

CONDENSED MATTER PHYSICS OF PLANETS: PUZZLES, PROGRESS AND PREDICTIONS

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ABSTRACT

Despite recent advances in observations, experiment and theory, there are many major unresolved issues concerning planetary interiors. This paper is not a comprehensive review but seeks to highlight these issues. Emphasis is on the cosmically most abundant materials, the dominant constituents of the giant planets. The important issues include: (1) What are the atomic and electronic degrees of freedom in hydrogen at high pressure and temperature and how do they behave? (2) To what extent does helium dissolve in hydrogen? (3) What is the behavior of water at megabar pressures and what is the H_2 - H_2O phase diagram? (4) How does carbon behave at high pressures, in the presence of oxygen and hydrogen? (5) What happens to clathrates (e.g. $CH_4 \cdot 5-3/4H_2O$) at high pressure? (6) How does the volatile ice assemblage expected in Titan (H_2O - NH_3 - CH_4 - N_2 - CO ?) behave at $P \sim 20-40$ kbar? (7) What is the nature of the core alloy in the Earth and the core-mantle phase boundary? (8) What are the electrical conductivities of all of the above?

INTRODUCTION

The symbiosis of high pressure research and planetary interior modeling is fragile. The laboratory worker or condensed matter theorist can often work in a well-constrained, precisely characterized thermodynamic and compositional domain and may be nonplussed by the inherent dirtiness and non-uniqueness of a planetary model. The modeler, in contrast, revels in the multimegabar freedom but harbors the ill-concealed suspicion that his constructs may actually be a very useful testing ground for the properties of materials at extreme conditions. My aim is to convince you that planetary modeling poses numerous fascinating questions that can be addressed by high pressure research; questions of sufficient fundamental importance that they demand attention even if their relevance to planets remains in the realm of speculation. In fact, the modeling game is better constrained than ever before (largely because of the dramatic improvement in data arising from deep space missions) and certainly better constrained than many non-experts suspect.

In assessing the relevance of high pressure research to planetary interiors, we need a cosmic perspective and a thermodynamic perspective. By cosmic perspective, I mean an understanding of the relative abundances of elements in the Universe and the forms and combinations in which these elements are likely to exist. This may seem obvious but it has non-trivial implications. For example, it suggests that the behavior of carbon dissolved in metallic hydrogen (with $C:H \sim 10^{-3}$) may be more important than the high pressure properties of CH_4 or pure carbon. The thermodynamic perspective referred to above means a sense of the pressures and temperatures encountered in planets and satellites. Above all, it means an understanding of the states of matter encountered. For example, a liquid state theory of

iron is much more useful than a solid state theory, since most of the iron in the solar system is in the liquid state.

TABLE I. Cosmic Abundances

Element	Abundance ^{a)} (as a number fraction)	Likely Forms
H	0.92	H ₂ , H (Met)
He	8 x 10 ⁻²	Dissolved in H ₂ , H
O	7 x 10 ⁻⁴	H ₂ O, CO; dissolved
C	4 x 10 ⁻⁴	CH ₄ , CO, elemental?; dissolved in H
Ne	1.5 x 10 ⁻⁴	Dissolved in H ₂ , H
N	1 x 10 ⁻⁴	NH ₃ , N ₂ ; dissolved
Mg	4.6 x 10 ⁻⁵	Silicates, oxide
Si	3.7 x 10 ⁻⁵	SiH ₄ , silicates; dissolved in H
Fe	3.3 x 10 ⁻⁵	Fe-cores (with S, O H, ...)

^{a)} From Anders and Ebihara [1].

Table I helps to provide the cosmic perspective. Although no planet has exactly cosmic abundances, the relative abundances within elemental groups of comparable volatility are likely to be nearly cosmic. The natural subdivision in order of decreasing volatility is permanent gases (hydrogen, helium, neon); ices (H₂O, CH₄, NH₃; possibly also CO, N₂) and "rock" (essentially everything else). To the extent that planets are layered (e.g. rock core, ice layer, gas envelope), this volatility sequence provides guidance in deciding the likely relative abundances within a layer. As examples, helium is usually encountered as a minor constituent in a hydrogen-rich environment and nitrogen is likely to be found as a minor constituent (NH₃ or NH₄⁺) in either a water-rich or a hydrogen-rich environment.

Figure 1 shows that these subdivisions relate closely to the observed densities of planetary bodies. The identification of primary planetary composition is straightforward except for Uranus and Neptune (ice-rich but with added gas) and Mercury (iron-rich). Obviously, identification of constituents requires knowledge of internal temperatures and (especially) pressures. Temperature is relatively less important for a first order characterization because planets are cold. In other words, $\alpha T \ll 1$ almost everywhere within a planet, where α is the volumetric coefficient of thermal expansion and T is the temperature. This is rather fortunate, since temperatures are more difficult to evaluate than pressures. A typical internal pressure of a body of radius R , average density $\bar{\rho}$ and gravitational acceleration g must clearly be $\sim \bar{\rho}gR$ and application of the equation of hydrostatic equilibrium can be made very accurately. Estimation of temperature depends on understanding the origin and mode(s) of thermal energy transport. Since transport properties are almost always much less well known than thermodynamic properties, the uncertainties are correspondingly larger. Nevertheless, it turns out that probably all planets are adiabatic in their interiors because convection is the dominant mode of heat transport. In this context, adiabatic means isentropic. It is the thermodynamic path that an element of fluid follows if displaced from some heat within a self-

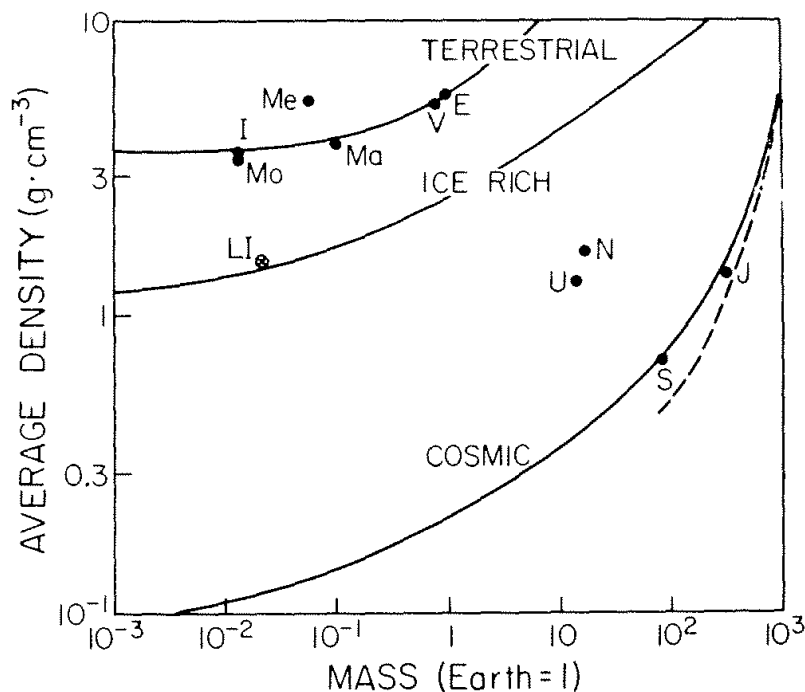


FIG. 1. Average densities of planets compared with the predicted densities for various compositional classes. The solid curves are theoretical, based on cold equations of state, and curve upwards because internal pressures (and hence densities) increase as the total mass increases. The "terrestrial" curve is for bodies of the same composition as Earth, "ice rich" refers to a body that has rock, H_2O , CH_4 and NH_3 all in relative cosmic abundance, and "cosmic" refers to a body which contains all elements in cosmic abundance. The broken curve is also "cosmic" but for internal temperatures appropriate to giant planets. In order moving outward from the Sun, the planets are represented by the symbols Me, V, E, Ma, J, S, U and N. I refer to Io, LI to large icy satellites (Ganymede, Callisto, Titan).

gravitating body, assuming the element transfers no heat to or from adjacent fluid but is always in exact pressure equilibrium with its environment. Of course, adiabaticity breaks down at boundaries or at interfaces between layers but the simplification in thermal structure resulting from the predominance of adiabaticity eliminates the need for precise knowledge of the thermal conductivity. The estimates of central temperature in Table II are consequently accurate to $\sim 20\%$, typically.

The significance of the pressures in this table is that in all but the smallest bodies, they are large enough to induce substantial electronic changes. (It is useful to recall that one megabar is roughly one electron volt divided by $10 a_0^3$, a typical volume per atom, where a_0 is the first Bohr radius.) The significance of the temperatures in the table is that they exceed the melting points of major constituents (gas, ice) in the giant planets but are comparable or less than the melting point in the terrestrial planets. Even though planets are cold in the sense that $\alpha T \ll 1$, they are hot enough that fluid phases predominate in most planets. This circumstance is not particularly remarkable since the energy required to melt a material

Table II. Relevant Thermodynamic Conditions

Body	P_{center} (Mbar)	T_{center} (K)
Moon, large satellites	~0.05	~1600
Mercury, Mars	~0.4	~2500
Earth, Venus	~3	~4500
Uranus, Neptune	~10	~8000
Saturn	~30	12,000+
Jupiter	~100	20,000+

is typically of order 0.1 eV per molecule, quite small compared to typical electronic energies.

PLANETARY MODELING

My intent in this section is not to provide a comprehensive description of how planets are modeled, but simply outline the basic ideas and main results. The emphasis is on the major planets and far greater detail can be found elsewhere [2-4]. References are given only for more recent work. The main observational constraints are gravity, the atmospheric boundary conditions, the energy balance, the magnetic field, and the presence and nature of satellites and/or rings.

The external gravity field of a planet deviates from that for a point mass because of the effect of rotation on planetary shape. The most important parameters characterizing this deviation are the gravitational moments J_{2n} ($n = 1, 2, \dots$) which are the coefficients in the expansion of the gravitational potential in even legendre polynomials. These parameters can be measured by fly-by spacecraft. The value of J_2 is a measure of the planetary moment of inertia, crudely speaking, while J_4 and higher moments are primarily sensitive to the outermost region of the planet (the rotational bulge). J_2 is known to 0.03% for Jupiter and 0.1% for Saturn, while J_4 is known to ~1% for Jupiter and ~5% for Saturn. Although J_2 is accurately determined for Uranus, the rotation rate is uncertain and so the moment of inertia is poorly constrained. In Neptune, the uncertainty is even larger. Thus, models of Jupiter and Saturn are currently rather well constrained but the situation is unsatisfactory for other bodies in the outer solar system.

The atmospheric conditions serve as an outer boundary condition for interior models. In an adiabatic planet such as Jupiter or Saturn, the temperature at the center is roughly proportional to the temperature in the atmosphere, even though the planets may have different internal energy sources. Thus, Saturn is internally colder than Jupiter at the same pressure level. The thermal boundary condition is usually characterized by the temperature at the one bar level (a somewhat arbitrary choice) and is known to ~10% in Jupiter and Saturn and perhaps 20-30% in Uranus and Neptune. The atmospheric composition is extremely important since these planets are convective and the interior and outer compositions should be the same except for the effects of phase transformation (including condensation to form cloud decks). Hydrogen predominates in all the giant planet atmospheres. Helium is present in cosmic proportions (~20% by mass) in the Jovian atmosphere but is depleted to ~10% by mass in the Saturnian atmos-

phere. The only plausible explanation for this is limited solubility of helium in hydrogen in the deep interior (discussed further below). The abundances of water and ammonia are not well known because of the problems of condensation. The observed depletion of NH_3 in the Uranian atmosphere [5], for example, could have an internal explanation (formation of an $\text{H}_3\text{O}^+ - \text{NH}_4^+ - \text{OH}^-$ ionic ocean), or a chemical explanation (formation of NH_4SH) or a simple condensation explanation (water-ammonia clouds). Methane is enhanced by a factor of two (relative to solar abundance) in Jupiter [6] and Saturn and probably much more enhanced in Uranus and Neptune [7]. It is conceivable that methane partitions upwards in phase separations in the deep interior, but the enhancement is more probably a consequence of the accretion of volatile-rich planetesimals (comet-like bodies) after planetary formation. It is unlikely that methane could have condensed at the orbit of Jupiter or Saturn so an enhancement suggests the accretion of planetesimals which formed out at Uranus and Neptune and were gravitationally scattered into Jupiter and Saturn-crossing orbits.

All the giant planets, except possibly Uranus, emit more energy than they receive from the Sun. The excess, derived from the deep interior, can be explained by cooling from an initially hot state 4.5×10^9 years ago, although gravitational energy release (e.g. the settling of insoluble helium) may be an important energy source in Saturn [4]. The internal heat flux is transported by convection, which ensures good mixing of constituents within layers (provided there are no phase separations) but rather inefficient mixing between layers [8].

Jupiter and Saturn have substantial magnetic fields, and it is likely that Uranus and Neptune also have fields [9]. In Jupiter and Saturn, these fields are probably the consequence of dynamo action sustained by convection in either the metallic hydrogen region or dense, partially conducting molecular hydrogen. Fluidity, flow and electrical conduction are needed for this process and all three requirements are readily satisfied. In Uranus or Neptune, the field could be generated in either an iron-rich inner core or in conducting fluid 'ice' (water is probably metallic or nearly so at $P \sim 5$ Mbar).

The satellite and ring systems of these planets are indirectly useful for understanding the interiors [8]. It appears, for example, that the region around Jupiter allowed condensation of water ice but not more volatile ices, whereas the Saturnian environment allowed more volatile condensates (e.g. Titan has large amounts of CH_4 and N_2). Triton (the large moon of Neptune) also has CH_4 and probably N_2 on its surface [10].

Construction of a planetary model also requires theoretical and experimental input: the theory of gravitational moments, experimental and theoretical equations of state (including phase diagrams) and other thermodynamic and transport properties. I will not discuss the gravitational moment theory here; it suffices to say that this is not a major difficulty since the theoretical capability is commensurate with existing observational capability. The situation with thermodynamic properties is much less satisfactory and will be elaborated in detail below. The procedure currently adopted is to construct parameterized free energies or equations of state which are correct in well-understood limiting cases (low pressure experimental data on the one hand and quantum-mechanically exact pressure-ionized states on the other hand). The interpolation between these limits is often rather poorly known; the most outstanding uncertainty concerns the molecular-metallic transition in hydrogen. In general, models are constructed by making one or more ad hoc assumptions about layering. For example, it is common practice to assume a 'rock' core, possibly overlaid by an 'ice' layer, overlaid in turn by a hydrogen-rich region. It is important to realize that although this procedure may be ad hoc, the details are unimportant for Jupiter and Saturn since they concern only a small fraction of the

total mass. The ad hoc flavor of Uranus and Neptune models is, by contrast, a serious problem and existing models must be regarded as highly uncertain. Similar comments apply to the large icy satellites. With these qualifications in mind, the figures below provide reference points which serve as a basis for discussing the outstanding high pressure physics problems.

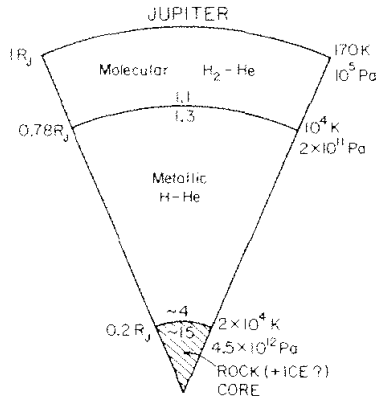


FIG. 2. Jupiter

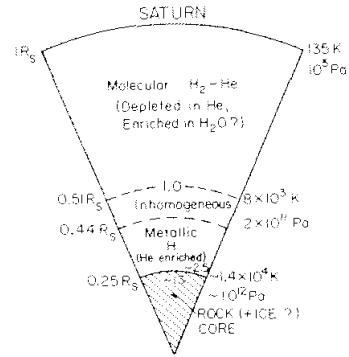


FIG. 3. Saturn

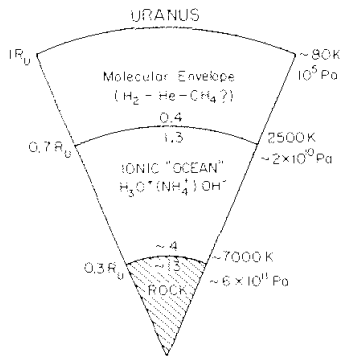


FIG. 4. Uranus

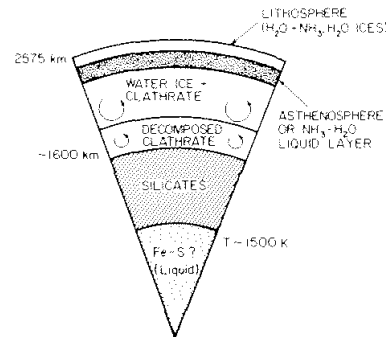


FIG. 5. Titan

The Jupiter model is rather simple: an approximately cosmic composition except for about a ten earth mass core of more dense material (probably rock). However, the envelope could be enhanced in other material (e.g. water). Saturn is more complicated, necessarily because of helium depletion observed in the atmosphere. The outer envelope could be enriched in constituents denser than helium (e.g. in water). The high density cores depicted for Jupiter and Saturn are required by J₂; the outer envelope densities are constrained by J₄. The depicted interiors for Uranus and Titan are much more speculative and uncertain and are offered merely as a guide for identifying the important issues discussed below.

IMPORTANT PROBLEMS

I will proceed down the list of cosmically abundant constituents (Table I) identifying in each instance the important problems that theoreticians and experimentalists could solve or address.

Hydrogen

The behavior of hydrogen between ~ 0.5 Mbar and 5 Mbar and $T \sim 10^4$ K is far from understood. The simple picture of a single well-defined and abrupt transition from molecular, insulating hydrogen to monatomic, metallic hydrogen is almost certainly wrong even at $T = 0$ K because of the likelihood of a band-overlap conducting state in H_2 at a pressure lower than the structural diatomic to monatomic transition. Current estimates suggest insulator \rightarrow conductor at $P \sim 1$ Mbar [11] and diatomic \rightarrow monatomic at $P \sim 3$ to 5 Mbar [12,13], both for $T = 0$ K. Additional complications arise at $T \sim 10^4$ K where all relevant phases are fluid and one would suspect gradual transitions. Both $\eta_{\text{cond}}/\eta_{\text{total}}$ and $\eta_H/\eta_{\text{total}}$ would then be analytic, gradually increasing from 0 to 1 as P increased, where η_{cond} is the number of conduction electrons, η_H is the number of free protons (not associated with molecules) and η_{total} is the total number of protons (or electrons). No rigorous calculation or argument exists to prove or disprove this hypothesis and non-rigorous arguments have been proposed which support either a gradual transition [4,14] or discontinuous behavior [15]. In some respects, the problem is related to the behavior of alkali metal plasmas [16] and the long-standing hypothesis of Landau and Zeldovich [17] concerning separate gas \rightarrow dense dielectric \rightarrow metallic plasma first order transitions. Regardless of the nature of the transition(s), there is likely to be a substantial pressure range at $T \sim 10^4$ K for which hydrogen is semiconducting. This is likely to be important for several aspects of planetary models: the thermodynamic properties (it will affect the adiabatic gradient and specific heat, especially), transport properties -- especially the electrical conductivity (important for understanding planetary magnetic fields) and the solubility of helium (see below). Theoretical calculations, both at $T = 0$ K and at $T \sim 10^4$ K, are desirable and experimental measurements of electrical conductivity would be valuable.

The internal structural degrees of freedom are as important as the electric degrees of freedom, especially for evaluating the Gruneisen γ (i.e. for determining the adiabatic temperature gradient). The characteristic energies for rotation and intramolecular vibration can be studied in a diamond cell [18] and need to be determined to $P \gtrsim 1$ Mbar. Some crude calculations suggest that the softening of intramolecular vibration together with finite dissociation ($H_2 \rightarrow 2H$) could reduce the Gruneisen γ dramatically, perhaps even to negative values. This could have profound implications for the dynamics of the giant planetary interiors. The specific heat could also be anomalous and is important since it affects estimates of the planetary thermal evolution and interpretation of the observed heat fluxes.

Helium in Hydrogen

The possible importance of limited solubility of helium in hydrogen has been recognized for a long time [19] but has only more recently been estimated quantitatively [20,21]. Helium is known to have limited solubility in molecular hydrogen at low pressure [22] and it would be valuable to extend our understanding of this mixture to much higher pressures, if only to establish a better understanding of the H_2 -He interaction. However, the most important issue is the interaction of neutral helium with itinerant electronic states. Figure 6 shows the likely dependence of the effective immersion energy for placing a helium atom into an electron gas (i.e. a jellium).

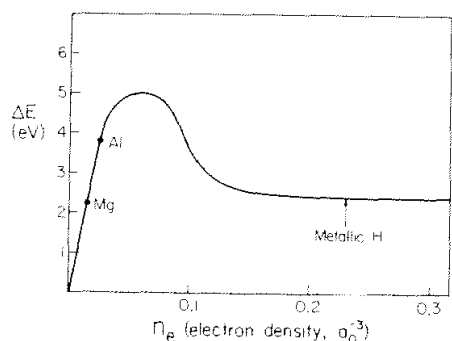


FIG. 6. Immersion energy for helium as a function of conduction electron density, η_e .

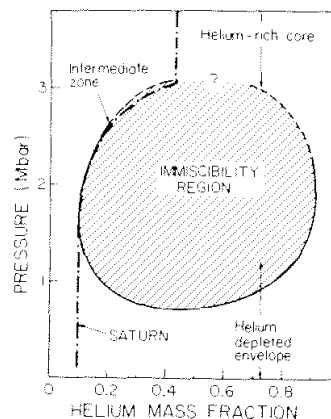


FIG. 7. Possible phase diagram for H-He with the helium distribution within Saturn indicated by the dot-dash curve.

At low η_e , ΔE is just the energy cost of inserting a free helium atom into the electron gas and is just a direct measure of the repulsive electron-helium pseudopotential [20]. At high η_e , ΔE is defined as the Gibbs energy difference, $\Delta E = G_{\text{He,H}} - G_{\text{He}}$ where $G_{\text{He,H}}$ is the chemical potential of helium placed in an electron gas while G_{He} is the chemical potential of pure helium evaluated at the same pressure (assuming the η_e corresponds to metallic hydrogen). The asymptotically flat behavior of ΔE as $\eta_e \rightarrow \infty$ corresponds to the well-understood Coulomb plasma of electrons, protons and α -particles [23].

The preceding discussion on pure hydrogen argued for a range of pressures in which η_e is finite but less than that for pure, metallic hydrogen. Since the solubility of helium is of order $\exp(-\Delta E/kT)$, it is clear that the lowest solubility may occur at some intermediate pressure (where $\eta_e \sim 0.05 \text{ a}_0^{-3}$) rather than deeper in the planet. This important possibility needs to be quantified, but obviously the pure hydrogen behavior has to be understood first. A possible phase diagram and its implications for Saturn are indicated in Figure 7.

Water and Hydrogen-Water

Water is even less well understood than hydrogen or hydrogen-helium mixtures. In shock wave experiments, where high temperatures as well as high pressures are achieved, dissociation into $\text{H}_3\text{O}^+\text{OH}^-$ is at least partially achieved and may be complete [24-26]. In static, room temperature experiments, it is probable that symmetrization of the O-H bonds, occurs (so that hydrogen bonds cease to be distinguishable from covalent bonds). There is currently no adequate theoretical description of water at $P \gtrsim 0.5$ Mbar [27]. A simple (and possibly inappropriate) application of the Herzfeld metallization criterion [28] suggests that water becomes a metal at $P \sim 4-6$ Mbar.

However, the greatest need at present is to understand better the mixing properties of water and hydrogen, two of the three most abundant constituents of the Universe. Recent experiments [29] have confirmed the expectation that $\text{H}_2\text{-H}_2\text{O}$ exhibits "gas-gas immiscibility of the first kind" above the critical point of water ($T \sim 650$ K, $P \sim 220$ bars). However, the critical line is almost isothermal, at least in the pressure regime cur-

rently studied. It is intriguing to speculate about the nature of this critical curve at much higher pressures where H_2O has some dissociation. Since the solubility of H_2 is low in (non-interacting) ionic systems, it is conceivable that the critical curve rises to much higher temperatures. This is very important for all the giant planets, but especially for Uranus and Neptune. As Figure 8 illustrates, the actual temperature profile expected for Uranus or Neptune is colder at the critical point but probably crosses the critical curve. (This temperature profile is, however, highly uncertain.)

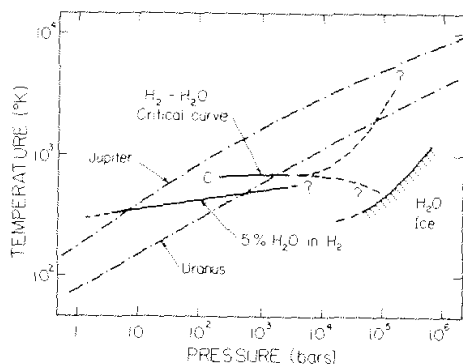


FIG. 8. Actual temperature profiles for Jupiter and Uranus (or Neptune) superimposed on the H_2 - H_2O critical curve [29] and speculative extrapolations of this curve. The curve for 5% solubility of H_2O in H_2 is also shown.

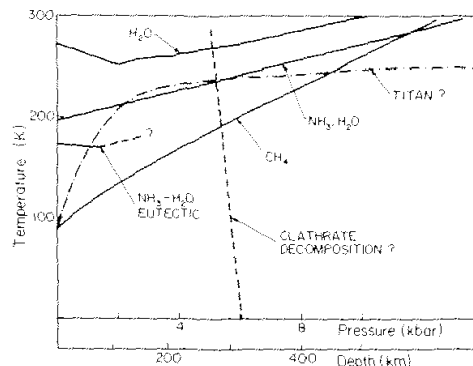


FIG. 9. Interior conditions for Titan, showing several freezing curves (H_2O , NH_3 - H_2O , CH_4 , NH_3 - $2\text{H}_2\text{O}$) an actual Titan temperature profile and an approximate decomposition curve for CH_4 clathrate hydrate.

A near-surface ocean cannot be excluded for Uranus. Indeed, microwave observations [5] can be interpreted in this way. If an ocean is present, it would be interesting to measure the partitioning of He, CH_4 and NH_3 between "ocean" (the H_2O -rich phase) and "atmosphere" (the H_2 -rich phase) by doing experiments on H_2 - H_2O with small additions of these other components. One would expect, for example, that NH_3 partitions preferentially into the water-rich phase, possibly helping to explain the observations [5].

Carbon and Hydrogen

As Ree [30] has discussed, the shock wave data suggest that all hydrocarbons behave like pure carbon plus hydrogen at high pressures ($P \geq 200$ kbar), suggesting decomposition. This was the basis for an interesting speculation by Ross [31] that elemental carbon can form a separate layer in the interiors of giant planets, more probably in Uranus and Neptune. More work is needed to answer two questions concerning this: (1) Does decomposition actually occur, in the sense that carbon undergoes phase separation from the hydrogen, or is a more dense (but intimately mixed) phase of carbon and hydrogen produced? (2) Even if phase separation is possible, will it occur if the C/H ratio is small? (Clearly the answer is no, if the ratio is small enough, because the entropy of mixing favors the mixed state.) Since it is difficult to characterize the phase assemblage in a shock experiment, static experiments would seem to be necessary (although possibly heated well above room temperature to overcome probable kinetic inhibitions of the type which "stabilize" diamond at low pressure and temperature).

Clathrates

A digression from the sequence in Table I is in order here, since there exist a class of compounds of probably high abundance in icy satellites and for which high pressure data are essential yet almost nonexistent. The general formula for these compounds, called clathrate hydrates, is $X'nH_2O$ where X is, in general, a mixture of molecular species chosen from CH_4 , N_2 , CO, noble gases and others [32] and $n \sim 6$, typically. Methane is the most likely guest molecule but substantial amounts of other gases are possible. Modeling of the large satellite of Saturn called Titan (see Figures 5 and 9) is likely to require an understanding of clathrates [33]. One would particularly like to know the decomposition pressure of the clathrates, since it may help explain the origin of Titan's atmosphere and, indirectly, the probable existence of an ethane-methane ocean [34] at the present surface. The rough estimate for decomposition indicated in Figure 9 does not allow for the possibility of more compact clathrate structures of the type suggested by the work on tetrahydrofuran clathrate [35].

Ammonia and Nitrogen

It is unlikely that either NH_3 or N_2 is present in pure form in a planet or satellite. The most important needs are to understand NH_3-H_2O at a range of T, P and composition (with an emphasis on near-cosmic mixtures, $\sim 0.8 H_2O-0.2NH_3$) and mixtures of N_2 with CH_4 , CO and possibly H_2 , H_2O . The existence and nature of eutectics in NH_3-H_2O and N_2-CH_4 are of particular interest because of their relevance to volcanic processes fed by low melting point fluids [33,36]. The effect that the presence of NH_3 has on the degree of ionization in H_2O at high pressures is also of importance for Uranus and Neptune, especially.

Neon

Although more abundant than nitrogen, neon does not condense under any plausible conditions and is likely to be present within planets only as a very minor constituent in a hydrogen-rich phase. Nevertheless, it would be of interest to know its partitioning behavior between, for example, helium-rich and hydrogen-rich phases in the hydrogen-helium miscibility gap. This may have observational consequences. (A probe, including a mass spectrometer, will descend into the Jovian atmosphere in the late 1980's and a probe should eventually be dropped into the Saturnian atmosphere. A comparison of the results for these two planets could be very diagnostic of internal conditions.)

Rock-Forming Elements

I turn briefly now to a consideration of the important issues for the terrestrial planets, bodies which assume significance more because of our anthropocentric viewpoint than because of cosmic considerations. "Rock" is a very loose term, meaning silicates and oxides in which the major elements are Mg, Si and O (but with significant amounts of Fe, Ca and other elements also included). A detailed discussion of problems encountered in the Earth's mantle ($P \lesssim 1.3$ Mbar) can be found in Jeanloz and Thompson [37]. I will mention here two very important and conceivably related issues: melting behavior and metallization. Almost nothing is known about the melting behavior of likely mineral assemblages at pressures exceeding a few hundred kilobars, especially the occurrence of low melting point partial melts. Shock wave experiments are not a satisfactory way of analyzing this problem, so the development of high temperature diamond cell techniques is needed.

No "rock" component has ever been conclusively metallized in an experiment, although some interesting claims and suggestions have been made.

Perhaps the most interesting is the isentropic compression work by Pavlovskii et al. [38] suggesting a doubling of the density of SiO_2 at $P \sim 1.3$ Mbar, presumably to a metallic phase. If correct, this would allow the Earth's core to be SiO_2 . It is so difficult to reconcile this with any theoretical estimates of the behavior of SiO_2 that it is tempting to discount the experiment. Obviously, more work is needed.

Iron and Iron-Alloys

The Earth's outer core is liquid and less dense than pure iron. Both observations suggest the presence of a low melting point alloy of iron with cosmically abundant elements such as O, S; perhaps Si, H, maybe even C, N or Mg [39]. Although shock wave data have provided important constraints on the melting curve [40] and equation of state, much more work needs to be done to establish the effect of alloying constituents on melting behavior and density. It is especially important to establish the nature of the Fe-O system at megabar pressures.

CONCLUDING REMARKS

This paper amounts to little more than a "wish list" of experiments and theory needed to make further advances in the physics of planetary interiors, hopefully placed in sufficient context that readers can judge for themselves the thermodynamic conditions and compositions of interest. Let high pressure researchers become imbued with an excessive lack of humility, it is worth mentioning that the correct application of high pressure results to plausible planetary models can be as difficult and intellectually challenging as the high pressure research. In any event, most of the ideas discussed here are of sufficient fundamental importance to merit analysis independent of their application to planets.

I will close with the predictions promised in the title. First, the application of high pressure physics will play a major (perhaps even dominant) role in unravelling many of the fundamental questions concerning planetary formation, primary differentiation, bulk composition and contemporary dynamics. Second, existing technology and theory are sufficient in principle to insure correctness of the first prediction. Third, improved technology is nevertheless extremely desirable. Both higher pressures and higher temperatures in well-controlled (preferably static) environments are needed. The enhanced scientific capability that would result from the regular attainment of, say, 2 Mbar as opposed to 1 Mbar, would be immense (assuming, of course, adequate calibration and diagnostic capability). Fourth, the planetary applications of high pressure research are sufficiently fundamental and rewarding to justify the continued support and active encouragement of this research by planetary scientists. Finally, the potential return to high pressure scientists from understanding the properties of planets is largely untapped and unrecognized, but if it is appreciated then all will benefit.

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REFERENCES

1. E. Anders and M. Ebihara, *Geochim. Cosmochim. Acta* **46**, 2362 (1982).
2. V.N. Zharkov and V.P. Trubitsyn, "Physics of Planetary Interiors," (Pachart, Tucson 1978) 338 pp.

3. D.J. Stevenson, *Ann. Rev. Earth Planet. Sci.* **10**, 257 (1982).
4. W.B. Hubbard and D.J. Stevenson, in "Saturn," T. Gehrels, ed. (Univ. Arizona Press 1984).
5. S. Gulkis, E.T. Olsen, M.J. Klein and T.J. Thompson, *Science* **221**, 453 (1983).
6. D. Gautier, B. Bezard, A. Marten, J.P. Baluteau, N. Scott, A. Chedin, V. Kunde and R. Hanel, *Astrophys. J.* **257**, 901 (1982).
7. J.T. Bergstrahl and J.S. Ness, *Icarus* **55**, 40 (1983).
8. D.J. Stevenson, *Planet. Space Sci.* **30**, 755 (1982).
9. D.J. Stevenson, *Rep. Prog. Phys.* **46**, 555 (1983).
10. D.P. Cruikshank, R.H. Brown and R.N. Clark, unpublished. (See *Science* **221**, 448 (1983).)
11. C. Friedli and N.W. Ashcroft, *Phys. Rev.* **16B**, 662 (1977).
12. S. Chakravarty, J.H. Rose, D. Wood and N.W. Ashcroft, *Phys. Rev.* **24B**, 1624 (1981).
13. W.J. Nellis, M. Ross, A.C. Mitchell, M. Van Thiel, D.A. Young, F.H. Ree and R.J. Trainor, *Phys. Rev.* **27A**, 608 (1983).
14. D.J. Stevenson and E.E. Salpeter, *Astrophys. J. Suppl.* **35**, 221 (1977).
15. M. Robnik and W. Kundt, *Astron. Astrophys.* **120**, 227 (1983).
16. F. Hensel, elsewhere in this volume.
17. L. Landau and G. Zeldovich, *Acta Phys. Chim. (USSR)* **18**, 194 (1943).
18. S.K. Sharma, H.K. Mao and P.M. Bell, *Phys. Rev. Lett.* **44**, 886 (1980).
19. R. Smoluchowski, *Nature* **215**, 691 (1967).
20. D.J. Stevenson, *J. Phys. F. Metal Physics* **9**, 791 (1979).
21. D.J. Stevenson, *Science* **208**, 746 (1980).
22. W.B. Streett, *Astrophys. J.* **186**, 1107 (1974).
23. D.J. Stevenson, *Phys. Rev.* **12B**, 3999 (1975).
24. S.D. Hamann and M. Linton, *Trans. Faraday Soc. (GB)* **62**, 2234 (1966).
25. A.K. Mitchell and W.J. Nellis, *J. Chem. Phys.* **76**, 6273 (1982).
26. F.H. Ree, *J. Chem. Phys.* **76**, 6287 (1982).
27. L-g. Liu, *Earth Planet. Sci. Lett.* **61**, 359 (1982).
28. M. Ross, *J. Chem. Phys.* **56**, 4651 (1972).
29. T.M. Seward and E.U. Franck, *Ber. Bunsenges. Phys. Chem.* **85**, 2 (1981).
30. F.H. Ree, *J. Chem. Phys.* **70**, 974 (1979).
31. M. Ross, *Nature* **292**, 435 (1981).
32. S.L. Miller, *Proc. Nat. Acad. Sci.* **47**, 1798 (1961); "Physics and Chemistry of Ice," E. Whalley, S.J. Jones, L.W. Gold, eds. (Royal Soc. Canada 1973), p. 42.
33. D.J. Stevenson, in "Saturn" T. Gehrels ed. (Univ. Arizona Press 1984) (Titan Chapter).
34. J.I. Lunine, D.J. Stevenson and Y.L. Yung, submitted to *Science* (1983).
35. R.G. Ross and P. Andersson, *Can. J. Chem.* **60**, 881 (1982).
36. D.J. Stevenson, *Nature* **298**, 142 (1982).
37. R. Jeanloz and A.B. Thompson, *Rev. Geophys. Sp. Phys.* **21**, 51 (1983).
38. A.I. Pavlovskii et al., *J.E.T.P. Lett.* **27**, 264 (1978).
39. D.J. Stevenson, *Science* **214**, 611 (1981).
40. J.M. Brown and R.G. McQueen, *Geophys. Res. Lett.* **7**, 533 (1980).