PART III

OUTER PLANETS AND THEIR SATELLITES

THE HYDROGEN TO HELIUM MIXING RATIO IN THE GIANT PLANETS

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Abstract. The theoretical bases for deducing the solar abundance of helium from the determination of the H_2/He mixing ratio in the giant planets are examined. The present state of the determination of the helium abundance is given. Experimental methods used to evaluate the H_2/He ratio in the giant planets are critically reviewed. Methods in prospect are also briefly exposed.

1. The Importance of the Knowledge of the H_2/He Mixing Ratio in the Giant Planets

From the low density of Jupiter and Saturn, it has been thought for a long time that these planets are mainly composed of hydrogen and helium. Moreover, high gravitational fields and low temperatures reduce the escape of molecules and atoms. Thus, the composition of these planets should be similar to the composition of the primitive nebula.

Hence many people believe that the cosmic abundance of hydrogen and helium will be simply and accurately given by determining the atmospheric composition of the giant planets.

I feel we should be more cautious. In fact, this assumption implies that the whole of each planet has a constant composition everywhere. Clearly, the problem can only be solved by a correct theory of the interiors of these planets. Such theories have to be checked by measurements of the boundary conditions including, among others, measurements of H_2/He in the atmospheres.

Sophisticated models of the interiors of Jupiter and Saturn have thus been calculated as a function of the H_2/He mixing ratio (for a review, see Hubbard and Smoluchowski, 1973).

Roughly, there are two theses proposed in the recent models.

In the model of Smoluchowski (1967, 1971), the ratio of H_2/He is not constant as a function of the radius of the planet and, accordingly, the atmosphere of the planet could be enriched in helium relative to the solar composition.

On the contrary, the model of Hubbard (1968, 1969) implies that Jupiter and Saturn should be chemically homogeneous and, as a consequence, the measurements of H_2/He in the atmosphere would give the relative abundance everywhere in the planet.

It is clear that the final choice between the interior models of Jupiter and Saturn cannot be made before an accurate determination of the H_2/He ratio in their atmospheres is obtained.

Because new deterninations of the radii of Uranus and Neptune have diminished the mean density of these planets, previous models of the interiors of these planets are obsolete. But their composition should be similar to that of Jupiter and Saturn, with possible addition of heavier elements in their cores (according to Prinn (1973), solar

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composition objects of the size of Uranus and Neptune would have maximum mean densities of 0.2 and 0.18 g cm^{-3} while the present measured values are 1.31 and 1.66 g cm^{-3}).

In any case, measurements of the H_2/He ratio in all the giant planets would confirm or invalidate the hypotheses that a large fractionation of hydrogen and helium could have occurred at the beginning of the evolution of the solar system.

2. The Present State of the Evaluation of the Solar Helium Abundance

Because of our lack of information on the exact composition of the giant planets it is usually assumed that the H_2/He mixing ratio in these planets is close to the solar or cosmic abundance. In fact, the information contained in this assertion is less than is generally suspected.

For cosmic abundance the situation looks rather confusing (Danziger, 1970); the helium to atomic hydrogen ratios (per volume) quoted are between 0.06 and 0.16, with a mean value of 0.1 or 0.11 for the majority of normal stars and for the interstellar medium. Adopting these values for the giant planets will lead to a helium percentage of between 11% and 27%.

For the Sun, the question is very uncertain since the different methods of determining the helium abundance refer to different regions of the solar atmosphere (except for measurements of neutrino flux which unfortunately cannot be correctly interpreted because of the lack of satisfactory theoretical solar models).

From a recent and careful analysis Hirsberg (1973) concludes that the most accurate measurement comes from helium line intensity measurements (5 to 8% of helium by number); for the above mentioned reasons, this author estimates that this value is uncertain to a factor of 2 or 3. As a consequence, the helium percentage in the giant planets as deduced from this solar composition can be anywhere between 10% and 26%, with some preference for the range 10%–20%.

3. Present Information from Experimental Data

What can be deduced from the experimental data? We used at the present time two indirect methods to obtain some upper (or lower) limit of helium percentage in the giant planets.

3.1. ABSORPTION SPECTROSCOPY

The first method is the spectroscopic method; it is based on the measurement of the line-width of CH_4 which is broadened by hydrogen and helium. From an independent measurement of the hydrogen abundance, the partial pressure of helium is then estimated. This method is very crude because both the measurements of CH_4 line widths and of hydrogen abundance are very inaccurate, because scattering is neglected and because the depths of line formation are assumed to be the same for both CH_4 and H_2, which is extremely unlikely.

Owen and Mason (1969) deduced from such an analysis of 6200 Å CH_4 band that H_2/He should be larger than 4.5.

However, because of the uncertainties of the method, Hunten and Munch (1973) consider that it is safer to set an upper limit of about 1 for H_2/He.

To illustrate the uncertainties only due to inaccurate measurements of line-width and hydrogen abundance, we did an analysis of the H_2/He determination from the measurements of the line-widths of the 3 ν_3 band of CH_4 located at 1.1 μ, recently made by Maillard *et al.* (1973) for Jupiter and De Bergh *et al.* (1973) for Saturn, with a Connes interferometer at Saint Michel de Provence Observatory.

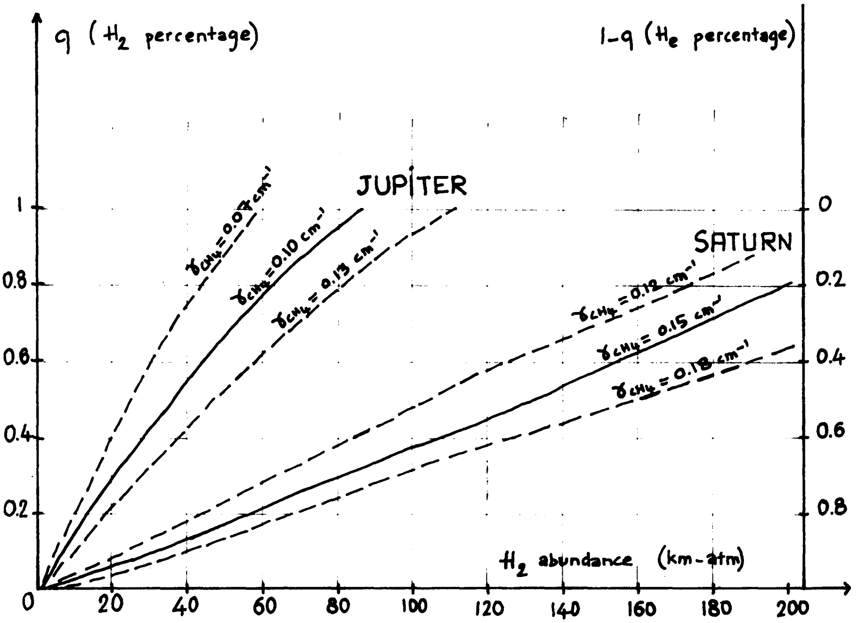

Fig. 1. Percentage, q, of hydrogen in Jupiter and Saturn vs abundance of hydrogen, for the mean value and extreme limits of the measured line-width.

On Figure 1, is plotted the percentage, q, of hydrogen in Jupiter and Saturn as a function of the abundance of hydrogen, for the mean value and the extreme limits of the measured line-widths γ, in cm^{-1}; $1-q$ is the percentage of helium. In his analysis of 6190 Å CH_4 band, Owen took a Jovian hydrogen abundance of 85 km-atm. From a more recent analysis of the earlier observations, Margolis and Hunt (1973) deduced an abundance of 65 ± 10 km-atm, a value in agreement with recent measurements of Trafton (1972).

For Saturn, ancient estimations of H_2 abundance were recently considerably reduced by new measurements. Trafton (1973) mentions the range 85–150 km-atm while Encrenaz and Owen (1973) announce 76 ± 20 km-atm.

All these results come from observations of quadrupole lines of H_2. On the other hand, De Bergh *et al.* (1974) give upper limits of 48 km-atm for Jupiter and 92 km-atm for Saturn, based on an evaluation of the hydrogen absorption, between 1.04 and 1.33 μ, due to the first overtone (2–0) pressure induced band centered at 1.2 μ.

The result for Jupiter has to be compared to the abundance of 45 km-atm deduced by Danielson (1966) from the fundamental (1–0) induced band of H_2 at 2.4 μ, observed at low resolution with Stratoscope II.

Clearly, quadrupole lines and pressure-induced bands of H_2 refer to different levels of formation.

In any case, even if we adopt only the results of quadrupole line measurements, from the examination of the diagram of Figure 1, we are faced with the following alternatives:

– either, because the above mentioned approximations are too crude, this method of inferring the H_2/He gives meaningless results;

– or a larger percentage of helium than the upper limit of the solar abundance cannot be excluded in the atmopheres of Jupiter and Saturn.

Hunt (1972) made a sophisticated analysis, including scattering, of the hydrogen quadrupole lines and of the $3\nu_3$ CH_4 band on Jupiter. He verified that the equivalent widths of the $3\nu_3$ band could be retrieved from a two-layer atmospheric model, with a mixing ratio H_2/He equal to 6 and a mixing ratio of CH_4/H_2 of $(7\pm1)\times10^{-4}$. However, it is not clear if the fitting of the $3\nu_3$ equivalent widths is sensitive to the H_2/He ratio, and what the exact influence of the atmospheric model and of each scattering parameter is.

For instance, Bergstralh (1973) in an analysis with scattering of the same $3\ \nu_3$ CH_4 band, mentions that five of the six combinations of continuum single scattering albedo ω_{oc} and total optical thickness τ_c of the upper level layer yield satisfactory fits to the observed equivalent widths with proper choices of other scattering parameters. Our lack of information on the properties of the Jovian clouds is so large that, in my opinion, the question remains open.

3.2. OCCULTATION EXPERIMENTS

Contrarily to a rather common belief, it is very difficult to simply infer the H_2/He ratio from measurements of star occultation by a giant planet. In fact, to deduce the mean molecular weight (and thus the H_2/He ratio) from the scale height we need to know the temperature profile, a quantity which is not known with any precision. The best thing we can do then is to infer a set of temperature profiles as a function of the H_2/He ratio. Very important results on the upper atmosphere of Jupiter were obtained by different teams from the 1971 β Scorpii occultation measurements. Both the results of Texas Group (Hubbard *et al.*, 1972) and the Meudon Group (Vapillon *et al.*, 1973) infirm the previous results of Baum and Code (1953) deduced from the 1952 σ Arietis occultation.

From the set of temperature profiles deduced by Vapillon (1974), it can be seen that the inferred thermal profiles become hotter and hotter with increasing values of helium percentage.

Admitting that a maximal value of 400K can hardly be exceeded, we can take as upper limit of the helium percentage the value 30%. Hubbard *et al.* (1972) consider that helium should be less than 25%.

An interesting experiment based on a method suggested by Brinckman (1971) was made by the Harvard-Cornell team during the same occultation. The method exploits the fact that the light curve is interrupted by a large number of spikes which are presumably due to inhomogeneities in the planetary atmosphere.

By measuring the difference of the two-spike arrival times at two different wavelengths, Brinckman estimated that one could infer the ratio of the refractivity of the atmospheres at these two wavelengths and deduce from that the H_2/He mixing ratio. However, Wasserman and Veverka (1973) pointed out that the complete occultation curve should be also measured, which in fact reduces the accuracy of the method. At rhis time, results of Harvard-Cornell teams have not yet been published, but from a teport of Veverka *et al.* (1973) the inferred percentage of helium would be between 5% and 42%.

High temperatures of the upper atmosphere of Neptune inferred by Kovalevsky and Link (1969) from the 1968 occultation measurement of BD −17°4388 by Neptune seem to indicate that the atmosphere of this planet is rich in hydrogen.

4. Methods in Prospect

Two other methods of remote determination of the helium abundance will be tried out in the next years from spatial missions of possible airborne experiments.

The first one consists of measuring the emissivity of the helium resonance line at 584 Å. Carlson and Judge (1971) showed that this dayglow depends on the H_2/He ratio in the lower atmosphere and the number density of the homopause. This latter quantity can be determined from Lα measurements. Pioneer 10 and 11 carry ultraviolet photometers for both the Lα and the helium resonance line. Simultaneous radio occultation measurements would bring information on thermal profiles. However from the analysis of Carlson and Judge (1971), it can be seen that the determination of helium will be very inaccurate for an abundance less than 50%.

Infrared experiments look more promising. They consist of measuring the infrared thermal spectrum of the studied planet at several wavelengths properly chosen in the spectral range where H_2 and He are only responsible for the absorption. It is the pressure induced spectrum due to collisions, between 18 and 50 μ for Jupiter and for wavelengths superior to 9 μ for the other giant planets. The H_2/He mixing ratio is then inferred from spectral measurements by an iterative method (Gautier and Grossman, 1972; Encrenaz and Gautier, 1973). Such measurements can be tried from an aircraft flying at the altitude of the tropopause where good atmospheric windows exist in the far infrared, or from a spacecraft in a fly-by or an Orbiter Mission.

Several experiments using Michelson interferometers are planned next year to measure the infrared spectrum of Jupiter from the NASA airborne infrared laboratory (C-141 aircraft). From a numerical analysis, taking into account the expected signal to noise ratios, it is hoped that the H_2/He ratio can be obtained from these experiments (Encrenaz and Gautier, 1973) but with a possible systematic error due to the lack of spatial resolution. An infrared radiometer with two broad band channels (channel *S* covering the range 13–26 μ and channel *L* covering 29–60 μ) is carried by Pioneer 10 and also by Pioneer 11. These radiometers should measure 'limb darkening' of Jupiter in the two channels. Hunten and Munch (1973) did a detailed analysis of the theory of this experiment and their conclusion is rather pessimistic. They are probably right mainly because it will not be possible to properly evaluate the influence of the emissivity due to the pure rotational bands of NH_3 in the *L* channel.

A much more sophisticated experiment is planned for the 1977 Mariner Jupiter/ Saturn Mission which will carry a radiometer or an interferometer.

A detailed analysis of the possibilities of remote sounding of the atmospheres of the four giant planets by infrared technics has been made by Taylor (1972). From this work, it appears that the H_2/He ratio could be inferred from far infrared measurements at four wavelengths for any Jovian planet with an accuracy of $\pm 1\%$ if $H_2/He \geqslant 10$; but this accuracy decreases with decreasing H_2/He ratios. Errors of calibration may have been underestimated in this work.

If these experiments do not succeed the final answer may be given by *in situ* measurements which are not planned before 1980's years.

5. Conclusion

At the present time there is no experimental evidence that the H_2/He mixing ratio in the giant planets should correspond to the solar composition, but it is probably the best choice to assume it. The solar helium abundance is itself very imprecise and the corresponding percentage of helium in the giant planets could be between 10% and 26%.

It can be reasonably expected that the H_2/He ratio will be accurately determined during the next ten years for Jupiter and Saturn. And the possibility cannot be excluded that in the future the 'cosmic abundance' will be deduced from the composition of these planets.

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DISCUSSION

Irvine: What do you consider to be the best current estimates of the density of Uranus and Neptune?

Gautier: From the measurements of the radius of Uranus made by Stratoscope, the mean density of this planet would be about 1.31 g cm^{-3}. From the measurement of the radius of Neptune inferred from occultation measurements by Kovalevsky and Link (1969) its density would be 1.49 g cm^{-3}.

Beer: Is there, in fact, any real, direct, evidence for there being any helium whatsoever in the outer planets?

Gautier: No, there is no direct evidence, but it would be extremely difficult to explain how helium of mass 4 would have escaped out of the atmosphere and not hydrogen of mass 2.

Fox: Are spectroscopic data on collision-induced absorption by mixtures of H_2 and He (as functions of temperature and ortho-para ratio, for example), and on pressure-broadening of CH_4 lines by H_2 and He in the 1.1 μ vibration-rotation band, sufficiently accurate for a precise determination of the H_2-to-He ratio?

Gautier: I took the values of the coefficients of pressure broadening in Varanasi *et al.* (*Astrophys. J.* **179**, 977, 1973). Even if the values are not very accurate, the causes of error come mainly from the assumptions I have mentioned above: using a reflecting-layer model, neglecting scattering, assuming the depths of line formation are the same for CH_4 and H_2.

Traub: In the near-infrared, at least, the greatest difficulty with measuring line widths on Jupiter is the contribution of image motion due to atmospheric 'seeing' effects. For example, in our H_2 quadrupole line observations on Jupiter, the seeing width is larger than the combined instrumental and intrinsic widths, even after the overall rotational broadening has been removed by proper spectrometer alignment.