The Gas Giants

Giant Planets

- The dominant masses of the Solar System.
- What determines their internal structure?
- How did they form and evolve?
- What about extra-solar planets?

Basic Parameters

	a (AU)	P_{orb} (yrs)	P_{rot} (hrs)	R (km)	M (10^{26} kg)	Obliquity	Density g/cc	T_s K
Jupiter	5.2	11.8	9.9	71492	19.0	3.1°	1.33	165
Saturn	9.6	29.4	10.6	60268	5.7	26.7°	0.69	134
Uranus	19.2	84.1	17.2R	24973	0.86	97.9°	1.32	76
Neptune	30.1	165	16.1	24764	1.02	29.6°	1.64	72

Data from Lodders and Fegley 1998. Surface temperature T_s and radius R are measured at 1 bar level.

Compositions (1)

- Briefly:
  - (Surface) compositions based mainly on spectroscopy
  - Interior composition relies on a combination of models and inferences of density structure from observations
  - We expect the basic starting materials to be similar to the composition of the original solar nebula
- Surface atmospheres dominated by H_2 or He:

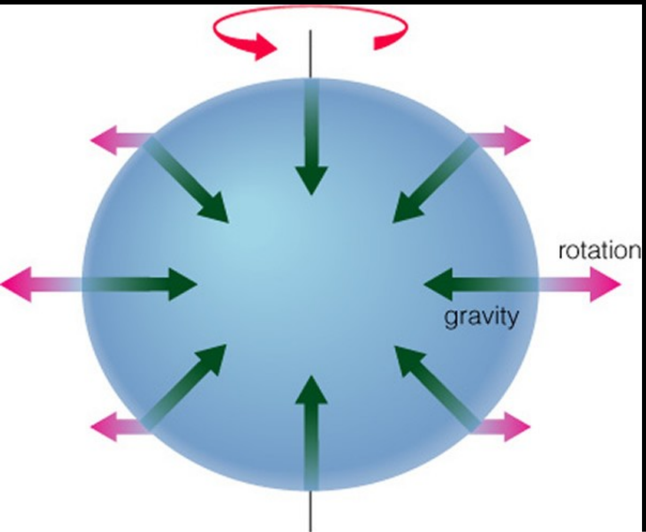
	Solar	Jupiter	Saturn	Uranus	Neptune
H_2	83.3%	86.2%	96.3%	82.5%	80%
He	16.7%	13.6%	3.3%	15.2% (2.3% CH_4)	19% (1% CH_4)

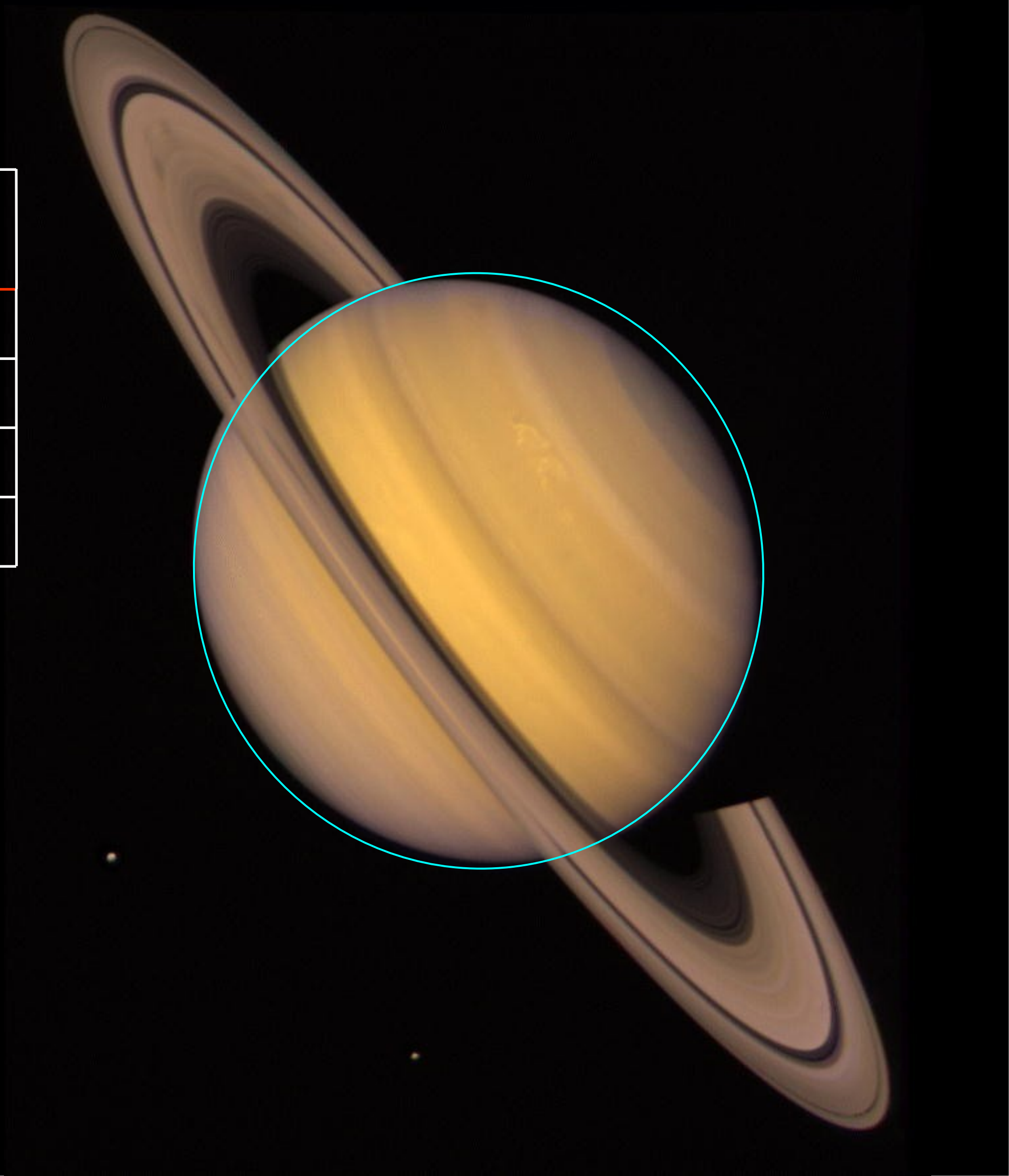
(Lodders and Fegley 1998)

Shapes

- Rotation induces significant flattening of compressible material

Body	a/(a-b)	Rotation Period (d)
Sun	10000	25.4
Earth	298	1.0
Jupiter	16	0.41
Saturn	10	0.426





Pressure

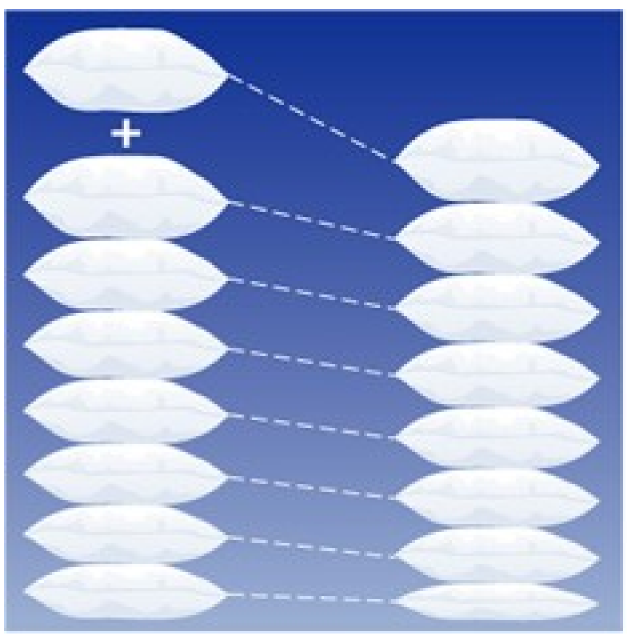
- Hydrostatic approximation $\frac{dP}{dr} = -\rho(r)g(r)$
- Mass-density relation $\frac{dM(r)}{dr} = 4\pi\rho(r)r^2$
- These two can be combined (how?) to get the pressure at the centre of a *uniform* body P_c:

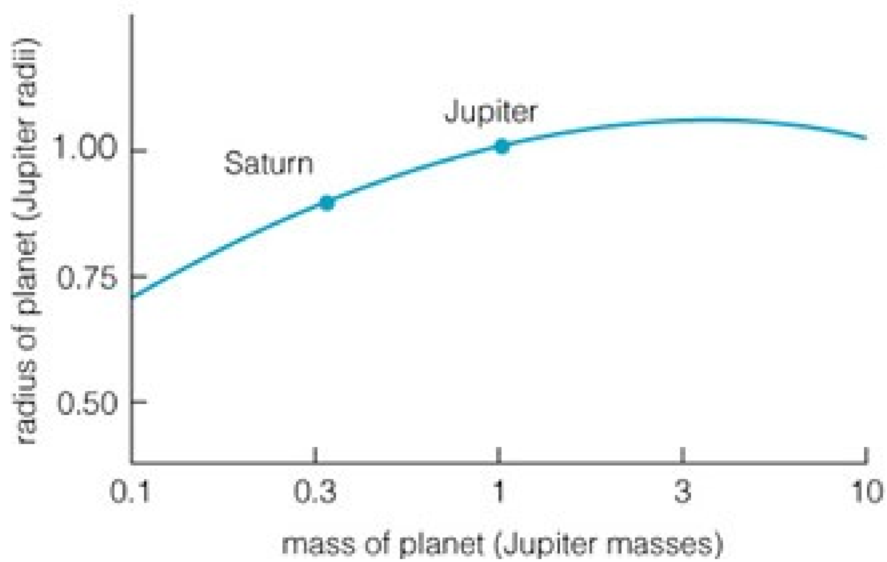
$$P_c = \frac{3GM^2}{8\pi R^4}$$

- Jupiter P_c=7 Mbar, Saturn P_c=1.3 Mbar, U/N P_c=0.9 Mbar
- This expression is only approximate (why?) (estimated true central pressures are 70 Mbar, 42 Mbar, 7 Mbar) (why larger than estimate?)
- But it gives us a good idea

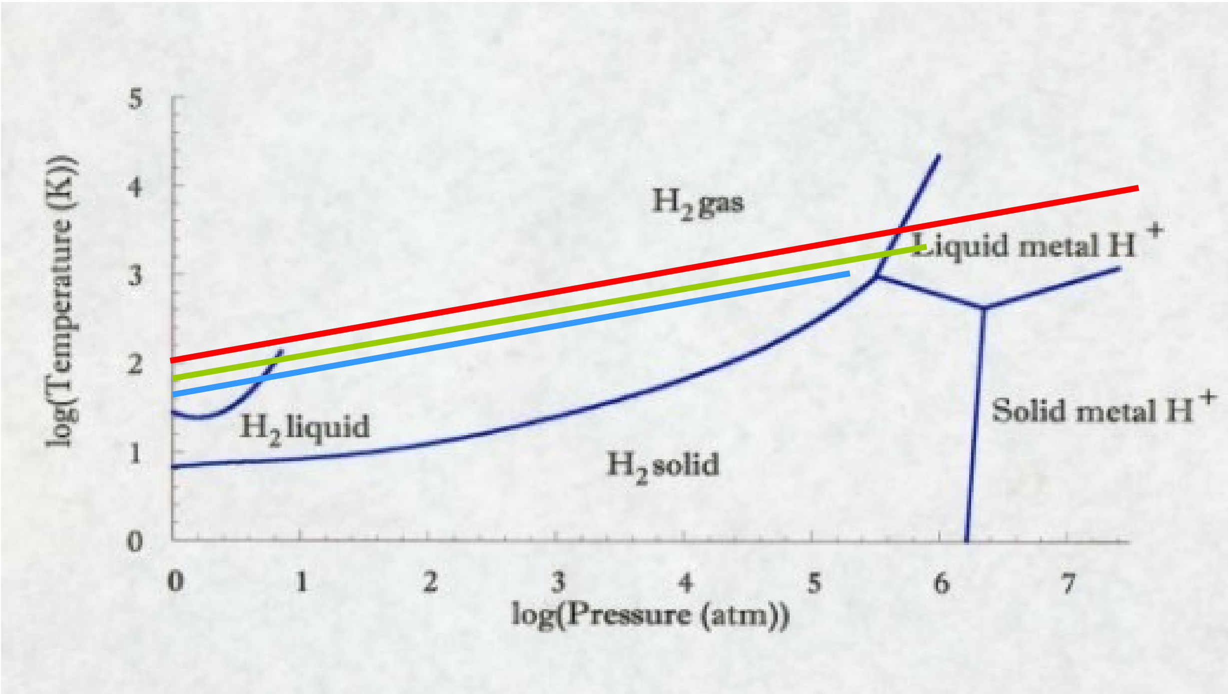
Size-Mass Relationship

- As with terrestrials, composition can be guessed from mean density. But the high compressibility of volatiles must be accounted for
  - Initially, as they accrete mass they grow in radius
  - But at a mass of ~300 earth masses, further accretion causes the radius to decrease.





Hydrogen phase diagram



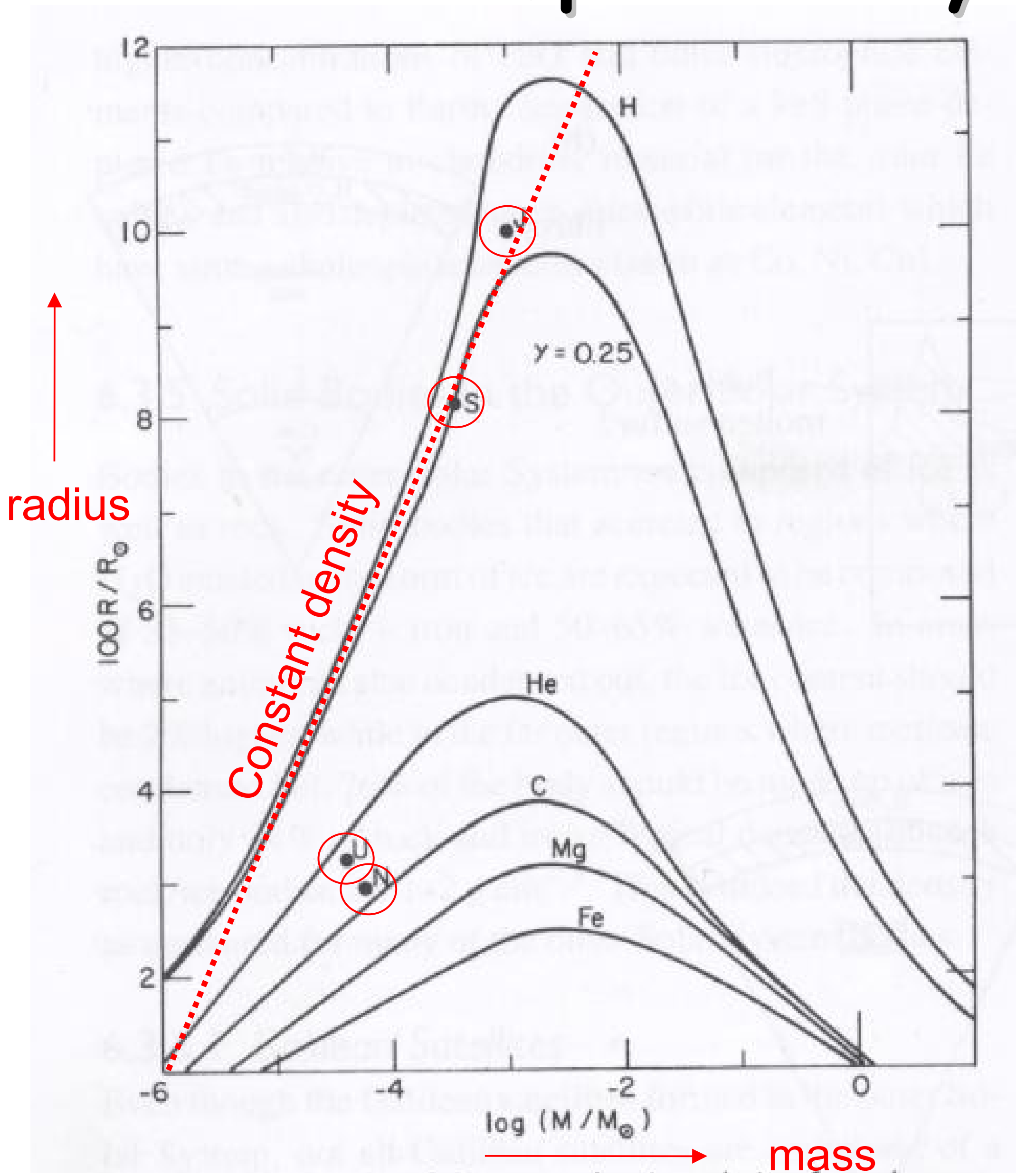
Hydrogen undergoes a phase change at ~100 GPa to metallic hydrogen (conductive)

It is also theorized that He may be insoluble in metallic H. This has implications for Saturn.

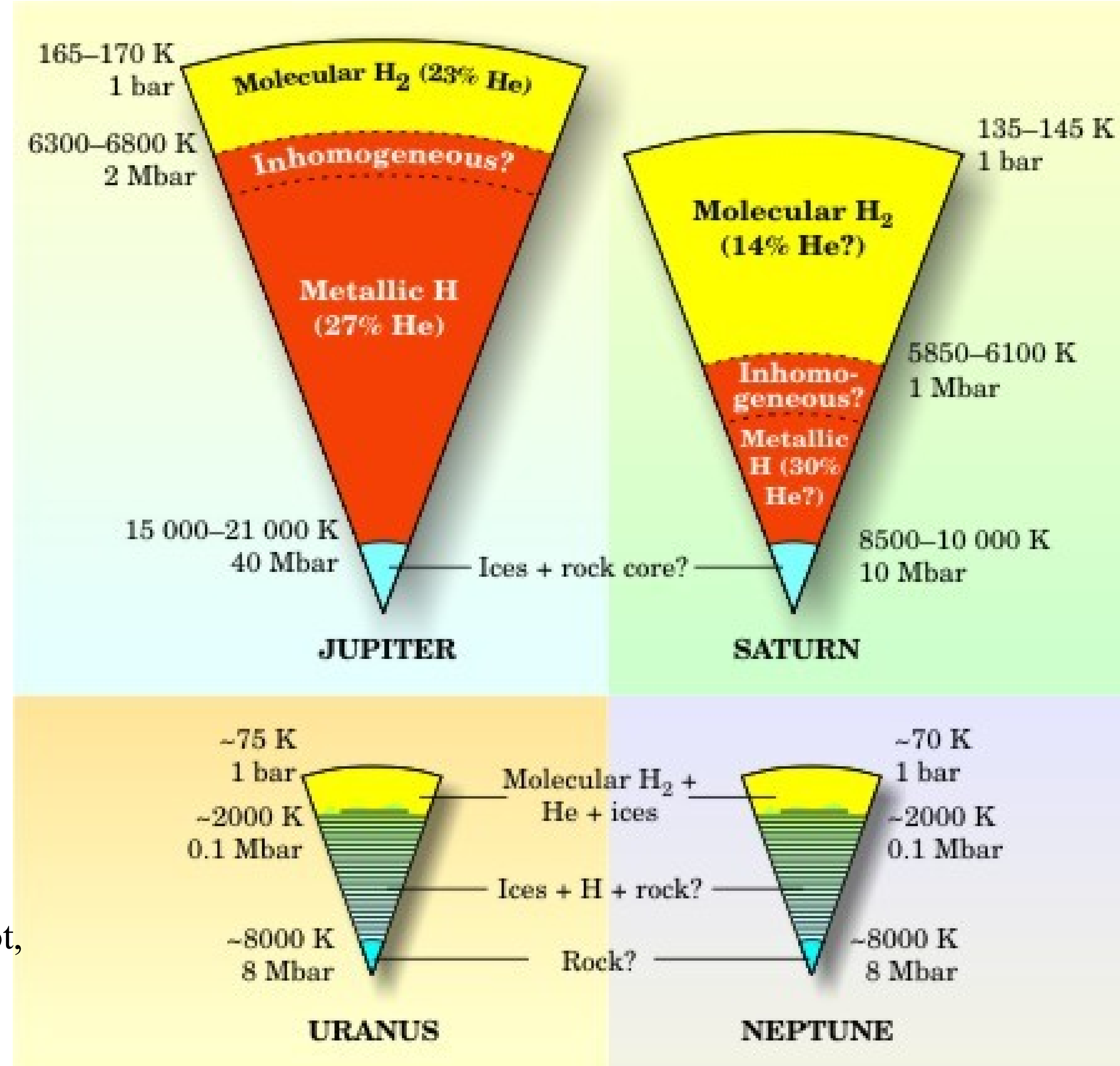
Interior temperatures are adiabats

- Jupiter – interior mostly metallic hydrogen
- Saturn – some metallic hydrogen
- Uranus/Neptune – molecular hydrogen only

Compressibility & Density



- *As mass increases, radius also increases*
- But beyond a certain mass, radius *decreases* as mass increases.
- This is because the increasing pressure compresses the deep material enough that the overall density increases faster than the mass
- The observed masses and radii are consistent with a mixture of mainly H+He (J,S) or H/He+ice (U,N)



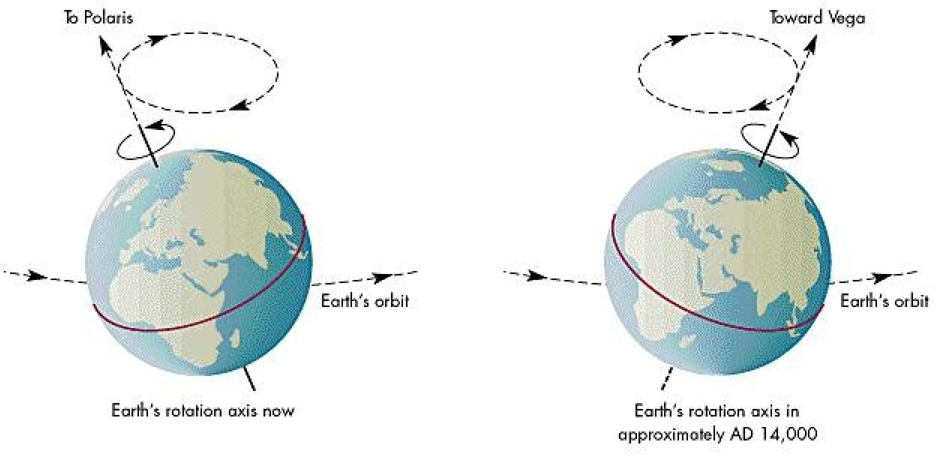
From Guillot, 2004

Recall: Moment of Inertia

- The moment of inertia is a measure of degree of concentration
  - Related to the "inertia" (resistance) of a spinning body to external torques
  - Shows giant planets are centrally concentrated: cores?

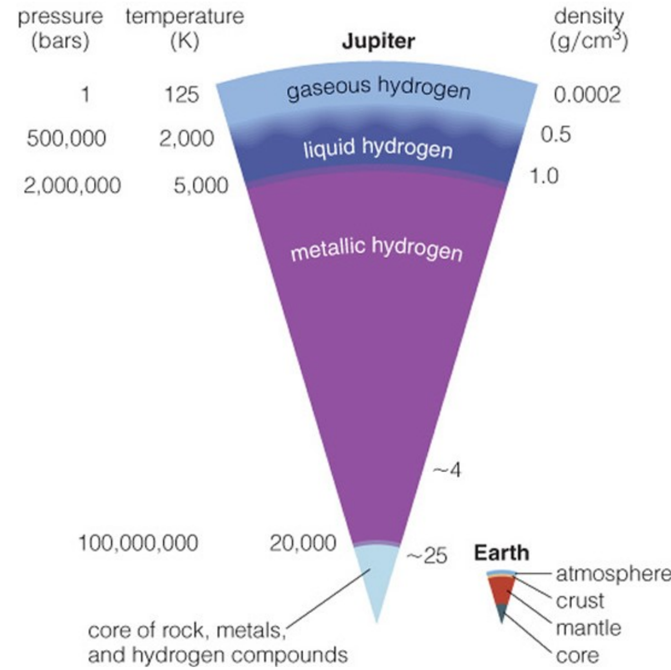
Body	I/MR^2
Sun	0.06
Mercury	0.33
Venus	0.33
Earth	0.33
Moon	0.393
Mars	0.366
Jupiter	**0.254**
Saturn	**0.210**
Uranus	**0.23**
Neptune	**0.23**

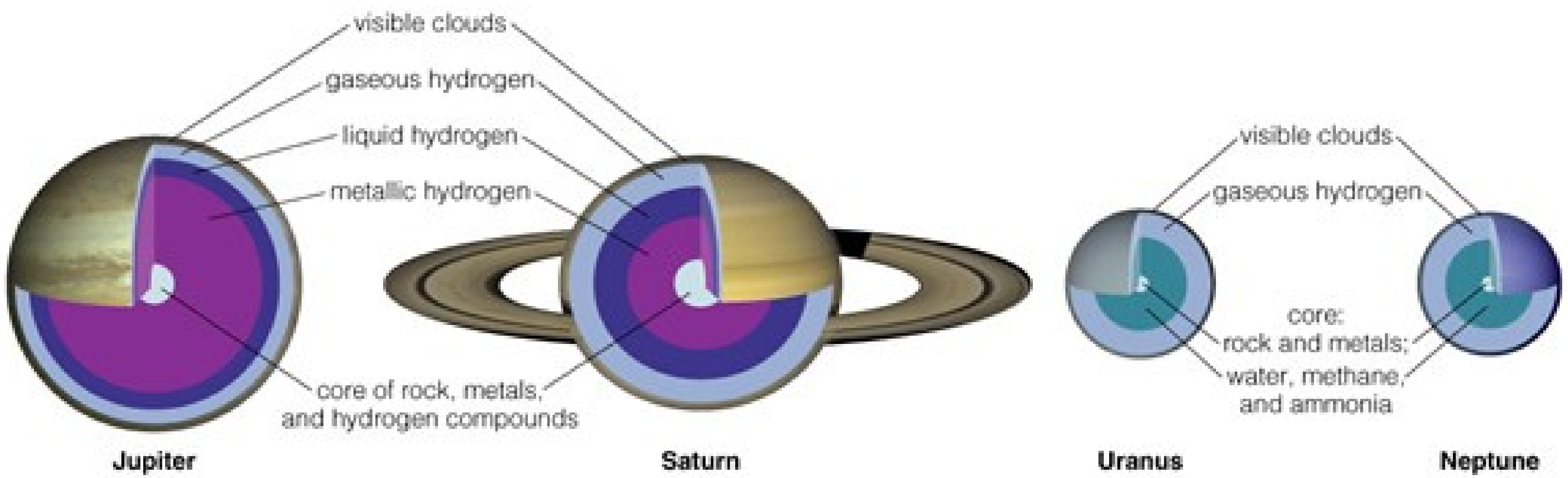
$$\frac{I}{MR^2} = \begin{cases} 0.4 \text{ for a homogeneous sphere} \\ 0.67 \text{ for a hollow shell} \\ 0 \text{ for a point mass} \end{cases}$$



Interiors

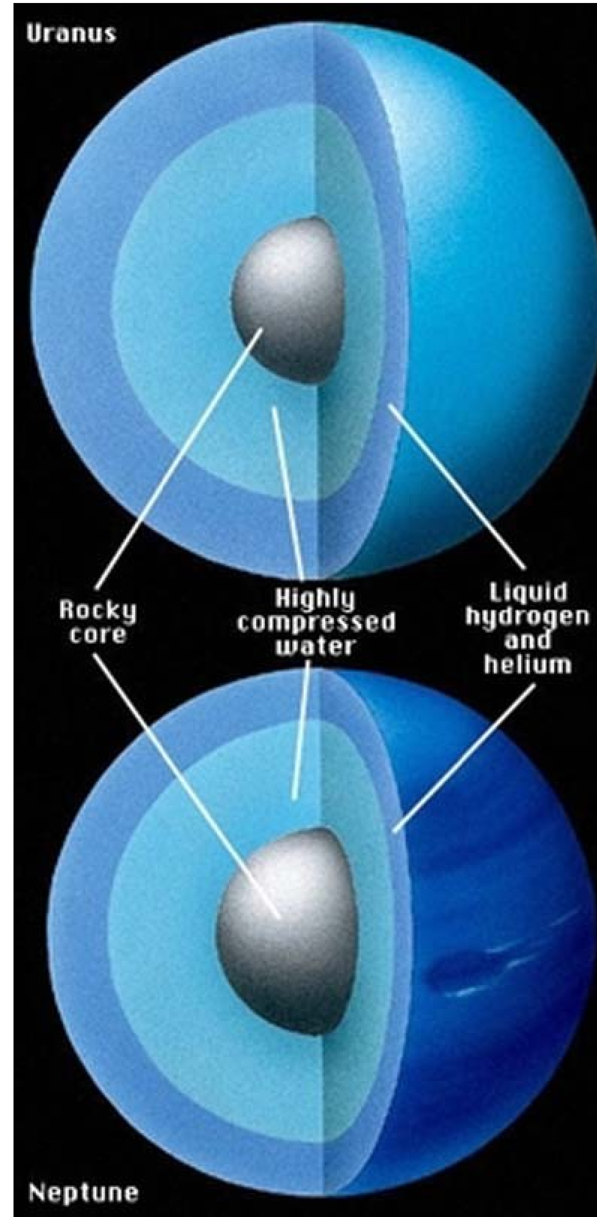
- Jupiter and Saturn are dominated by an atmosphere of fluid, metallic hydrogen
- Neptune and Uranus are dominated by an icy mantle, probably as a fluid, conducting ocean, surrounded by a H and He atmosphere





Uranus and Neptune: Interiors

- Likely have a rocky core, but are dominated by a fluid, icy and ionic ocean
- Surrounded by an atmosphere rich in H and He
- Uranus is the only *gas giant* that does not emit much more heat than it receives from the Sun
  - Internal convection disrupted?
  - Consistent with lack of storms



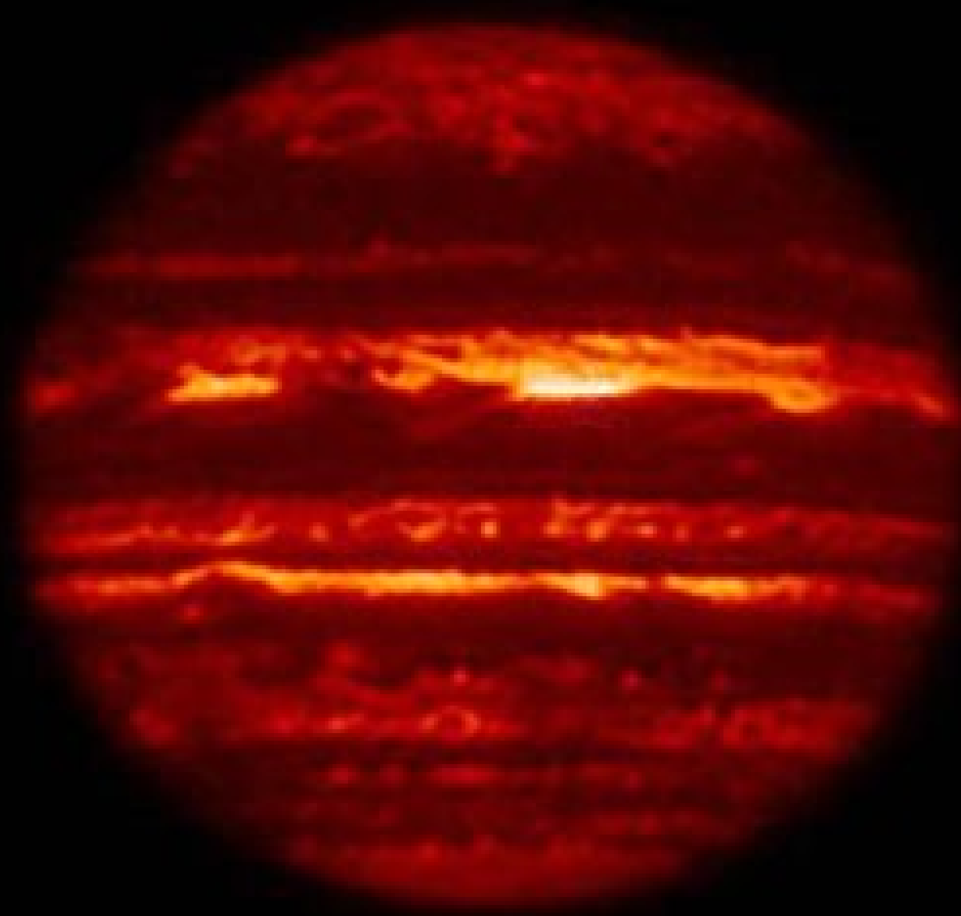
Summary

- Jupiter - mainly metallic hydrogen. Rock-ice core ~10 M_E.
- Saturn - mix of metallic and molecular hydrogen; helium may have migrated to centre due to insolubility. Similar rock-ice core to Jupiter. Mean density lower than Jupiter because of smaller self-compression effect (pressures lower).
- Uranus/Neptune – thin envelope of hydrogen gas. Pressures too low to generate metallic hydrogen. Densities (and moment of inertia data) require large rock-ice cores in the interior.
- All four planets have large magnetic fields, presumably generated by convection in either metallic hydrogen (J,S) or conductive ices (U,N)

Heat Balance

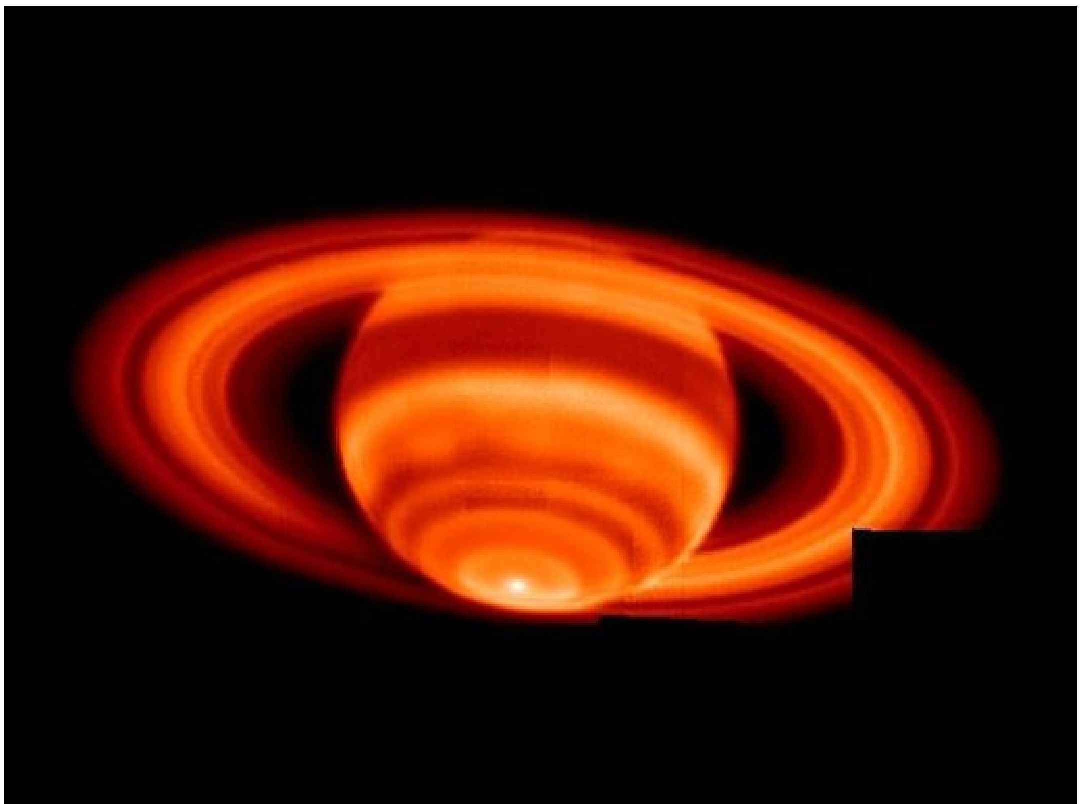
- The average temperature of Jupiter is 160 K. Is it in thermal equilibrium? (Assume a visible albedo of 0.43, but a perfect blackbody in the infrared).

- An infrared picture of Jupiter



Internal heating

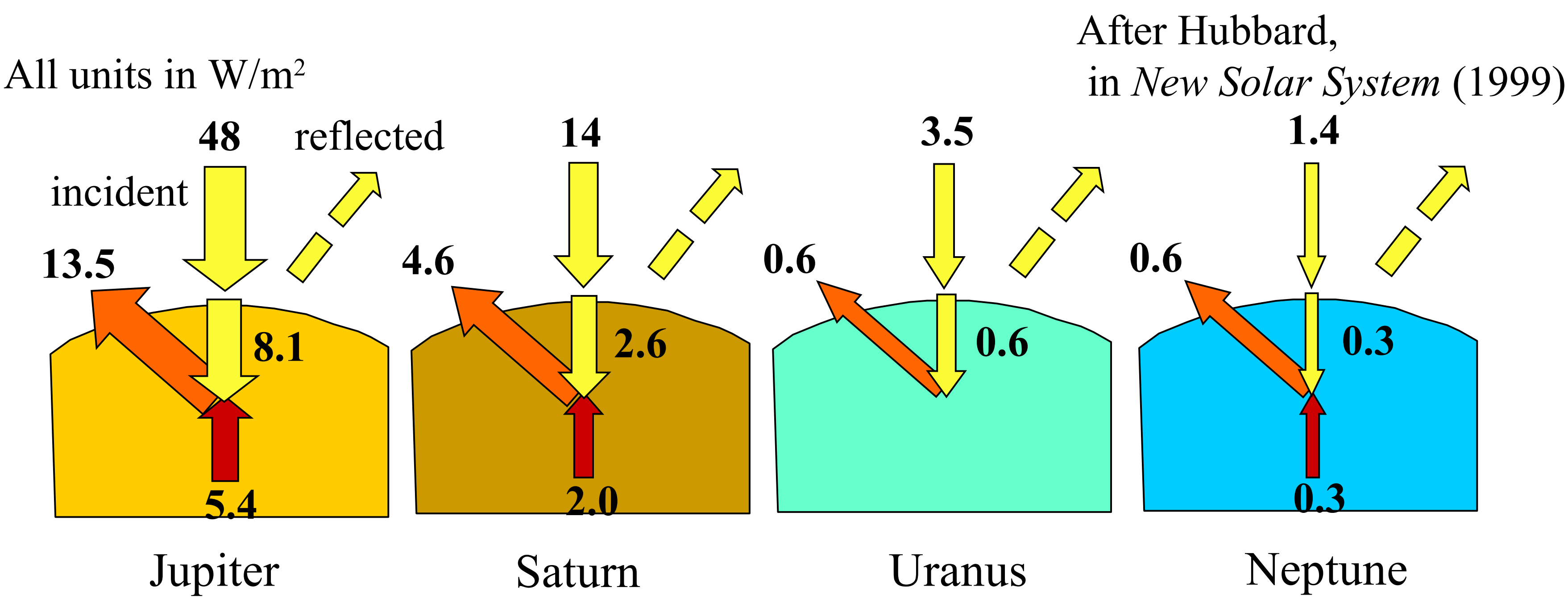
- Saturn radiates more energy than it receives, by the same amount as Jupiter does.
  - It is thought that He forms droplets and sinks downward, releasing gravitational energy



Thermal infrared picture of Saturn

Energy budget observations

- Incident solar radiation much less than at Earth
- So surface temperatures are lower
- We can compare the amount of solar energy absorbed with that emitted. It turns out that there is usually an excess. Why?



Sources of Energy

- One major one is contraction – gravitational energy converts to thermal energy. Helium sinking is another.
- Gravitational energy of a uniform sphere is

$$E_g = 0.6 GM^2 / R$$ Where does this come from?

- So the rate of energy release during contraction is

$$\frac{dE_g}{dt} = -0.6 \frac{GM^2}{R^2} \frac{dR}{dt}$$

e.g.Jupiter is radiating 3.5×10^{17} W in excess of incident solar radiation
This implies it is contracting at a rate of 0.4 km / million years

- Another possibility is tidal dissipation in the interior. This turns out to be small.
- Radioactive decay is a minor contributor.

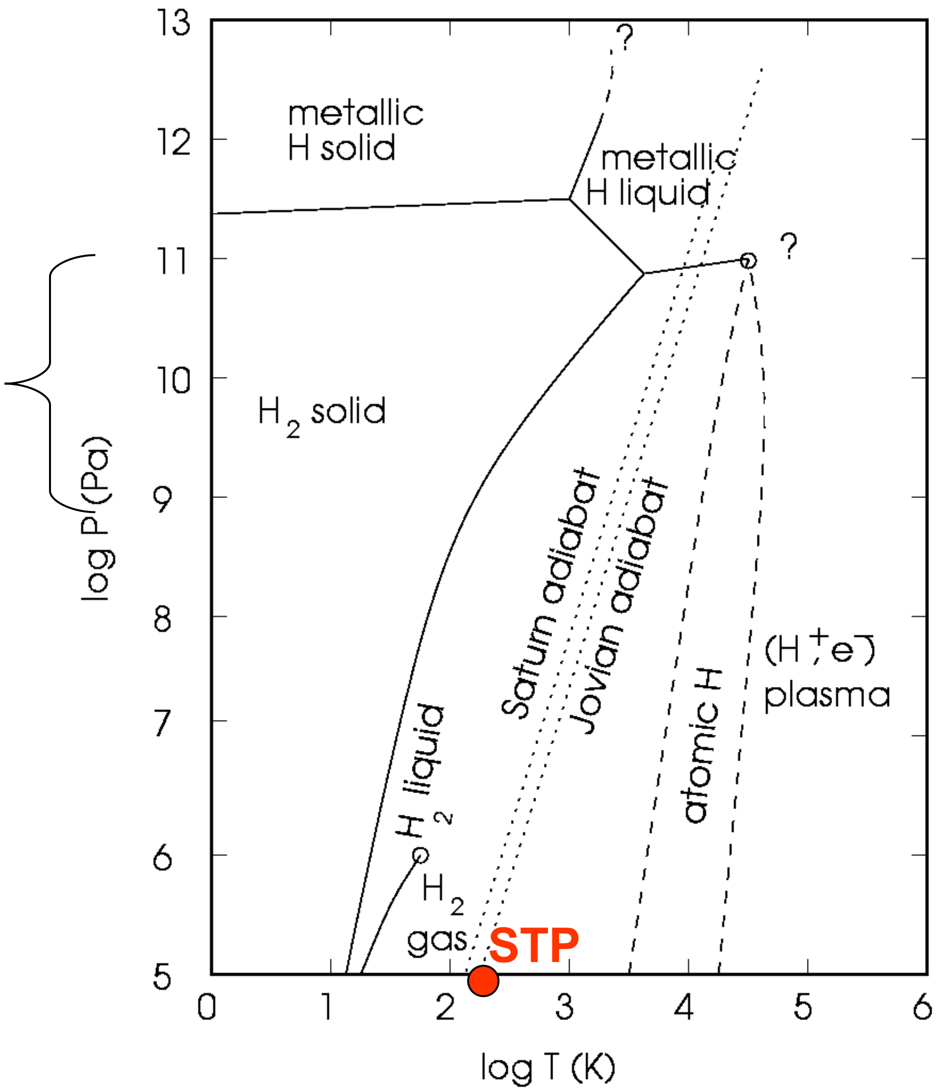
Puzzles

- Why is Uranus' heat budget less?
  - Detailed comparison of Uranus & Neptune may yield some clues
- Why is Uranus tilted on its side?
  - A possible explanation is an oblique impact with a large planetesimal (c.f. Earth-Moon)
  - This impact might even help to explain the compositional gradients which (possibly) explain Uranus' heat budget

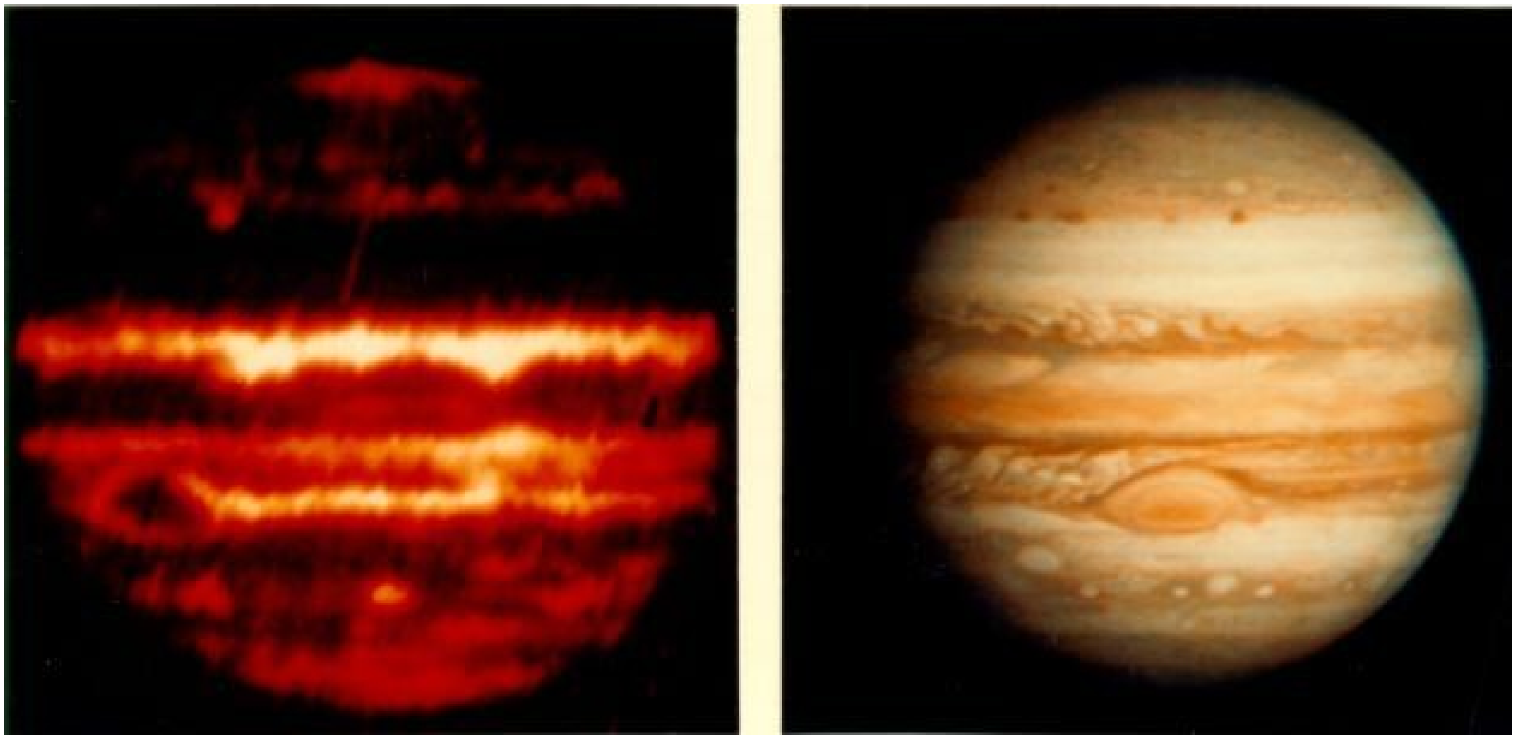
H at high temperatures and pressures

- Atmosphere of Jupiter and Saturn is mostly "liquid" H_2.
- At very high pressures, H atoms dissociate from each other and their electrons
  - Forms a metallic liquid
  - Good conductor

Maximum of Earth-based laboratory experiments



Infared and Optical



- Regions of white in visible light are dark in infrared
    - internal heat is blocked by the clouds
- Darkest visible bands are brightest in the infrared
    - seeing deeper into the atmosphere where it is hotter
- Red spot also dark in IR: cool, high altitude storm