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Constraints on the Formation of Giant Planets from their Atmospheric Chemical Composition

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Constraints on the formation of giant planets from their atmospheric chemical composition

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There are currently two classes of theories of formation of giant planets: the nucleation model and the gas instability model. The comparison of atmospheric compositions of giant planets permits a test of these. The observed enhancement in CNO compounds in all giant planets, and in deuterium in Uranus, compared with the solar abundance, is consistent with the nucleation model in which a core first grows from accretion of planetesimals and subsequently attracts the surrounding gaseous material of the nebula. However, available data do not permit us to definitively exclude the gas instability model. The agreement of the helium abundance observed in Uranus with the solar value and the depletion observed in Jupiter and Saturn is well explained by the differentiation of helium from metallic hydrogen occurring in the interiors of Jupiter and Saturn but not within Uranus where hydrogen cannot become metallic. Accurate *in situ* measurements of elemental and isotopic ratios made aboard atmospheric probes descending into atmospheres of giant planets are indispensable for a firm discrimination between various theories of planetary formation.

1. Introduction

The low density of giant planets has suggested for some time (de Marcus 1958) that these objects are mainly made of hydrogen and helium, the two major components of the primordial solar nebula from which all planets and the Sun presumably condensed. Spectroscopic measurements confirm the presence of molecular hydrogen in large amounts in the outer atmospheres of all giant planets. Therefore, one or two decades ago, it was commonly thought that these planets have atmospheric compositions similar to that of the primitive solar nebula and of the Sun (Cameron 1973).

Progress in observations, especially from space missions, and in theories of planet formation revealed the complexity of the real situation. The relative proportions of elements initially present in the solar nebula may be modified, first as a result of processes occurring during the formation of planets, and second during the subsequent evolution of their atmospheres. In turn, observed compositions of outer atmospheres may provide a way to discriminate between various scenarios of planetary formation and evolution.

Whatever the situation, no differentiation of helium from hydrogen is predicted during planetary formation. However, different scenarios lead to different abundances of carbon, nitrogen, oxygen and deuterium in the outer atmospheres of giant planets. On the contrary, no variation of relative abundances of these components is expected during planetary evolution, whereas helium can be differentiated from hydrogen in thermodynamical conditions that may occur within interiors of Jupiter and Saturn, leading to a depletion of helium in outer atmospheric layers accessible to observations.

The plausible composition of the primitive solar nebula in the region of formation of giant planets is briefly summarized in § 2. In § 3, the various theories of planet formation are discussed as well as the possible consequences on observed compositions. Observed abundances of CNO compounds in the atmospheres of giant planets are compared to predictions from various scenarios in § 4. The case of deuterium, which is controversial, is discussed in § 5. Observed atmospheric helium to hydrogen ratios are considered in § 6 in the framework of evolutionary models. Section 7 is devoted to conclusions.

2. The composition of the solar nebula

The global chemical composition of the primitive solar nebula may be derived from the elemental composition of the Sun (Cameron 1982). By assuming that thermochemical equilibrium exists in the nebula and models for temperature-pressure profiles throughout the nebula, radial distributions of various components can be calculated (see, for instance, Lewis & Prinn 1980, 1984). Although the temperature structure of the nebula is uncertain and controversial, it is well established that giant planets formed in cool regions of the nebula where most of the species could condense, except the two major components, hydrogen and helium, and also neon. As concerns the three other most 'cosmically' abundant elements, carbon was mainly in form of CO or CH_4, nitrogen in form of N_2 or NH_3, and oxygen in form of H_2O. An example of calculated radial distributions of these species in the nebula is shown in figure 1. Should the thermochemical equilibrium prevail everywhere in the nebula, CH_4, NH_3, and H_2O are clearly predominant for the assumed temperature–pressure model at distances exceeding 2 AU from the centre of the nebula. However, Lewis & Prinn (1980) estimate that the rates of conversion of CO to CH_4 and N_2 to NH_3 were slow compared with the rates of radial transport throughout the nebula. They conclude that nitrogen and carbon were largely present in form of N_2 and CO in the region of formation of giant planets.

Note that whatever the initial form of CNO components was they were subsequently reprocessed in giant planets according to thermochemical laws. In particular, in the outer atmospheres where observations are possible, CH_4, NH_3 and H_2O must be the predominant CNO compounds (Barshay & Lewis 1978; Fegley & Prinn 1985, 1986).

Grains were embedded in the nebula. They were composed of refractory materials and also of ices of H_2O, and possibly of CH_4 and NH_3 if these species were predominant. More likely was the presence of clathrates containing either CH_4 and NH_3 or CO, Ar and various noble gases. A discussion in depth of clathrate physics and of their possible contribution to the present composition of giant planets has been made by Lunine & Stevenson (1985). The possible predominance of clathrates in the outer nebula has strong implications on the composition of giant planets and Titan atmospheres, icy satellites and comets.

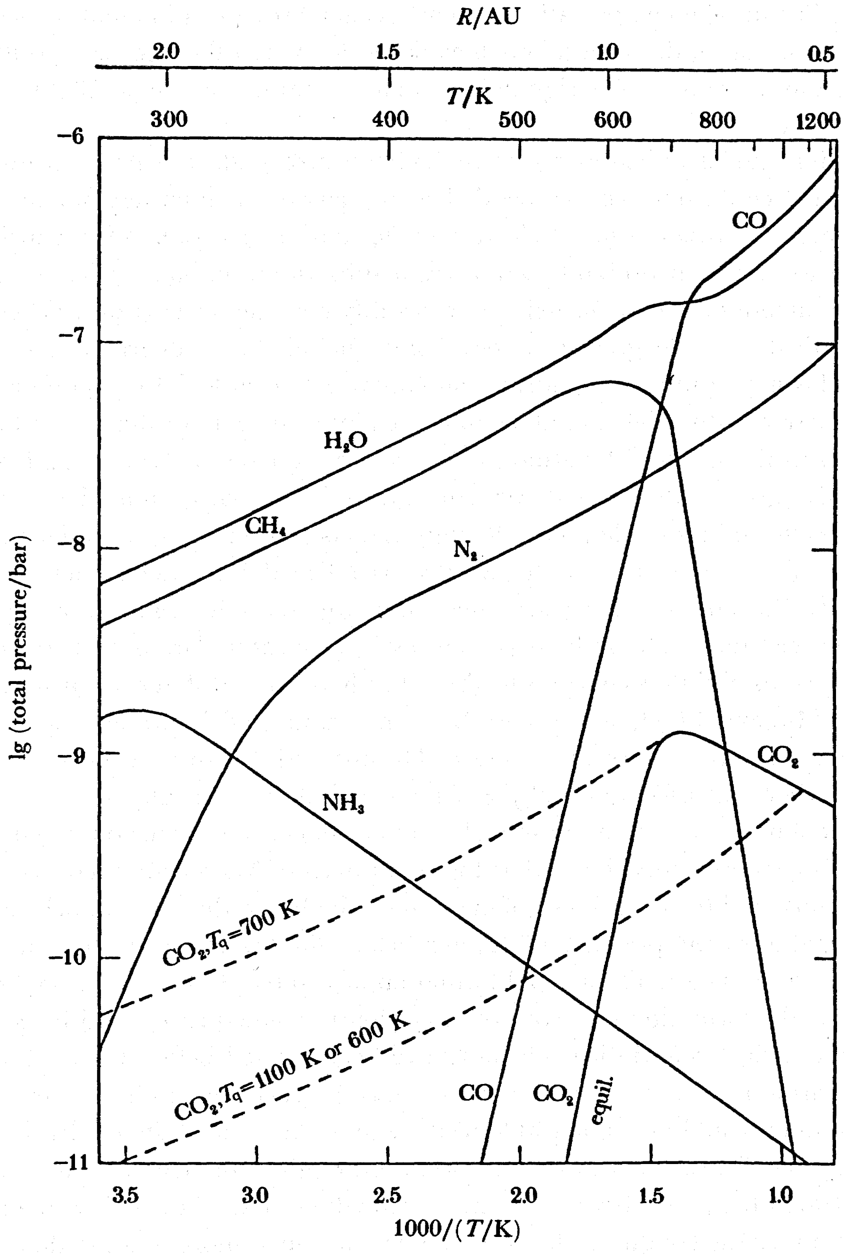

FIGURE 1. Partial pressures of major CNO compounds in gaseous phase along a plausible solar nebula adiabat, R is the distance from the Sun, and T is the temperature. Solid lines correspond to pressure calculations made under the assumption of a strict thermodynamic equilibrium throughout the nebula. The dotted lines show the effect of quenching at 600, 700 and 1100 K on the CO_2 pressure profile (from Lewis & Prinn 1980).

3. Scenarios for giant planets formation

The models for the formation of planets proposed by various authors can be classed in two typical models; the gas-instability or homogeneous-collapse model, and the core-instability or nucleation model.

The first (see, for instance, De Campli & Cameron 1979) assumes that gravitational instabilities in the primitive nebula result in extended gaseous protoplanets which collapse by radiating energy. The subsequent formation of a core occurs through sedimentation of refractory compounds. In this scenario, the atmosphere is expected to exhibit the same composition as the primitive nebula and the Sun, and no significant enhancement in volatiles as CNO compounds is predicted.

In the nucleation model (Mizuno 1980; Bodenheimer & Pollack 1986), grains made of silicates and ices (or clathrates) and embedded in the gaseous nebula agglomerate in planetesimals. Subsequent accretion processes lead to the formation of a core, as for telluric planets. The heating due to accretion probably vaporizes a substantial amount of ices or clathrates which mix in the surrounding gaseous nebula or possibly recondense as grains. When the core has grown to a critical mass, the gaseous material of the nebula becomes gravitationally bound to the nucleus. This model predicts a substantial enhancement of CNO compounds in jovian atmospheres compared with solar abundances, especially if the core of the planet has a large mass compared with the mass of the atmosphere, as it is the case for Uranus and Neptune.

No model totally agrees with observational constraints. The nucleation model explains well, contrary to the gas instability model, that all giant planets exhibit cores of similar sizes, about 10–15 M_E (where M_E is the mass of the Earth), as inferred from determinations of their gravitational fields (Stevenson 1982*a*). Moreover, the large solubility of most of the elements, with the notable exception of He, in hydrogen at high pressures makes difficult the formation of a core in the gas-instability scenario. On the other hand, the differences in mass of giant planets (318, 95, 14.5 and 17 M_E for Jupiter, Saturn, Uranus and Neptune, respectively) are not well explained: it may require that cores of Uranus and Neptune reached their critical masses at a time where the dissipation of the nebula had already begun.

The main objection to the nucleation model comes from considerations on dynamics of the Solar System. It is generally considered 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, is due to the presence of Jupiter before the formation of the inner planets. Meteorite data seem to suggest also a rapid formation of Jupiter (P. Pellas personal communication). However, the formation of a core by accretion is a slow process and it seems that if Jupiter had followed this scenario it could not have been formed before the birth of telluric planets (for a discussion, see for instance Pollack (1985)). As concerns Uranus and Neptune, their time of formation could be comparable to the age of the Solar System. On the contrary the gas-instability model permits a quite fast formation of giant planets. Lissauer (1987) has recently demonstrated the possibility of a runaway growth of solid cores of giant planets in less than 10 Ma, but under the condition that the nebula was much more massive than currently accepted. To solve this difficulty, Stevenson & Lunine (1988) imagine a diffusive redistribution and condensation of water vapour in the region of the nebula where the planet forms, but the proposed process does not cause by itself a fast formation of the other giant planets. For his part, Artymowicz (1987) sees the solution in an improved description of the dynamics of formation of planetesimals.

Because both scenarios lead to different atmospheric compositions, the examination of observed abundances of volatiles, namely CNO compounds, in the outer atmospheres of giant planets may be a test of formation theories, as discussed in the following section.

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4. The observed CNO compounds abundances in the outer atmospheres of the giant planets

The C/H, N/H, O/H elemental ratios observed in the outer atmospheres of giant planets are summarized in table 1, in solar units. The C/H ratio is derived from the CH_4 abundance through the relation

$$\frac{C}{H} = \frac{1}{2}\frac{CH_4}{H_2},$$

where CH_4 and H_2 represent the molar fractions of the two species in the atmosphere.

Table 1. Elemental ratios, in solar units, observed in the outer atmospheres of giant planets

	Sun	Jupiter/Sun	Saturn/Sun	Uranus/Sun	Neptune/Sun
C/H	4.7×10^{-4} (a)	2.32 ± 0.18 (b)	2–6 (c, d)	*ca.* 25 (e)	*ca.* 25 (f)
N/H	9.8×10^{-5} (a)	*ca.* 2 (g, h)	2–4 (g, h)	$\leqslant$ 1? (h)	$\leqslant$ 1? (h)
O/H	8.3×10^{-4} (a)	1/50 (i) (from H_2O) $\geqslant$ 1/3 (j) (from CO)			
P/H	2.4×10^{-7} (k) (from carbonaceous chondrites)	1 ± 0.3 (l)	2.8 ± 1.6 (c)		

References: (a) Lambert (1978); (b) Gautier *et al.* (1982) revised by Gautier & Owen (1983); (c) Courtin *et al.* (1984); (d) Buriez & de Bergh (1981); (e) Lindal *et al.* (1988); (f) Lutz *et al.* (1976); (g) Marten *et al.* (1980); (h) de Pater & Massie (1980); (i) Bjoraker *et al.* (1986*a*); (j) Noll *et al.* (1988*b*), Fegley & Prinn (1988); (k) Cameron (1982); (l) Kunde *et al.* (1982).

The most precise determination of the CH_4 mixing ratio in Jupiter has been derived from *Voyager* infrared observations of the ν_4 band of CH_4 centred at 7.7 μm and clearly indicates a carbon enhancement by at least a factor of two compared with the solar abundance (Gautier & Owen 1983). Although the Saturn abundance is not so precisely determined, both *Voyager* and ground-based spectroscopy measurements suggest a carbon enhancement by at least a factor of 2, probably a factor 4. The remote determination of the CH_4 abundance in Uranus is difficult because the gas condenses in the upper troposphere. However, the radio-occultation experiment aboard *Voyager* agrees with previous ground-based spectroscopic measurements to conclude to a large enhancement of carbon in the planet. The Neptune value is still uncertain but seems also to be significantly greater than that of the Sun (oversolar).

The N/H ratio is related to the NH_3 abundance through

$$\frac{N}{H} = \frac{1}{2}\frac{NH_3}{H_2}.$$

The difficulty is that NH_3 condenses around the 145 K level in atmospheres of giant planets. Moreover, NH_3 possibly can be trapped at deeper levels to form NH_3–H_2O or NH_4SH clouds (Lewis 1969; Atreya 1986). Infrared measurements of NH_3 lines of Jupiter at 5 μm, which are formed at relatively deep atmospheric levels at temperature of about 280 K, indicate a N/H value of the order of 1.5 solar units (Bjoraker *et al.* 1986*b*). Measurements of the microwave jovian emission that originates from tropospheric levels at temperature significantly higher than 300 K and probably below the expected containing NH_3 cloud, indicate an enhancement in nitrogen by about a factor of two, as indicated in table 1. A similar nitrogen enrichment is derived, also from microwave measurements, in the deep troposphere of Saturn. As concerns Uranus and Neptune, radioelectric measurements suggest instead a strong depletion in ammonia but it seems that NH_3 is trapped in the deep interior below the observable regions and as a consequence it is not possible to determine a value of N/H in these objects at present.

The case of O/H is more delicate; it can be determined from H_2O through the relation

$$\frac{O}{H}=\frac{1}{2}\frac{H_2O}{H_2}.$$

Infrared measurements of H_2O lines at 5 μm, at temperatures around 280 K. suggest that the O/H ratio is much less than that of the Sun (undersolar). However, at this level, H_2O may be depleted as a result of dynamical process as it is frequently in the Earth troposphere.

A quantitative model of moist convection leading to the required depletion of H_2O at the observed levels has been proposed (Lunine & Stevenson 1987). On the other hand, under the conditions of the thermochemical equilibrium, CO is not supposed to be present in the upper troposphere of Jupiter; its detection implies that substantial upward movements do exist in the troposphere of the planet in agreement with our current understanding of convective heat transport in Jupiter's interior. Fegley & Prinn (1988) calculate non-equilibrium abundances of CO and Silane SiH_4 in the upper troposphere of Jupiter as a function of vertical eddy diffusion coefficients. For plausible values of these coefficients estimated from Jupiter's internal heat flux, they demonstrate that the observed value of the CO abundance and the stringent upper limit of SiH_4 is incompatible with a significant global water depletion in the Jupiter's interior. Thus O/H could be solar or even slightly oversolar.

CO has also been detected in Saturn (Noll *et al.* 1988*b*) but it is not clear if it is formed in the troposphere or the stratosphere of the planet. A stratospheric formation, because of photolysis of infalling oxygen material (from Saturn rings) precludes the inference from CO of the O/H ratio in the deep interior.

Another piece of information comes from the measurement of the phosphine abundance in the outer atmosphere of Jupiter and Saturn. On the basis of chemical equilibrium models, PH_3, as CO, should not be present in the upper tropospheres of these planets. It is still observed, as a result of upwards convective movements, especially in Saturn where the observed P/H ratio is more than three times the protosolar value (Courtin *et al.* 1984). Because chemical reactions with H_2O would tend to reduce the amount of PH_3 reaching observable levels, this result suggests that P/H is really oversolar in the deep interior of Saturn.

To sum up at this stage, there is an evidence that all giant planets are enriched in carbon, and at least Jupiter and Saturn in nitrogen. Saturn is enriched in phosphorus and Jupiter may be enriched in phosphorus and oxygen. These results favour the nucleation model. However, Stevenson (1982*b*) proposes as an alternative solution that the CNO enrichment comes from planetesimals infalling into the atmospheres of giant planets after their formation. Stevenson argues that the convection is not sufficient enough to permit the transport of minor components from the core up to the outer atmosphere. (The argument may be irrelevant because the heating due to accretion resulted in a large internal energy just after the planetary formation, energy

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which was transferred by convection to the outer layers, according to current evolutionary models (Bodenheimer & Pollack 1986).)

Should the Stevenson model be correct, the observed CNO enhancement would be compatible with the gas instability model as well. The nucleation model, however, holds more plausible because, as previously mentioned, it is difficult to imagine how the cores of giant planets, considering the solubility of heavy components in hydrogen, could have grown up to *ca.* 10 M_E in the homogeneous collapse model. The problem is that it is difficult to say, on the basis of volatiles abundances only, if the observed enhancement occurred before or after the planetary formation. In the following section we will discuss whether observed deuterium abundances may help to solve this question.

5. The deuterium case

The comparison of deuterated isotopes in giant planets provides an other test of formation models. Deuterium was in the nebula mainly in form of HD, but as a result of high cosmic CNO abundance, also substantially in form of deuterated species of H_2O, CH_4 and NH_3. At low temperature occurring in the outer part of the nebula, calculations show that, assuming the isotopic equilibrium, deuterium tends to become strongly concentrated in molecules such as HDO, CH_3D and NH_2D (Richet *et al.* 1977). Therefore, the ices and/or clathrates which, in the framework of the nucleation model are constituents of the cores of giant planets, contain a substantial amount of deuterium. They subsequently vaporize and reequilibrate with HD in the atmosphere which becomes enriched in deuterium compared to the abundance in the solar nebula. This scenario has initially been proposed by Hubbard & McFarlane (1980) as a test of formation theories. These authors estimate that, due to the large mass of the primordial H_2–He atmospheres of Jupiter and Saturn, the observed deuterium enhancement should be negligible in these objects, while in Uranus and Neptune which exhibit relatively thin atmospheres, the enhancement should be quite substantial, possibly by a factor of five or more.

The D/H ratio in atmospheres of giant planets may be estimated by two different methods.

The first method consists in measuring the abundance of HD and of H_2 from measurements of intensities of spectral lines of the two absorbers. Then, the D/H ratio is derived through

$$\frac{\mathrm{D}}{\mathrm{H}}=\frac{1}{2}\frac{\mathrm{HD}}{\mathrm{H_2}},$$

where HD and H_2 are the abundances of each species.

The advantage of this approach is that no fractionation is expected because HD is the main reservoir. Unfortunately, the analysis of the weak absorption lines of HD is very difficult. Observed in the visible range, they are strongly affected, and the H_2 quadrupolar lines as well, by scattering due to aerosols and clouds particles so that a model-dependent radiative transfer analysis must be used. As a result, systematic errors, difficult to evaluate, probably affect the determination of the HD/H_2 ratio.

The second method consists in measuring the intensities of the lines of CH_3D and CH_4. The D/H ratio is derived through

$$\frac{\mathrm{D}}{\mathrm{H}}=\frac{1}{4a(T)}\frac{\mathrm{CH_3D}}{\mathrm{CH_4}},$$

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where $\alpha(T)$ is the fractionation factor of the temperature T. The analysis of these lines is generally less complex, especially when they are measured in the thermal infrared range where scattering is probably negligible. The main difficulty is to properly estimate the fractionation factor.

A general discussion of determinations of D/H in giant planets may be found in Gautier (1985) and Gautier & Owen (1988), and the set of various results is summarized in table 2.

Table 2. Deuterium abundances in giant planets[(a)] and in the protosun[(b)] (10^5D/H)

	protosun	Jupiter	Saturn	Uranus
from HD	—	3.7–17	4–13	4–10
from CH_3D	—	1.2–5.5	0.7–3	4.5–18
from ^{3}He (in solar wind)	$2^{+1.5}_{-0.5}$			

References: (a) Gautier (1985), Gautier & Owen (1988); (b) Geiss & Boschler (1981).

Values inferred from HD are systematically higher than values derived from CH_3D, for Jupiter and Saturn. They are also higher than the protosolar deuterium abundance inferred by Geiss & Boschler (1981) from ^{3}He solar-wind measurements. The D/H ratio from HD then implies an initial deuterium enrichment in all giant planets, which is not predicted by any plausible scenario. If, however, we assume that some systematic error affects HD determinations and consider that D/H is properly inferred from CH_3D measurements, jovian and saturnian abundances appear in a good agreement with the protosolar value. Moreover, the uranian value suggests a deuterium enrichment in Uranus, in agreement with the Hubbard model. Present estimates of the neptunian value (Orton *et al.* 1978) are not accurate enough to confirm or refute the scenario. Therefore, we may conclude that observed deuterium abundances in giant planets are not in conflict with the nucleation model. However, because meteorites, and apparently the comets as well (Eberhard *et al.* 1987) are also enriched in deuterium, it is not possible from the above considerations only, to exclude the infalling planetesimals model proposed by Stevenson. In §6, we will examine the information that may be derived from helium abundance.

6. The helium abundance in the giant planets

Both models of planetary formation described in §3 predict that the hydrogen to helium ratio in atmospheres of giant planets should be equal to the ratio in the solar nebula and in the protosun. Observations disagree with the predictions.

In figure 2 and in table 3 the values of the helium abundance (per mass) measured in the outer atmospheres of Jupiter, Saturn and Uranus, and the Sun are summarized. The Saturn value is significantly less than the Jupiter value, which is somewhat less than the Uranus value. On the other hand, the Uranus value agrees well, considering error bars, with protosolar values derived from the most recent evolutionary models that are fitted to the present mass, luminosity and age of the Sun. From improved radiative mean opacities and updated nuclear data, four groups have independently derived protosolar He abundances in the range 0.27–0.28 (instead of the previously assumed value of 0.25), which is consistent with values inferred from less-

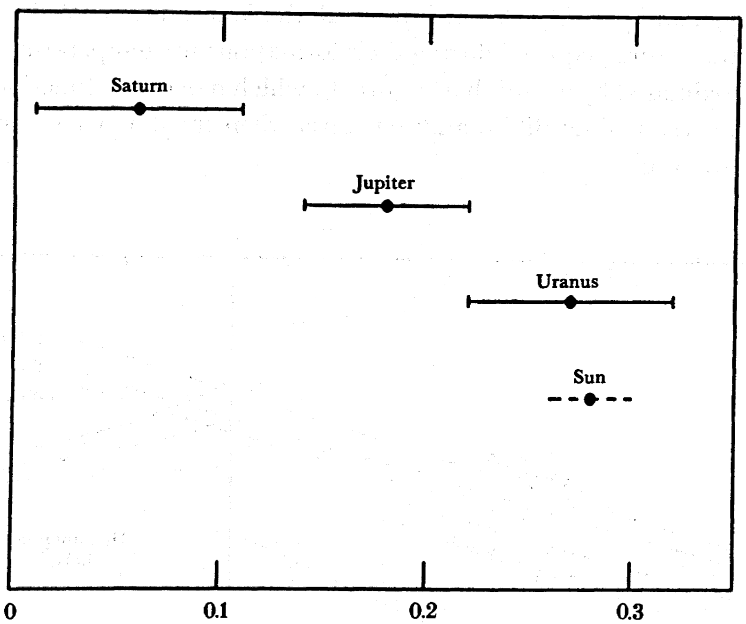

FIGURE 2. Helium abundances (per mass) in the atmospheres of Jupiter, Saturn and Uranus, compared with the protosolar value. He abundances in giant planets were measured by *Voyager* and correspond to values given in table 2. The protosolar value is inferred from solar evolutionary models: uncertainties are not indicated but all recent models propose values between 0.27 and 0.28 per mass (adapted from Conrath *et al.* 1988).

TABLE 3. HELIUM ABUNDANCES IN THE OUTER ATMOSPHERES OF GIANT PLANETS AND IN THE PROTOSUN

Y (per mass abundance)			
Jupiter	Saturn	Uranus	protosun
0.18 ± 0.04[a]	0.06 ± 0.05[b]	0.262 ± 0.048[c]	0.27-0.28[d]

References: (a), Gautier *et al.* (1981) revised by Conrath *et al.* (1984); (b), Conrath *et al.* (1984); (c), Conrath *et al.* (1988); (d), Lebreton & Maeder (1986); Cahen (1986).

precise methods and with the estimate for the abundance in the vicinity of the Solar System (for a detailed discussion, see Conrath *et al.* 1988). It seems then that the He abundance is depleted compared to the solar value in Saturn, and to a less extent in Jupiter, but not in Uranus.

High-pressure thermodynamics and theories of planetary evolution provide a satisfying interpretation of these results. At pressures higher than 300 G Pa which occur in the interiors of Jupiter and Saturn hydrogen undergoes, according to quantum mechanism calculations, a transition from a molecular to a metallic state (Nellis *et al.* 1983). Although helium mixes completely with molecular hydrogen at all temperatures occurring within giant planets, it may become immiscible in metallic hydrogen at relatively high temperature, as shown in figure 3: in such a case helium droplets form and migrate toward the centre of the planet leading to a depletion of helium in the outer atmosphere (Stevenson 1982*a*).

Models of planetary interiors and of planetary evolution indicate that this situation exists in

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the interior of Saturn and possibly also in Jupiter. Both planets have cooled continuously from the initial high temperature acquired during their formation; the temperature against pressure profile is well approximated by an adiabat (figure 3), which moves as a function of time towards lower temperatures; the helium differentiation starts when the 3 Mbar pressure level reaches the saturation temperature.

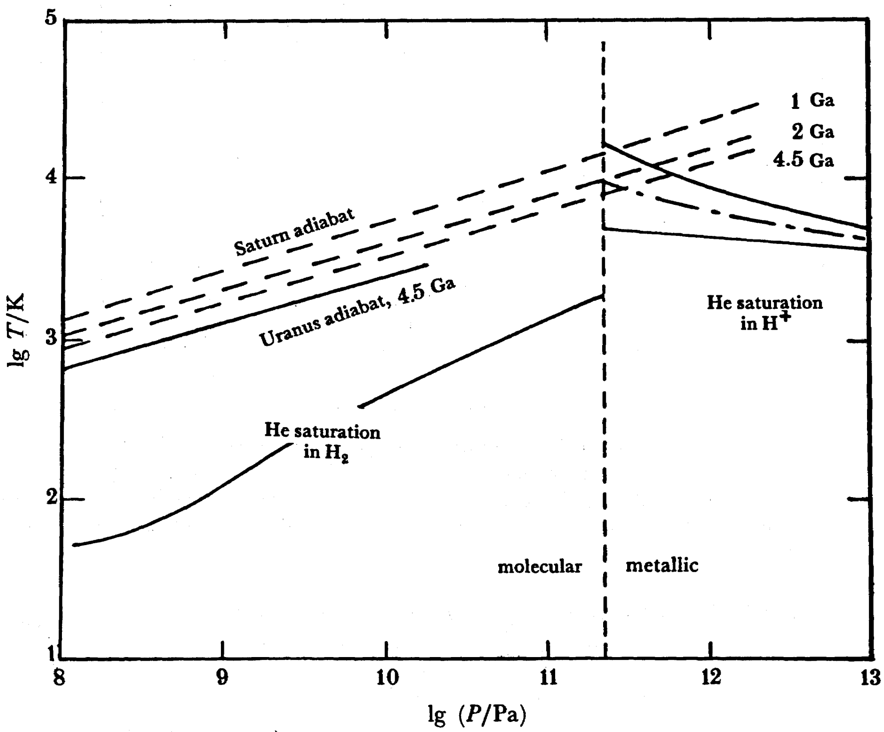

FIGURE 3. Saturation temperature of helium for a mixture of H and He in 'cosmic' abundance (75% of H, 25% of He), in a temperature–pressure diagram. The vertical dashed line indicates the molecular metallic hydrogen transition. The upper and lower curves on the right represent the extreme possibilities, due to theoretical uncertainties of helium solubilities in metallic hydrogen, and the dash–dot line represents the most plausible curve. The dashed line at the top represents three Saturn adiabats (lines 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 Ga 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 Ga after formation of the planet and 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 1982*a*.)

Because of Saturn's smaller mass and dimensions its luminosity due to accretion heating is expected to vanish earlier than that of Jupiter, so that the helium differentiation starts also earlier in Saturn, in agreement with the comparison of the observed depletion in the two planets.

For Uranus interior models indicate that, as for Neptune, the hydrogen pressure at the edge of the core should not exceed around 20 GPa (Hubbard 1984), well below the pressure where the molecular to metallic hydrogen transition occurs. Therefore, no helium depletion due to differentiation is expected in the uranian atmosphere. This analysis and the good agreement, considering the error bars, between Uranus and solar values lead to the conclusion that the composition of the uranian atmosphere has probably not significantly changed since its formation. These results might also provide a test of the Stevenson idea of CNO enrichments from infalling planetesimals; if these objects were composed of CO, CO_2, N_2 in ices or clathrates, or of organic matter as found in carbonaceous chondrites, their chemical reduction when they are dissolved in the gaseous envelope should consume some of the initially present hydrogen, leading to an increase of the He:H_2 ratio compared with the solar value (Lewis & Prinn 1980; Fegley & Prinn 1986; Pollack *et al.* 1986). The expected effect is small in Jupiter and Saturn where other phenomena play a major role, as discussed above, but could be very important in Uranus and Neptune (Pollack *et al.* 1986).

The difficulty is that we ignore the real composition of grains imbedded in the nebula and which formed planetesimals. Fegley & Prinn (1986) propose a number of very different models for composition of condensates in the region of formation of Uranus: the composition of grains is indeed strongly dependent on the local temperature of the nebula and on the accretion process (slow or fast) which actually occurred. If the thermochemical equilibrium prevails in the outer part of the nebula, CNO compounds were mainly in form of ices or clathrates of NH_3, CH_4, H_2O, and no important reduction of H_2 subsequently occurred. If the thermochemical equilibrium was not reached because of kinetic inhibitions as advocated by Lewis & Prinn (1980), CNO compounds may have been mainly in form of CO, CO_2, N_2 and H_2O ices and/or clathrates, and in such a case a large depletion of H_2 is expected. Pollack *et al.* (1986) from a semi-empirical model fit to the observed carbon enhancement in Uranus, and assuming a carbonaceous chondrite-like composition for planetesimals, suggest a He/H_2 enrichment above solar from 3 to 9%, which would result, assuming a helium solar abundance of 0.27–0.28, to $0.28 < Y < 0.31$. Because the upper limit of the value observed in Uranus is 0.31 (Conrath *et al.* 1988), it is unfortunately not possible, at this time, to derive any firm conclusion. More precise measurements of elemental and isotopic ratios are clearly needed to test theories of formation of giant planets safely.

7. Conclusion

Atmospheres of all giant planets exhibit oversolar abundances in carbon; Jupiter and Saturn are enriched in nitrogen, Saturn in phosphorus, possibly Jupiter in oxygen. Uranus seems to be enhanced in deuterium compared with the protosolar abundance. On the other hand, the helium abundance is equal to the protosolar value in the outer atmosphere of Uranus and is depleted, substantially in Saturn, to a smaller extent in Jupiter.

The set of these results is consistent with the nucleation model of formation of giant planets in which a core first grows from accretion of planetesimals up to a critical mass and subsequently attracts the surrounding gaseous material of the primitive solar nebula. The model proposed by Stevenson in which planetesimals fall into the atmospheres after their formation makes the gas-instability model compatible with observed compositions of giant planets. However, it is not possible at present to confirm or refute the validity of the Stevenson model.

A better understanding of planetary formations requires precise determinations of elemental and isotopic ratios (especially of noble gases) which can be obtained only from *in situ* measurements by mass spectrometers aboard a probe descending into the atmosphere. Such an experiment will be made in Jupiter by the *Galileo* mission in the 1990s. The proposed Cassini

ESA-NASA mission to the Saturn system includes a probe to be launched into the atmosphere of Titan. It is obviously necessary to continue the exploration of the Outer Solar System by a family of probes in the atmospheres of Saturn, Uranus, Neptune, Titan and Triton.

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