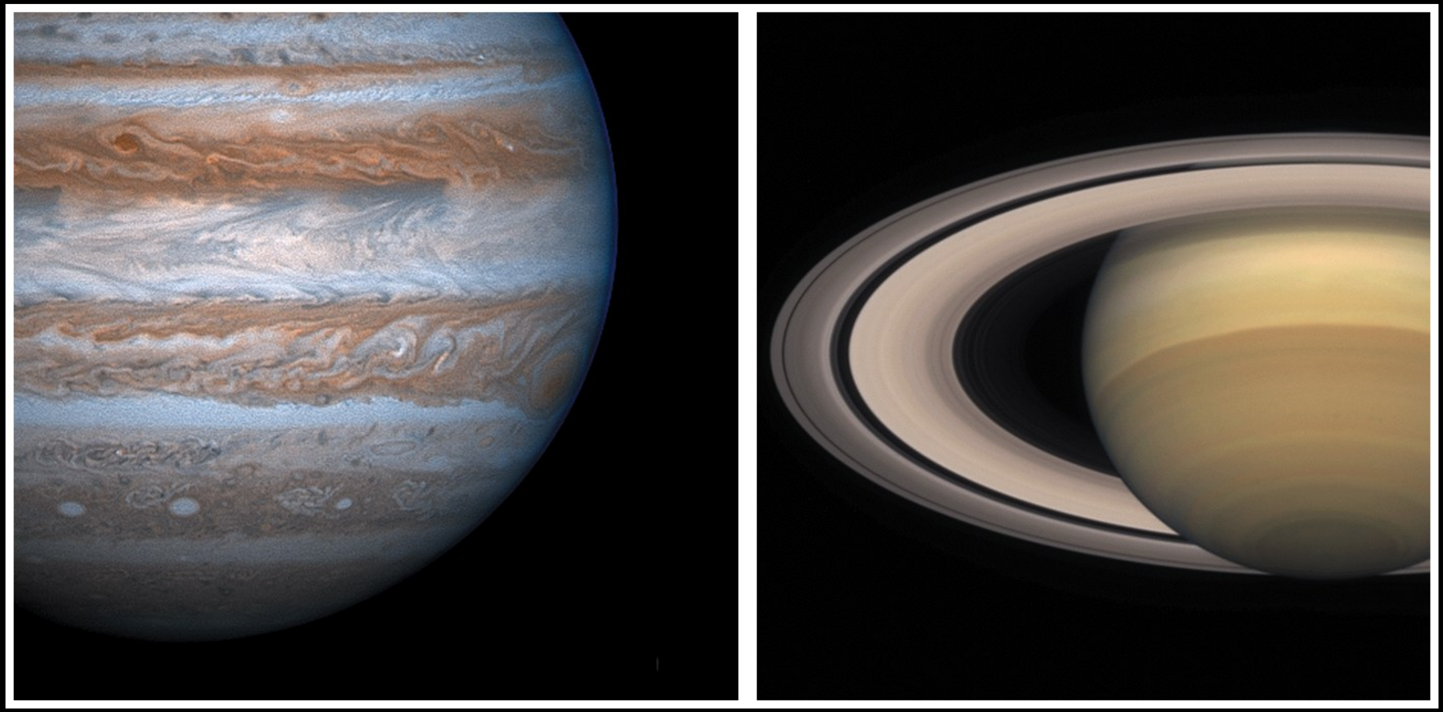
Lecture 13



Jovian Planets

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Opening Q: Jovian planets are farther away from the Sun than terrestrial planets. Given all we know about terrestrial planets, what do you expect Jovian planets are like?

- Motion
- Mass and composition
- Atmosphere
- Energy
- Geology (?)
- Magnetic fields
- Satellites and rings

Guiding Questions

1. What is going on in Jupiter and Saturn’s belts and zones and the Great Red Spot?
2. What is the composition of Jovian atmospheres? How does it compare with terrestrial atmospheres?
3. What is the nature of the clouds of Jupiter and Saturn?
4. How do astronomers know about the deep interiors of Jupiter and Saturn?
5. How do Jupiter and Saturn generate their intense magnetic fields?
6. Are Saturn’s rings actually solid bands that encircle the planet? How uniform and smooth are Saturn’s rings?

13.1 Introduction: the outer Jovian planets are gas giants.

the Jovian (outer) planets

	Jupiter	Saturn	Uranus	Neptune
Average distance from Sun (10^6 km)	778.3	1429	2871	4498
Average distance from Sun (AU)	5.203	9.554	19.194	30.066
Orbital period (years)	11.86	29.46	84.10	164.86
Orbital eccentricity	0.048	0.053	0.043	0.010
Inclination of orbit to the ecliptic	1.30°	2.48°	0.77°	1.77°
Equatorial diameter (km)	142,984	120,536	51,118	49,528
Equatorial diameter (Earth = 1)	11.209	9.449	4.007	3.883
Mass (kg)	1.899×10^{27}	5.685×10^{26}	8.682×10^{25}	1.024×10^{26}
Mass (Earth = 1)	317.8	95.16	14.53	17.15
Average density (kg/m^3)	1326	687	1318	1638

- Being far, they are slow orbiters: $a^3 = P^2$
- Being far, they are cold: T = 55 - 165 K
- Retain large amounts of light elements (similar to the Sun)
- More reflective than most terrestrial planets: A = 0.4 - 0.6
- Have global magnetic fields, rings, and satellites.

table 14-1 Jupiter Data

Average distance from Sun:	5.203 AU = 7.783×10^8 km
Maximum distance from Sun:	5.455 AU = 8.160×10^8 km
Minimum distance from Sun:	4.950 AU = 7.406×10^8 km
Eccentricity of orbit:	0.048
Average orbital speed:	13.1 km/s
Orbital period:	11.86 years
Rotation period:	$9^h\ 50^m\ 28^s$ (equatorial) $9^h\ 55^m\ 29^s$ (internal)
Inclination of equator to orbit:	3.12°
Inclination of orbit to ecliptic:	1.30°
Diameter:	142,984 km = 11.209 Earth diameters (equatorial) 133,708 km = 10.482 Earth diameters (polar)
Mass:	1.899×10^{27} kg = 317.8 Earth masses
Average density:	1326 kg/m^3
Escape speed:	60.2 km/s
Surface gravity (Earth = 1):	2.36
Albedo:	0.44
Average temperature at cloudtops:	−108°C = −162°F = 165 K
Atmospheric composition (by number of molecules):	86.2% hydrogen (H_2), 13.6% helium (He), 0.2% methane (CH_4), ammonia (NH_3), water vapor (H_2O), and other gases

fast and differential rotation

massive, large, low density, oblate

atmosphere dominated by H_2 and He

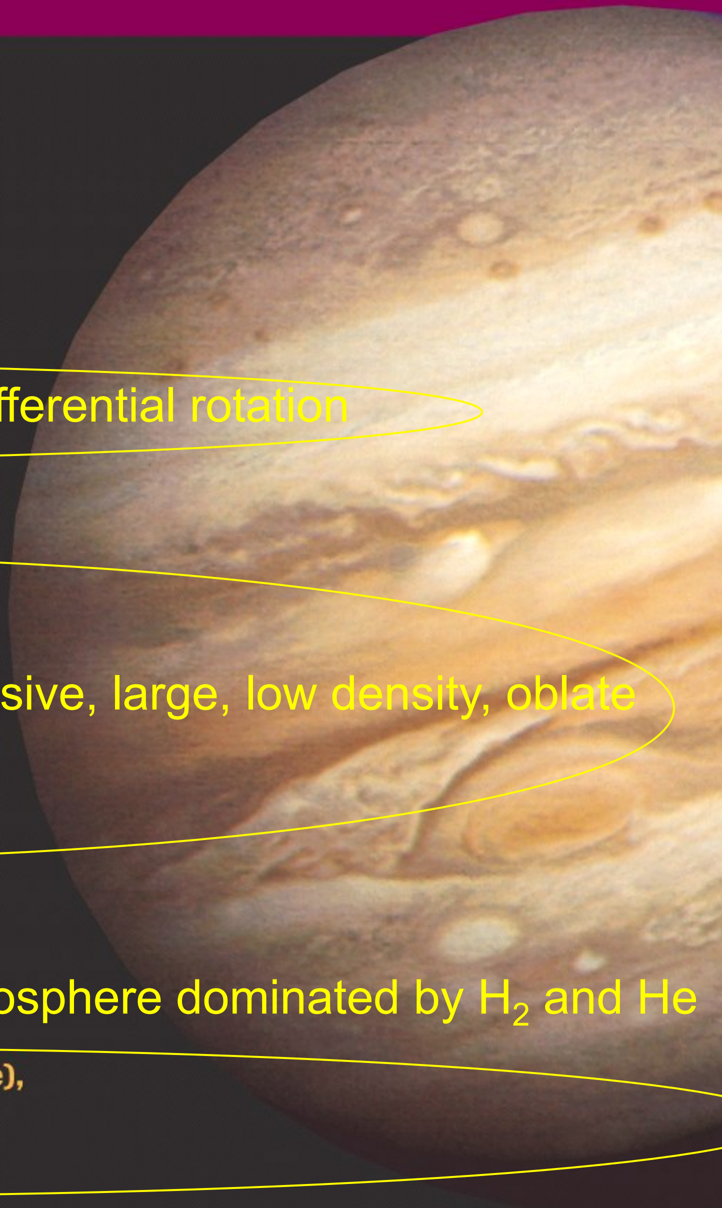
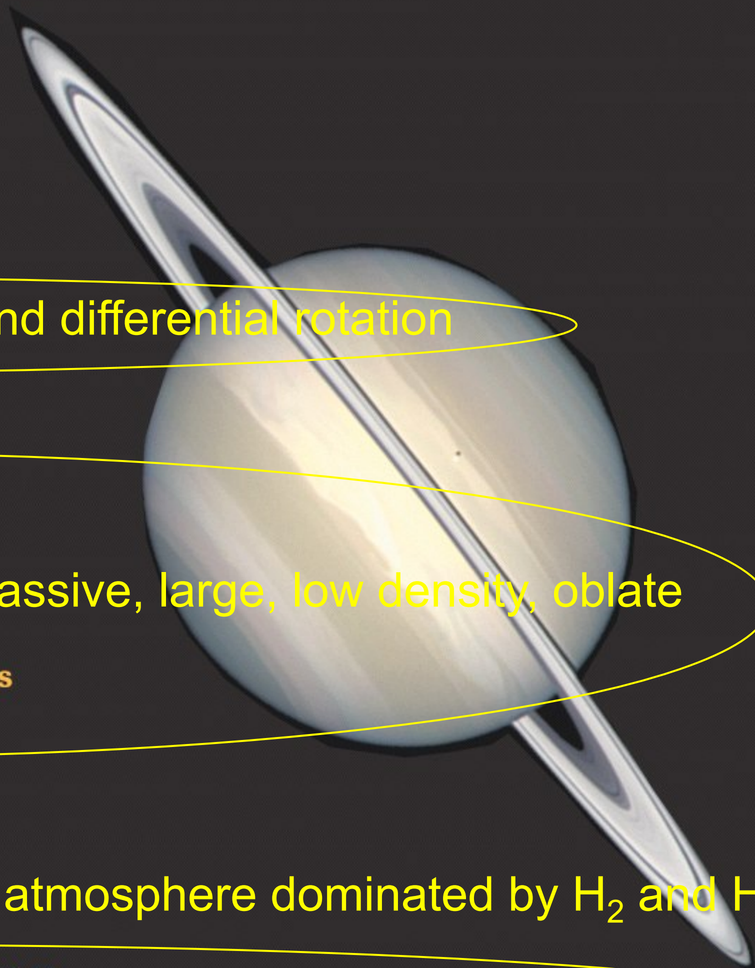


table 14-2 Saturn Data

Average distance from Sun:	9.572 AU = 1.432×10^9 km
Maximum distance from Sun:	10.081 AU = $1.508 \times 3\ 10^9$ km
Minimum distance from Sun:	9.063 AU = 1.356×10^9 km
Eccentricity of orbit:	0.053
Average orbital speed:	9.64 km/s
Orbital period:	29.37 years
Rotation period:	$10^h\ 13^m\ 59^s$ (equatorial) $10^h\ 39^m\ 25^s$ (internal)
Inclination of equator to orbit:	26.73°
Inclination of orbit to ecliptic:	2.48°
Diameter:	120,536 km = 9.449 Earth diameters (equatorial) 108,728 km = 8.523 Earth diameters (polar)
Mass:	5.685×10^{26} kg = 95.16 Earth masses
Average density:	687 kg/m^3
Escape speed:	35.5 km/s
Surface gravity (Earth = 1):	0.92
Albedo:	0.46
Average temperature at cloudtops:	−180°C = −292°F = 93 K
Atmospheric composition (by number of molecules):	96.3% hydrogen (H_2), 3.3% helium (He), 0.4% methane (CH_4), ammonia (NH_3), water vapor (H_2O), and other gases



fast and differential rotation

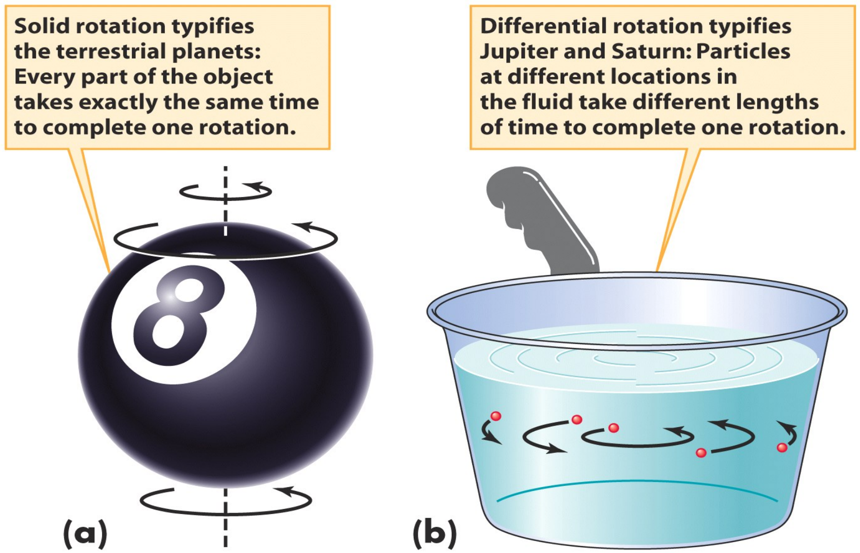
massive, large, low density, oblate

atmosphere dominated by H_2 and He

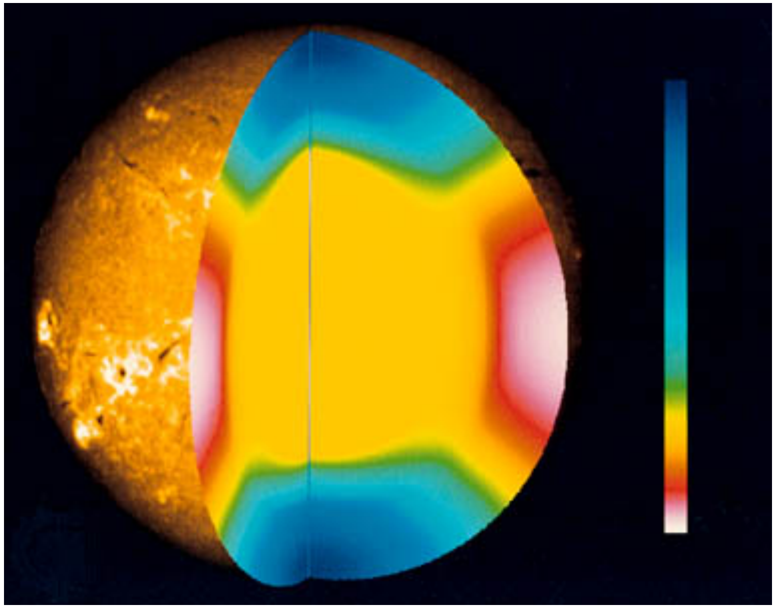
13.2 Motions

- Jovian planets are best seen at oppositions about once a year: Jupiter is 50" and Saturn is 20".

- They exhibit **fast** (10 -16 hrs) **differential rotation:** it takes shorter time for equatorial regions to finish one round about the axis than for polar regions (similar to the Sun's differential rotation) -- they're **fluid**.



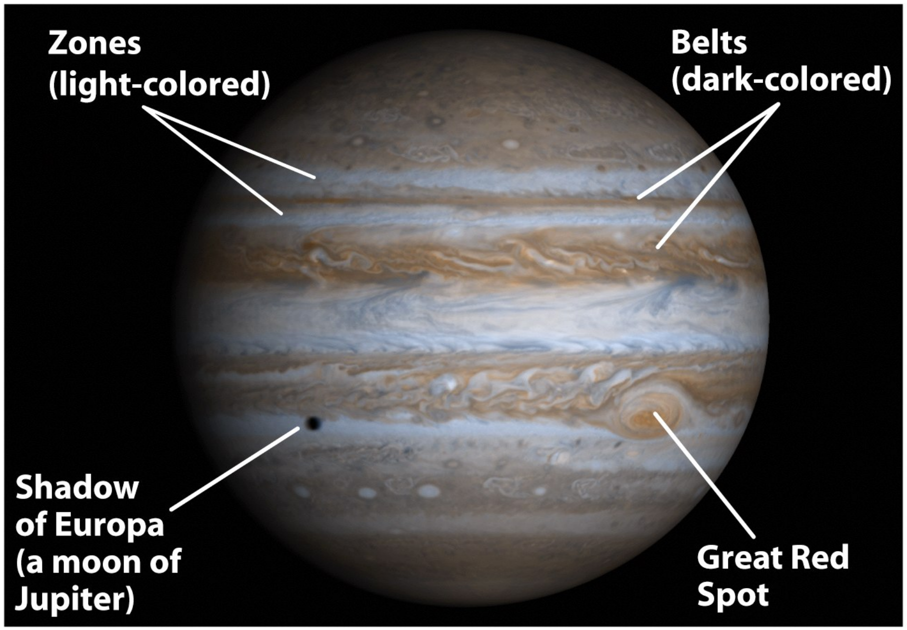
rigid rotation and differential rotation



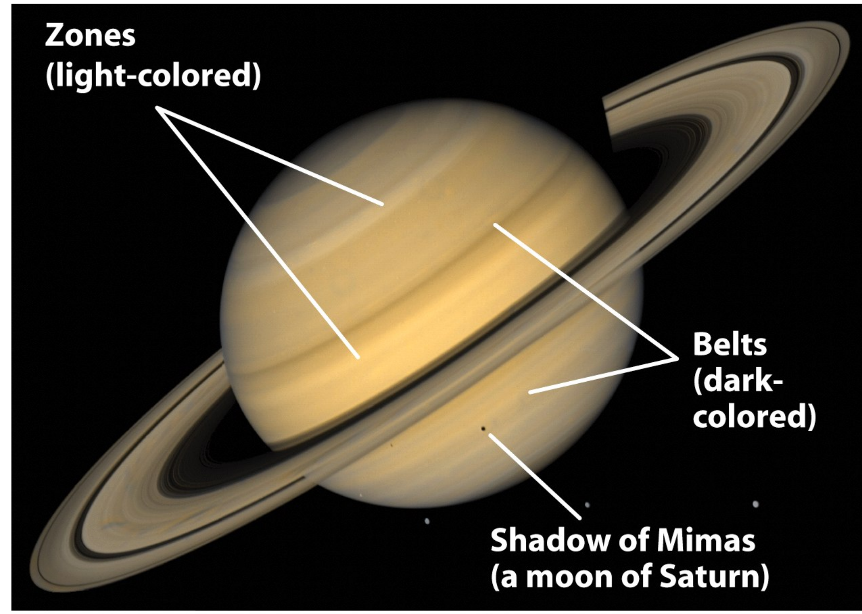
Ex.1: Sun's differential rotation

14.3 Dynamic atmospheres

The visible "surfaces" of Jovian planets are the cloud tops.



Jupiter

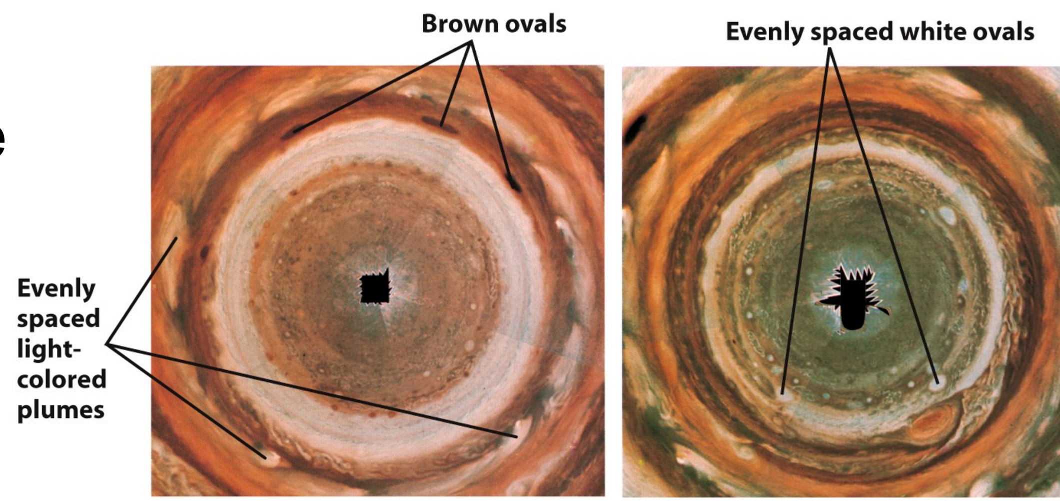


Saturn

Jupiter and Saturn have characteristic observable features different from other planets: light-colored **zones,** dark-colored **belts,** and **spots** and **ovals.** The red/white/brown colors indicate clouds at different altitudes with different compositions -- nitrogen compounds and water vapor.

(a) *Pioneer 11*, December 1974 (b) *Voyager 2*, July 1979 (c) HST, February 1995

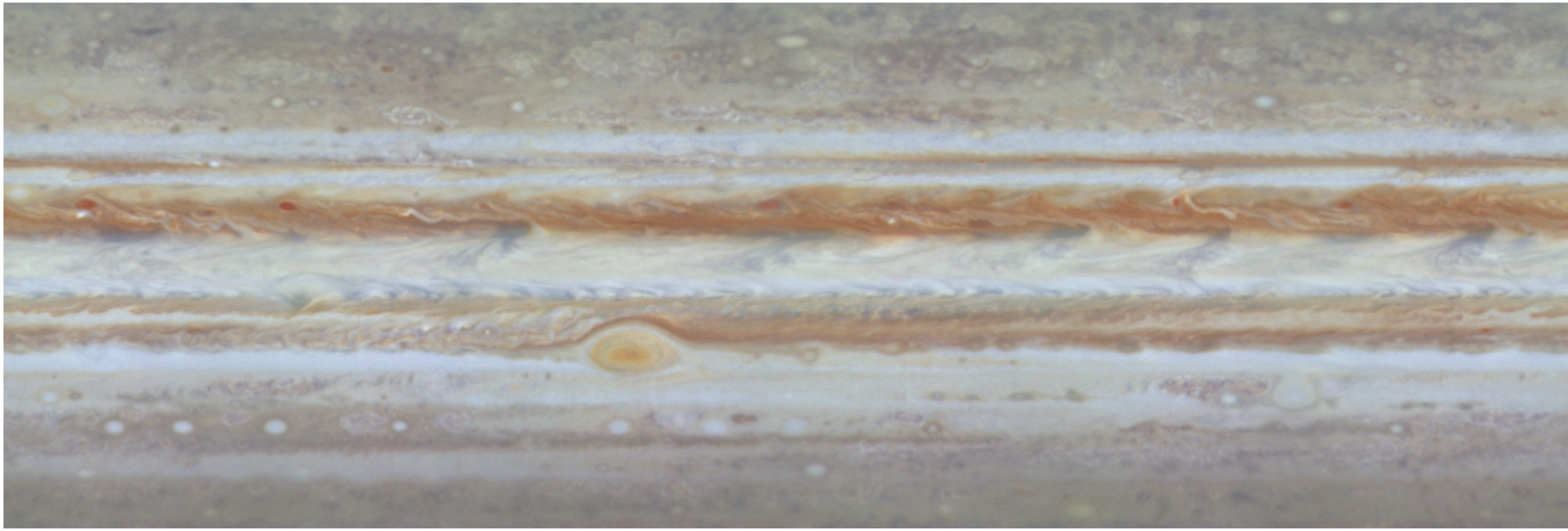
The fast rotation twists the clouds into light **zones** and dark **belts** parallel to the equator, indicative of convection patterns.



(a) Northern hemisphere (b) Southern hemisphere

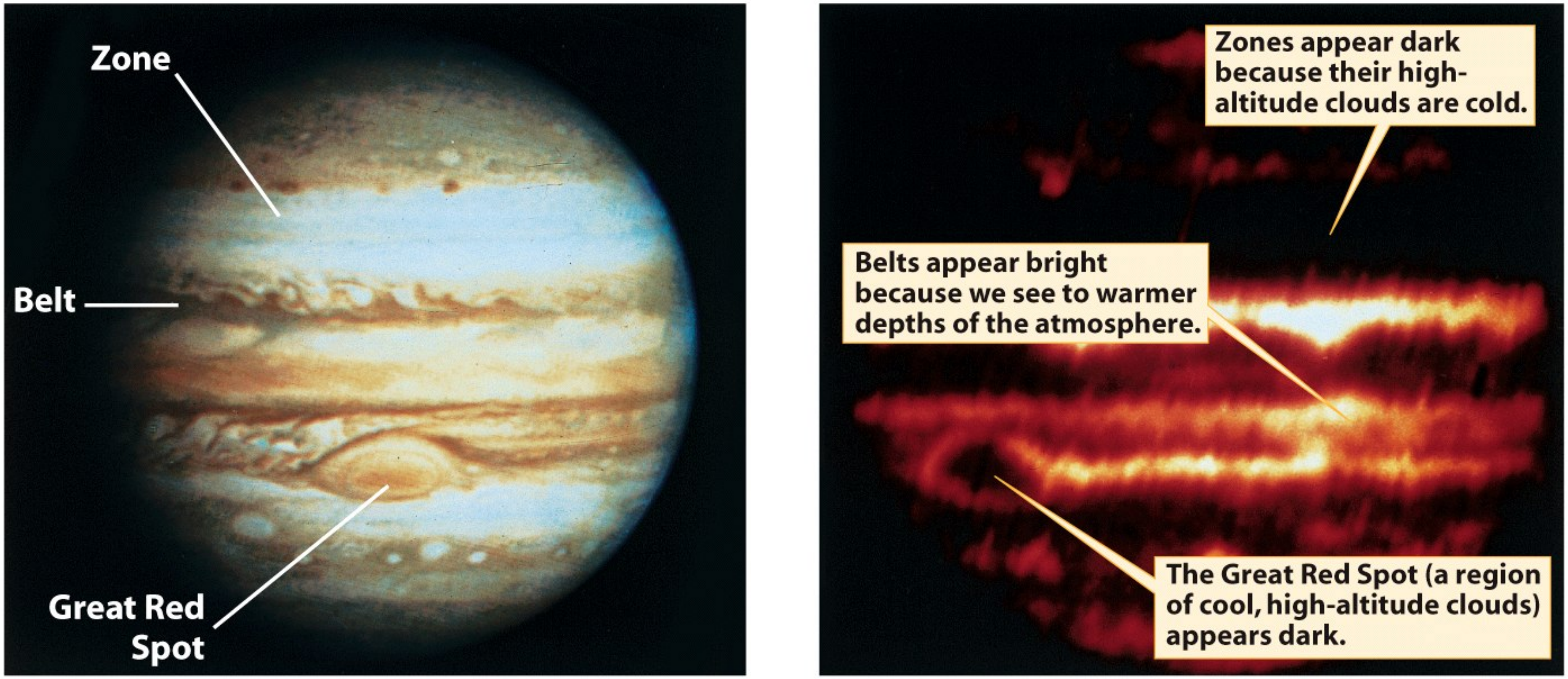
Jupiter's poles

The dynamic atmosphere of Jupiter



"Various patterns of motion are apparent all across Jupiter at the cloudtop level seen here. The Great Red Spot shows its counterclockwise rotation, and the uneven distribution of its high haze is obvious. To the east (right) of the Red Spot, oval storms, like ball bearings, roll over and pass each other. Horizontal bands adjacent to each other move at different rates. Strings of small storms rotate around northern-hemisphere ovals. The large grayish-blue "hot spots' at the northern edge of the white Equatorial Zone change over the course of time as they march eastward across the planet. Ovals in the north rotate counter to those in the south. Small, very bright features appear quickly and randomly in turbulent regions, candidates for lightning storms.” Image Credit: NASA/JPL/University of Arizona

Jupiter's clouds in visible and infrared light.

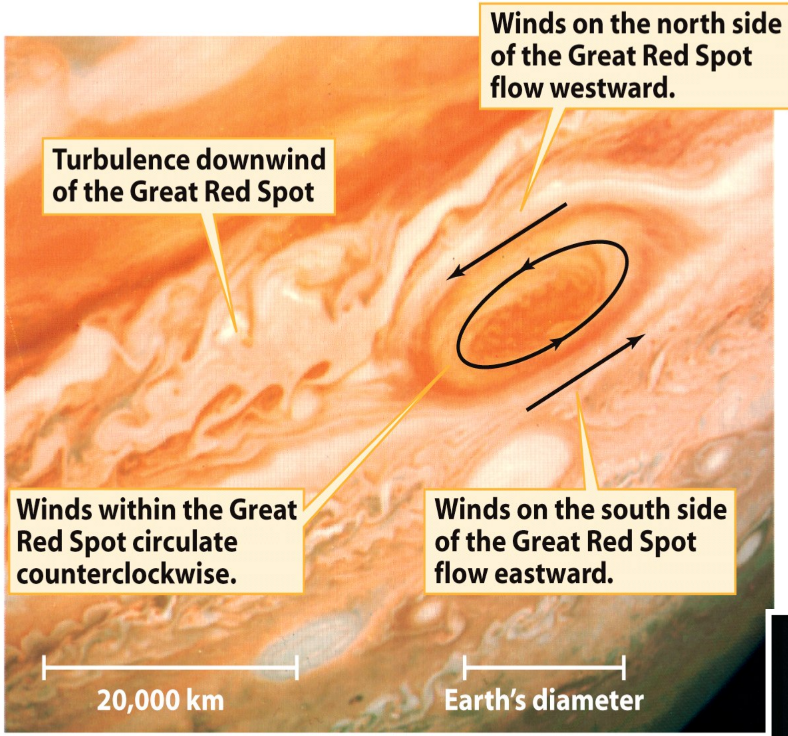


(a) Visible-light image (b) Infrared image

Q: what are the origins of the visible and infrared light?

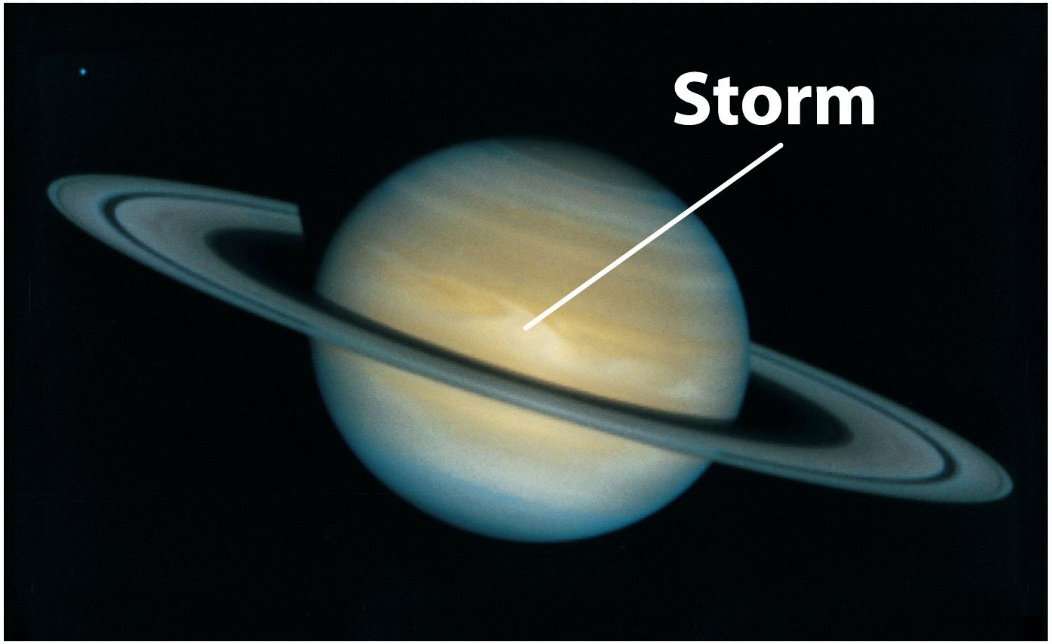
Jupiter's dark belts are bright in infrared, indicative of low-lying warmer clouds. White zones are dark in infrared, indicating cool high-altitude clouds.

Storms on Jupiter and Saturn

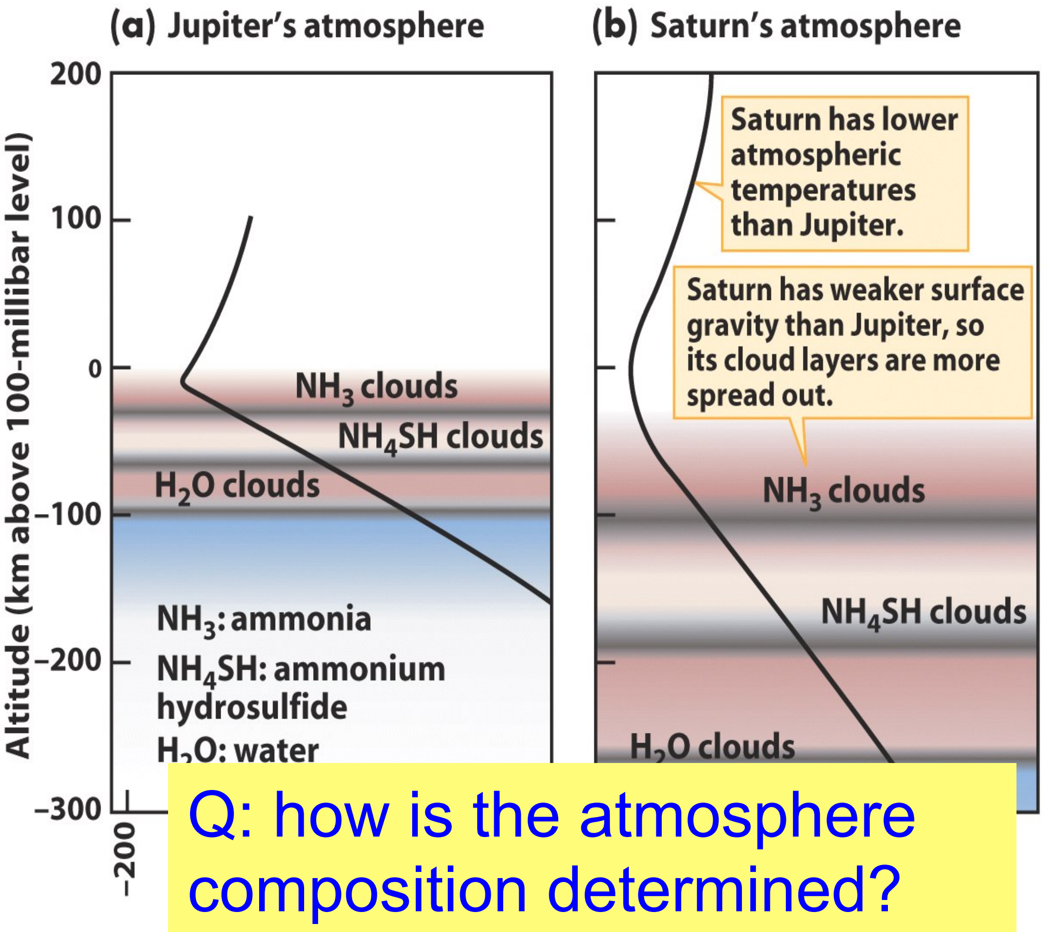


Gigantic storms are present in the Jovian atmosphere and visible as colored **ovals**. The **Great Red Spot**, located in a white zone, is such a storm center persisting for centuries.

Short-lived storms, "**white spots**", are occasionally seen on Saturn.



Atmosphere structure and composition on Jupiter and Saturn



Q: how is the atmosphere composition determined?

Differences:

- Saturn's cloud layers are more spread out and cooler.
- Composition of Jupiter's atmosphere is very similar to that of the Sun: 75% H, 24% He, 1% others (by mass).
- Saturn's atmosphere has a serious He deficiency, perhaps due to helium rains.

Similarities:

- Three cloud layers on the top with distinctive colors.
- Temperature decreases with altitude
- Atmosphere consists nearly entirely of H & He.

The atmosphere dynamics are driven by the **internal energy** of Jovian planets. Jovian planets emit more energy (infrared) than they receive from the Sun (visible).

Ex.3: If Jupiter emitted the same amount of energy it receives from the Sun, its surface temperature would be 107K; if Jupiter emitted twice the incoming energy, what's its temperature?

$$\text{Stefan - Boltzmann Law}: \; F_1 = \sigma T_1^{\,4}, \;\; F_2 = \sigma T_2^{\,4}$$

$$\frac{F_2}{F_1} = \frac{\sigma T_2^{\,4}}{\sigma T_1^{\,4}} = \frac{T_2^{\,4}}{T_1^{\,4}} \;\Rightarrow\; \frac{T_2}{T_1} = \left(\frac{F_2}{F_1}\right)^{1/4}$$

$$\Rightarrow T_2 = \left(\frac{F_2}{F_1}\right)^{1/4} T_1 = (2)^{1/4} \times 107\text{ K} = 127\text{ K}$$

(optional) Ex. 4: Jupiter is still under gravitational contraction, the Kelvin-Helmholtz contraction, to turn gravitational energy (U) into internal heat.

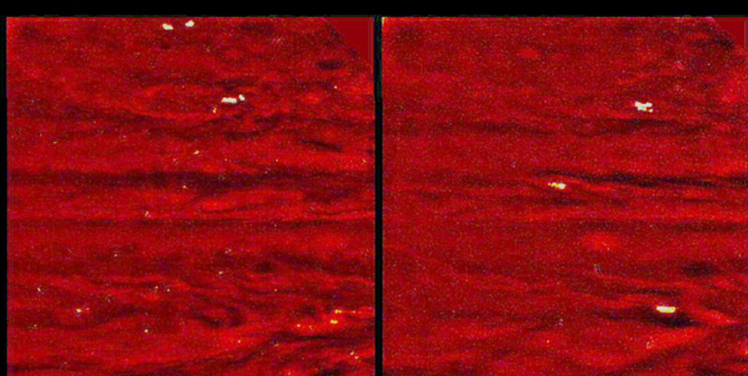
$$U = -\frac{3}{5}\frac{M^2 G}{R}$$

With decreasing R, U is converted to internal heat.

Kelvin-Helmholtz contraction was thought to provide energy to maintain sunshine. It provides energy for proto-stars before fusion ignition.

Discoveries of Jupiter's atmosphere by Galileo Probe:

- first observations of ammonia clouds.
- lightening charges in Jupiter's atmosphere
- more heavy elements than in the Sun
- missing water
- abundant noble gas

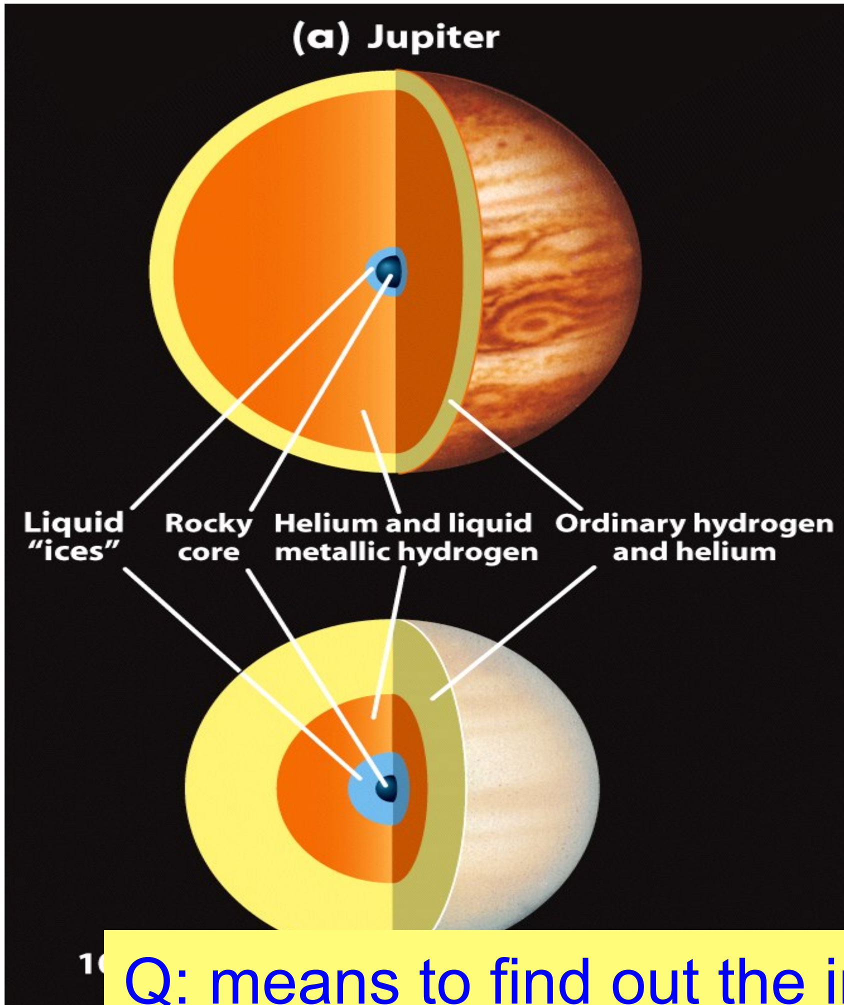


Lightening on Jupiter

Galileo was launched in 1989. The Probe was released to Jupiter's upper atmosphere in 1995, and plunged into Jupiter's dense atmosphere in 2003.

13.4 Internal structure

Oblateness of Jupiter and Saturn reveals their **rocky cores**, surrounded by liquid ices, **metallic liquid hydrogen**, and hydrogen and helium gases.



- Oblateness is produced by **fast rotation** (pulling mass outward) against **gravity** (pulling mass inward).

  dense core => strong gravity => small oblateness.

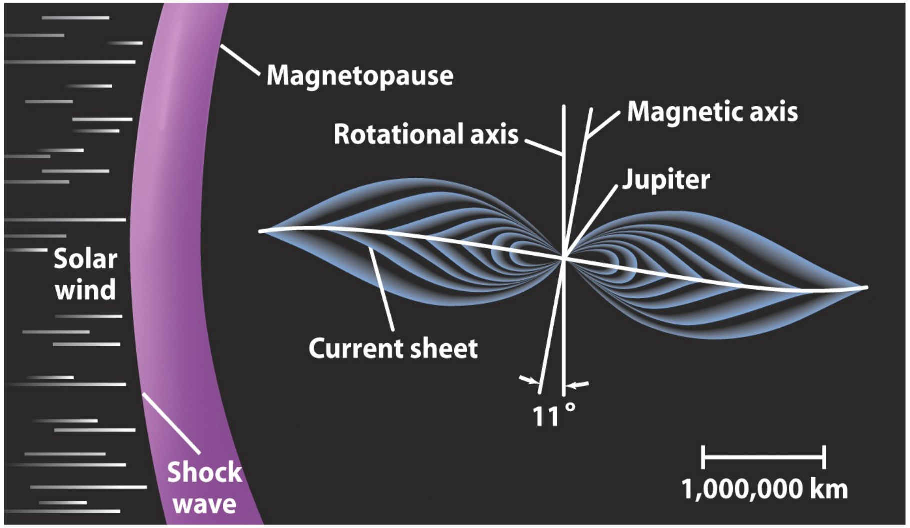
- Complicated models of **mass distribution** are built to fit the observed oblateness.

- Saturn's internal structure is similar to that of Jupiter, but with a larger rocky core (by percentage) and shallower liquid metallic hydrogen mantle.

Q: means to find out the interior structure of a planet?

13.5 Magnetosphere

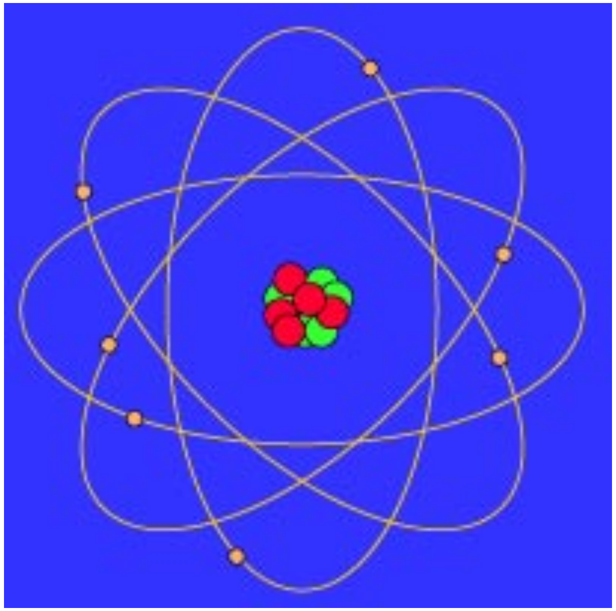
Jupiter and Saturn have strong global magnetic fields for rapid rotation of **liquid metallic hydrogen** (how is this compared with the Earth?)



Jovian magnetosphere is filled with **plasmas**, some from the volcanoes on Io caught by Jupiter's magnetic fields.

Jupiter's magnetosphere is larger than the Moon (apparent angular size) and its size fluctuates with the balance between plasma pressure and solar wind.

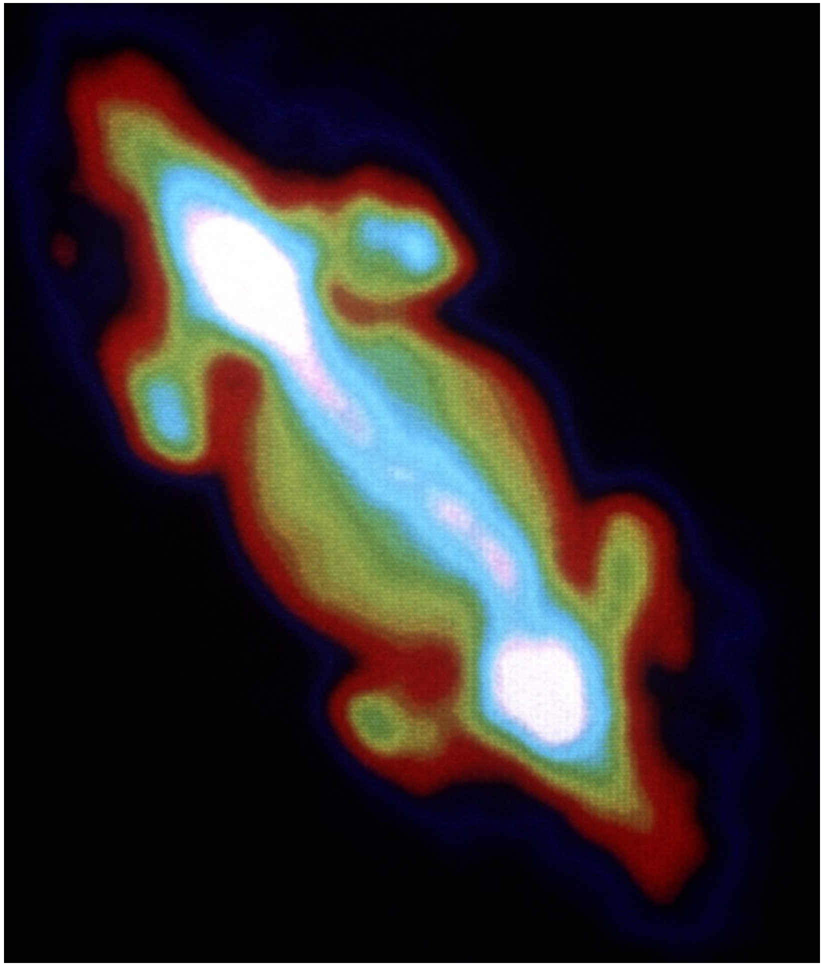
Ex.5: what is plasma? How does plasma behave in magnetic fields?



When electron is freed from the orbit around the nucleus, the atom is ionized. Ionized gases, which are globally neutral, are plasmas.

Ex.6: Synchrotron radiation by charged electrons spiraling around magnetic field lines.

Synchrotron radiation is **non-thermal radiation** by very high-speed (close to the speed of light) electrons, different from **thermal radiation** (e.g., blackbody radiation).



Radio Jupiter

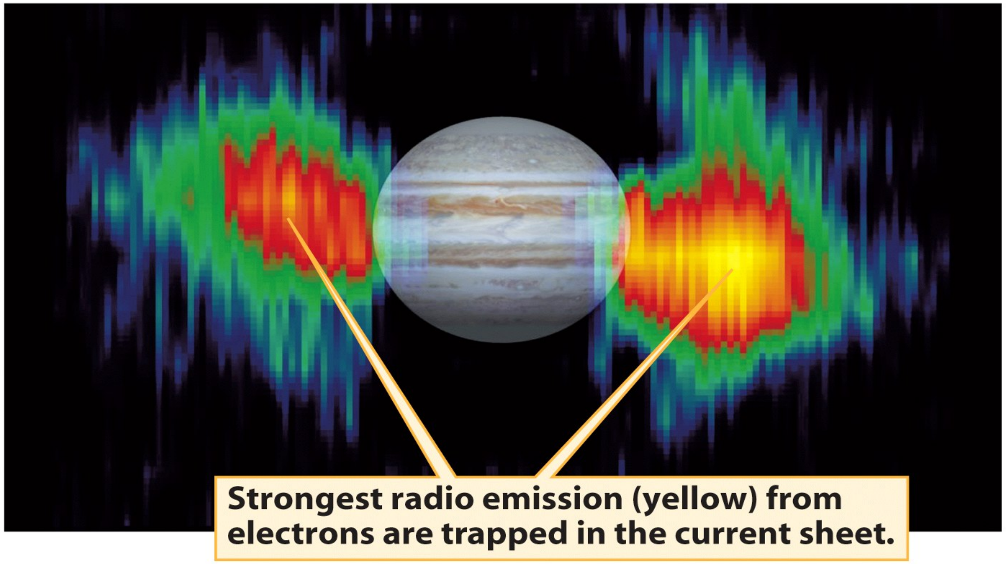
Credit: I. de Pater (UC Berkeley)
NRAO, AUI, NSF

Ex.7: Radio Jupiter recorded at VLA, New Mexico. The radio waves mapped in this false-color image are produced by **energetic electrons** trapped within Jupiter's intense magnetic field. The radio emitting region extends far beyond Jupiter's cloud tops and surrounds Jupiter. While it glows strongly at radio wavelengths, Jupiter's radiation belt is invisible in the more familiar optical and infrared views which show the Jovian cloud tops and atmospheric features in reflected sunlight.

NB: this type of radio emission is a non-thermal emission, different from blackbody continuum radiation or line emission.

Review Q: what do we learn from spectroscopy?

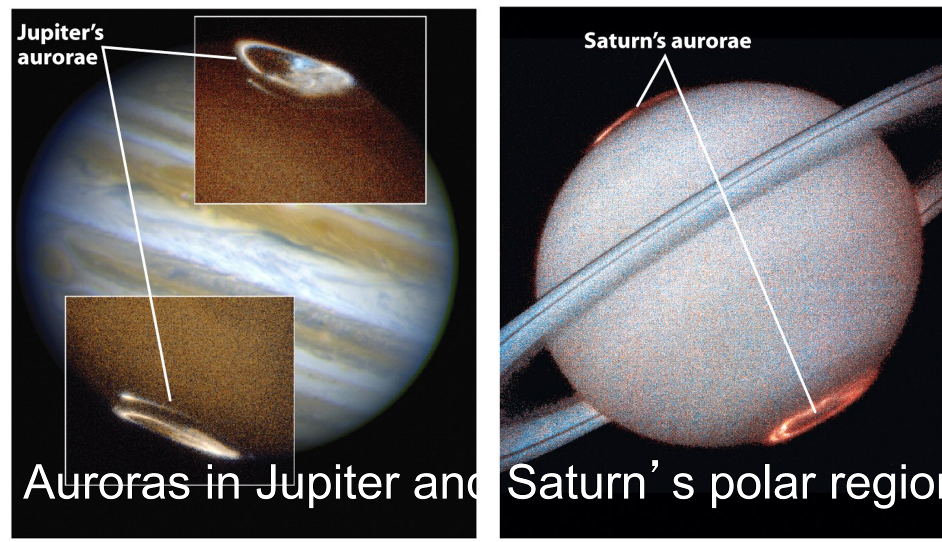
- thermal continuum (blackbody radiation): temperature of the opaque radiator; can NOT tell the material of the radiator.
- spectral lines: composition, temperature, density, abundance, line-of-sight motion of a gas
- Non-thermal synchrotron radiation: particle properties (number and speed) and magnetic field.
- reflective spectrum: surface properties (composition, texture etc.).



Trapped plasmas emit **synchrotron radiation** at radio wavelengths. The strongest emission is at the distance of the orbit of Io: **the Io plasma torus**.

Leaking particles produce auroras.

Auroras are seen in polar regions and torus is along the equator.

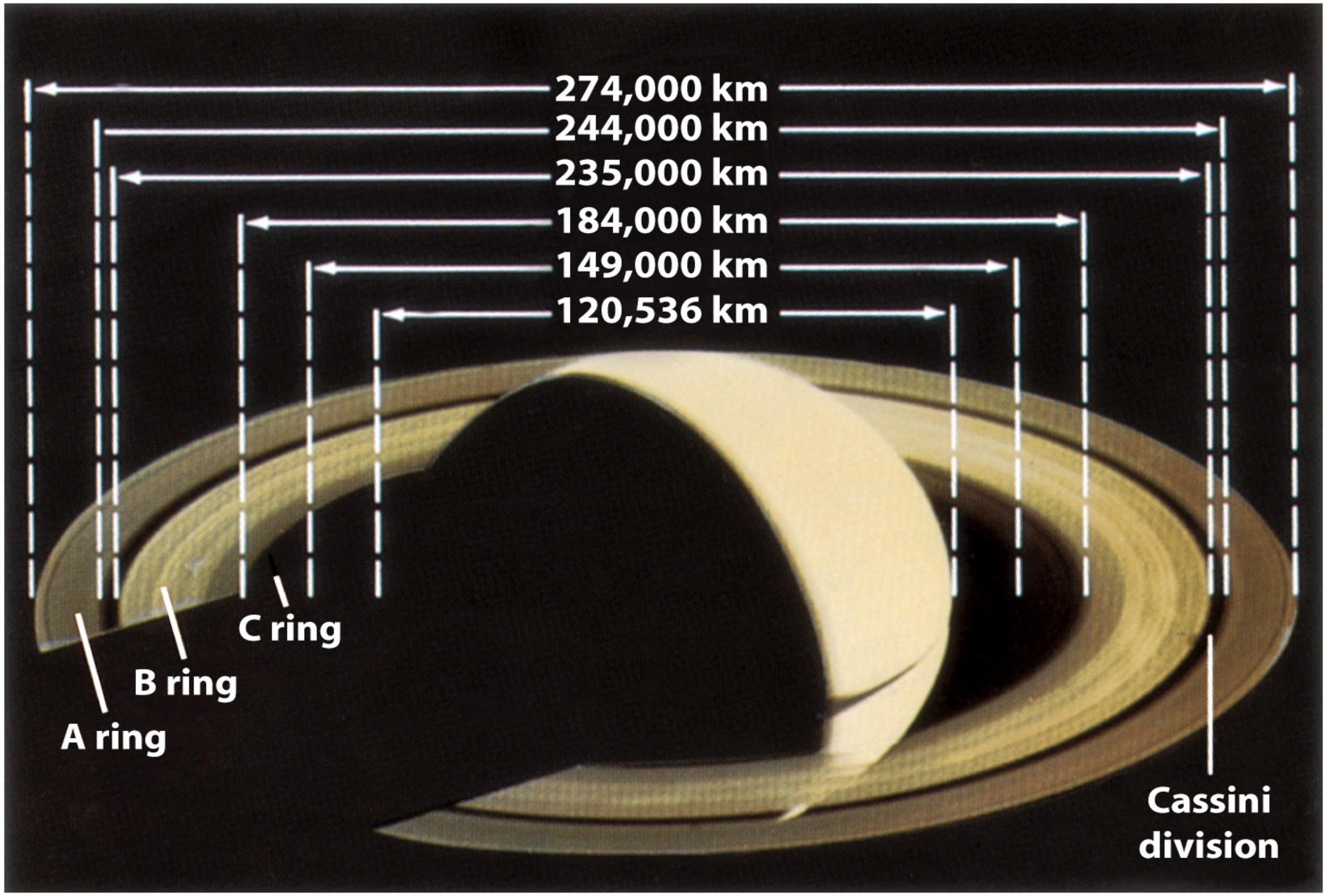


(a) Jupiter (b) Saturn

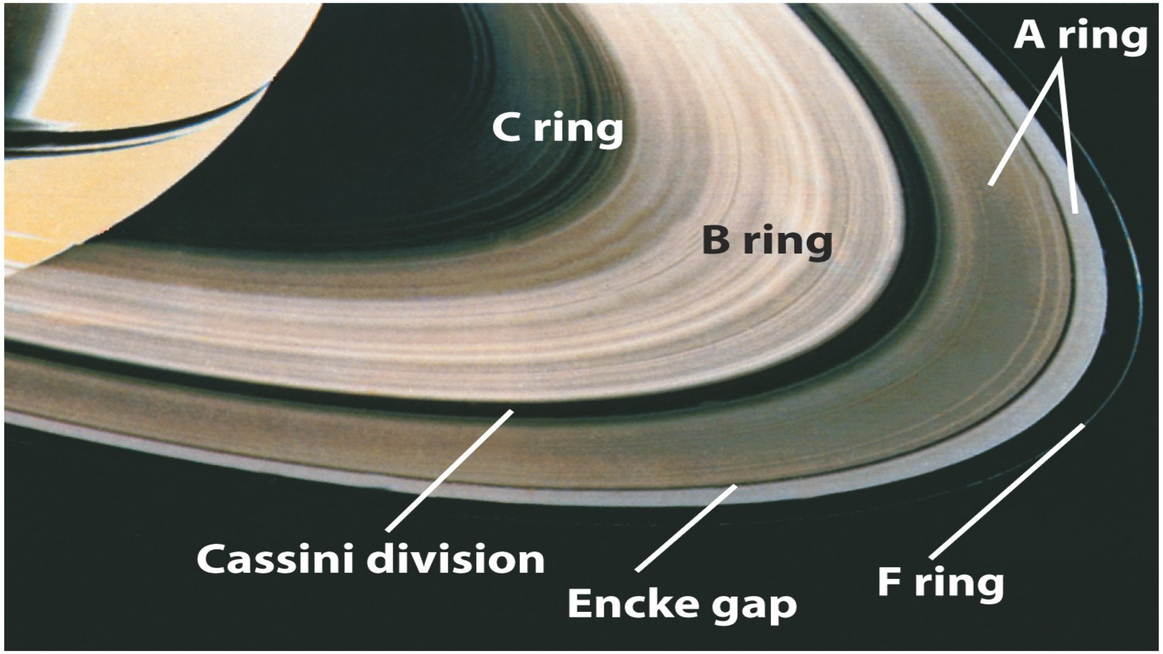
Saturn's magnetosphere is less strong with much fewer particles.

13.6 Rings

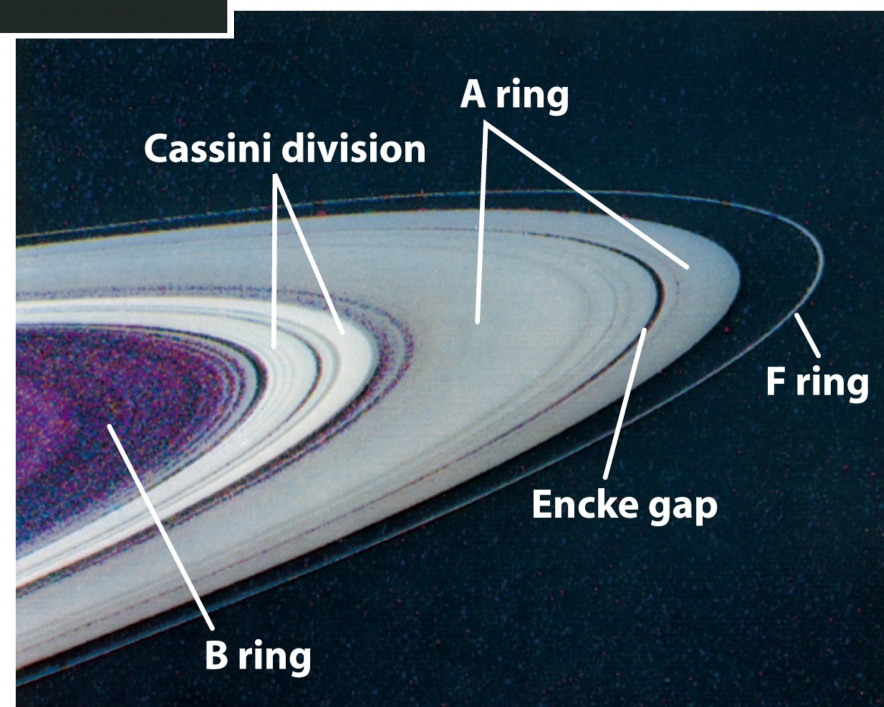
Observations on Earth reveal three broad rings encircling Saturn.



Saturn is circled by a system of thin, broad rings -- most famous being A, B, and C rings -- lying in the plane of the planet's equator, with gaps in between.

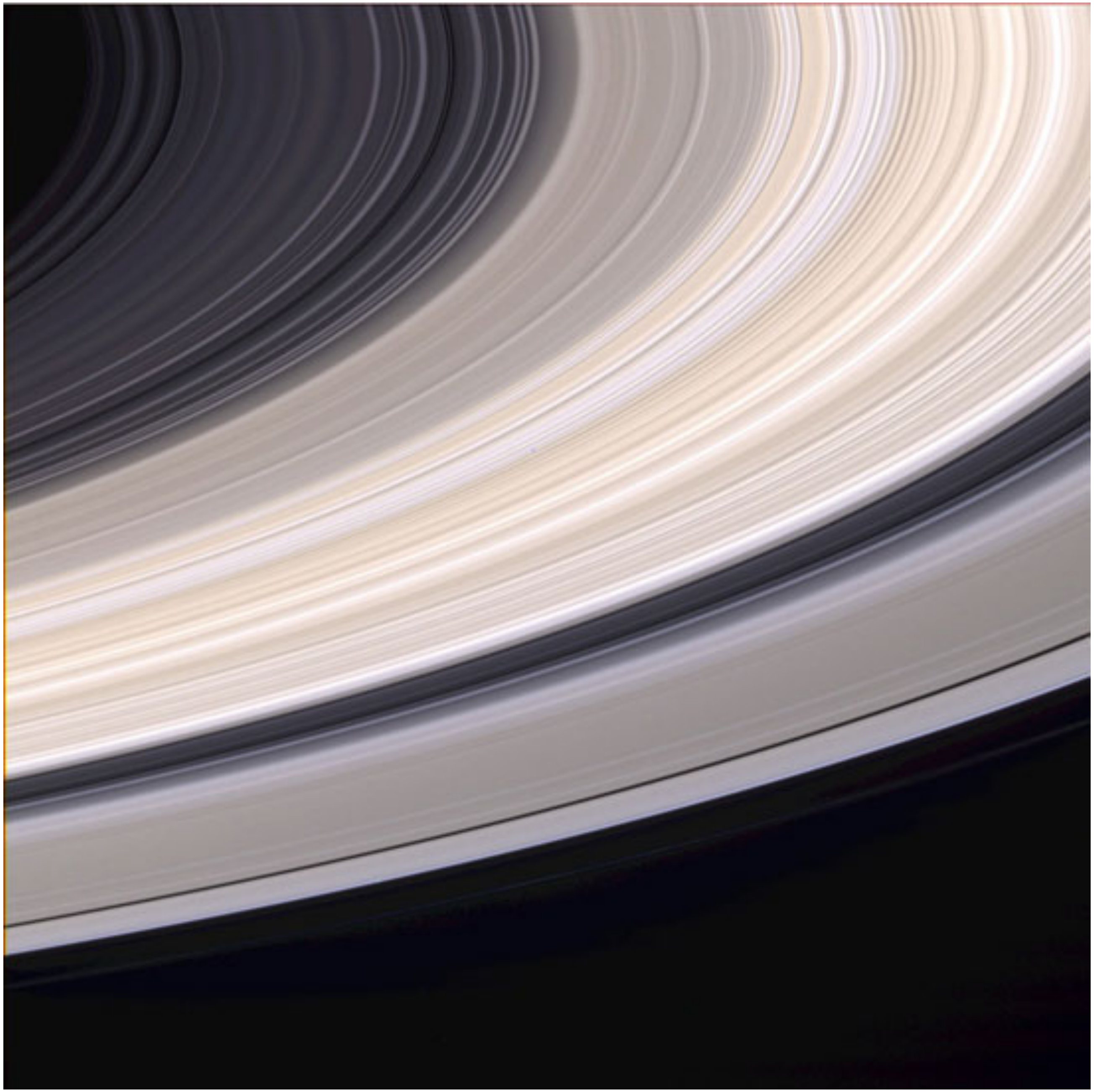


On the sunlit side, B ring is bright, or most **reflective**. **Cassini division** is dark.



On the far side, B ring is dark. **Cassini division** is bright.

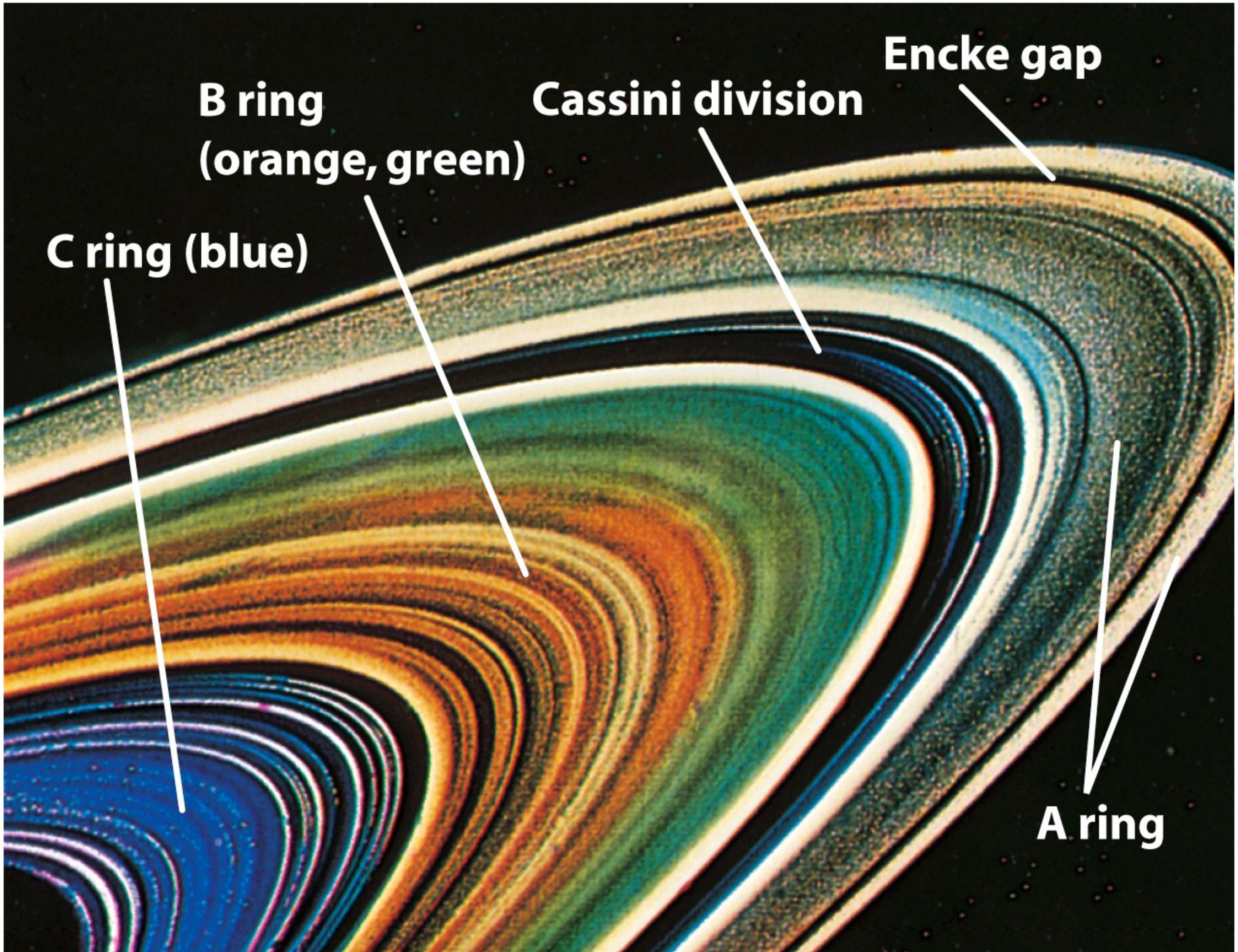
Cassini division is NOT an empty gap!



Saturn's majestic rings

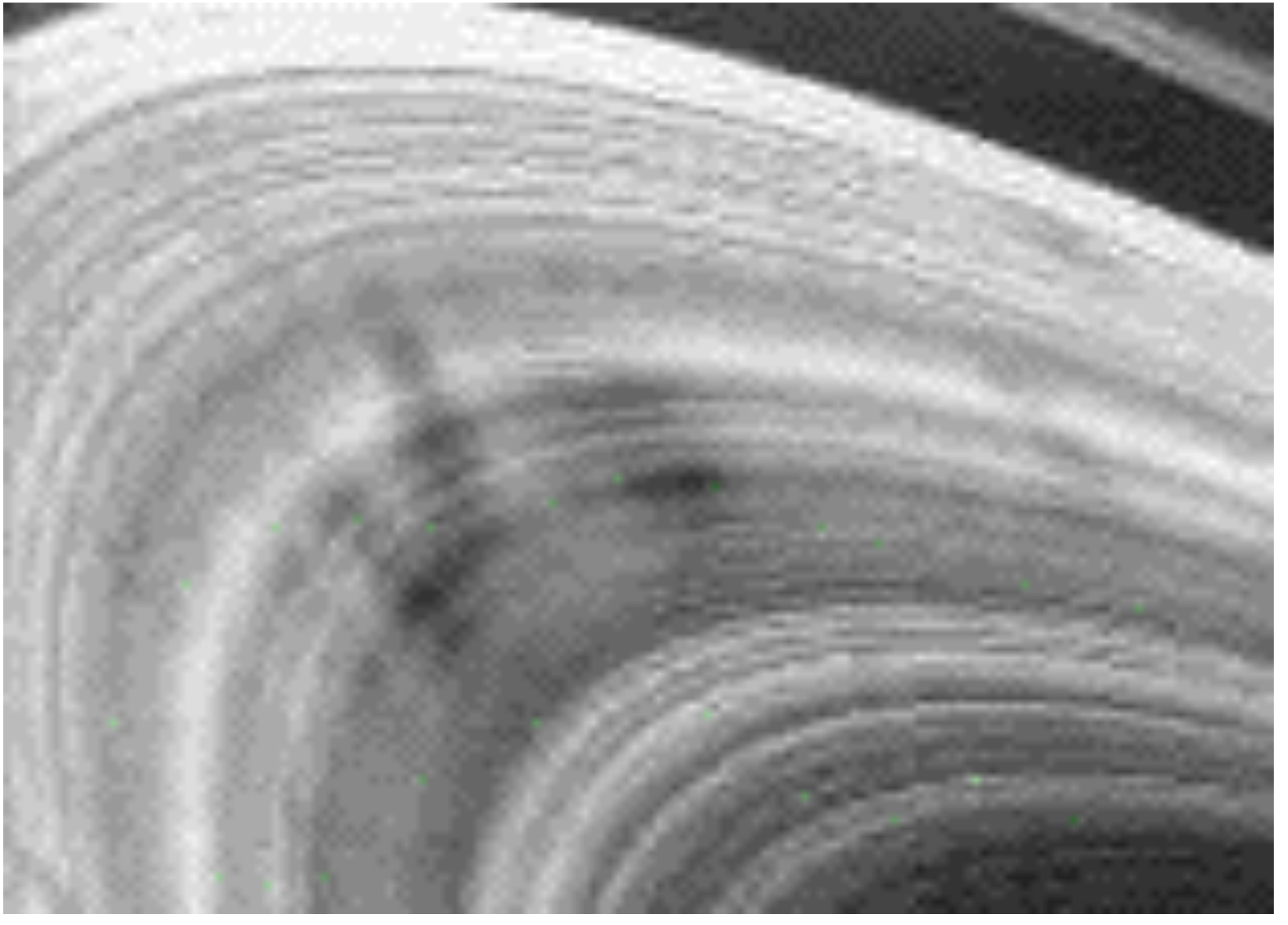
from Cassini Huygens. http://saturn.jpl.nasa.gov/home/index.cfm

Color variations in Saturn's rings: colors can tell compositions.



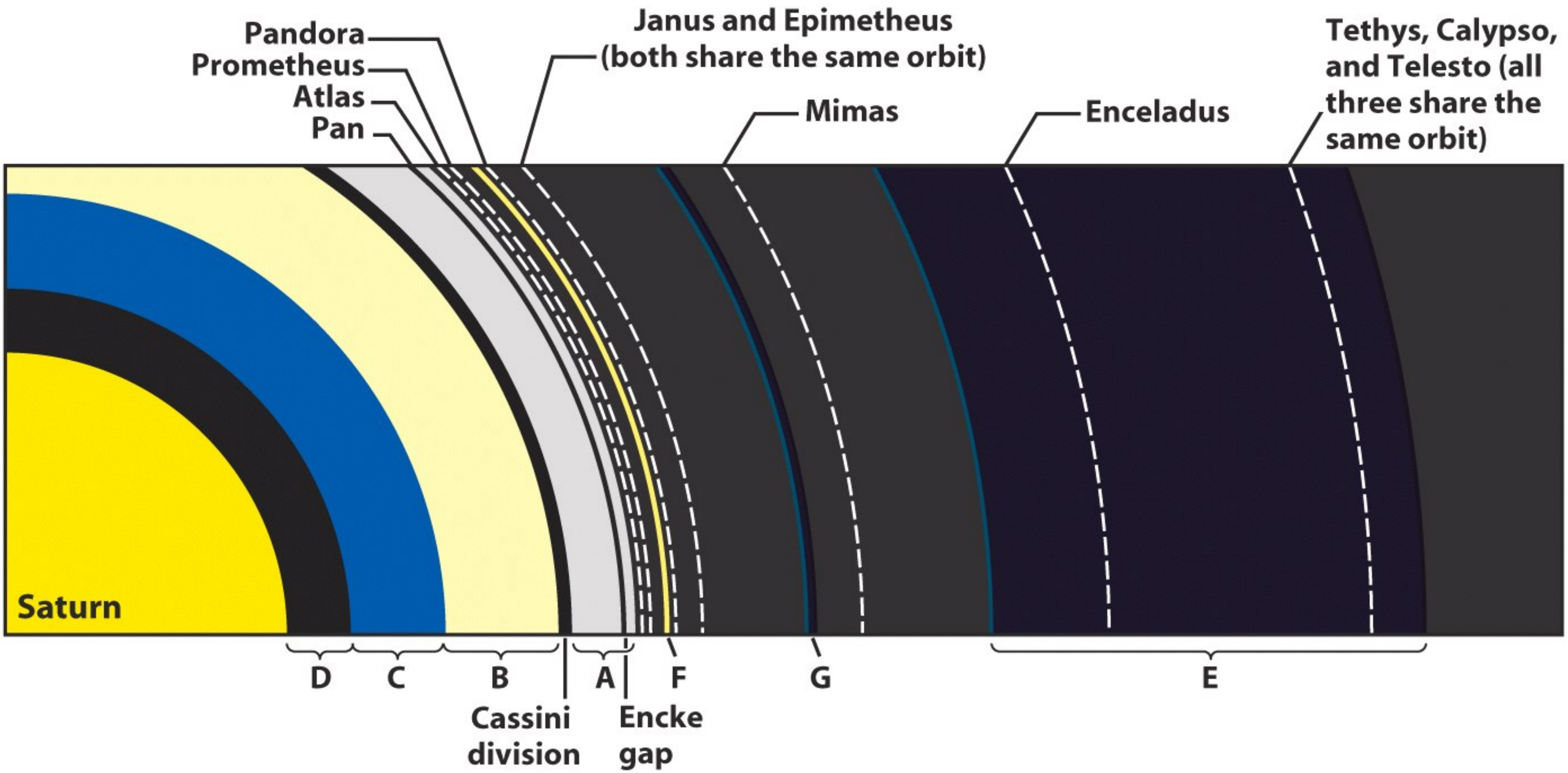
False color image from Voyager.

fine structures of Saturn's rings

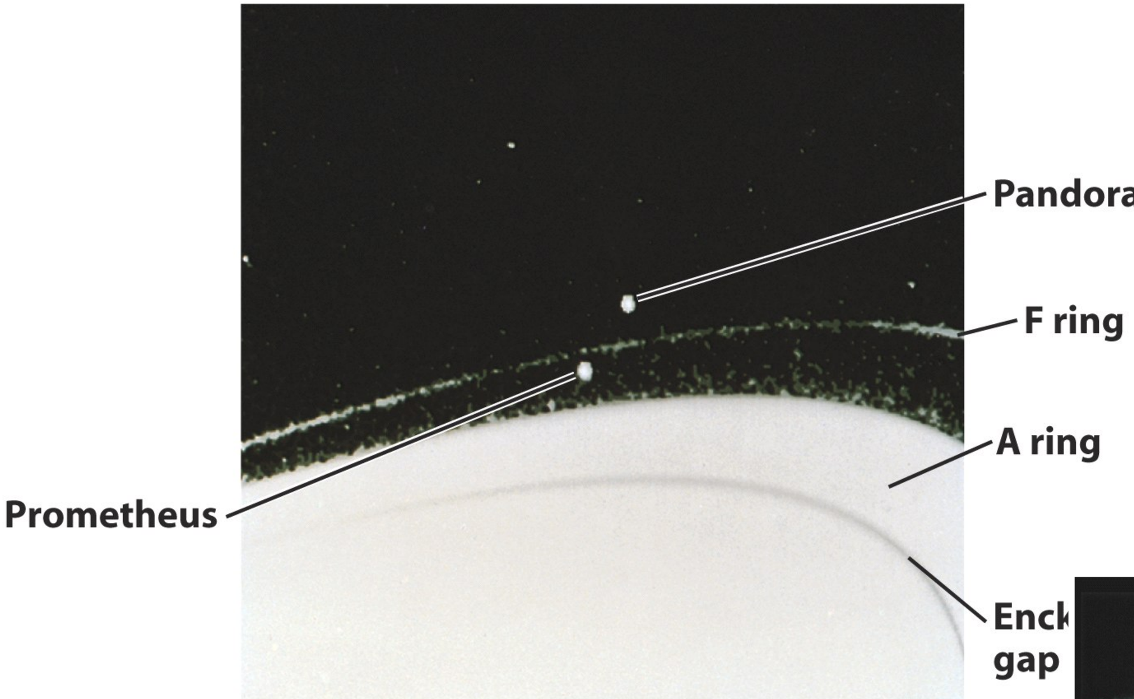


from Cassini Huygens. http://saturn.jpl.nasa.gov/home/index.cfm

Still more work by gravity: Saturn's inner satellites affect, by **gravitational force**, the appearance and structure of its rings.

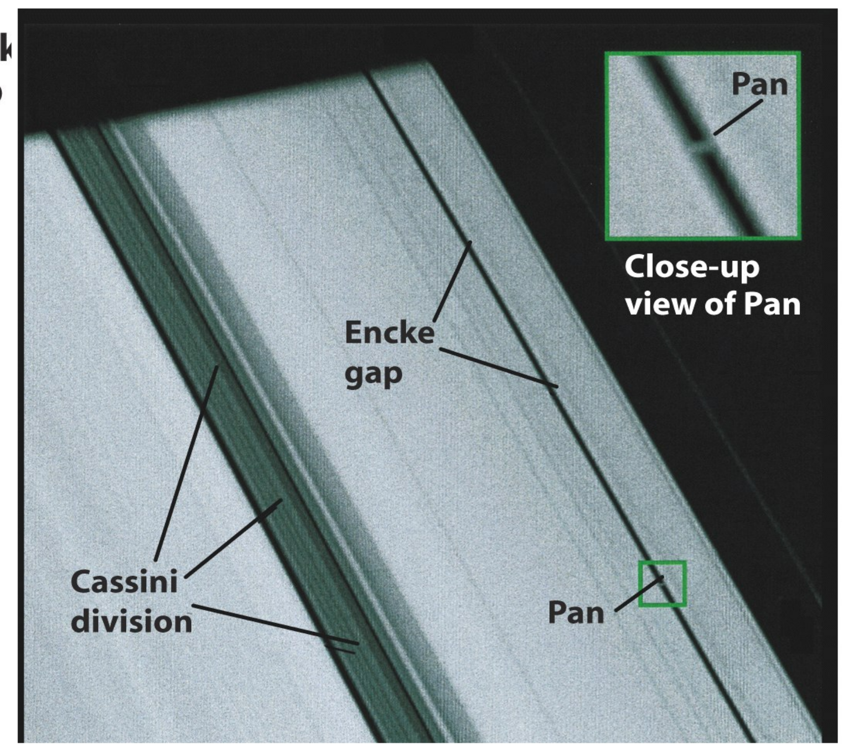


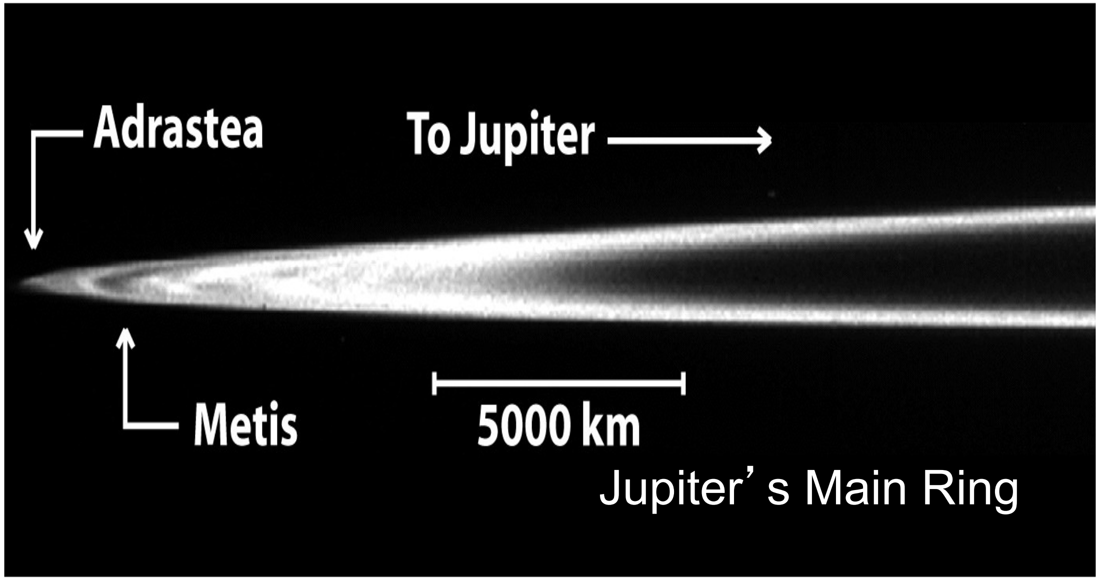
The arrangement of Saturn's rings



Formation of Saturn’s F ring by the two **shepherds** pushing particles into the F ring.

The Pan satellite pushes particles outside the Encke Gap.





Jupiter's Main Ring

Jupiter's faint rings are composed of a relatively small amount of small, dark, rocky particles that reflect very little light

Data from the Galileo spacecraft show that rings were created by **meteoroid impacts** on small nearby moons.

Credit: M. Belton (NOAO), J. Burns (Cornell) et al., Galileo Project, JPL, NASA


Solar eclipse by Jupiter seen by Galileo

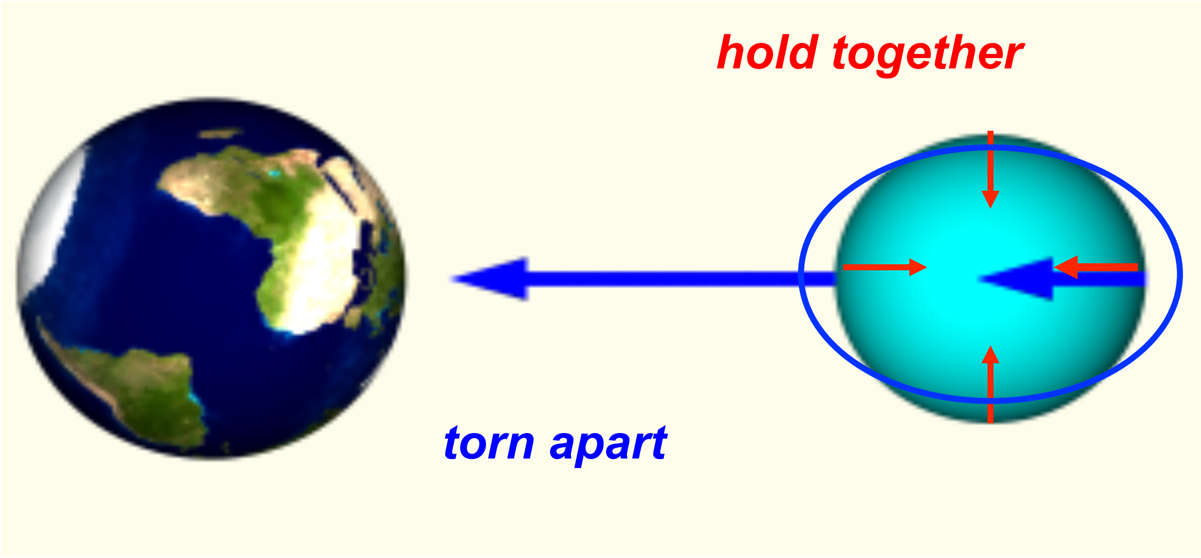
Small dust particles in Jupiter's atmosphere and the rings, can be seen by reflected sunlight.

Saturn's ring system is made of a great number of **ringlets** each consisting of **ring particles**, or highly reflective ice-coated rocks, orbiting around Saturn:

- inner rings revolve faster than outer rings, following Kepler's third law: $a^3 \sim P^2$
- Radio observations determine the size of ring particles to be 1 cm to 5 m.
- Rings have different compositions.
- There are ring particles in the gaps as well.
- Arrangements of rings by combined gravitational forces.

Ex.9: why rings exist as a collection of ring particles other than a whole piece of ring or a sizable satellite?

A whole piece of ring close to a planet would be torn apart by the **tidal force** winning over the **self-gravity** of the ring piece (or satellite). The critical distance is the **Roche limit**.



tidal force ~ $M_P R_S / d^3$

self-gravity ~ M_S / R_S^2

$\longrightarrow$ $d_R \sim R_P(\rho_P/\rho_S)^{1/3}$

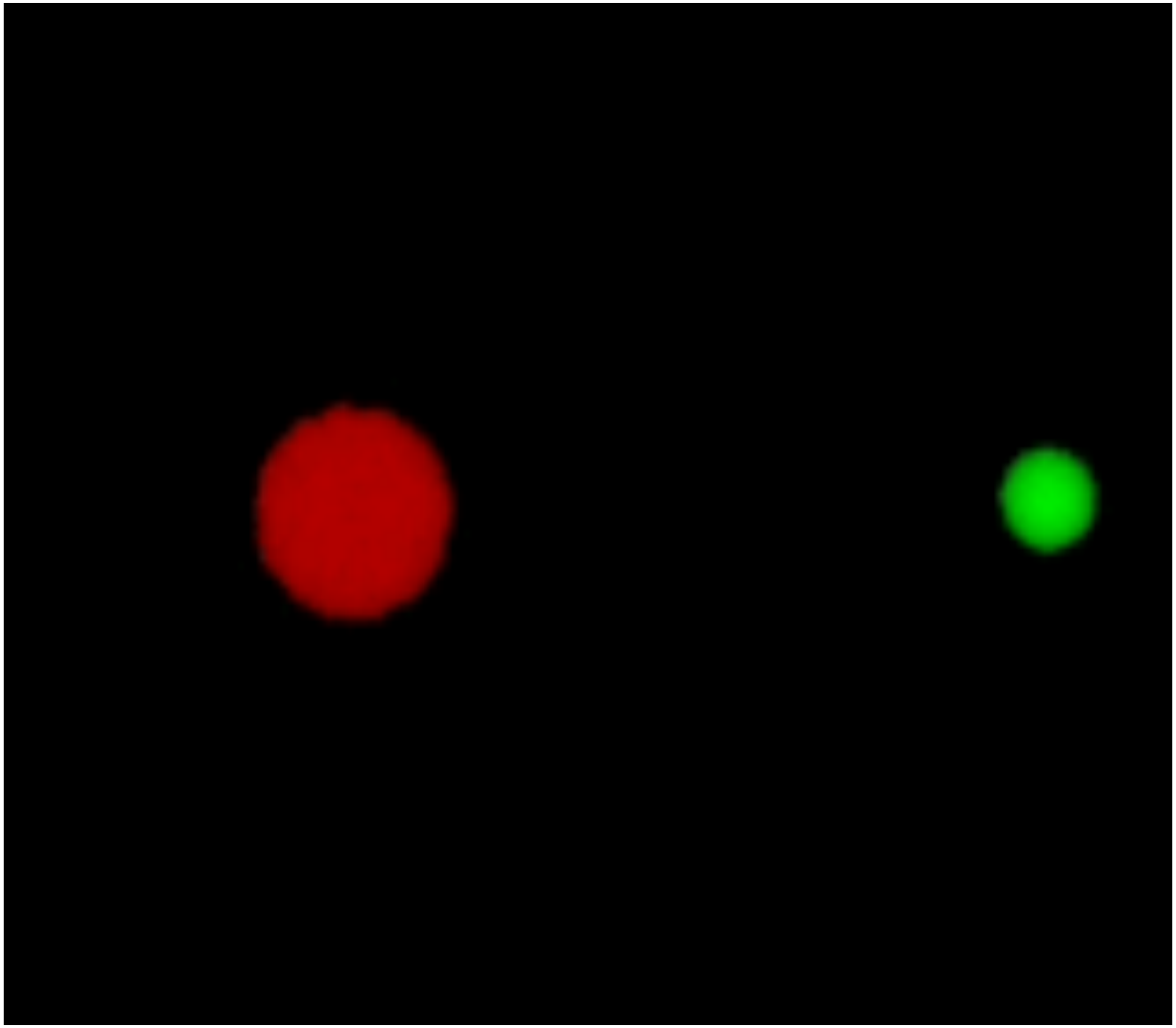
Roche limit depends on the gravity of the planet and satellite.

- The **Roche limit** is where the **tidal force** of a planet balances the **self-gravity** of a satellite orbiting the planet. Within the Roche limit, a satellite is torn apart.
- If a planet and a moon have identical densities, then the Roche limit is 2.446 times the radius of the planet.
- The Roche limits for some planets are:

  Earth - 18, 470 km
  Jupiter - 175,000 km
  Saturn - 147,000 km
  Uranus - 62,000 km
  Neptune - 59,000 km

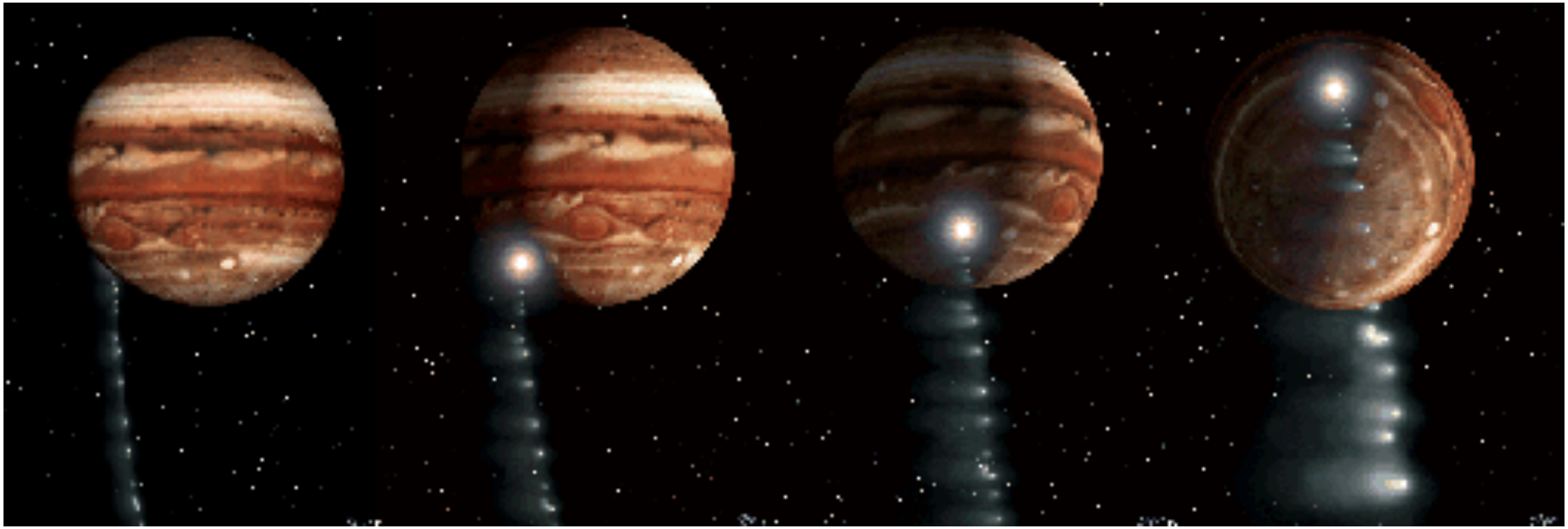
- The Roche limit for the Sun is about 0.01 AU.

Roche limit: the point of no return



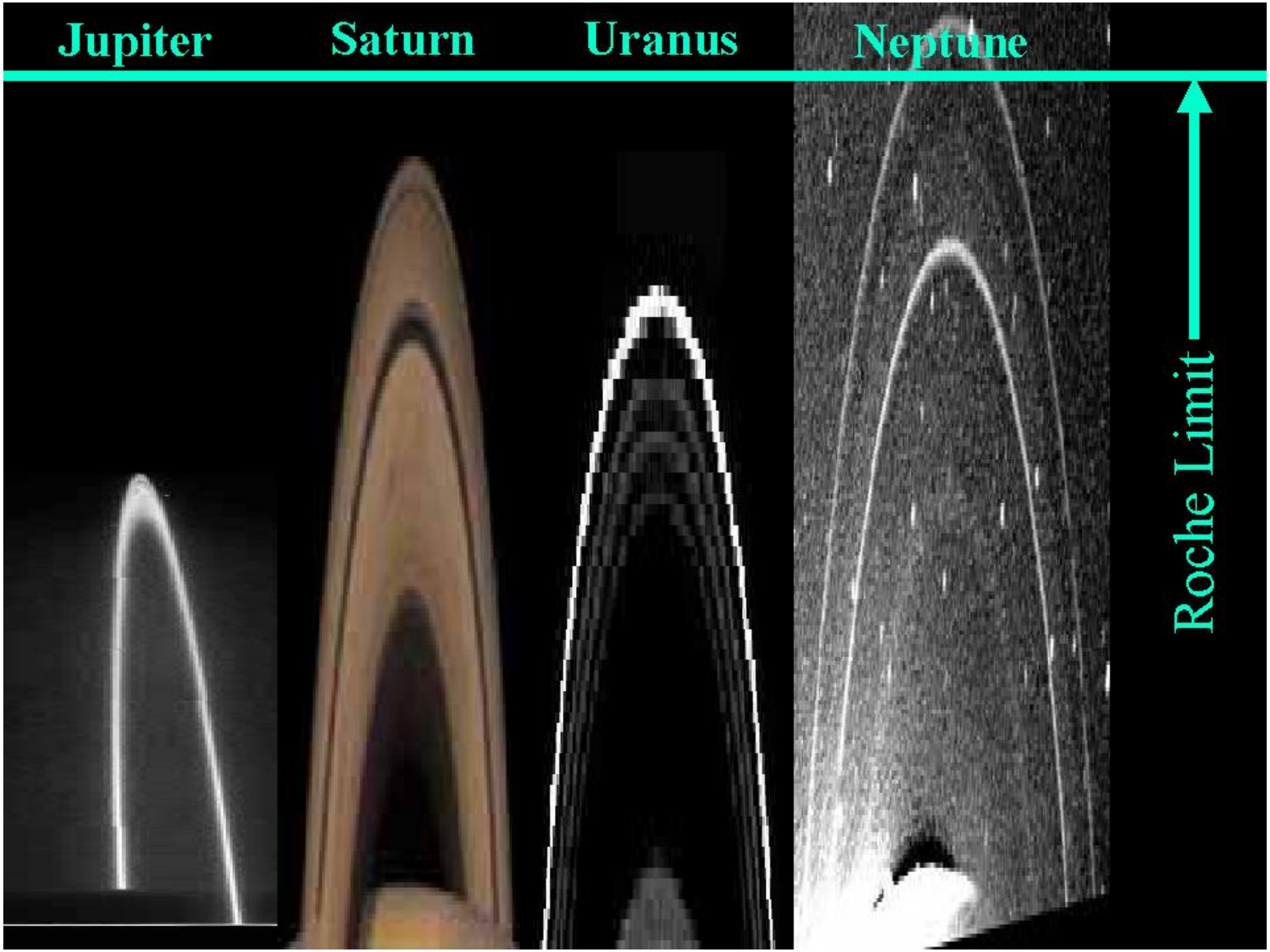
http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/moonsandrings.htm

Ex.10: On July 7, 1992, Comet Shoemaker-Levy 9 broke apart in 21 pieces due to tidal forces when it made a close approach of Jupiter which was within the Roche limit.



Find all interesting images at http://www2.jpl.nasa.gov/sl9/sl9.html

Rings in the solar system within the Roche limit



Tidal force (differential gravitational force) accounts for many phenomena in the solar system.

The tidal force by a planet mass M on the unit mass at two edges of a satellite of radius R and distance d.

$$f_{tidal} = G\frac{4MR}{d^3}$$

Ex 12: examples of tidal force effect in the solar system.

- tides on earth; tidal bulges of planets and moons;
- synchronous rotation of many moons in the solar system
- 3-to-2 spin-to-orbit coupling of Mercury's motion
- future of Moon and Triton
- tidal heating of Jovian moons
- Roche limit and Jovian rings

Summary of Jovian planets

- Far away from the Sun, they are cold.
- Large amounts of light elements aggregating, they are massive.
- Being massive and cold, they retain atmosphere of H and He.
- Being massive, they have significant internal heat and radiate more energy than received from the Sun.
- The large internal heat drives atmosphere dynamics.
- Being massive, they contain metallic hydrogen or mineral water to produce global magnetic fields.
- Radio observations reveal gyro-synchrotron radiation by plasmas trapped by and spiraling around the magnetic field.
- Being massive, dust particles within the Roche limit form rings.

Key Words

- belts
- brown oval
- Cassini division
- differential rotation
- Encke gap
- Great Red Spot
- liquid metallic hydrogen
- magnetic axis
- nonthermal radiation
- oblate, oblateness
- plasma
- ring particles, ringlets
- Roche limit
- shepherd satellite
- synchrotron radiation
- tidal force
- white oval, brown oval
- zones