Giant planets of the Solar System

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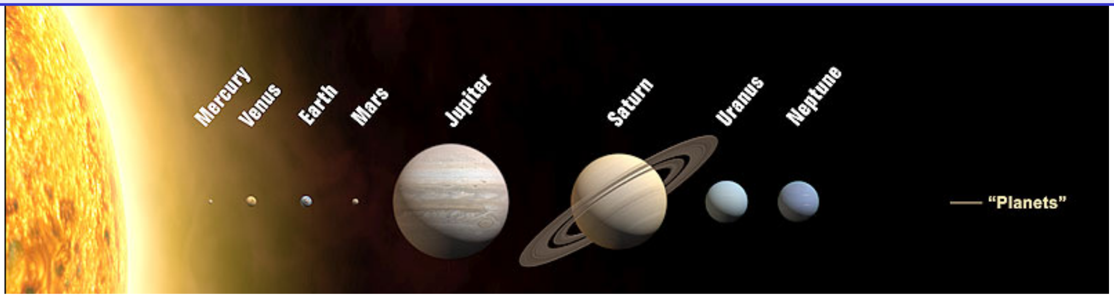
Gaseous and icy giant planets

Planet	R [R_{earth}]	M [M_{earth}]	ρ [g/cm^3]	a [AU]	e	i [º]
Jupiter	11.2	318	1.3	5.2	0.048	1.3
Saturn	9.4	95	0.7	9.5	0.054	2.5
Uranus	4.0	14	1.3	19.2	0.047	0.8
Neptun	3.9	17	1.6	30.1	0.008	1.8



Giant planets

- Effective temperature
  - Low values with respect to the rocky planets of the Solar System

    Below the condensation point of ices

- Albedo
  - Relatively high albedo

    External atmospheric layers are quite reflective due to the presence of clouds (water, ammonia and other molecules)

Allen (2000)

Planet	Effective temperature [K]
Earth	255
Jupiter	124
Saturn	95
Uranus	59
Neptun	59

Planet	Albedo in the visible
Earth	0.38
Jupiter	0.52
Saturn	0.47
Uranus	0.51
Neptun	0.41

Giant planets

- Atmospheric height
  - Giant planets are characterized by extended atmospheres
  - Thanks to their high mass, giant planets have been able to capture a large quantity of volatiles during the last stages of their formation
  - Optical observations can only penetrate the outermost layers

Allen (2000)

Rocky planets	Surface atmospheric pressure [bar]	Scale height H [km]
Earth	1	8
Giant planets	Atmospheric pressure at the level of the visible surface of the clouds [bar]	Scale height at the level of the visible surface of the clouds [km]
Jupiter	~ 0.3	19-25
Saturn	~ 0.4	35-50
Uranus	…	22-29
Neptun	…	18-22

Chemical composition of giant planets

- Inferred from spectroscopic observations of the upper atmospheric layers
- At variance with rocky planets, the main constituents of the atmospheres of giant planets are H and He, as in the Sun
  - Thanks to their high mass, giant planets have been able to accumulate and preserve most of the gas of the protosolar nebula from which the Solar System was formed
- The atmospheres are characterized by the presence of molecules
  - The most abundant are H_2, CH_4 e NH_3
- Heavy elements (metals) in the atmospheres
  - Gaseous giants (Jupiter and Saturn) show a slight overabundance of metals over hydrogen with respect to the Sun
  - In icy giants (Uranus and Neptun) this overabundance is more pronounced
  - The metal/H ratio might be higher because giant planets did not keep all the hydrogen of the material from which they formed

Jupiter's atmospheric composition

– Broadly similar to the solar composition

Due the high abundance of H, the atmosphere has a "reducing" behaviour from the chemical point of view

As a result the elements tend to appear in "reduced", rather than "oxidated", form

for instance, CH_4 rather than CO_2

89.8±2.0%	hydrogen (H_2)
10.2±2.0%	helium (He)
≈0.3%	methane (CH_4)
≈0.026%	ammonia (NH_3)
≈0.003%	hydrogen deuteride (HD)
0.0006%	ethane (C_2H_6)
0.0004%	water (H_2O)

Ices:

- ammonia (NH_3)
- water (H_2O)
- ammonium hydrosulfide (NH_4SH)

Saturn's atmospheric composition

– Very similar to Jupiter's composition
  - Exception: He is less abundant
  - Quantity of heavier elements not known
  - The total mass of metals is estimated to be between 19 and 31 times the Earth mass
  - The metals are probably concentrated in an inner core

≈96%	hydrogen (H_2)
≈3%	helium (He)
≈0.4%	methane (CH_4)
≈0.01%	ammonia (NH_3)
≈0.01%	hydrogen deuteride (HD)
0.0007%	ethane (C_2H_6)

Ices:

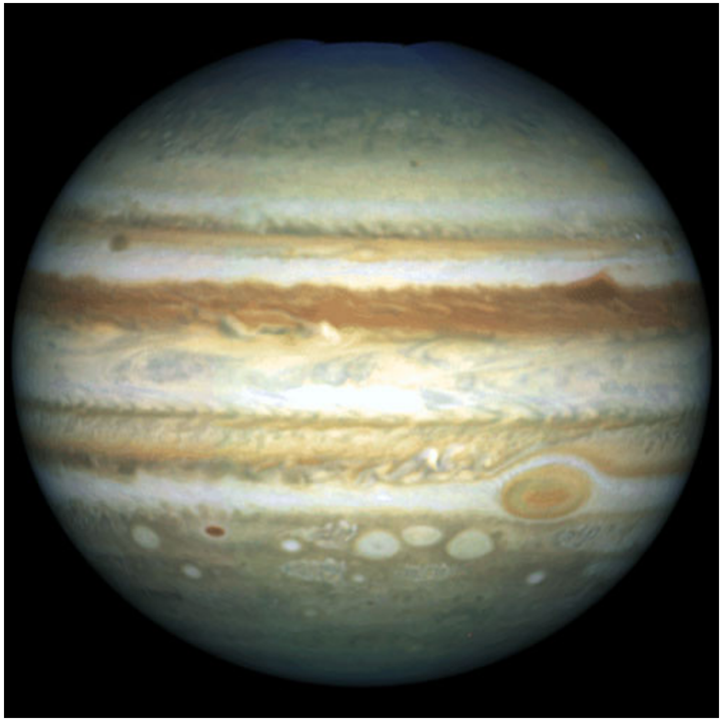
- ammonia (NH_3)
- water (H_2O)
- ammonium hydrosulfide (NH_4SH)

Rotational velocity of giant planets

- The rotational velocity of the external and internal layers is measured in the visible and radio bands, respectively
- Jupiter and Saturn have quite high rotational velocities

  Both have rotation periods $P \sim 10$h
- Because giant planets are not solid bodies, their upper atmospheres undergo <u>differential rotation</u>

  They rotate faster at the equator than at the poles
- Also Uranus and Neptun have fast rotation, but with slightly longer periods ($P \sim$ 16-17h)

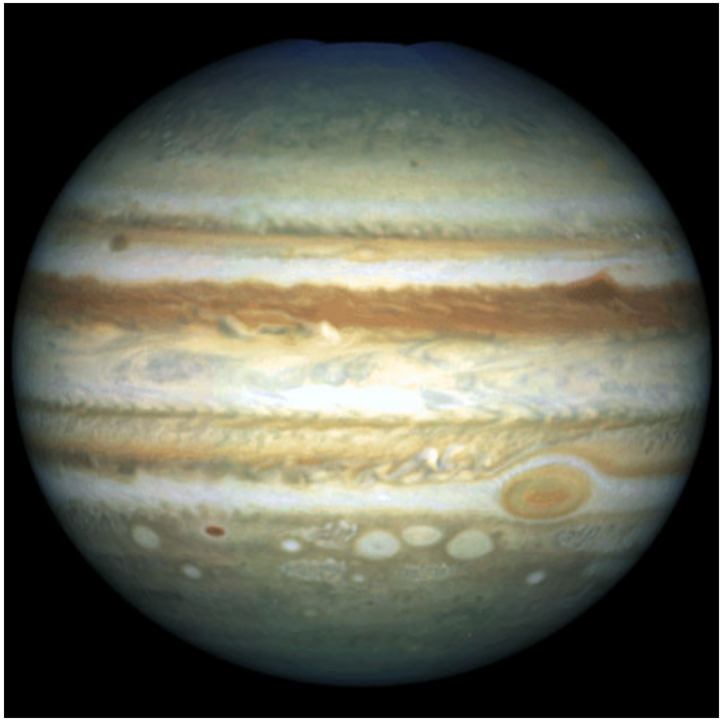


Band structure of giant planets

- The band structure is due to the zonal orientation (i.e. along the parallels) of the atmospheric winds
- The equator-pole gradient of solar insolation is the main driver of the atmospheric circulation
- The circulation is severely conditioned by Coriolis forces due to the high rotational velocity of the giant planets

Further example of the fact that the number of atmospheric convective cells increases with increasing rotational velocity:

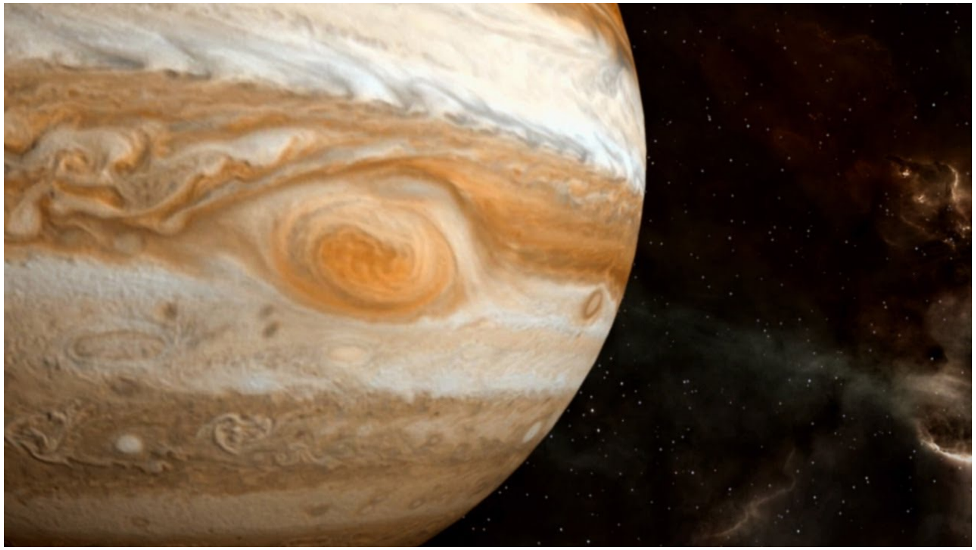
Venus -> Earth -> Giant planets



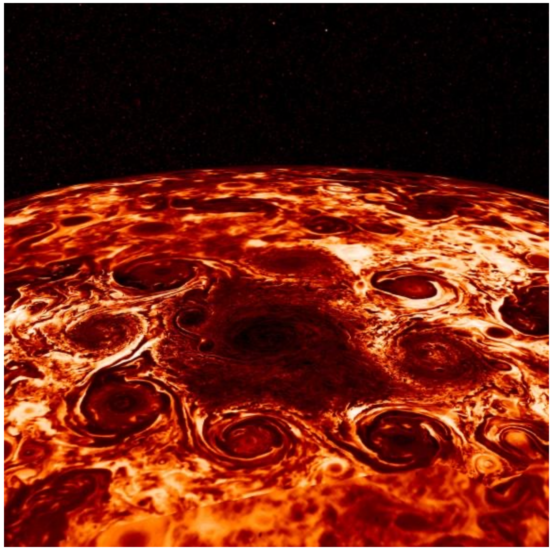
Long-lived atmospheric structures

Long-lived macroscopic structures (e.g., $\gtrsim 10^4$ km) are common within the turbulent atmospheres of giant planets. They provide a unique way of probing fluidodynamical laws in a variety of physical conditions.

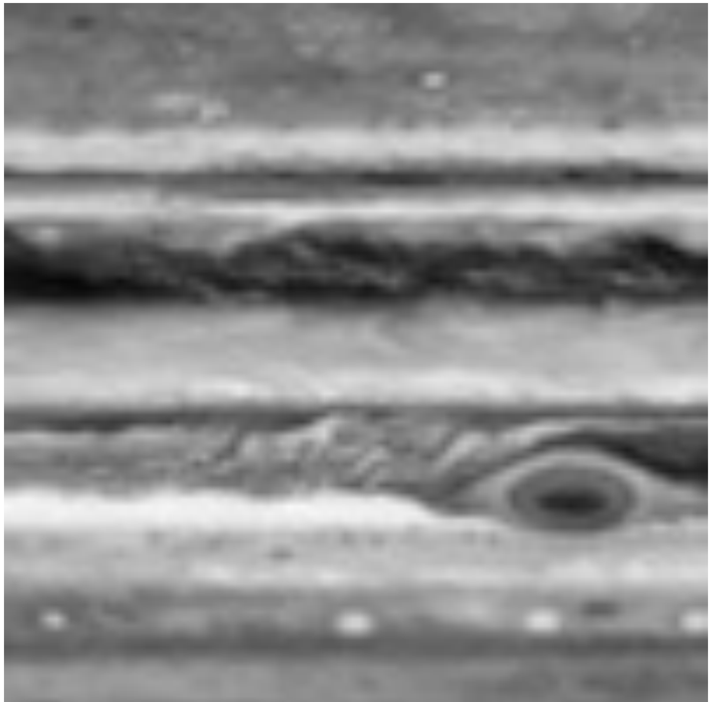
Jupiter's red spot
Known to exist for a few centuries.
Proven to be a persistent storm by the *Voyager* mission.

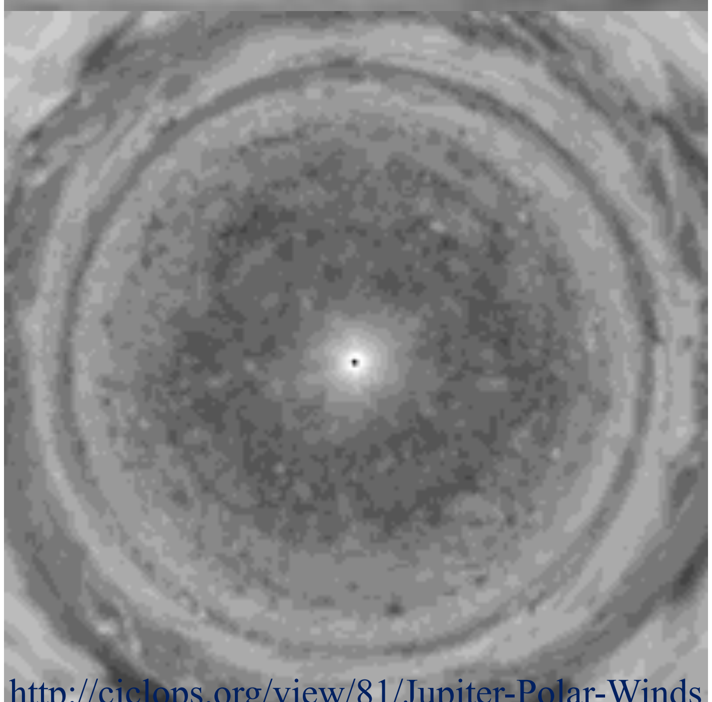


Jupiter's North Pole
As seen by the Juno mission



Dynamics of the Jovian atmosphere





http://ciclops.org/view/81/Jupiter-Polar-Winds

- Rapid rotation (12km/s at the equator).
- Produces the atmosphere structure in belts and zones
- Convective motions: the light zones are ascending and the dark belts are descending.
- Many dynamic structures at a smaller scale with a variable lifetime.

Bands of eastward and westward winds on Jupiter appear as concentric rotating circles in a movie composed of Cassini images which have been re-projected to appear as if the viewer were floating over Jupiter's north pole. The sequence covers 70 days, from October 1 to December 9, 2000. Cassini's narrow-angle camera captured the images of Jupiter's atmosphere in near-infrared light.

Long-lived atmospheric structures

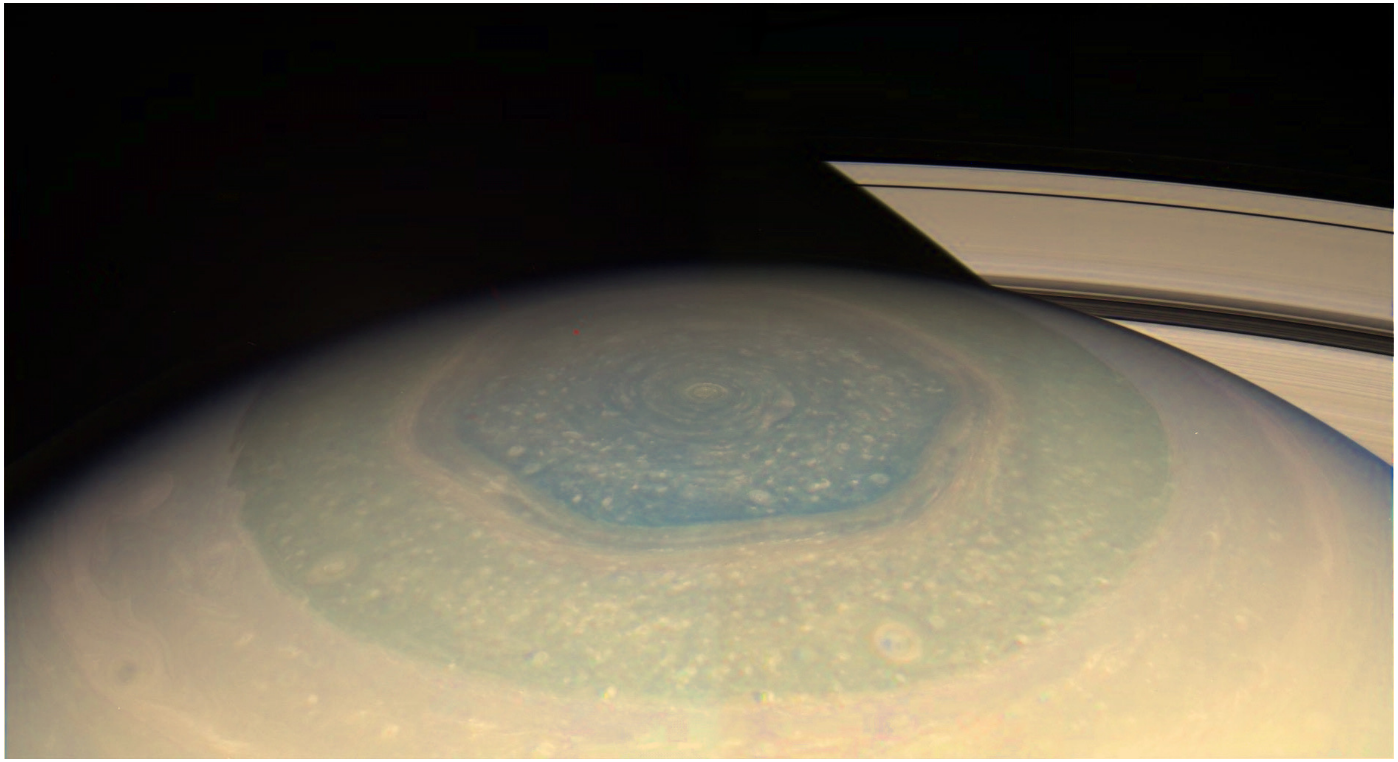
Hexagonal cell at Saturn's north pole

Not present in the south pole, nor in Jupiter's poles.

The cell is rotating and a vortex is present in the inner part.

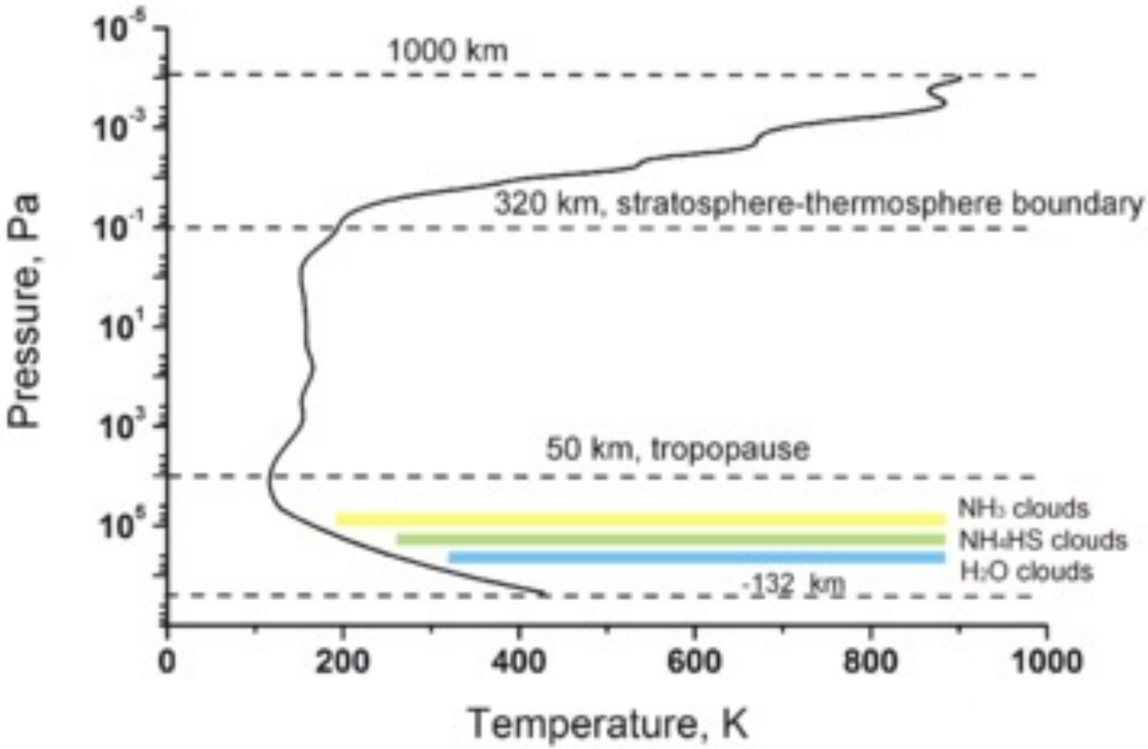
The existence of this structure requires very specific boundary conditions

Seen by Cassini-Huygens mission



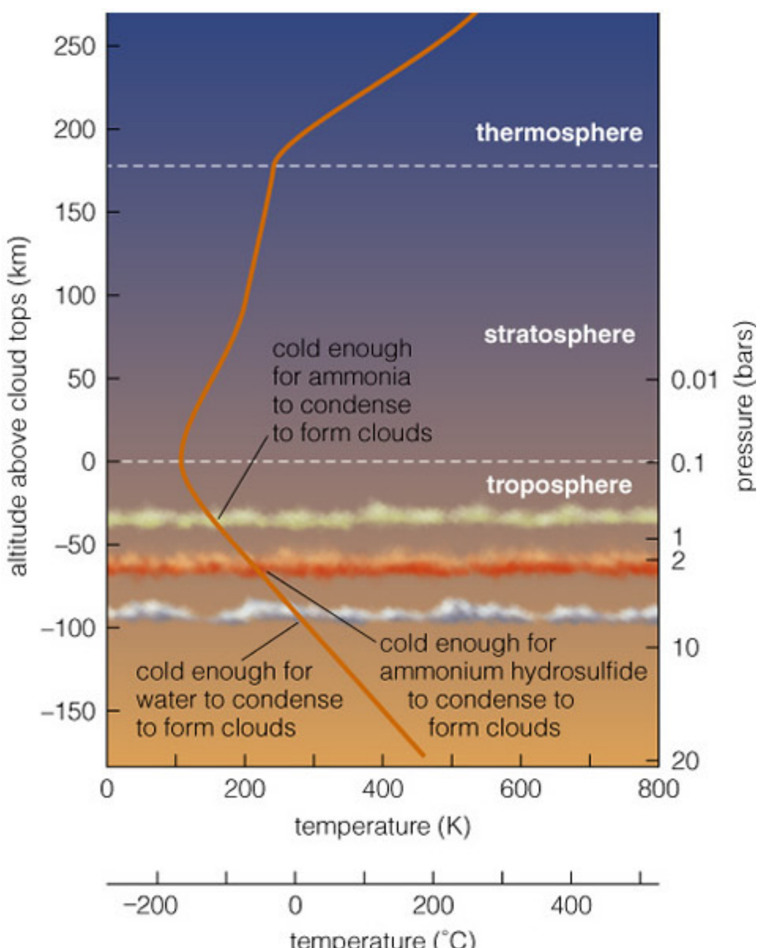
Temperature profiles of the upper atmosphere (1)

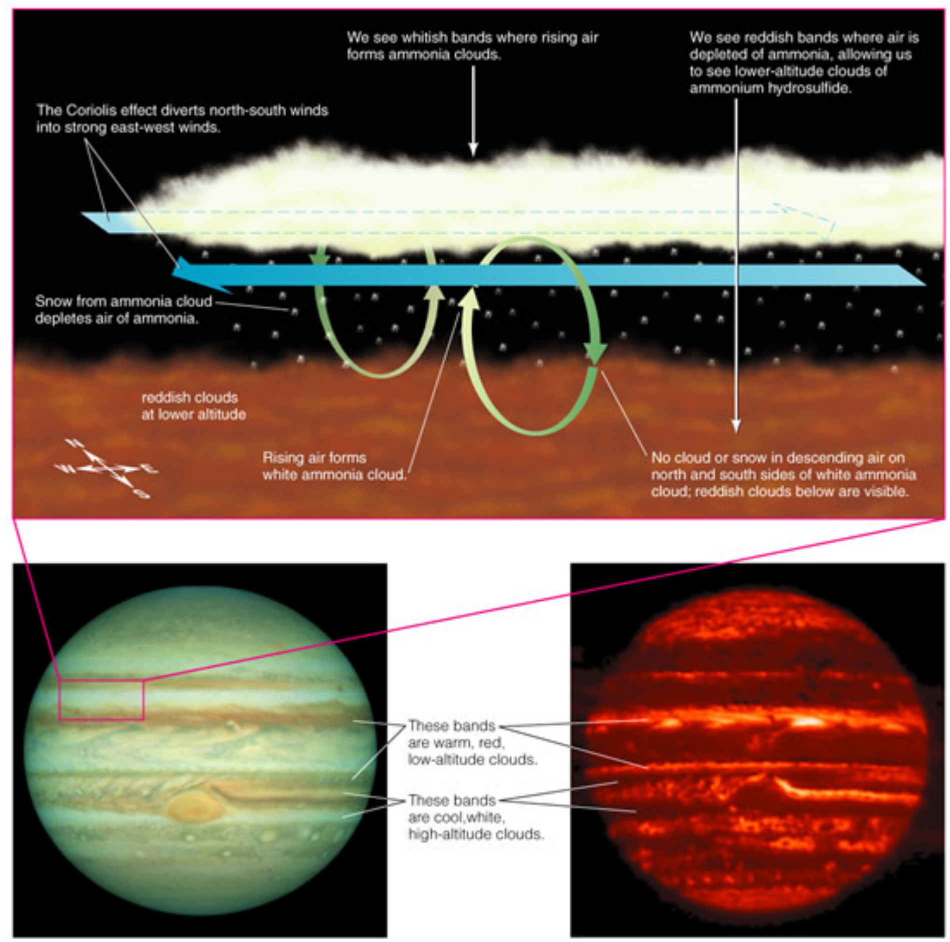
- Jupiter
  - the troposphere gradually merges with the planet interior due to the lack of a solid surface
  - the cloud layers are stratified in the troposphere, according to the condensation temperatures of the different molecules
  - For instance, upper clouds are composed of ammonia cristals, whereas water cristals lie in lower layers
  - some tropospheric layers have T and p reminiscent of Earth surface



Jupiter's atmosphere

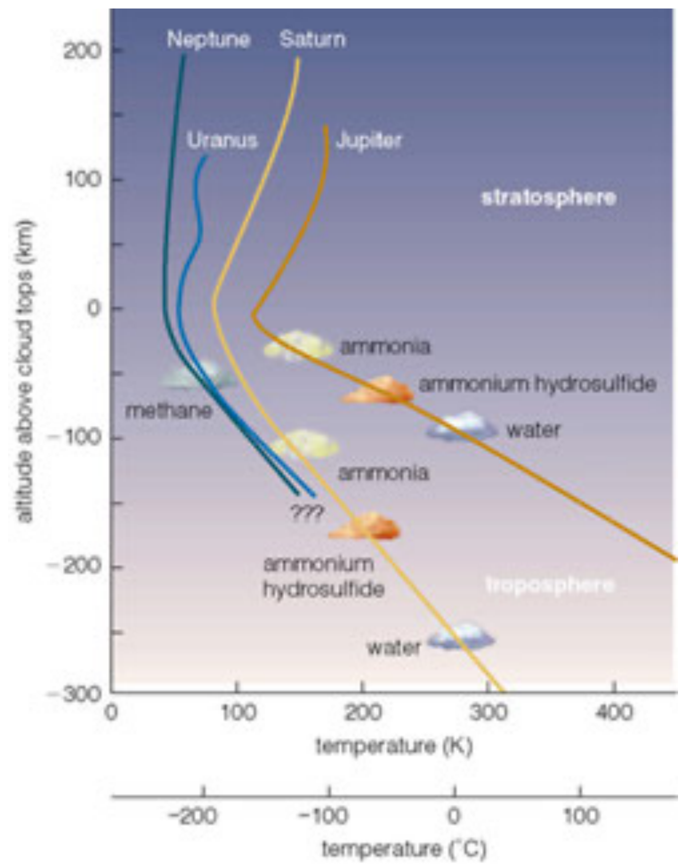
Rising air from the deeper layers cools and forms clouds as it rises; we see deeper where the high ammonia clouds have been depleted by precipitation, much as on Earth rain will often mean clearer skies.





Temperature profiles of the upper atmosphere (2)

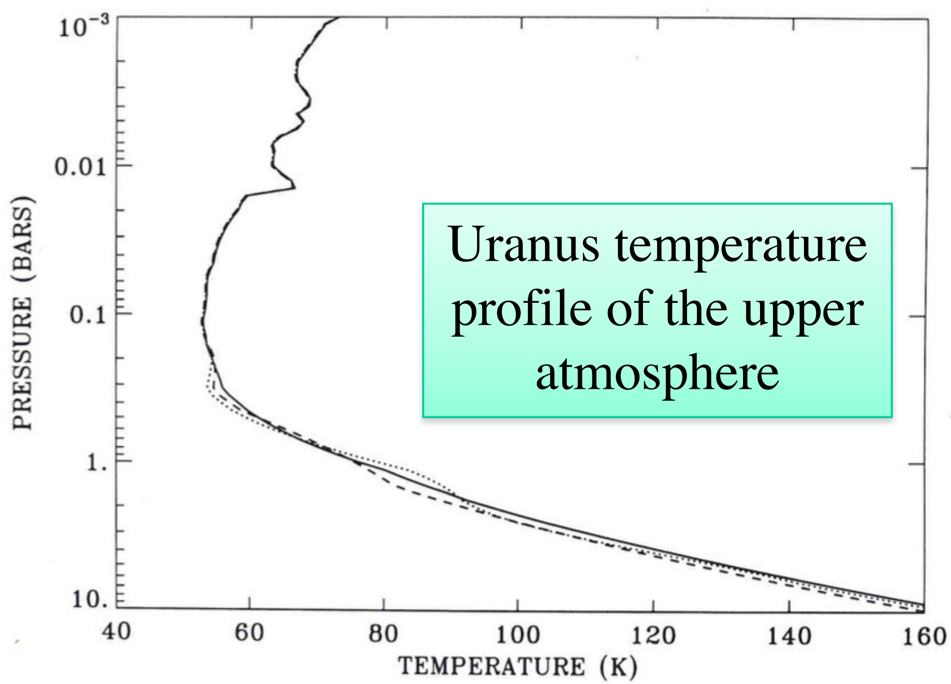
- Saturn
  - The structure of the upper atmosphere of Saturn is similar to the Jovian one
  - The primary difference is that, at a given atmospheric depth (pressure), the atmosphere is cooler due to the increased distance from the Sun
  - Clouds of a particular composition always occur at about the same temperature, corresponding to the condensation temperature of the molecules that characterize each layer



Temperature profiles of the upper atmosphere (3)

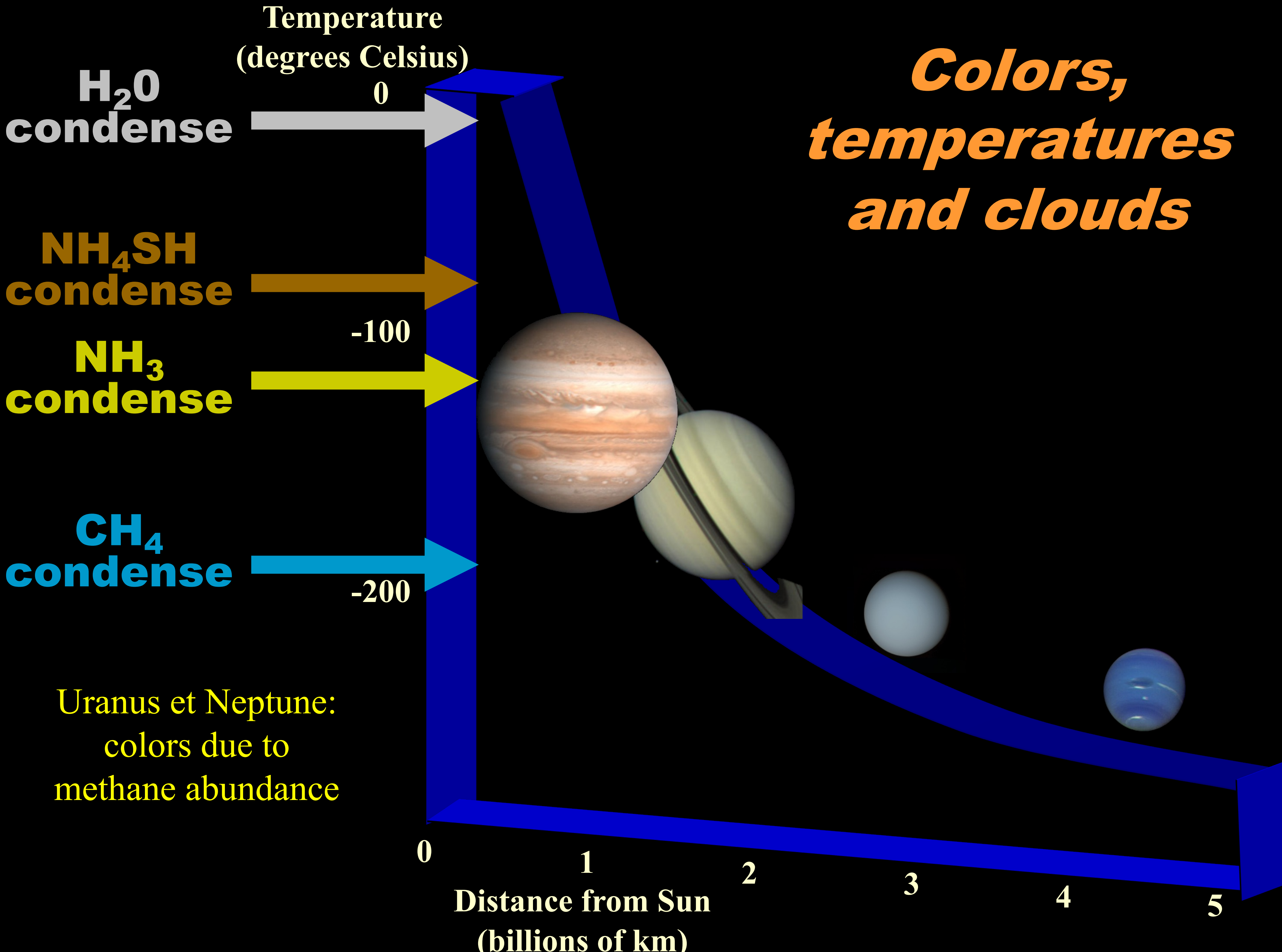
- Uranus and Neptun
  - At a given pressure of the outer layers, the temperature is lower than in the case of Jupiter and Saturn

Data obtained from Voyager radio occultations of the middle and upper atmosphere, with an extrapolation into the deep atmosphere



Uranus temperature profile of the upper atmosphere

Colors, temperatures and clouds



Uranus et Neptune:
colors due to
methane abundance

Jupiter's energy balance

- Jupiter radiates more heat than it receives from the Sun
- The amount of heat produced inside is comparable to the total solar radiation it receives
- A possible source of this additional heat is through contraction, via the Kelvin–Helmholtz mechanism:
  - The cooling of external layers causes the pressure to drop, and the planet shrinks as a result. This compression, in turn, heats up the interior of the planet
  - This process causes Jupiter to shrink by about 2 cm each year
  - According to this scenario, Jupiter was much hotter and was about twice its current diameter when it was formed

Heat flow balance of giant planets

Energy balance:
ratio of the average total infrared energy from the planet
to the value of thermalized sunlight alone

Heat Flow Parameters for Giant Planets

Parameter	Jupiter	Saturn	Uranus	Neptune
Effective temperature (K)	124.4±0.3	95.0±0.4	59.1±0.3	59.3±0.8
Energy balance	1.67±0.09	1.78±0.09	1.06±0.08	2.61±0.28
Internal energy flux (W m^{-2})	5.44±0.43	2.01±0.14	0.042±0.047	0.433± 0.046
Internal power/unit mass (10^{-11} W kg^{-1})	17.6±1.4	15.2±1.1	0.392±0.441	3.22±0.34

With exception of Uranus, the giant planets show evidence for a significant excess of heating with respect to their level of insolation indicating that there must be an internal source in addition to the thermalized sunlight

Magnetic fields of giant planets

Russel & Dougherty 2010

- The most intense of all Solar System planets
  - Suggestive of a strong dynamo activity and hence of a convective layer of a conductive fluid, coupled with the high rotational velocity
  - The convective/conductive layer should be particularly extended in Jupiter and Saturn
  - The magnetic dipole moments are given in the table

Planet	M_{mag} [T m^3]	$M_{mag}/M_{mag,earth}$	Tilt with rotation axis [deg]
Jupiter	1.55×10^{20}	$\sim 2 \times 10^4$	10
Saturn	4.6×10^{18}	~600	~1
Uranus	4.4×10^{17}	~50	~98
Neptun	2.2×10^{17}	~25	~47

Interiors of giant planets

Experimental data on the interiors of giant planets are rather sparce

The mean density and gravimetric measurements provide some constraints on the composition of the interiors

The interiors need to be modelled using phase diagrams with an assigned chemical composition

The thermal models assume that the temperature distribution follows and adiabat as a function of pressure

Model constraints

- Phase diagram of hydrogen

  Most important diagnostic tool

  In the range of temperature and pressure characteristic of the interiors of giant planets, the equation of state (EOS) of hydrogen is still uncertain from the experimental and theoretical point of view

  This uncertainty affects our capability of modelling the interiors

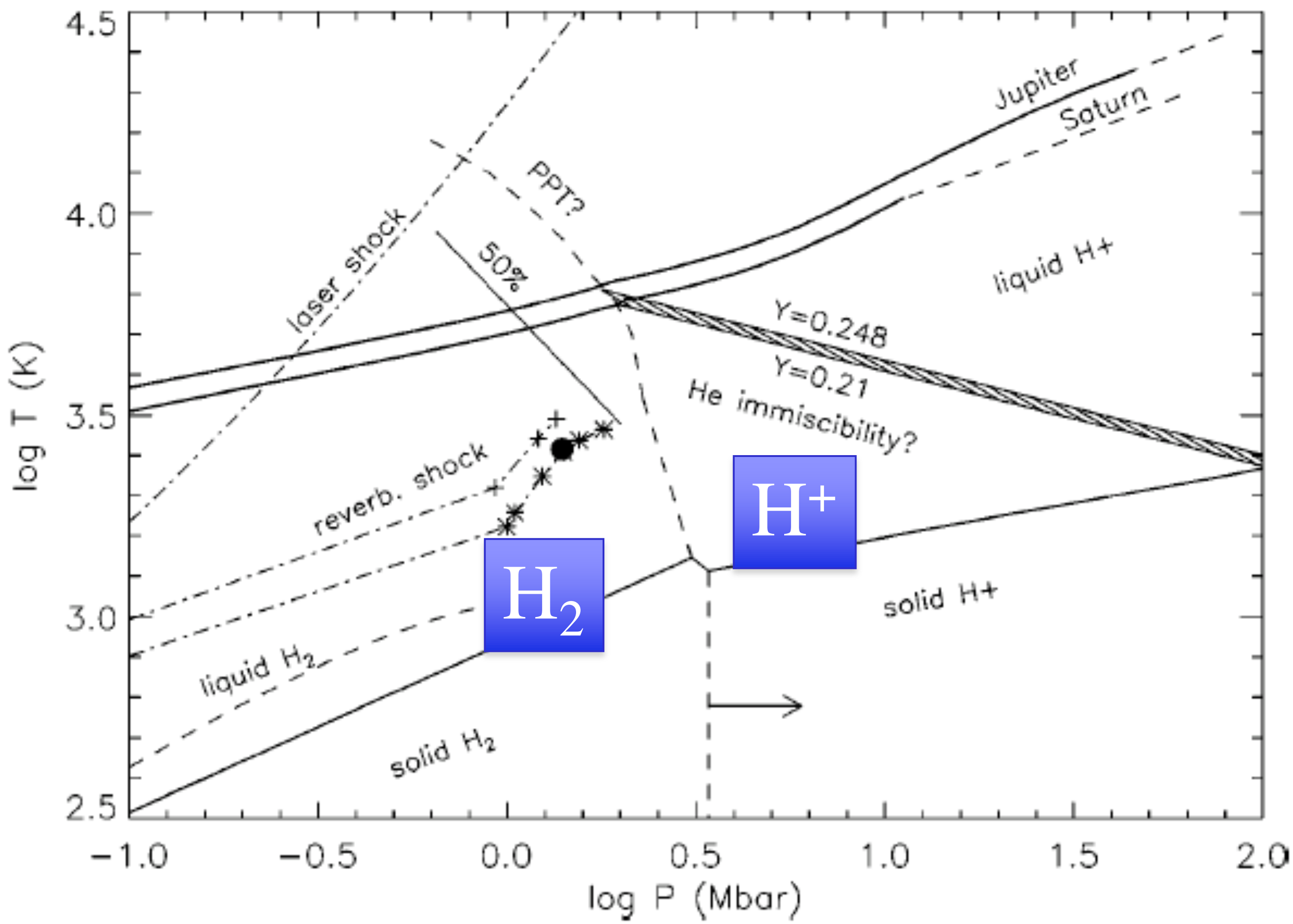


Figure 1 The phase diagram of hydrogen, showing regions of stability of liquid and solid molecular hydrogen (H_2), and of liquid and solid metallic (pressure-ionized) hydrogen (H+). Also shown are trajectories of experimental shock-compression experiments (*dashed-dot lines*) and trajectories of the interiors of Jupiter and Saturn at the present epoch (*heavy solid lines*). See text for discussion of further details of this figure.

Interiors of Jupiter and Saturn

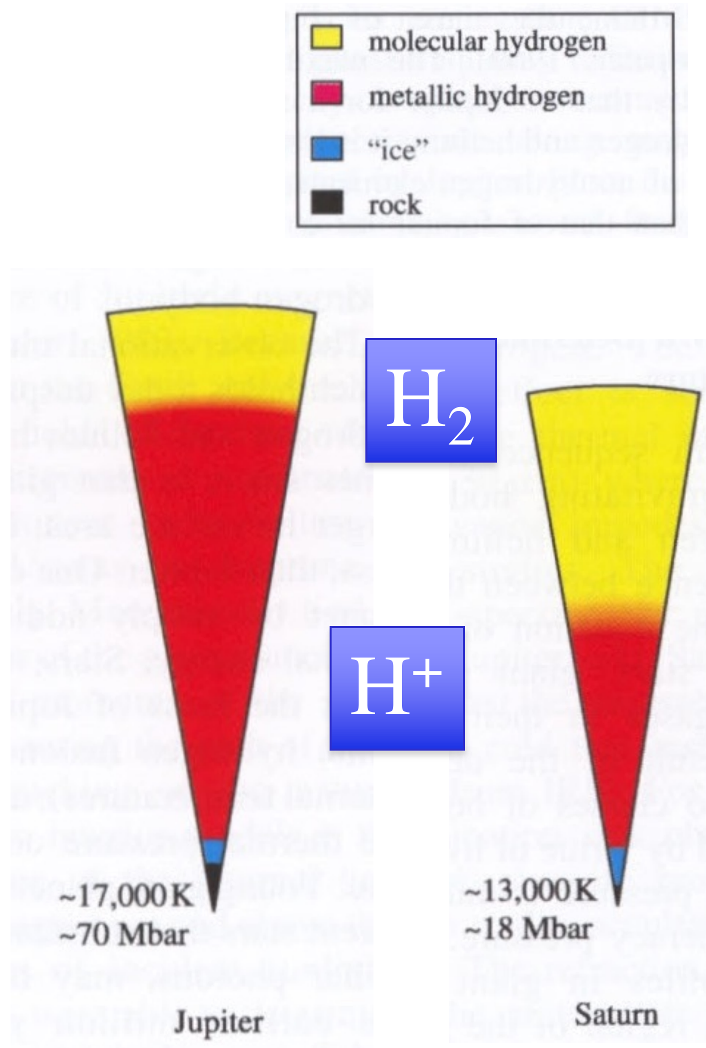
- Main phases
  - Molecular hydrogen H_2 in liquid phase

    In the upper layers (yellow)
  - Metallic hydrogen H^+ in liquid phase

    <u>Pressure ionized</u>

    In the lower layers (red)

    This phase of liquid metallic hydrogen is expected to play a key role in the generation of the strong magnetic fields of gaseous giants

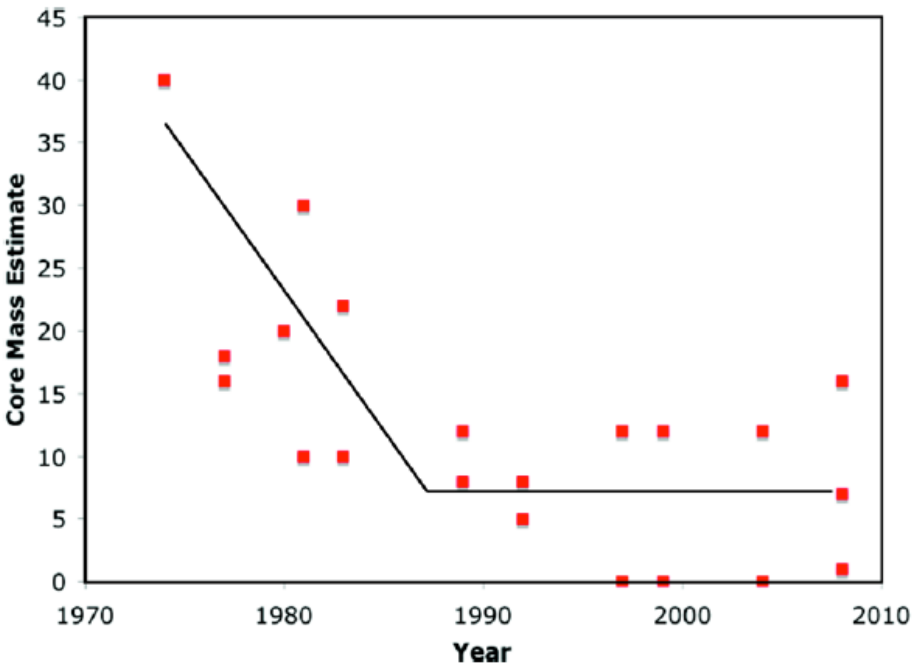


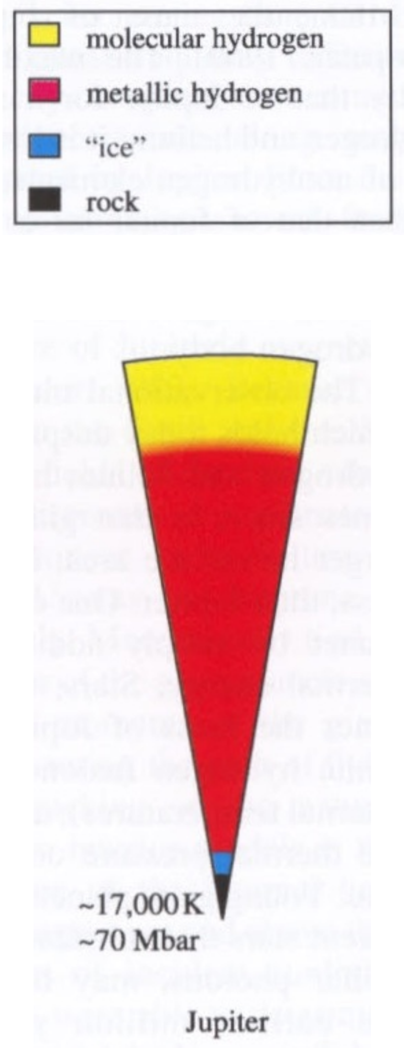
The core of Jupiter and Saturn

- Existence of a solid/rocky core
  - Quite hard to confirm experimentally
- Jupiter

  Apparently confirmed (M_{core}~12 M_{earth}) after a long debate in the literature
- Saturn

  M_{core}~ 9 - 22 M_{earth}





Interiors of icy giants

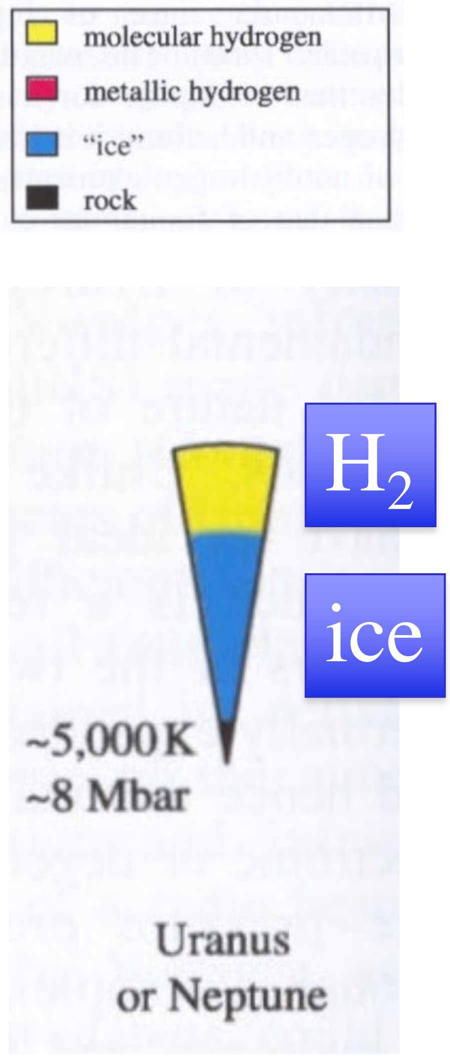
- Neptun
  - Upper layer rich of molecular hydrogen

    Occupies about 20% of the planet radius
  - Deeper layers of ice and rock

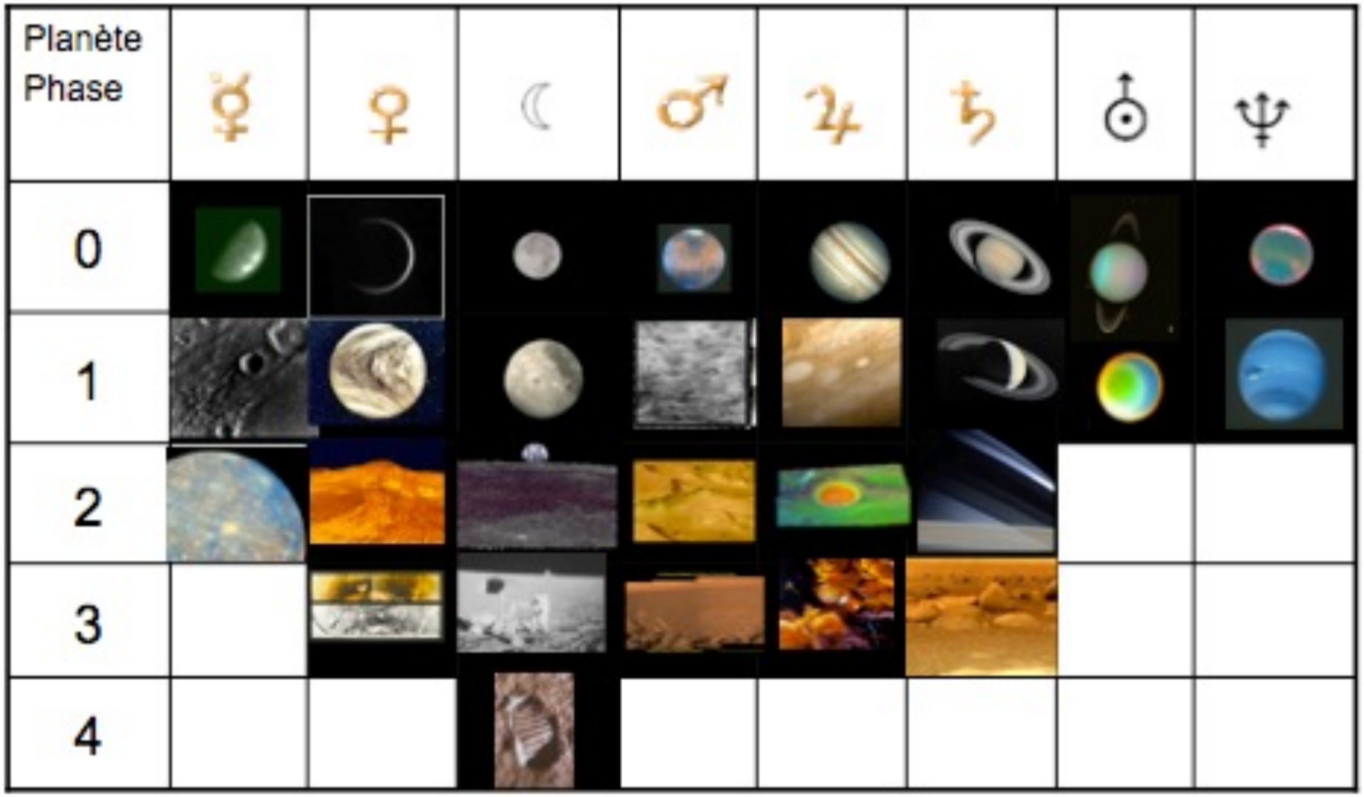
    Part of the rock could be separated in a core
- Uranus
  - Very similar structure

    Probably more concentrated in the center

Prototypes of icy giant planets in exoplanet studies



The roadmap of planetary exploration



Phases of the planetary exploration

0 – Ground based or from orbit observation
1 – Fly-by
2 – orbiting probe
3 – descent in th 'atmosphere and or landing
4 - human exploration