

## NOTE

# New Constraints on the Composition of Jupiter from Galileo Measurements and Interior Models

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Using the helium abundance measured by Galileo in the atmosphere of Jupiter and interior models reproducing the observed external gravitational field, we derive new constraints on the composition and structure of the planet. We conclude that, except for helium which must be more abundant in the metallic interior than in the molecular envelope, Jupiter could be homogeneous (no core) or could have a central dense core up to  $12 M_{\oplus}$ . The mass fraction of heavy elements is less than 7.5 times the solar value in the metallic envelope and between 1 and 7.2 times solar in the molecular envelope. The total amount of elements other than hydrogen and helium in the planet is between 11 and  $45 M_{\oplus}$ . © 1997 Academic Press

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As shown by Wildt (1938), Jupiter is mainly composed with hydrogen and helium. However, the question of the abundance and partitioning of the other species ("heavy elements") throughout the planet is still unsolved. Answering this question would yield much better constraints on models of formation of the giant planets. It would also give insight into the behavior of chemical species at high pressures and generally into physical processes in the planet's interior.

A precise determination of the seismic properties of the planet would certainly be the best way to determine accurately its internal composition. Global oscillations of Jupiter seem to have been detected (Mosser *et al.* 1993), but the accuracy of the measurements have yet to be improved and the vibration modes more clearly identified. To date, constraints on

the interior structure of the planet can be provided solely by interior models matching the observed gravitational field (i.e., the radius, mass, and gravitational moments  $J_2$ ,  $J_4$ , and  $J_6$ ) and surface conditions (temperature, luminosity, atmospheric helium abundance).

Studies of the interior of giant planets (Hubbard and Marley 1989, Zharkov and Gudkova 1992, Chabrier *et al.* 1992, Guillot *et al.* 1994b) have generally been focused on calculating one possible interior model rather than calculating the ensemble of all possible models. It is therefore difficult, from these models, to give constraints on the amount or distribution of elements in the interior of the planet. Furthermore, the new determination of the abundance of helium in the upper troposphere by the Galileo probe (Niemann *et al.* 1996) requires a revision of these quantities.

Previous calculations using the Voyager data indicated that  $Y/(X + Y) = 0.18 \pm 0.04$  (Gautier *et al.* 1982, Conrath *et al.* 1984), where  $X$  and  $Y$  are the mass fractions of hydrogen and helium, respectively. The mass fraction directly measured by the probe is now  $Y/(X + Y) = 0.238 \pm 0.007$  (von Zahn and Hunten 1996). These values must be compared to the protosolar value estimated to be  $Y/(X + Y) = 0.275 \pm 0.005$  (Bahcall and Pinsonneault 1995).

Since no significant escape of the original hydrogen and helium could occur over the lifetime of the planet, the interior of the planet must then be richer in helium than the upper regions in order to ensure that the global hydrogen/helium ratio is equal to the protosolar ratio. This conclusion holds for both the Voyager and Galileo measurements. However, the higher atmospheric helium mass fraction measured by Galileo results in a smaller abundance of heavy elements in this region than previously estimated.

We have calculated new optimized Jupiter models using the method described by Guillot *et al.* (1994b). We refer the reader to that article for details on the calculations and references for the data used. We have used the Galileo helium/hydrogen ratio and have included the following uncertainties:

1. on the equations of state (EOS), for hydrogen, helium and heavy elements

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2. on the temperature profile (convective/radiative)
3. on the internal rotation (solid/differential)
4. on the distribution of helium in the interior.

These uncertainties are discussed in detail below. In addition, we have included the observational 1- $\sigma$  uncertainties on the gravitational moments, atmospheric helium abundance, and protosolar helium abundance.

The equation of state of hydrogen and helium is certainly the most important source of uncertainty in the calculations. A large part of the jovian interior encompasses a pressure/temperature region where interactions between particles are important, and molecules, atoms, ions, and electrons coexist. In such a region, the behavior of even the simplest molecule, hydrogen, is poorly understood. It undergoes a phase transition from a molecular to a metallic phase at pressures on the order of one to a few megabar, but it is not known whether this transition is of first order (i.e., includes a discontinuity of the specific entropy). The characterization of the two phases is also not obvious: experimental and theoretical evidence suggests that, at pressures of two megabars or less, a fraction of the electrons become itinerant while molecules still exist, before hydrogen eventually reaches a monoatomic truly metallic state at higher pressures (on the order of a few megabars). Uncertainties in the equation of state are thus both quantitative and qualitative.

In this work, we choose to estimate these uncertainties by using two hydrogen–helium EOSs calculated by Saumon *et al.* (1995). The first one (*i*-EOS) assumes that the transition is continuous and is calculated by smoothly interpolating between the low-pressure molecular fluid and the high-pressure ionized plasma. Their second EOS (PPT-EOS) is consistently calculated and predicts the presence of a first-order plasma phase transition between molecular and metallic hydrogen, the so-called PPT. This transition occurs around 1.7 Mbar for a typical jovian interior profile. In the molecular region, the densities calculated with these EOSs along isentropes characteristic of the jovian interior agree with those experimentally determined by Weir *et al.* (1996) to better than 2% (Saumon and Xie, in preparation), even though the adiabatic temperature gradients (and hence temperatures) differ. However, the electrical conductivities measured indicate a continuous transition around 1.4 Mbar (Nellis *et al.* 1996), and no PPT, at least for pressures lower than 1.8 Mbar. On the other hand, Monte-Carlo simulations by Magro *et al.* (1996) indicate that a PPT occurs at slightly larger pressures. We have therefore considered a third case, using the PPT-EOS, but displacing the PPT to  $P = 2.5$  Mbar. Although the resulting EOS is thermodynamically inconsistent in the region 1.7–2.5 Mbar, this approach yields a well-behaved density profile (see Fig. 1) and therefore provides another useful estimation of the uncertainty of the hydrogen–helium EOS. Finally, we choose to ignore the complexity of the molecular/metallic hydrogen transition itself, but this is mostly a semantic issue, assuming that the corresponding uncertainty on the density profile is properly represented by the different EOSs.

The partitioning of elements in Jupiter’s atmosphere, and in particular of helium, represents the second main uncertainty. There are two mechanisms affecting equilibrium partitioning of elements in Jupiter’s hydrogen. Stevenson (1982) showed that in the metallic-hydrogen phase, pressure-ionized elements with  $Z > 1$  have limited solubility. However, only helium is abundant enough to be directly affected by such limited solubility (noble gases such as Ne might be indirectly affected by He immiscibility—Roulston & Stevenson 1995). The standard explanation of Jupiter’s (slightly) reduced atmospheric helium abundance relies on such a phase separation via immiscibility in the metallic phase at pressures just above the molecular–metallic transition.

On the other hand, if a true PPT is present as a first-order phase transition, then the Gibbs phase rule requires that the concentrations of *all* elements in hydrogen be discontinuous across this boundary. Such partitioning between the metallic and molecular phases of hydrogen would be in *addition* to any possible phase separation of helium due to limited miscibility in the metallic phase, and would in principle affect all elements rather than helium alone. However, helium and most heavy

elements are expected to be partitioned preferentially into the molecular phase. The Galileo probe results for elemental concentrations do not particularly argue for the predominance of one partitioning mechanism over the other, but they do confirm that helium is not enriched in the molecular region. We emphasize that a composition change due to the PPT or that caused by limited helium miscibility are expected to occur in the same pressure region and therefore cannot be distinguished by our models. Were it not the case (for example, if a helium-rich core was formed at pressures much larger than a few megabars), a slightly wider range of ice/rock core masses (see below) would be found.

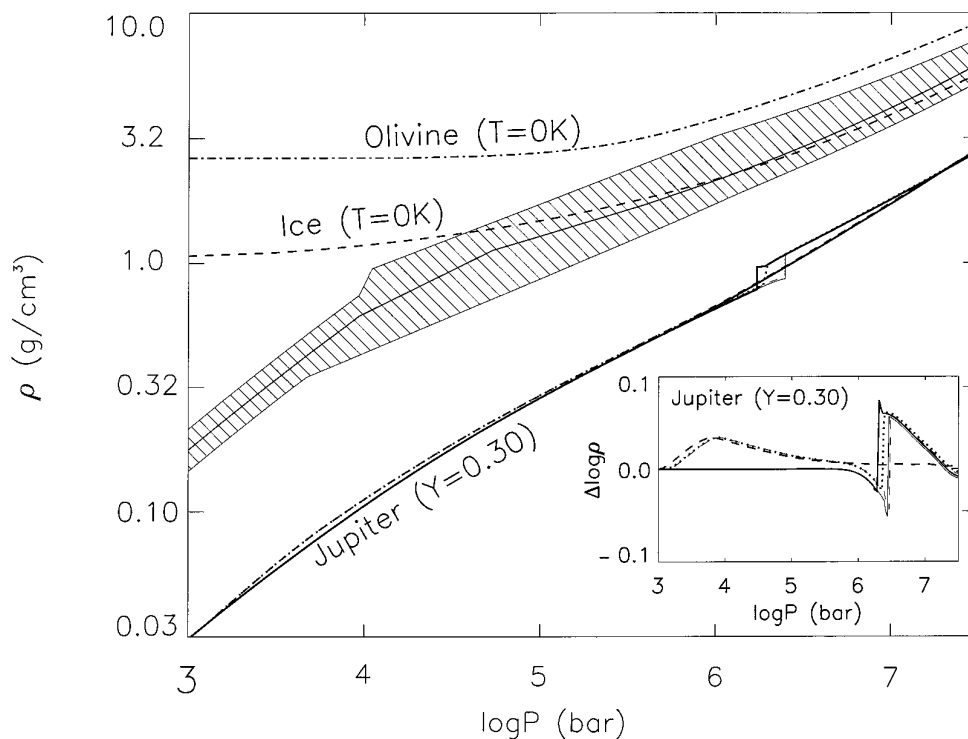
Although it bears little consequences for the structure of the interior models themselves, our poor knowledge of the equation of state of heavy elements in Jupiter directly affects the abundance of heavy elements that is inferred from these models in order to conserve the protosolar helium/hydrogen ratio. As described by Chabrier *et al.* (1992) and Guillot *et al.* (1994b), the mass fraction of heavy elements is obtained after optimization of a model using

$$Z = (Y_Z - Y) \frac{\rho_H^{-1} - \rho_{He}^{-1}}{\rho_H^{-1} - \rho_Z^{-1}}, \quad (1)$$

where  $Y_Z$  and  $Y$  are the equivalent and real mass fraction of helium, respectively, and  $\rho_H$ ,  $\rho_{He}$ , and  $\rho_Z$  are the density of pure hydrogen, pure helium, and heavy elements respectively, along a pressure–temperature profile. Note that  $Z$  is uniform (independent of  $T$  and  $P$ ) only in the limit  $\rho_Z = \rho_{He}$ , or if the ratios  $\rho_H/\rho_Z$  and  $\rho_H/\rho_{He}$  are independent of  $T$  and  $P$ . These variations of  $Z$  having no physical meaning, we used a mass average over the molecular and metallic regions,  $Z_{mol}$  and  $Z_{met}$ , respectively. In order to estimate the uncertainty on  $\rho_Z$ , we calculated a low, a high, and an intermediate  $\rho_Z$  profile. In the case of the low one, we assumed a small mean molecular weight at low pressures, and interpolated to high pressures where we used a zero temperature EOS for pure  $H_2O$  ice adding thermal effects using Zharkov (1986). The high  $\rho_Z$  was calculated using a larger mean molecular weight at low pressures, including refractory elements (rocks) above 10 kbar, assuming a 10 times solar rocks/ices mass mixing ratio and interpolating with zero temperatures EOSs for Olivine ( $Mg_2SiO_4$ ) and  $H_2O$  at high pressures. An intermediate profile was calculated in the same way, but assuming solar ices/rocks ratio. At the molecular/metallic transition,  $\rho_Z$  was allowed to jump from the low to the high profile, and vice versa. The corresponding profiles are shown in Fig. 1 as a hatched region, which represents the uncertainty on  $\rho_Z$ , both due to the unknown composition and to the poorly known EOSs of these elements.

The possibility that the interior temperature gradient strongly departs from adiabaticity yields another important source of uncertainty in the model. The temperature profile retrieved by the Galileo probe is close to an adiabat at least down to the 20-bar level (Seiff *et al.* 1996) but condensation could yield brief subadiabatic or superadiabatic events (Guillot 1995). The possibility that a radiative region exists in the kbar region (Guillot *et al.* 1994b) represents the largest source of uncertainty by far. This was estimated by calculating Rosseland opacities as in Guillot *et al.* (1994a), but using new available opacity data for  $H_2O$  and  $H_2S$  (see Marley *et al.* 1996). In other regions (except at the PPT) we assumed the temperature structure to be adiabatic, as any departure from adiabaticity in the interior (e.g., due to a compositional gradient) would be indistinguishable from uncertainties in the EOS itself.

A comparison of the density profiles calculated from the different equations of state and temperature profiles is given in Fig. 1. The presence of a radiative region induces an uncertainty on the order of 5% on the density in the 10-kbar region of the planet. The uncertainty in the H–He EOS is small at both low pressures and at very high pressures, but reaches as much as 10% in the intermediate pressure range of around 1 to 5 or so megabars, a pressure range that involves around a third of the planetary mass. The *i*-EOS is, on average, significantly less dense than the PPT-



**FIG. 1.** Density profiles in models of Jupiter with a fixed composition ( $Y = 0.30$ ), using an adiabatic temperature profile and the  $i$ -EOS (plain line), adiabatic and PPT-EOS (plain line with discontinuity), nonadiabatic  $i$ -EOS (dashed line), and nonadiabatic PPT-EOS (dotted line). The thin plain and dashed lines correspond to adiabatic and nonadiabatic 2.5-Mbar PPT-EOS, respectively (see text). The temperatures of the models range between 2050 and 2450 K at a pressure of 10 kbar, 5300–6300 K at 1 Mbar, 10,000–13,000 K at 10 Mbar, and 14,000–21,000 K at 30 Mbar. Upper curves are  $T = 0$  K density profiles for water ice and olivine (from Thompson 1990). The dashed region represents the assumed uncertainty on the EOS for heavy elements ( $\rho_Z(P, T)$ ). Within this region, the continuous line corresponds to our “preferred” profile for  $\rho_Z$ . *Inset:* Differences of the decimal logarithm of the Jupiter density profiles with the same profile using the  $i$ -EOS and an adiabatic structure. The presence of a radiative region leads to a colder and denser model in the kilobar region and deeper. The presence of a PPT yields a denser metallic region.

EOS, and therefore requires a larger amount of heavy elements in order to reproduce the observed mean density of the planet. The presence of a radiative region has the opposite effect, as it leads to a cooler planet.

As in Guillot *et al.* (1994b), we assumed that a dense central core was present and included possible variations in composition (pure ices/pure rocks). Its mass was allowed to vary in order to fit the observational constraints. The presence of such a core is important for constraining formation theories (e.g., Mizuno 1980). Although it is often thought that its mass is constant after the hydrogen–helium envelope has been captured, it is quite possible that convection redistributes it toward external regions, therefore yielding a smaller core, if any (see Stevenson 1985). We emphasize that the presence of a well-defined core is *assumed*, and is not a consequence of the observed gravitational field of the planet. Very similar results would be obtained by distributing the core over the inner half of the planet. There is therefore little difference between heavy elements in the core and in the metallic region.

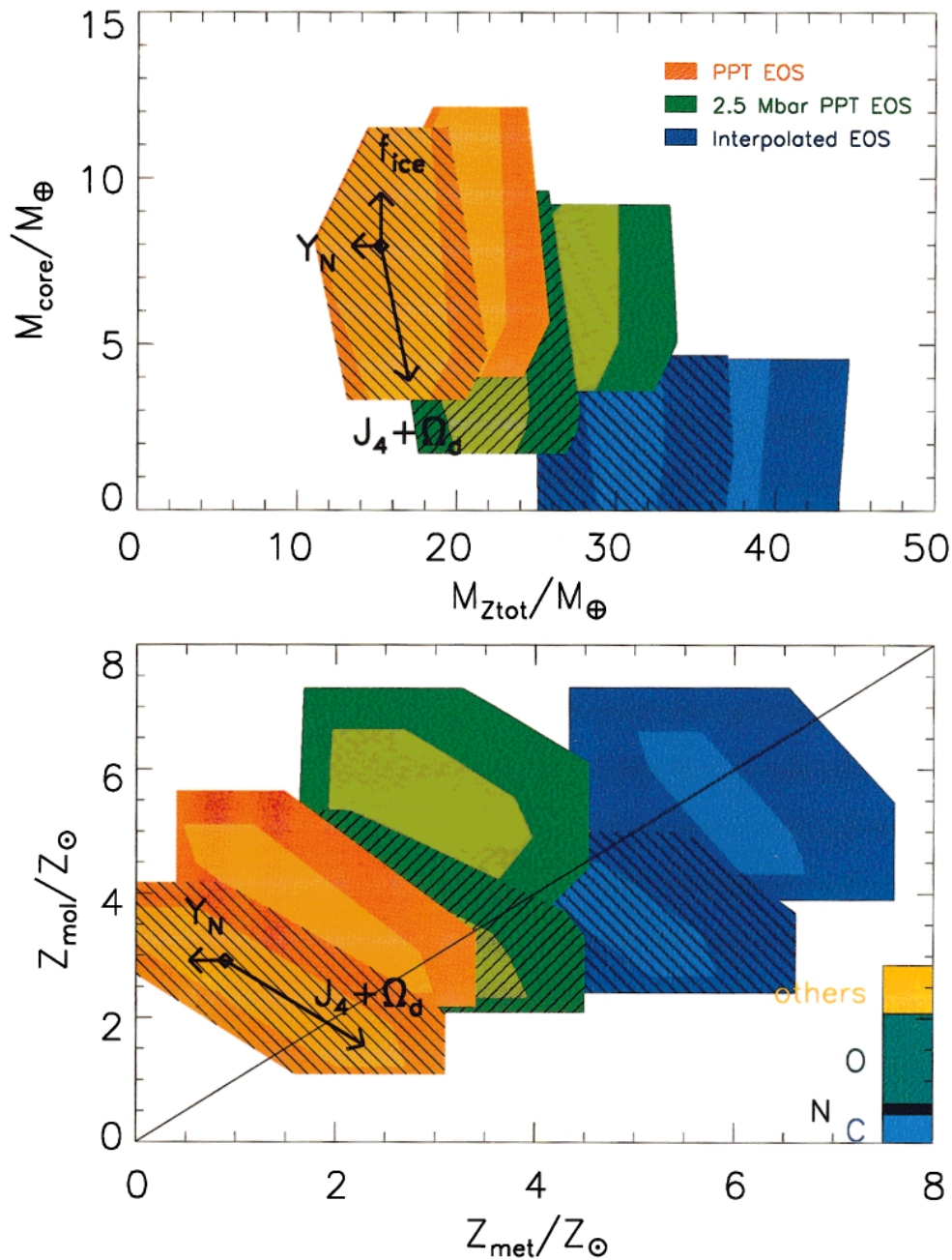
Finally, a small uncertainty arises from the unknown rotational state of Jupiter’s interior. As shown by Hubbard (1982), assuming that the planet is differentially rotating on cylinders (with angular velocities constrained by observations) yields gravitational moments  $J_2$ ,  $J_4$ , and  $J_6$  slightly different than those inferred from a solid rotation model. This uncertainty was also included in the present work.

The observed gravitational moments provide no constraints on density changes which encompass small masses, in particular on the structure of regions of pressures lower than several kilobars. Similarly, no real

constraints exist on the structure of the core or its composition (Hubbard 1989, Guillot *et al.* 1994b). Moreover, we find that the resulting models are very *insensitive* to the location of the helium abundance discontinuity, as long as it is between about 0.5 and 5 Mbar. On the contrary, the models are fairly sensitive to changes in the location of the PPT because it induces significant changes of the density profile (see Fig. 1).

The resulting constraints on the abundance and distribution of heavy elements in Jupiter are given in Fig. 2. The colored surfaces represent possible solutions for given hydrogen–helium EOSs and temperature profiles. Within each patch all other uncertainties were included, as discussed previously. The most significant are: (i) the EOS for heavy elements; (ii) the value of  $J_4$ ; (iii) the value of  $Y_N$ ; and (iv) the unknown composition of the core. The observational error on the atmospheric helium abundance measured by the Galileo probe is small, but it is interesting to note that calculations using the Voyager value would have yielded values of  $Z_{\text{mol}}$  larger by 2 or 3 solar values. The difference between adiabatic and nonadiabatic models is smaller than that in Guillot *et al.* (1994b) because improved  $\text{H}_2\text{O}$  opacities have increased the Rosseland opacities by a factor  $\sim 3$  (see the discussion of the problem of hot bands in Guillot *et al.* 1994a).

A first important result is that the mass of the core can be equal to zero. In that case, we find it even possible for Jupiter to be homogeneous ( $Z_{\text{mol}} = Z_{\text{met}}$ ), if we except small-scale phenomena and variations of the abundance of helium. This requires that the density of the metallic phase is not too large compared to that of the molecular phase ( $i$ -EOS), and



**FIG. 2.** Constraints on Jupiter’s  $M_{\text{core}}$  (mass of the central core),  $M_{Z\text{tot}}$  (total mass of heavy elements),  $Z_{\text{mol}}$  (mass fraction of heavy elements in the molecular envelope), and  $Z_{\text{met}}$  (mass fraction of heavy elements in the metallic envelope) from interior models. Each colored surface represents models calculated with a given hydrogen–helium EOS: PPT-EOS (red), PPT-EOS with PPT at 2.5 Mbar (green),  $i$ -EOS (blue) (see text). The central regions with a slightly lighter hue have been calculated with the “preferred” heavy elements EOS (see Fig. 1), and can be used to estimate the uncertainty related to the EOS of heavy elements ( $\rho_Z$ ). Plain and hatched surfaces correspond to adiabatic and nonadiabatic temperature profiles, respectively. Arrows indicate the magnitude and direction of uncertainties on  $f_{\text{ice}}$  (mass fraction of ices in the core, from 0.5 to 1.0),  $Y_N$  (mass fraction of helium in the protosolar nebulae, from 0.275 to 0.28), and  $J_4 + \Omega_d$ . The latter corresponds to an increase by  $1\sigma$  of  $|J_4|$ , and to the assumption that Jupiter rotates on cylinders and not as a solid planet. The second effect is responsible for about half of the uncertainty, but only in one direction. For clarity, arrows are only shown for the PPT nonadiabatic models. The mass mixing ratios of C, N, O, and all other elements (except H and He) in abundances such that  $C/H = 3 \times (C/H)_{\odot}$ ,  $N/H = 3 \times (N/H)_{\odot}$ ,  $O/H = 3 \times (O/H)_{\odot}$ , etc. (the solar abundances are from Anders and Grevesse 1989) are shown in the bottom right corner of the figure. The value of  $Z$  for any other composition can be inferred from this “ruler.” The molecular envelope represents about 15% (20% in the case of the 2.5-Mbar PPT EOS) of the total mass of the planet ( $M_{\text{Jupiter}} = 317.83 M_{\oplus}$ ). We used  $Z_{\odot} = 0.0192$ .

an important enrichment in heavy elements (4 to 7 times the solar value). In the case of the more realistic PPT-EOS, we find that the presence of a central core is necessary. For all cases, the core is relatively small: less than  $12 M_{\oplus}$  (and less than  $8.5 M_{\oplus}$  in the case of a pure rock core). Again, we stress that the elements that form the core could be distributed over the inner half of the planet, and that the distinction between heavy elements in the core and heavy elements in the metallic region is not obvious.

Other constraints on the amount of heavy elements present in the planet suffer mainly from our relatively poor knowledge of the equation of state of hydrogen (and helium) at pressures of around one to a few megabars. Figure 2 shows that the total mass of heavy elements (core + metallic + molecular envelope) lies between 11 and  $45 M_{\oplus}$ . The upper limit corresponds to an enrichment of a factor 7.4 compared to the solar value, which is quite large. We estimate that it is probable that the density in the metallic region lies closer to that predicted by the PPT-EOS than by the *i*-EOS, as in fact favored by Saumon *et al.* (1995). It is thus more likely that  $M_{Z_{\text{tot}}} \leq 33 M_{\oplus}$ . Similarly, we obtain that in the metallic region,  $Z_{\text{met}}/Z_{\odot} \leq 7.5$ , or, when we disregard the *i*-EOS,  $Z_{\text{met}}/Z_{\odot} \leq 4.5$ .

The constraint found on the mass fraction of heavy elements in the molecular envelope,  $1 \leq Z_{\text{mol}}/Z_{\odot} \leq 7.2$ , can be compared to the measurements of Galileo's mass spectrometer (Niemann *et al.* 1996). Those confirmed that Jupiter's atmosphere is enriched in  $\text{CH}_4$  by a factor 2.9 compared to the solar value of Anders and Grevesse (1989), and in  $\text{H}_2\text{S}$  by about the same factor. The N/H ratio has not yet been evaluated from Galileo, but Voyager infrared data suggest an enhancement of 2.2 to 2.4 (Lellouch *et al.* 1989, Carlson *et al.* 1992). The case of  $\text{H}_2\text{O}$  is not clear because it condenses relatively deep in the atmosphere, but it is probably at least in solar abundance. Figure 2 shows that an enrichment in all heavy elements by a factor 2 or 3 in the molecular region is certainly consistent with all possible interior models.

Reciprocally, it is possible to show from our models that, even though O is responsible for almost 50% of the value of  $Z_{\odot}$ , large values of the O/H ratio can be consistent with the observed gravitational moments. For example, assuming that all other elements are enriched by a factor 3 in the molecular region, we infer that the enrichment in  $\text{H}_2\text{O}$  can be as high as 12 times the solar value. However, this requires a relatively hard (low density) H–He EOS in the molecular region. Using the PPT-EOS only, we find that it is more likely that  $\text{H}_2\text{O}$  is less abundant than 8 times solar in the molecular envelope. In any case, these results do not permit to choose between very different assumptions concerning the enrichment of Jupiter's outer envelope by meteorites and comets (e.g., Pollack *et al.* 1986, Owen and Bar-Nun 1995). It is difficult to infer a lower limit to the abundance of water in the molecular envelope of the planet, but it appears that it would be difficult to reconcile an abundance less than solar with the values of  $Z_{\text{mol}}$  found, as this would require significant enrichments in all other elements.

Most of the uncertainties in the results shown in Fig. 2 are due to the relatively poor knowledge of the equation of state of hydrogen in the megabar region. Recent improvements in shock-wave experiments (Nellis *et al.* 1996) let us hope that a more accurate representation of the molecular/metallic transition of hydrogen will be achieved in the near future. These improvements could easily yield abundances of heavy elements in Jupiter more accurate by 50%. Similarly, a more precise value of  $J_4$  would lead to better constraints on the structure of the planet. The optimal precision that should be attained on  $J_4$  is about 3 times the actual one, as one is limited by the uncertain internal rotation rate of the planet (see Hubbard 1989 for a discussion). In order to be a useful constraint,  $J_6$  should be measured with a 10 times higher accuracy. Even so, the problem of differential rotation is even more acute than for  $J_4$ , and a detailed study of the internal rotation of the planet should be done in order for such a measurement to be useful. Finally, more accurate high pressure opacities and generally a better understanding of transport processes in the planet are also required in order to determine precisely the abundance and partitioning of elements in Jupiter's interior.

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