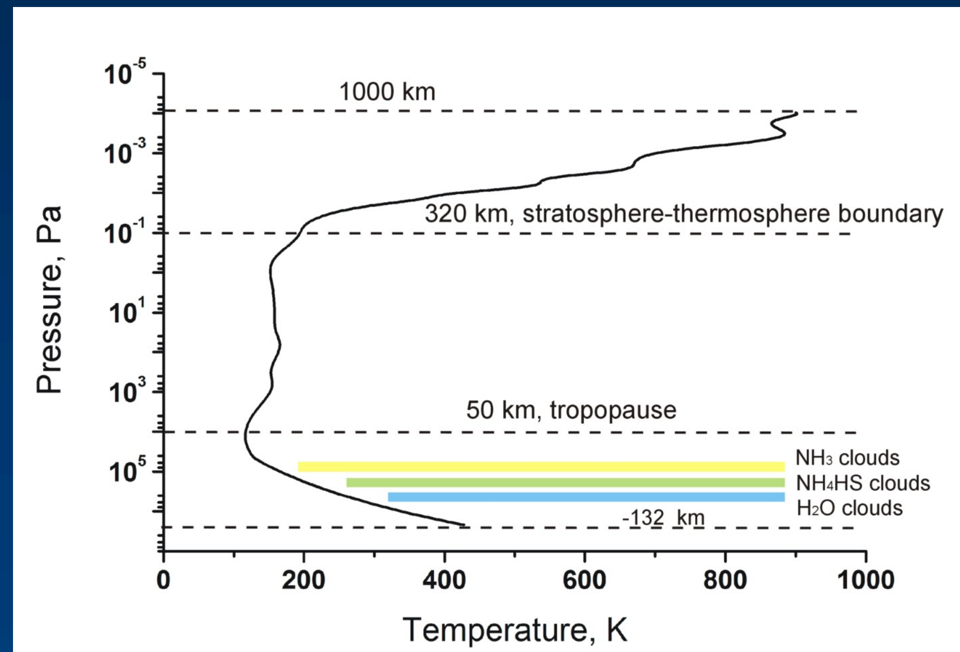
ordinary hydrogen, helium dominate



Atmospheric composition

From spectroscopy, probing a few 100 km down.

- 86.2% H_2
- 13.6% He
- 0.2% CH_4, H_2O, NH_3, etc



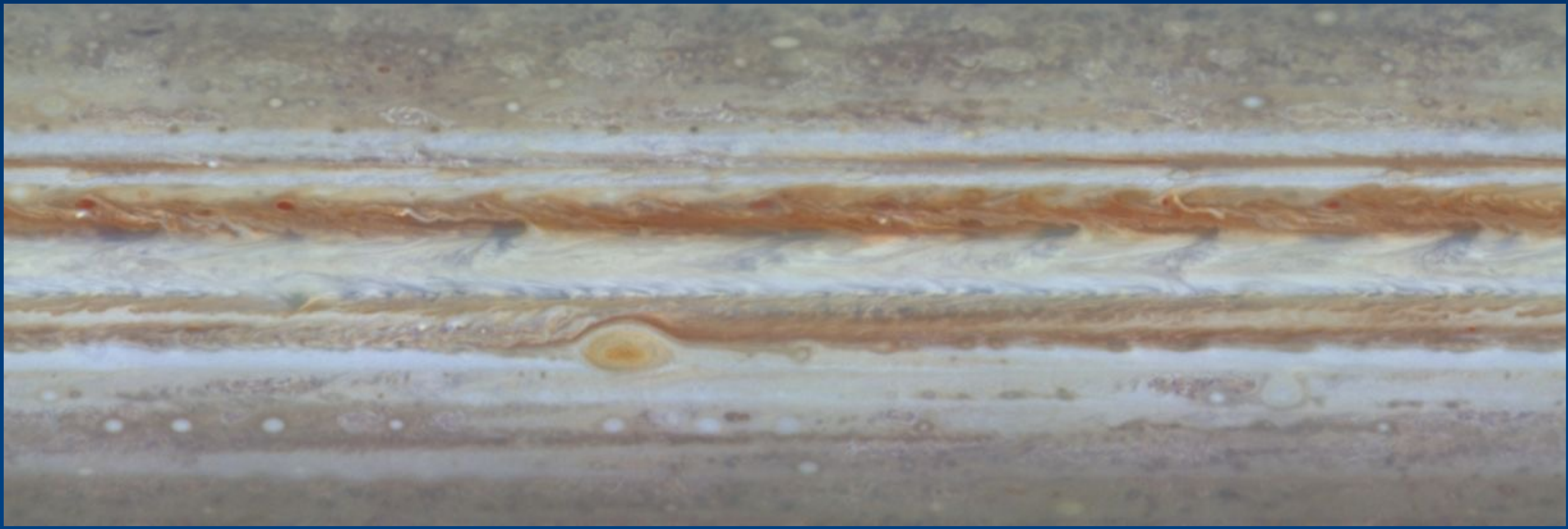
By mass, 75% H, 24% He, 1% others

Overall composition

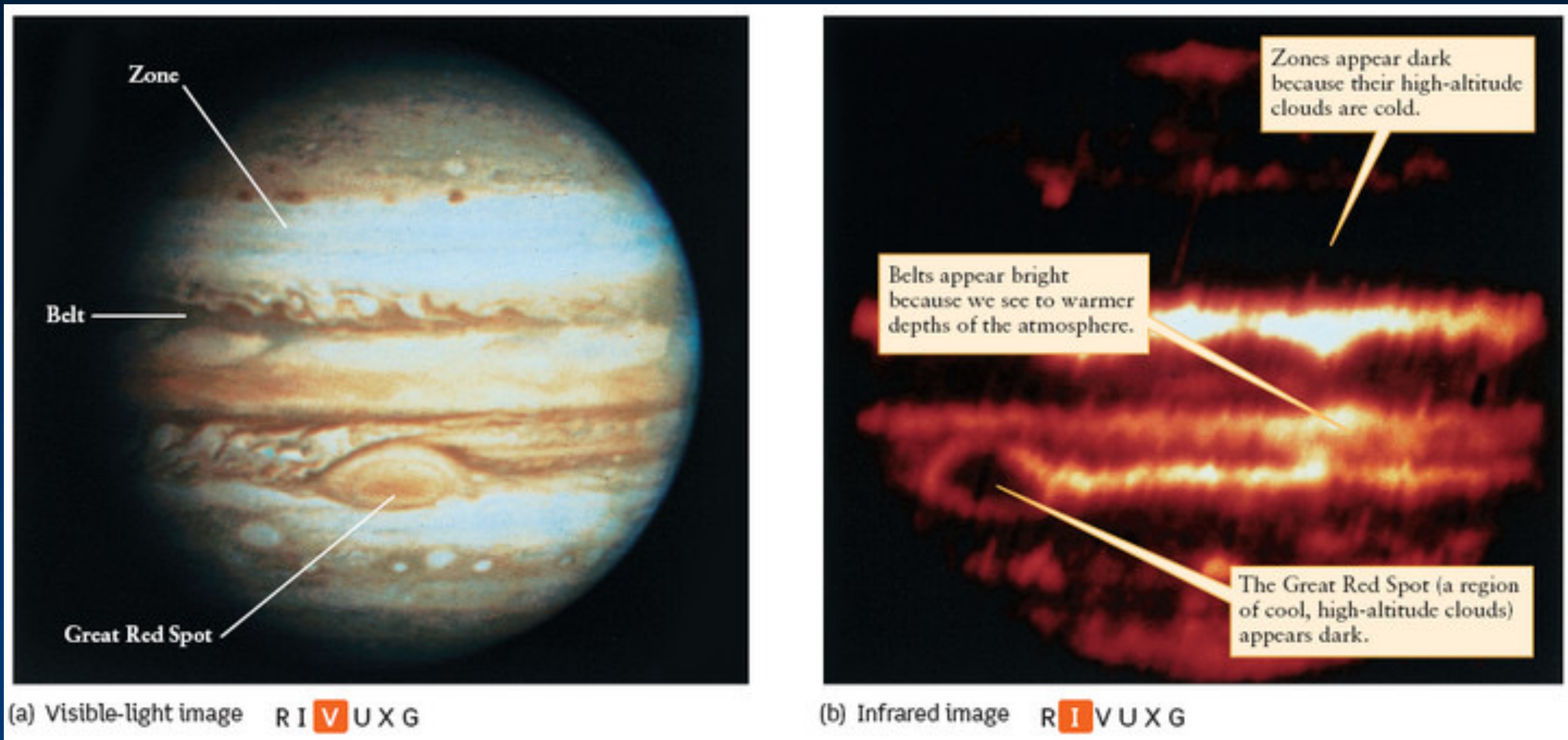
By mass, 71% H, 24% He, 5% others

“Zones” and “Belts”

- Zones are light colored bands, belts are dark bands.
- Colors due to how various molecules reflect sunlight.
- The rapid rotation shapes the belts and zones into tight structures that parallel the equator.



Jupiter “unwrapped” - Cassini images



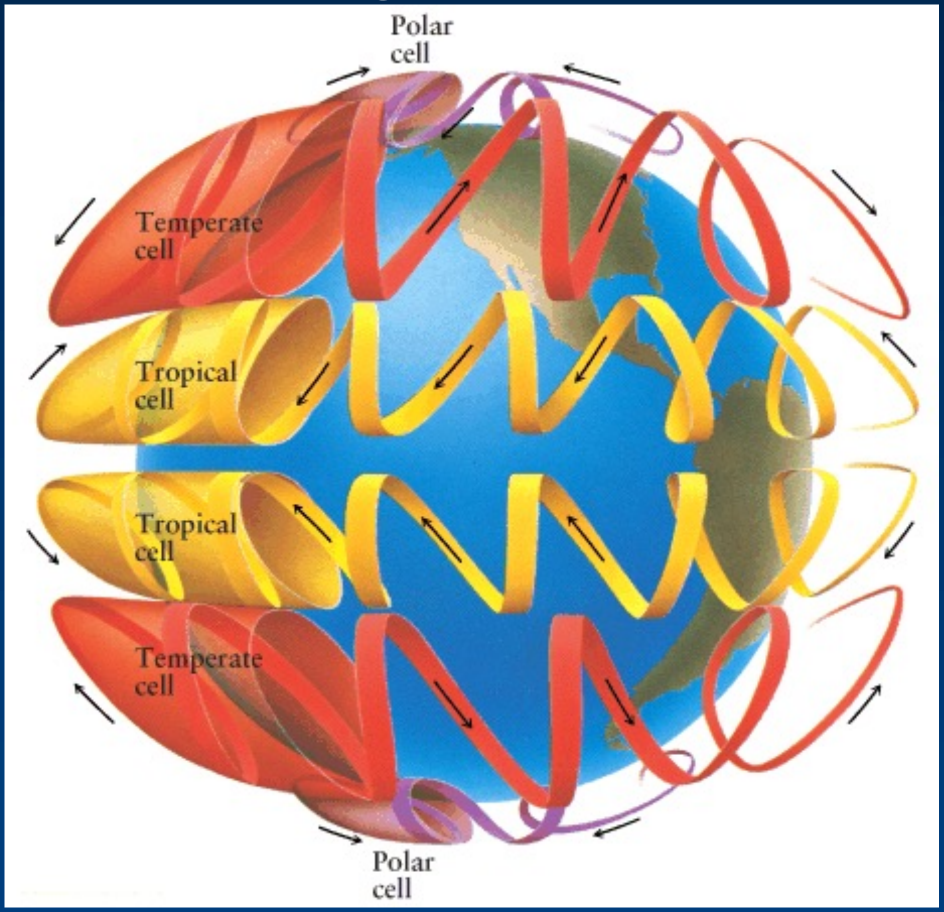
Visible image: colors determined by how molecules reflect sunlight

IR image: traces heat, white = warm, dark = cold

Zones: cold, light-colored, high altitude gas

Belts: warm, dark-colored, low-altitude gas

Analogous to atmospheric circulation on Earth driven by convection, but stretched into tight horizontal structures by rapid rotation.



Wind flows in opposite directions in zones vs. belts (differential rotation). Differences are 100s of km/h.

Internal energy source

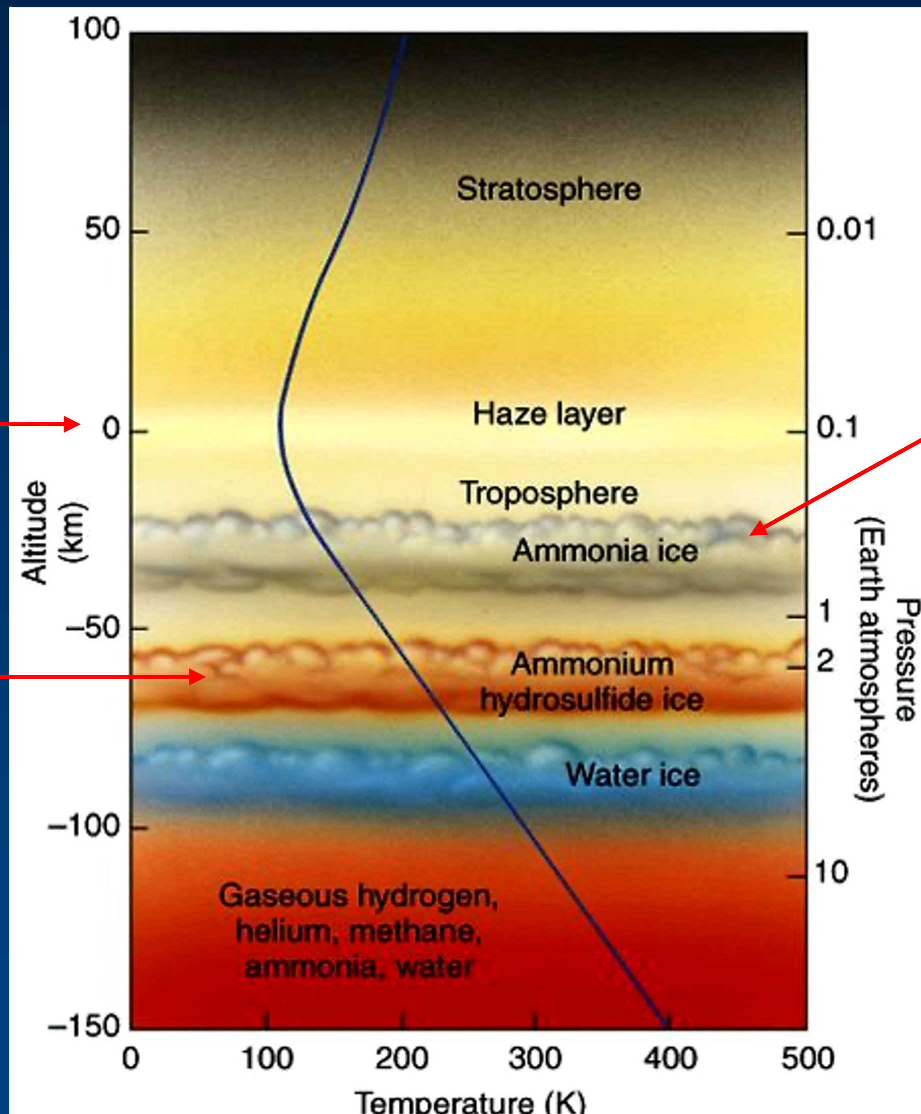
- IR: Jupiter radiates about 2.5 times more energy than it receives from the Sun.
- Jupiter must still be getting rid of its heat of formation
- This internal heat helps power Jupiter's weather.

By contrast, the weather on the Earth, Venus, and Mars is powered by solar energy, as the internal "geothermal" heat is insignificant compared to sunlight.

Atmospheric structure

Altitude 0 km <u>defined</u> as top of troposphere (cloud layer)

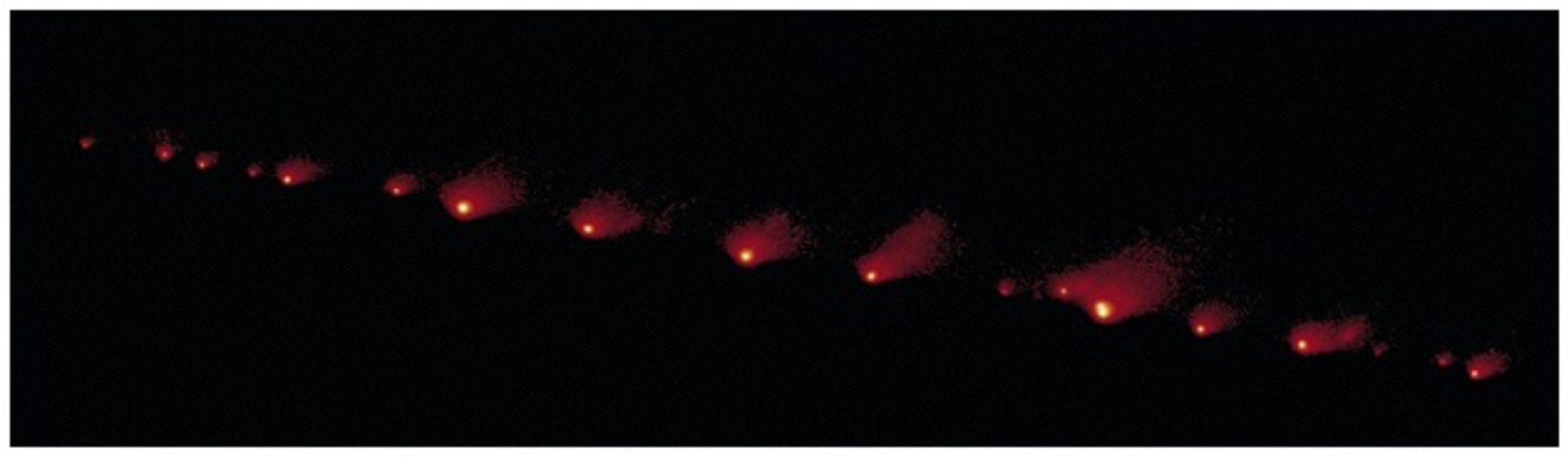
NH_4SH



(NH_3)

Despite this figure, these molecules should all give white clouds. Molecules responsible for colors actually not clear!

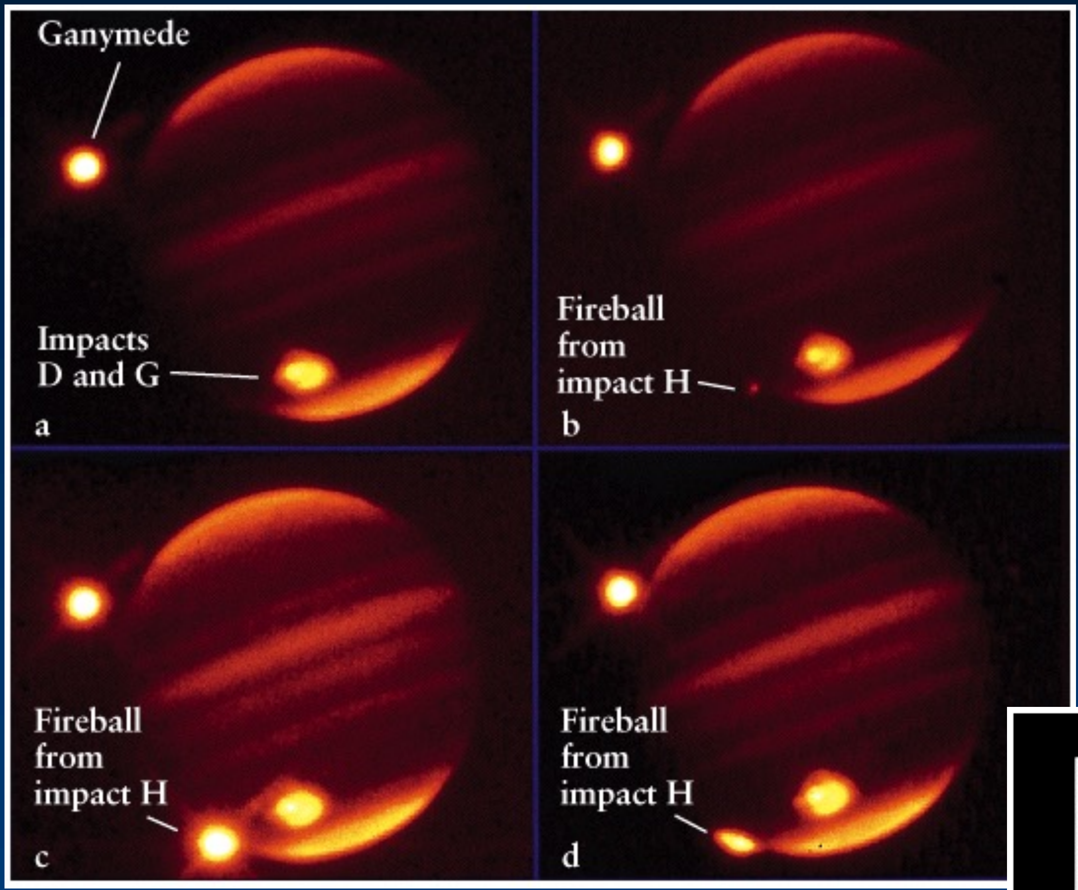
- Galileo spacecraft dropped probe into Jupiter to study clouds in atmosphere (1995)
- The Galileo probe sank 132 km below the cloud tops to a point with pressure = 24 atm and temp of more than 150 ° C.
- Verified the expected H and He abundances, but measured very little of the molecules thought responsible for the clouds.
- Seems it fell into a cloud-free region, unfortunately.



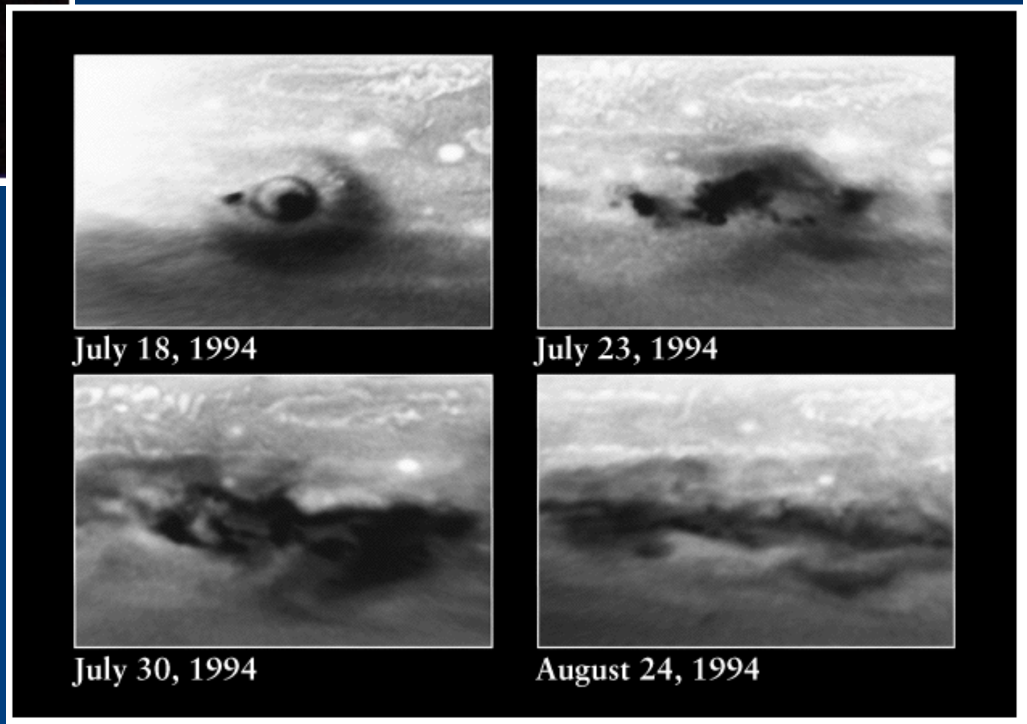
1994 - Shoemaker/Levy 9

- Atmosphere also probed by the comet Shoemaker/Levy 9 (1994). Broke into 23 fragments (Q: why would it break into fragments?) with the largest imparting 6×10^8 megatons - much more than all nuclear weapons on Earth!

- It was hoped that spectroscopic examination of impacts would tell us about the atmosphere, but composition of the comet was also uncertain, so results are not conclusive.



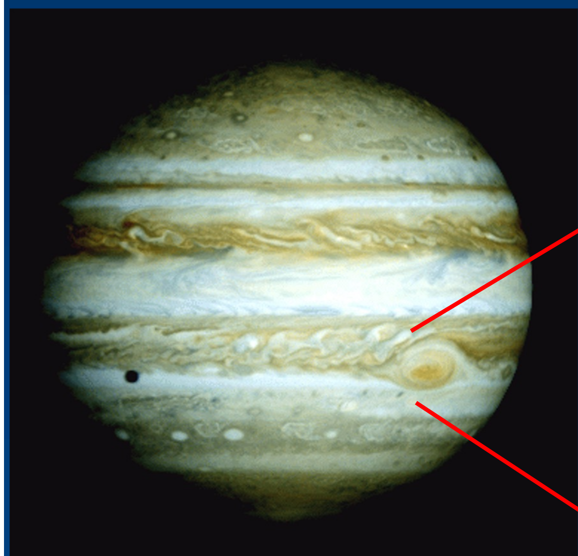
IR image – 10,000° C fireball.



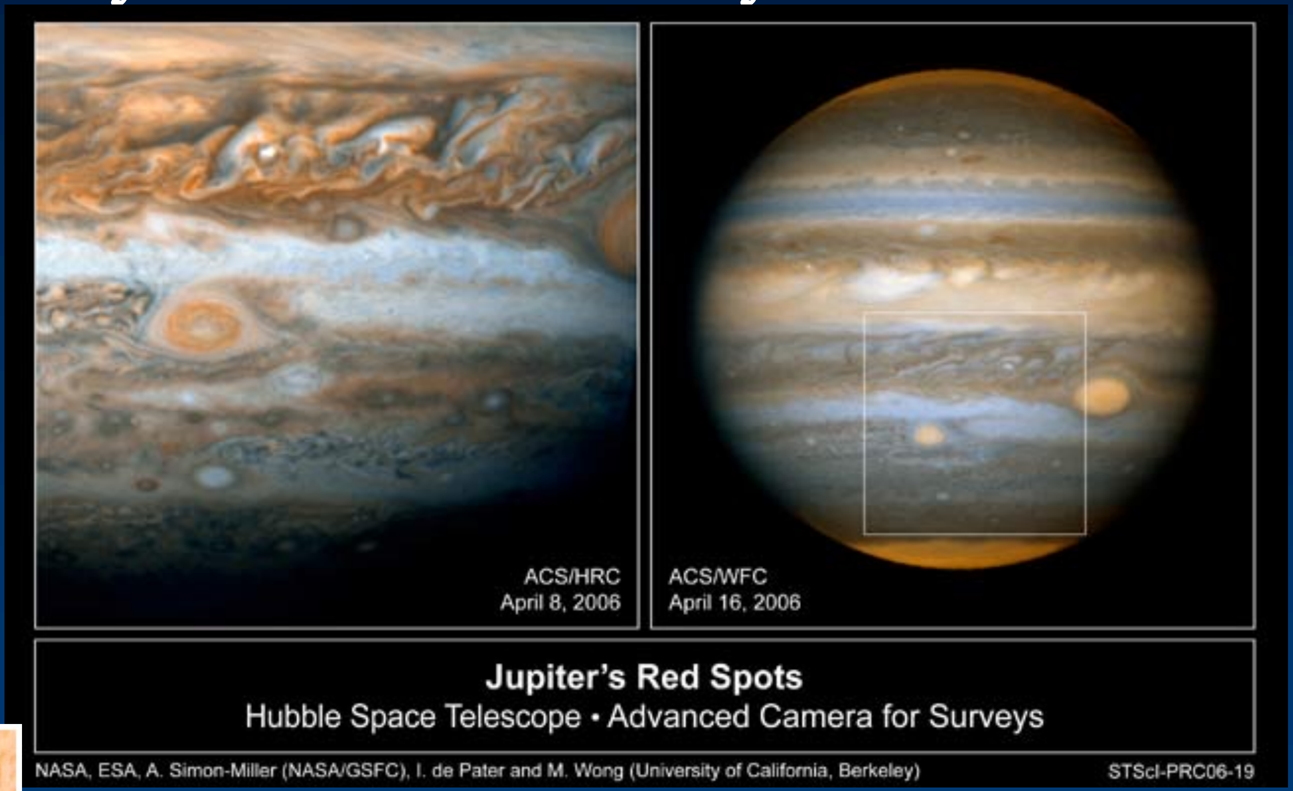
Evolution of impact G. High speed winds eventually erased scars.

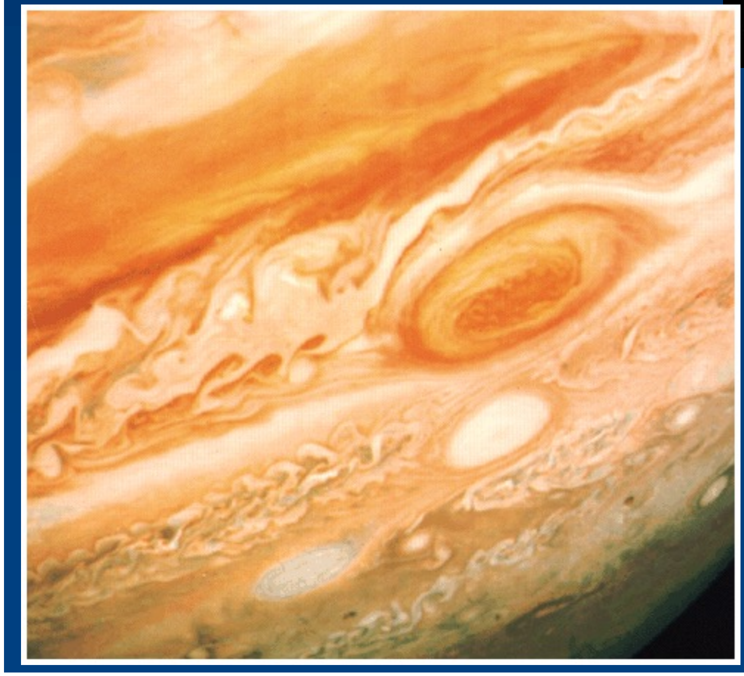
The Great Red Spot

- Visible since time of first telescopes (>340 years!) (Why so much longer-lived than Earth storms?)
- The GRS is a gigantic storm system, twice the size of Earth
- High pressure system in the southern hemisphere
- Period ~ 6 days

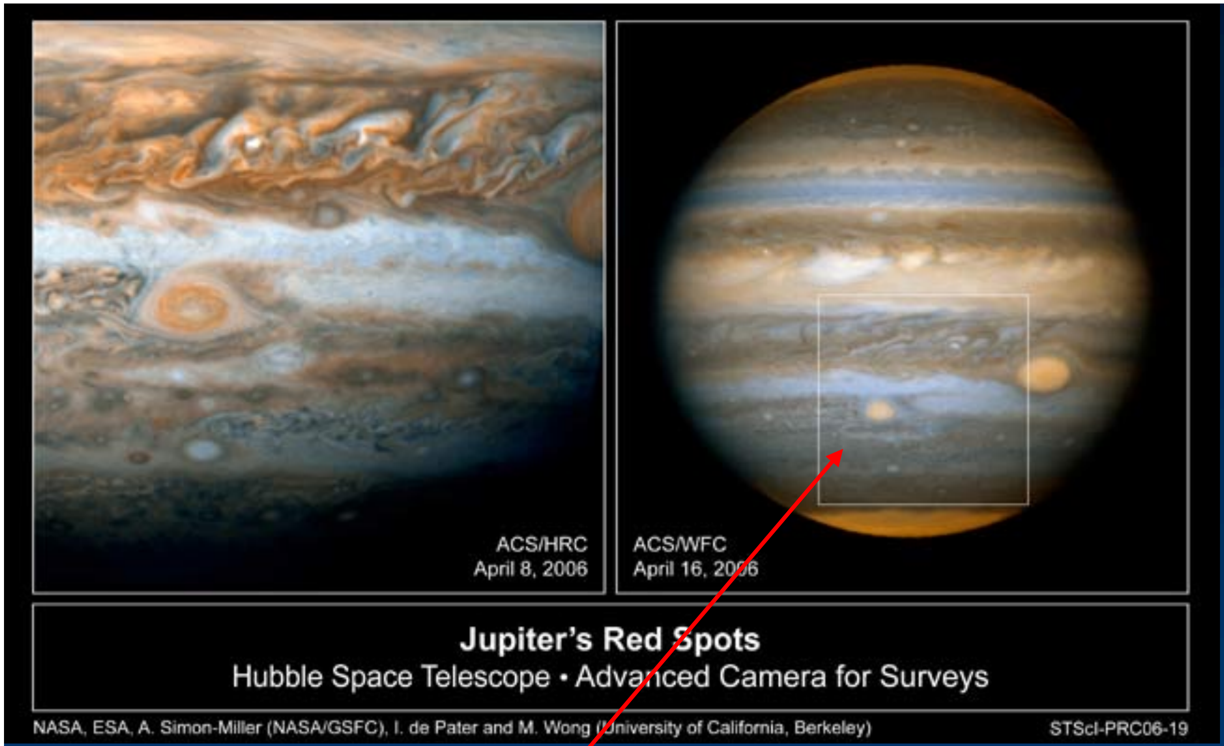


The GRS is not the only storm. Also see cyclonic *white ovals*.





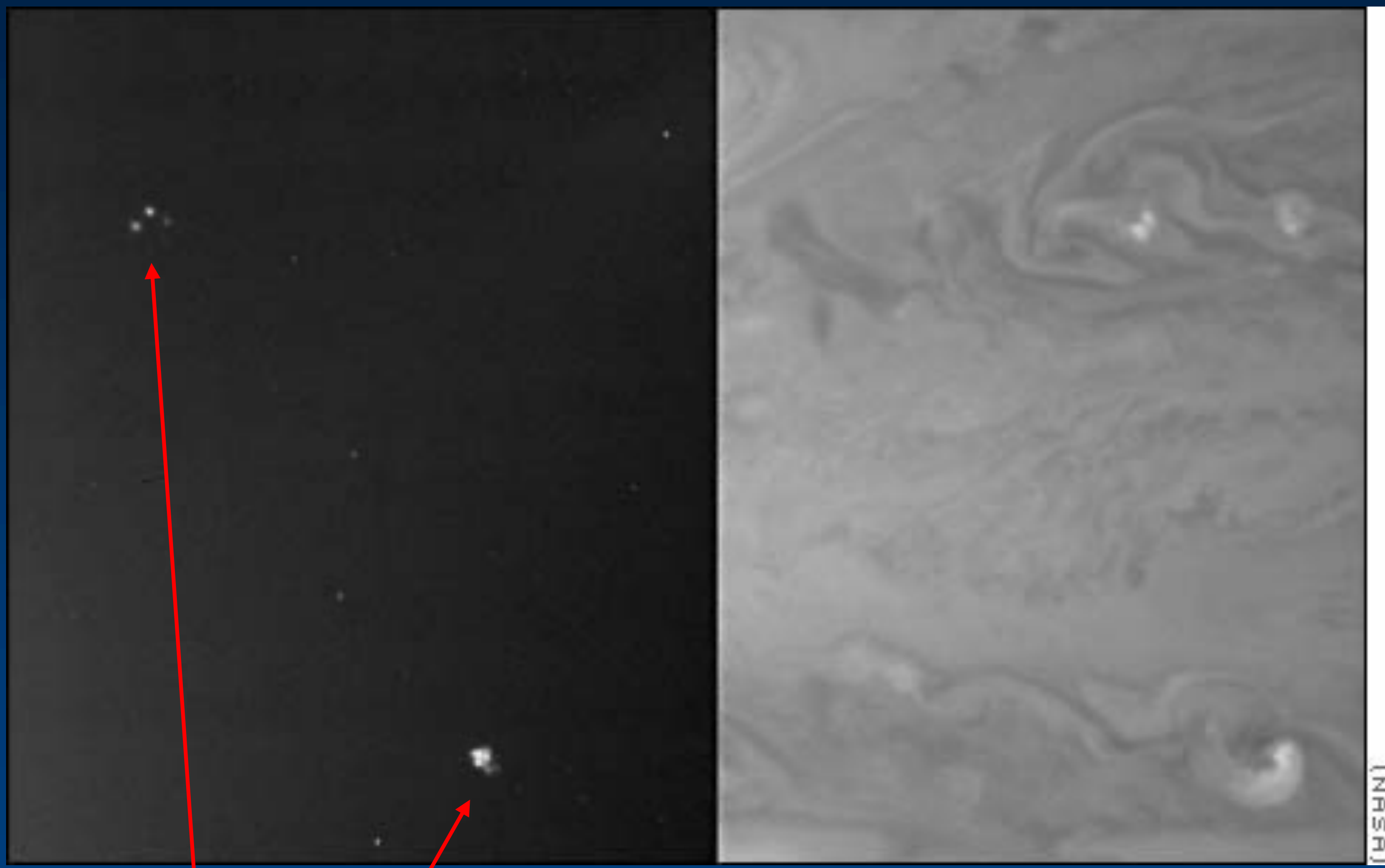
White ovals may last decades



New storm "Oval BA": 3 white ovals merged in 2000. Turned red in 2006.

"Brown ovals" only seen near 20° N latitude. Not known why. May last years or decades. May be holes in cloud cover – they are bright in IR.

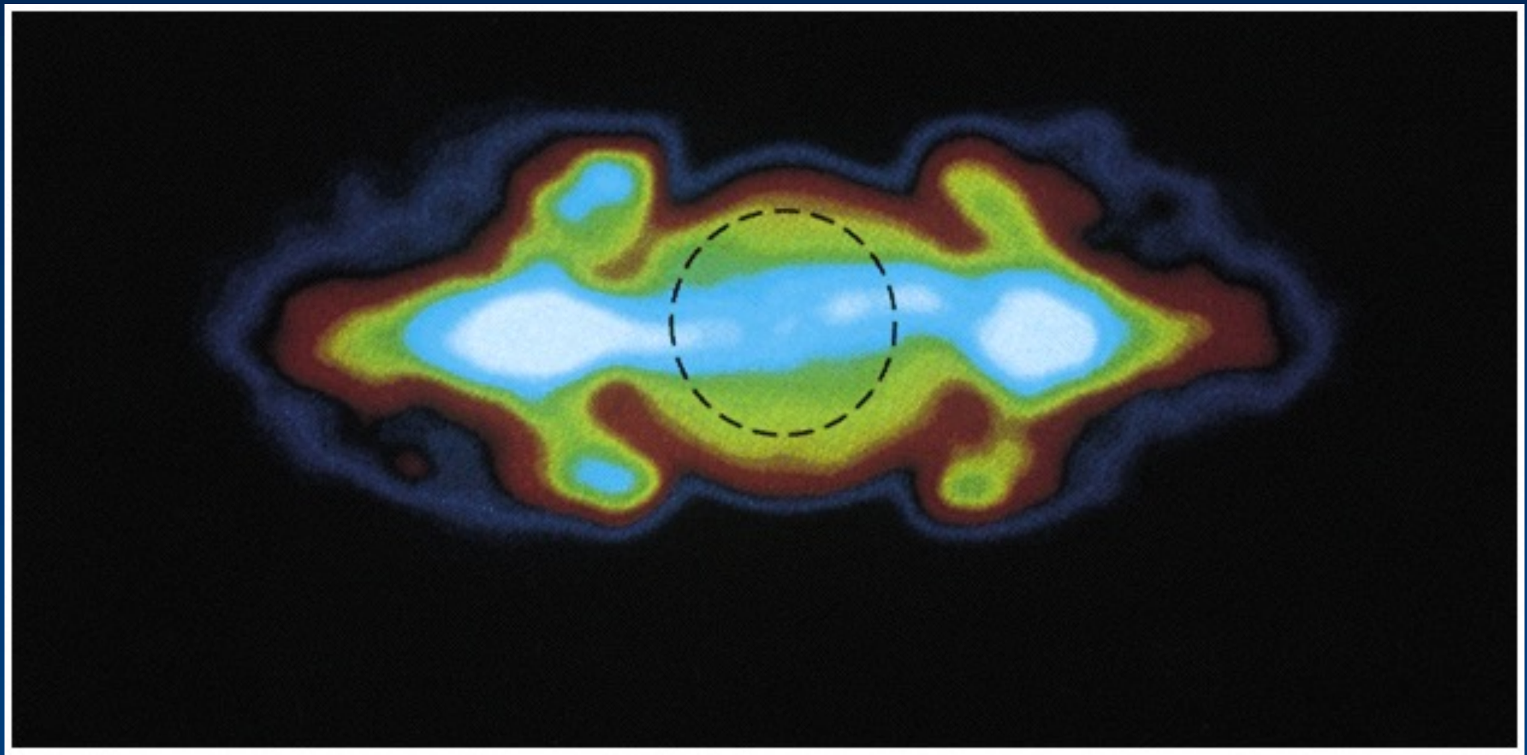
Storms on Jovian Planets



Lightning on Jupiter: Cassini captured images of lightning during a nighttime pass over the planet. Each stroke is about 10,000 times more energetic than one on Earth.

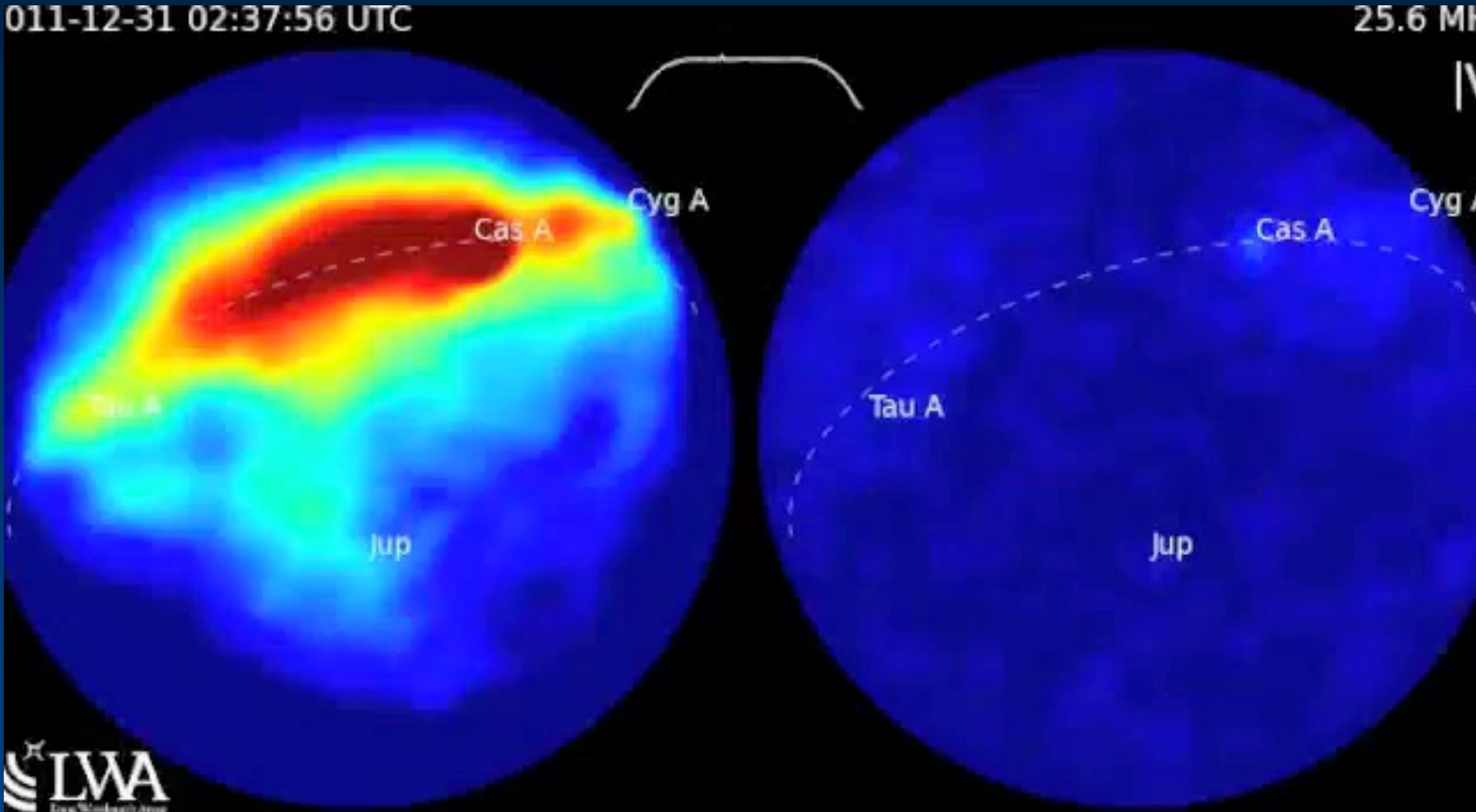
Magnetosphere

The liquid metallic hydrogen + rapid rotation produces a strong magnetosphere and radio emission.



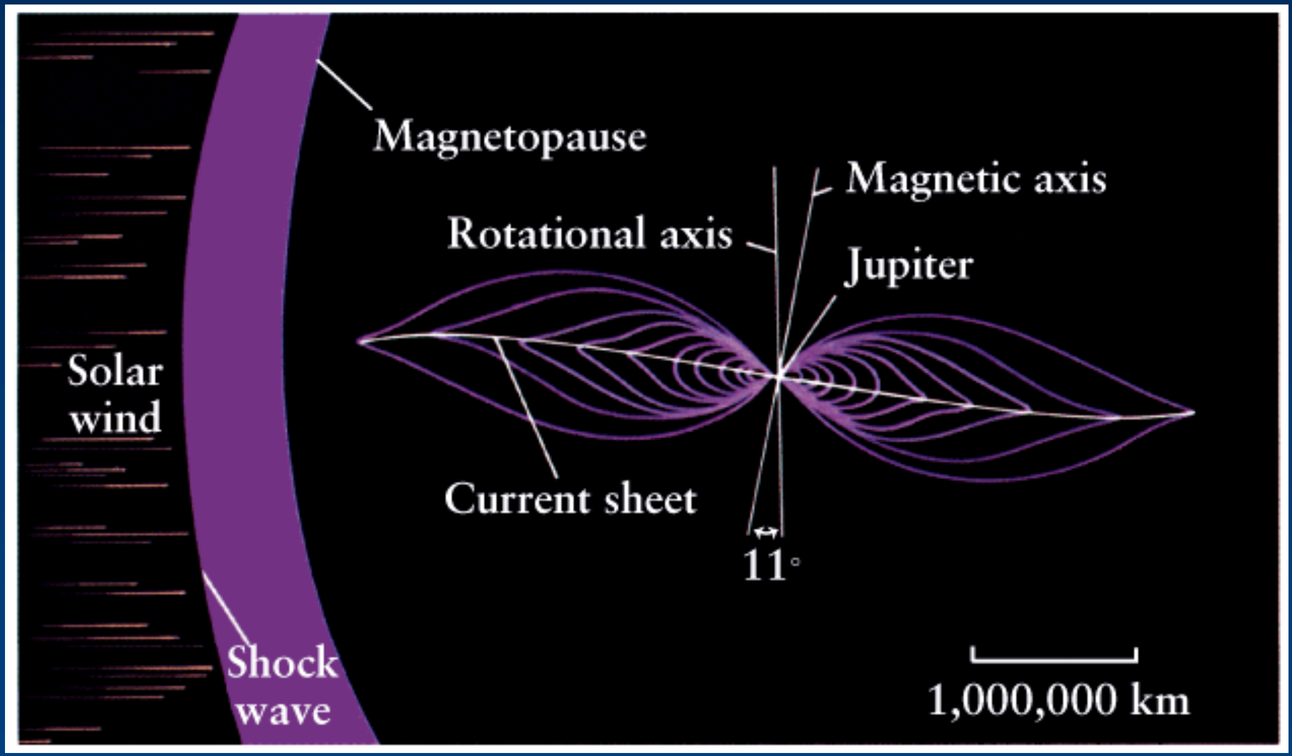
VLA image of magnetic belts around Jupiter (caused by a satellite, more later): synchrotron emission from charged particles spiraling in magnetic fields.

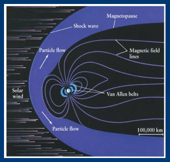
Jupiter at 25 MHz



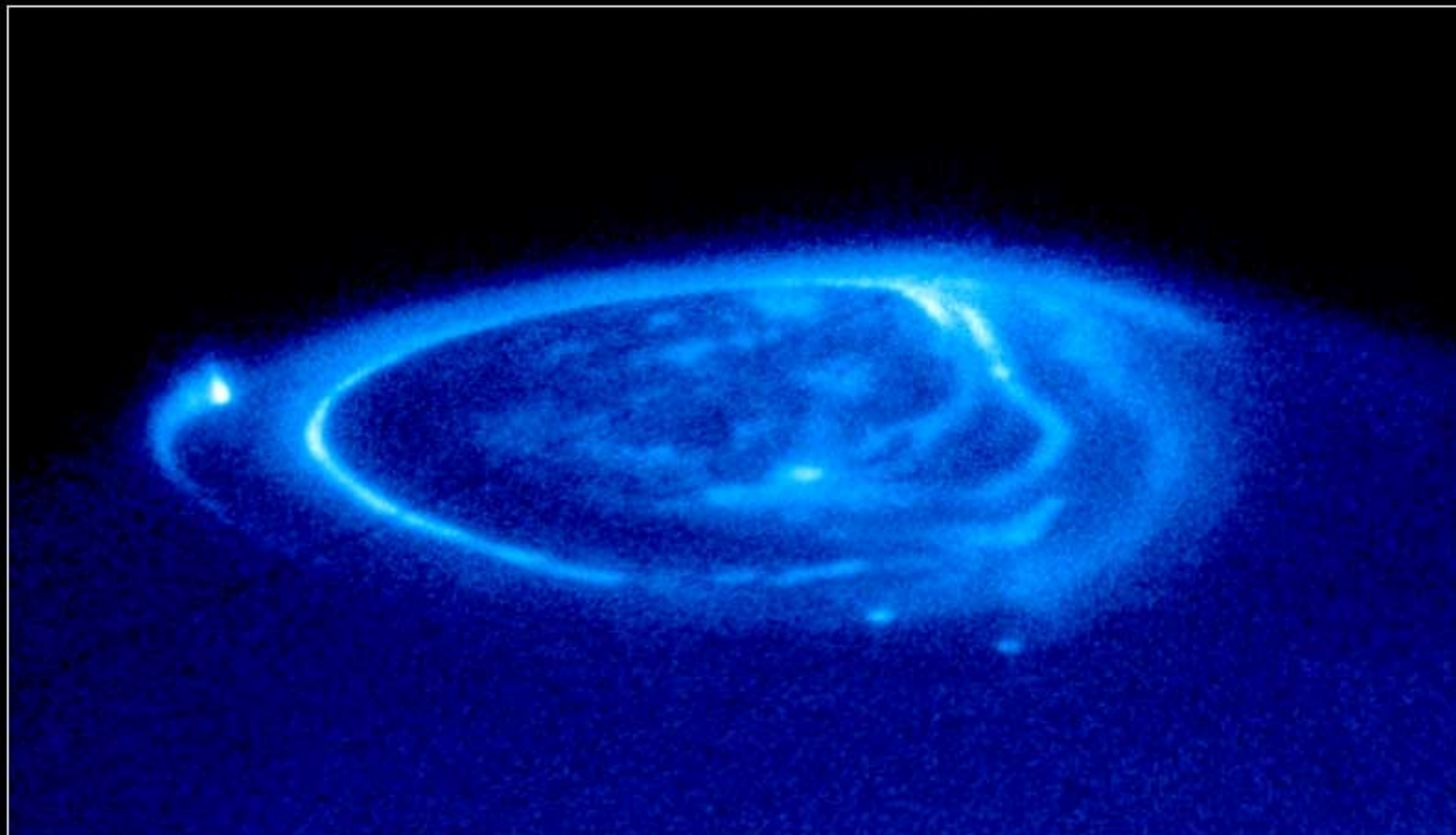
Powerful bursts of coherent emission below 40 MHz

Note enormous scale of Jupiter's magnetic field compared to Earth. If you could see it directly, it would cover area in sky 16 x full moon!





Aurorae - HST image



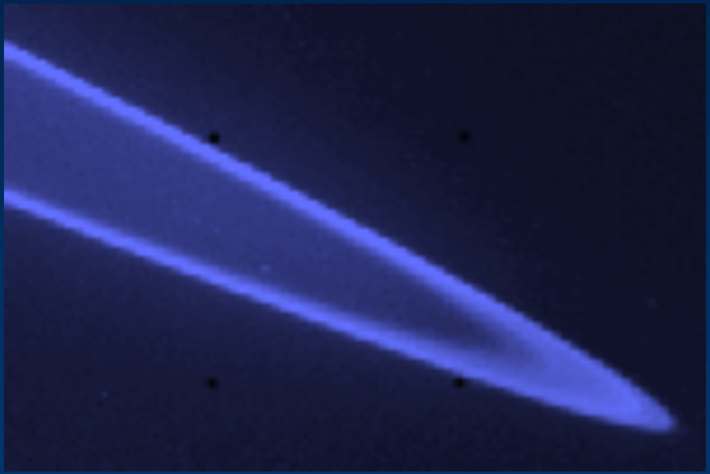
Jupiter Aurora

HST • STIS

NASA and J. Clarke (University of Michigan) • STScI-PRC00-38

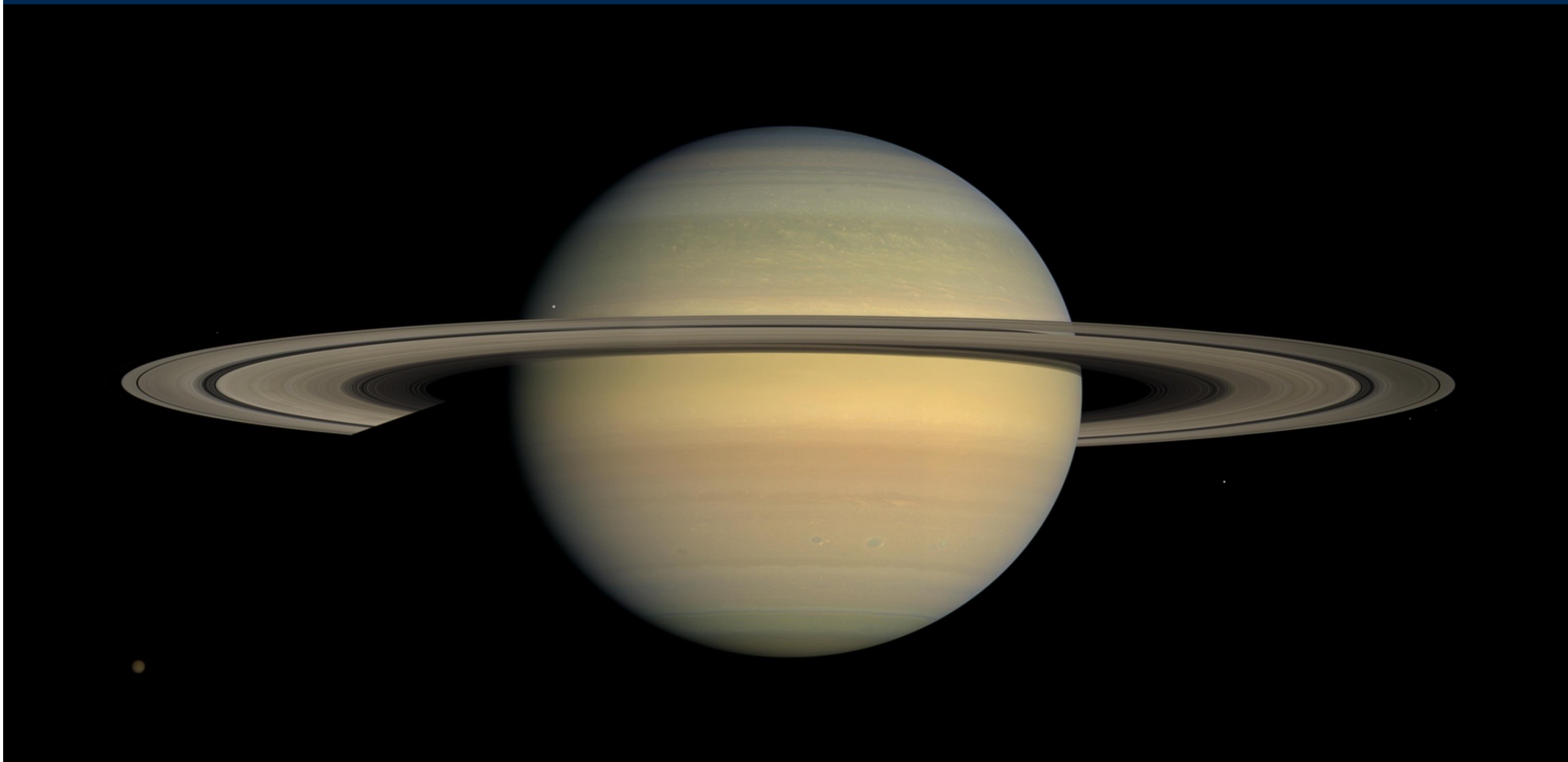
Same process as on Earth: charged particles traveling along magnetic field lines, then striking atoms in the upper atmosphere

Rings



- Discovered by Voyager 1 (1979) looking “back”; much less impressive than Saturn’s. Reflect <5% of sunlight.
- Radius 1.8 times the radius of the planet, composed of micron-sized particles knocked off from meteor impacts from moons and from Io's volcanoes.

Saturn



Saturn basic data

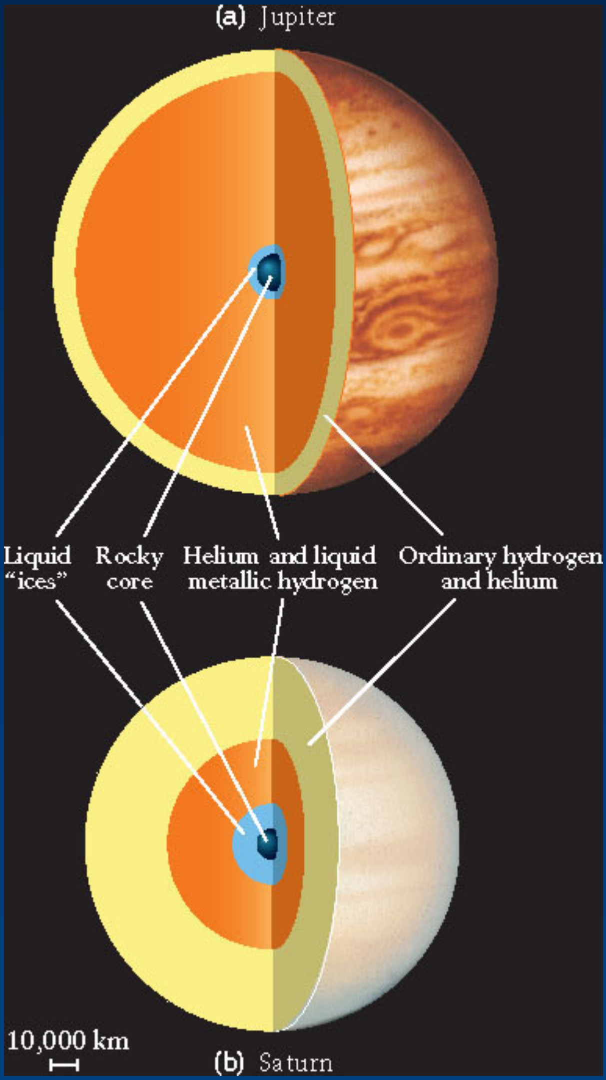
Semi-major axis	9.6 AU
Orbital period	29.4 Earth years
Rotation period	$10^h\ 14^m$ (equatorial)
	$10^h\ 39^m$ (polar)
Diameter	9.5 times Earth's
Mass	95 times Earth's
Density	687 kg/m^3 = 0.7 g/cm^3
V_{esc}	36 km/s
Surface gravity	0.92 times Earth's
Temp	93 K (cloud tops)

Saturn - similarities to Jupiter

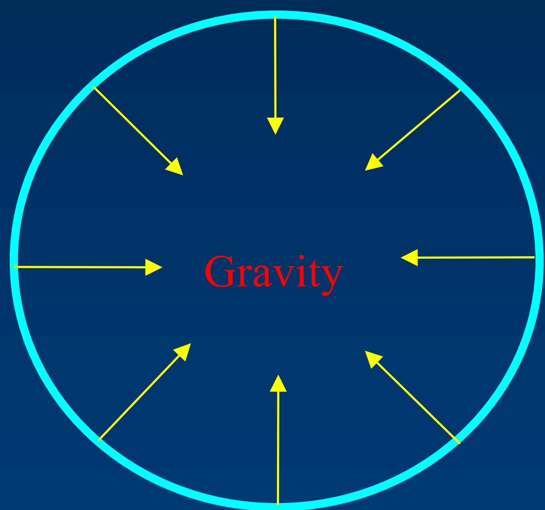
- Composed of H and He
- Radiates 2.3 times more energy than it gets from the Sun
- Liquid metallic hydrogen below atmosphere, magnetic field
- Core of rock and ice, similar mass

Saturn - differences from Jupiter

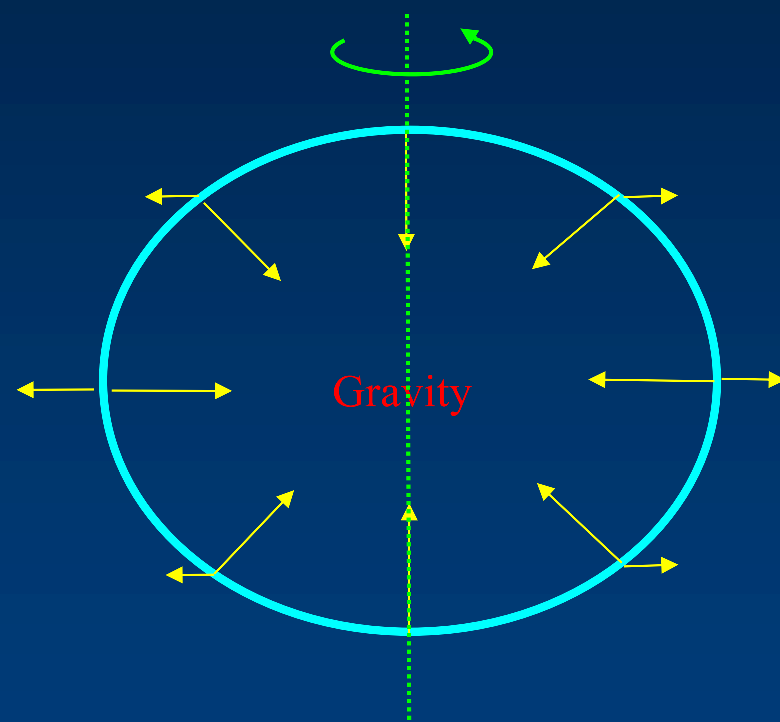
- Less dense (0.7 g/cm^3)
- More oblate (10%) by rotation
- Less metallic hydrogen due to lower internal pressure
- Less helium, due to "rainout" (cooler compared to Jupiter)
- Even faster winds: 1000-1800 km/hr. Not known why



Rotational flattening



without rotation



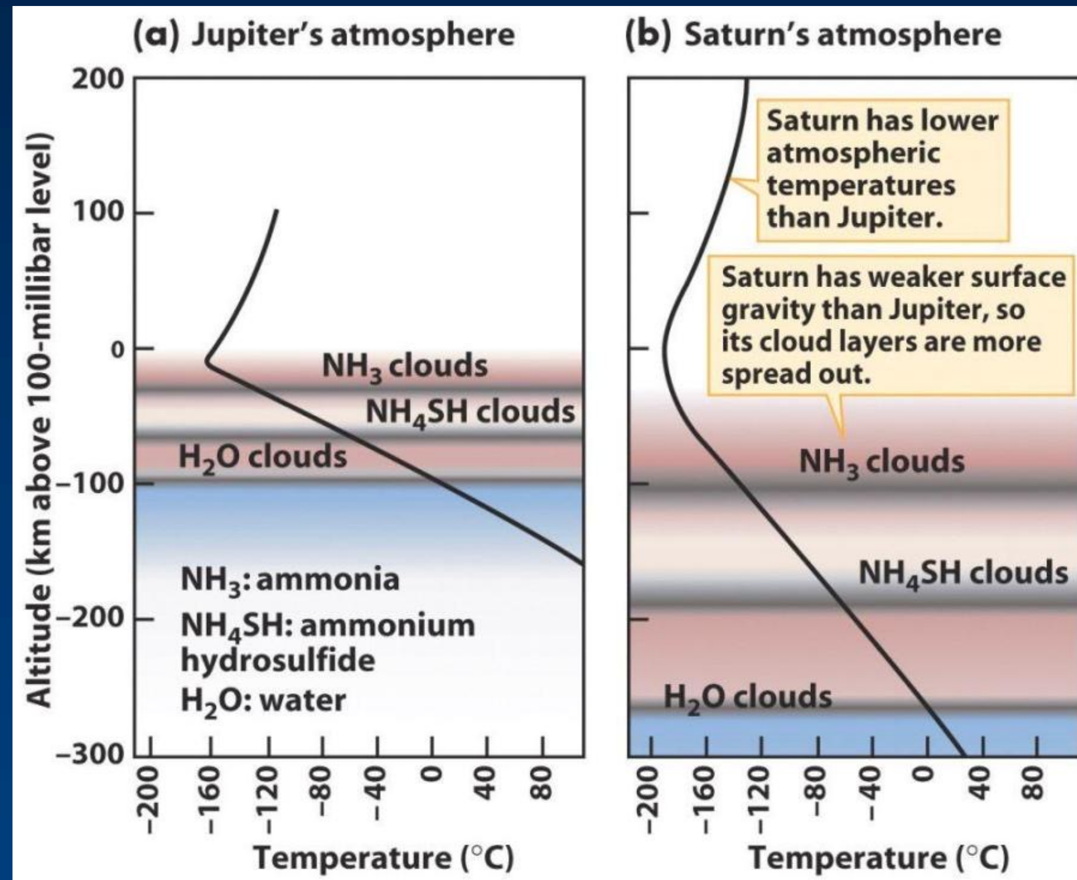
with rotation

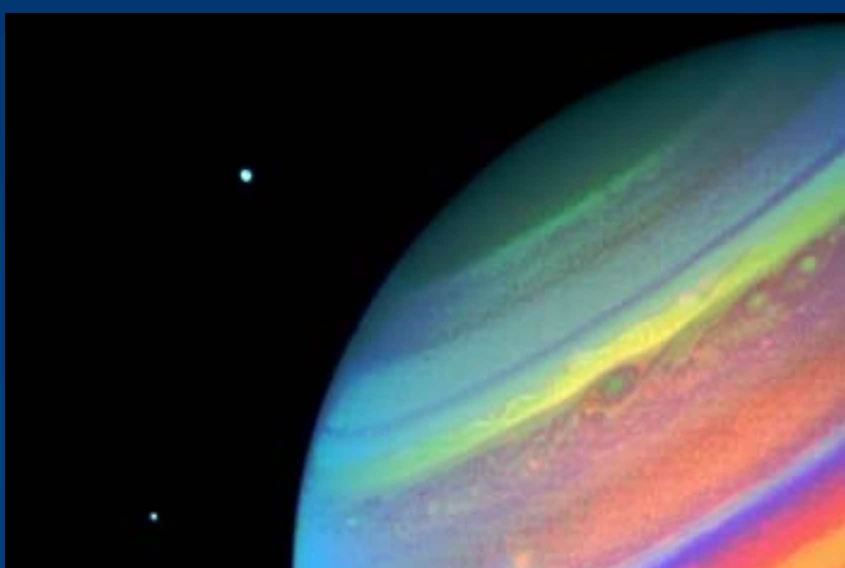
Jupiter and Saturn rotate every ~10 hours.

Atmosphere of Saturn

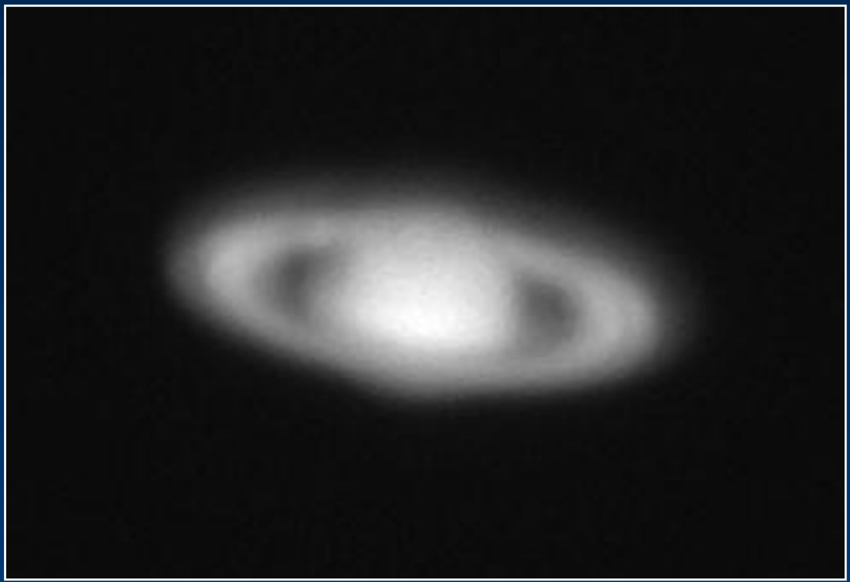
- Uniform haze prevents view of cloudier, lower atmosphere (more colors?).
  An effect of weaker gravity.

- Some storms seen





The rings of Saturn



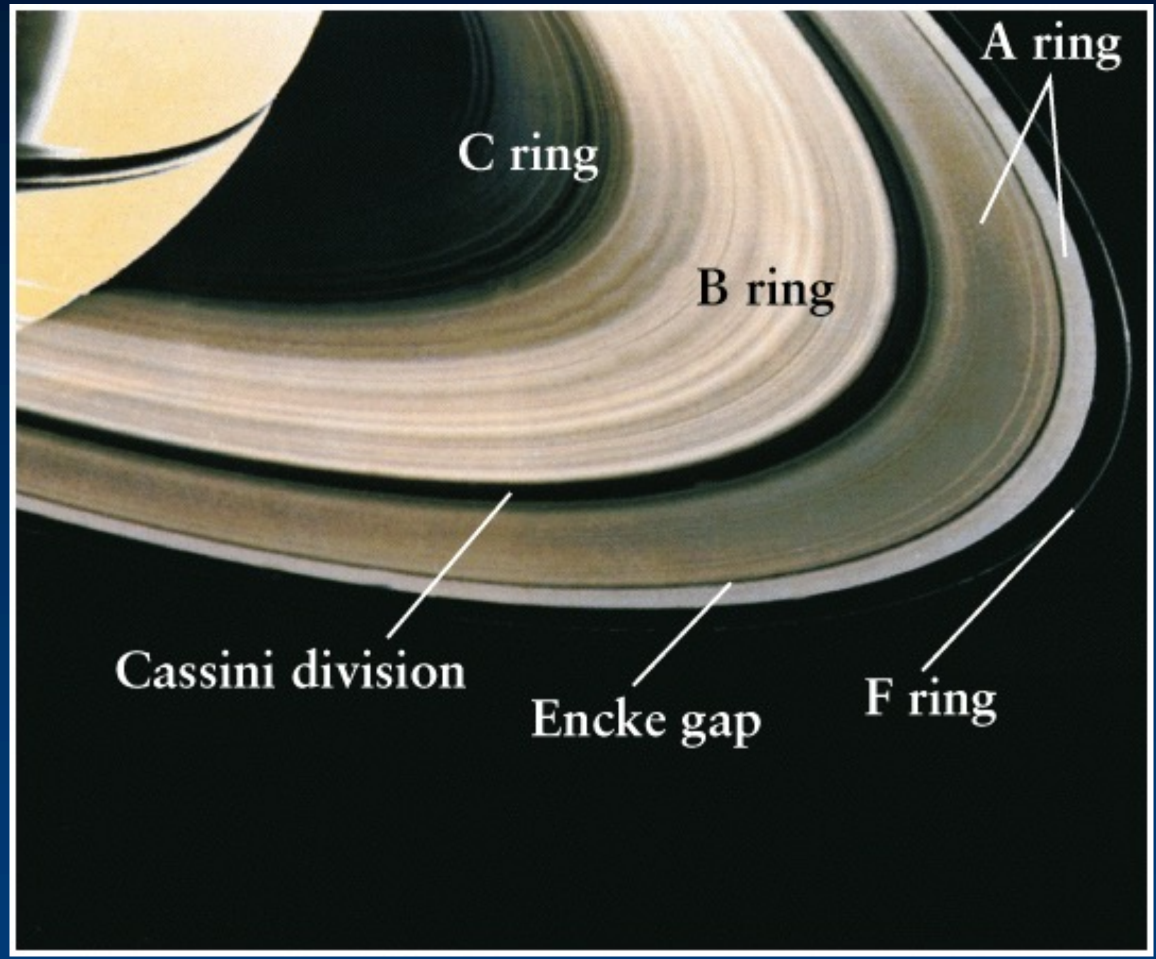
- 1610 Galileo saw 'ears'
- 1655 Huygens resolved ring from planet
- 1675 Cassini found a gap

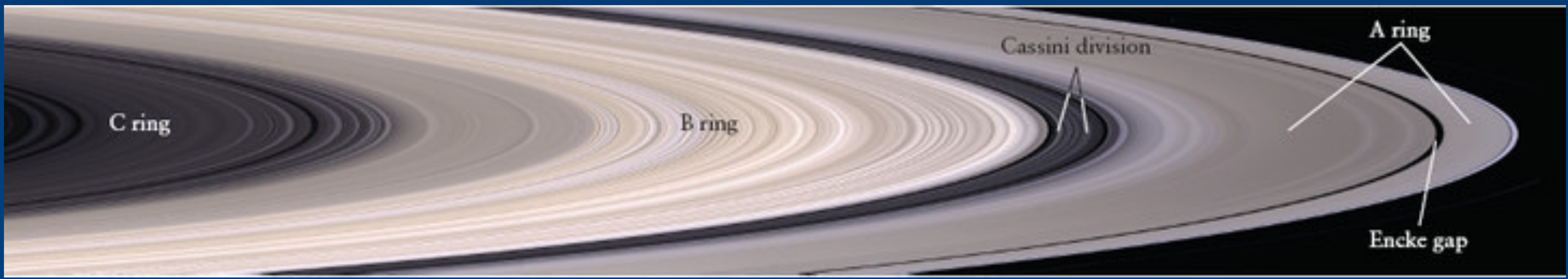
- (1857) J.C. Maxwell showed rings are not solid => tidal forces would rip it apart, must be made of innumerable separate particles

- (1895) Keeler found Doppler shifts in spectrum of reflected sunlight - higher near planet, individual particles follow Kepler's 3rd law

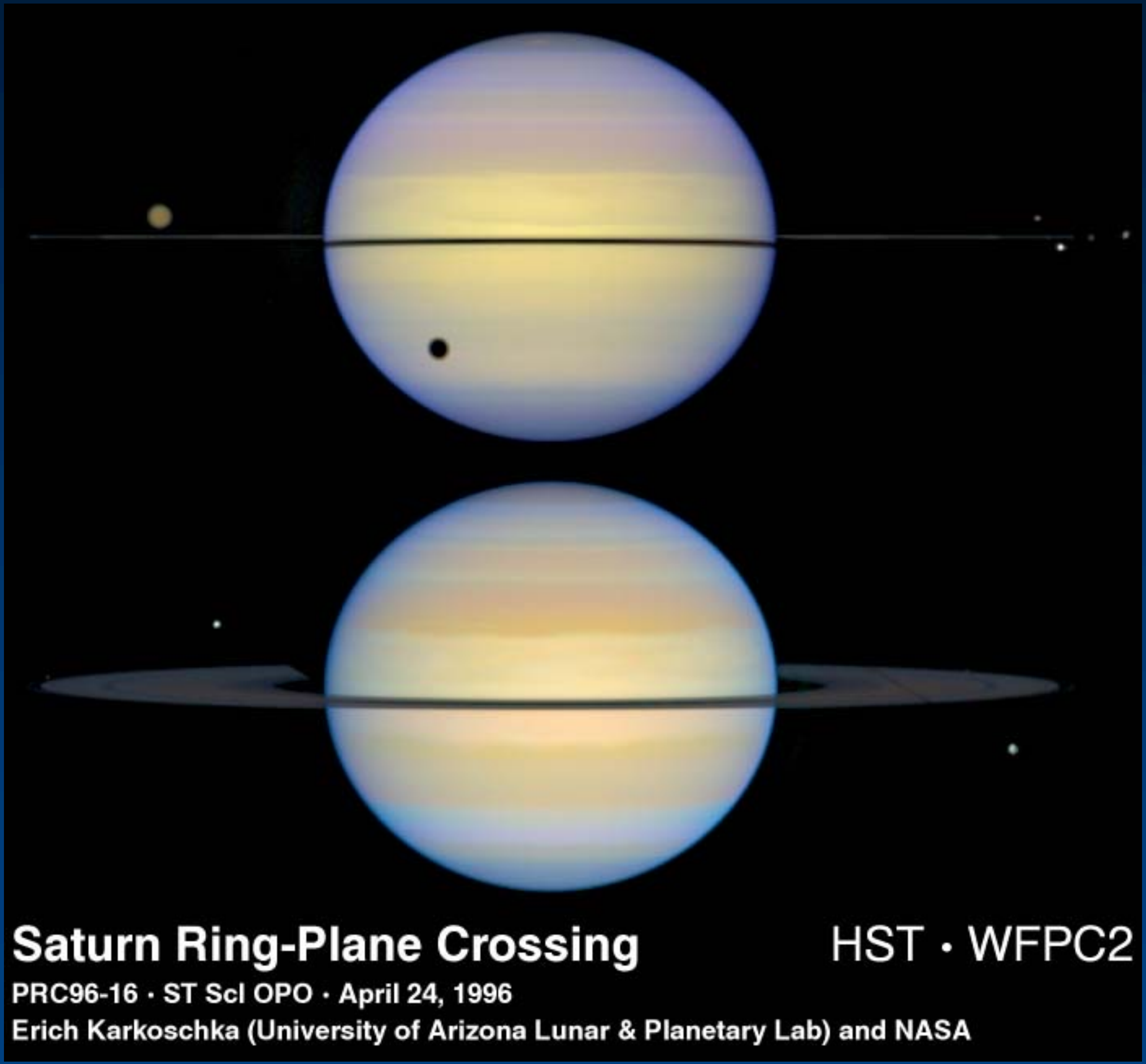
Voyager 1

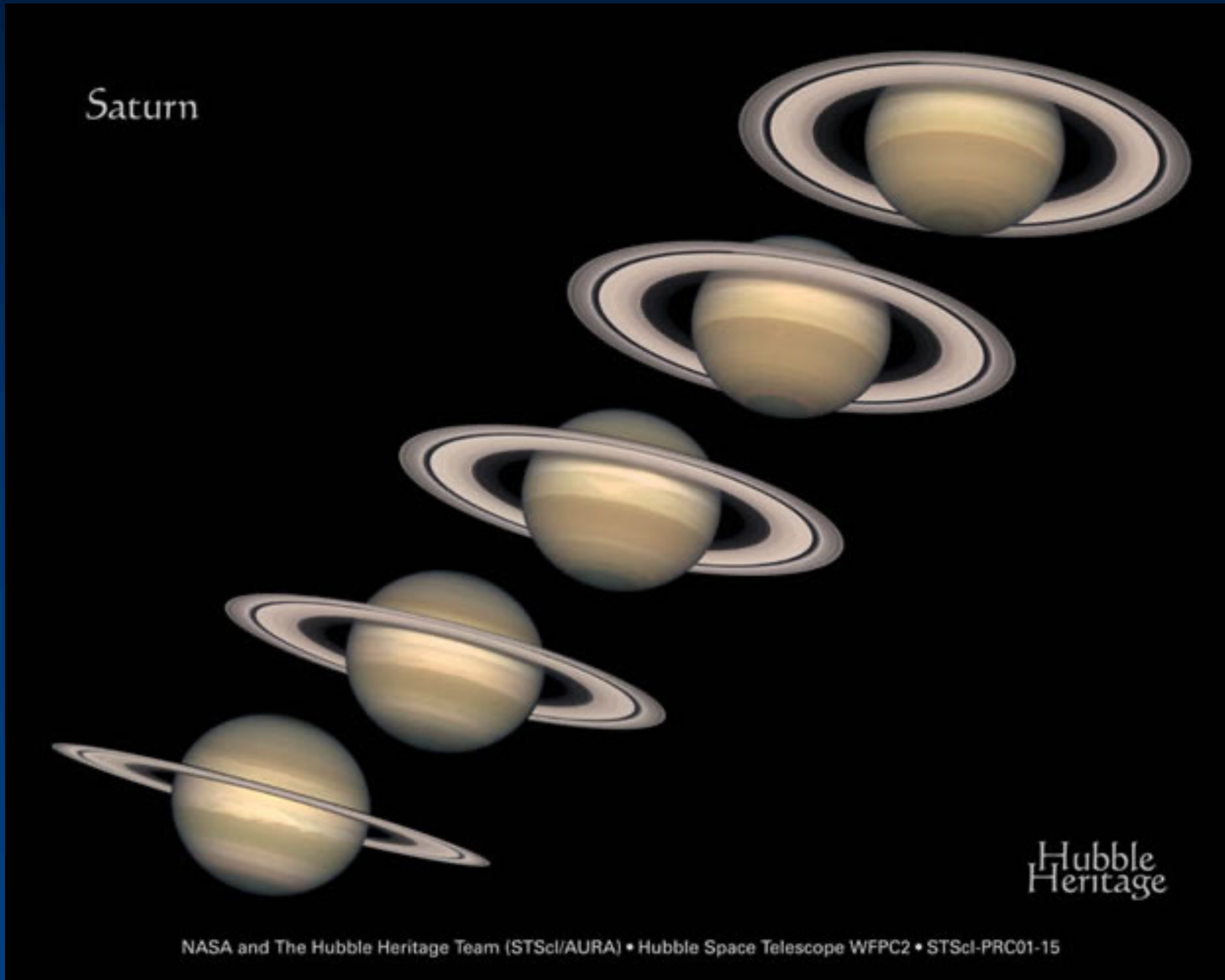
Note: Cassini division not completely empty





Rings are very thin: only tens of meters thick – compared to 100,000's of km across!




Saturn
Hubble Heritage
NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-15

- Size of particles ~ 10 cm in diameter, with a size range 1 cm - 5 m. Known from how they transmit and scatter radiation of different wavelengths (Voyager, Cassini)

- Albedo 80% => composed of ice and coated rocks

- Rings are inside the Roche limit – a clue to formation
- How close can a moon be to a planet before the tidal force rips it apart?
- Take Earth and Moon as an example:

Why doesn't Earth's strong tidal force tear Moon apart?
Consider two rocks of mass m on either side of Moon:

Tidal force causing acceleration away from each other is

$$\Delta F = 2GM_{Earth}\, m \frac{d_{Moon}}{r_{Earth-Moon}^{3}}$$

Gravitational force on each rock is

$$F = \frac{GM_{Moon}m}{(d/2)_{Moon}^{2}}$$

Ratio is $$\frac{M_{Earth} d_{Moon}^{3}}{2M_{Moon} r_{Earth-Moon}^{3}}$$ or $\sim 10^{-5}$

Then how close would they have to be to Earth to be drawn apart? Solve for distance from Earth for which this ratio is > 1:

$$r <\sim \left(\frac{M_{Earth}}{M_{Moon}}\right)^{1/3} d_{Moon}$$

this is a rough calculation of the Roche Limit, for the Moon due to Earth's tides

In general, for some object close to a planet:

$$r <\sim \left(\frac{M_{Planet}}{M_{object}}\right)^{1/3} d_{object}$$

Since $d_{object}/(M_{object})^{1/3} \alpha \rho_{object}^{-1/3}$, can re-express in terms of density:

$$\frac{r}{r_{planet}} < 2.44\left(\frac{\rho_{Planet}}{\rho_{object}}\right)^{1/3}$$

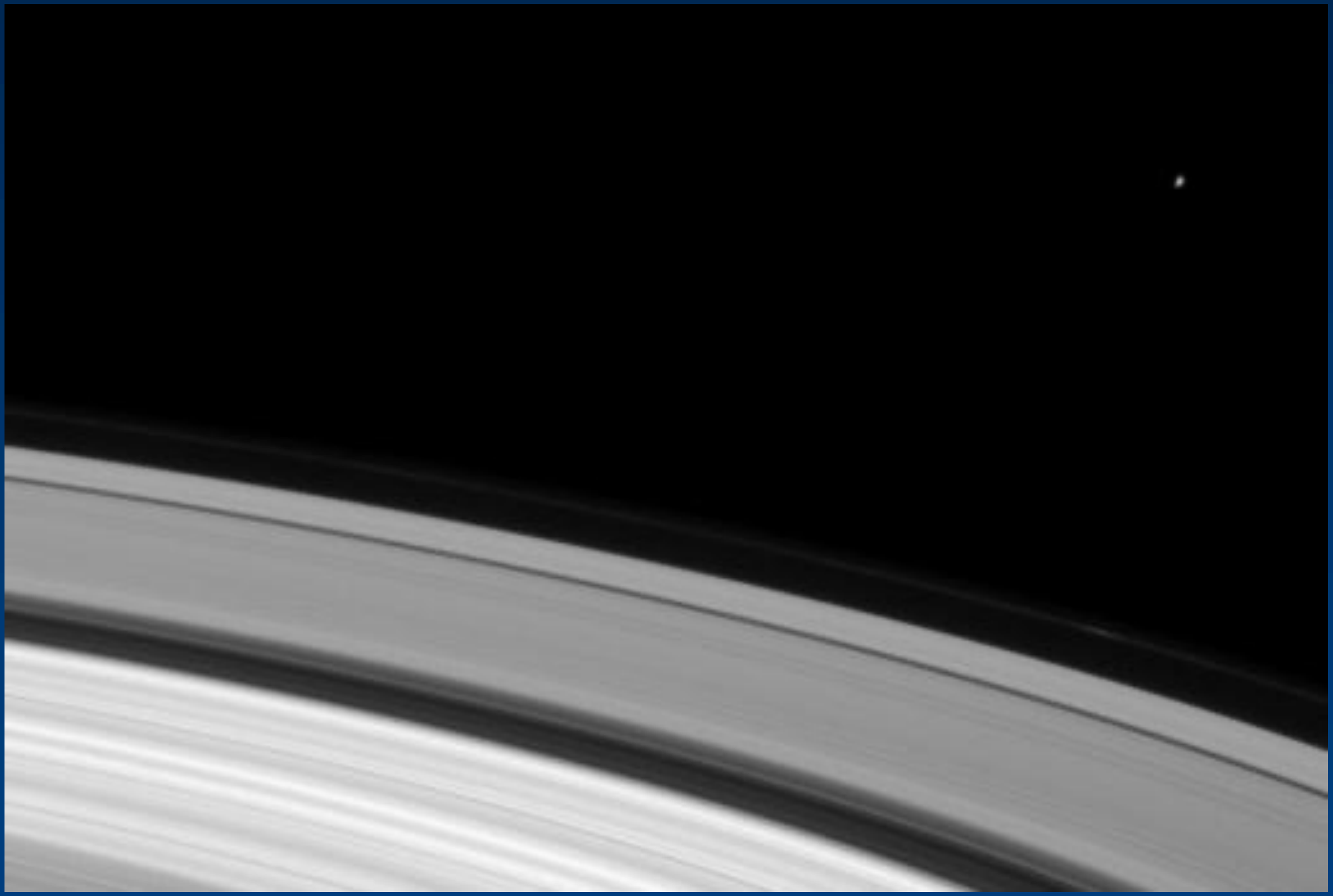
This is the classical expression for the breakup of a spherical body

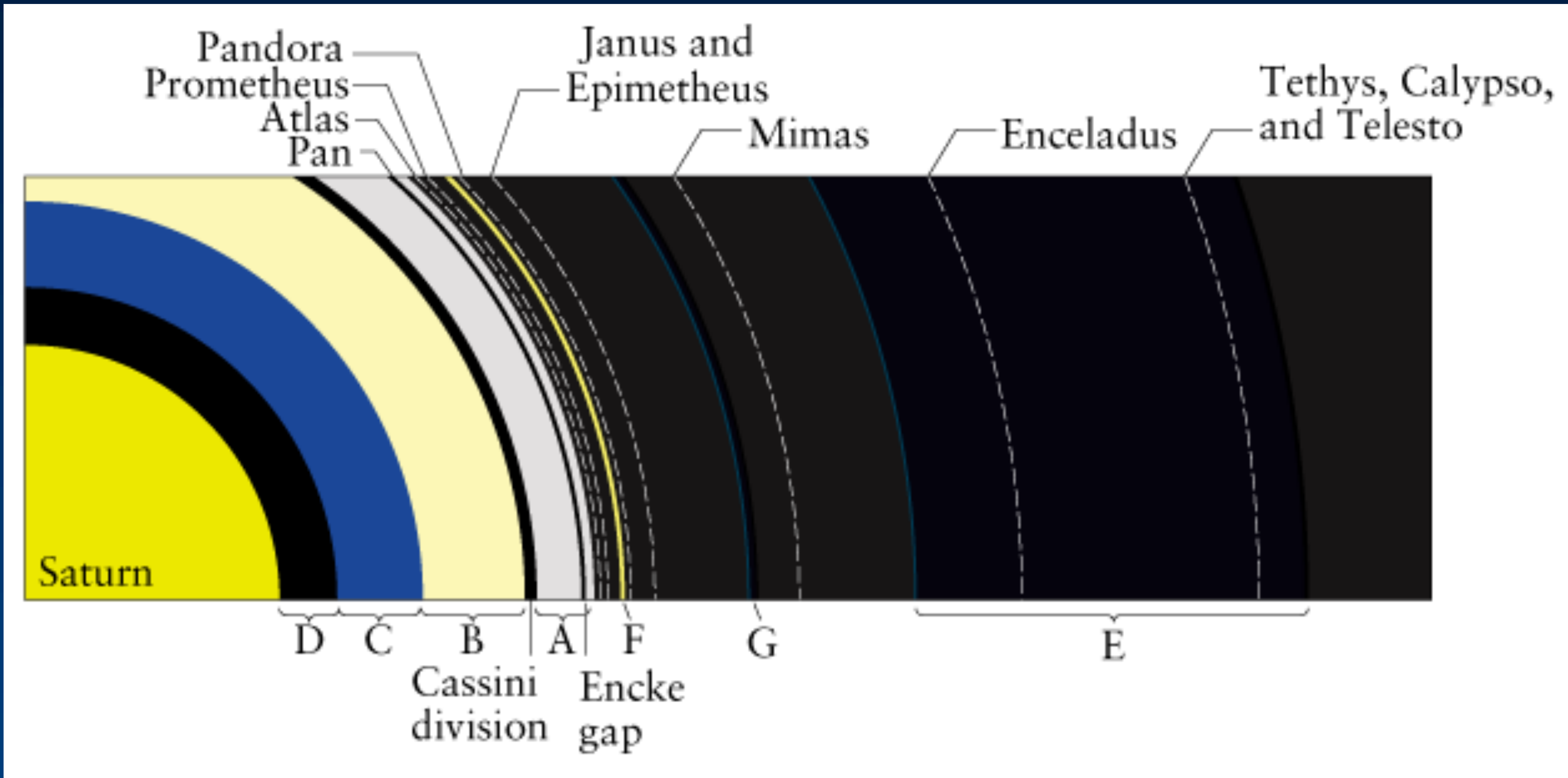
Almost all rings of Jovian planets are within their Roche limits. Note – you are within Roche limit for Earth. Why aren't you torn apart by tides?

Gravitational resonances

- Gravitational resonances with satellites cause gaps in ring structure, eg. Cassini division and Mimas
- Ring particles with periods equal to exact ratios (1:2, 1:3, 2:3 etc.) of moon orbit get gravitationally tugged at the same point in its orbit, moving into a higher, elongated orbit

- Mimas and Cassini division




Pandora
Prometheus
Atlas
Pan
Janus and
Epimetheus
Mimas
Enceladus
Tethys, Calypso,
and Telesto
Saturn
D
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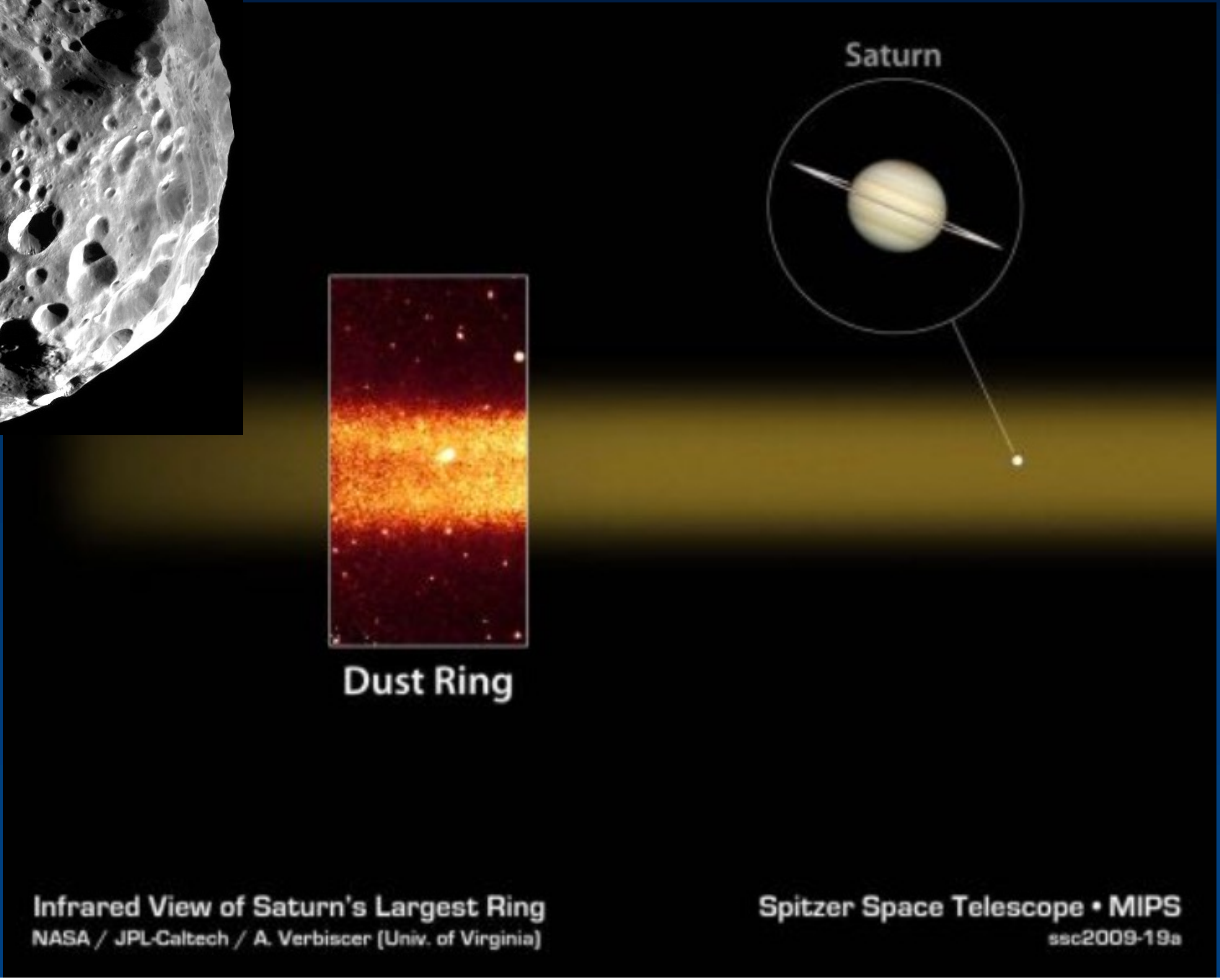
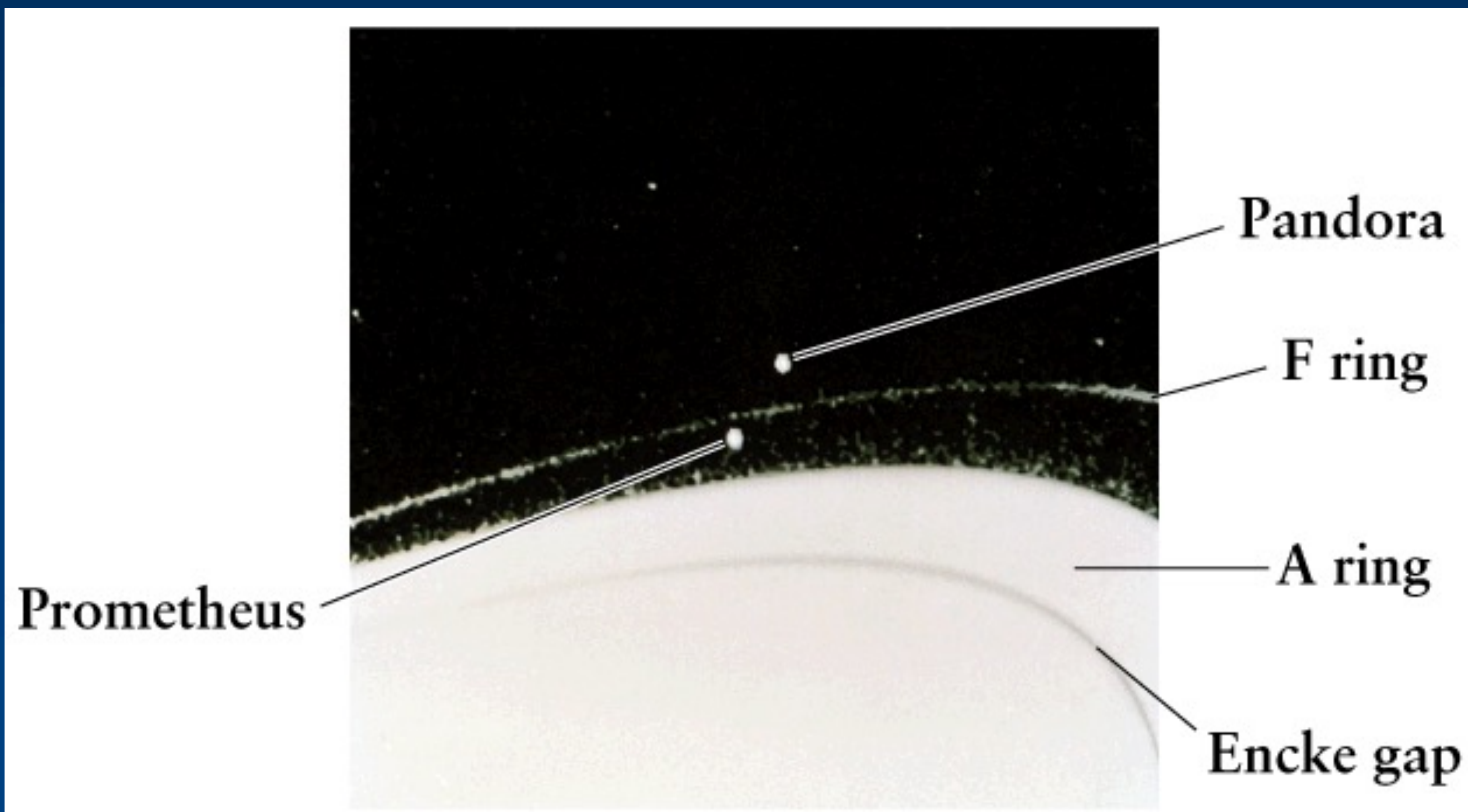
A
F
G
E
Cassini
division
Encke
gap

Phoebe's retrograde ring



Shepherd satellites

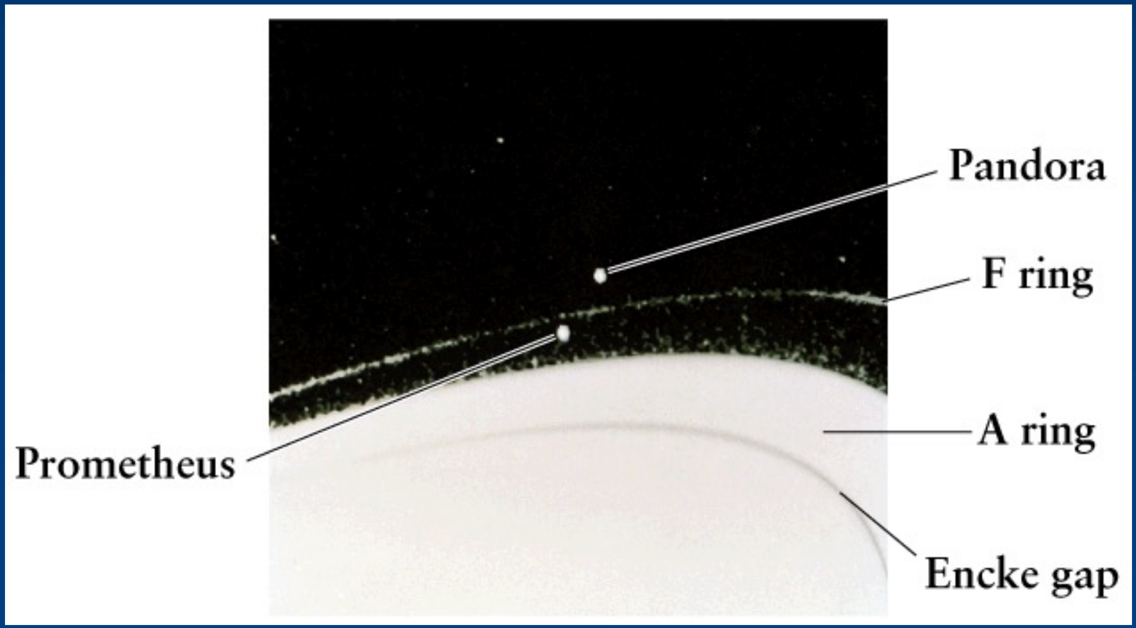
- Pandora (outer) and Prometheus (inner) on either side of narrow F-ring.



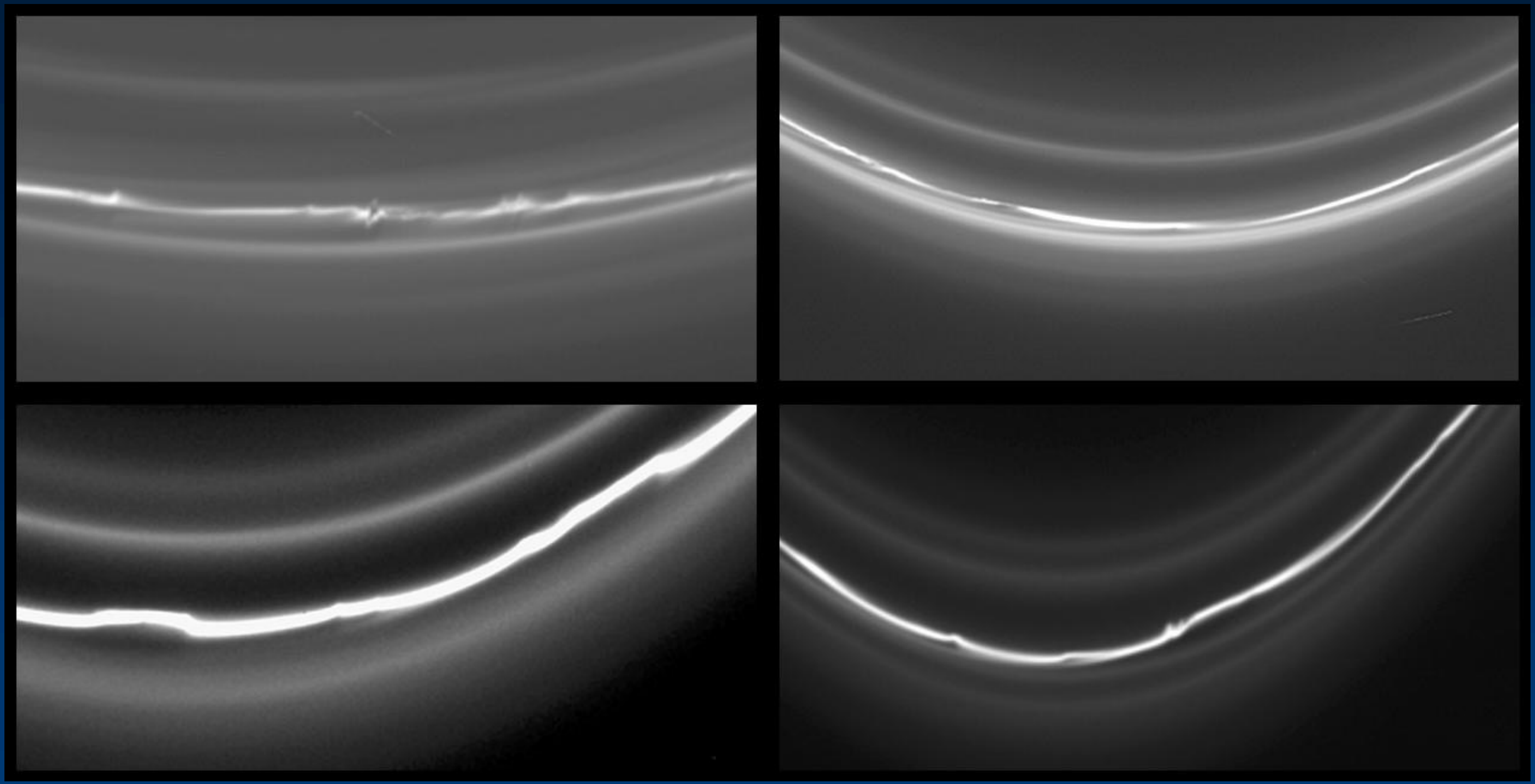
Voyager 2

- Ring particles pass Pandora, are slowed down by gravitational interaction with Pandora, lose a little energy $\Rightarrow$ fall in lower orbit.

- Prometheus orbits faster than ring particles. As they are passed by Prometheus, get gravitational kick, speed up a little, get extra energy $\Rightarrow$ pushed into higher orbit.



extra



Cassini 2005: F-ring structure, depending on the timing of passage.

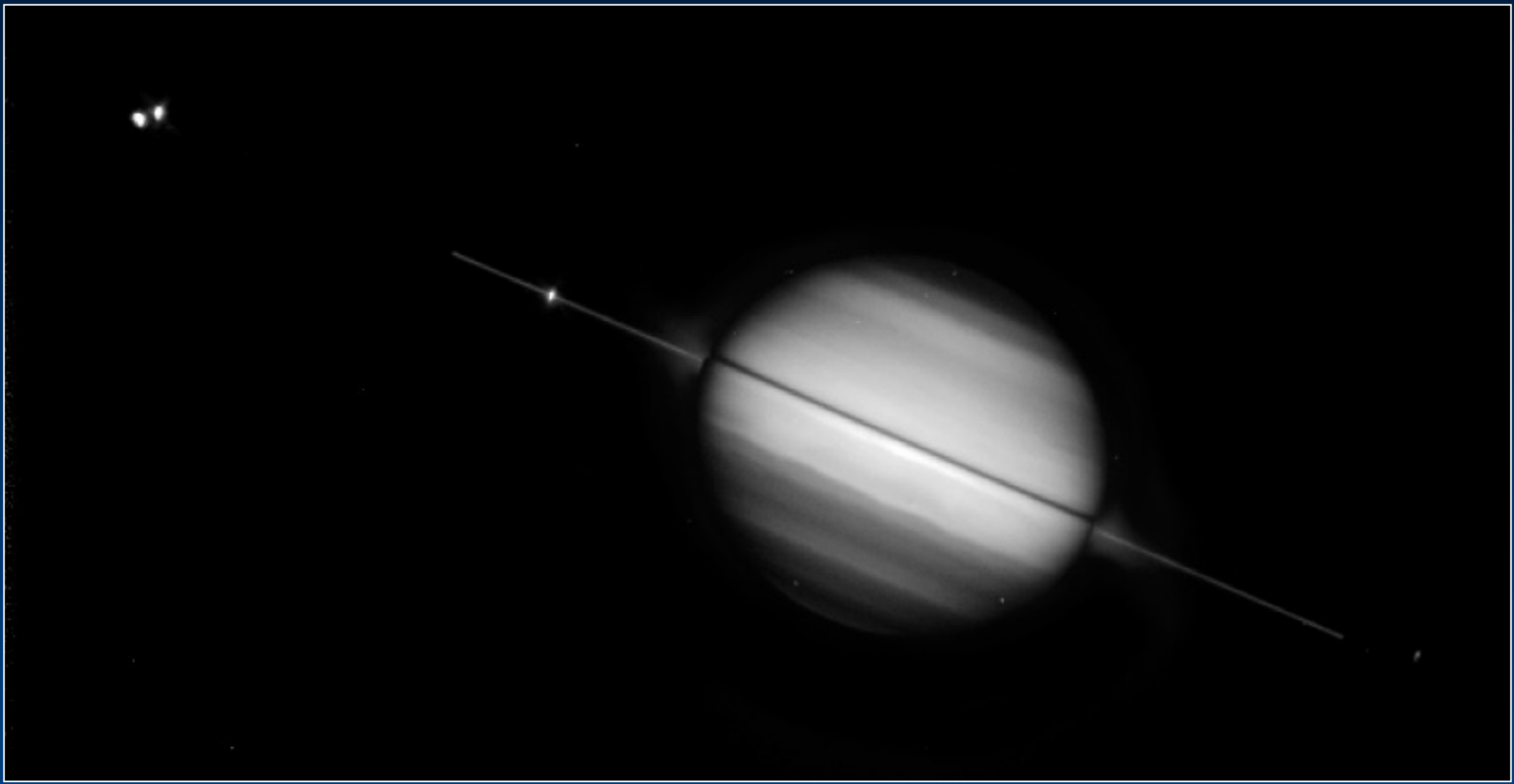
Atmosphere by number of molecules

- 86.4% H_2
- 13.6% He
- <0.1% H_2O
- 0.21% CH_4
- 0.07% NH_3
- 0.008% H_2S (Hydrogen Sulfide)

What is 'the atmosphere'? No surface?

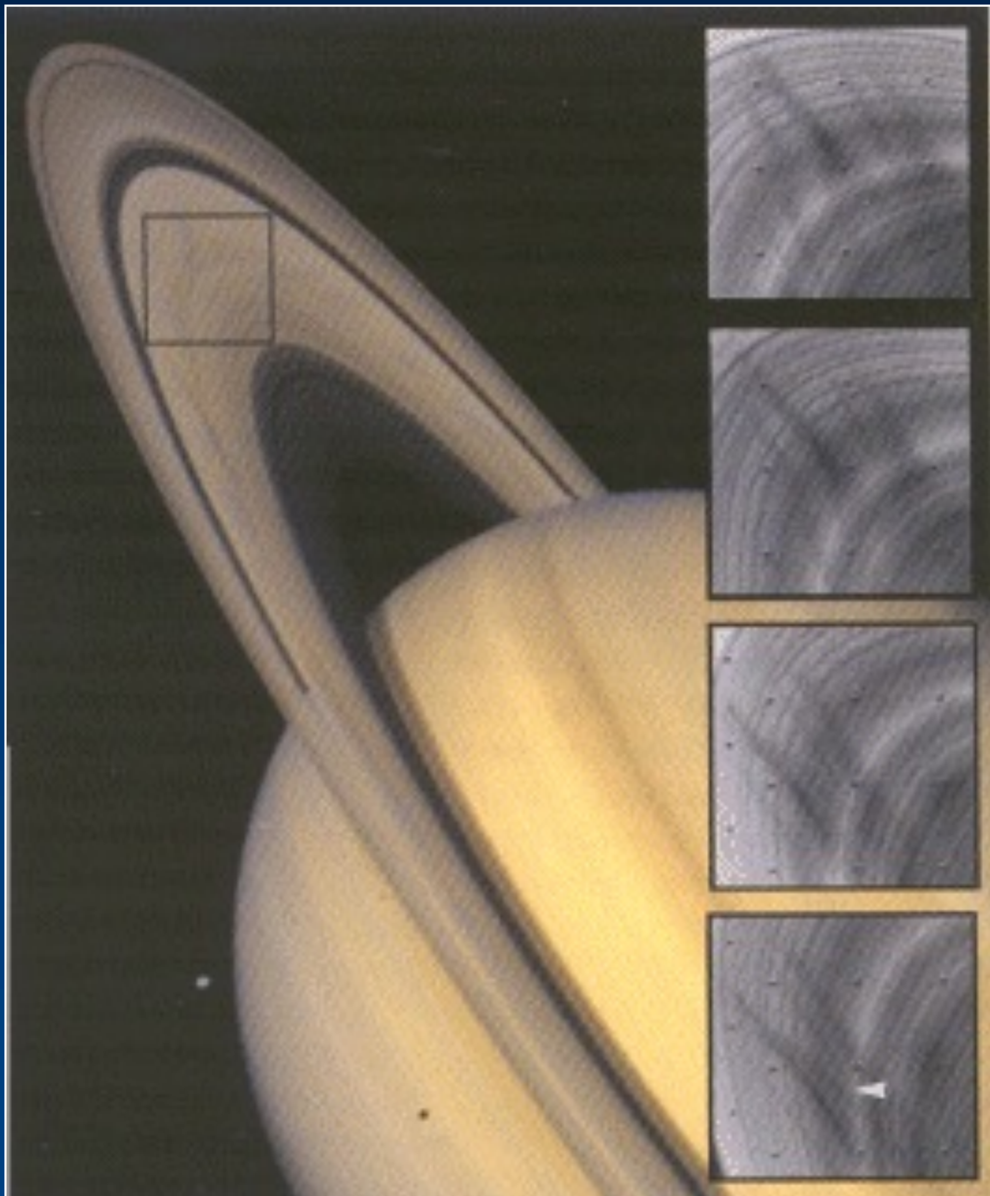
Here, atmosphere really means "upper" atmosphere! That's where the clouds we see are forming. A few 100 km thick.

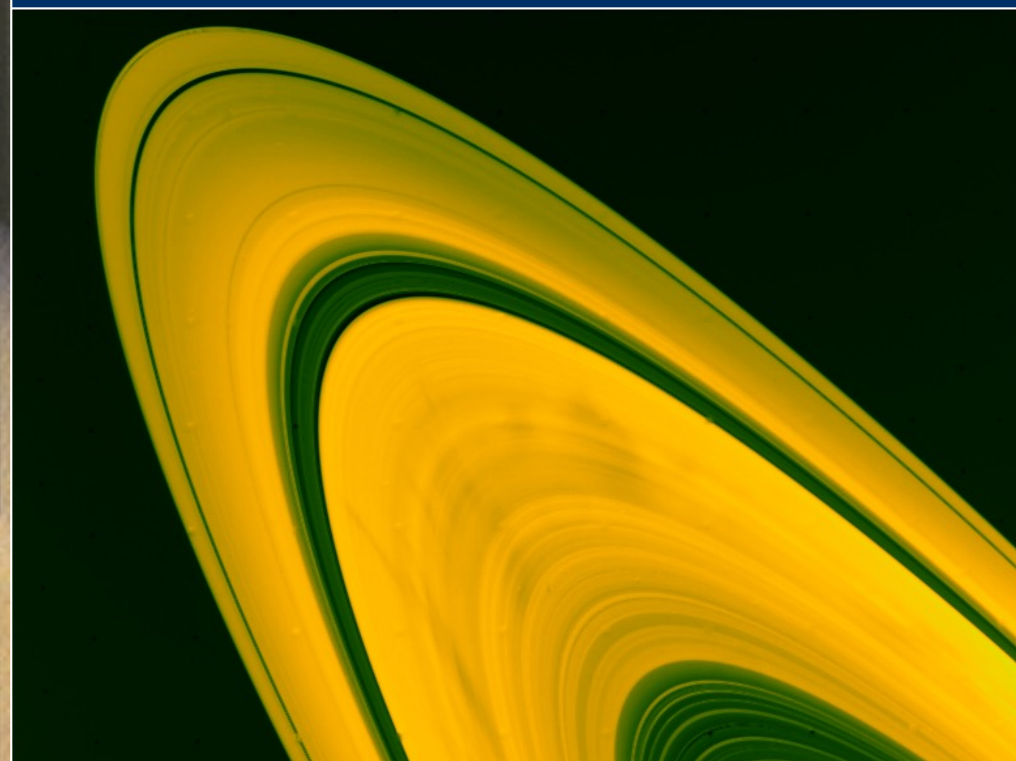
- This is an example of a *reducing atmosphere* (hydrogen compounds). Terrestrial planets by comparison have *oxidizing atmospheres*.

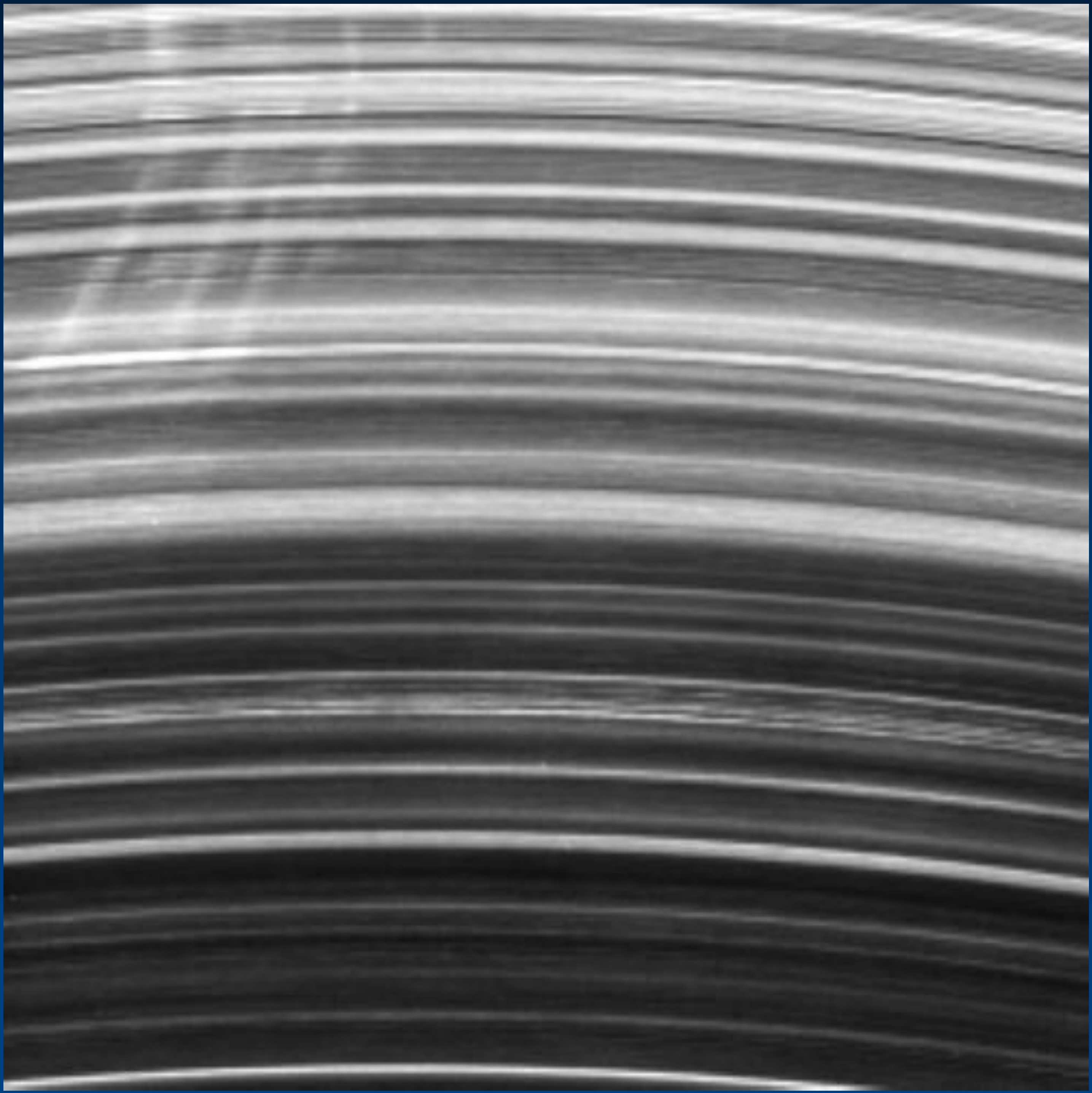


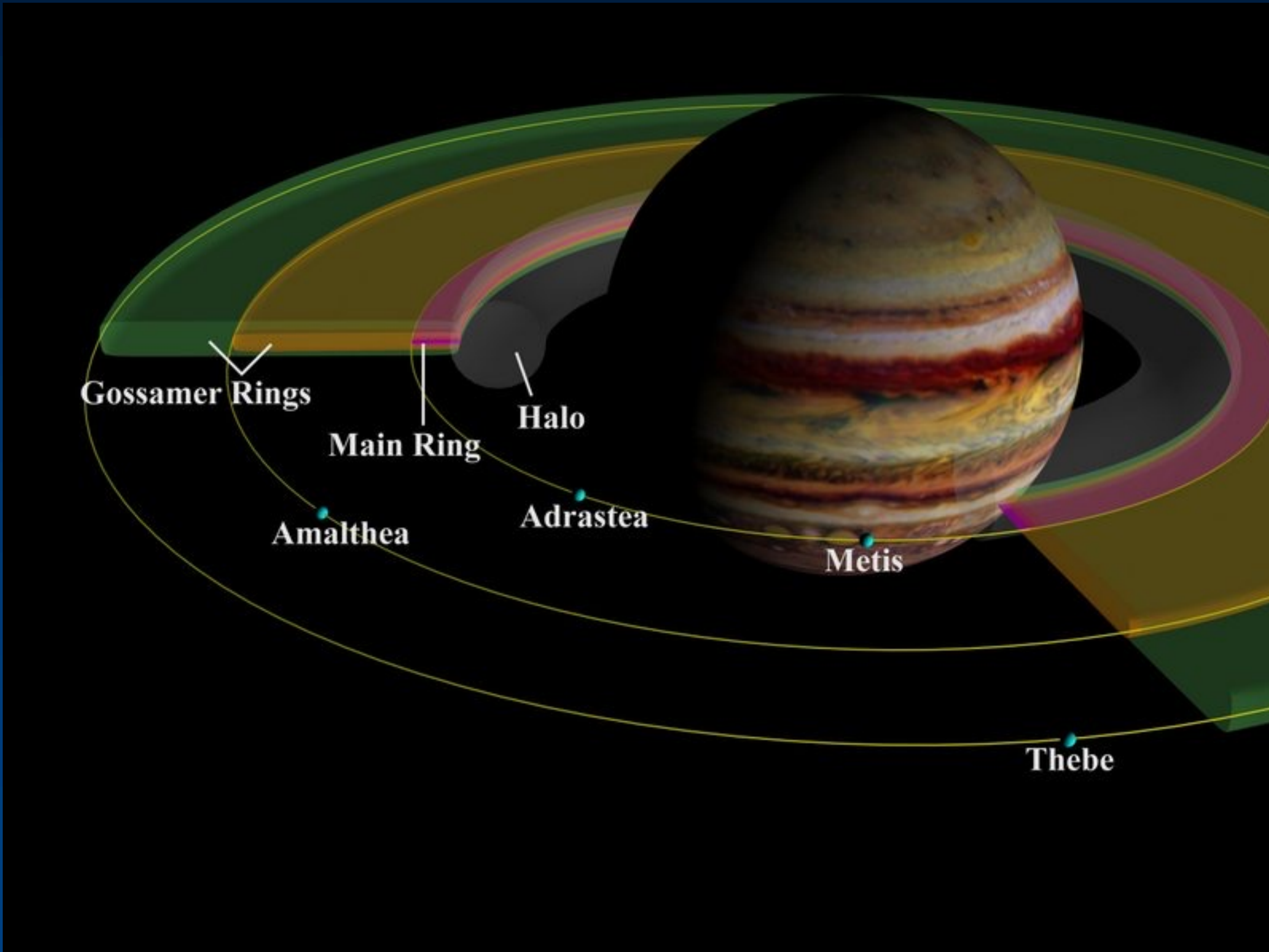
HST image of Saturn and four moons: Enceladus, Tethys, Dione and Mimas.

A Mystery: Voyager discovered “Spokes” - dark bands moving. Perhaps dust particles from moon fractures breaking apart.









Gossamer Rings
Main Ring
Halo
Amalthea
Adrastea
Metis
Thebe

Saturn's Hexagon