Comparative Evolution of the Atmospheres of Giant Planets

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The four giant planets of the Solar System exhibit similar structures: the interpretation of the measured values of their gravitational moments suggest that they all have cores, probably made of rocks and ices, and of about 10-15 Earth masses. The cores are surrounded by atmospheres of low density, mainly composed of hydrogen and helium. The total masses of Jupiter, Saturn, Uranus and Neptune are 318, 95, 14.5 and 17 Earth masses respectively, so that the atmospheres of Jupiter and Saturn must be extremely deep while those of Uranus and Neptune are relatively thin.

One decade ago, it was commonly accepted that all giant planets had atmospheric compositions similar to that of the primitive solar nebula from which all planets and the Sun presumably condensed. This assumption was based on theories of the escape of gases from a planetary atmosphere. According to the well-known Jeans formula, the rate of escape is proportional to the exospheric temperature and inversely proportional to the mass of the planet. Because of the high masses and low exospheric temperatures of the giant planets, even the lightest molecules cannot escape from their atmospheres. Therefore, contrary to telluric planets which have lost their primary atmospheres, if any, giant planets should have kept their initial atmospheres formed from the gaseous material of the primitive solar nebula.

Progressively, the study of the outer planets has revealed the complexity of the physical conditions obtaining in their interiors, and more accurate determinations of their atmospheric composition has made obvious a significant departure from the solar abundance. For instance the observed helium and deuterium atmospheric abundances vary substantially from one planet to another while the carbon abundance is obviously oversolar in the four giant planets.

In fact, as discussed below, the relative abundances of the gases present in the solar nebula may be substantially modified, during planetary formation and during the subsequent planetary evolution as well.

Scenarios for Planet Formation

Scenarios for planet formation can be classed into two typical models: the gas-instability model and the nucleation model.

The first assumes that gravitational instabilities in the primordial nebula resulted in local condensations of matter in extended regions (several thousand times greater than the present radii of giant planets). Subsequent hydrodynamical collapse of the protoplanet, followed by slow contraction in hydrostatic equilibrium led to the present stage. An internal stratification in layers of different compositions result from chemical processes conditional on thermochemical equilibrium.

Molecular hydrogen, helium and neon, which do not condense in conditions prevailing in the outer atmospheres of giant planets, should exhibit atmospheric abundances in proportions similar to those of the primitive solar nebula and the Sun. Similarly, carbon, nitrogen, oxygen, the three other most abundant cosmic elements, which are mainly in the form of methane, ammonia and water in giant planets, should be in solar proportions relative to hydrogen, except in the cold upper tropospheres where these molecules may condense.

The second approach considers that grains made of refractory materials (silicate, iron...) and also of ices (H_2O, NH_3, CH_4) or of mixed clathrates (unbonded compounds) and hydrates of volatile components (CH_4, NH_3, N_2, CO, Ar...), were embedded in the gaseous solar nebula. They agglomerated in planetesimals. Subsequent accretion processes led to the formation of a core, as for the telluric planets. Once the core became sufficiently massive, it captured gas from the surrounding solar nebula material and formed an atmosphere. In this scenario also, components non-condensable in conditions prevailing in the regions of formation of giant planets should be in solar proportions, but CH_4, NH_3, H_2O could be enriched in the outer atmosphere compared to the solar abundance since the strong heating resulting from accretion probably evaporates volatiles and leads to the formation of a CNO atmosphere which subsequently mixes with the gaseous material of the primitive nebula.

The gas instability model does not explain why the value of the core mass is nearly the same for the four giant planets while it is correctly predicted by the core instability model. Moreover, local physical conditions may not be favourable for the precipitation of the heavy elements forming the core, as is assumed in the first scenario. On the other hand, it is generally considered by dynamicists that the small mass of Mars compared to the mass of the Earth and Venus, and the occurrence of many small bodies in the asteroid belt rather than a single planet are due to the presence of Jupiter prior to the formation of the inner Solar System. However, the formation of core by accretion is a slow

Table 1 — Abundances of C, N and O in the Giant Planets

	SUN	JUPITER / SUN	SATURN / SUN	URANUS / SUN	NEPTUNE / SUN
C/H	4.7×10^{-4}	2.3	3–6	20–25	25 ?
N/H	9.8×10^{-5}	$\cong 2$	2–4	?	?
O/H	6.8×10^{-4}	1/50 from H_2O ~ 1 from CO			

In the upper atmospheres of giant planets, most of the carbon is in the form of CH_4, and a very small amount in the form of CO. Nitrogen is in the form of NH_3, oxygen is in the form of H_2O and a very small amount in the form of CO.

process and it seems that Jupiter could not have been formed before the telluric planets. As concerns Uranus and Neptune, their time of formation could be comparable to the age of the Solar System or even possibly exceed it.

Another element of the puzzle is the comparison of observed atmospheric abundances in giant planets with values predicted by both scenarios.

Observed Atmospheric Composition of Giant Planets as a Test of Formation Scenarios

The C/H, N/H, O/H elemental ratios observed in the atmospheres of giant planets are given in Table 1 in solar units.

All planets exhibit an enhancement of carbon compared to the solar abundance, a result which is not consistent, as previously mentioned, with the gas instability model, but which is compatible with the nucleation model.

The observed increase of carbon when moving from Jupiter to Saturn to Uranus and Neptune is also consistent with the nucleation model. In Jupiter and Saturn, which exhibit massive gaseous envelopes and relatively small cores, the contribution of cores to the atmospheric composition is expected to be relatively modest in agreement with the observed weak carbon enrichment. In Uranus and Neptune, where cores are large and envelopes relatively small, the carbon enrichment is much stronger than in Jupiter and Saturn. However, Stevenson [1]) objects that the convection in planetary interiors is not powerful enough to provide a sufficient upward mixing of core constituents. (This argument may be irrelevant since just after their formation, giant planets should have a much stronger internal energy and thus a much more intense convection than at the present time.) Therefore, he proposes that comets and meteorites infalling in Jupiter and the other giant planets at the time of their formation supplied the observed carbon abundance. He still favours the nucleation model because estimates of the solubility of minor constituents in metallic hydrogen lead to the conclusion that the rain-out of the core implied by the gas instability model is very unlikely. Note that the Stevenson scenario does not explain simply the observed variations of carbon enrichment in various giant planets.

Any inhomogeneous scenario of planetary formation, with or without infalling planetesimals, implies a simultaneous enrichment in carbon, nitrogen and oxygen. Deep tropospheres of Jupiter and Saturn seem to be enhanced in ammonia. In contrast, NH_3 is depleted in Uranus and Neptune at observable levels, although that may be explained if NH_3 is dissolved in the deep interior in an ionic water ocean, as predicted by models of internal structures of these planets [2]). The case of oxygen in Jupiter is somewhat puzzling since infrared measurements suggest an important depletion of water vapour not predicted by thermochemical models. It may be that at observed atmospheric levels, water is dried by upward convective movements. This assumption is confirmed by the determination of the O/H ratio from CO abundance measurements which exclude a depletion of oxygen compared to the solar value. A definite answer will be obtained from *in situ* measurements made aboard the atmospheric probe of the Galileo mission to Jupiter which is unfortunately now postponed to the 1990s.

Another piece of information comes from the comparison of deuterium abundances in giant planets. According to current cosmological theories, most of the deuterium present in the Universe was initially built during the first minutes of the "big-bang". Subsequently, it has been destroyed in stars forming ^{3}He. Supernovae explosions and stellar winds enrich the interstellar medium in nucleo-

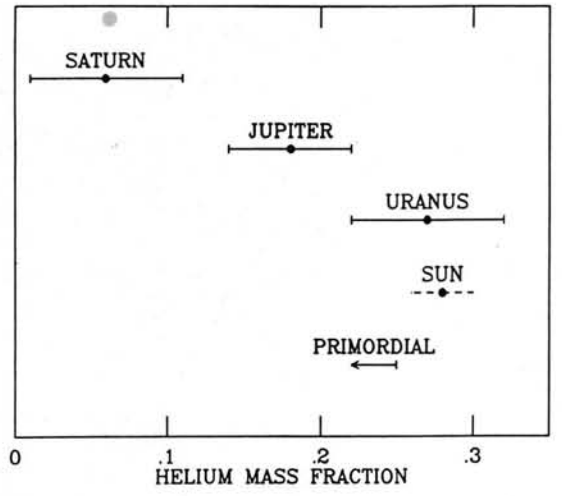

Fig. 1 — Helium abundances (per mass) in the atmospheres of Jupiter, Saturn and Uranus compared to the protosolar and the primordial value. He abundances in giant planets were measured by Voyager. The protosolar value is inferred from solar evolutionary models: uncertainties are not indicated by the modellers but all recent models propose values between 0.27 and 0.28 per mass. The primordial value is controversial; the most recent determinations of helium in old galaxies are ca. 0.23 – 0.24 (according to Conrath et al., Ref. 5).

synthetic components except in deuterium so that the relative abundance of this constituent decreases with time in the interstellar medium. A good estimate of the D/H ratio present in the primitive solar nebula 4.5 billions of years ago, has been derived from ^{3}He measurements in the solar wind [3]). It was initially expected that giant planets should exhibit D/H ratios equal to the protosolar value.

The determination of the deuterium abundance in giant planets is still uncertain (for a review, see for instance Ref. 4). Deuterium is mainly in the form of HD, and is also present in smaller proportions in the form of CH_3D, HDO and NH_2D. However, at the present time, only HD and CH_3D are observable. The problem is that determinations of the D/H ratio from HD and H_2 absorption lines on the one hand and from CH_3D and CH_4 absorption lines on the other disagree.

A detailed discussion of the problem is out of the scope of this paper. To summarize the question — still controversial — in a few words. It seems reasonable to favour the derivation of D/H from the CH_3D/CH_4 ratio since in Jupiter and Saturn, results are in agreement with the "protosolar" value [3]) of about 2×10^{-5} while D/H ratios derived from HD/H_2 do not. Moreover, the shape of the very weak lines of HD in the visible range is strongly model dependent so that systematic errors, difficult to evaluate, probably affect the results.

With this assumption, the D/H ratio appears to be enhanced in Uranus by a factor of 5 compared to Jupiter and Saturn. This result is also in agreement with the nucleation scenario, since because of the low temperatures, a large isotope fractionation effect is expected to occur in ices of H_2O, CH_4 and NH_3, leading to D/H ratios much higher than the protosolar D/H value. Since the cores of Jupiter and Saturn are small compared to planetary masses, the evaporation of HDO, CH_3D and NH_2D has enriched the atmosphere by a negligible amount. In contrast, the relatively thin atmosphere of Uranus is expected to have been significantly enriched in deuterium — in agreement with observations.

To sum up at this stage, the observed compositions of giant planets strongly suggest that these objects were formed in an inhomogeneous way, leading to a substantial enhancement of CNO compounds in their atmospheres, compared to solar abundances. The influence on the composition of planetesimals infalling in the atmospheres is not clear and its evaluation requires more studies and observations. Precise isotopic ratio measurements are crucial for a better understanding of the question.

In the following section, we shall examine what information on the evolution of giant planets after their formation can be derived from the comparison of ratios of their two atmospheric major components, hydrogen and helium.

Helium Abundance in Giant Planets as a Test of their Atmospheric Evolutions

Both scenarios of planet formation discussed in the previous section predict that H_2 and He should be in the same proportions as in the primitive solar nebula and in the protoSun, since these elements could not condense in the physical conditions obtaining in the nebula. Observations do not agree with these predictions.

In Fig. 1 are summarized the values of the helium abundance measured in the outer atmospheres of Jupiter, Saturn, Uranus and the Sun (the value in Neptune is still unknown).

The Saturn value ($Y = 0.06 \pm 0.05$ per mass) is significantly less than the Jovian value ($Y = 0.18 \pm 0.04$) which is itself somewhat less than the value recently determined for Uranus ($Y = 0.267 \pm 0.048$, Ref. 5). The helium abundance in Uranus agrees well, considering the error bars, with protosolar values derived from the most recent evolutionary models ($Y \cong 0.27 - 0.28$). In these models, the initial helium content at the time of the formation of the Sun is used as a parameter. The right value is the one which leads to the best fit of the present mass, luminosity and age of the Sun. The evolutionary models have been recently improved by introducing more accurate radiative opacities and nuclear reactions rates.

High pressure thermodynamics and theories of planetary evolution provide a satisfying interpretation of these results. At pressures higher than about 3 Mbar, which occur in the interiors of both Jupiter and Saturn, hydrogen is expected, according to theoretical studies, to undergo a transition from a molecular to a metallic state. Helium miscibility is less easy in metallic than in molecular hydrogen (Fig. 2) and at sufficiently low temperatures, helium droplets must form and migrate toward the centre of the planet, leading to a depletion of helium in the outer atmosphere.

Whether this process occurs or not in planetary interiors depends on the thermal history of the planet. Initially a giant planet acquires a very high temperature as a result of accretion processes. Then, its luminosity decreases rapidly with time as a result of the Kelvin mechanism in which a self-luminous body derives its intrinsic power from the cooling of a thermal energy reservoir. Helium differentiation starts when the 3 Mbar pressure level reaches the saturation temperature and then generates an additional source of energy.

Because of Saturn's smaller mass and dimensions, its luminosity is expected to vanish earlier than that of Jupiter. Indeed, according to current evolutionary models, Saturn's luminosity should have disappeared 1 or 2 billions of years ago. The fact that Saturn exhibits a substantial internal source of energy is explained by the downward migration of helium droplets which liberates the gravitational energy required to maintain Saturn at the observed luminosity — significantly higher than the value which would result from the absorption of solar energy alone. The assumption of a helium differentiation from hydrogen in the interior of Saturn is then well consistent with the observed helium depletion in the outer atmosphere of the planet compared to the solar value.

The case of Jupiter is less obvious because it is difficult to know in view of the uncertainties in the equations of state and the thermodynamic parameters of H_2-He mixtures at high pressures whether Jupiter has already completely lost its initial excess of luminosity or not. The comparison with the helium solar abundance however suggests that helium differentiation has already begun in Jupiter.

Uranus, like Neptune, has a relatively thin H_2-He atmosphere. Accordingly, the hydrogen pressure at the edge of the core should not exceed around 200 kbar, a value much below that required to permit the molecular to metallic hydrogen transition.

Consequently, no helium differentiation is expected to occur in the Uranian atmosphere. The validity of this analysis is confirmed by comparing the Uranus atmosphere with the solar value which appears (considering the error bars) to be in good agreement. We can then conclude that the composition of the Uranian atmosphere has probably not significantly changed since its formation. Particularly, the non-condensable components: H_2, He, Ne, must be in the same relative proportions as in the primitive solar nebula.

To sum up, all giant planets have cooled since their formation and lost a large part of the luminosity they initially acquired from accretion processes. In the case of Jupiter and Saturn, this cooling is regulated by a redistribution of vertical profiles of the major atmospheric components, hydrogen and helium. When the temperature is sufficiently low at pressure levels where hydrogen becomes metallic (around the 3 Mbar level), helium droplets form and sink towards the centre of the planet. In contrast, the hydrogen to helium mixing ratio in the atmospheres of Uranus and Neptune should have held constant since their formation. Note that the internal energy source of Uranus is now quite small compared to the energy coming from the Sun and liberated in the upper atmospheric layers of the planet. The thermal evolution of the planet is thus now very slow. Neptune, which receives less energy from the Sun than Uranus since it is located further, exhibits an internal energy significantly higher than the solar energy it absorbs.

Conclusion

The exploration of the Outer Solar System undertaken during the last decade has revealed the complexity of the history of giant planets. They were formed not only from gases but also from grains present in the primitive solar nebula. As a consequence, a substantial enrichment in volatiles, compared to the solar abundance, occurred in their atmospheres at the time of the formation. The largest planets, Jupiter and Saturn, have subsequently deeply evolved, as a result of the differentiation of helium from metallic hydrogen in planetary interiors. The phenomenon started later in Jupiter than in Saturn. Minor components are, however, probably well mixed in both atmospheres (Ref. 1).

On the other hand, helium is not expected to have differentiated from hydrogen within the deep atmospheres of Uranus and Neptune since their formation. Therefore, the precise determination of abundances of uncondensable components of the primitive solar nebula could be inferred from measurements made in the outer atmospheres of these two planets. That can be made by *in situ* measurements using mass spectrometers aboard atmospheric probes descending into their upper atmospheres, following the strategy initiated by the Jupiter probe of the Galileo mission and by the Titan probe of the Cassini project currently studied by NASA and the European Space Agency in cooperation.

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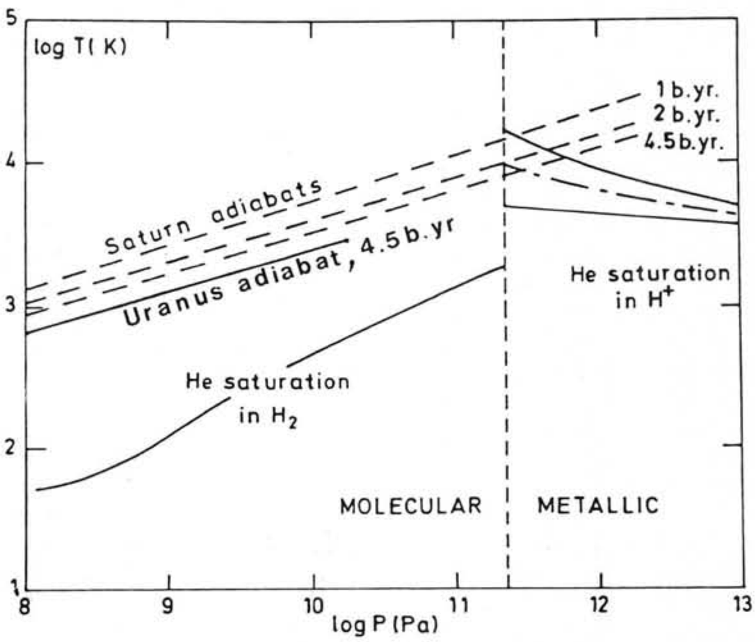

Fig. 2 — Saturation temperature of helium for a mixture of H and He in "cosmic" abundance (75% H, 25% He), in a Temperature-Pressure diagram. Pressure is in pascals (1 bar = 10^5 Pa), and temperature in Kelvin. The vertical dashed line indicates the molecular metallic hydrogen transition. The upper and lower curves on the right represent the extreme possibilities taking into account the theoretical uncertainties of helium solubilities in metallic hydrogen, while the dash-dot line represents the most plausible curve. The dashed line at the top represents three Saturn adiabats (line of constant entropy satisfying boundary conditions at the top of the atmosphere) at different ages, calculated from the origin of Saturn, as the planet cools down (4.5 billion years correspond to now). In the molecular H_2 region, adiabats are always above the saturation curve but in the metallic range the adiabat begins to intercept the dash-dot line at about 2 billion years after the formation of the planet when helium raindrops form. Jovian adiabats, not shown for clarity, are located slightly above Saturn adiabats but should also intercept, somewhat later (i.e. more recently) the solubility curves. Uranus (and Neptune) adiabats are cooler than Saturn but they are believed to stop at the edges of the cores of both planets at about 2×10^{10} Pa and thus never reach the metallic H range. (Adapted from Stevenson, Ref. 2.)