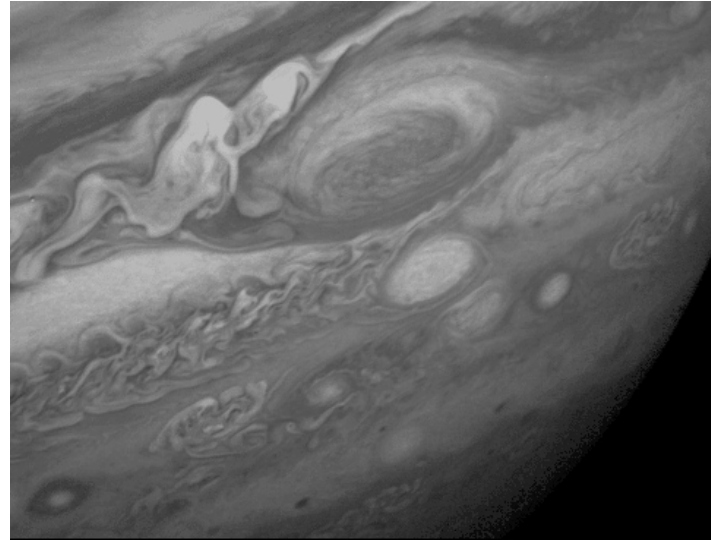


Lecture 11:

The Giant (or Jovian) Planets



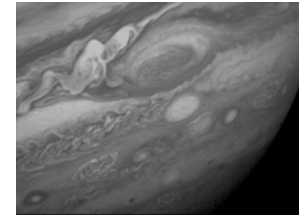
Jupiter's Great Red Spot

Claire Max
November 2, 2010
Astro 18: Planets and Planetary Systems
UC Santa Cruz

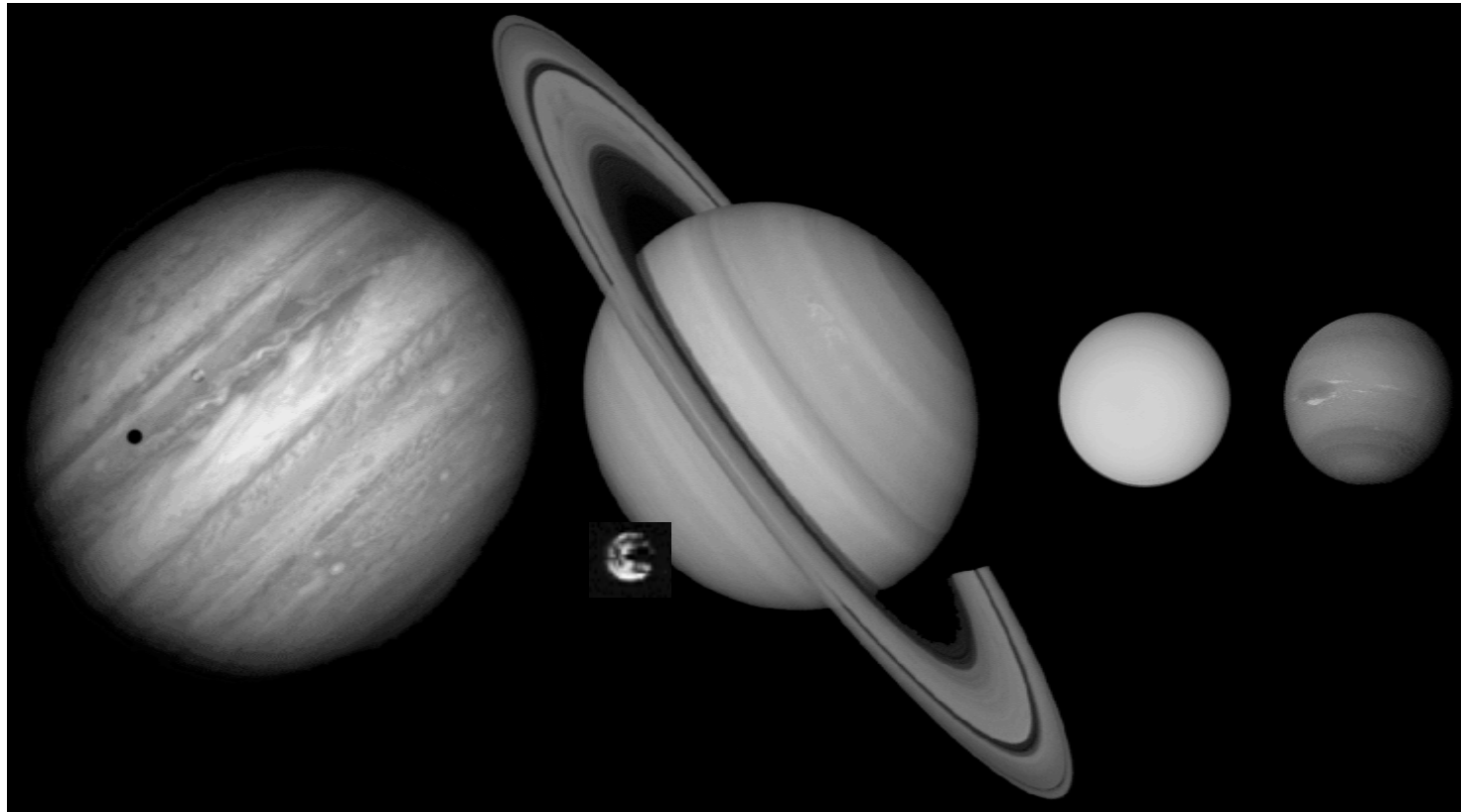
Public lecture on finding earth-like planets with the Kepler spacecraft

- **Wednesday, Nov. 17th, 2010, at 7 pm**
- **Astronomer Natalie Batalha from San Jose State University**
- **Catching Shadows: Kepler's Search for New Worlds**
- **Smithwick Theater, Foothill College, El Monte Road and Freeway 280, in Los Altos Hills, California.**
- **Parking on campus costs \$2. Call 650-949-7888 for more information and driving directions.**

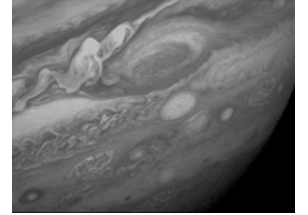
The Giant Planets in our own Solar System



- **Jupiter, Saturn, Uranus, Neptune**
(and Earth for comparison)

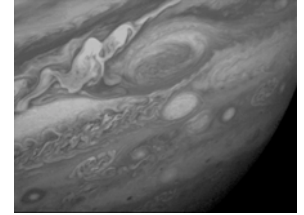


Outline of lecture



- **Jovian Planets:**
 - **Properties**
 - **Formation**
 - **Interior structure**
 - **Atmospheres**

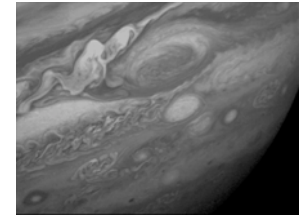
The Jovian Worlds: A Different Kind of Planet



Goals for learning:

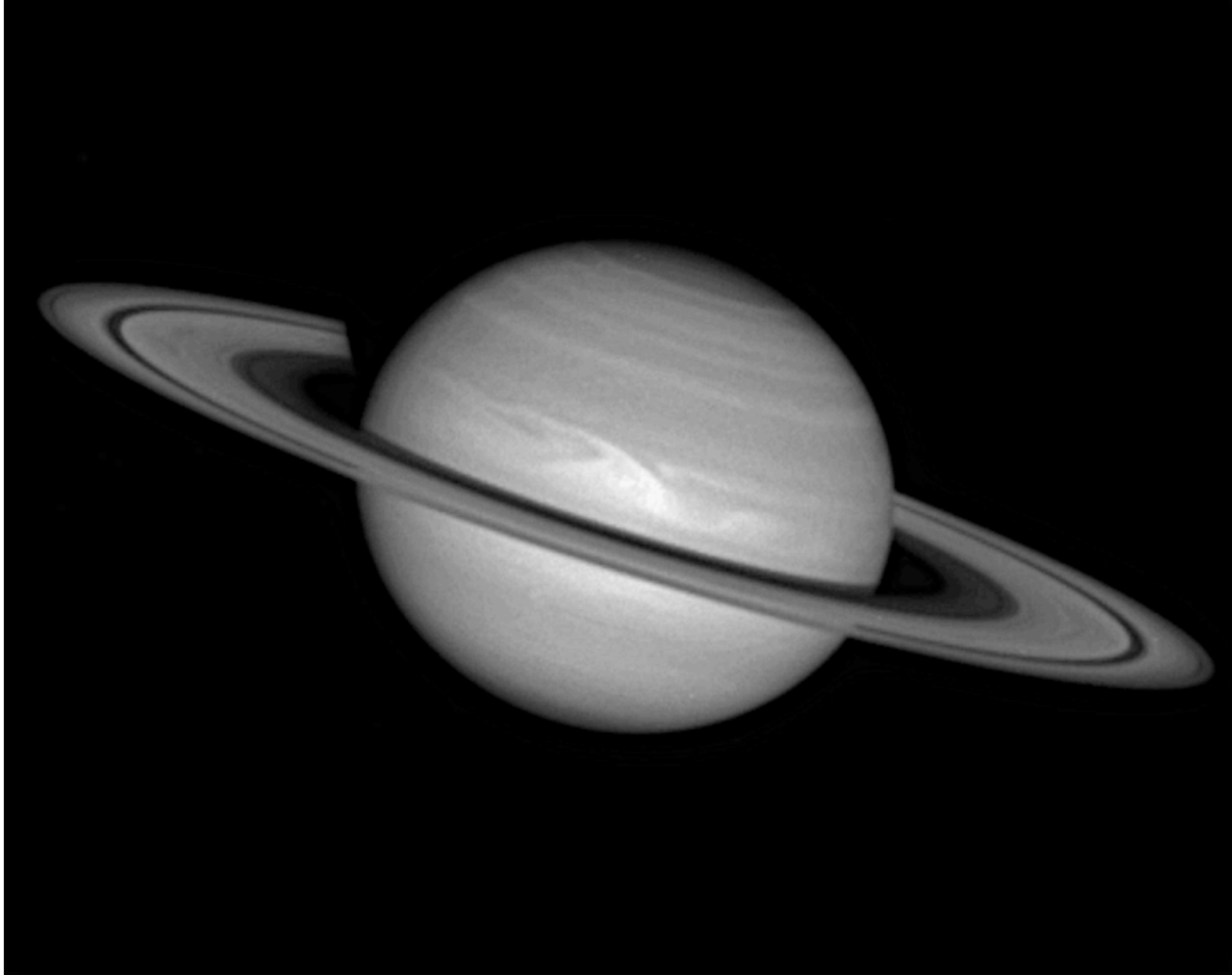
- **Briefly describe the major features of the Jovian planets.**
- **Why are Jovian planets so different from terrestrial planets?**

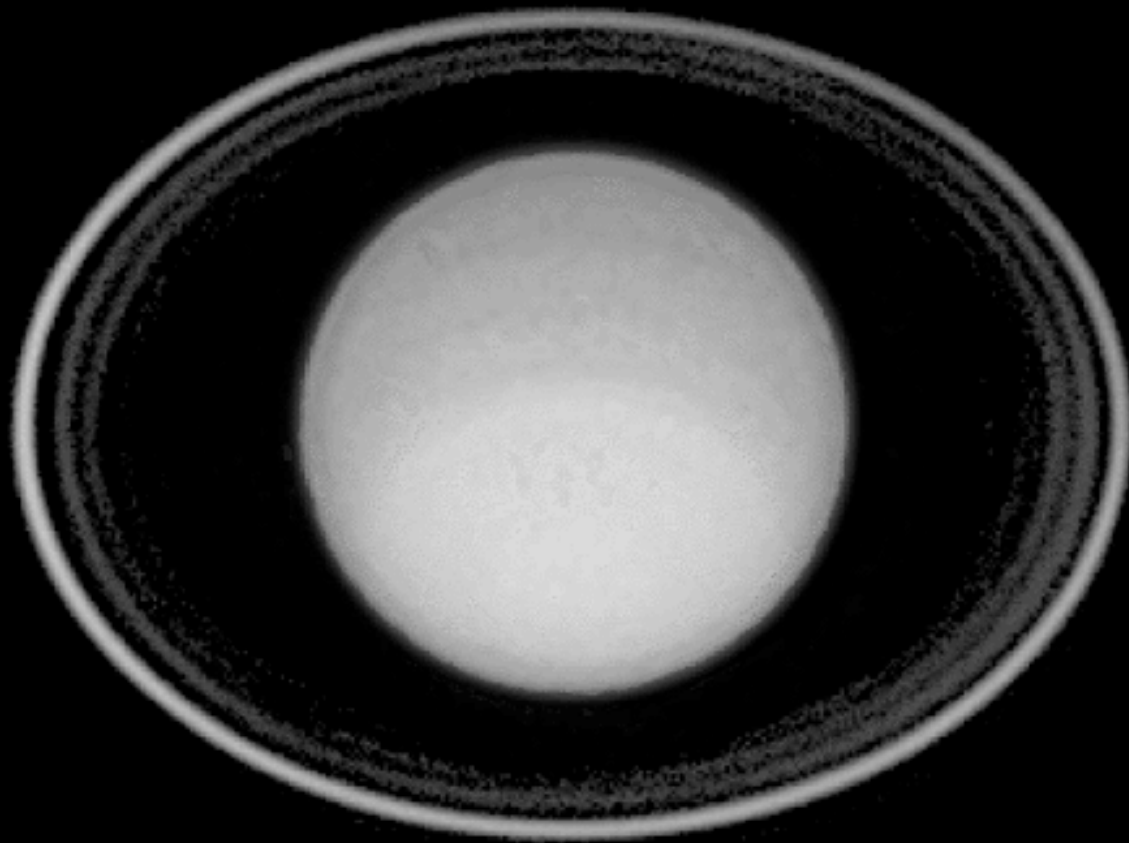
Jovian Planet Properties



- **Compared to the terrestrial planets, the Jovians:**
 - are much larger & more massive
 - are composed mostly of Hydrogen, Helium, & Hydrogen compounds
 - have no solid surfaces
 - rotate more quickly
 - have slightly “squashed” shapes
 - have ring systems
 - have many moons







Uranus

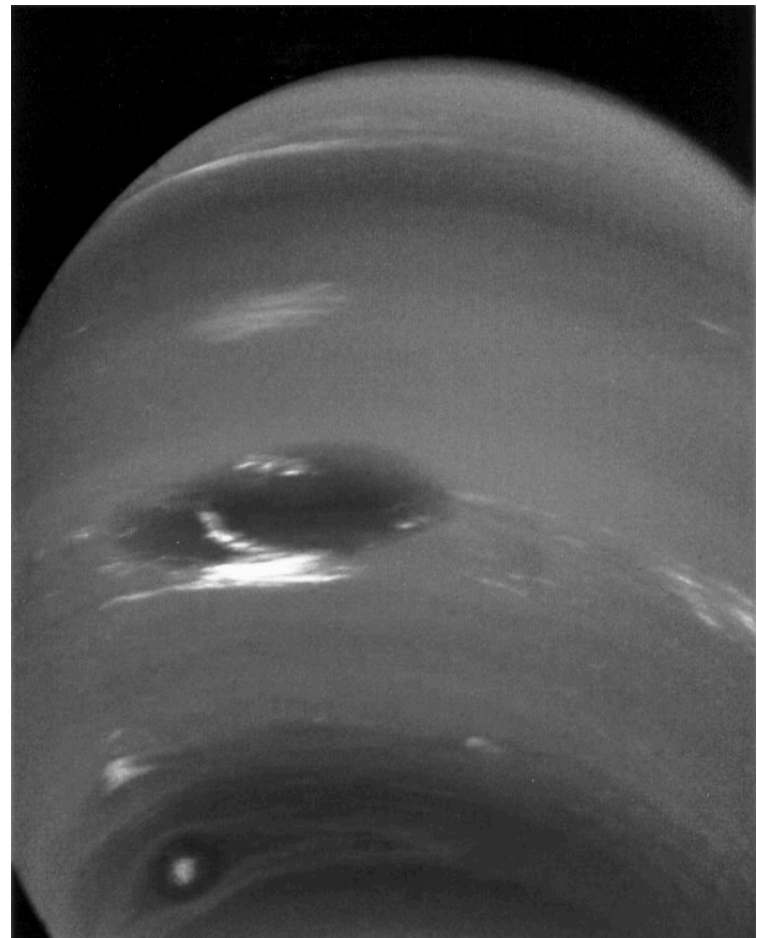
PRC96-15 · ST ScI OPO · April 24, 1996

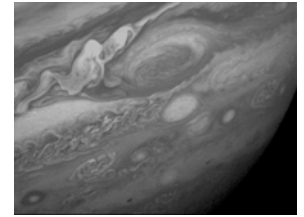
Erich Karkoschka (University of Arizona Lunar & Planetary Lab) and NASA

HST · WFPC2

Neptune

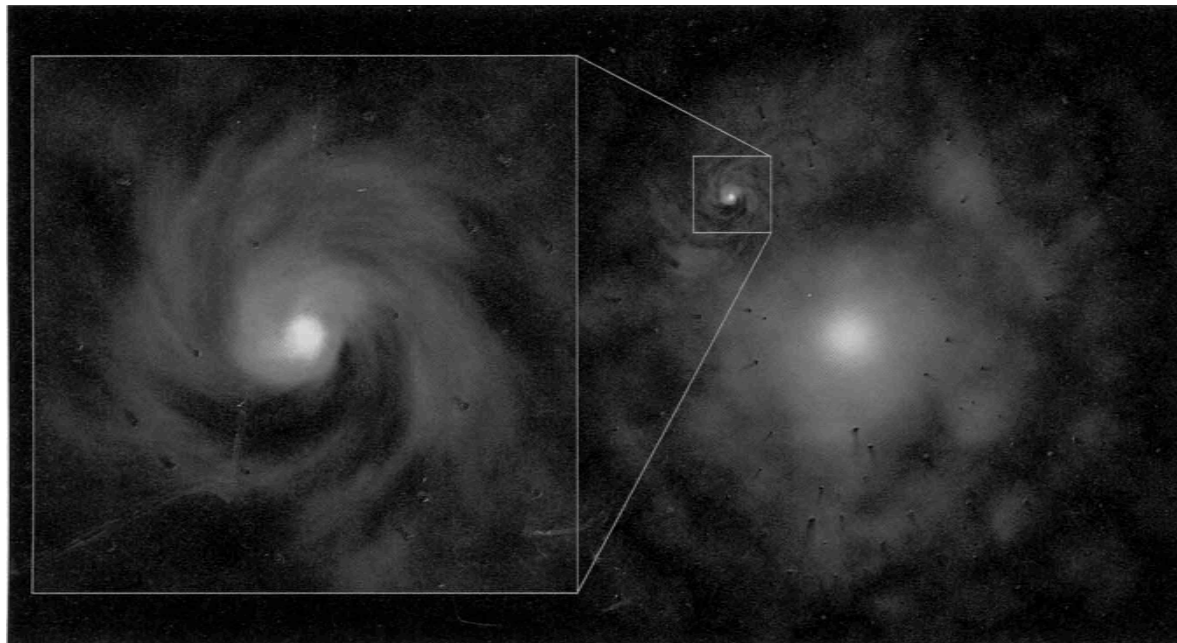
17x Earth



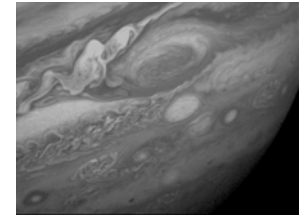


Why are the Jovian Planets so Different?

- **They formed beyond the frost line to form large, icy planetesimals which were massive enough to...**
 - **Capture H/He far from Sun to form gaseous planets.**
 - **Each Jovian planet formed its own “miniature” solar nebula.**
 - **Moons formed out of these disks.**

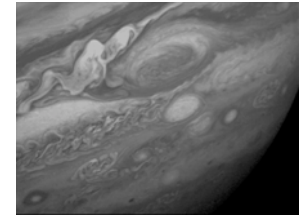


What are the distinguishing features of the Giant Planets?

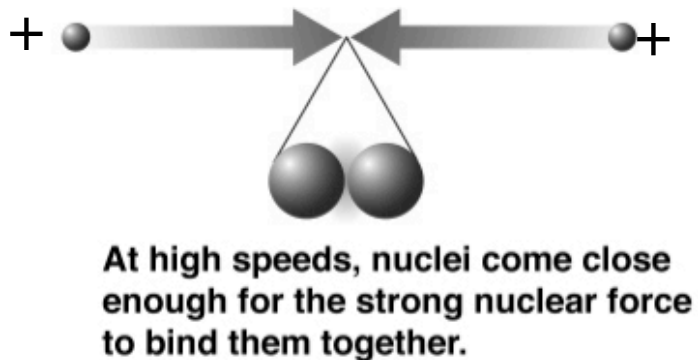
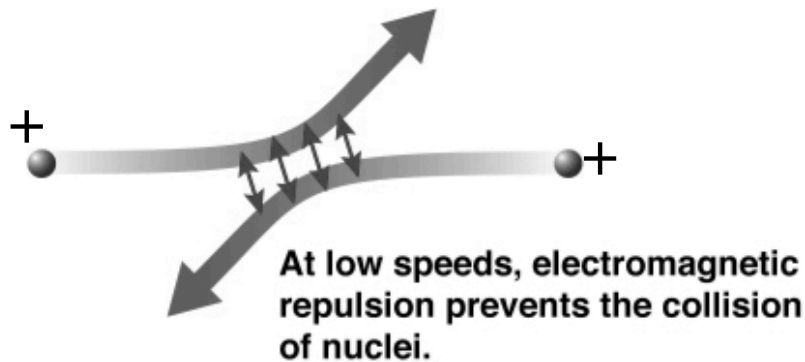


- **Big puffy gas balls!**
 - No solid surface, in contrast with terrestrial planets
- **Mostly hydrogen and helium**
 - Terrestrial planets are made of rocks - little H and He
 - Because of small mass, low gravity, of terrestrial planets, light elements like H, He escaped to space
- **Giant Planets are farther from Sun**
 - Beyond the “ice line” in the early Solar System
 - Water and other hydrogen compounds were solid
 - Allowed higher-mass objects to form by accretion

Difference between a Giant Planet and a star?

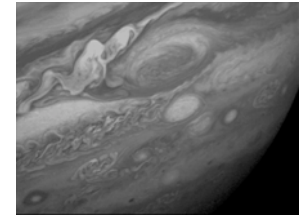


- **Stars get their heat from nuclear fusion**
 - Four hydrogen atoms fuse to form a helium atom



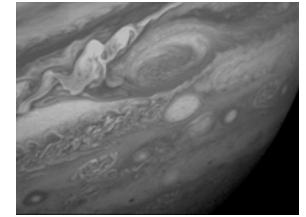
- To make hydrogen atoms move fast, need high temperatures in core of star
- The more massive a ball of gas is, the hotter its core
- Don't get any fusion for masses $< 13 - 14 M_{\text{Jupiter}}$

More about stars and fusion energy



- **Giant Planets ($M < 13 M_j$): no nuclear fusion energy**
 - Not enough mass lying over core to create high temperatures in center
- **Stars: how does nuclear fusion release energy?**
- **Einstein explained it all!**
 - Helium is a bit less than four times as heavy as hydrogen
 - Difference in mass: $\Delta m = 4m_H - m_{He}$
 - By Einstein's famous rule, mass difference is released as energy: $E = \Delta m c^2$
- **This “mass energy” keeps to core of a star hot, until it has “fused” all its hydrogen**

Distances of Giant Planets from Sun



• **Earth** **1 AU**

• **Jupiter** **5.2 AU**

Five times farther from Sun

• **Saturn** **9.5 AU**

• **Uranus** **19 AU**

• **Neptune** **30 AU**

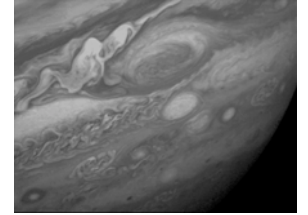
30 times farther from Sun!

Jovian Planet Composition

- **Jupiter and Saturn**
 - **Mostly H and He gas**

- **Uranus and Neptune**
 - **Mostly hydrogen compounds: water (H₂O), methane (CH₄), ammonia (NH₃)**
 - **Some H, He, and rock**

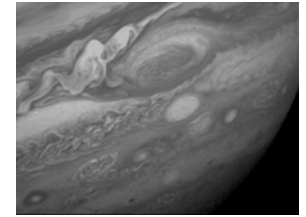
Jovian Planet Interiors



Goals for learning:

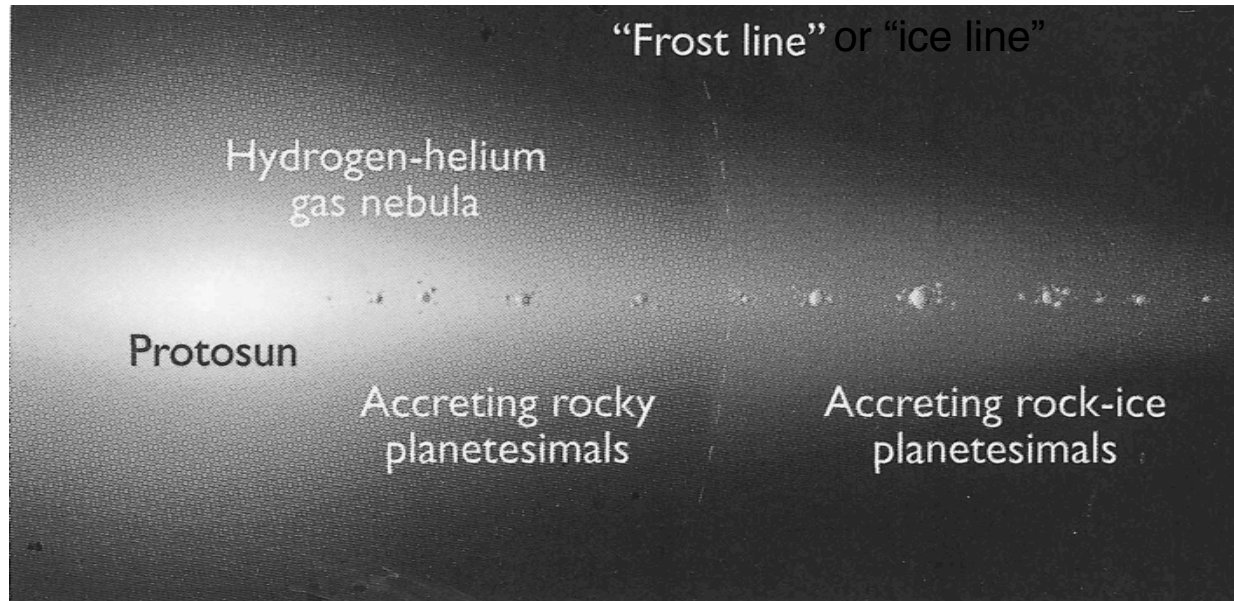
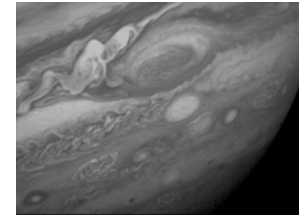
- **Briefly describe the interior structure of Jupiter.**
- **Why is Saturn almost as big in radius as Jupiter?**
- **How do the Jovian planet interiors differ, and why?**

Interiors: qualitative description

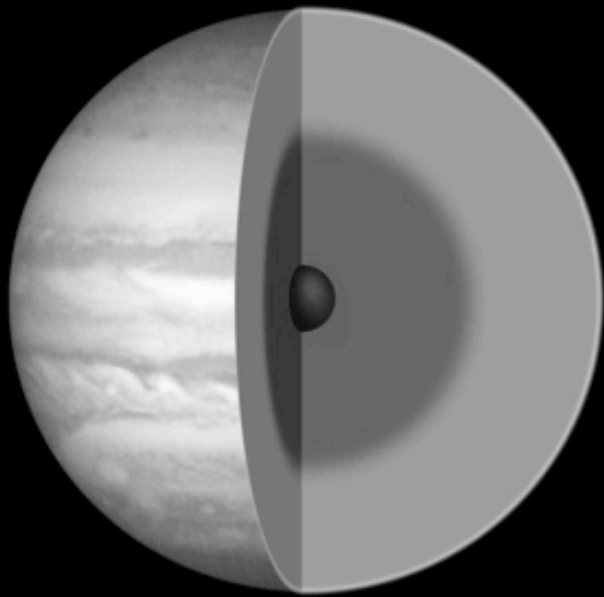


- **Mostly gases plus the odd forms of matter that are made when gases are put under high pressure**
 - **Liquid hydrogen, metallic hydrogen**
- **It is probable (but not completely proven yet) that all the Giant Planets have rocky cores at their centers**
 - **Accretion of matter to make planets started with these rocky cores, then added ices**

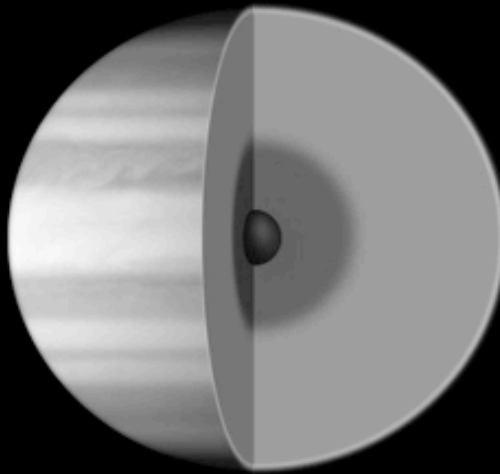
Giant planets were farther from early Sun than the “ice line” or “frost line”



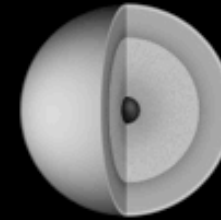
- **Best estimate: “frost line” was between current orbits of Mars and Jupiter**
- **Outside “frost line”: rocky cores could attract icy solid material fast enough that planets were already quite massive before early solar wind blew gas nebula away**



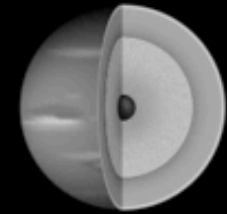
JUPITER



SATURN



URANUS



NEPTUNE

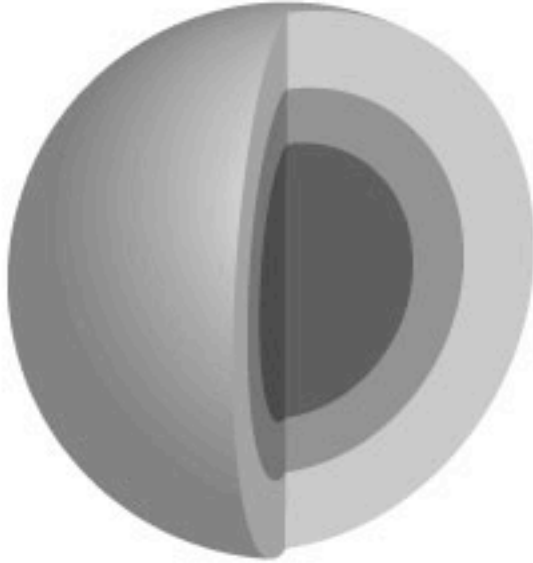


EARTH

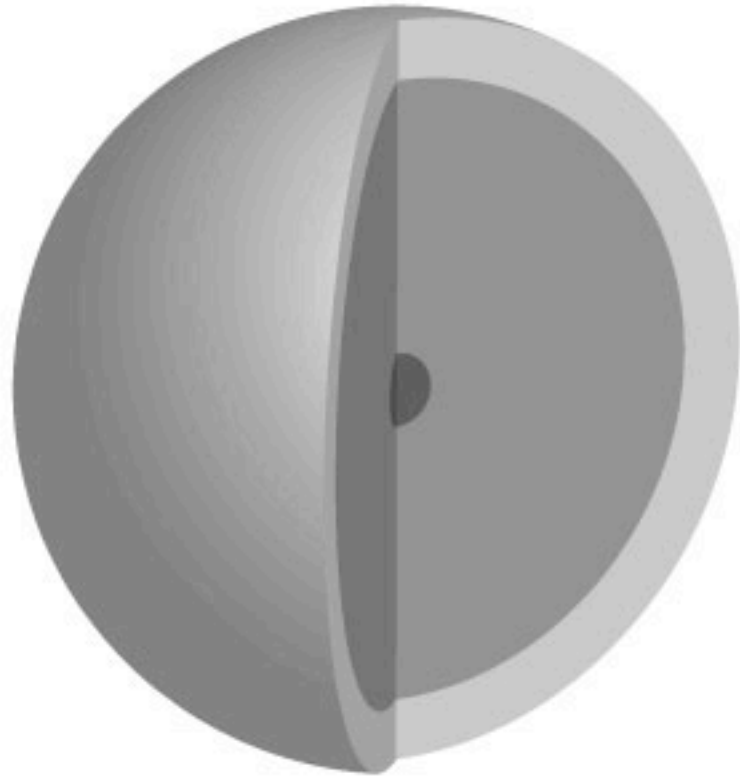
- Molecular hydrogen
- Metallic hydrogen

- Hydrogen, helium, methane gas
- Mantle (water, ammonia, methane ices)
- Core (rock, ice)

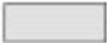


An unusually dense
extrasolar planet



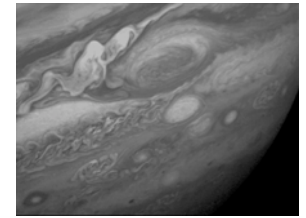
HD 149026 b



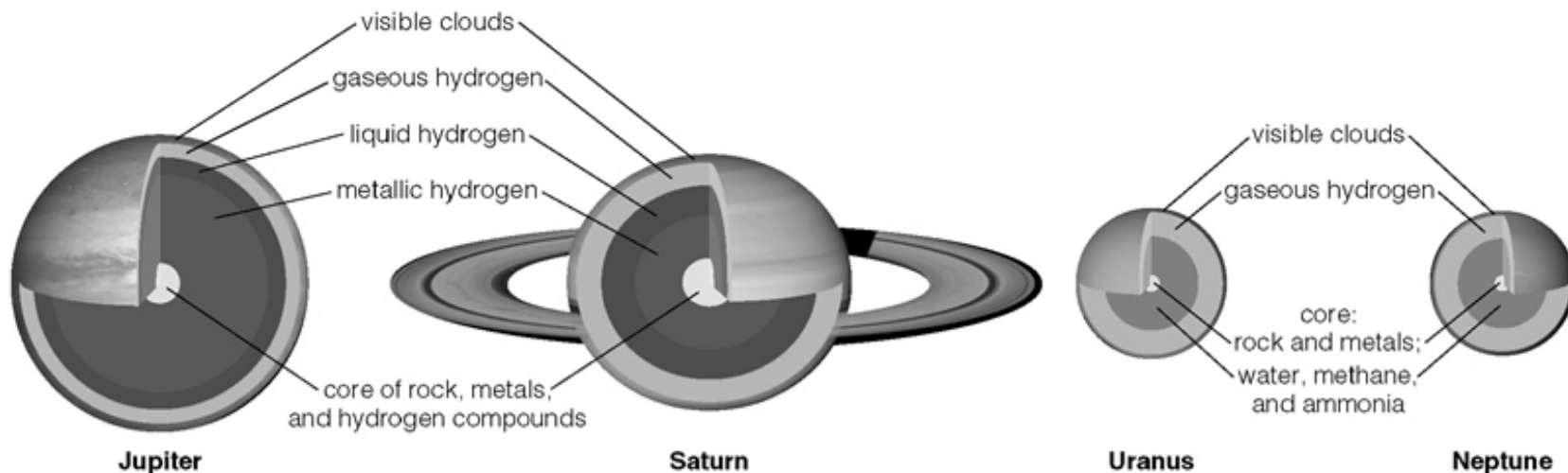
Jupiter

-  hydrogen and helium gas
-  liquid metallic hydrogen
-  heavy element core

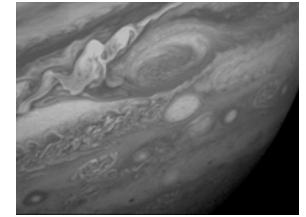
Inside the Jovian Planets



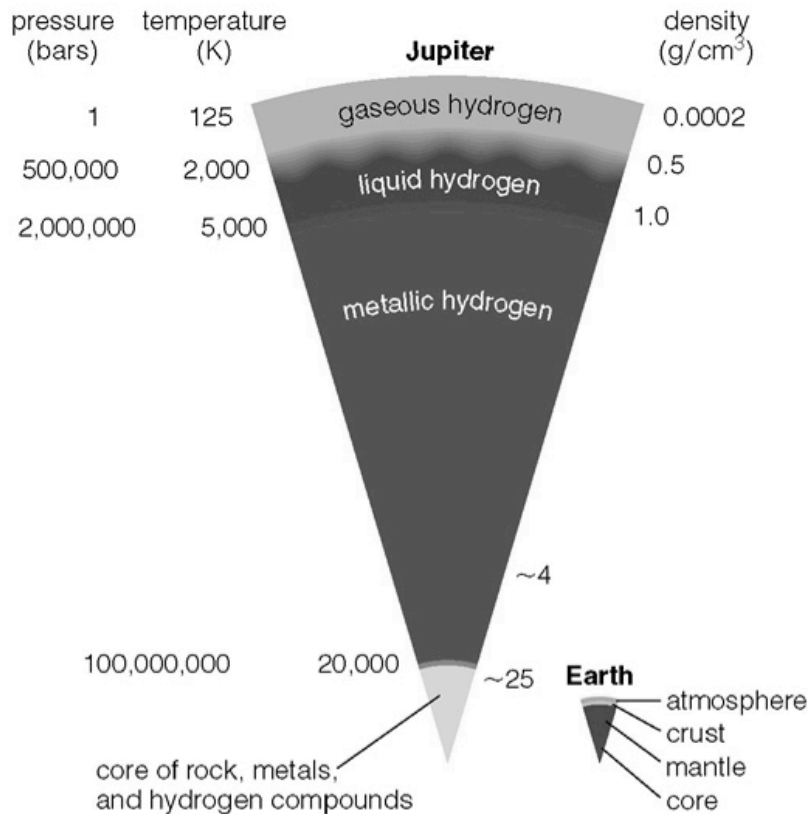
- **All Jovian cores appear to be similar.**
 - made of rock, metal, and Hydrogen compounds
 - about 10 x the mass of Earth
- **Uranus & Neptune captured less gas from the Solar nebula.**
 - accretion of planetesimals took longer
 - not much time for gas capture before nebula was cleared out by Solar wind
- **Only Jupiter and Saturn have high enough pressure for H & He to exist in liquid and metallic states.**



Inside Jupiter

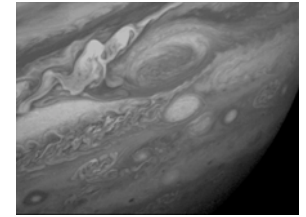


Although Jupiter has no solid surface and consists mostly of H & He, it does have distinct interior layers, defined by *phase*.



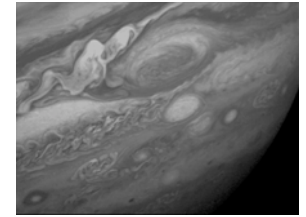
- **Moving from the surface to the core:**
 - temperature increases
 - pressure & density increases
- **The core of Jupiter is slightly larger than Earth in size.**
- **But it is 5 times as dense!**
 - thank to tremendous weight from above
- **So Jupiter's core has 10 times the mass of Earth.**

More about Jupiter's core



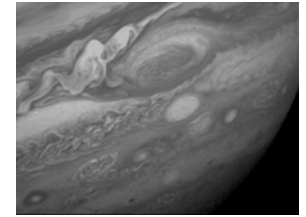
- **“Liquid metallic hydrogen”**: a very unusual state of matter (“degenerate”).
- **Predicted many years ago**
 - **Jupiter’s core has temperature of 25,000 K and pressure of 12 million bars -- 12 million times as large as sea level pressure on the Earth**
- **Such a state for hydrogen has now been reproduced in labs on Earth.**

How do we know this?

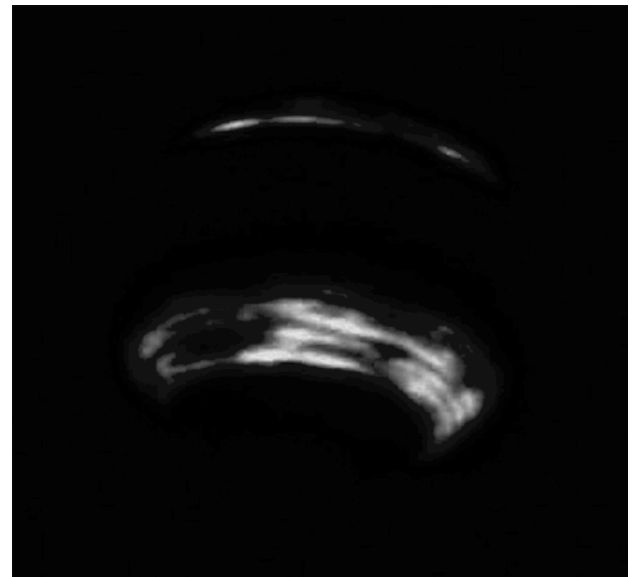
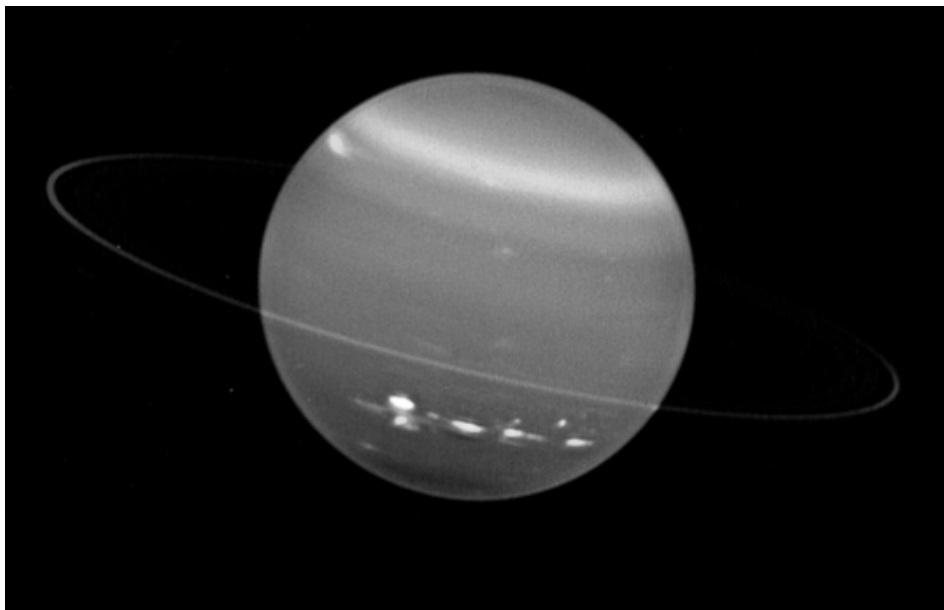
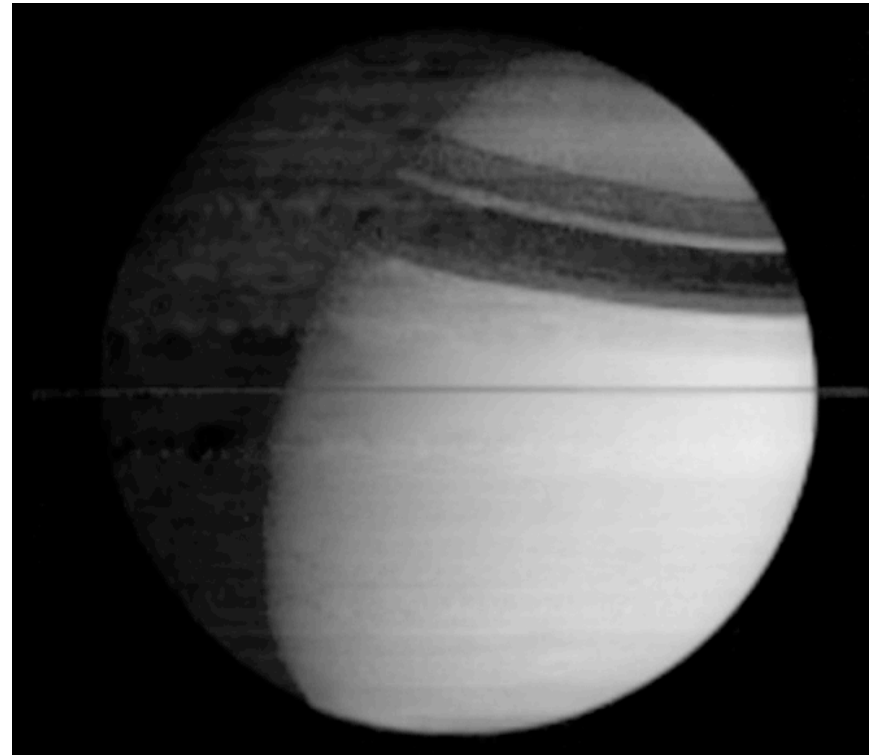
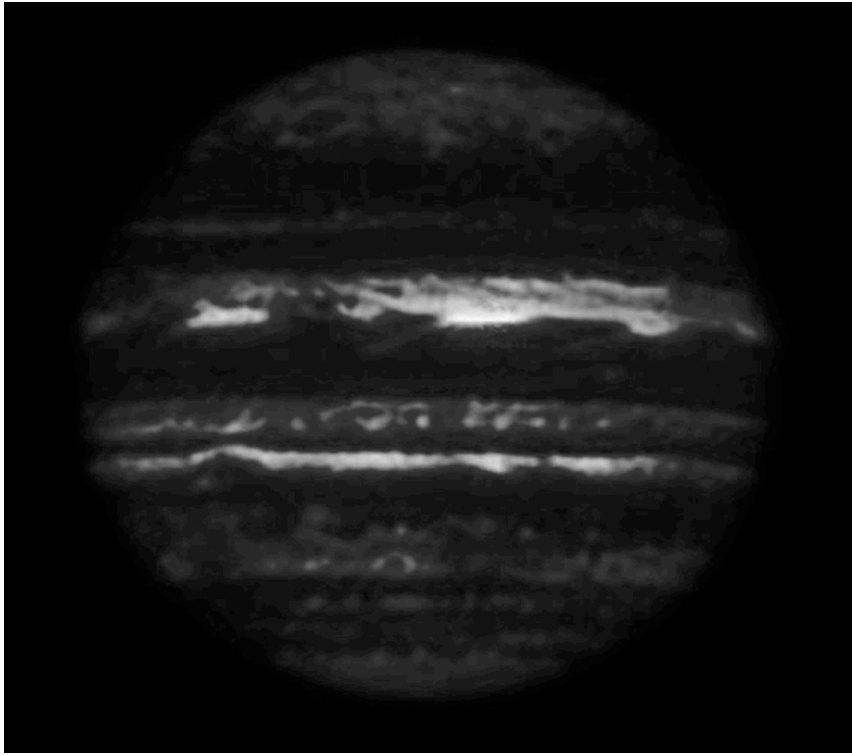


- **Density ---> made of primarily light stuff ---> hydrogen and helium**
 - Jupiter: density 1.3 gm/cc
 - Saturn: density 0.7gm/cc
- **Magnetic fields ---> yes; all jovians have strong magnetic fields ---> molten, electrically conducting interiors**
- **Nonspherical shapes (flattening due to rapid rotation) ---> interior structure ---> rocky cores 5-20 x mass of the Earth (both Jupiter and Saturn)**

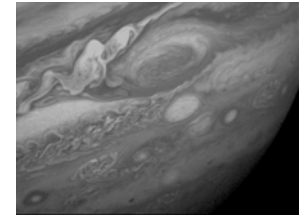
Liquid metallic hydrogen?



- **Liquid hydrogen: if you poured it into a cup, it would assume the shape of the cup, but would not spread out throughout the entire volume (as would a gas).**
- **Metallic hydrogen: will conduct electricity.**
- **Fact that this layer can flow and can conduct electricity means that Jupiter and Saturn can support large internal electrical currents and should thus show large magnetic fields.**

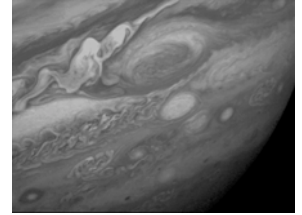


All the Giant Planets except Uranus are generating some of their own heat



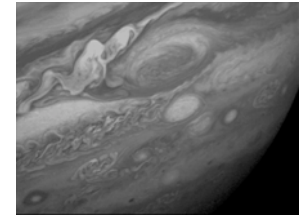
- **Jupiter, Saturn, Neptune radiate more energy into space in infrared light than they receive from Sun in visible light**
- **Reason: they are still contracting under their own gravity!**
 - **Planet contracts or gets more centrally condensed**
 - **Material in core is squeezed, feels more pressure**
 - **Temperature of core increases**
 - **Additional heat conduction to outer parts of planet, stronger infrared radiation to space**

Internal heat, continued

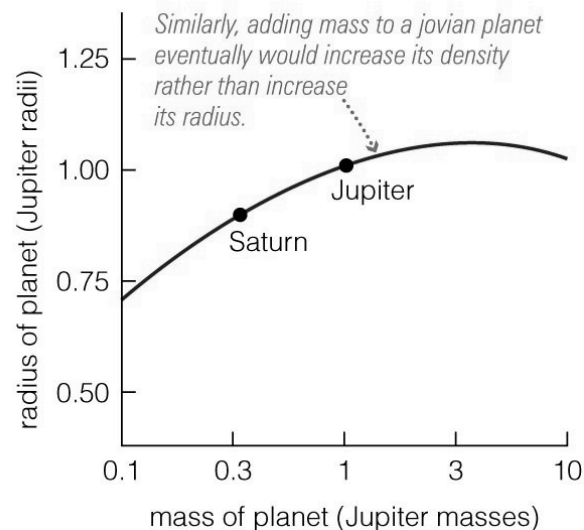
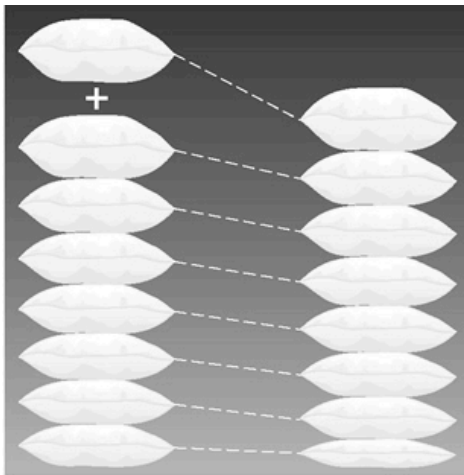


- **Another way to think about gravitational contraction making heat**
 - **Planet contracts**
 - **Decreases its gravitational potential energy – GmM/r**
 - **Total energy = kinetic energy – $GmM / r = \text{constant}$**
 - **So kinetic energy must increase**
 - **Particles in core move faster (random motions)**
 - **Means their temperature is higher**

Radii of Jupiter and Saturn

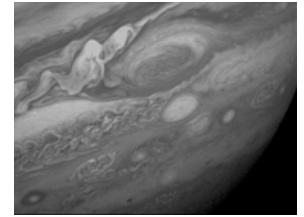


- **Jupiter emits almost twice as much energy as it absorbs from the Sun.**
 - **accretion, differentiation, radioactivity can not account for it**
 - **Jupiter must still be contracting**
- **Jupiter has 3 x more mass than Saturn, but is not much larger!**
 - **the added weight of H & He compresses the core to a higher density**
 - **just like stacking pillows**

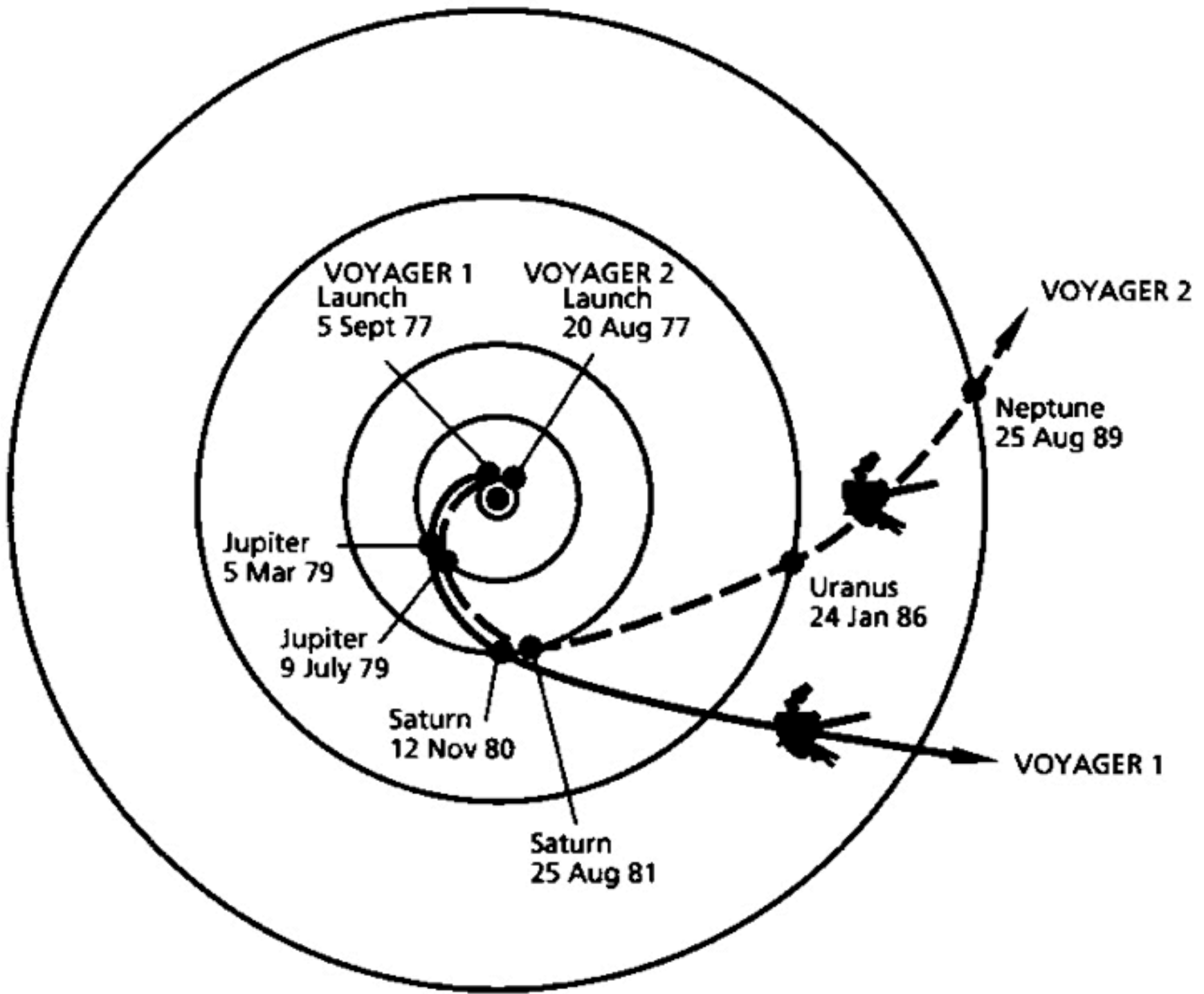


- **If you added even more mass, Jupiter would get smaller.**
- **Jupiter is about as large as a planet can get.**

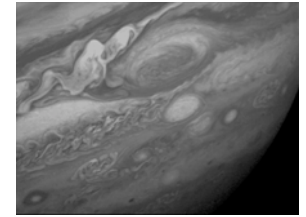
Very important spacecraft



- **Voyager 1 and 2 (1980's)**
 - Flew by Jupiter, Saturn, Uranus, Neptune
 - First close-up views of all these planets
- **Galileo (recently ended mission)**
 - In orbit around Jupiter for several years
 - Also sent a probe into Jupiter's atmosphere
- **Cassini (in orbit around Saturn now, but passed by Jupiter)**



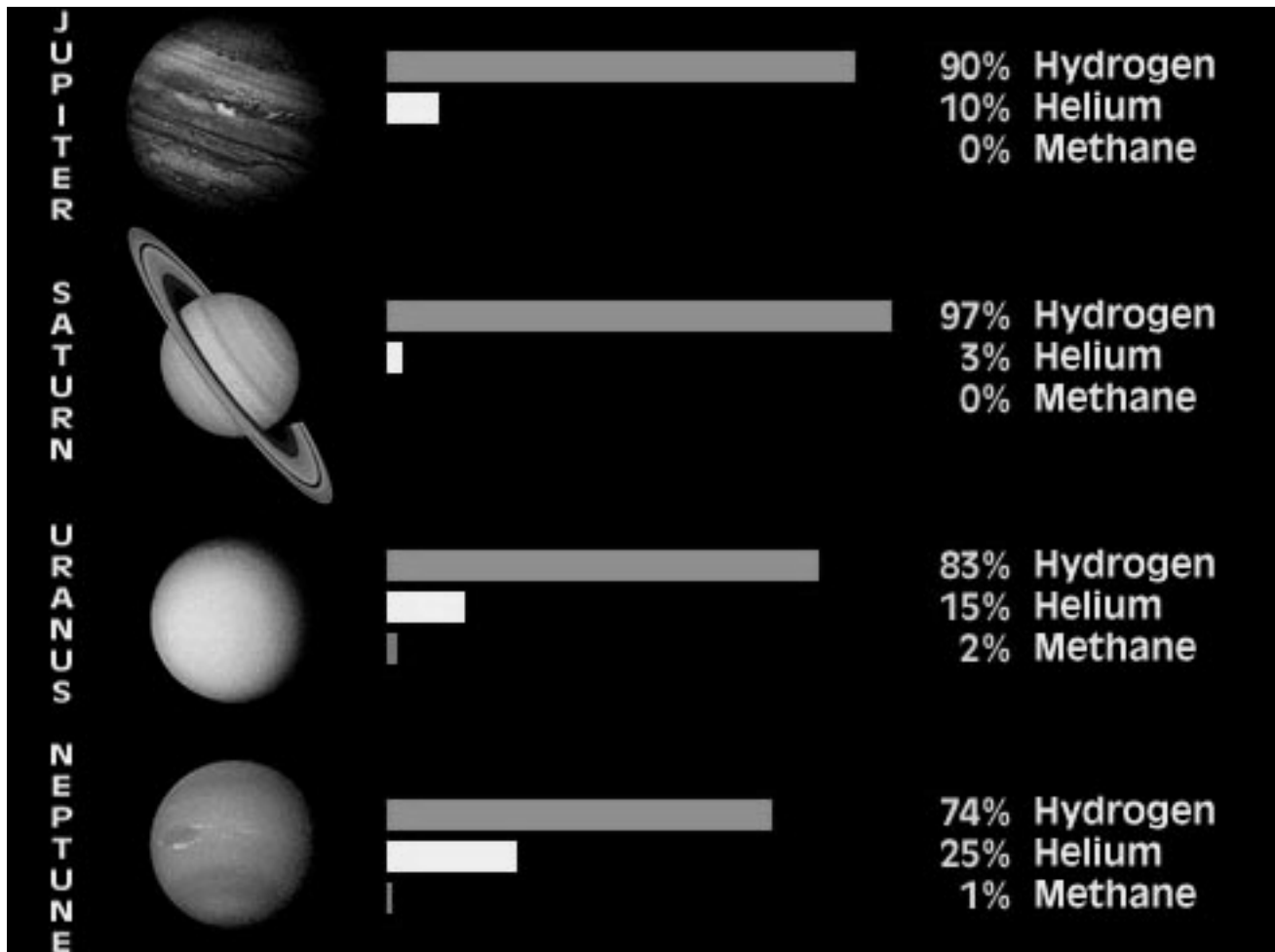
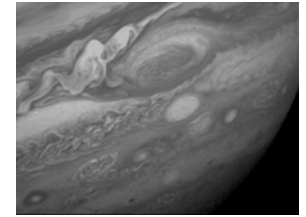
Jovian Planet Atmospheres



Goals for learning:

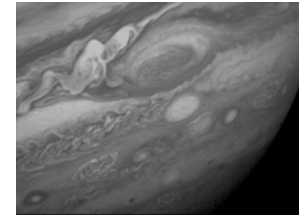
- **How is Jupiter's atmospheric structure similar to Earth's?**
- **Why does Jupiter have three distinct cloud layers?**
- **What is the Great Red Spot?**
- **How do other Jovian atmospheres compare to Jupiter's?**

Composition of atmospheres: mostly hydrogen and helium

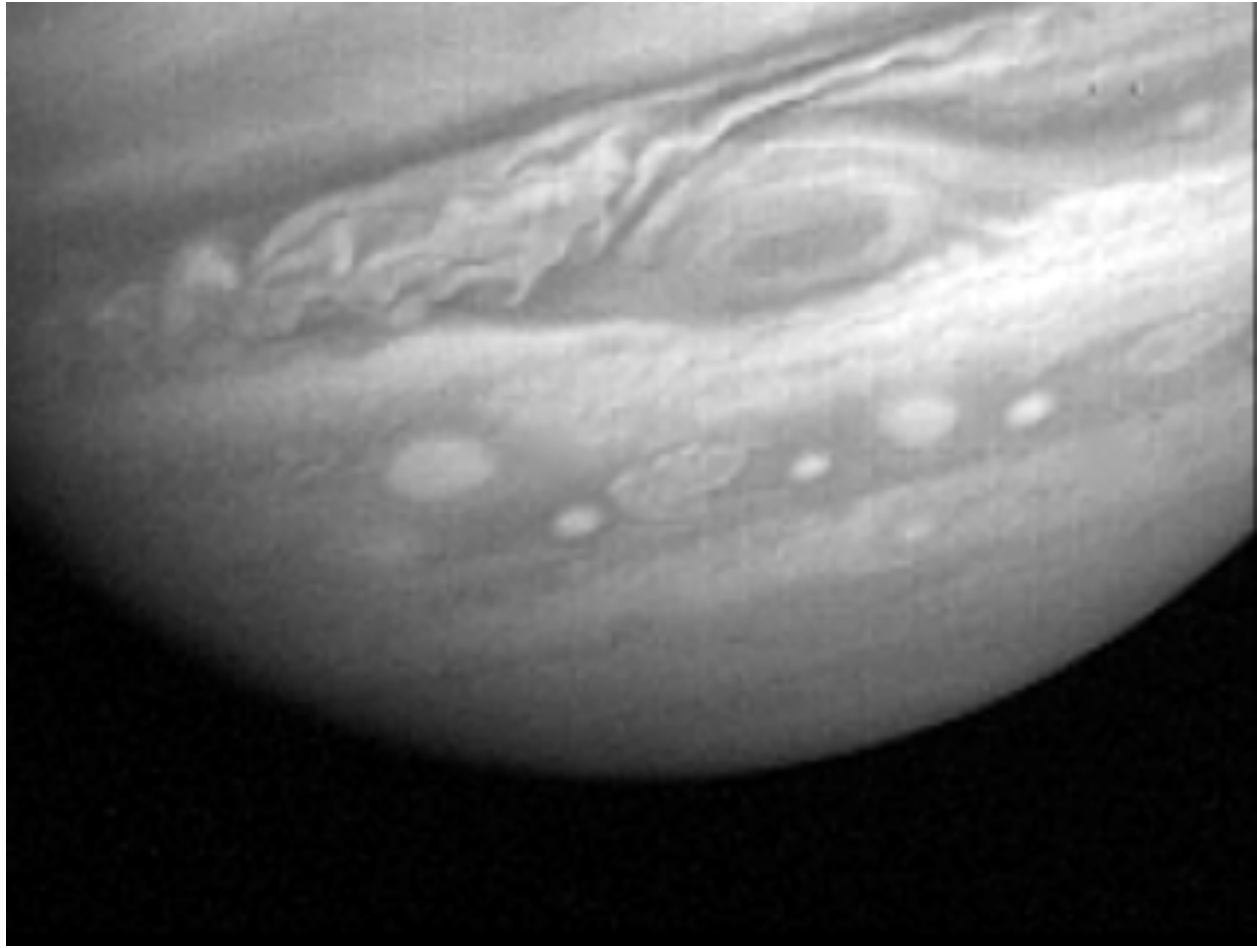


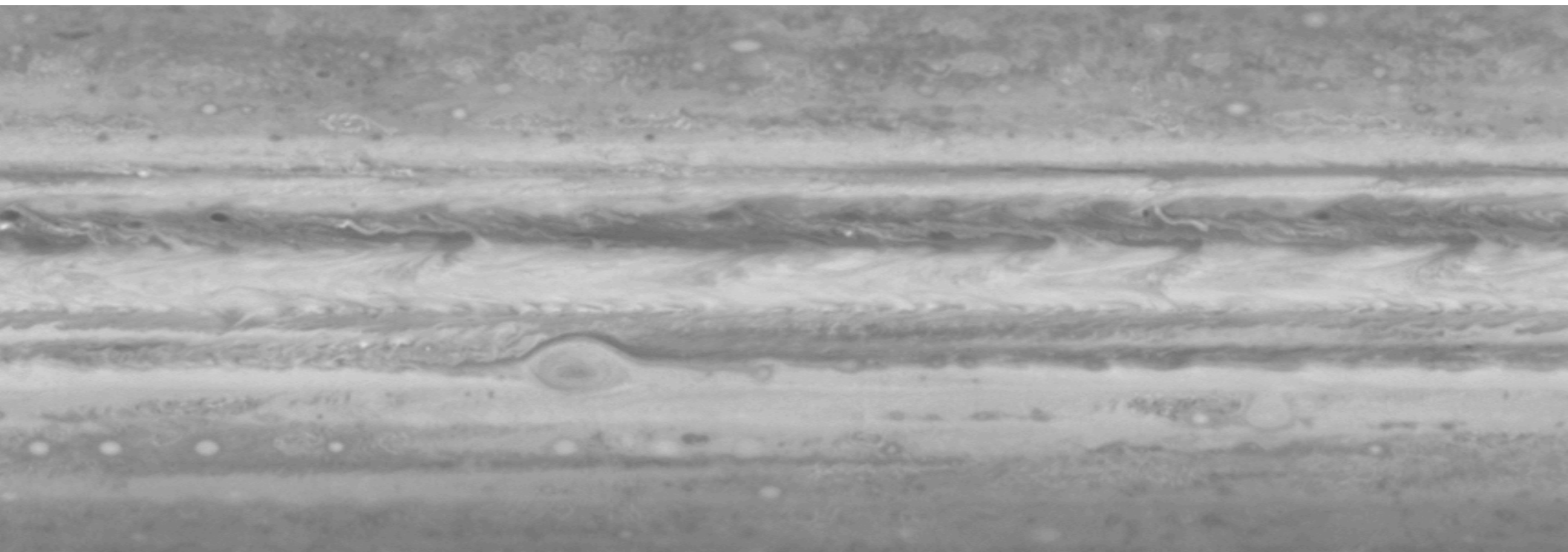
- **Giant planets are massive enough that light elements (H, He) didn't entirely escape to space (as on Earth)**
- **This is very similar to the Solar composition!**

Atmospheres of the Giant Planets



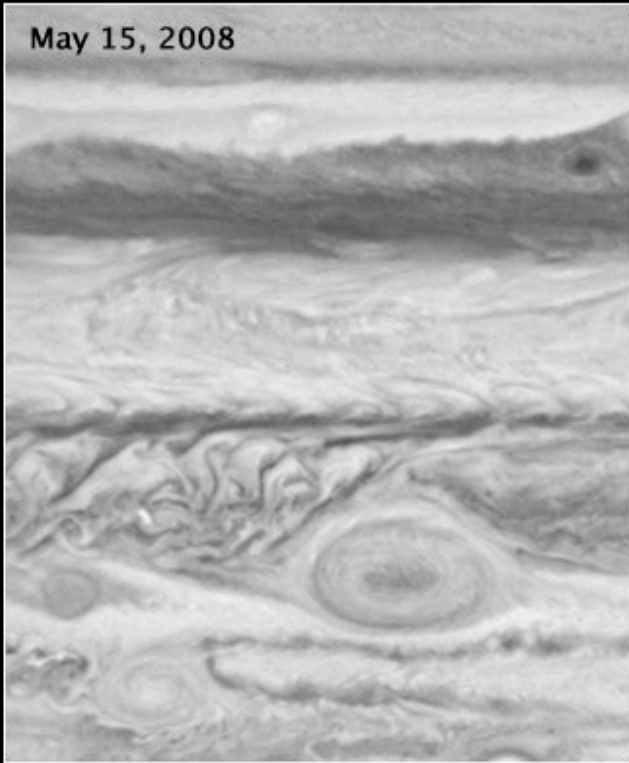
- **Dominated by hydrogen and helium gases**
 - Thus very different from terrestrial planets
 - Earth's atmosphere mostly nitrogen
- **Clouds form out of this gaseous soup in a variety of striking colors**
- **Cloud patterns are organized by winds, which get their energy from the planets' internal heat**
 - By contrast, terrestrial planets' weather is determined by heat from the Sun



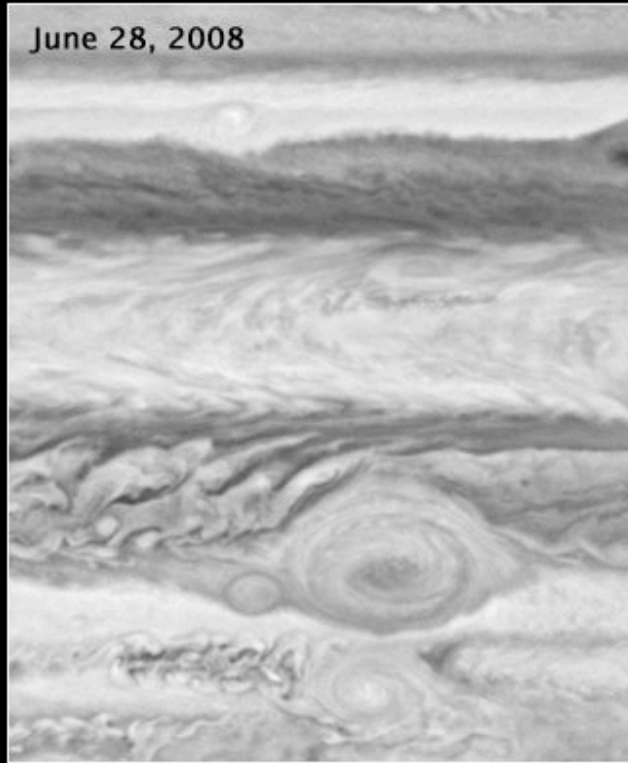


Jupiter's Red Spots ■ *Hubble Space Telescope* WFPC2

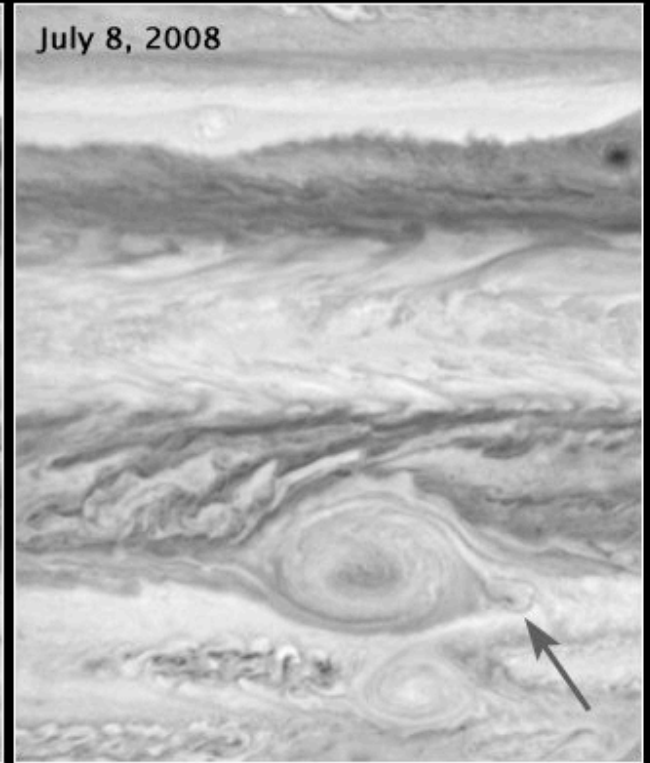
May 15, 2008



June 28, 2008

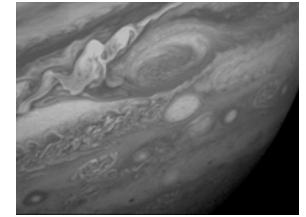


July 8, 2008

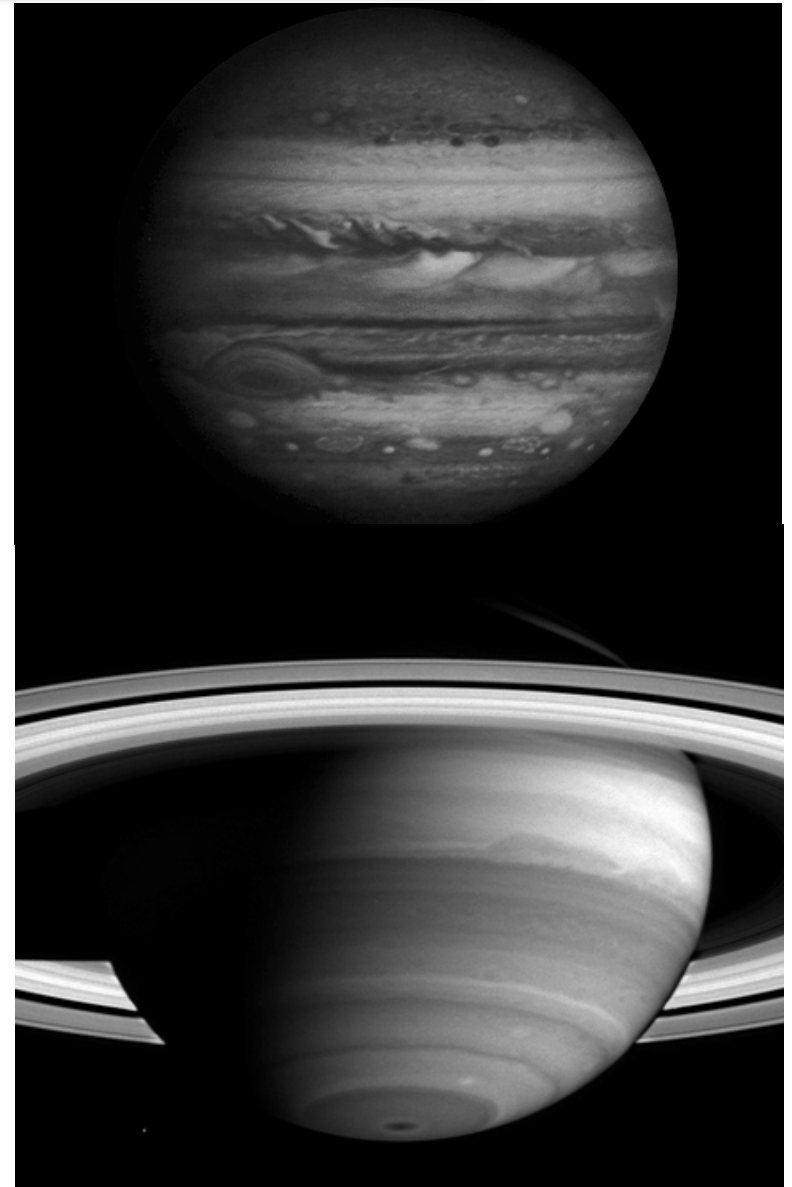


NASA, ESA, and A. Simon-Miller (NASA Goddard Space Flight Center) ■ STScI-PRC08-27

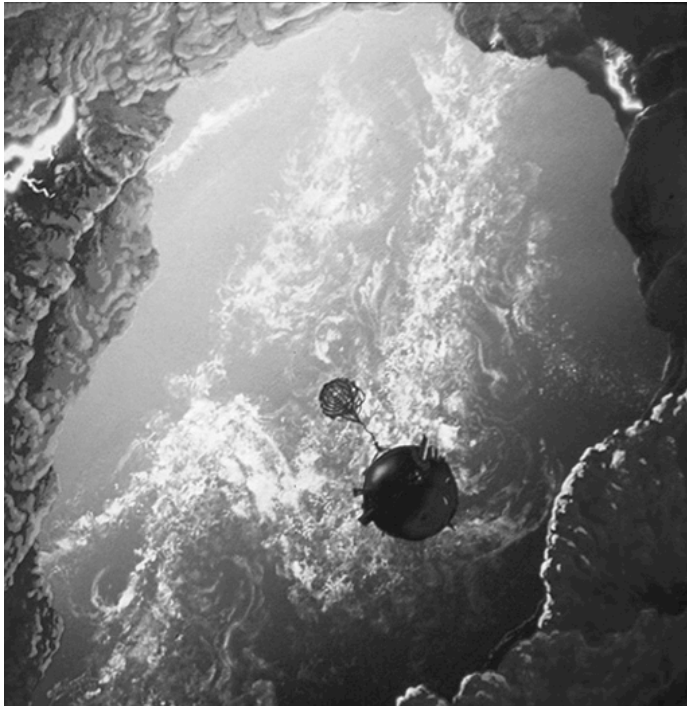
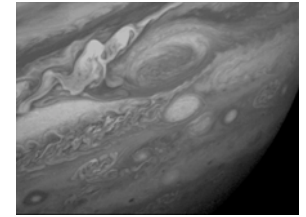
Cloud bands



- **Jupiter, Saturn clouds in fast-moving bands**
- **On Earth, transient storms break up such bands, but not on Jupiter or Saturn**
- **Storms on Jupiter can last tens to hundreds of years!**
- **Why the cloud bands are particular colors is not clear; color depends on chemistry which we don't understand.**

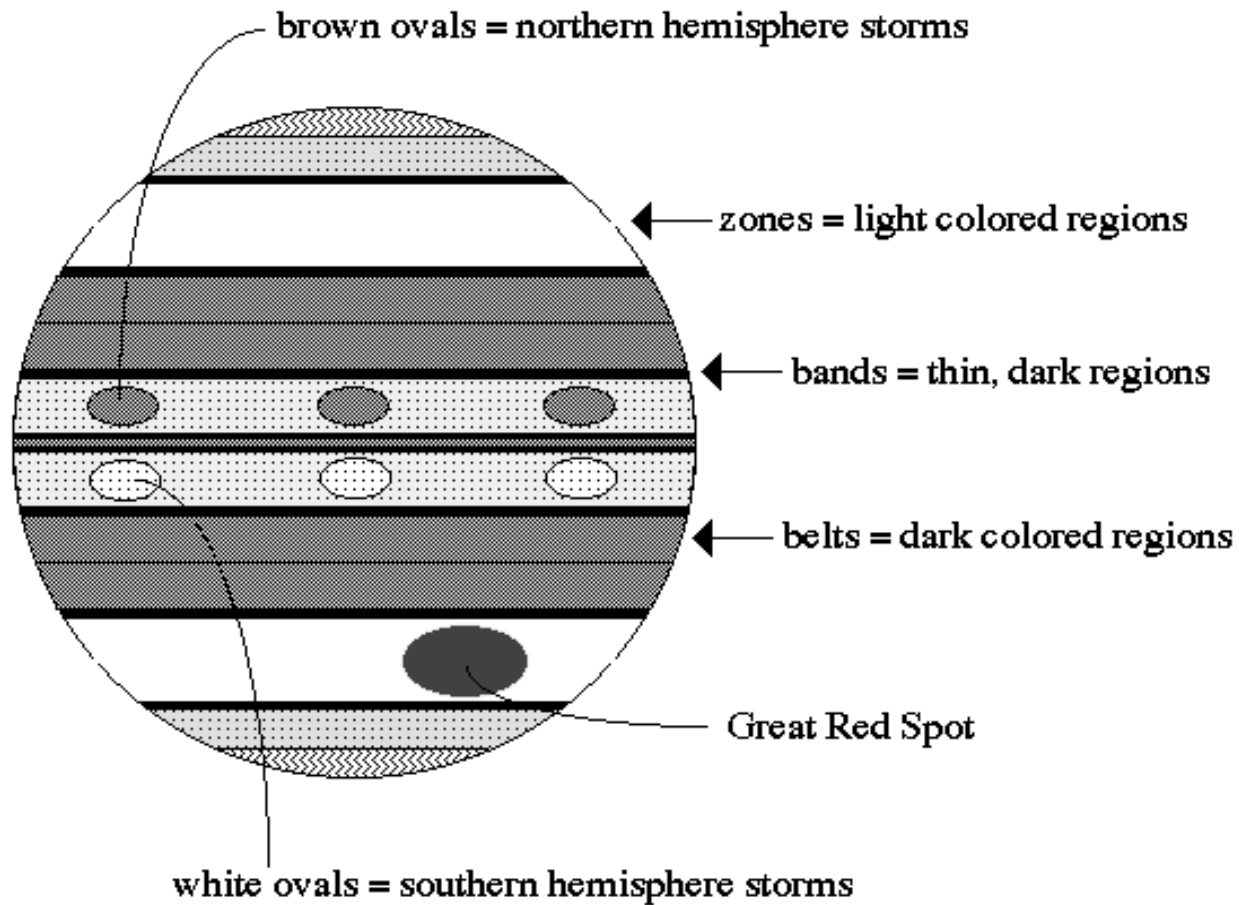
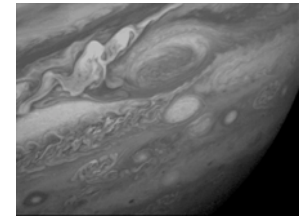


Jupiter's Atmosphere

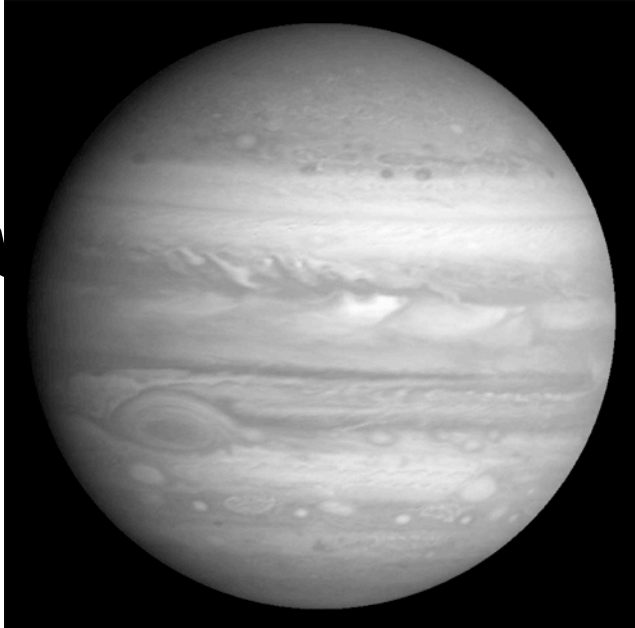
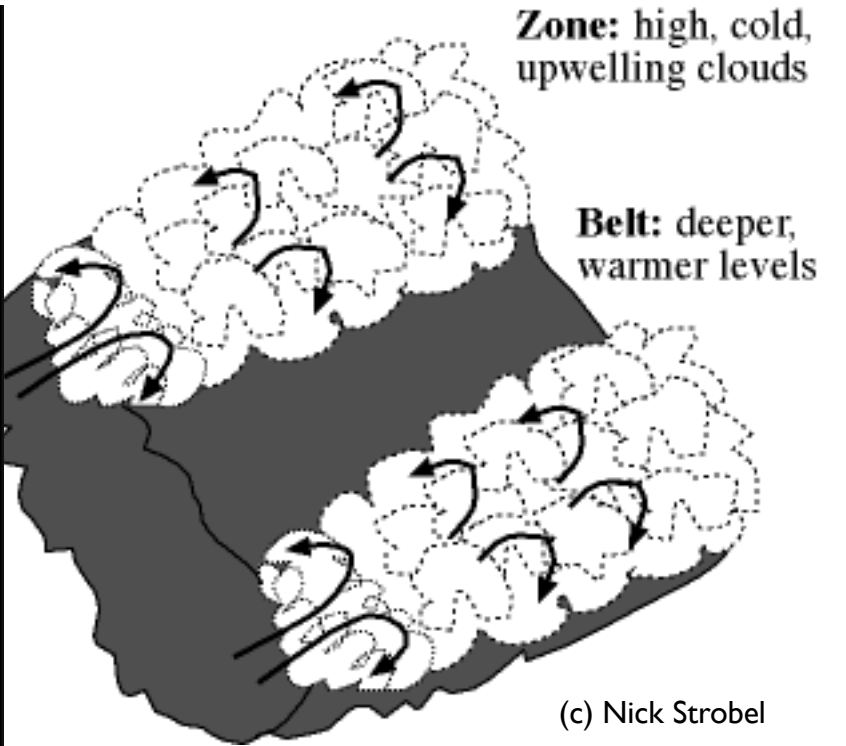
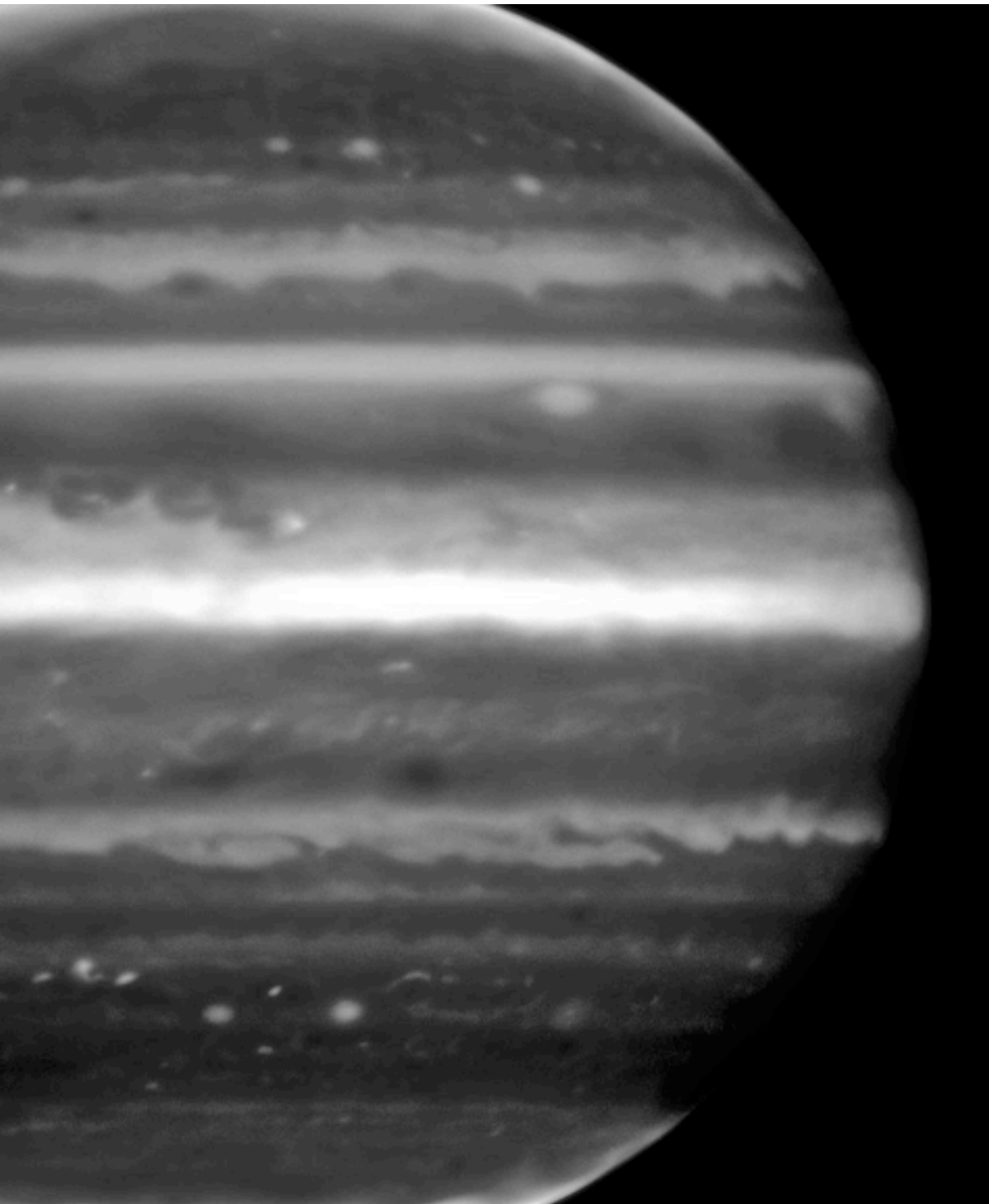


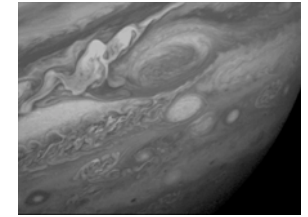
- **In 1995, the Galileo space probe plunged into the planet Jupiter!**
- **It measured the atmospheric structure of Jupiter**
 - **thermosphere absorbs Solar X-rays**
 - **stratosphere absorbs Solar UV**
 - **troposphere greenhouse gases trap heat from both Jupiter and the Sun**
- **These are the same structures found in Earth's atmosphere.**
- **Atmospheres are governed by interactions between sunlight and gases.**

Features on Jupiter

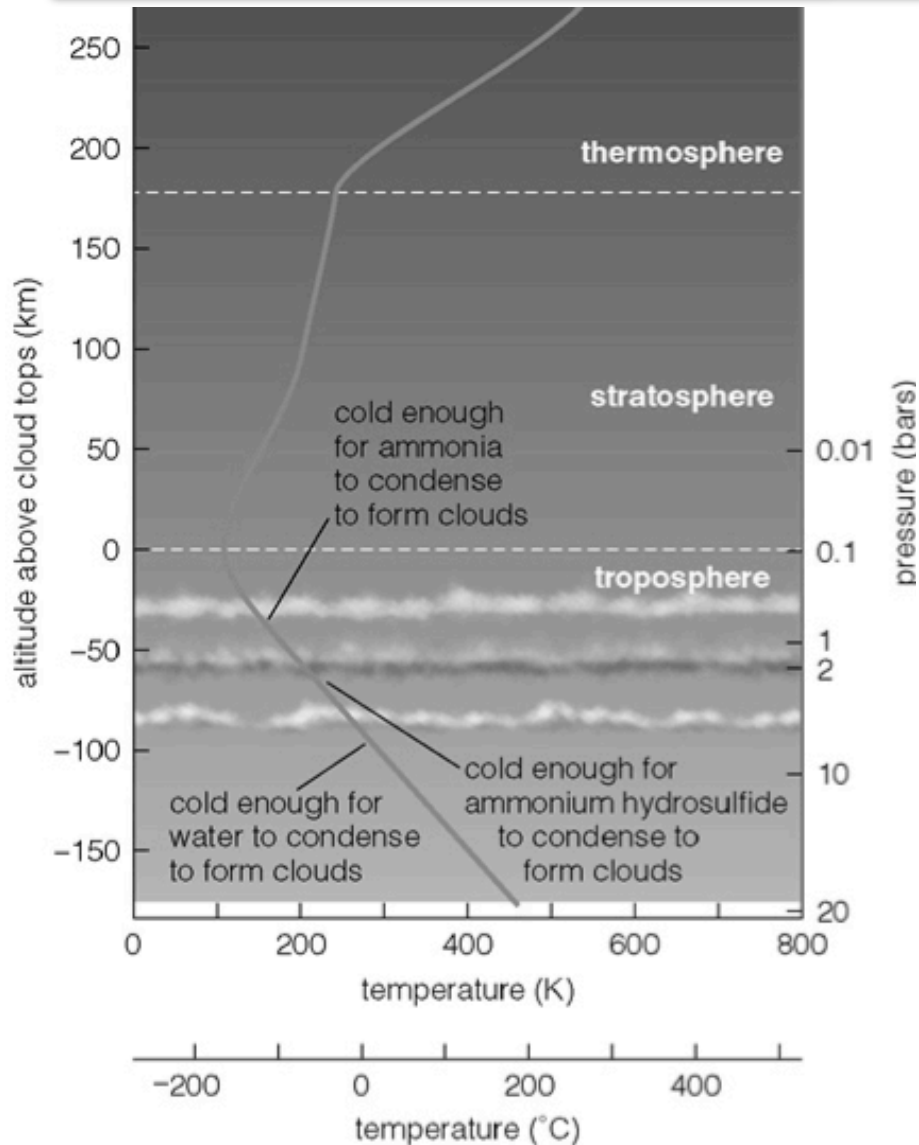


- **Credit: Imamura, U. Oregon**



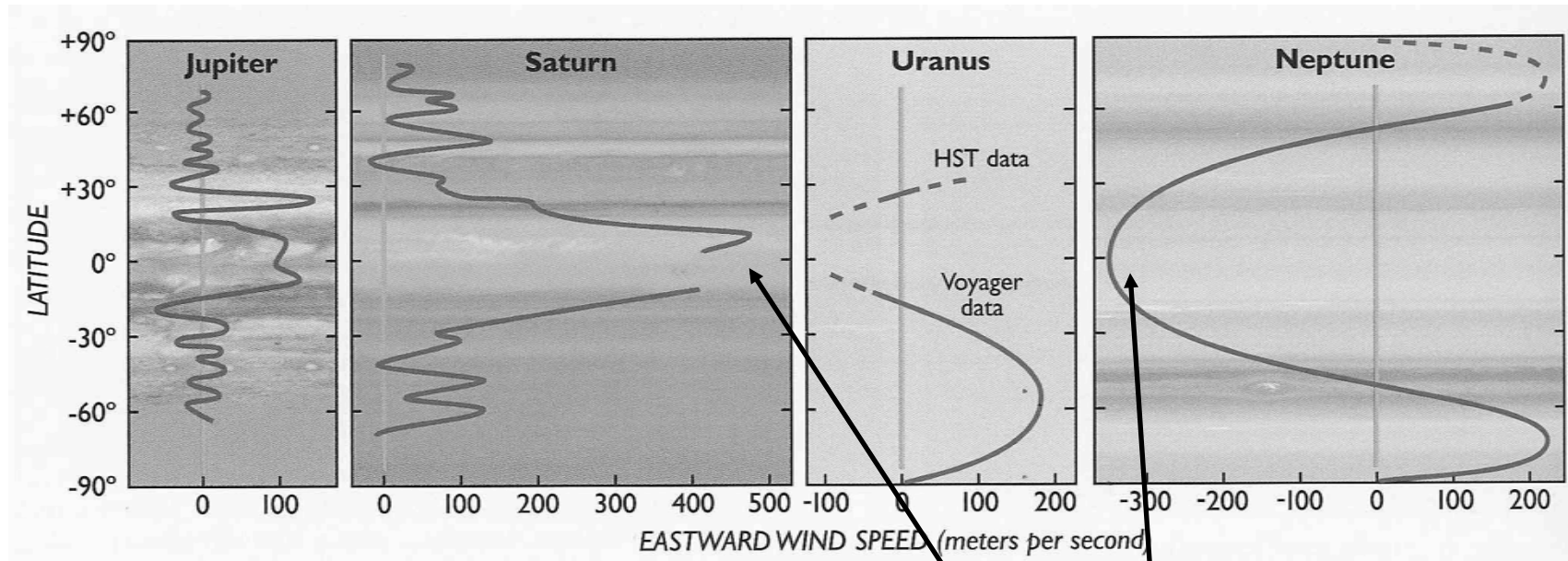
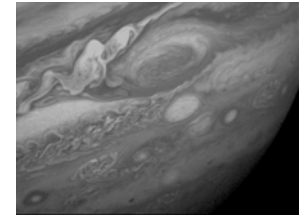


Jupiter's Cloud Layers



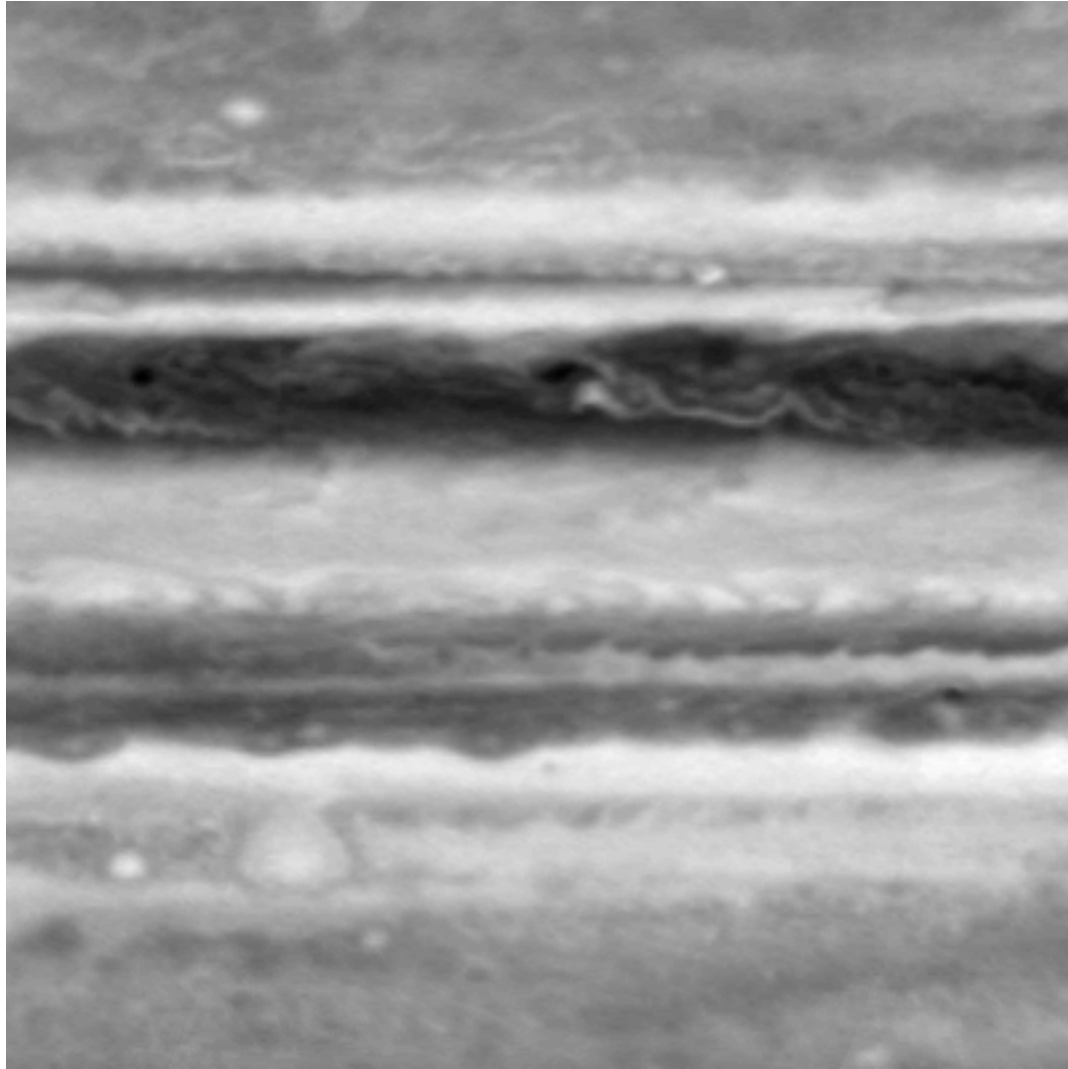
- **Convection in the troposphere causes Jovian weather.**
- **Warm gas rises to cooler altitudes, where it condenses to form clouds.**
- **Three gases condense in the Jovian atmosphere:**
 - **ammonia (NH_3)**
 - **ammonium hydrosulfide (NH_4SH)**
 - **water (H_2O)**
- **They condense at different temperatures, so their clouds form at different altitudes.**

Winds are strongly latitudinal

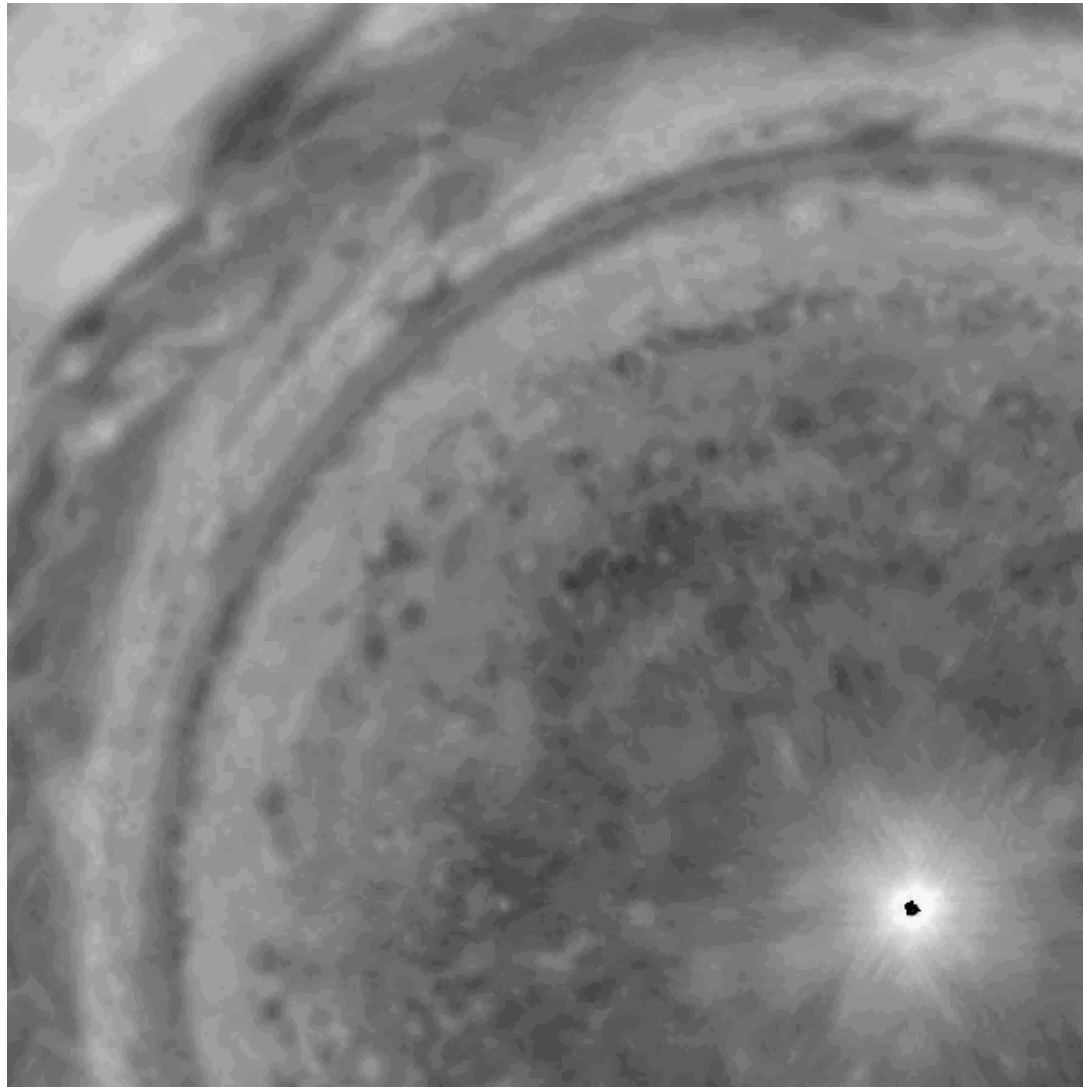
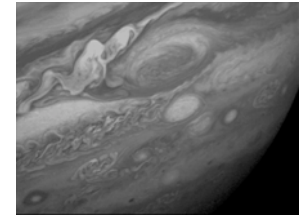


“Zonal winds” of alternating direction

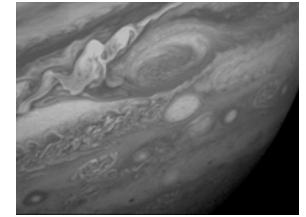
Huge wind speeds on Saturn, Neptune



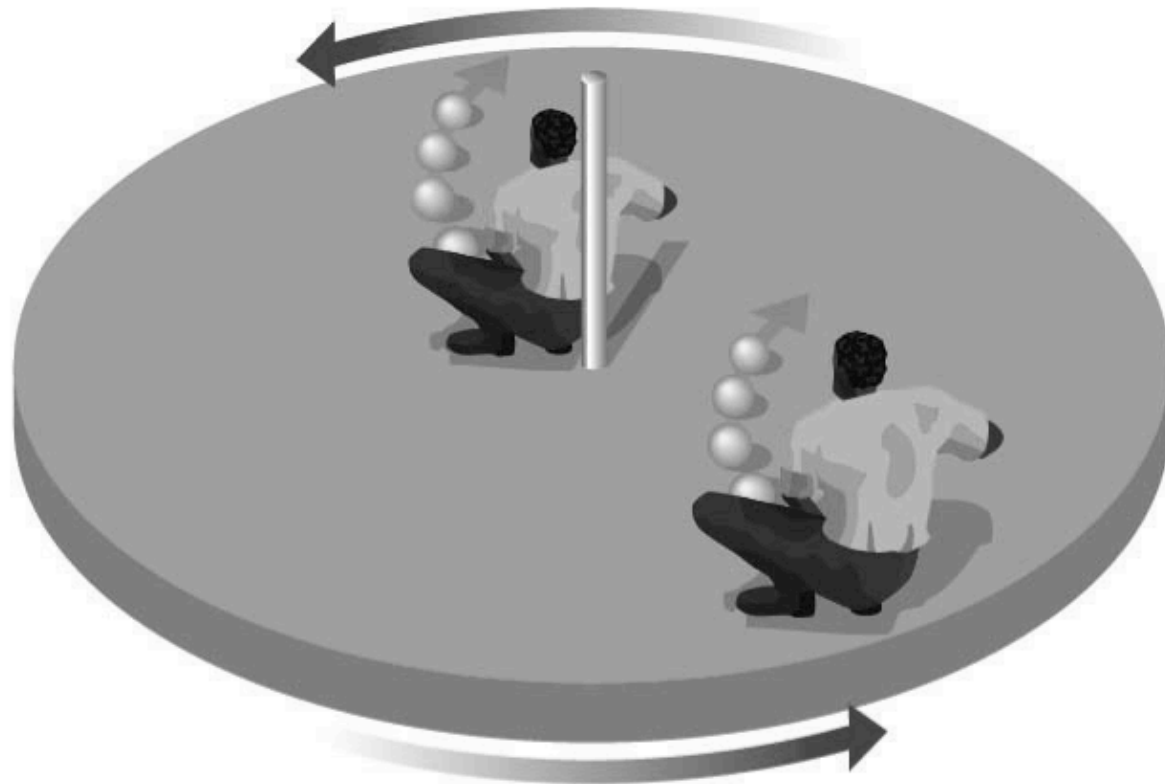
There are even opposing zonal winds at poles!



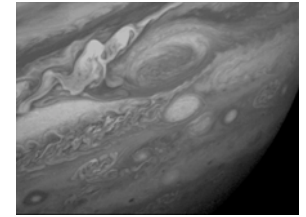
What is the coriolis force?



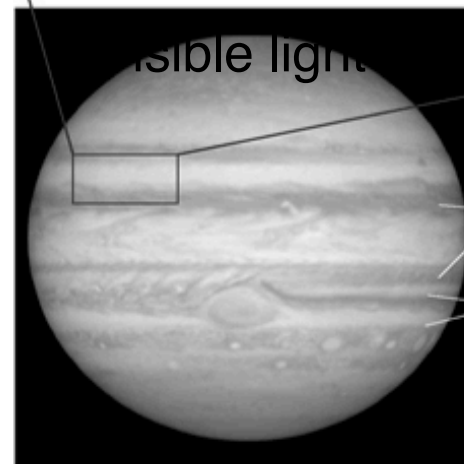
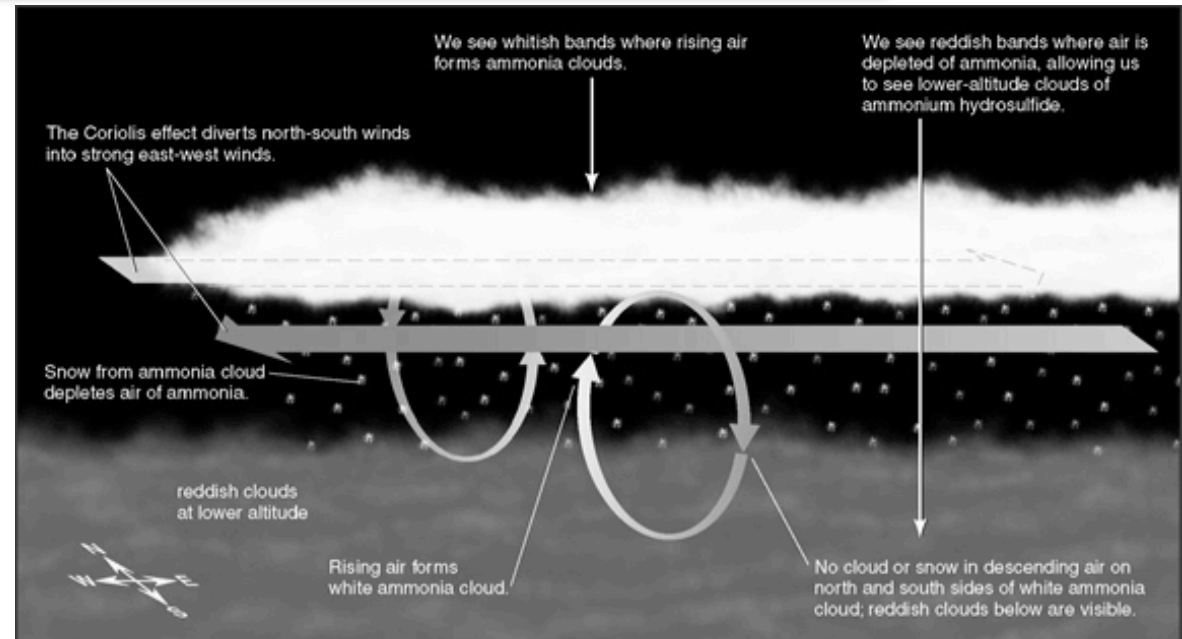
- Coriolis force: if you try to move radially in or out on a spinning merry-go-round, you are deflected to the side



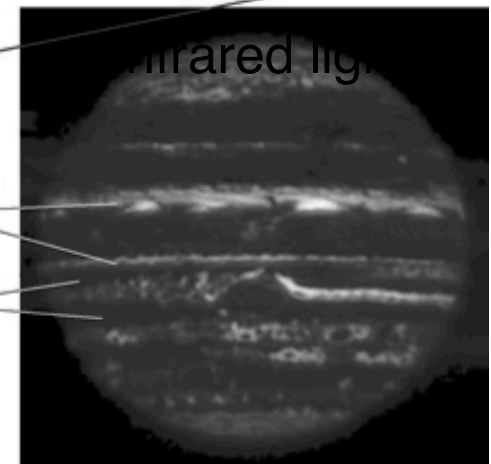
What makes Jupiter's cloud bands so colorful?



- Like Earth, Jupiter has circulation cells in its atmosphere.
- Jupiter is much larger & rotates much faster.
 - Coriolis effect is much stronger
 - circulation cells are split into many bands of rising and falling air
 - these are the colored “stripes” we see
- Belts: warm, red, low altitude
- Zones: cool, white, high altitude



Visible light

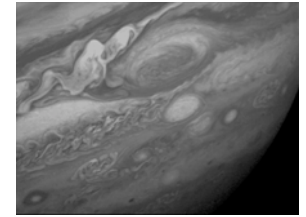


Infrared light

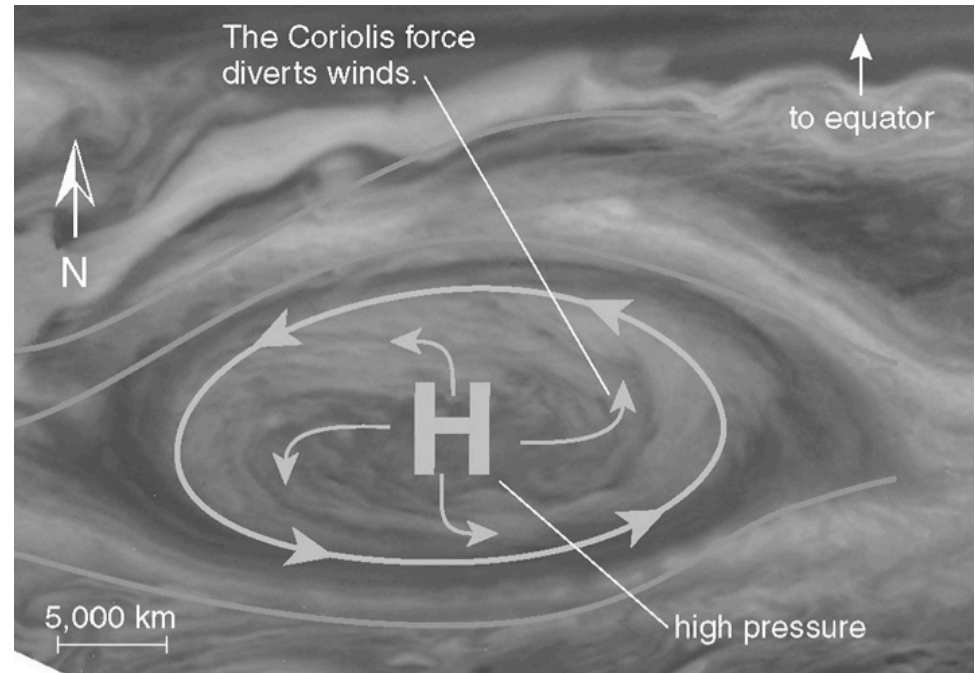
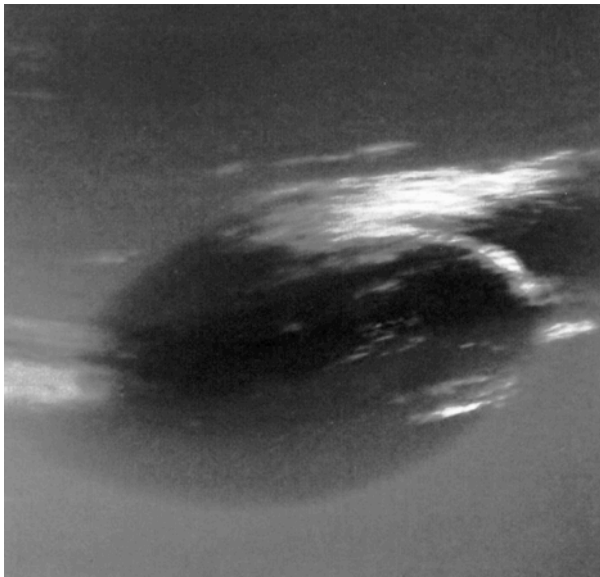
These bands are warm, red, low-altitude clouds.

These bands are cool, white, high-altitude clouds.

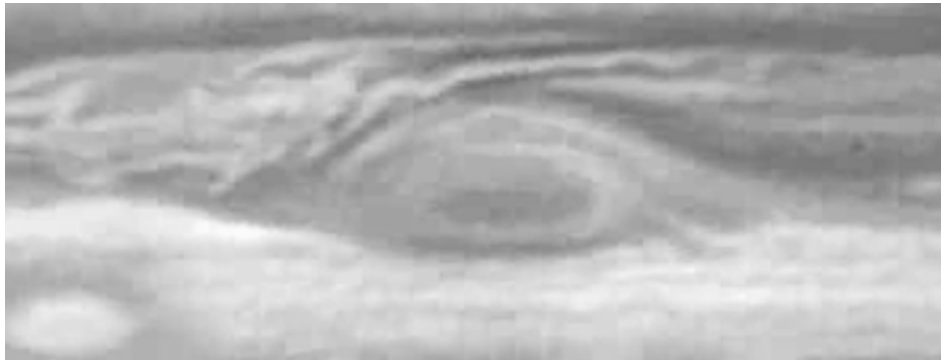
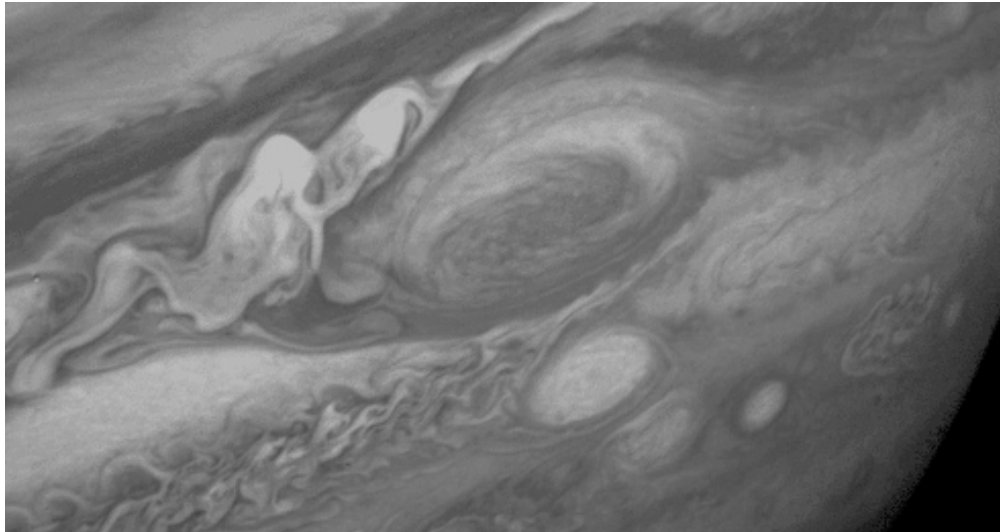
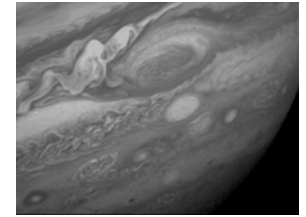
We also see high pressure storms



- **Jupiter**
 - the **Great Red Spot**
 - we are not sure why it is red
- **Neptune**
 - the **Great Dark Spot**

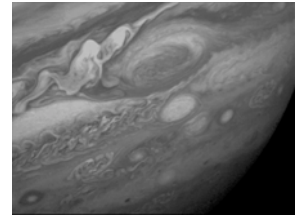


Jupiter Storms: best example is the Great Red Spot

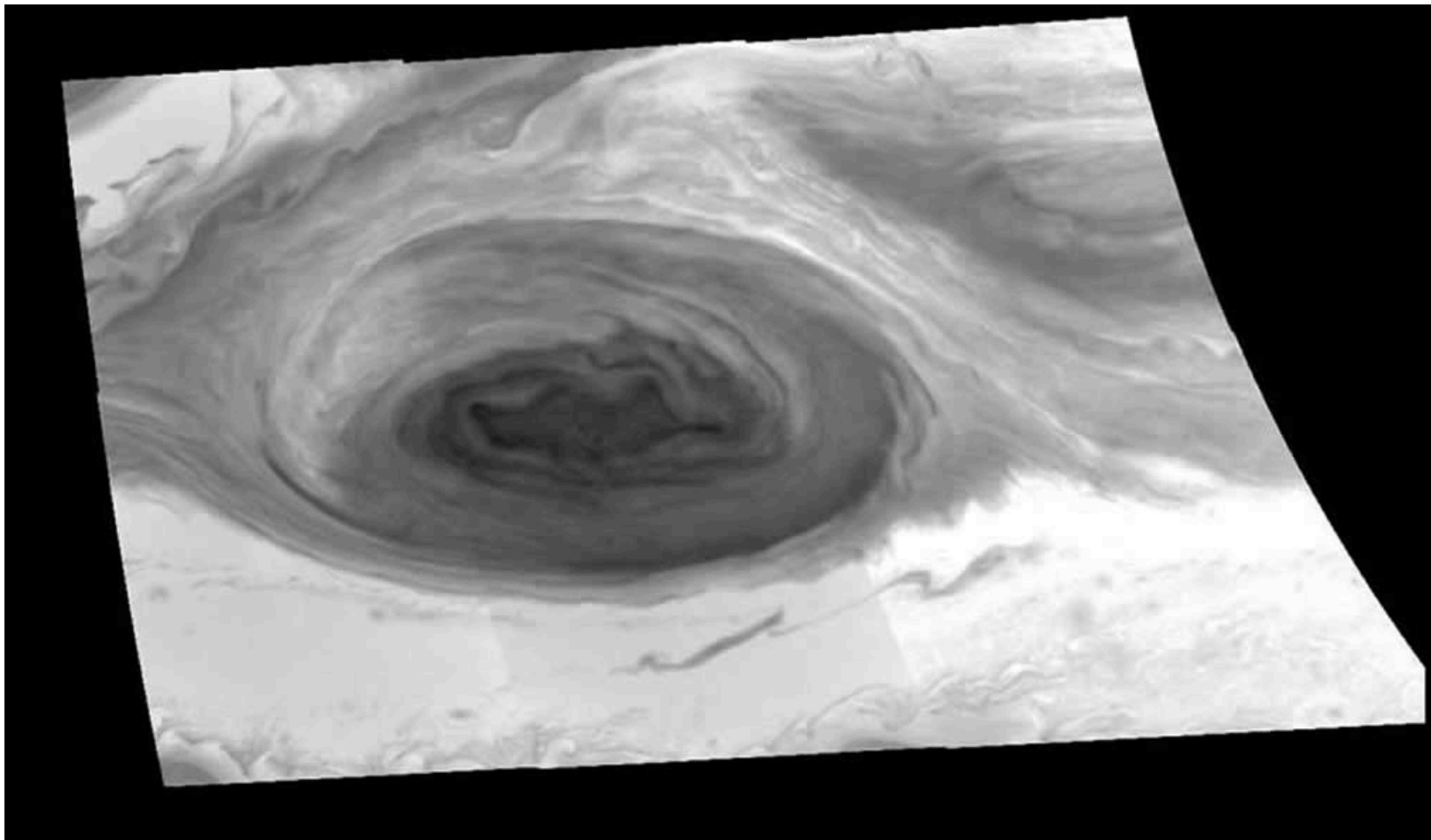


- **Great Red Spot has been around for at least 300 yrs**
 - **Seen in 17th century!**
- **A stable vortex**
- **Wind speeds >400 km/hr**

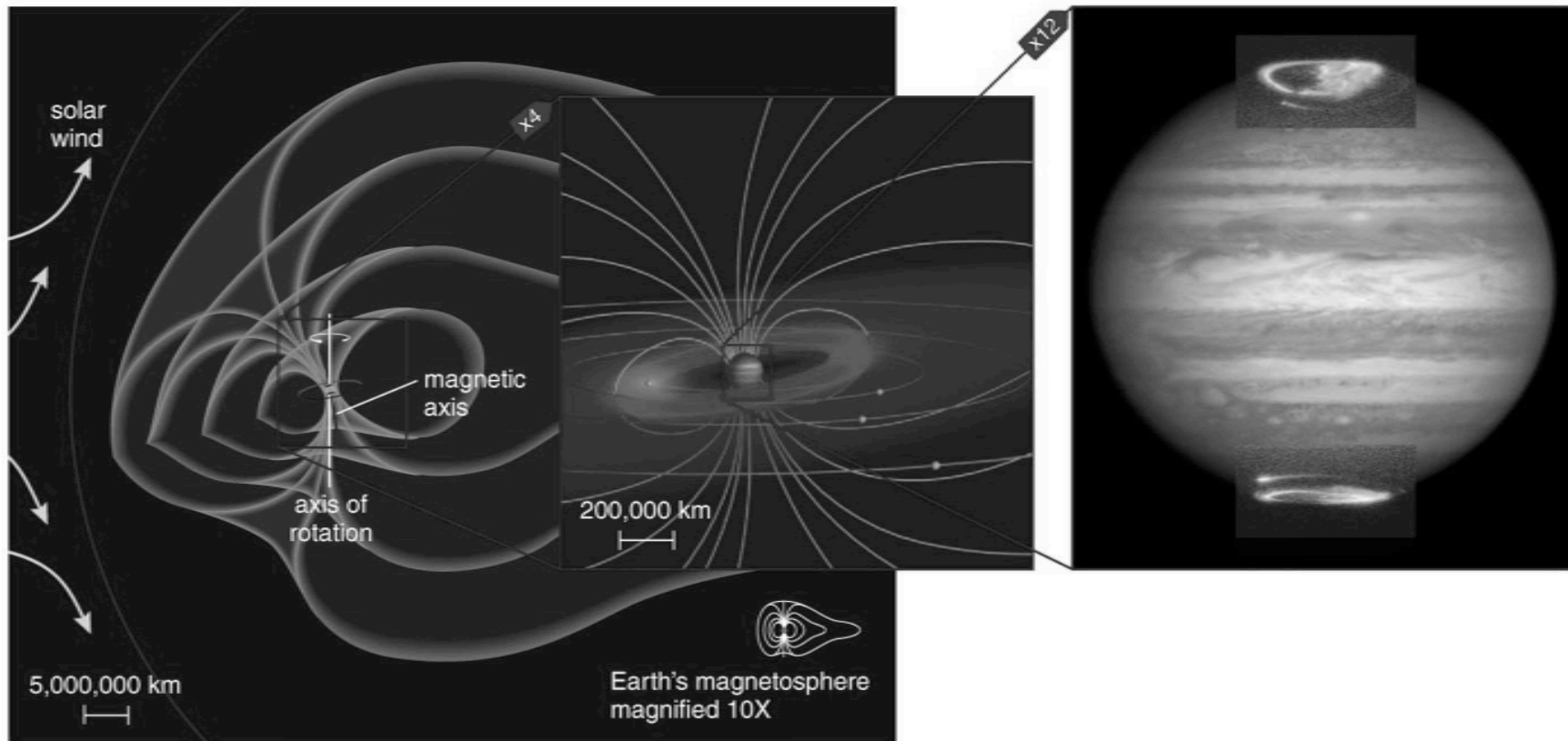
Another view of Jupiter's Great Red Spot



- **From Galileo spacecraft**

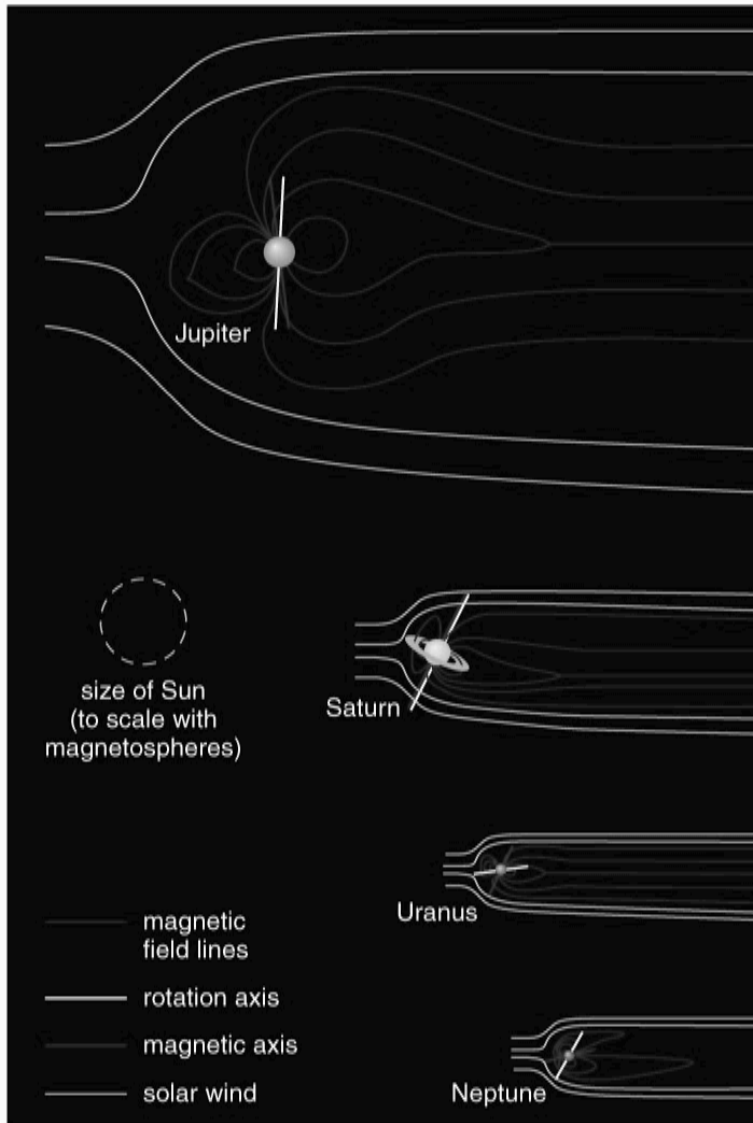


Jupiter's Magnetosphere



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

Magnetospheres of other giant planets



- **All jovian planets have substantial magnetospheres, but Jupiter's is the largest by far.**

Thought Question

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

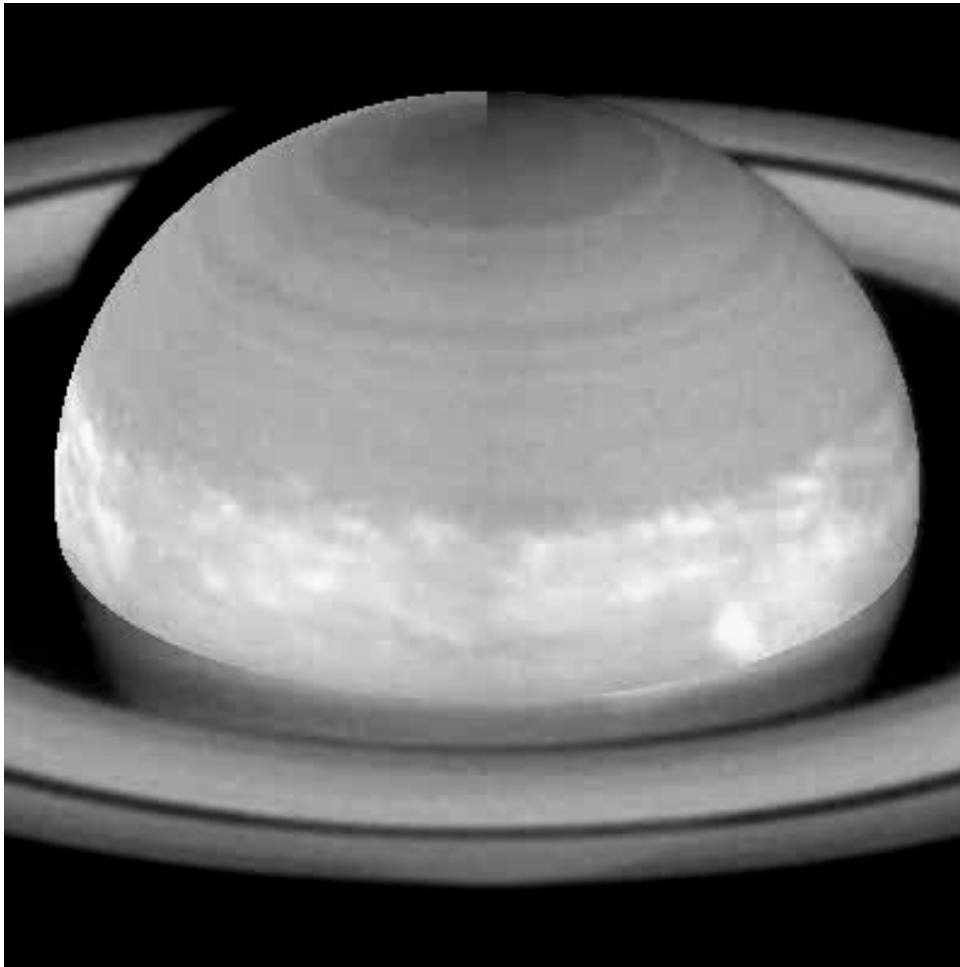
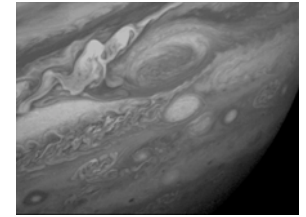
- a) The magnetic field is left over from when Jupiter accreted.**
- b) Its magnetic field comes from the Sun.**
- c) It has metallic hydrogen inside, which circulates and makes a magnetic field.**
- d) Its core creates a magnetic field, but it is very weak.**

Thought Question

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

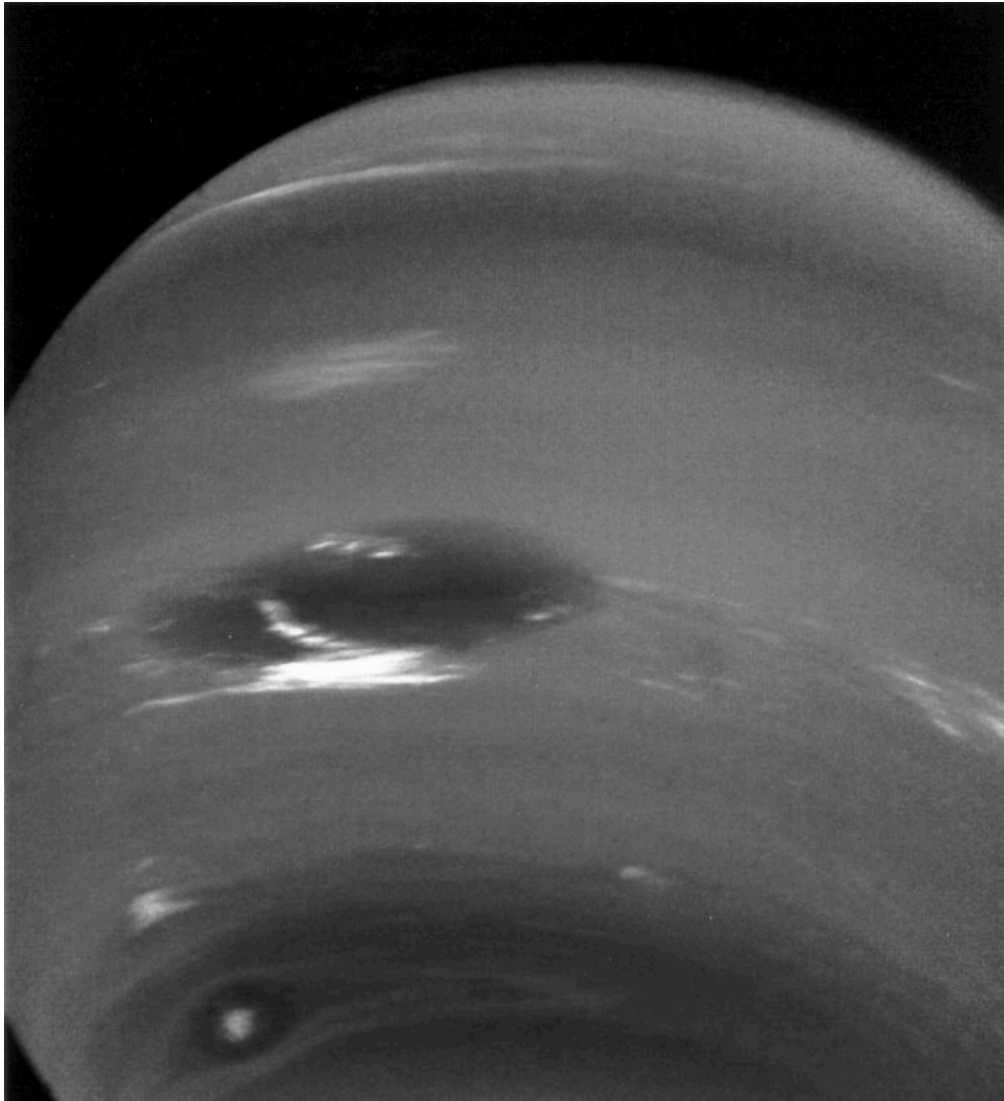
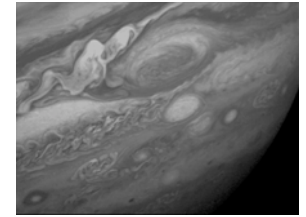
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Saturn has giant storms



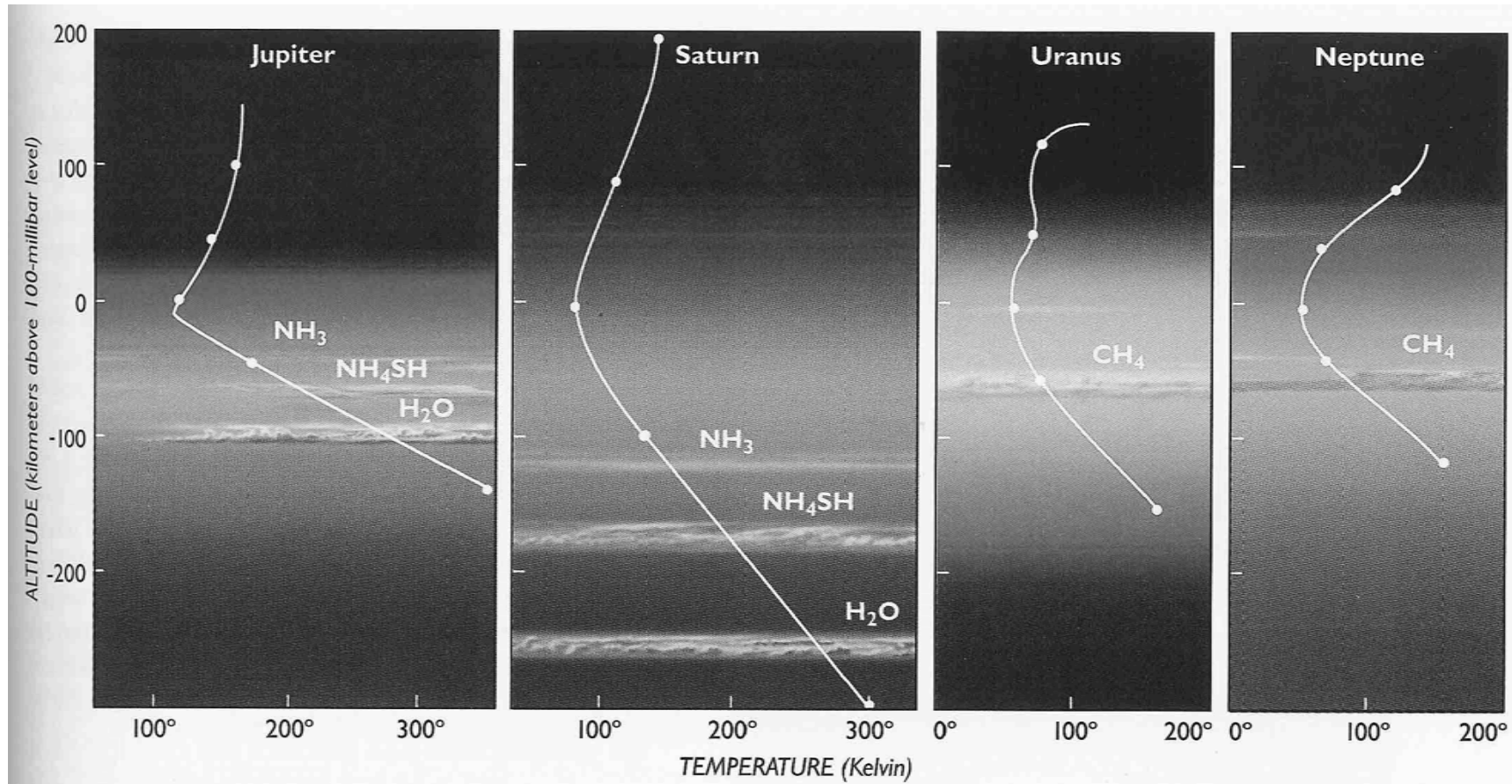
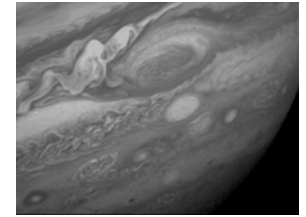
- **Outbreaks of Saturn storms every ~30 yrs**
- **Corresponds to summertime in Northern Hemisphere**
 - **Not seen in S.**
- **Origin of storms not yet understood**

Neptune: Great Dark Spot

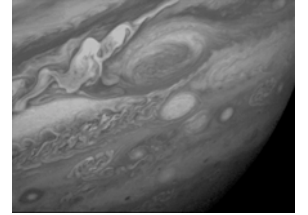


- **Lasted for several months as Voyager 2 spacecraft flew by**
- **Wasn't there a decade later when Hubble Space Telescope looked**

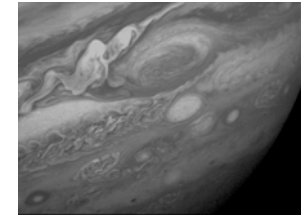
Temperature structure of all the Giant Planet atmospheres



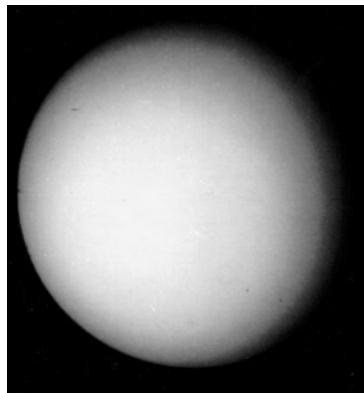
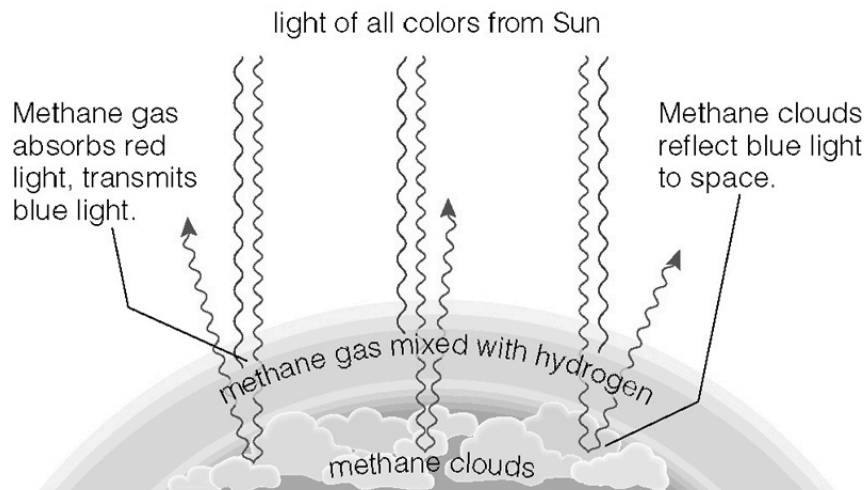
Concept Question



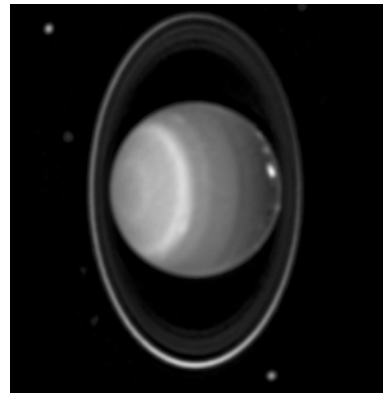
- **On Earth, convection cells are formed when air is heated at the Earth's surface**
- **What sources of heating might power convective cells on Jupiter?**



Why Uranus & Neptune are Blue



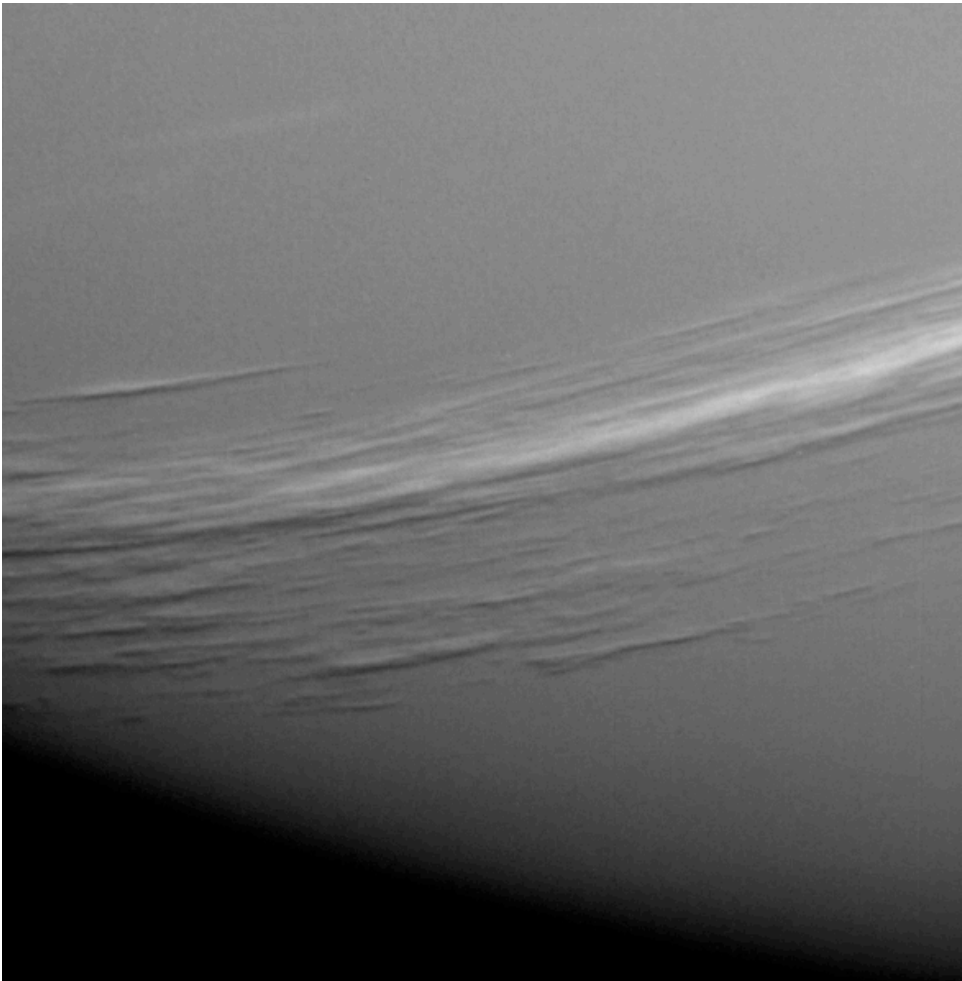
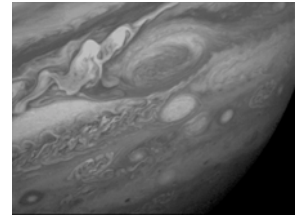
1986 - Visual



1998 - IR

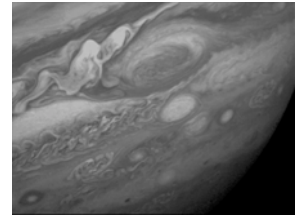
- **They both have a higher fraction of methane gas.**
 - **Methane absorbs red sunlight.**
 - **Only blue light is reflected back into space by the clouds.**
- **Uranus is “tipped” on its side.**
- **It should experience the most extreme seasonal changes.**
 - **no clouds or banded structure seen in 1986 when N pole facing Sun**
 - **no weather, no internal heat?**
 - **HST saw storms in 1998, perhaps because the S hemisphere is warming now**

Circumferential cloud bands seen by Voyager spacecraft as it flew by Neptune

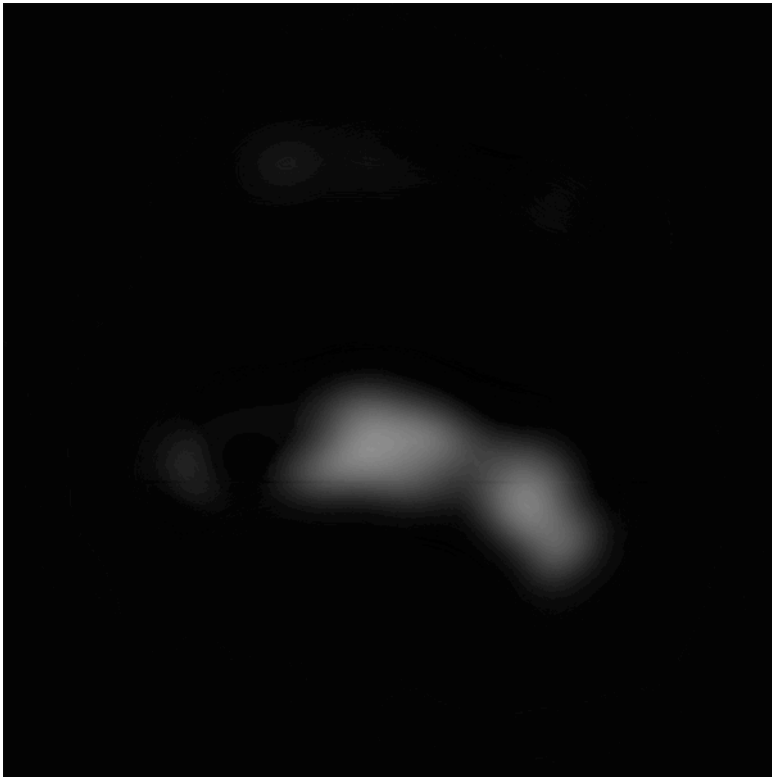


- **Linear features seen by Voyager in visible light were very thin**
- **Circumferential (followed lines of constant latitude)**
- **Similar in location and shape to the bands we see in infrared light**
- **Probably “pulled out” into circumferential shape by Neptune’s huge winds**

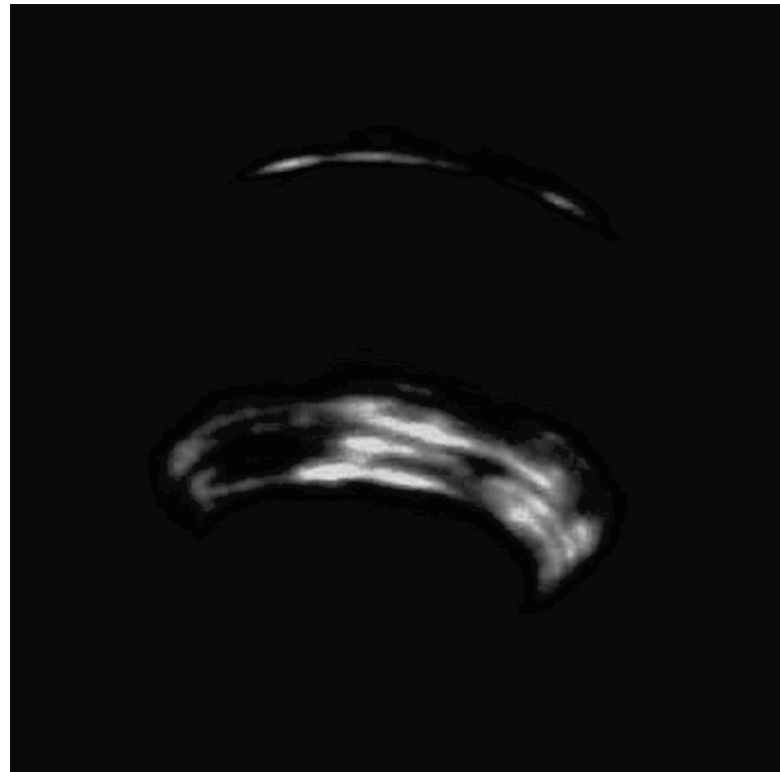
Adaptive optics has been big help in studying Neptune from the ground

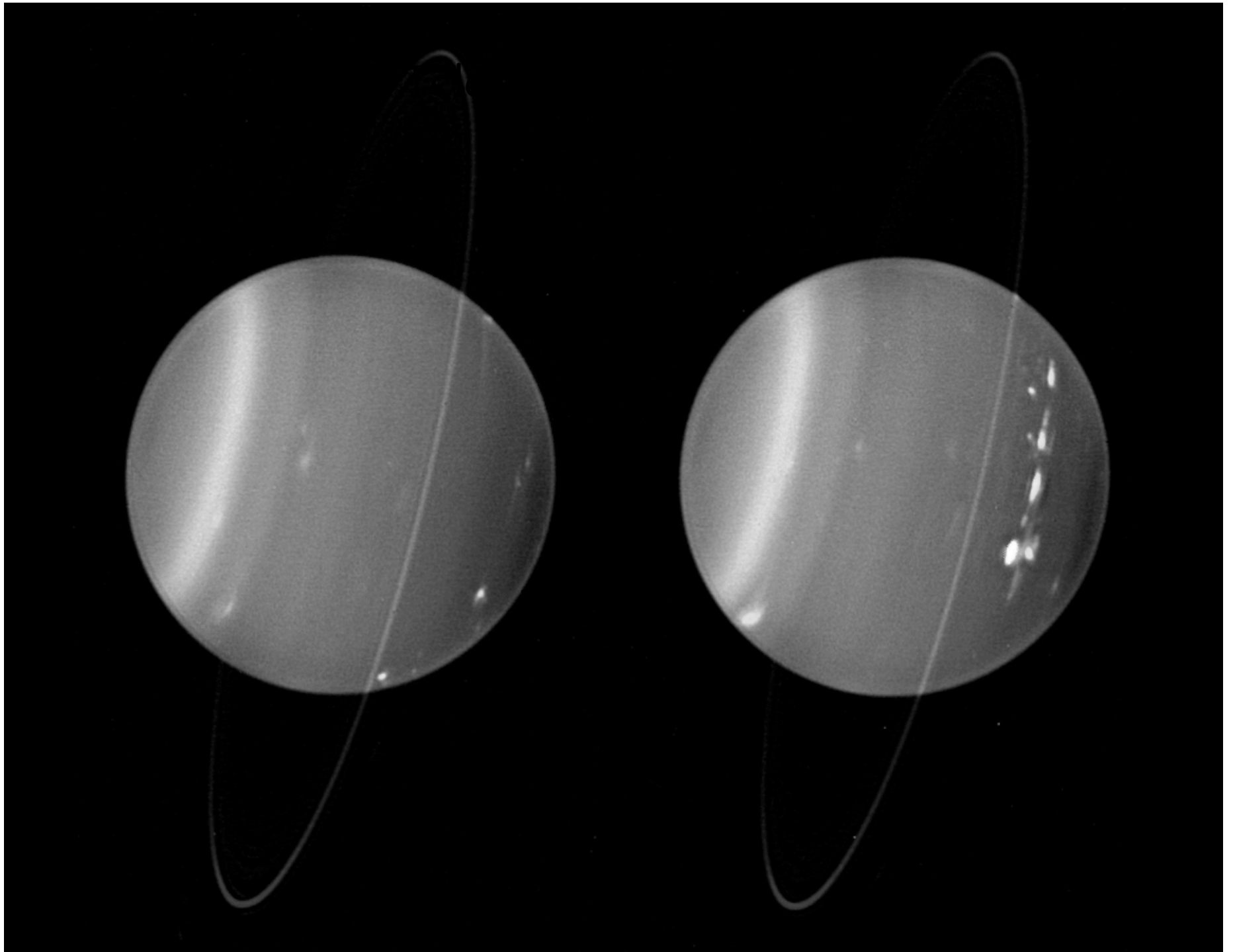


**Neptune in infrared light
without adaptive optics**

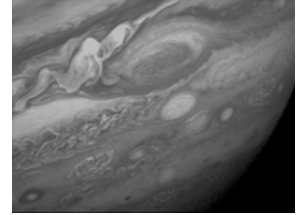


**Neptune in infrared light
with Keck adaptive optics**



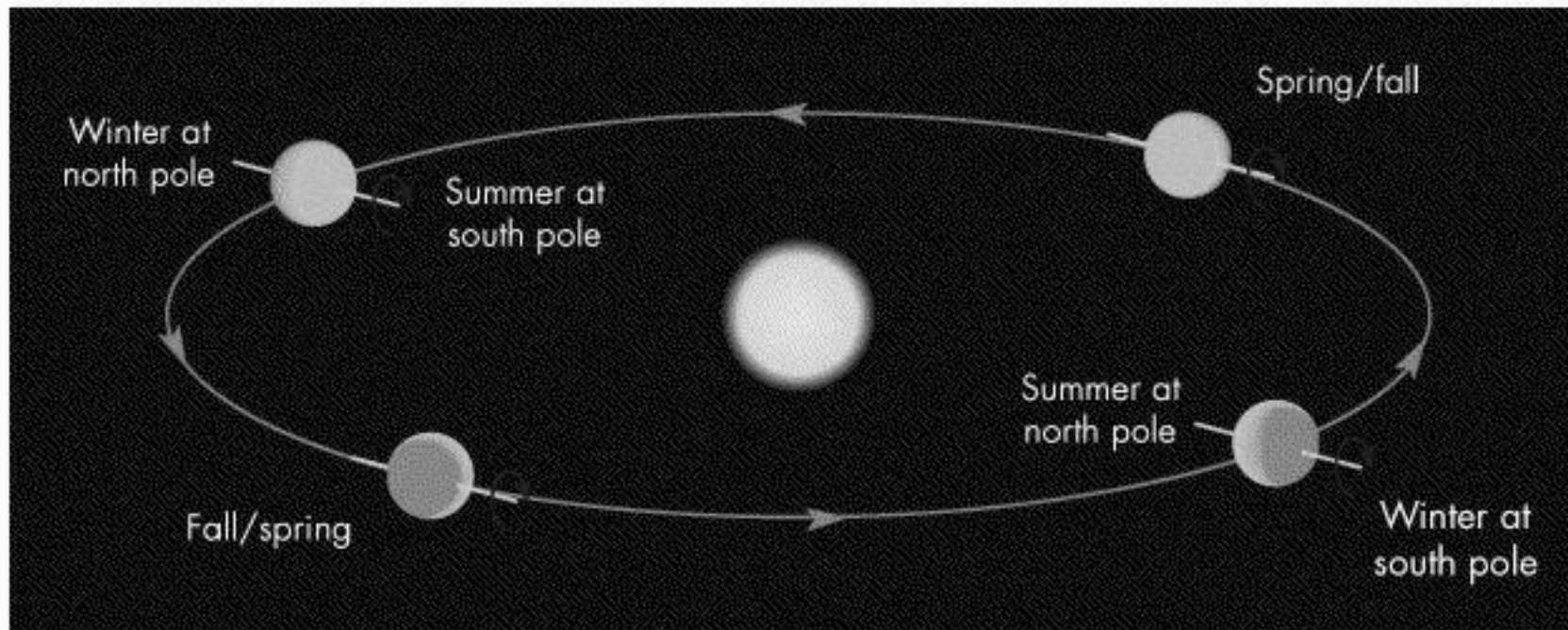
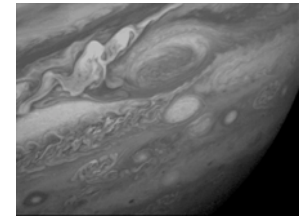


Concept Question

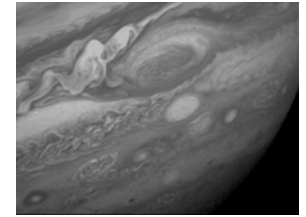


- **Uranus' year is 80 Earth-years long**
- **The axis of rotation of Uranus lies almost in the plane of Uranus' orbit, so that the planet "rolls its way around the Sun."**
- **As a consequence, seasons on Uranus are**
 - a) **As long as one Uranus year**
 - b) **Non-existent**
 - c) **One fourth of Uranus' year, or about 20 Earth years long**
 - d) **Four times Uranus' year, or about 320 Earth years long**

Concept Question

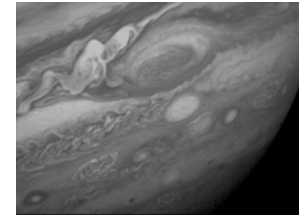


The Main Points



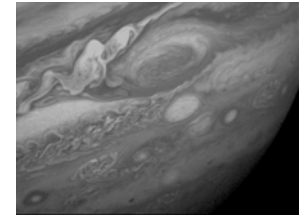
- **Briefly describe major features of the Jovian planets.**
 - Largely composed of hydrogen, helium, & hydrogen compounds. No solid surfaces. Fast rotation. Slightly “squashed” shapes. Many moons. Ring systems.
- **Why are Jovian planets so different from terrestrial planets?**
 - Formed in cold, outer Solar System at the centers of “miniature protoplanetary disks.”
- **Briefly describe the interior structure of Jupiter.**
 - Central core of H compounds, rocks, & metals.
 - Next layer up contains metallic H, followed by a layer of liquid H, followed by the gaseous atmosphere.
 - Pressure, density, & temperature all increase with depth.

The main points, continued



- **Why is Saturn almost as big in radius as Jupiter?**
 - Adding mass to a Jovian planet does not necessarily increase its size, because the stronger gravity compresses the mass to greater density.
 - Jupiter is near the maximum possible size for a Jovian planet.
- **How do the Jovian planet interiors differ, and why?**
 - All have cores of about the same mass, but differ in the amount of surrounding H and He.
 - Accretion took longer in the more spread out regions of the outer Solar System, so the more distant planets captured less gas from the Solar nebula before it was blown away by the Solar wind.

Main points, continued



- **How is Jupiter's atmospheric structure similar to Earth's?**
 - Troposphere, stratosphere, and thermosphere created by similar interactions of gas and sunlight.
- **Why does Jupiter have three distinct cloud layers?**
 - Different gases condense at different temperatures. Jupiter has three cloud layers, each at the altitude where a particular gas can condense.
- **What is the Great Red Spot?**
 - A giant, high-pressure storm.
 - Great Dark Spot on Neptune is probably similar.