# Announcements

- HW 4 due now
  - 50% credit if handed in on Tuesday

- Mid-term #2
  - Coming up in one week
  - Material includes everything since the last Mid-term
  - Same format
    - 5-option multiple-choice questions
    - 1 hour – so don't be late

# Gas Giants: Jupiter and Saturn

PTYS/ASTR 206 – The Golden Age of Planetary Exploration

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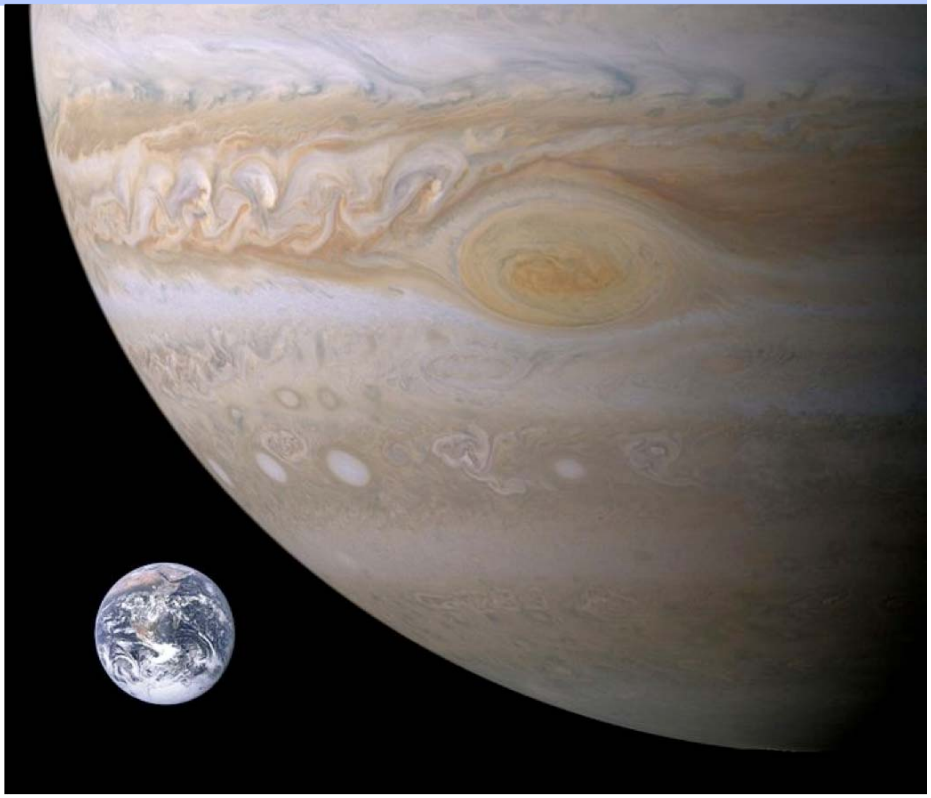
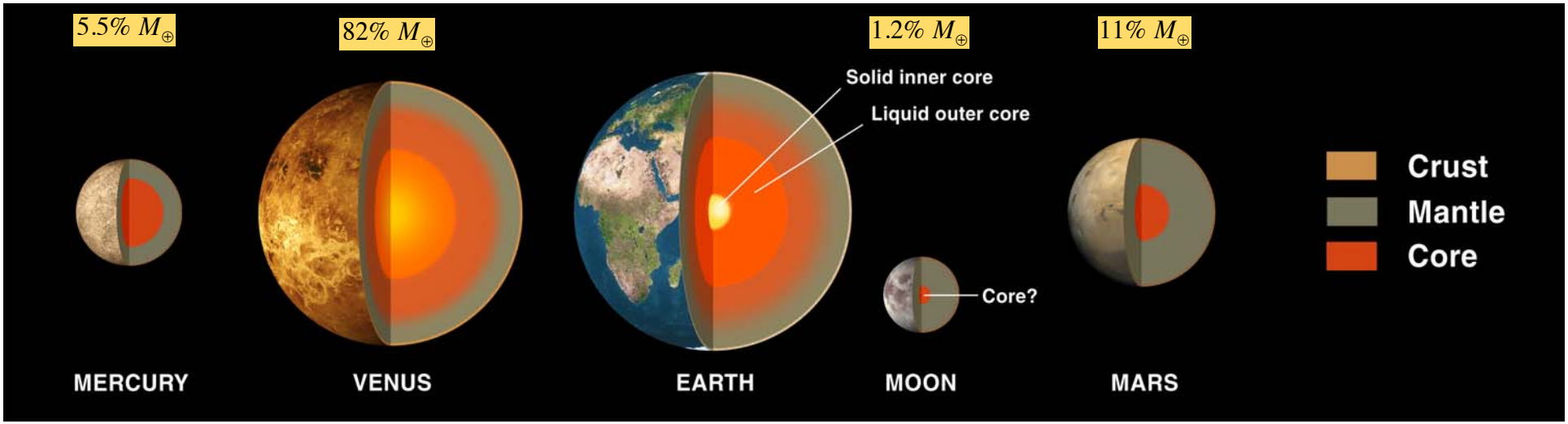
## In this lecture…

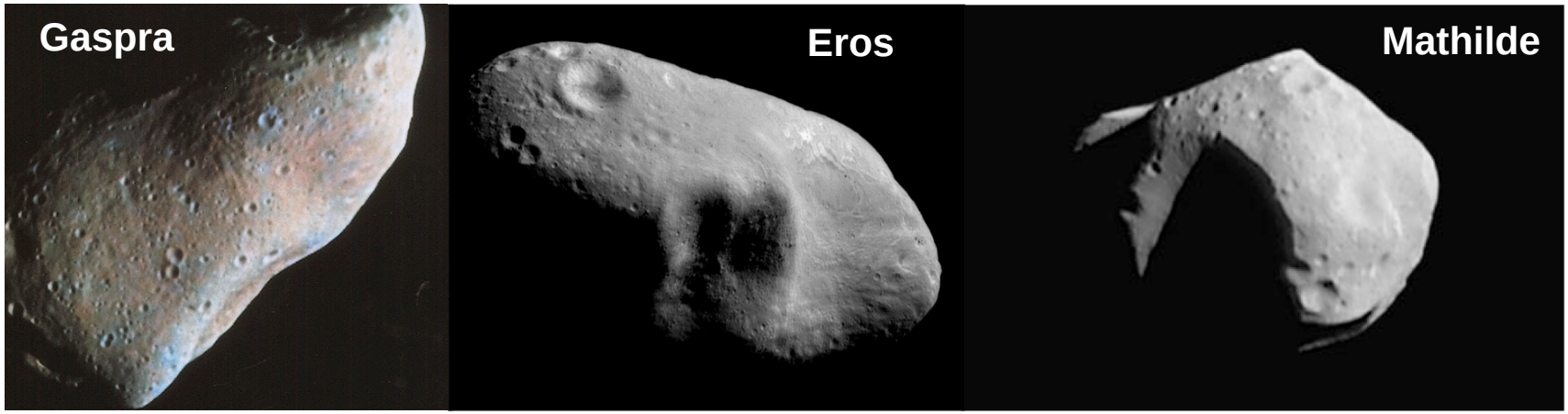
- The frost line
  - A two-part solar system
- Formation of Jupiter and Saturn
- Jupiter and Saturn Basics
- Exploration of Jupiter and Saturn
- Interiors of Jupiter and Saturn
  - Metallic Hydrogen
  - Helium rainfall
  - Magnetic fields
- Atmosphere of Jupiter and Saturn
- Impact of comet Shoemaker-Levy 9



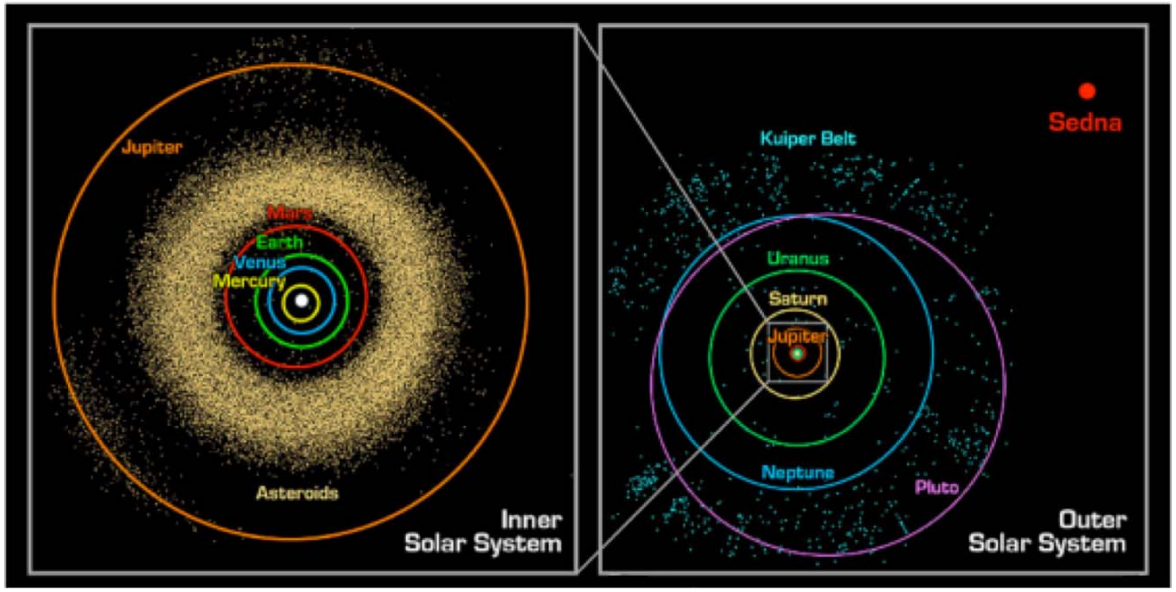
# The frost line

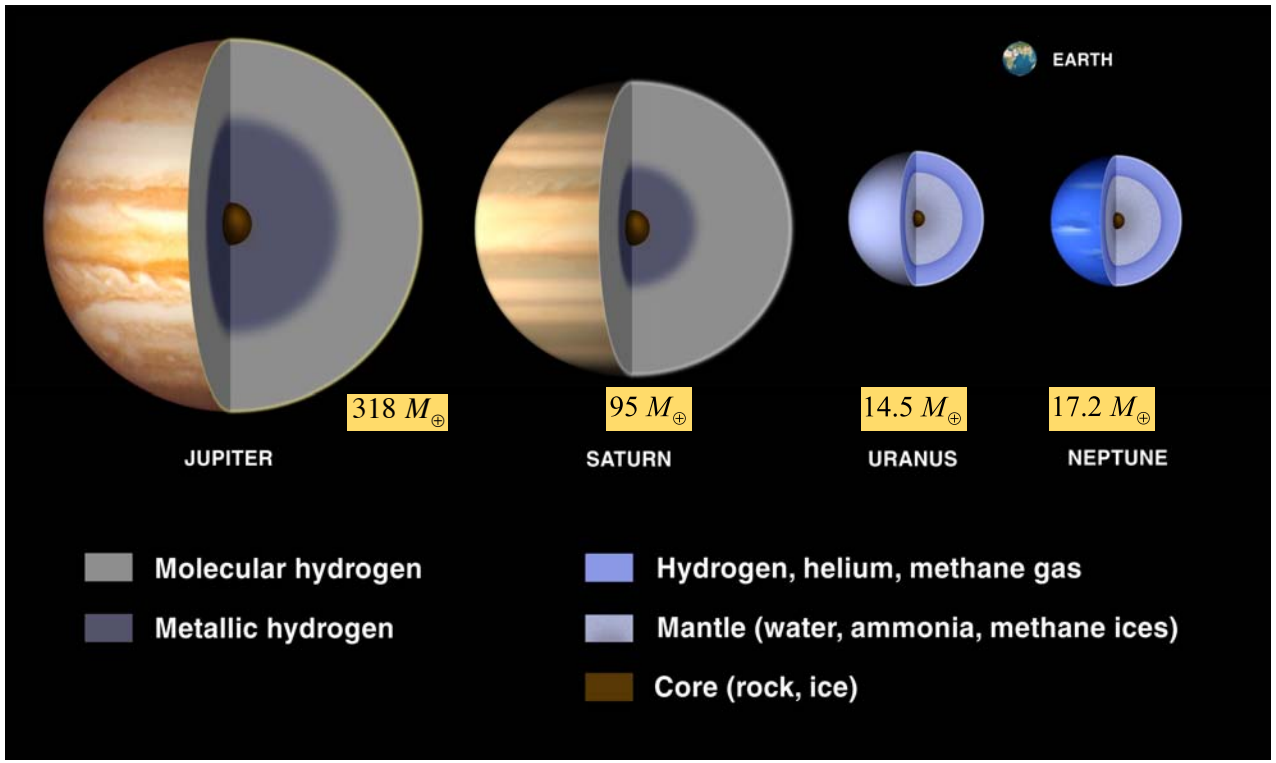
- We've been talking about the inner solar system so far
  - Dominated by solid bodies made from rock and iron



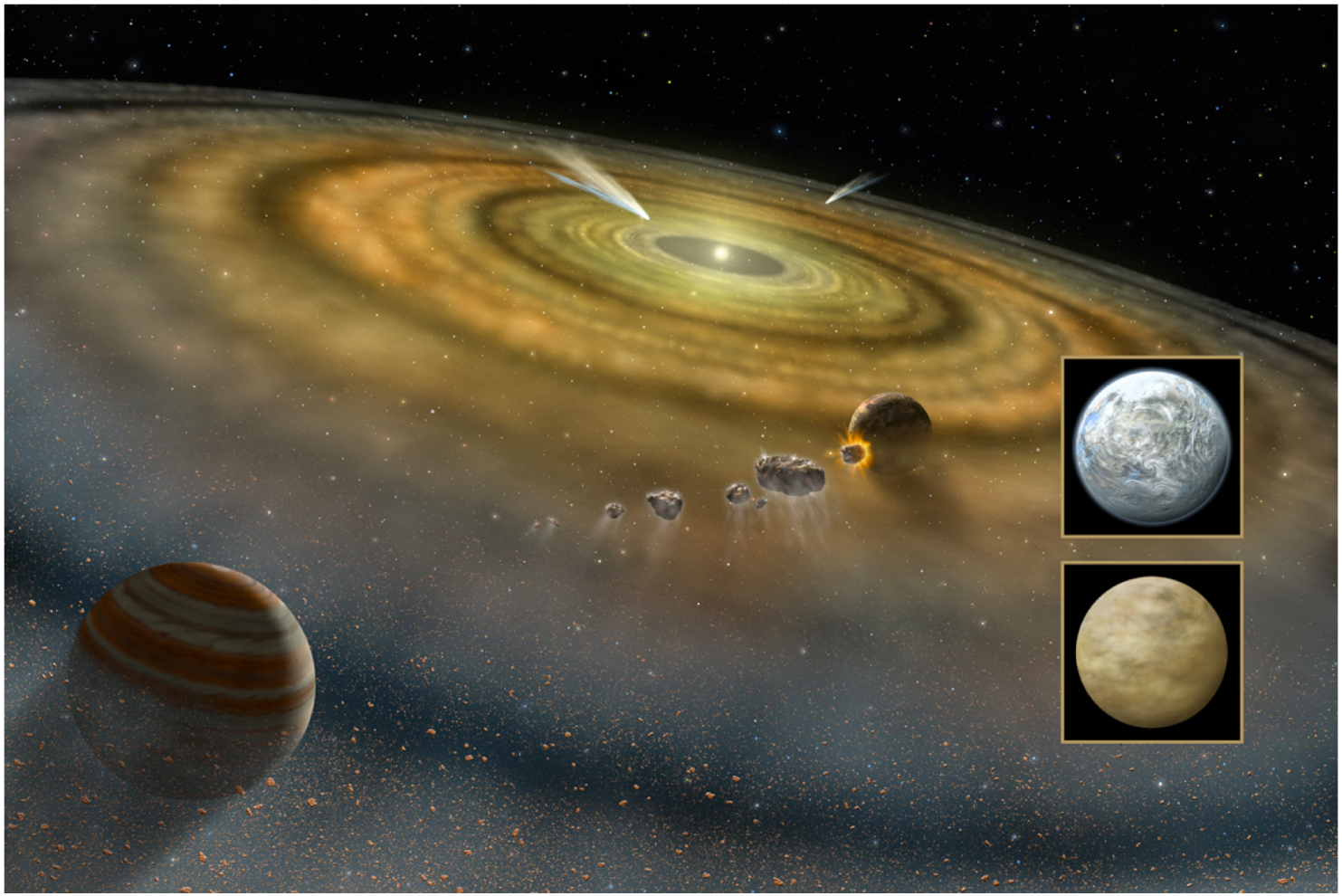



- The outer solar system
  - Jupiter and beyond
  - Gas Giants
    - Jupiter
    - Saturn
  - Ice Giants
    - Uranus
    - Neptune
  - Icy moons
  - Comets
  - Kuiper belt objects



- How did the outer solar system planets get so big?
- Why are all the small bodies so icy?
- All down to how the solar system formed.
  - A disk dominated by hydrogen and helium



- **Temperature in the disk drops with distance from the sun**
- **At some distance water ice become stable**
  - **Water is very abundant so things outside this line grow very rapidly**

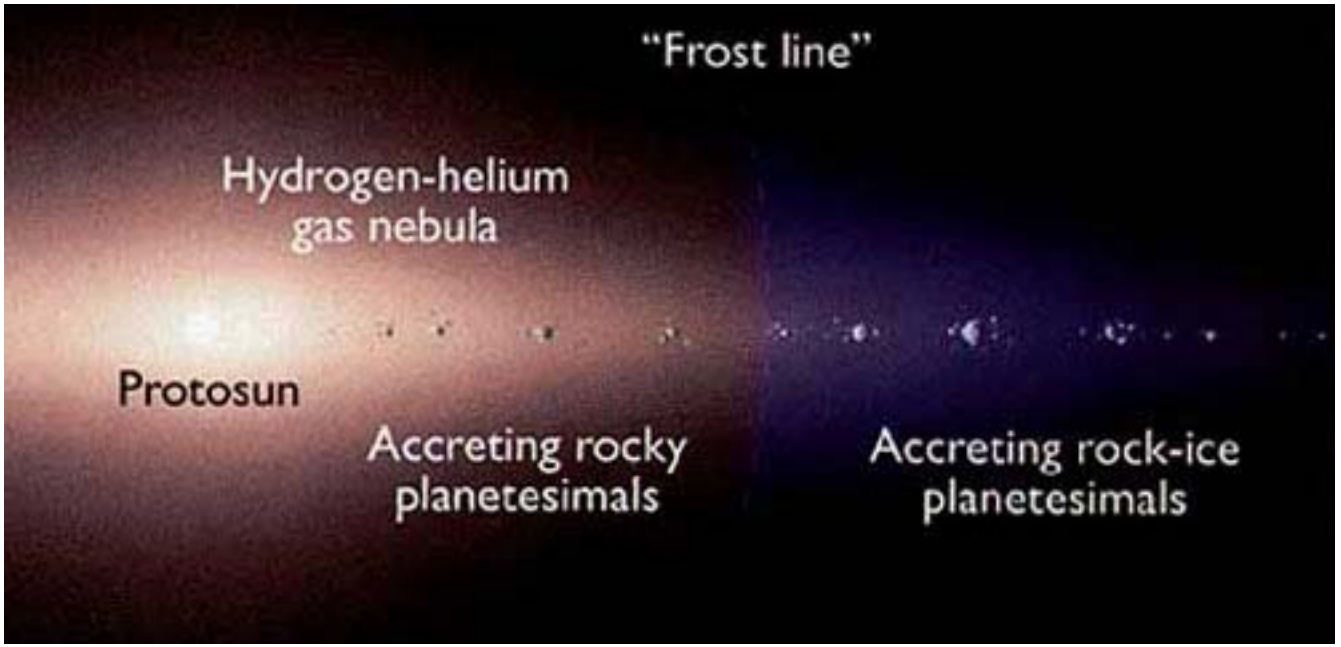
**Table 9.1.** Cosmic abundance of volatile elements*

| H | He | O | C | N | Ne | Si | Mg | Fe |
|---|---|---|---|---|---|---|---|---|
| 22000 | 14000 | 16 | 9 | 2 | 1 | 1 | 0.9 | 0.7 |

* Element abundances are normalized by the abundance of Si.

**Arakawa and Kouchi, 2007**

  - **In our solar system, this line was in the asteroid belt**
    - **Inner asteroids all rock/iron**
    - **Outer asteroids are icy**
  - **Solid objects beyond the asteroid belt are very icy**



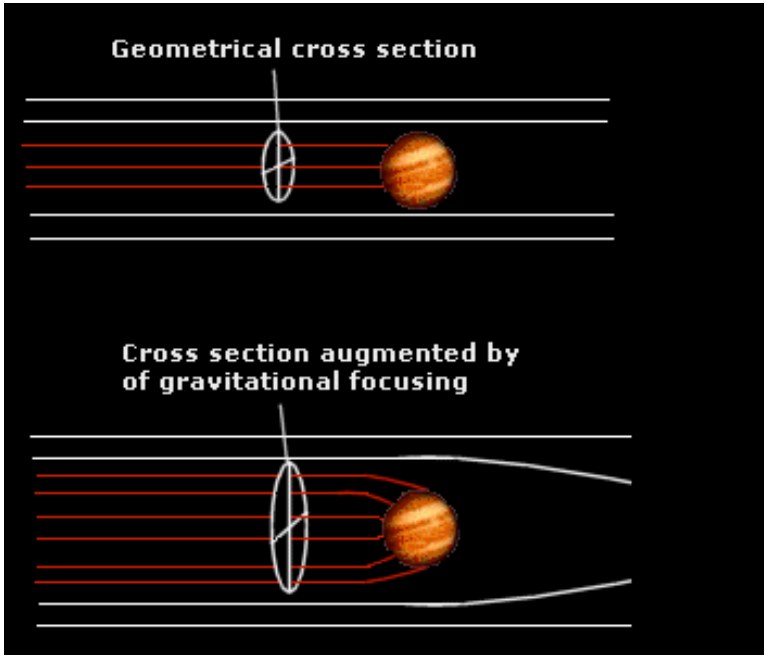
## Formation of Jupiter and Saturn

- Two basic theories on how to get started

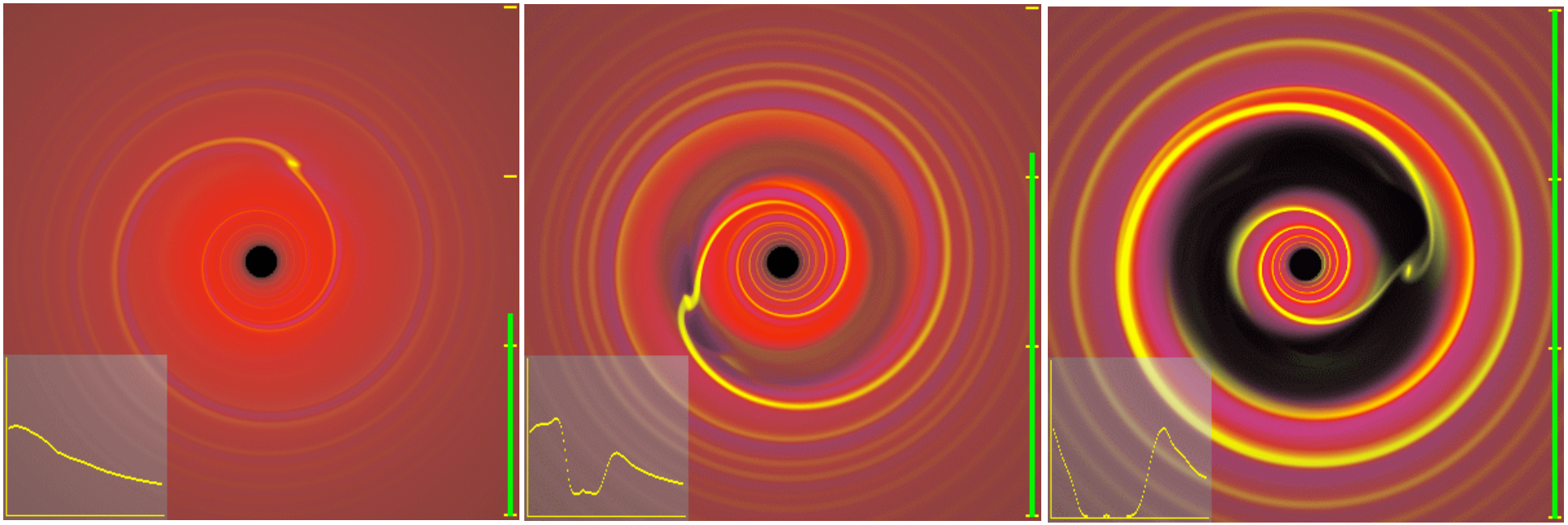
- Direct collapse of part of the gas disk around the sun
  - Instability in the disk triggers local collapse
  - This is how stars form

- Accumulation of a solid rocky/icy core
  - Core gets large - ~10 Earth Masses
  - Starts to capture gas from the disk, gets larger etc…

- **Once started, planets grow fast**
  - **More gas captured from the disk**
  - **When planets get big they grow faster by using gravitational focusing**
  - **Causes oligarchic growth**
    - **Big planets grow fastest**
    - **Big planets gobble up all the available material**
    - **Gas giants are BIG**
  - **These planets need to grow fast as the disk will disappear within ~10 million years**



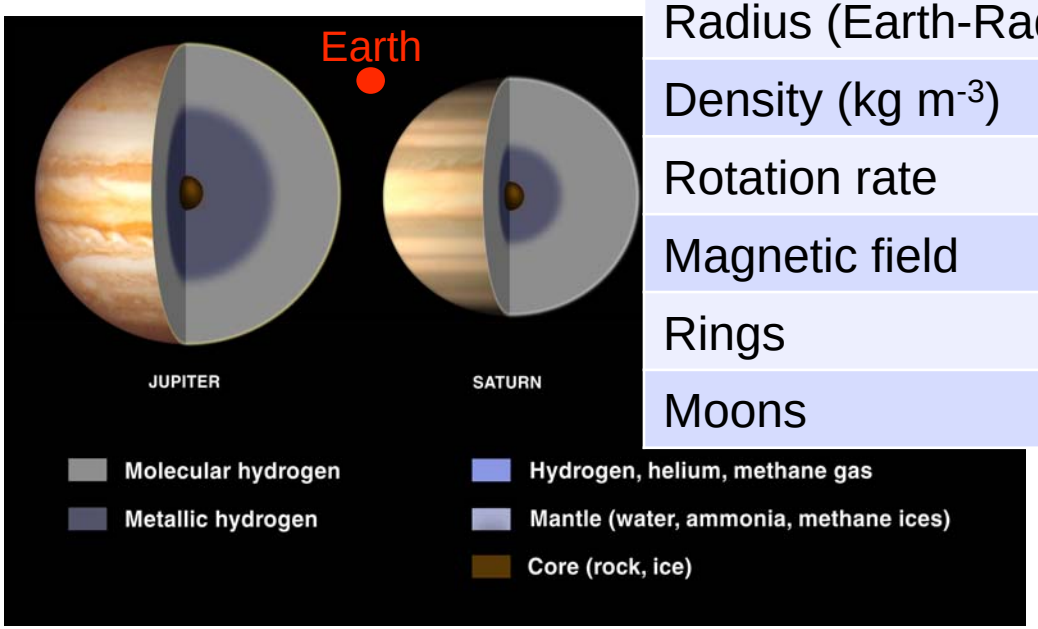

- **Gas giant planets grow so large that they can clear gaps in the disk**



## Jupiter and Saturn Basics

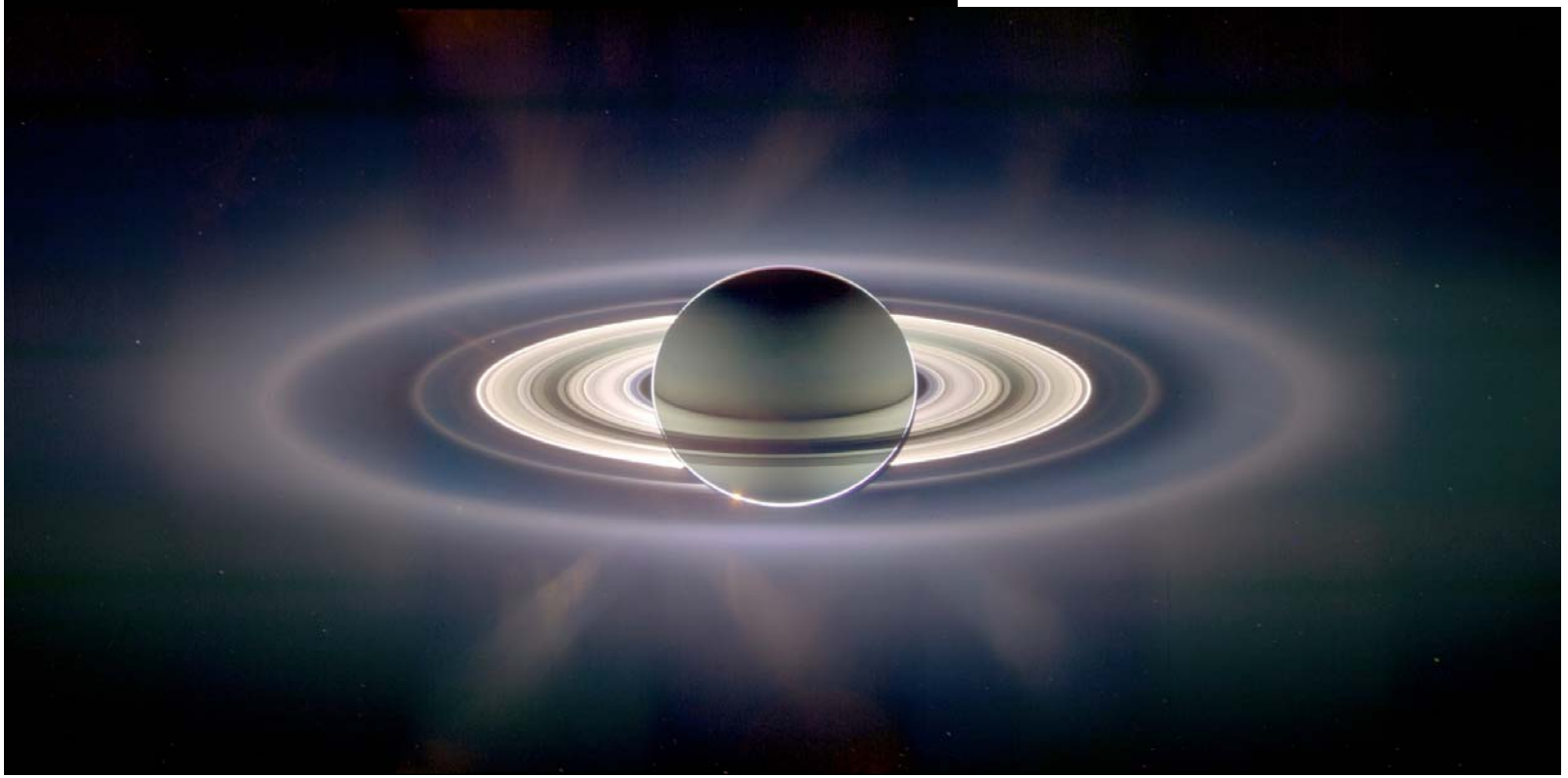
- **So what did we end up with after this…**
  - **Jupiter and Saturn are mostly hydrogen and helium**
  - **Rocky core (if there is one) is very small**
  - **Small amounts of ammonia and water produce the nice colored clouds**

| | Jupiter | Saturn |
|---|---|---|
| Distance from Sun | 5.2 AU | 9.5 AU |
| Orbital Period | 12 years | 29.5 years |
| Mass (Earth-masses) | 318 | 95 |
| Radius (Earth-Radii) | 11 | 9.4 |
| Density (kg $m^{-3}$) | 1380 | 687 |
| Rotation rate | 10 hrs | 10.2 hrs |
| Magnetic field | YES | yes |
| Rings | yes | YES |
| Moons | ~60 | >> 60 |



- Both planets have rings – but that's a story for another day

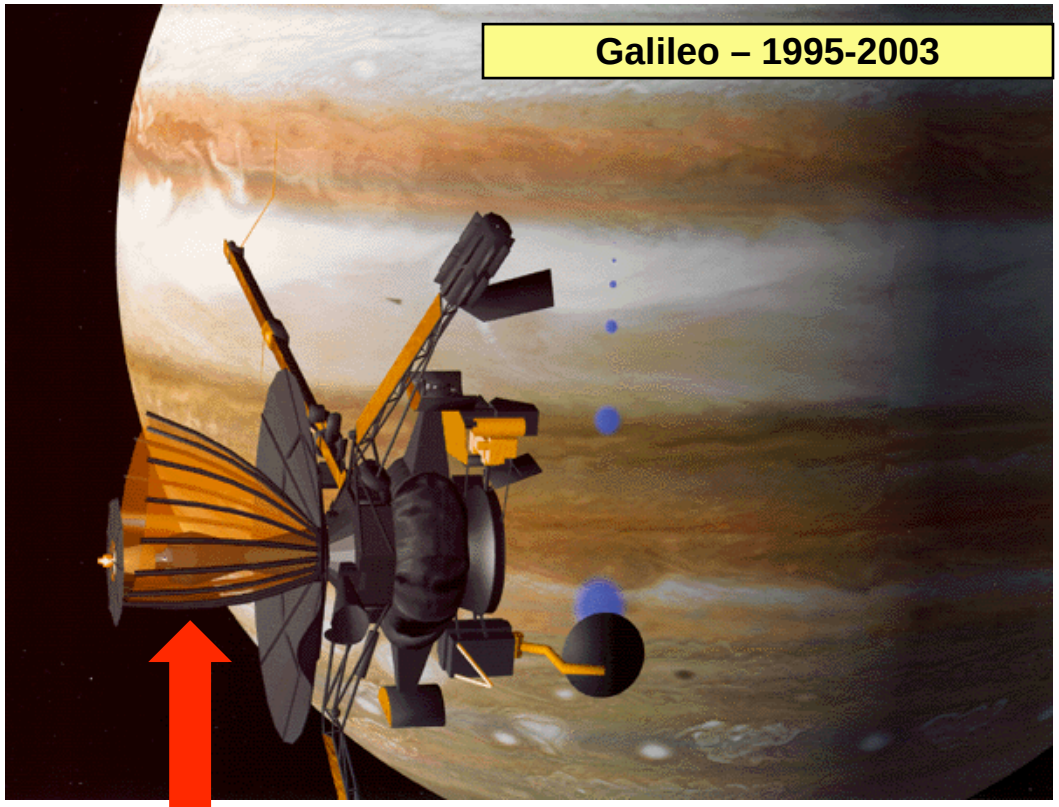
- Jupiter
  - Dust from asteroid collisions
- Saturn
  - Chunks of ice
  - cm to meter sized



- **Both planets have interesting Moons – but that's another lecture (x3 !)**

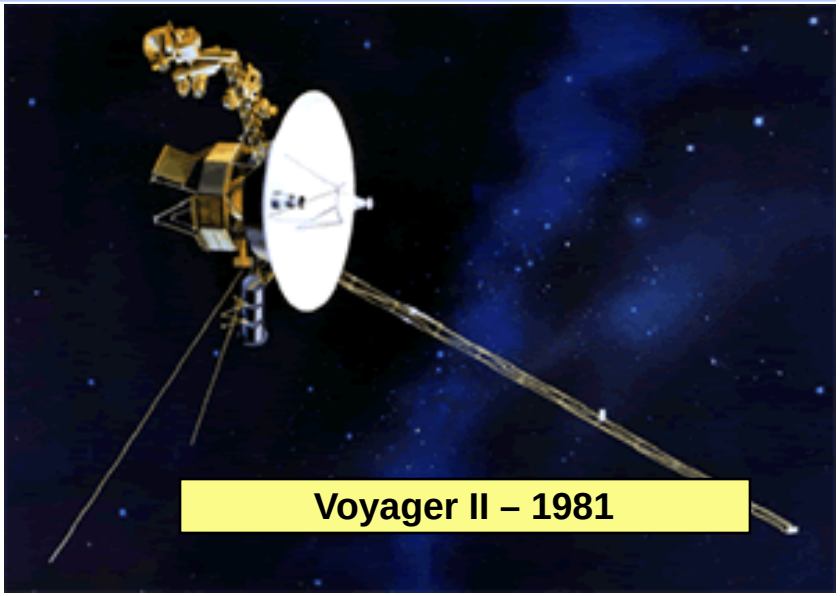
# Exploration of Jupiter and Saturn

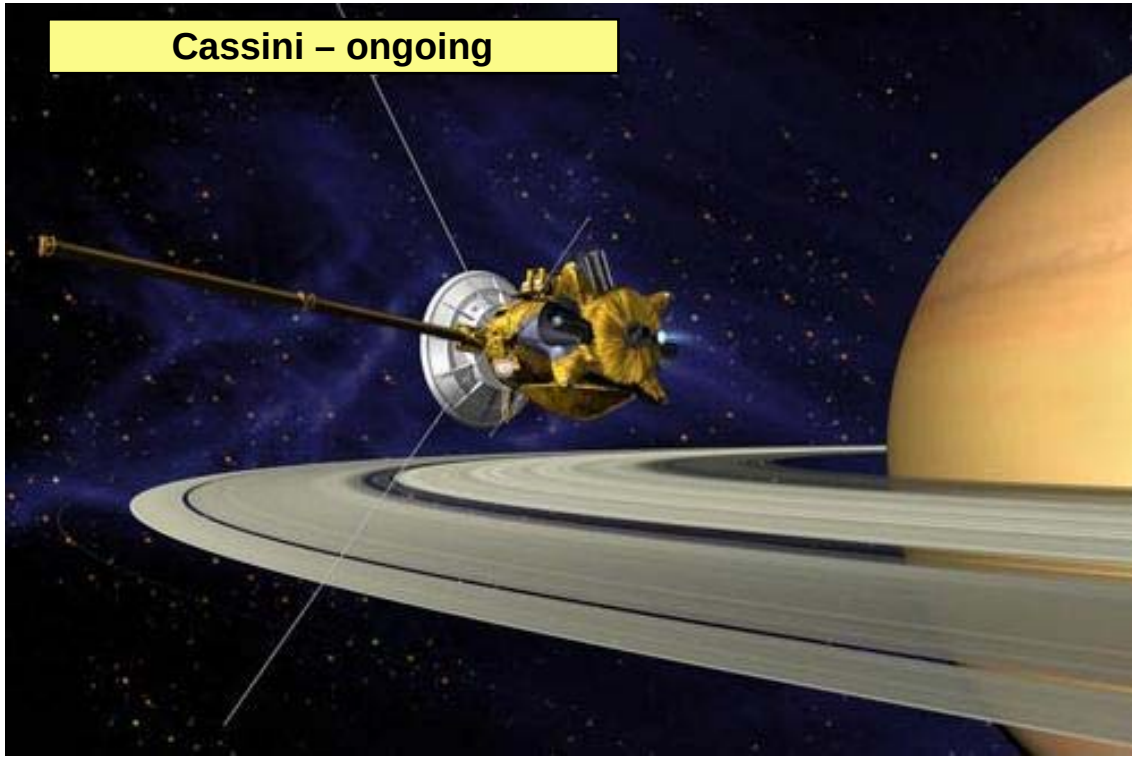
- **Many spacecraft have visited Jupiter**
  - **Jupiter commonly provides gravitational sling shots for spacecraft destined for the outer solar system**
  - **Fly-bys**
    - **Pioneer 10 and 11 (1973 and 1974)**
    - **Voyager 1 and 2 (1979)**
    - **Ulysses (1992)**
    - **Cassini (2000)**
    - **New Horizons (2007)**
  - **Galileo orbiter and entry-probe**


**What's wrong with this picture?**

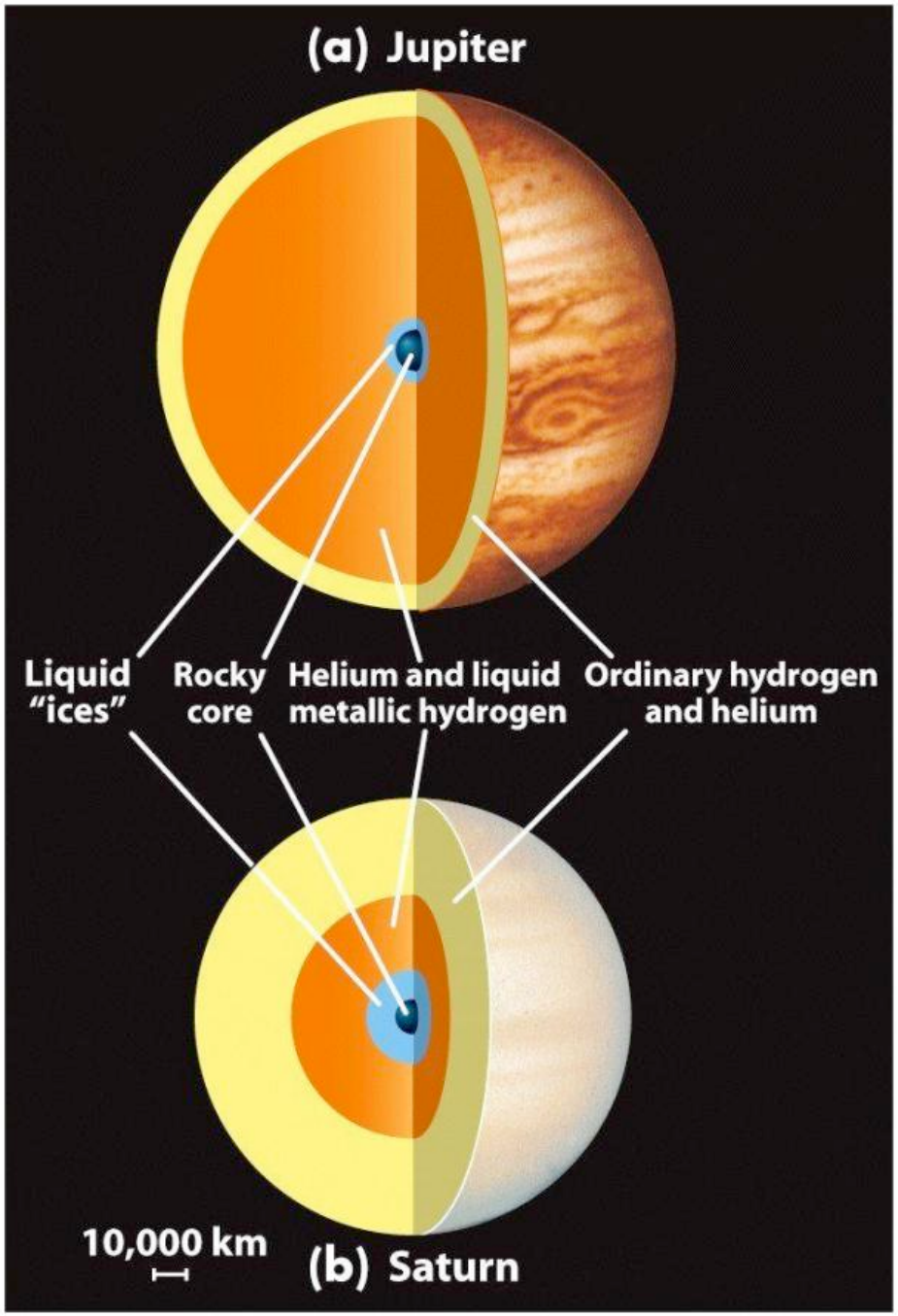
- **Fewer spacecraft have visited Saturn**
  - **Flybys**
    - **Pioneer 11 (1979)**
    - **Voyager I and II (1980 and 1981)**
    - **End of Voyager I planetary encounters**
    - **Voyager II went on to Uranus and Neptune**
  - **Cassini orbiter**
    - **Carried Huygens probe to study Titan**
    - **Ongoing mission**


Voyager II – 1981

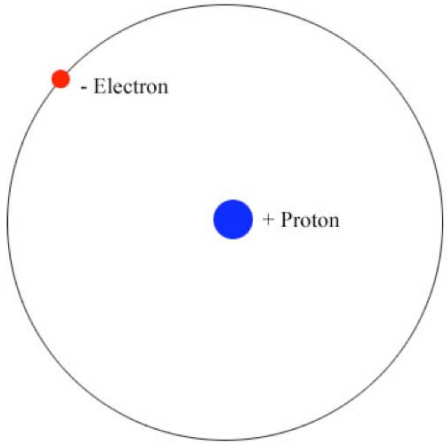

Cassini – ongoing

## Interiors of Jupiter and Saturn

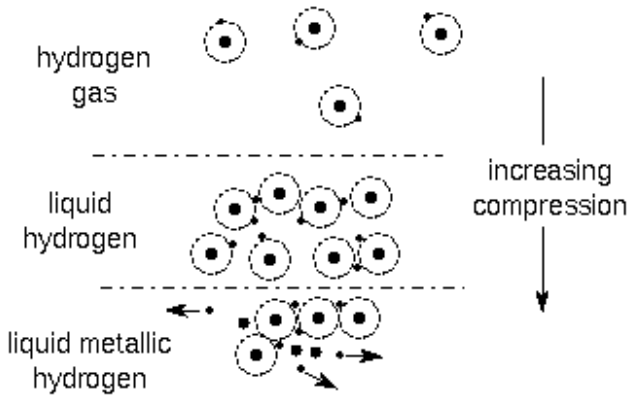
- Rocky/icy core
  - Figured out from oblate shape
  - 2.6% of Jupiter's mass in a core
  - 10% of Saturn's mass in a core
- Deep metallic hydrogen layer
  - High pressure
- Regular hydrogen and helium near the surface
  - Lower pressure
  - But still like a liquid
  - These 'gas' giants are more like liquid giants



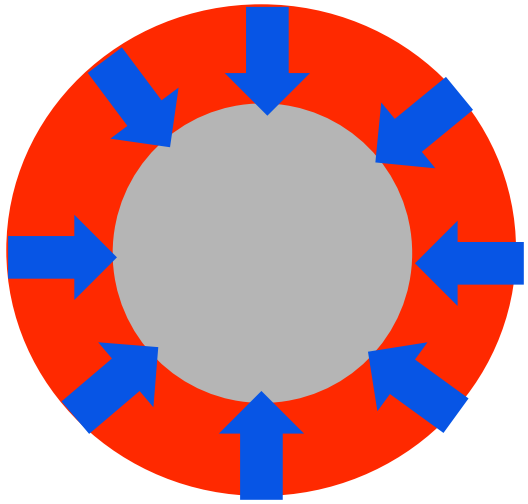
- **Metallic Hydrogen**
  - **Hydrogen is usually a gas – each atom has 1 electron orbiting 1 proton**



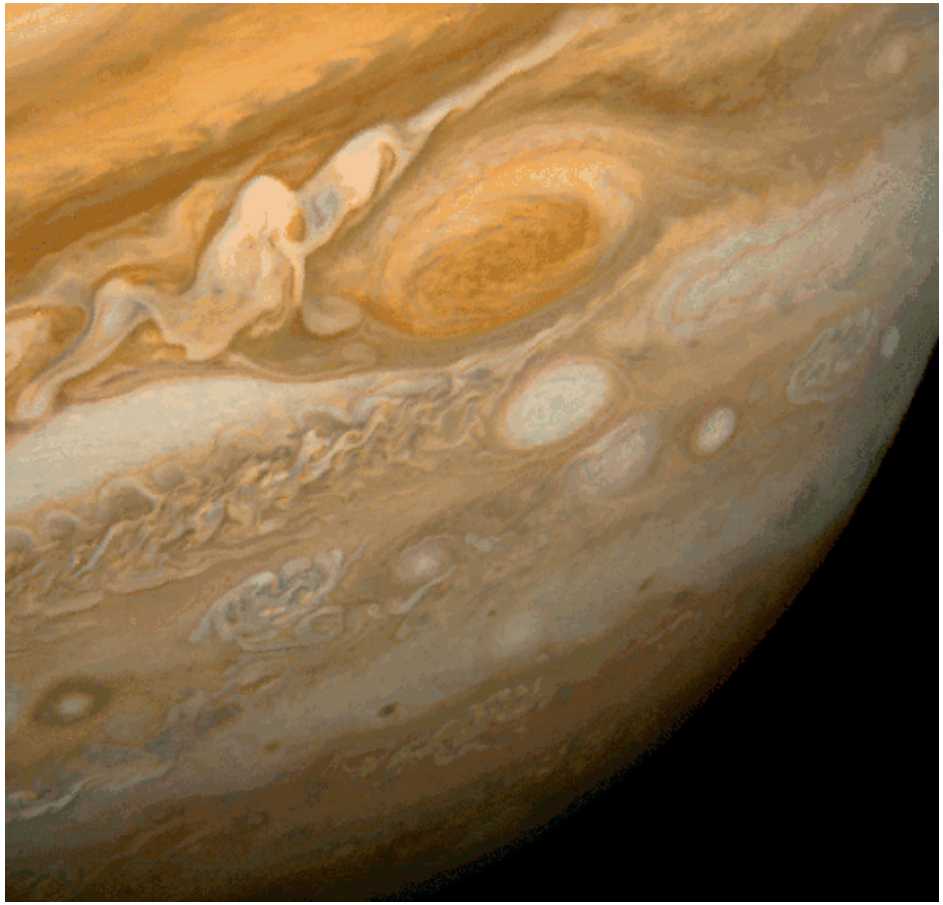

  - **Under very high pressure electrons are not tied to a single atom**
  - **Freely moving electrons make metallic hydrogen a very good conductor of electricity**
    - **Like a metal! – even though it's a liquid**
  - **This pressure comes from gravity**
    - **From the weight of the overlying material**



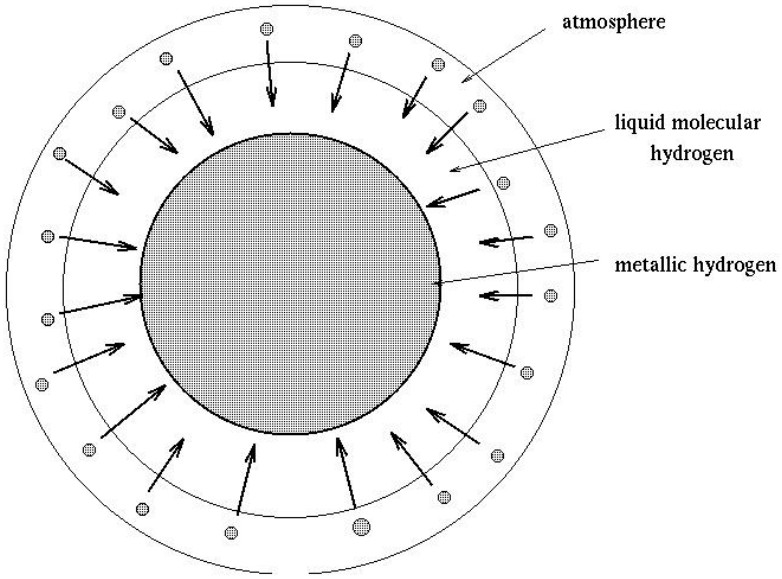

In Jupiter and Saturn the gravitational compression is great enough to squeeze electrons out of the hydrogen atoms so they move easily in the liquid and conduct electricity—liquid "metallic" hydrogen.



- **Jupiter is still cooling off**
  - Jupiter emits 1.6 times as much energy as it absorbs from the sun
  - This extra energy is probably left-over heat from its formation
  - Jupiter is contracting slowly as it cools off
  - This energy can power Jupiter's extreme weather
    - On Earth solar radiation powers our weather
- **Saturn also emits more than it absorbs**
  - The source of this energy is different



- Saturn also emits more than it absorbs
  - The source of this energy is different
- Helium can condense into liquid at Saturn's temperatures
- Liquid Helium can't mix with metallic hydrogen
  - Immiscible – like oil and water
  - So liquid helium binds together into droplets
  - These droplets are Denser than metallic hydrogen – so they sink
- It's raining liquid helium in Saturn's interior
  - This releases energy that powers some of Saturn's weather



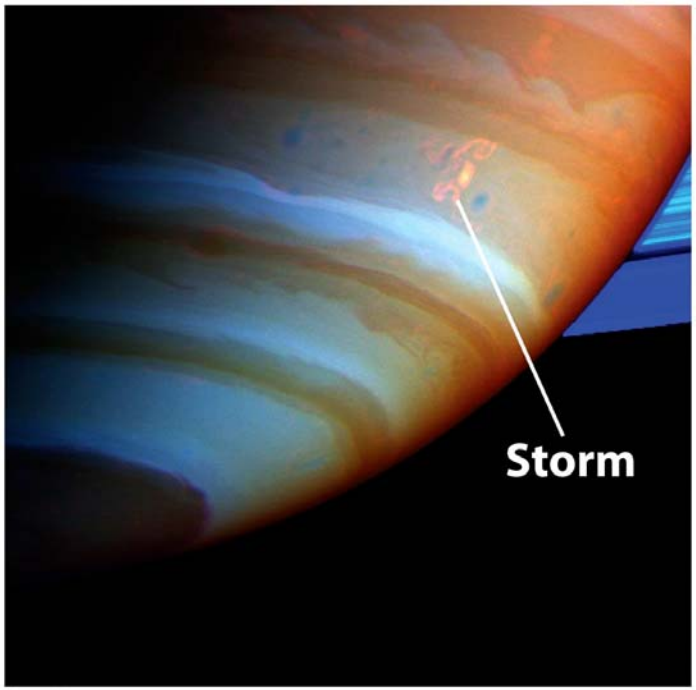
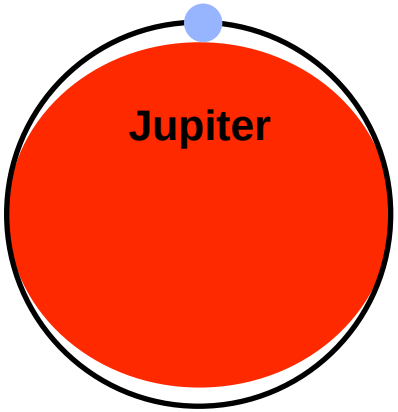
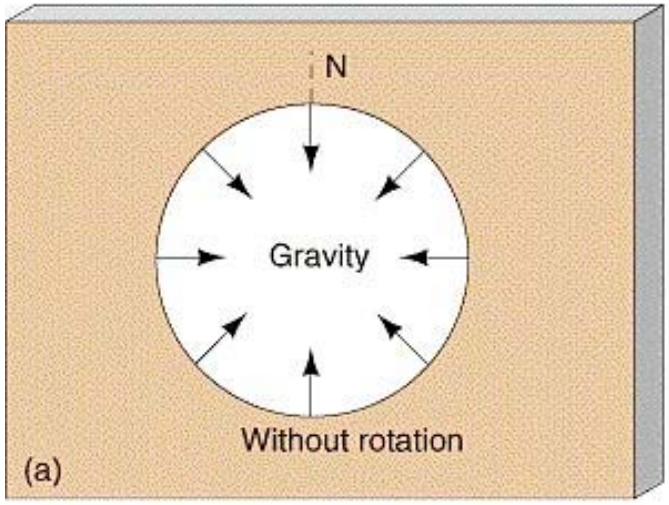



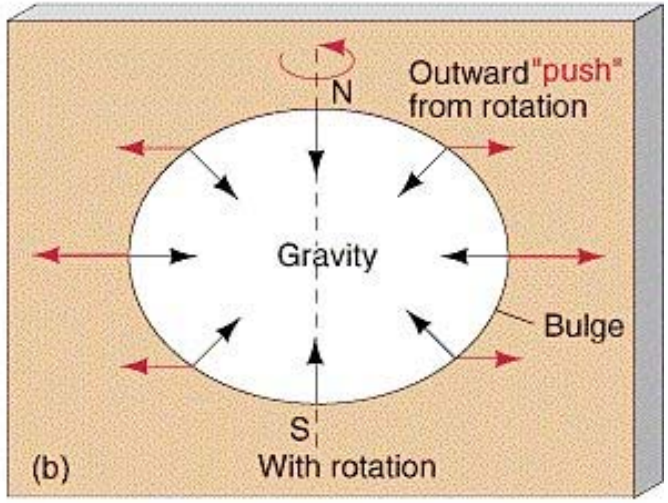

Figure 12-8
*Universe, Eighth Edition*

- **Jupiter and Saturn are both fast rotators**
  - **10 and 10.2 hours**
  - **Both are liquid planets and so have no strength**
  - **Result is that they're both very oblate**
  - **The difference between Jupiter's polar and equatorial diameters equals the size of the Earth!**

| Planet | Equatorial Radius | Polar Radius |
|---|---|---|
| Earth | 6378 km | 6357 km |
| Mars | 3396 km | 3376 km |
| Jupiter | 71,492 km | 66,854 km |

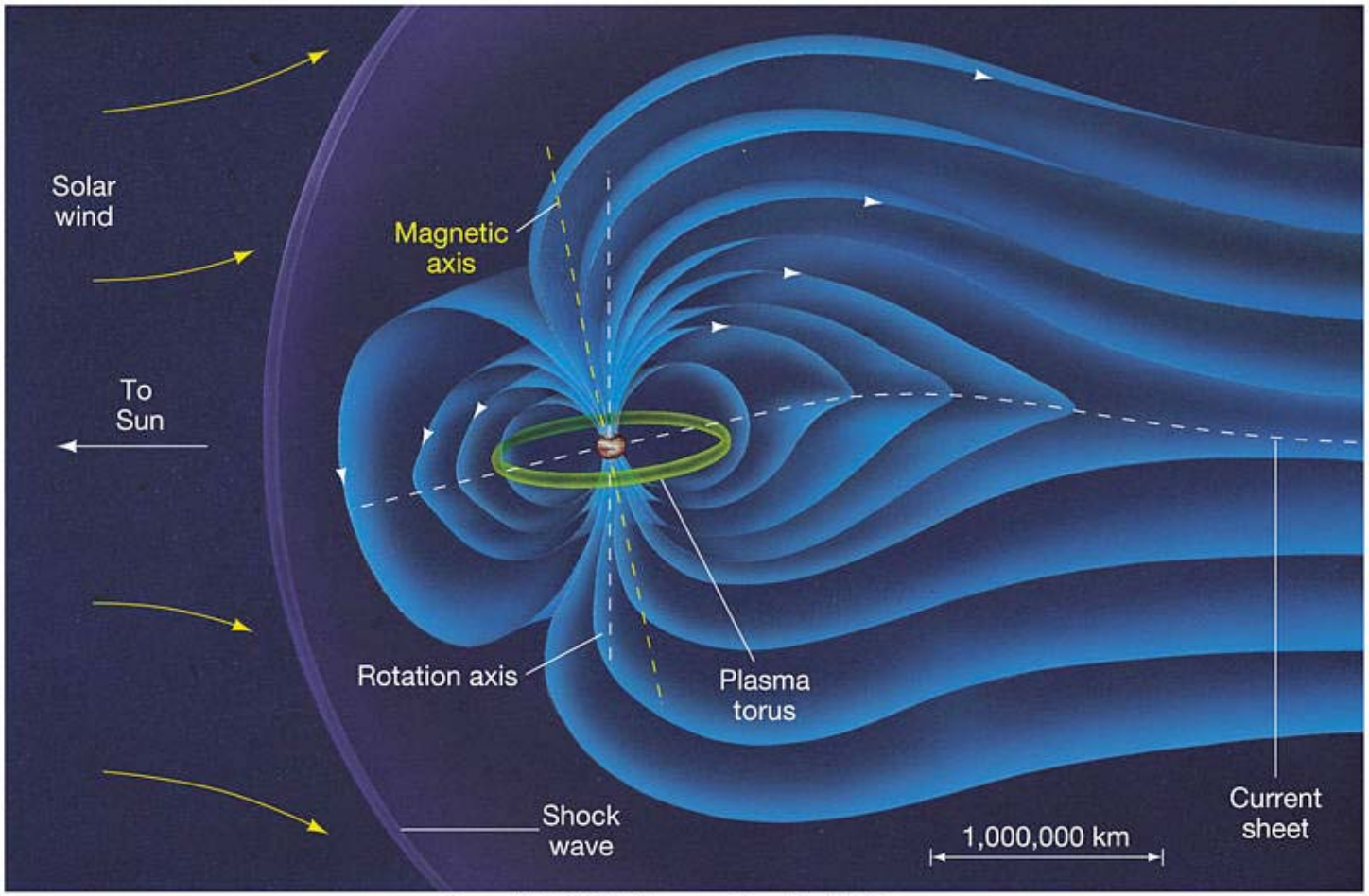


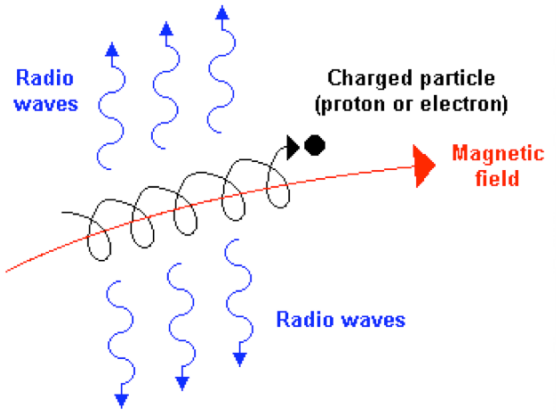



- **What do you get if you combine…**
  - **A highly conductive interior….**
    - **Metallic hydrogen**
  - **Cooling of the interior…**
    - **Vigorous heat loss drives vigorous convection in the interior**
  - **Rapid Rotation….**
    - **The fastest in the solar system**

- **What do you get if you combine…**
  - **A highly conductive interior….**
  - **Cooling of the interior…**
  - **Rapid Rotation….**
- **A magnetic field – a large one…**



- **We can 'see' Jupiter's magnetic field**
  - **Radio emission can be seen from the Earth**
  - **Charged particles spiral along field lines**
- **This is a pretty punishing environment for spacecraft**
  - **Radiation damage in this region fries the electronics**
  - **Special radiation-hardened circuits for Jupiter spacecraft**

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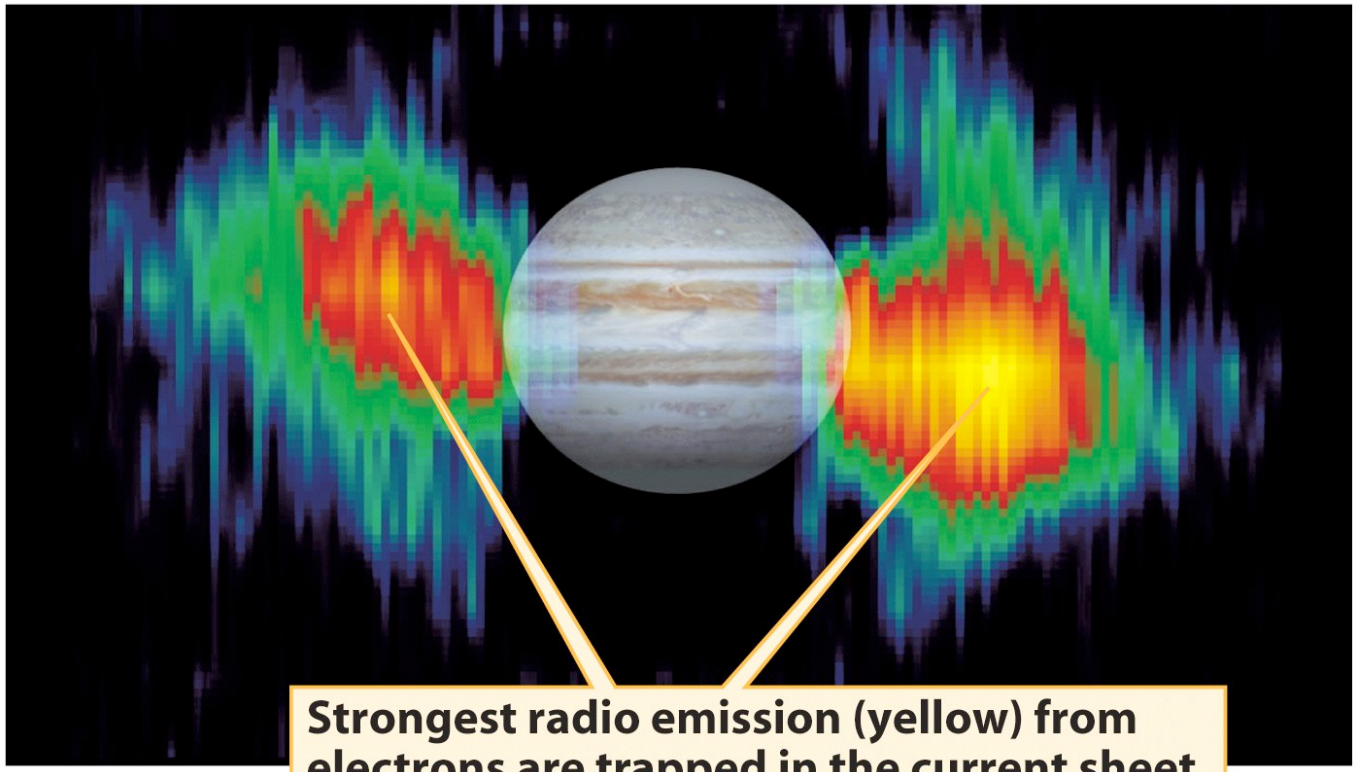
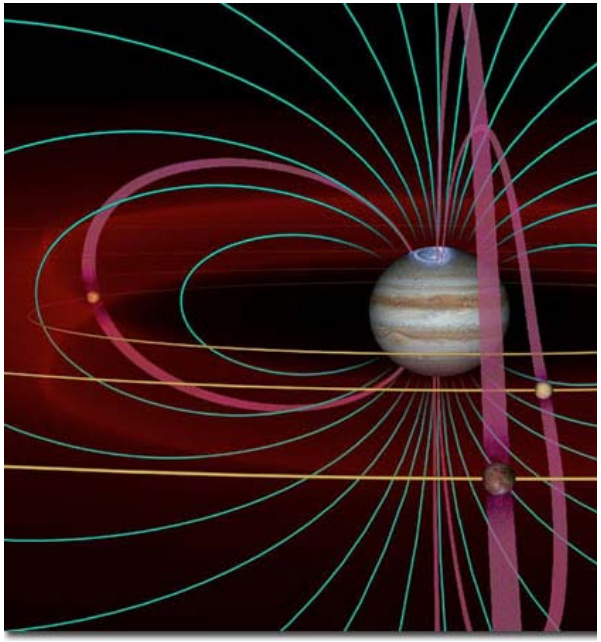
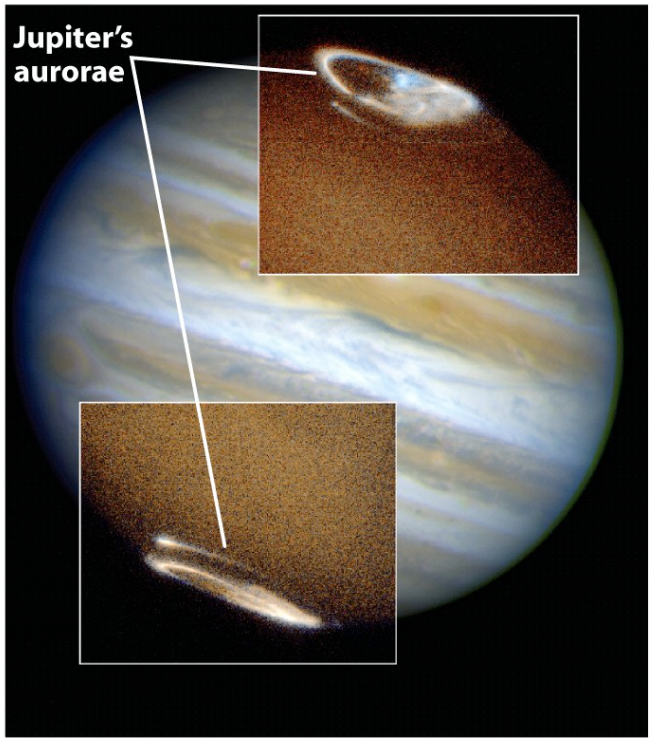
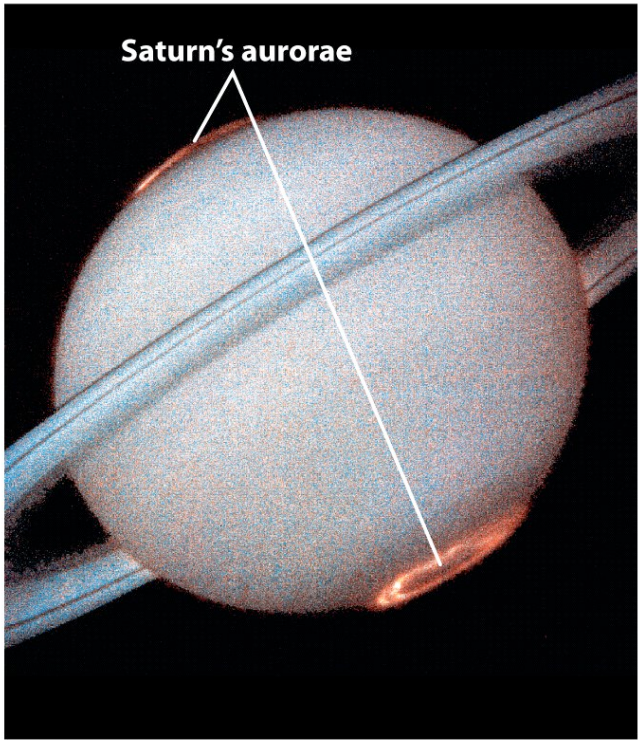


- Charged particles travel along the field lines all the way to the pole
  - Hit the upper atmosphere causing emission
  - Aurora – works the same on the Earth





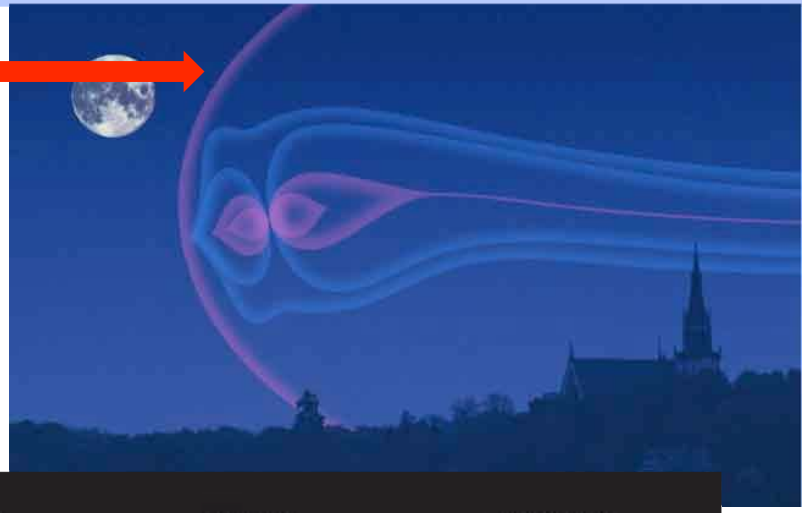

(a) Jupiter

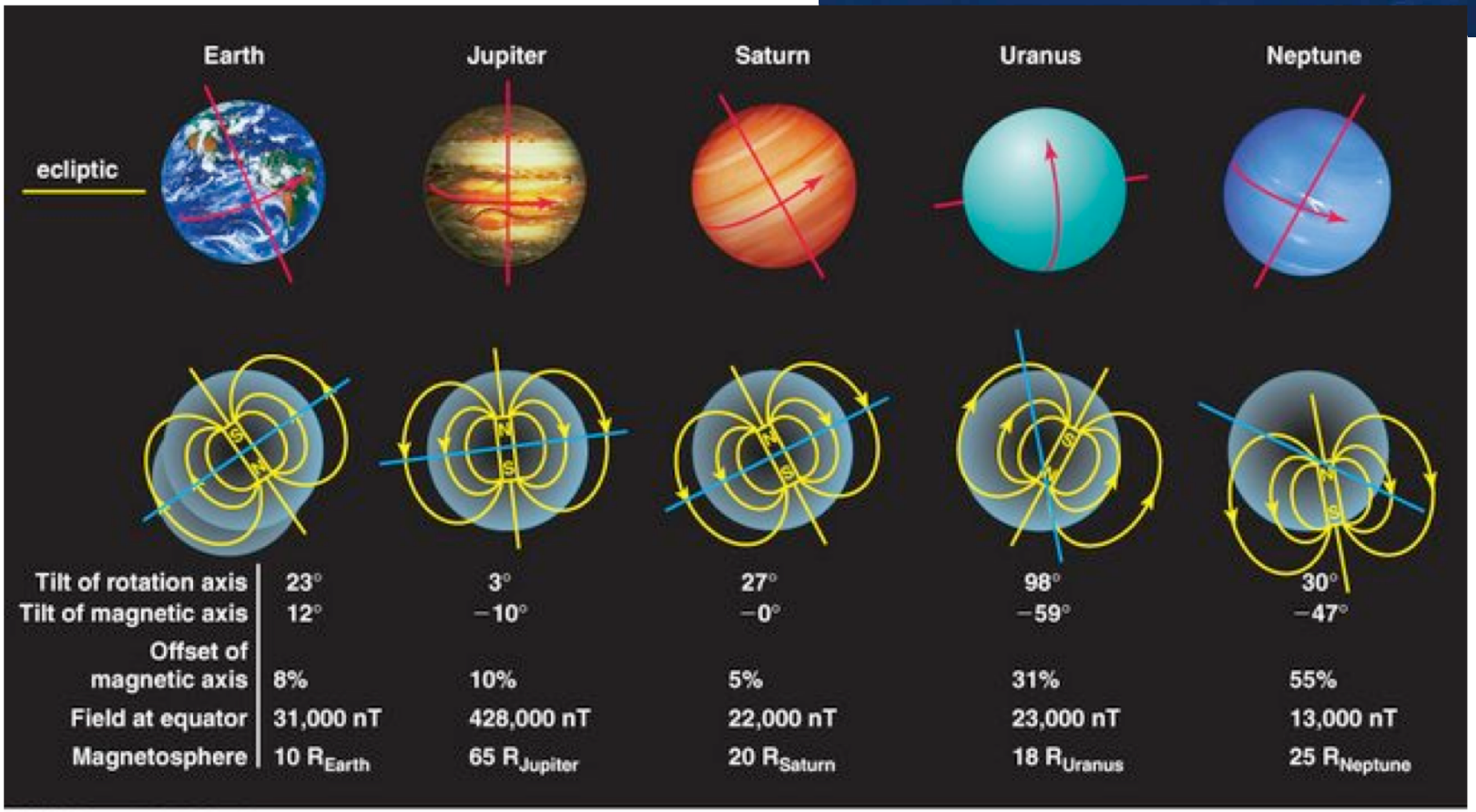



(b) Saturn

Figure 12-15
*Universe, Eighth Edition*

- **Jupiter's magnetic field is**
  - **14 times more powerful than Earth's**
  - **About 70 times larger**
- **Saturn's magnetic field is**
  - **Weaker than Earth at it's surface**
  - **But still larger**

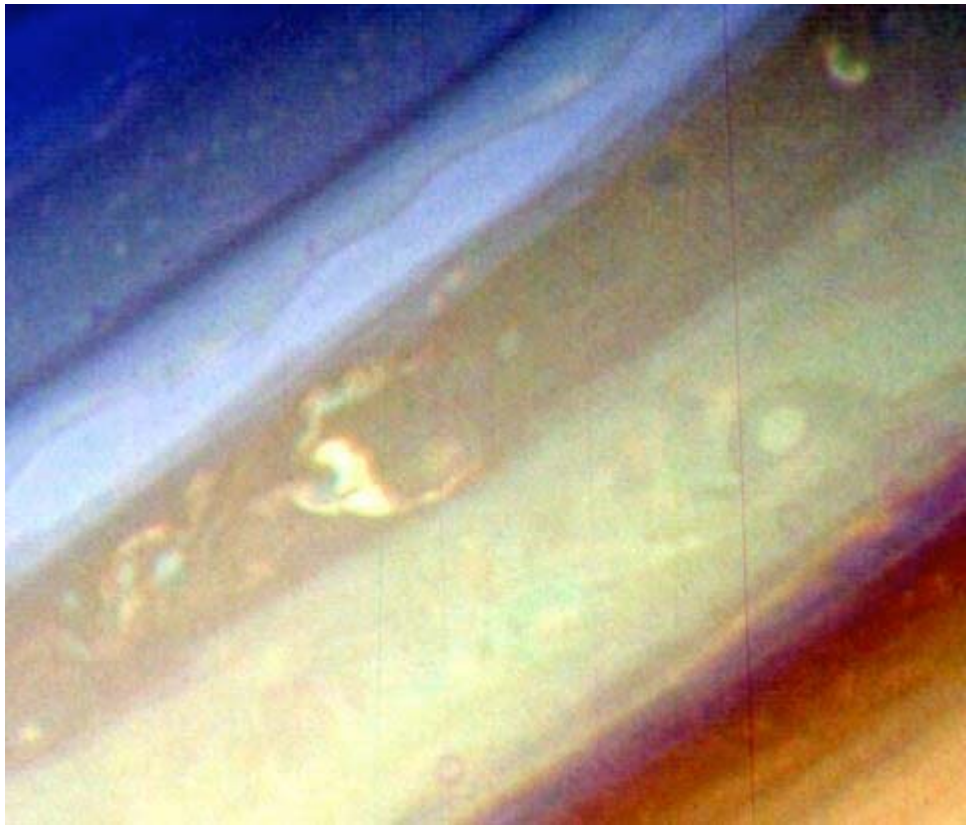


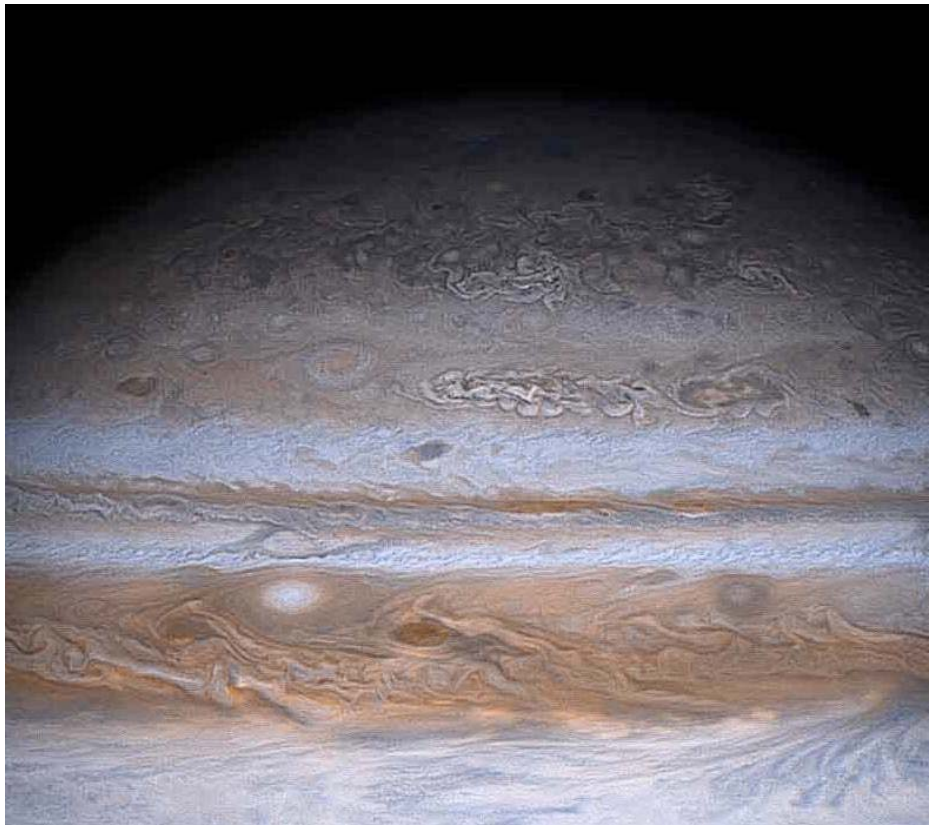



| | Earth | Jupiter | Saturn | Uranus | Neptune |
|---|---|---|---|---|---|
| Tilt of rotation axis | 23° | 3° | 27° | 98° | 30° |
| Tilt of magnetic axis | 12° | −10° | −0° | −59° | −47° |
| Offset of magnetic axis | 8% | 10% | 5% | 31% | 55% |
| Field at equator | 31,000 nT | 428,000 nT | 22,000 nT | 23,000 nT | 13,000 nT |
| Magnetosphere | 10 $R_{Earth}$ | 65 $R_{Jupiter}$ | 20 $R_{Saturn}$ | 18 $R_{Uranus}$ | 25 $R_{Neptune}$ |

## Atmospheres of Jupiter and Saturn

- Both Jupiter and Saturn have very active atmospheres
- Powered by
  - Internal heat – more weather than expected from solar energy alone
  - Rapid rotation – circulation stretched out into zones





- **Composition is very similar except...**
  - **Jupiter's gravity makes for a more compressed cloud structure**
  - **Saturn's Helium has mostly rained out into the interior**

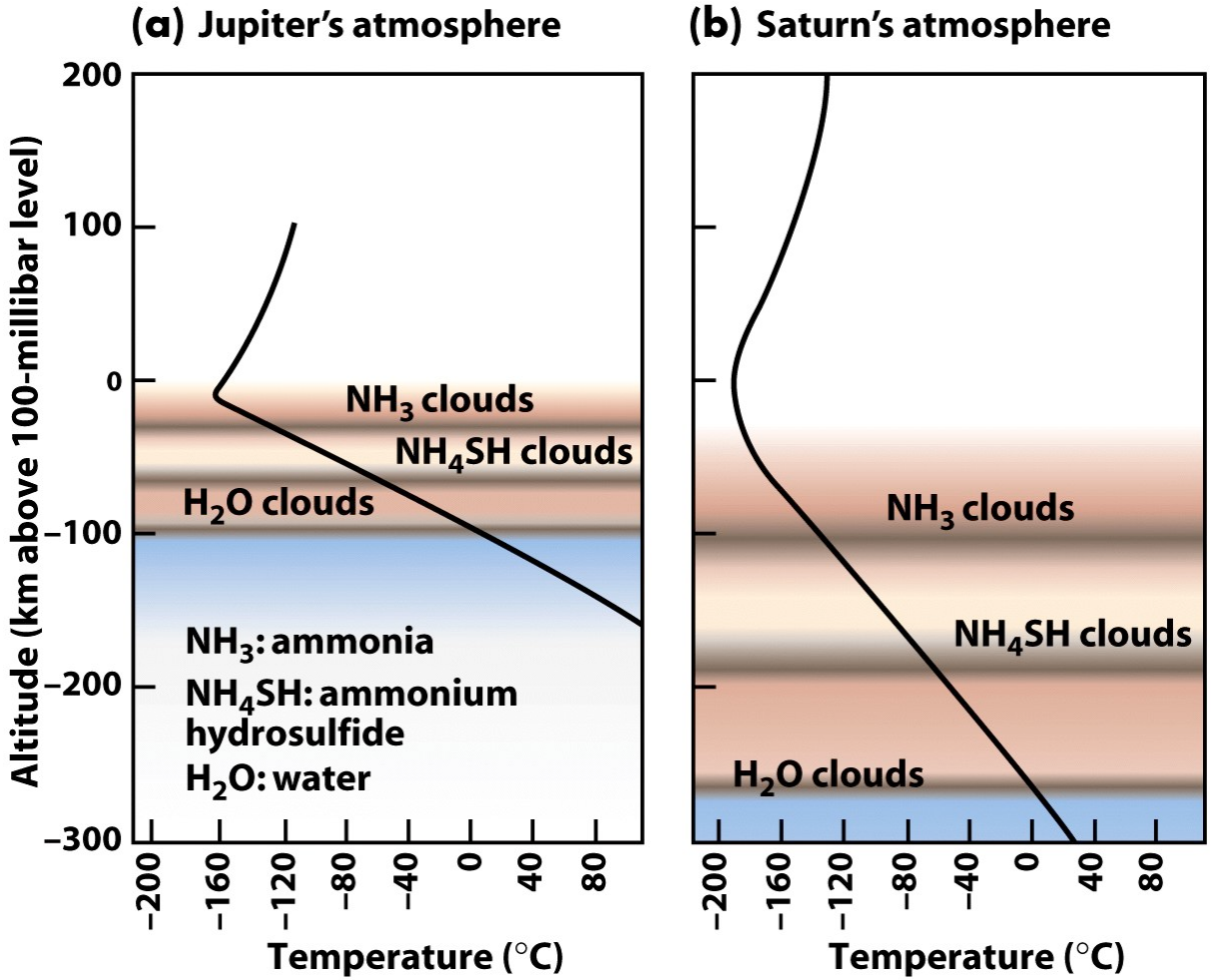



Figure 12-9
*Universe, Eighth Edition*

- **Rotation is a mess**
  - **Surface rotates faster than interior**
    - **Known from magnetic field**
  - **Equator rotates faster than the pole**

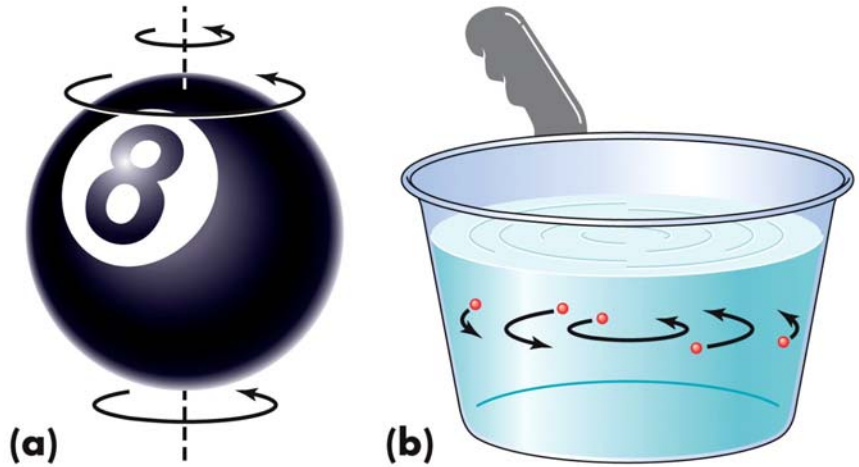



Figure 12-3
*Universe, Eighth Edition*

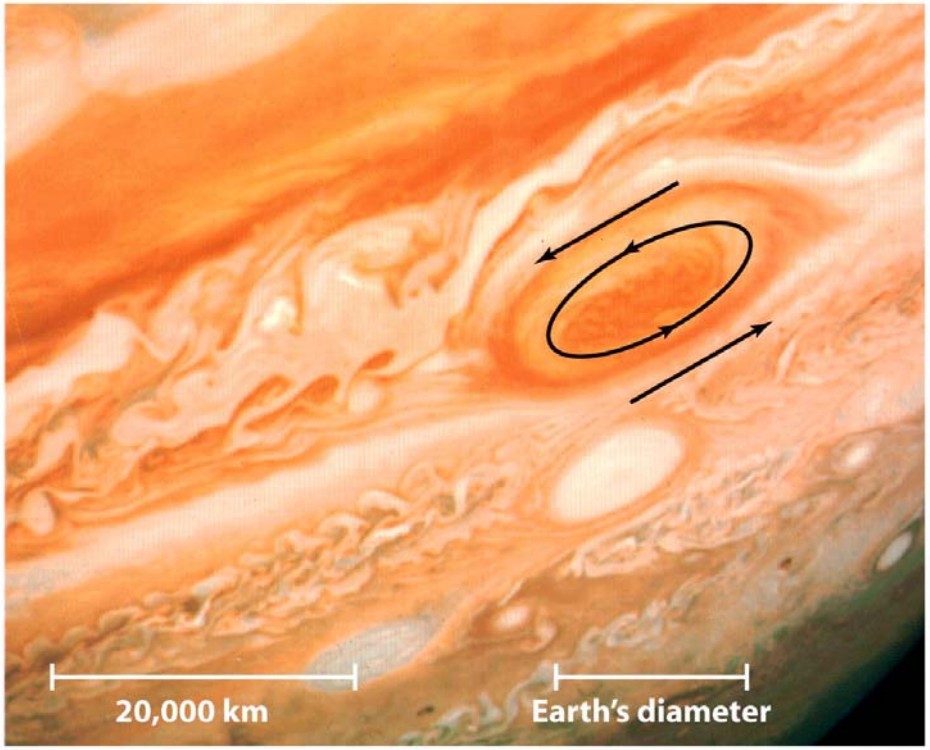
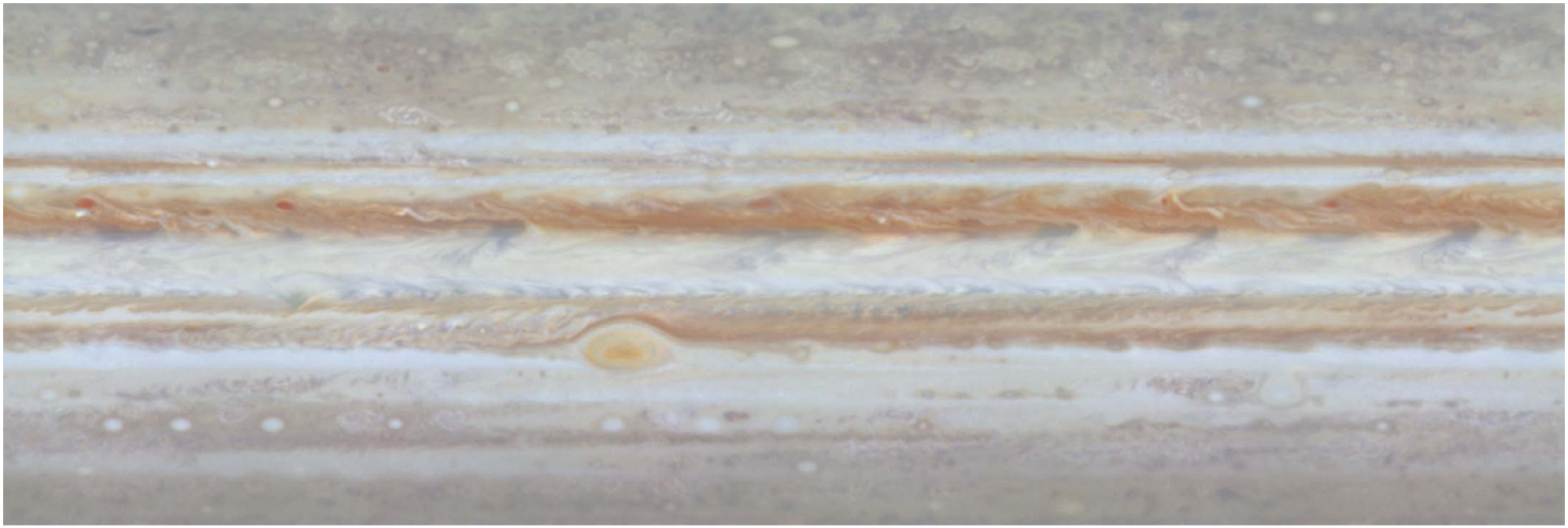



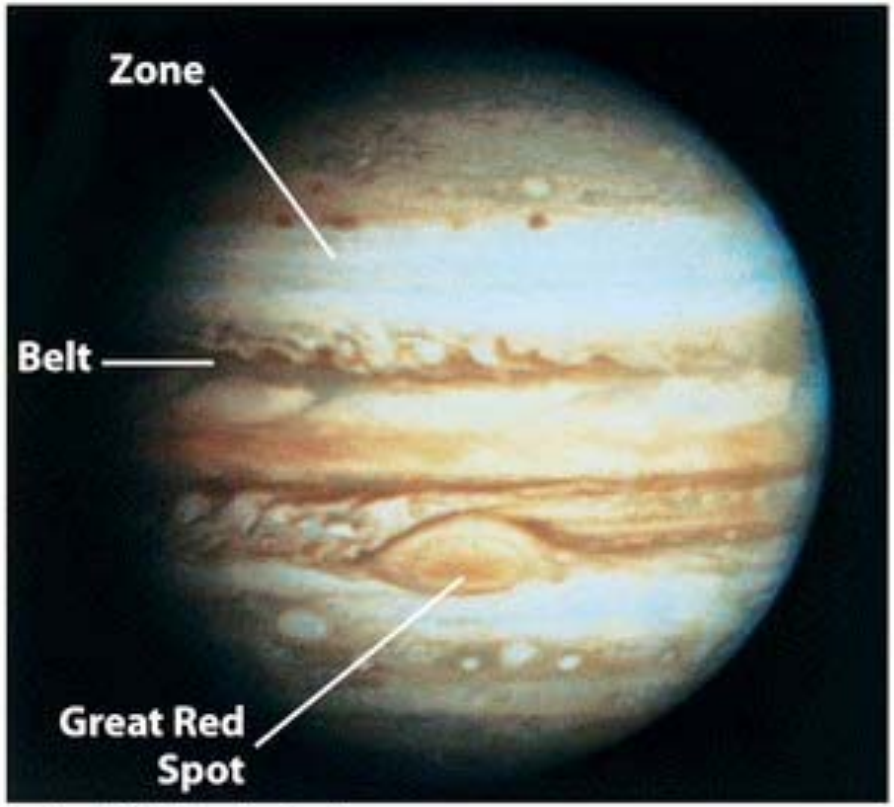

Figure 12-5
*Universe, Eighth Edition*


- **Consequence is that bands shear past each other**
  - **Creates turbulence and storms**

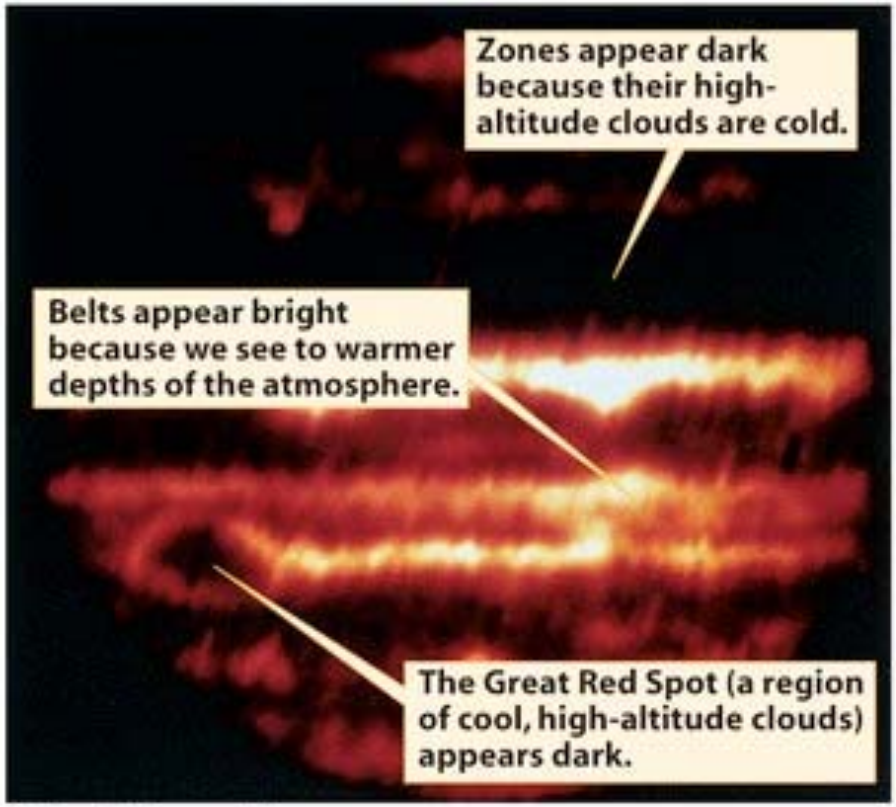
- **Jupiter's atmosphere consists of belts and zones**
  - **Light areas are zones**
  - **Dark areas are belts**
- **Composition almost all hydrogen and Helium (99%)**
  - **Trace amounts of water, ammonia and methane give colors**
- **Storms form at the boundaries of belts and zones**



- **Belts**
  - Dark bands in visible
  - Bright in infrared – warm
  - Deeper clouds
- **Zones**
  - Bright bands in visible
  - Dark in infrared – cold
  - Higher clouds



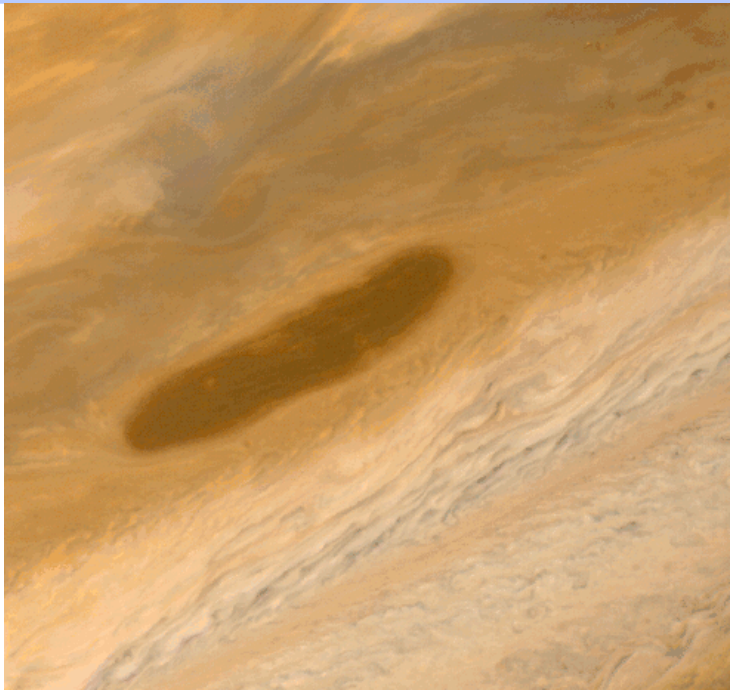

(a) Visible-light image




(b) Infrared image

- **Storms on Jupiter come in two types**

- **Brown ovals**
  - **Holes in the clouds that show warmer layers below**



- **White ovals**
  - **Higher altitude clouds that are cooler**

- **The mother of all storms – The Great Red Spot**
  - **At least 400 years old**
  - **Anti-cyclone**


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

**Figure 12-4**
***Universe, Eighth Edition***

- **Dark in the infrared – cold = high altitude**
  - **But also dark in the visible…**
  - **Opposite to the usual high-altitude storms**

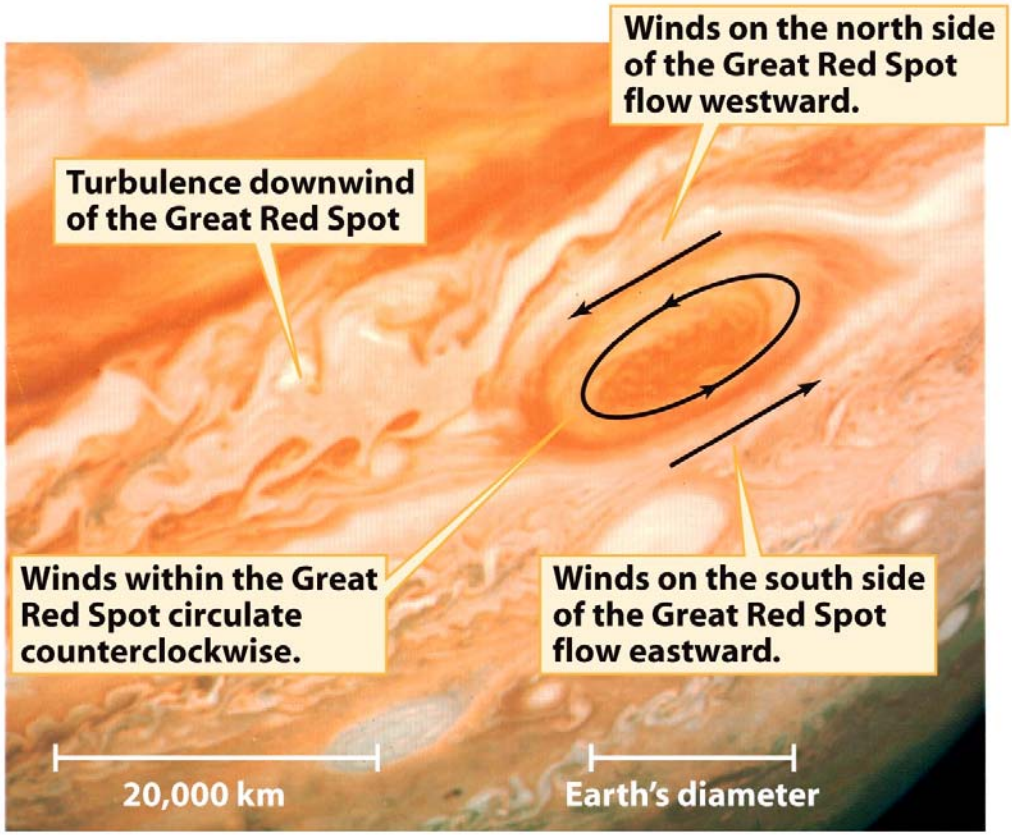



Figure 12-5
*Universe, Eighth Edition*

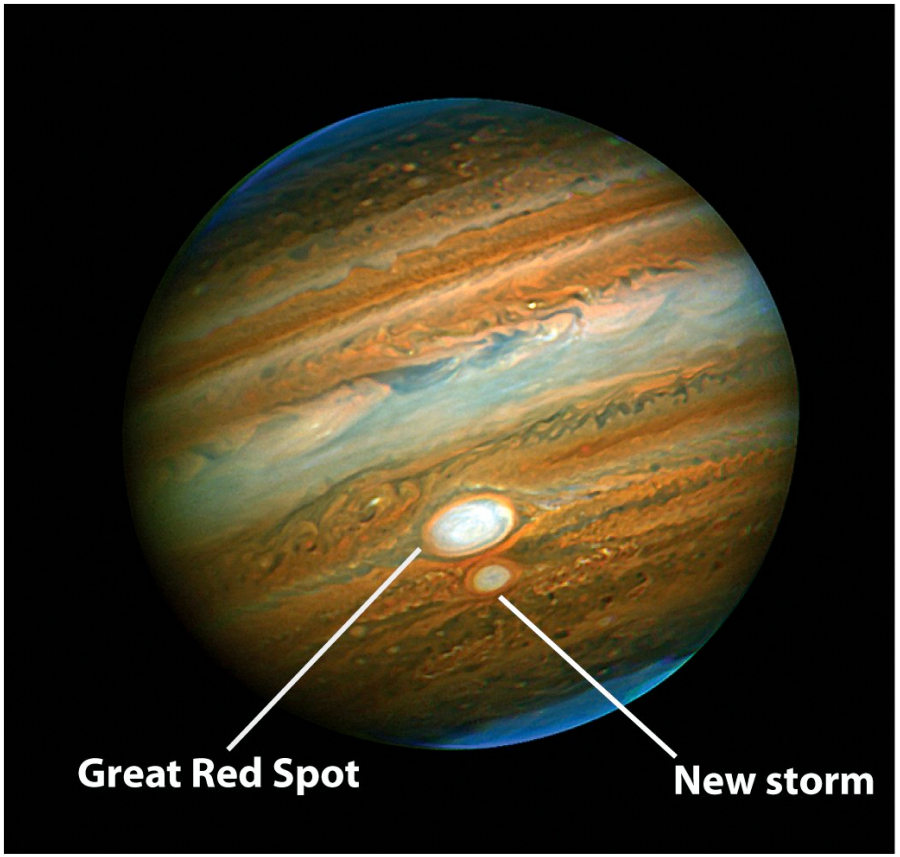




Figure 12-6
*Universe, Eighth Edition*

- Saturn also produces storms
  - Higher wind speed – reason unknown
  - Shorter lifetime than Jupiter's storms
  - Saturn's winds exceed 1000 km per hour

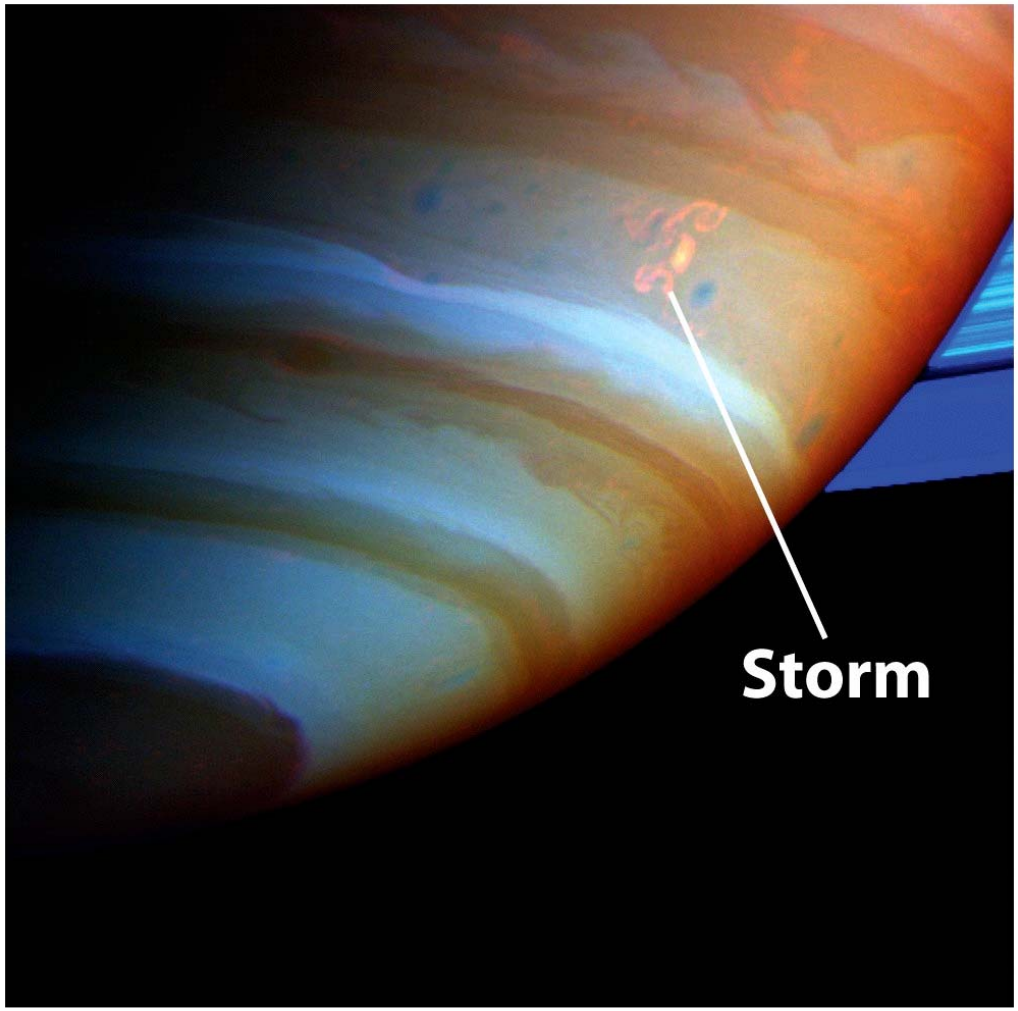
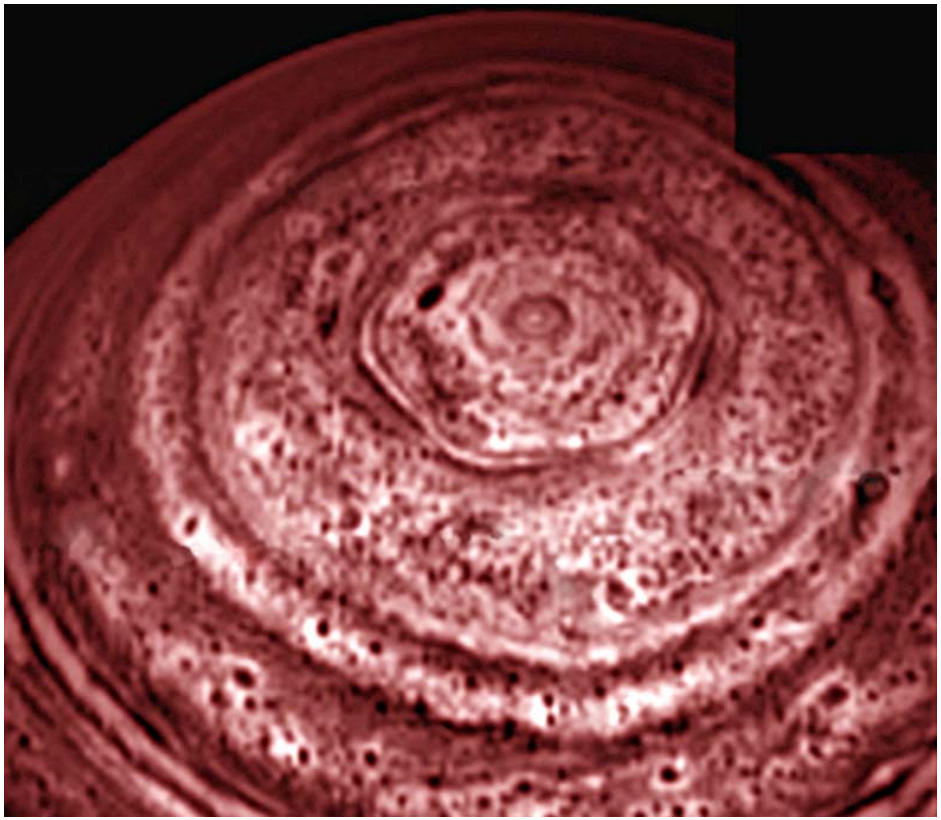
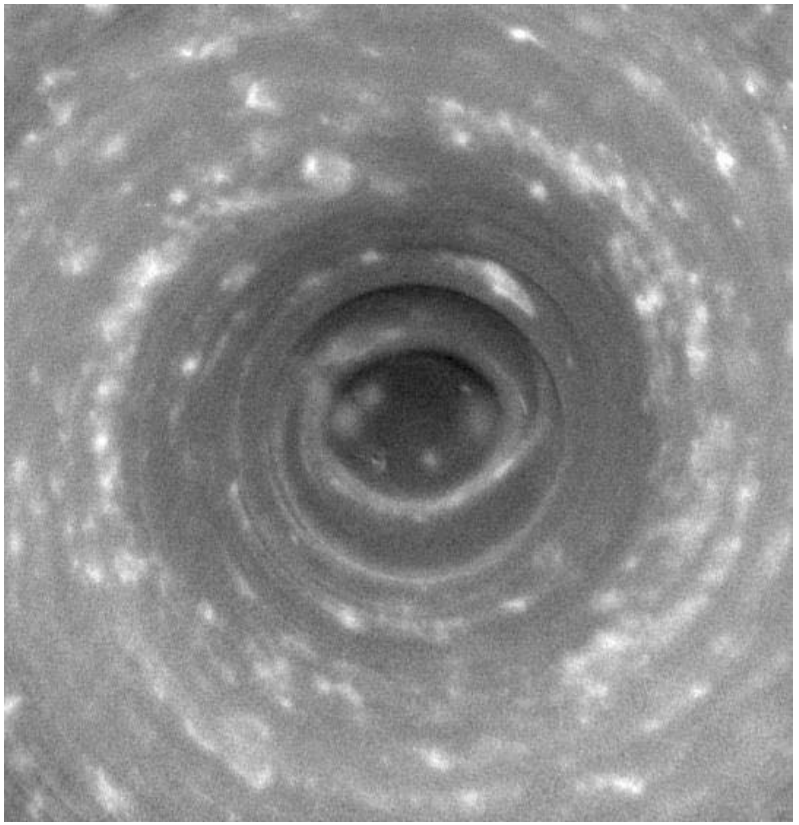



Figure 12-8
*Universe, Eighth Edition*

- **Cassini is studying unusual storms at Saturn's north and south poles**



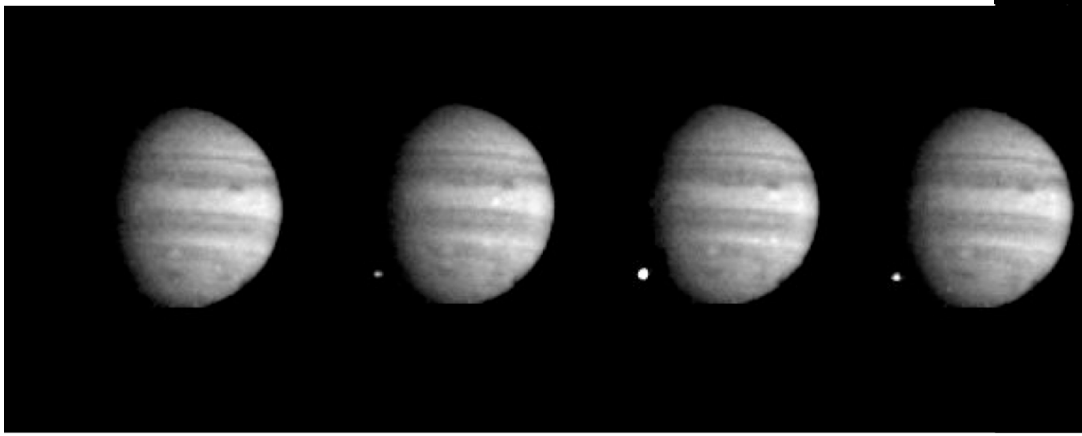
**North Pole**



**South Pole**

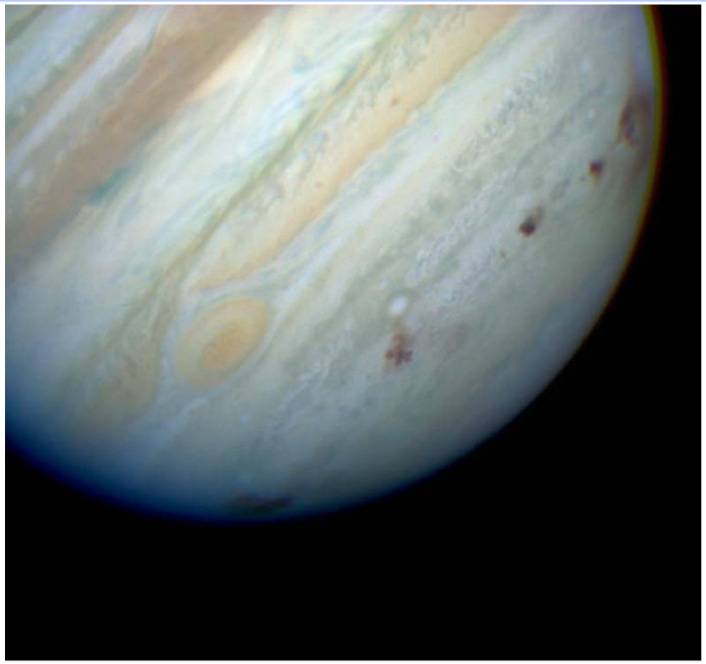
## Impact of comet Shoemaker-Levy 9

- Occurred in 1994
- Previous close pass to Jupiter cause the comet to break up
- Created a chain of impacts
- Unfortunately the impacts occurred on the night side
  - We had to wait for them to rotate into view

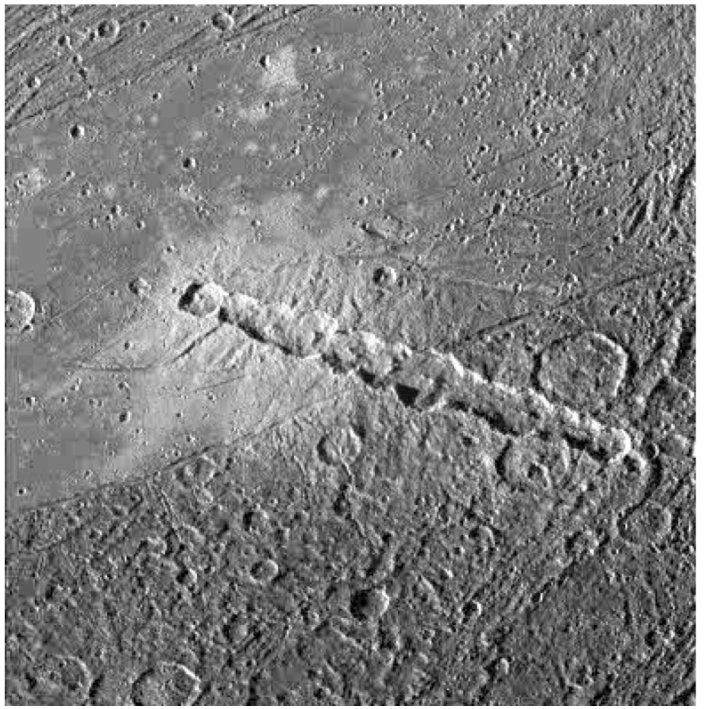


View of fireball from Galileo

- We were able to see the impact sites from telescopes
  - Clues about the interior



- This has happened many times before
  - Many crater chains visible on Ganymede
  - Comets are commonly disrupted into strings of particles by Jupiter's gravity



## In this lecture…

- The frost line
  - Dominance of ice in the outer solar system
- Formation of Jupiter and Saturn
  - Oligarchic growth
- Interiors of Jupiter and Saturn
  - Metallic Hydrogen
  - Helium rainfall
  - Magnetic fields
- Atmosphere of Jupiter and Saturn
- Impact of comet Shoemaker-Levy 9

## Next: Moons of Jupiter

- Reading
  - Chapter 12 to revise this lecture
  - Chapter 13 for next lecture