The Gas Giants

The outer part of the solar system, beyond Mars and the asteroid belt, is dominated by the giant gas planets. There are four - Jupiter, Saturn, Uranus and Neptune, in that order - but although they are similar in many ways, we can also divide these into two sub-groups. Jupiter and Saturn form one: these are roughly the same size, and both have compositions thought to be near that of the primordial nebula. Uranus and Neptune are smaller than Jupiter and Saturn, are about the same size, and are deficient in Hydrogen and Helium compared to their larger brothers and the nebula composition.

Temperatures

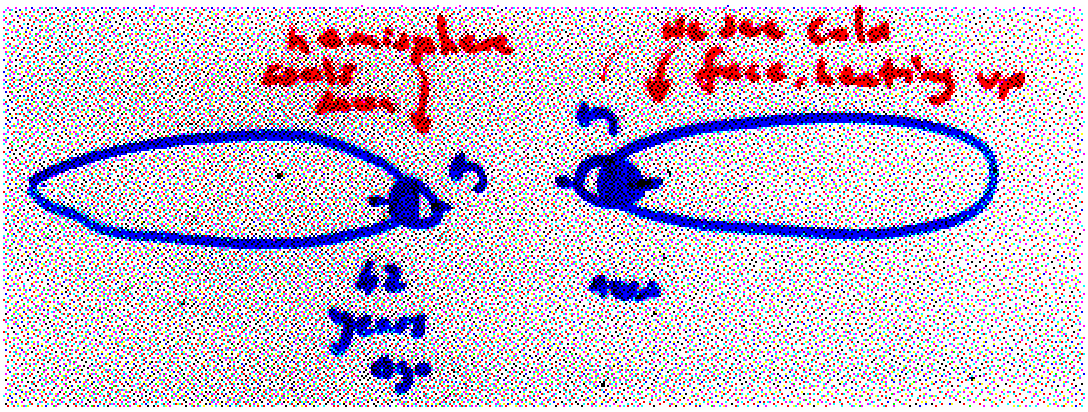
From the thermal balance equations we looked at before we expect temperatures:

Jupiter	c. 106K
Saturn	c. 71K
Uranus	c. 58K
Neptune	c. 46.6K

Actually, we find:

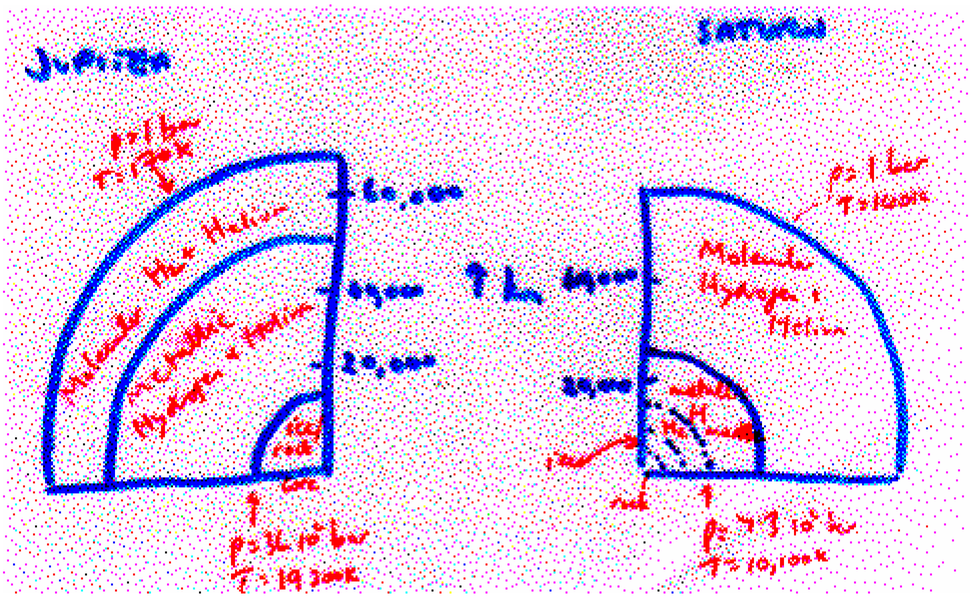
Jupiter c. 126K $(126/106)^4 = 2.3$ times the effective heat output expected
Saturn c. 95K $(95/71)^4 = 3.2$ times the effective heat output expected
Uranus c. 55+/-3 K
Neptune c. 57.2+/- 1.6K = $(57/46)^4 = 2.7$ times the effective heat output expected.

So it seems that some of these bodies, at least, must have some sort of internal heat s must have some sort of internal heat source. In the cases of Uranus and Neptune the sizes are so similar that if one has an internal heat source it would seem strange the other doesn't, andin fact it is believed that Uranus' temperature is the anomalous one. It may be that we have a false impression of the average temperature of Uranus because of the large spin axis inclination and the way we look at the planet. Uranus is heated as two hemispheres, with little heat transfer between them, first one hemisphere for 42 years (half an orbit) then the other for 42 years. We may be seeing the face that has been cold for 42 years and is only now warming up:



So what we need is a planet-wide heat flux, averaged, before we can truly say it is at the temperature we expect. This explanation requires that there is poor heat flow fromone hemisphere to the other, but there is other evidense to suggest this is indeed the case - certainly Uranus' winds blow in zonal belts like the other gas giants, which implies transport is mostly E-W.

Interiors of Jupiter and Saturn



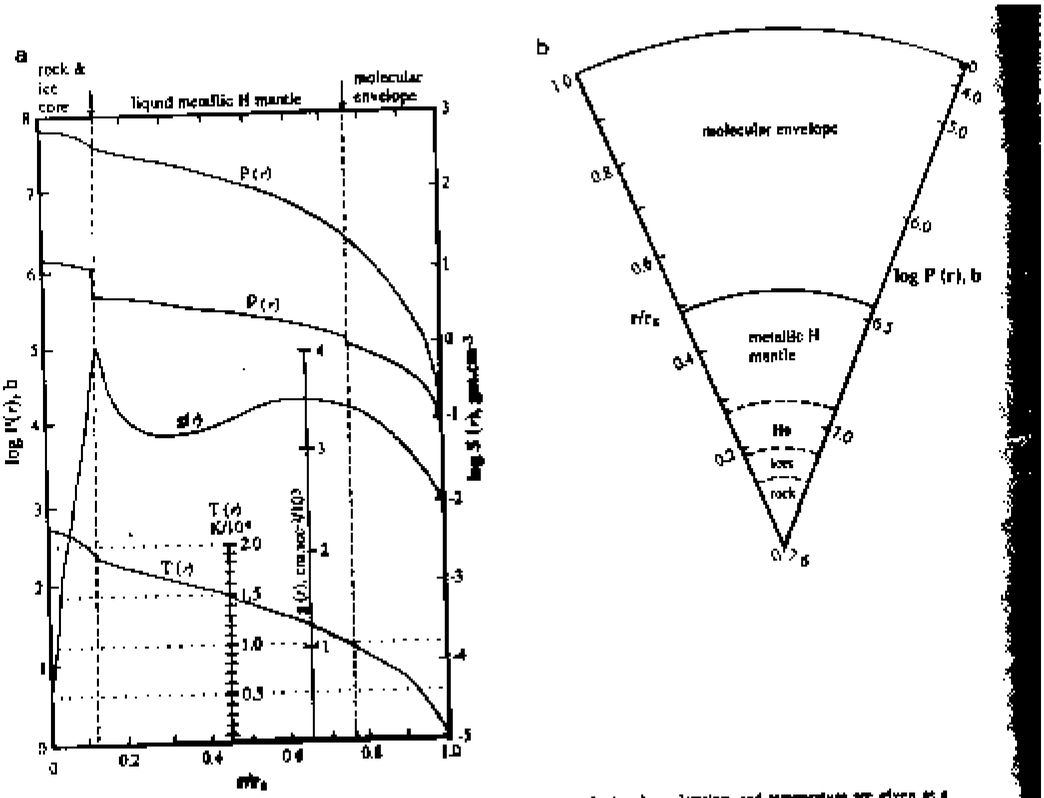
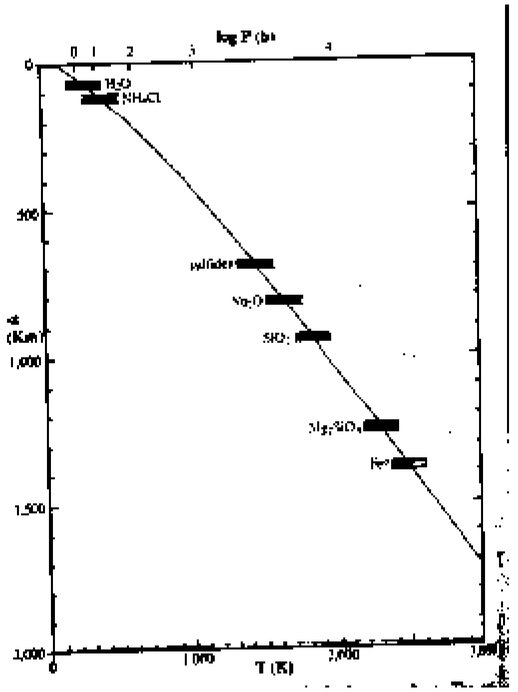


Figure V.4 The interiors of Jupiter and Saturn. The pressure, density, gravitational acceleration, and temperature are given as a function of radius for typical internal models. a illustrates the great importance of metallisation of hydrogen on Jupiter. b is a "pie" diagram of a likely internal structure for Saturn. Note the smaller metallic hydrogen region and the helium-rich layer formed because of the limited solubility of helium in fluid metallic hydrogen. It is not clear whether helium would mix with the icy component or how well the ice-forming elements will mix with (dissolve) the rocky core materials. The boundaries between these layers are thus merely schematic, and no distinct boundaries may exist.

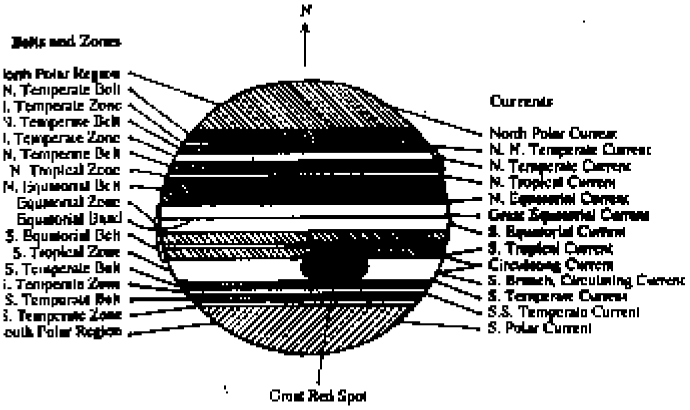
Although the radii are very similar Jupiter is more massive than Saturn - 298M_E compared to 76.6M_E. We will discuss the reasons for this later; it is largely to do with the properties of Hydroge the properties of Hydrogen as one adds Hydrogen to a large planetary body, but there may be a factor to do with the size of the ice/rock core of the planet. What we have here are models, of course, which are our current "best guesses" to fit the dynamical and surface properties measured for the bodies.

Spectra from as early as the 1930s have shown methane (CH_4) and ammonia (NH_3). The "combination bands" seen implied immense amounts of these. Yet both these species are destroyed by ultra-violet light, so the suggestion was made that they are stabilized by equilibration with Hydrogen at high pressures. This was later confirmed. In 1952 Kuiper suggested that the main clouds on Jupiter were made of solid Ammonia, in small crystals.



The H:C ratio on both Jupiter and Saturn are very close to that of the sun - in the range 1-3 x solar. Yet the N:H ratio on Jupiter is several times lower than solar. This may be due to the NH_3 having condensed out. The N:H ratio on Saturn shows even less N than expected. The Helium abundances - measured from spacecraft flybys by looking at the effect of Hydrogen-Helium collisions on the absorption of long-wavelength infra-red radiation) - gives H/He of 17.2 +/12 for Jupiter and 32+/- 8 for Saturn, compared to 14.4 for the Sun.

The Jovian cloud band structure looks at first sight complex and randomt sight complex and random, but this structure is apparently very stable:



The same seems to be true of the Saturnian system. The different bands on both planets also seem to rotate to a large extent with different speeds, decoupled from their neighbours:

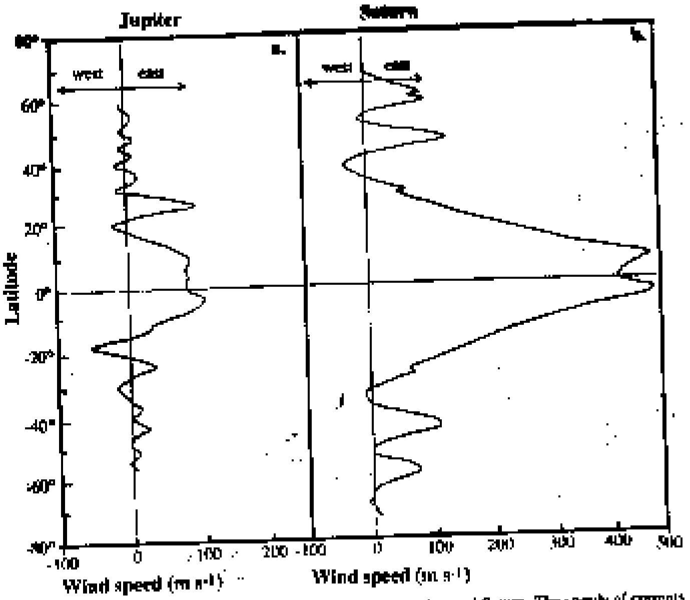
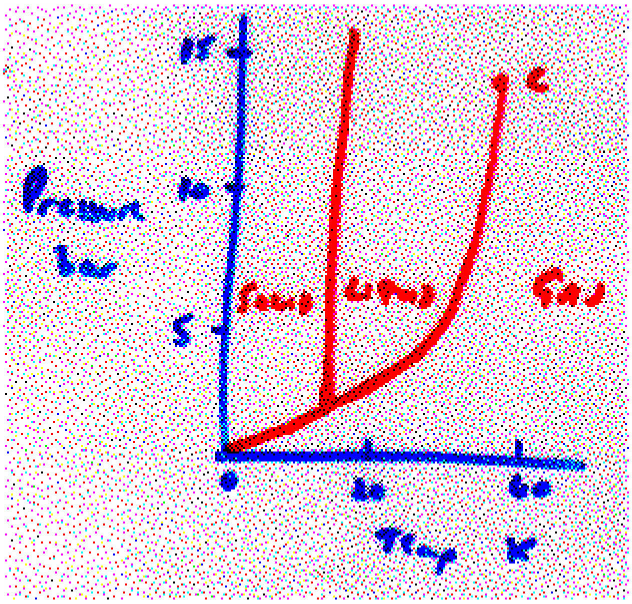


Figure V.20 Speeds of currents in the atmospheres of Jupiter and Saturn. The speeds of currents deduced from the motions of observed bright spots on Jupiter (the east–west or zonal wind speeds) are shown in a. b uses the far smaller data set on spot motions on Saturn to construct a similar figure.

Physics of Hydrogen under great Pressure

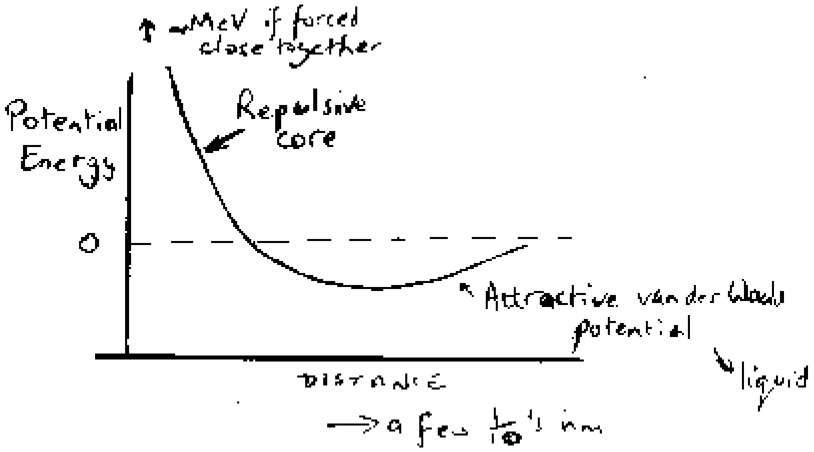
Obviously the physics of "bulk" Hydrogen is important for the gas giants, particularly the way it behaves under immense pressure. The phase diagram for Hydrogen up to 50K and 15 bar shows us the low temperature, low pressure behaviour:



We see that the triple point is around 15bar, so as we go down into the interiors of the gas giants we would soon reach a point where the gas and liquid are indistinguishable. In the laboratory H_2 stays liquid to about 10^6 bars at 170K, the lowest temperature likely to be met in the body of Jupiter. We need to do theoretical studies to get beyond this. (This is only equivalent to a few 1000 km below the clouds.) It is predicted that at any plausible temperature you can get no solid Hydrogen formed in the interiors of the giant planets.

However, at somewhere around 2-5 10^6 bars the molecules of Hydrogen are forced together so tightly that the wave functions of adjacent at wave functions of adjacent atoms overlap, and effectively the bonds between the atoms of one molecule become no more important than the bonds with the atoms in the next molecule: what we have is effectively a continuum of protons through which the electrons swim. This is similar to the situation in a metal, so this is termed "metallic Hydrogen".

When trying to model the behaviour of Hydrogen at high pressures we can no longer use the Perfect Gas Law to describe the pressure. As atoms come closer together we have first an attractive force, due to induced charge separation effects, called the van der Waals force. It is in this regime that liquids are formed. Closer still, however, and the cores of the atoms - the nuclei - start to repel. This force is very strong and rises exponentially as the distance between them:



For the van der Waals regime we modify this so that P=RT/V becomes:

$$P = [RT/(v-b)] - a/v^2$$

This van der Waals equation of state has to be modified further once $P>P_c$ and $T>T_c$ (supercritical), to give:

$$P = \frac{RT(e^{-\alpha/vRT})}{(v-b)}$$

The Dieterici equation of state near the critical point is complex so one often uses the simpler Berthelot equation:

$$P = [RT/(v-b)] - a/Tv^2$$

which improves over the van der Waals equation. Thisr the van der Waals equation. This Berthelot equation is often rewritten using reduced variables:

$$\Pi = P/P_c \qquad \tau = T/T_c \qquad \phi = V/V_c$$

$$P = \left(\frac{RT}{V}\right)\left[1 + \left(\frac{9}{128}\tau - \frac{27}{64}\tau^3\right)\Pi\right]$$

$$\left\{\pi = [128\,\tau/9(4\phi-1)] - \frac{16}{3}\tau\,\phi^2\right\}$$

More complex, less physical and more accurate are the <u>virial</u> equations of state:

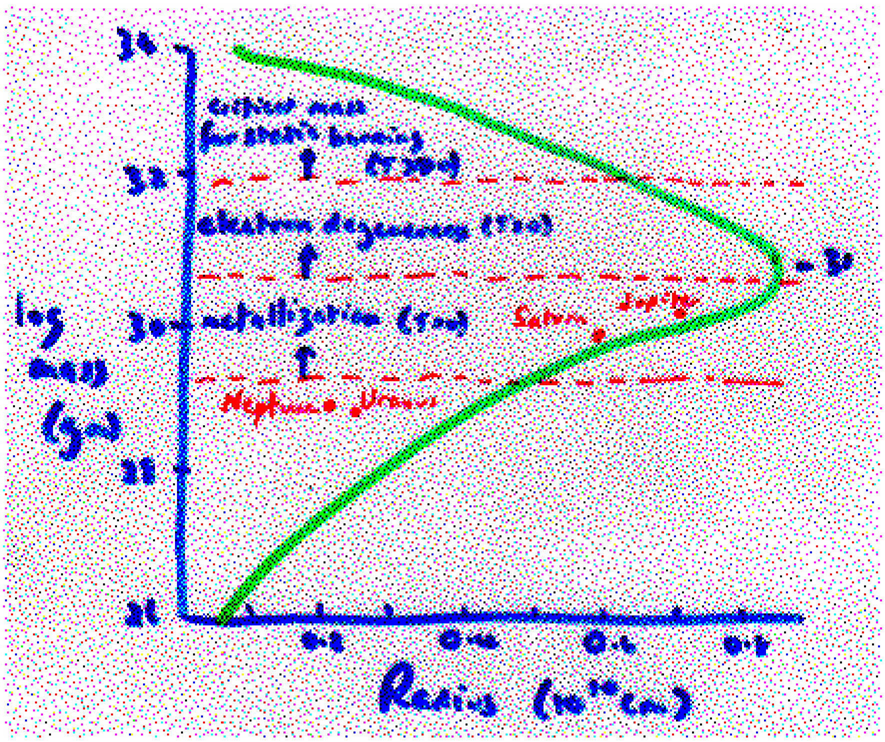
$$PV = RT(1 + b/V + c/V^2 + d/V^3 \;....)$$

and the Beattie-Bridgman equation:

$$PV = RT + B/V + C/V^2 + D/V^3 + \;.....$$
where $B=B(T)$, $C=C(T)$, $D=D(T)$ etc.

The difficult part can be finding the values for the coefficients once we reach pressure regimes that are not reachable in the Lab, as then we have to rely on theory alone.

If we combine all the information we have about the behaviour of hydrogen under pressure and then use theory to try to extrapolate to great pressures we can predict what will happen as a body grows by accumulating more and more Hydrogen:



This calculation is very complex and difficult so for this diagram we have had to make some simplifying assumptions. Thus this is for a body at 0K, and it is a spherical, non-rotating body composed of pure hydrogen. Bodies at non-zero temperature would be larger and so the curve would move to the right.

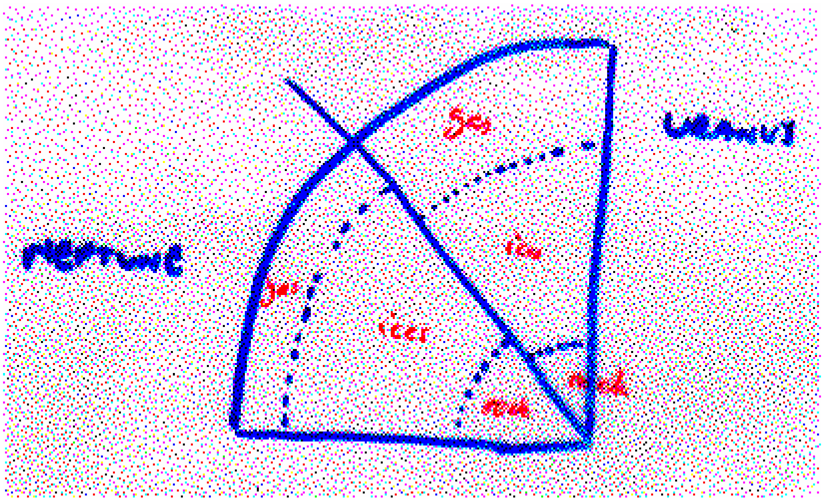
We see that as Hydrogen is added the body does not grow linearly with mass (note the left hand axis is a log scale - the bottom axis is linear). This is because ttom axis is linear). This is because as we add more material the total mass goes up and so the material that was there already is compressed. Eventually we see that we getto a point where there is a balance - as we add more mass the body stays the same size as the added volume of material is compensated for exactly by the compression of the material that is already there. This behaviour goes some way to explaining why Saturn is roughly the same size as Jupiter even though it is much lighter.

Above the turn-over point, of course, we see that the body actually shrinks as we add material, the added volume being more than compensated for by the added mass's compression effect. Above 10^{29} kg the body reaches critical mass where the nuclei are forced so close toghether that fission is initiated and Hydrogen burns to Helium - the body has become a sun.

Below this regime we see that we have first, at around 10^{26}kg, the region we have described where Hydrogen becomes metallic in nature, and then at around 10^{28}kg we have a region of electron degeneracy.

We have marked on this diagram the positions of the giant planets (and sub-giants). We see that Neptune and Uranus are nowhere near the regim where metallic hydrogen is formed. We see also that Jupiter and Saturn are inside the curve, since they are not pure Hydrogen and the extra mass of their cores makes them smaller than a pure hydrogen bodan a pure hydrogen body. There is an added difference in that this curve is for 0K - if the temperature is also taken into account it is possible that Saturn moves out of the metallization region. Thus, it is not entirely sure that metallic hydrogen is found inside Saturn, as it undoubtedly is in Jupiter. The cross-sections above assume it is, but there is a large scope for uncertainty in these models.

Interiors of Uranus and Neptune



Note that a much larger proportion of these planets is rock and ice, hence their higher average densities. The gas layers have a large fraction of hydrogen and helium, but also contain a larger proportion of other gases than is seen in the outer envelopes of Jupiter and Saturn.

These diagrams again represent only models of the planets, of course - we cannot actually "see into" the planets, so we have to try to deduce the internal structure by making up plausible models and then see if they fit the observations we have. Fully separated three-layer models have too small a rotational moment of inertia, whereas homogeneous models have too small a J_2. There must be a strong radial composition gradient, but probably not well-defined interfaces.

One "allowed" composition would be to have solar-like H/He with a rocky core. At the other extreme one could enrich all the other elements exceptall the other elements except Hydrogen, which gives 70% He, 20% ice and 10% rock by mass, with Hydrogen only in smaller quantities. This large range of possible models illustrates how difficult it is to "invert" the gravity field data to give a unique solution.

Spectra taken from ground-based and space probe observations, and Voyager radio occultation experiments find CH_4 (methane) at 1.4 - 2% in the clouds, but condensation physics makes this measurement difficult. It seems likely there will be enhanced NH_3 (ammonia) too.