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Constraints on the origin and interior structure of the major planets

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From fitting models to the external gravity field of the major planets, Uranus, Neptune, Jupiter and Saturn, we find that certain interior characteristics may be common to all four. For Uranus and Neptune, a model with a central iron–silicate core of about $4M_E$ (M_E = mass of Earth), an 'ice' layer of H_2O, CH_4 and NH_3 in solar proportions of *ca.* $10M_E$, and an H_2–He atmosphere of *ca.* M_E–$2M_E$ gives a good fit to available constraints, including heat flow measurements. Models of Jupiter and Saturn have cores very similar to those of Uranus and Neptune; the H_2–He layer, however, is much more extensive. Modes of origin consistent with these features are discussed. Such models predict a considerable enrichment of deuterium relative to primordial solar abundances in Uranus and Neptune. Such enrichment is not observed in Uranus; implications for interior structure and origin are discussed. Abundances of other elements are discussed in terms of interior structure and origin. We review various problems related to observed heat flow values and constraints on the dimensionless tidal quality factor, Q.

INTRODUCTION: DIAGNOSTICS AND PROBLEMS

Inversion of seismic data provides the most direct and detailed information about the structure of a planet's interior. As this technique is unavailable for the Jovian planets, we must apply more indirect methods. The foremost of these is calculation of models in an effort to match the observed mass, radius and gravitational multipole moments. Because the Jovian planets are expected to be almost entirely in the liquid state, hydrostatic equilibrium is attained to a much higher degree of approximation, and so the high-order multipole moments provide significant constraints on internal structure, unlike for the terrestrial planets.

Jovian planet atmospheres play a major role in determining internal heat flow and dynamics. There is no definite interface between the atmosphere and the interior, since the hydrogen-rich material has a temperature that is well above the critical point at all pressures. It can be shown (Hubbard 1980) that energy transport in the interior of most Jovian planets is by convection, and that the loss of heat from the planet is ultimately regulated by the radiative properties of the atmosphere at an average optical depth of approximately unity. The atmosphere, in other words, serves as a 'bottleneck' for the escape of internal heat. As a consequence of properties mentioned above, the study of relative abundances and heat flow in Jovian planet atmospheres has great significance for the deduction of interior properties. Convective mixing of the planet provides an efficient interaction between the atmosphere and the deep interior. Nevertheless, high-pressure phase transitions in a hydrogen-rich fluid can produce chemical layering in the interior, and must be properly accounted for in interpreting atmospheric observations.

As we might expect, the quality and quantity of constraints on interior structure decrease as we proceed outward from Jupiter and Saturn to Uranus and Neptune. Nevertheless, a number of definite anomalies have arisen as we compare theory and observations. Resolution of each of these riddles is, we believe, a key to considerable further progress in understanding the processes of origin of the Jovian planets and the Solar System as a whole. The problems are:

(i) The standard Kelvin mechanism for the origin of Jupiter's heat flow seems to work well, and thus we conclude that the planet is simply cooling from an earlier high-temperature state. For Saturn, the Kelvin model fails to provide an adequate heat source by a factor *ca.* 2, and we are thus forced to consider alternative sources, of which gravitational unmixing of helium is the most attractive (Stevenson & Salpeter 1976). However, there is little observational evidence that the distribution of helium with respect to hydrogen is different in the outer layers of Jupiter and Saturn.

(ii) As a working hypothesis, it has been traditional to assume that volatile compounds such as CH_4, NH_4 and H_2O are in solar proportions to H_2 and He in the envelopes of Jupiter and Saturn. However, recent evidence for Jupiter shows that the CH_4/H_2 ratio is approximately five times solar in the Jovian atmosphere (Wallace & Hunten 1978), while the H_2O/H_2 ratio is *ca.* 10^{-3} times solar (Larson *et al.* 1975). In Uranus and Neptune, the CH_4/H_2 ratio is *ca.* 10 times solar (Macy *et al.* 1978). Since methane condenses at a much lower temperature than water, the above results may indicate phase partitioning of CH_4 and H_2O within the interiors of Jovian planets. Analysis of Saturn's gravity field shows no evidence for enhancement of compounds such as CH_4 or H_2O in the planet's outer envelope.

(iii) Deuterium is a convenient tracer of processes of formation of the Jovian planets since it does not preferentially partition to any significant extent under the high-temperature, high-pressure conditions within a Jovian planet. At low temperatures and pressures during the presumed condensation of 'ices' such as CH_4, H_2O and NH_3, which are enriched in Uranus and Neptune, deuterium is strongly fractionated into the ice phases. Yet there is no evidence that the D/H ratio differs substantially from the primordial value in the atmosphere of any Jovian planet.

(iv) The phenomenon of volcanism on Io is most naturally explained as due to tidal dissipation (Peale *et al.* 1979), and this model requires that the tidal Q† of Jupiter be *ca.* 10^6. However, reasonable interior models of Jupiter indicate that $Q \gg 10^6$.

(v) The observed heat flow from the interior of Neptune is *ca.* 30 μJ/(cm² s), but for Uranus the value is less than 18 μJ/(cm² s). The two planets are otherwise similar in many respects.

EVIDENCE FROM GRAVITY FIELD AND HEAT FLOW

As is well known, the external gravitational potential

$$V(r,\theta) = \frac{GM}{r}\left[1 - \sum_{l=1}^{\infty} (a/r)^{2l} J_{2l} P_{2l}(\cos\theta)\right], \tag{1}$$

where r is the distance from the centre of mass, θ is the angle from the rotation axis, G is the gravitational constant, M is the mass, a is some normalizing radius (usually taken to be the equatorial radius at 1 bar (10^7 Pa) pressure), J_{2l} are the dimensionless zonal harmonics, and P_{2l} are Legendre polynomials. In a liquid planet, the J_{2l} are excited by response to rotation and can be calculated through application of the equation of hydrostatic equilibrium and

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† The symbol Q stands for the dimensionless tidal quality factor, which is inversely proportional to the rate of dissipation of the tidal energy in a planet.

TABLE 1. GRAVITATIONAL FIELD PARAMETERS FOR JUPITER AND SATURN

parameter	Jupiter	Saturn
rotation period	9 h 55 min 29.7 s (Allen 1973)	10 h 39.9 min (Kaiser *et al.* 1980)
a (normalizing radius)/km	71398 (Anderson 1976)	60200 (Hubbard *et al.* 1981)
$10^2 J_2$ (normalized to a)	1.4733 ± 0.0004 (Null 1976)	1.635 ± 0.005 (Anderson *et al.* 1980)
$10^4 J_4$ (normalized to a)	-5.87 ± 0.07 (Null 1976)	-9.8 ± 0.8 (Anderson *et al.* 1980)
$10^5 J_6$ (normalized to a)	3.4 ± 5.0 (Null 1976)	—

a knowledge of the rotational state of the planet. In hydrostatic equilibrium, it can be shown that $J_2 \approx q$, $J_4 \approx -q^2$, $J_6 \approx q^3$ etc., where the dimensionless parameter q is given by

$$q = \omega^2 a^3 / GM \tag{2}$$

for a planet rotating with angular velocity ω (Zharkov & Trubitsyn 1978). For Jupiter, $q = 0.089$, and for Saturn $q = 0.15$, while the values of q for Uranus and Neptune are highly uncertain due to a lack of consensus on the appropriate rotation rates (Hubbard & MacFarlane 1980). Observed values for gravitational field parameters of Jupiter and Saturn are given in table 1.

Great care must be taken when calculating the gravity field to high order in q. Inaccuracies in purely numerical schemes for solving the equation of hydrostatic equilibrium can mask the correct values of the higher-order gravity coefficients, and so it is usually desirable to develop a perturbation hierarchy that guarantees that the desired precision is preserved in each order in q. Such a hierarchy has been developed by Zharkov & Trubitsyn (1978) and applied by them to very high order in q. The literature on the structure of rotating bodies in hydrostatic equilibrium is very extensive; some of the more commonly used schemes are discussed by Tassoul (1978). An approach based upon work by James (1964) and Hubbard *et al.* (1975) has been used by Hubbard *et al.* (1981) to carry out an analysis of the interior structure of Jupiter and Saturn.

Hubbard *et al.* (1981) have fitted models to the data of table 1 under the following assumptions. (*a*) Both Jupiter and Saturn contain dense central cores of rock and 'ice' in approximate solar proportions. (*b*) The cores are overlain by hydrogen–helium envelopes with an adiabatic temperature gradient. Adjustable parameters in the models are the total core mass and the abundance of helium relative to hydrogen in the envelope. It is assumed that any separation of helium relative to hydrogen would produce an enhancement of the total core mass and a decrease of the helium abundance in the envelope.

The most difficult region to treat in Jupiter and Saturn models is in the vicinity of the transition from molecular to metallic hydrogen at a pressure of *ca.* 3 Mbar. Calculations have been carried out by the author using linear response theory for liquid metallic hydrogen and empirical intermolecular potentials for the liquid molecular phase. Assuming that the derived free energies are valid up to the point of the phase transition, we find that a first-order transition occurs in pure hydrogen at a pressure of *ca.* 4 Mbar and a temperature of 10000 K. As the temperature increases to 20000 K, the transition pressure decreases to *ca.* 3 Mbar. For Jupiter, the phase transition would occur at a temperature *ca.* 19000 K and, for Saturn, at *ca.* 11000 K.

TABLE 2. PROPERTIES OF INTERIOR OF JUPITER AND SATURN WITH CHEMICALLY HOMOGENEOUS HYDROGEN–HELIUM ENVELOPES

	Jupiter	Saturn
pressure/Mbar		
centre	105	44
core/ice boundary	66	22
ice/H–He boundary	36	7
density/(g/cm^3)		
centre	27	19
core/ice boundary	22–12	14–7
ice/H–He boundary	9–3.7	4.5–1.8
T/K		
centre	24000	15000
core/ice boundary	24000	15000
ice/H–He boundary	19000	10000
mass/M_E		
rock	5	5
ice	15	14
H–He	298	77

When helium and other impurities are present, the Gibbs phase rule demands that the composition of the fluid must change across the phase transition, and preliminary calculations indicate that helium is strongly partitioned into the molecular phase. Thus, an enrichment of the planetary atmosphere in helium is likely to occur if chemical equilibrium is maintained between the metallic and molecular hydrogen. Recent observations, on the other hand, indicate that the helium mass fraction Y in the atmosphere of Jupiter is 0.19 ± 0.05 (Gautier *et al.* 1980), and the value for Saturn is 0.18 ± 0.05 (Ingersoll & Orton 1980); these values are not significantly different from the primordial solar value $Y_s = 0.21 \pm 0.03$. The best escape from this contradiction would be to assume that the transition from molecular to metallic hydrogen is not first order, but rather extends over a range of pressures and/or temperatures in a manner analogous to the familiar phenomenon of thermal ionization in ideal gases. In this case, the Gibbs phase rule plays no role and the composition is not required to change as the hydrogen ionizes. The price that we pay for this model is that there is currently no good description of the thermodynamics of the extended transition region.

Hubbard *et al.* (1981) assume that the molecular–metallic transition in hydrogen is a gradual one, and derive the thermodynamics in the transition region by smoothly interpolating between the two régimes. Since the interpolation process is not unique, derived values for the helium mass fraction are quite model-dependent. Nevertheless, the results of this modelling study indicate that the values of Y for the envelopes of Jupiter and Saturn are very similar, and lie in the range 0.12 to *ca.* 0.19. Some other properties of the interior models are listed in table 2. It is probably significant that the deduced core masses for Jupiter and Saturn are very similar to the total masses of Uranus and Neptune.

Heat flow measurements for Jupiter indicate that the ratio of emitted thermal to absorbed solar energy is 1.66 ± 0.12 (Hanel *et al.* 1980), while for Saturn this ratio lies in the range 2.3 to 4.2 (Ingersoll & Orton 1980). For adiabatic interior models with homogeneous helium distribution, a Kelvin cooling model works satisfactorily for Jupiter and can account for the present heat flow if one assumes a high-temperature origin approximately 4.6 aeons† earlier (Hubbard 1977). On the other hand, regardless of the initial starting temperature for Saturn,

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† 1 aeon = 10^9 years.

TABLE 3. PROPERTIES OF THREE-LAYER INTERIOR MODELS OF URANUS AND NEPTUNE

	Uranus	Neptune
pressure/Mbar		
centre	17	22
core/ice boundary	6	7
ice/H_2–He boundary	0.2	0.2
density/(g/cm^3)		
centre	13	14
core/ice boundary	9–4	10–5
ice/H_2–He boundary	1.3–0.4	1.2–0.4
T/K		
centre	7000	7000
core/ice boundary	7000	7000
ice/H_2–He boundary.	2500	2200
mass/M_E		
rock	3.5	4.3
ice	9.5	11.7
H_2–He	1.6	1.1

the planet cools through its current heat flow value after only 2 to 3 aeons (Pollack *et al.* 1977; author's unpublished calculations). Stevenson & Salpeter (1976, 1977) have proposed that phase separation of helium-rich fluid from hydrogen-rich fluid at high temperature can liberate additional gravitational energy and supply the missing component of Saturn's heat flux. Thus one expects to find differences in the helium distributions between Jupiter and Saturn. However, as discussed above, no evidence has appeared that these distributions are in any way different. Since the critical temperatures for the separations of helium and hydrogen fluid phases are uncertain, particularly at the low pressures (*ca.* 3 Mbar) that are relevant, it is possible that phase separation has not ensued in either planet. But, in this case, a substantial alternative energy source must be found for Saturn.

Models for Uranus and Neptune are much more poorly constrained at present, because of conflicting evidence about the rotation rates (Hubbard & MacFarlane 1980), leading to uncertainty in the appropriate value of the parameter q. Values of the rotation period for Uranus range from *ca.* 24 to *ca.* 12 h (Slavsky & Smith 1980). For Neptune, reported periods are *ca.* 18 to *ca.* 11 h (Smith & Slavsky 1980; Münch & Hippelein 1980), and there also exists uncertainty in the location of Neptune's pole, which leads to increased uncertainty in the value of Neptune's J_2 (Harris 1980). Because of the current disarray in this important data base, interior models for Uranus and Neptune are primarily constrained by the mass and radius, while the degree of central concentration remains undetermined. Hubbard & MacFarlane (1980) have calculated Uranus and Neptune models, assuming a high degree of differentiation. The planets are assumed to have central cores of 'rock', mantles of 'ice' (H_2O, CH_4, and NH_3 in solar proportions), and outer layers of H_2–He in solar proportions. The 'ice'/'rock' ratio was likewise assumed to be solar. The resulting models indicate that the mass of the H_2–He outer layer decreases from Uranus to Neptune, continuing the trend from Jupiter to Saturn. Some of the properties of the Hubbard & MacFarlane models are given in table 3. The temperature distribution is assumed to follow an adiabat in the H_2–He layer and the 'ice' layer (which is therefore really liquid), and to be isothermal in the 'rock' core.

Radial positions of the various layers in Jovian planet models are shown to scale in figure 1. The observed net heat flow from Neptune's interior is *ca.* 30 μJ/cm^2 s (Loewenstein *et al.*

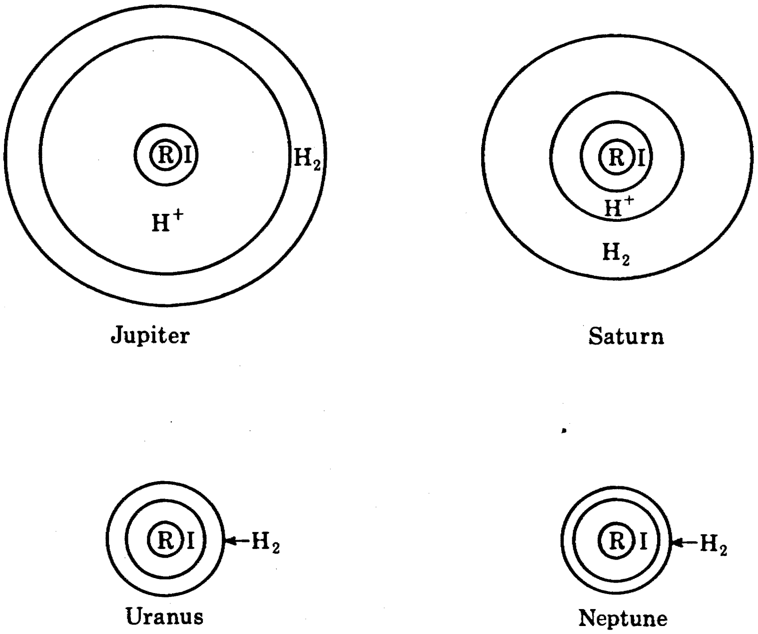

Figure 1. Interior structure models for the Jovian planets. The innermost core, marked R, is of rock (iron and magnesium silicates). The outer core (marked I) is composed of ice (H_2O, CH_4 and NH_3). The outer envelope (marked H_2) is primarily molecular hydrogen and helium in solar proportions. For Jupiter and Saturn, there is a zone of metallic hydrogen (marked H^+). The H^+ zone and H_2 zone may not be separated by a sharp transition.

1977), and a Kelvin cooling model appears to be successful in explaining this value. If we define the effective temperature T_e by the relation

$$4\pi a^2 \sigma T_e^4 \equiv L, \tag{3}$$

where L is the total infrared luminosity (J/s) of the planet, a is the planetary radius, and σ is the Stefan–Boltzmann constant, then we have $T_e = 55.5 \pm 2$ K at present, while if the planet radiated only heat absorbed from the sun the value would be *ca.* 46 K. The thermal history of Neptune depends sensitively upon the composition of the interior. Figure 2 shows the calculated effective temperature as a function of time before present. This model assumes that the observed heat flow is produced by the Kelvin mechanism (radioactivity scaled from the Earth could account for only *ca.* 2 μJ/cm^2 s). Energy transport in the interior is assumed to be accomplished by efficient convection, so that the atmosphere governs the escape of internal heat. The two lower curves assume the abundance of 'ice' given in table 3, and show the effect of plausible uncertainties in the heat capacity of H_2O, CH_4 and NH_3 under the assumed conditions. The upper curve assumes an extreme model in which 'ice' is assumed to be essentially absent; note that the heat capacity is then insufficient to account for current heat flow.

We find that the lack of a detectable heat flow from Uranus may be due to the effect of sunlight in modifying the atmospheric boundary condition, since Uranus receives substantially more solar power than does Neptune (Hubbard 1978). Our understanding of the coupling between Uranus's atmosphere and its deep interior may be improved by further observations of the effective temperature as the planet approaches a pole-on presentation to the Sun during the coming years.

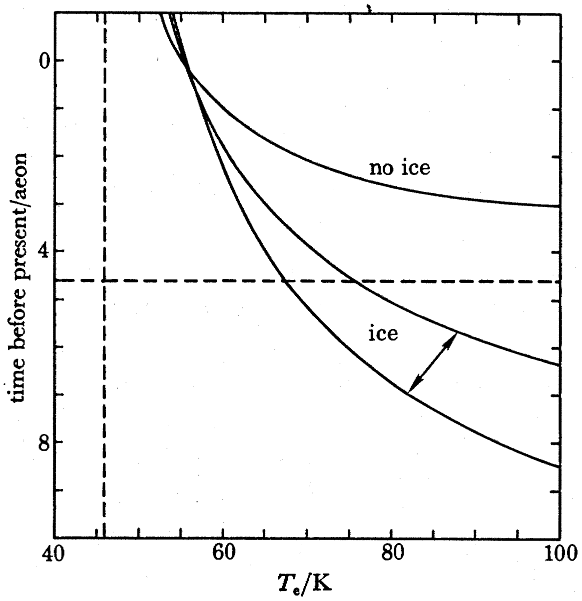

FIGURE 2. Thermal evolution of Neptune for models with normal ice abundance (lower curves with arrows), and for an extreme model composed only of a rock core with a hydrogen–helium envelope.

EVIDENCE FROM ATMOSPHERIC COMPOSITION

To interpret the abundances of compounds that are observed in the atmospheres of the Jovian planets, it is necessary to consider alternative models of planetary origin. There are basically two types of model that have been proposed. The *homogeneous collapse model* proposed by DeCampli & Cameron (1979) assumes that the giant planets originated as distended gaseous protoplanets. The onset of hydrogen molecular dissociation produces a dynamical collapse which leads to a self-luminous, convective protoplanet. This scenario provides a natural explanation for the origin of the heat flows on Jupiter and Saturn, but meets with difficulty in explaining the properties of the cores. In the homogeneous collapse model, cores are produced by rain-out of refractory materials during the gradual cooling of the planet. More volatile materials such as H_2O, CH_4 and NH_3 are expected to remain in roughly solar proportion to the H–He component. This model is clearly unable to explain Uranus and Neptune, or the marked deviations from solar ratios for the abundances of H_2O and CH_4 observed in Jupiter, as well as derived methane abundances in the other Jovian planets.

An alternative model for the origin of the Jovian planets has been proposed by Mizuno *et al.* (1978) and by Mizuno (1980). In this model, it is assumed that a protoplanetary nucleus of low-temperature condensates has already been formed by accretion. In this *nucleation model*, formation of a hydrogen–helium outer layer occurs by an instability in the surrounding nebula which occurs when the core mass has grown to approximately ten times the mass of the Earth ($10M_E$). This result is essentially independent of the region of the primordial nebula where collapse takes place. The amount of hydrogen and helium that collapses on to the core is small according to Mizuno, and is *ca.* $5M_E$. Therefore this mechanism works well to explain the origin of Uranus and Neptune, but requires a further mechanism for the addition of large quantities of hydrogen and helium in Jupiter and Saturn.

The composition of the nucleus of a proto-Jovian planet depends upon the nebular temperature at the time that the nucleus accretes. At a temperature of $\lesssim 150$ K, H_2O condenses but

CH_4 and NH_3 remain in the gaseous phase and therefore would be expected to be in roughly solar proportions in the planetary atmosphere. At $T \lesssim 100$ K NH_3 condenses, and at $T \lesssim 60$ K CH_4 would be added to the nucleus. A possible explanation of the abundances in the Jovian atmosphere is that H_2O, NH_3 and CH_4 all condensed (thus requiring remarkably low nebular temperatures at Jupiter). The H_2O might be insoluble in the metallic hydrogen and thus have remained trapped in the core, explaining the low abundance of water in the Jovian atmosphere. If we further assume that methane then dissolves in the hydrogen, the numbers come out approximately right: we obtain an enhancement of *ca.* 3 to 5 in the methane abundance relative to solar. A greater enhancement would also be predicted for Uranus and Neptune. Curiously, microwave data indicate that ammonia is approximately in solar proportions in the deep atmosphere of both Jupiter and Saturn (Gulkis & Poynter 1972). We may actually be observing the result of very complex internal fractionation processes in the Jovian planets, which greatly obscures the significance of observed atmospheric abundances.

A further enigma results when we consider the abundance of deuterium. The primordial solar nebula value for the number ratio of deuterium to hydrogen is $D/H = 8 \times 10^{-7}$ to 3×10^{-5} (Black 1973). However, the value for terrestrial waters (standard mean ocean water) is $D/H = 1.56 \times 10^{-4}$. The enrichment in terrestrial waters by roughly a factor of ten over primordial, is commonly interpreted as being due to equilibrium partitioning of deuterium from HD into HDO, at temperatures of *ca.* 200 K (Black 1973). It is also easy to show that deuterium partitions strongly into methane and ammonia at similar temperatures. As mentioned above, the preferential accumulation of the 'ices' into cores of the Jovian planets would seem to require low condensation temperatures, and therefore strong enhancement of deuterium in the ice component. If this component is subsequently heated and compressed, the high temperatures at the interface of the 'ice'/H–He layers produces a redistribution of the deuterium into the outer hydrogen-rich layers. Convection may cause the resulting deuterium-enriched hydrogen molecules to mix into observable layers of the planet.

A conservative estimate of the resulting deuterium enrichment factor for the planet as a whole is obtained by adopting for the 'ice' layer the terrestrial enrichment factor of ten. We then have

$$(D/H)_{pl} = (D/H)_s \frac{X_e M_e + 10 X_i M_i}{X_e M_e + X_i M_i} \tag{4}$$

where $(D/H)_{pl}$ is the planetary-average D/H value, $(D/H)_s$ is the primordial solar nebula value, X_e is the mass fraction of hydrogen in the outer envelope of the planet, M_e is the mass of the outer envelope, X_i is the mass fraction of hydrogen in the 'ice' layer, and M_i is the mass of the ice layer.

Figure 3 shows D/H ratios observed for various Solar System objects. For carbonaceous chondrites, values of D/H range from *ca.* 10 $(D/H)_s$ to *ca.* 100 $(D/H)_s$ (Kerridge 1980; Robert & Merlivat 1979; Robert *et al.* 1980). The values for the Jovian atmosphere are $(5.2 \pm 2) \times 10^{-5}$ (Beer & Taylor 1973), $(5.1 \pm 0.7) \times 10^{-5}$ (Trauger *et al.* 1977) and $(2.3 \pm 1.1) \times 10^{-5}$ (Combes *et al.* 1978). For Saturn we have $2\ (+2, -1) \times 10^{5}$ (Fink & Larson 1978) and $(5.5 \pm 2.9) \times 10^{-5}$ (Macy & Smith 1978). For Uranus the values are $(3 \pm 1.2) \times 10^{-5}$ (Macy & Smith 1978) and $(4.8 \pm 1.5) \times 10^{-5}$ (Trafton & Ramsay 1980). The dots in figure 3 show values computed from equation (4) derived from interior models described above. Note that these figures are actually lower limits on the planetary average value of D/H since condensation temperatures in the Jovian planet zone of formation were presumably much lower than the temperature for

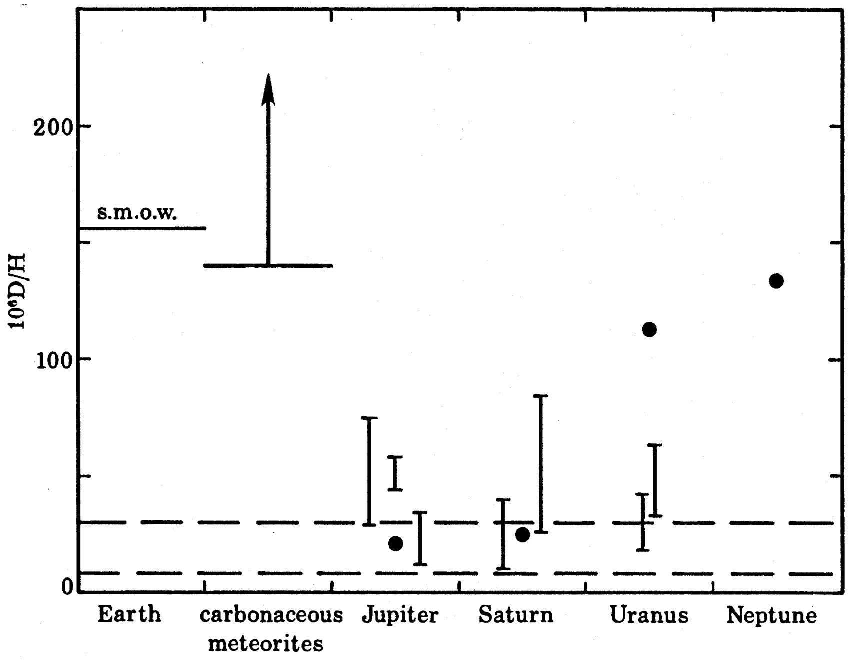

FIGURE 3. Deuterium/hydrogen ratios for various Solar System bodies. Dashed lines show the range for the primordial D/H value. Dots are predicted values for planetary D/H for Jovian planets, if it is assumed that deuterium is enriched in the ice component by the same factor as in terrestrial sea water(s.m.o.w.).

isotopic equilibration of terrestrial seawater. There is evidently a gross discrepancy between observed values and the predicted value for Uranus. The implication may be that Uranus is very inactive and has been inactive for much of its existence, such that deuterium-rich material has never been mixed into the observable part of the atmosphere. Since Neptune has a higher internal heat flow rate than has Uranus, an eventual measurement of Neptune's D/H ratio may help to clarify the situation.

EVIDENCE FROM TIDAL EVOLUTION CONSIDERATIONS

Although the question of whether the dense cores of the major planets are largely solid or liquid may at first seem to be an academic one, Dermott (1979) has pointed out that the orbital evolution of major planet satellites may depend sensitively on the phase of the core material of their primary. In simplified terms, the argument is as follows. The tidal torque acting on a satellite due to tides raised by the satellite on its primary is given by

$$T \propto a^5/Q, \tag{5}$$

where a is the radius of the primary and Q is the dimensionless tidal quality factor applicable to the planet as a whole (Goldreich & Soter 1966). For Jupiter or Saturn, a value $Q \approx 10^6$ lies in an interesting range, for the tidal torques on satellites are then sufficient to cause a moderate degree of evolution of orbits over the age of the Solar System, perhaps establishing the observed resonances. Moreover, Greenberg (1981) has shown that a value Q of *ca.* 10^6 to 10^7 for Jupiter may be implied by the phenomenon of volcanism on Io (Peale *et al.* 1979). The difficulty is that, for Jupiter or Saturn as a whole, such a value of Q is not readily explained in terms of models with a hot, liquid interior, since such models do not dissipate tidal energy at anything like the

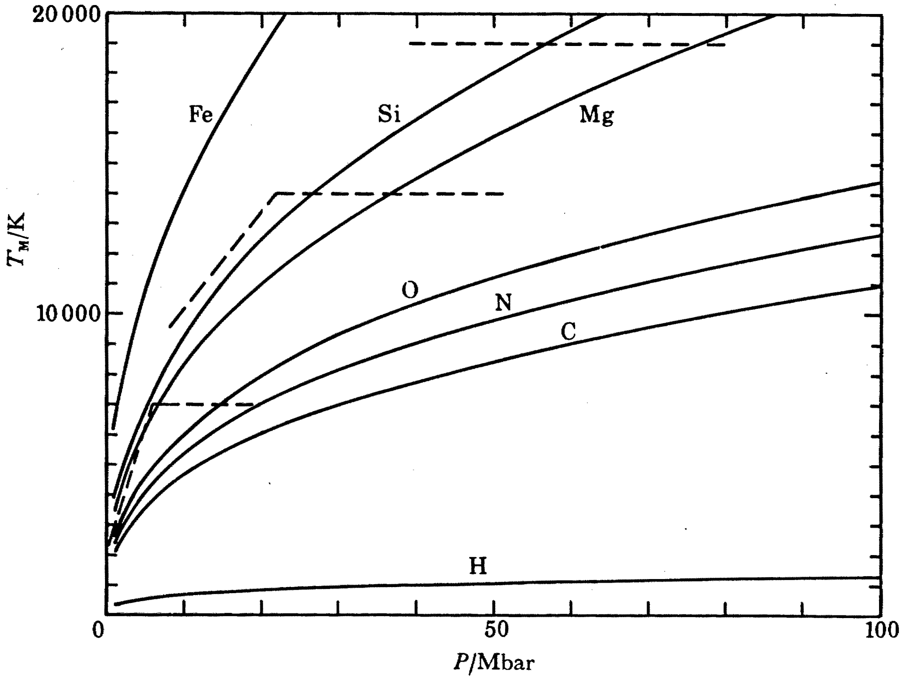

Figure 4. Estimated melting temperatures for various elements at high pressure. Dashed lines show approximate core temperature profiles for (top to bottom) Jupiter, Saturn, and Uranus and Neptune combined.

required rate (Hubbard 1974; Goldreich & Nicholson 1977). Dermott has suggested that tidal dissipation may occur in a small solid core with radius a' and a quality factor Q'. Evidently such a core can produce the required torque if $Q' \approx (a'/a)^5 Q$. Thus if $a' \approx 0.1a$, $Q' \approx 10$ for $Q \approx 10^8$. In fact there is some amplification of core tides by the envelope, and Dermott finds that $Q' \approx 40$ would be sufficient to produce the required amount of orbital evolution.

Since $Q' \propto a'^5$, the viability of the core-dissipation mechanism depends very sensitively on the size and properties of a postulated core. A typical solid-body value of $Q' \approx 10^2$ obviously requires that the inner 'rock' cores of the Jovian planets be solid.

No accurate theory for the melting of substances at pressures of *ca.* 10^2 Mbar is available, but we may apply the Lindemann melting criterion, which can be expressed in the form

$$T_{\mathrm{M}} = T_{\mathrm{M0}}(\rho_{\mathrm{M0}}/\rho_{\mathrm{M}})^{\frac{2}{3}}(\theta/\theta_0)^2, \tag{6}$$

where T_{M} is the melting temperature, ρ_{M} is the average density of the two phases at melting and θ is the Debye temperature (Zharkov & Trubitsyn 1978). The symbols with subscript zero refer to experimentally determined constants. To apply equation (6) to each pure substance, we evaluate θ in the limit of high pressure for an unscreened Coulomb lattice, and then apply screening corrections to θ from Thomas–Fermi theory (Zharkov & Trubitsyn 1978). Results of the calculation are shown in figure 4. Also shown are approximate interior temperature profiles for the Jovian planets. Now it is not clear what the chemical state of 'rock' materials such as SiO_2 and Fe will be in the core. A reasonable procedure might be to average the melting temperatures of the individual atomic components, although for eutectic behaviour this would yield an upper limit to actual melting temperatures.

We conclude from figure 4 that the 'ice' layers in Jovian planet interiors should clearly be molten, while 'rock' layers may be partially molten. It thus seems reasonable to conclude that 'rock' and 'ice' should be largely separated. However, a 'rock' core alone, even if solid, is not sufficiently large to account for much tidal dissipation in Jupiter or Saturn. The volumes of the 'rock' cores of our models are (expressed in units of the volume of the earth) 1.1, 1.6, 1.8, and 2.0 for Jupiter, Saturn, Uranus, and Neptune. From Dermott's figure 4, this implies unrealistically small values of Q for all of the Jovian planets, especially for Jupiter and Saturn.

Conclusions

We have considered a variety of lines of evidence for the interior structure and past history of the Jovian planets. The simple concept that the Jovian planets are adiabatically stratified, convective objects of primarily solar composition, cooling from an earlier high-temperature state, has been useful in understanding much of the earlier observations. At present, however, this picture is beginning to show defects as more data become available. The chemical and dynamical evolution of the interiors of the Jovian planets will probably turn out to be fully as complex as the evolution of the Earth's interior.

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