Equation of State Experiments and Theory Relevant to Planetary Modelling

M. Ross, H. C. Graboske and W. J. Nellis

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Equation of state experiments and theory relevant to planetary modelling

BY M. ROSS, H. C. GRABOSKE JR AND W. J. NELLIS
University of California, Lawrence Livermore National Laboratory,
Livermore, California 94550, *U.S.A.*

In recent years there have been a number of static and shockwave experiments on the properties of planetary materials. The highest pressure measurements, and the ones most relevant to planetary modelling, have been obtained by shock compression. Of particular interest to the Jovian group are results for H_2, H_2O, CH_4 and NH_3. Although the properties of metallic hydrogen have not been measured, they have been the subject of extensive calculations. In addition recent shock wave experiments on iron report to have detected melting under Earth core conditions. From this data theoretical models have been developed for computing the equations of state of materials used in planetary studies. A compelling feature that has followed from the use of improved material properties is a simplification in the planetary models.

INTRODUCTION

Advances in high pressure experimental physics have made possible accurate measurement on many of the properties of materials constituting the planetary interiors. Similar advances have taken place in theoretical and computational physics.

The giant planets and their major satellites present a range of systems from a star-like object, Jupiter, down to a moon-like rocky body, Europa. The exact compositions of these planets and satellites are uncertain, but current studies (Graboske *et al.* 1974; Slattery 1977) indicate that Jupiter and Saturn have solar composition envelopes of H, He and 'rock-like' cores of Fe, Ni and Si and Mg, mainly as oxides. Uranus and Neptune have 'ice-like' (H_2O, NH_3, CH_4) shells with a solar envelope of H, He and the characteristic rock core of the giant plants (Hubbard & MacFarlane 1980).

Estimates of the state conditions and compositions for the four giant planets and four Galilean satellites are shown in figure 1. It is clear that the state properties of H and He are important over the widest pressure range from 1 atm† to 45 Mbar‡ (Jupiter). The pressures of the 'ices' range from 0.2 to 6 Mbar, and the rock components are important from low pressure to 100 Mbar at the centre of Jupiter. In addition to uncertainties in the equation of state resulting from an absence of data and sufficiently reliable theory, these conditions give rise to a number of physical states that are poorly understood, but important for planetary modelling. Some are listed below.

(i) The molecular–metallic phase transition in hydrogen. This substantial change in hydrogen thermodynamics can affect the storage and release of gravitational energy, and in turn modify the evolution modelling of Jupiter and Saturn. Also, a significant density change across the transition would alter the mass distribution, thus affecting the predicted gravitational field.

(ii) Hydrogen–helium immiscibility. Studies (Stevenson & Salpeter 1977 *a*, *b*) indicate

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† 1 atm $\approx 10^5$ Pa.
‡ 1 Mbar $= 10^6$ bar $= 10^{11}$ Pa.

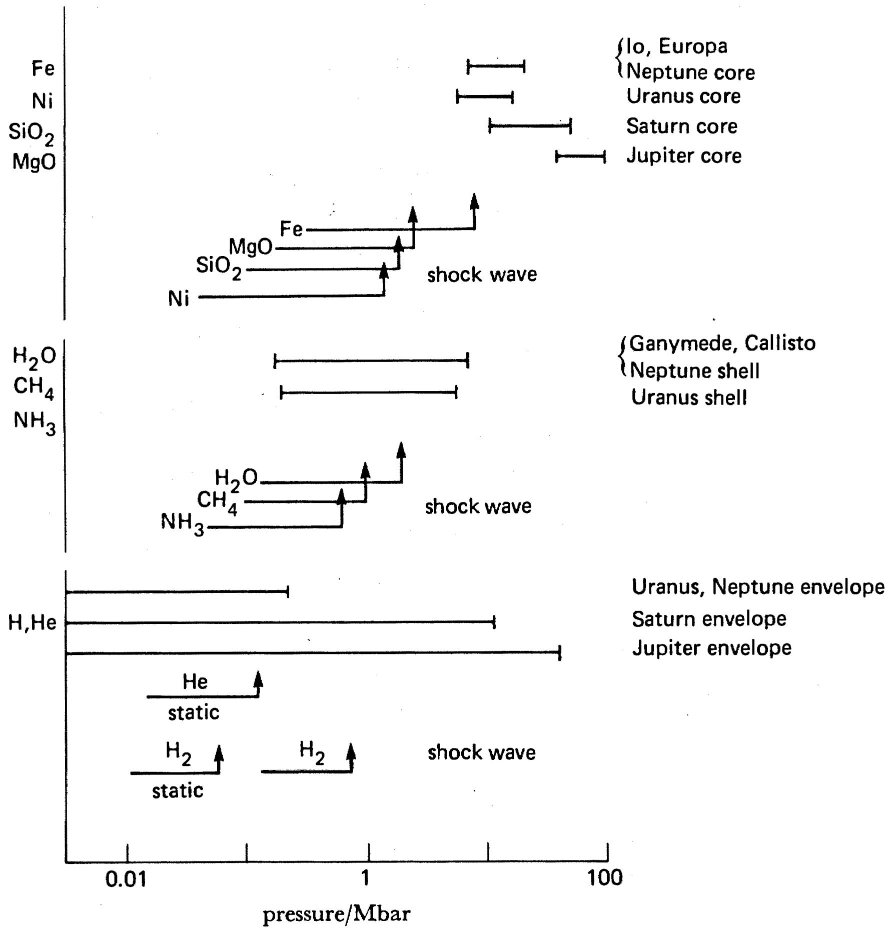

Figure 1. The range of pressure for outer Solar System planetary objects, for the various composition groups. Maximum pressures range from about 100 Mbar in the Jupiter rock–ice core down to the roughly 1 Mbar in the Galilean satellites. Highest experimental pressures, both static and dynamic, are indicated by arrows. Values for Jupiter (Stevenson & Salpeter 1976), Saturn (Slattery 1977; Podolak & Cameron 1974), Uranus, Neptune (Hubbard & MacFarlane 1980) and Galilean satellites (estimated), are all approximate.

immiscibility régimes coincident with Jupiter and Saturn central regions. Immiscibility, accompanied by gravitational differentiation, will add a novel heat source to the planets' contraction. This mechanism may be occurring in Saturn (Grossman *et al.* 1980).

(iii) High pressure condensed phases of candidate core materials. The suggested core components, Fe, SiO_2, MgO, H_2O, have complex phase structure at sub-megabar pressures. Insulator–metal transitions in the ices, melting in rocks and ices and phase separation are all probable high pressure phenomena that influence predicted planetary structure and evolution.

(iv) Electrical conductivity of ice, rock and elements in the megabar range. Dynamos and other flow related phenomena are sensitive to electrical properties and require accurate data.

This leads to the question of what are the appropriate experimental measurements, pressures, accuracies and, of course, priorities. Since all modelling is keyed on assumed candidate materials, all of these should be investigated. In order of importance are: H, He, H_2O, CH_4, NH_3, then Fe and the other rock components. Previous research has demonstrated the need for highest possible experimental accuracy for constraining theory or determining the best theoretical model. However, high pressure – high temperature experiments are very difficult or, over much of the

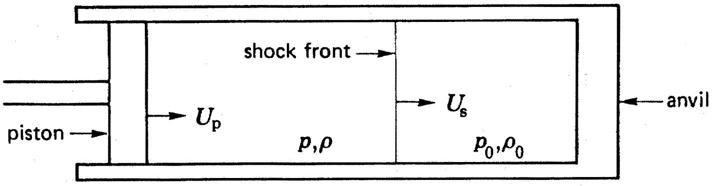

FIGURE 2. Schema of shock wave experiment. Piston moving at velocity U_p generates a steep compression wave (shock wave) travelling at a velocity U_s into undisturbed fluid. The velocities U_p and U_s are measured.

range characteristic of planetary interior conditions, not yet possible. Consequently a great deal of planetary modelling has been based on theory untested by data. We restrict our discussion of theories to those that have been validated by comparison with experiment.

Before 1945 almost all high pressure data on fluids was obtained from experiments carried out hydrostatically. The pressure was generated by a piston squeezing down on a liquid sample in a cylinder and all this was contained in the pressure vessel. The pressure that can be achieved is limited by the strength of the materials used in the construction of the pressure vessel.

After 1945 the shock wave method emerged from wartime research as a fully fledged scientific tool (Rice *et al.* 1958). The method used high explosives to generate very high pressures. In recent years high velocity gas guns have become more widely used (Jones *et al.* 1966; Mitchell & Nellis 1981). Virtually all the pressure–volume data on fluids above 25 kbar have been obtained by shock compression. With shock waves some of the conditions comparable to those found in the giant planets can be achieved in the laboratory. As an illustration, figure 1 also shows the maximum experimental pressures that have been attained in planetary materials. The highest pressures have all been reached by the shock wave method.

SHOCK WAVE EXPERIMENTS

The brief duration of a shock experiment, of the order of a microsecond or less, places certain constraints on the diagnostics. Measurements precise to 1 % require instrumentation with subnanosecond response times. However, the virtually instantaneous nature of the experiment has the great advantage that it eliminates the need for a strong containing vessel for the specimen and as a result the maximum pressure attainable is not limited by the strength of materials as it is for the static method. It can be shown that the measured state is one of thermodynamic equilibrium. The highest pressure reported so far is 67 Mbar in uranium (Ragan 1980). It was the result of add-on experiments to a nuclear device test. With a two-stage gas gun, typical maximum pressures in favourable cases, like transition metals, are of the order 3–5 Mbar. In liquids, pressures near a megabar are obtained, depending on the initial density.

Most of the shock wave data discussed in this paper were obtained with the Lawrence Livermore National Laboratory (L.L.N.L.) two-stage light gas gun (Mitchell & Nellis 1980). This apparatus can accelerate a 20 g metal projectile against a target sample to velocities of 7 km/s. The projectile impacting the target may be envisaged, as in figure 2, as equivalent to a piston moving at a velocity U_p. It generates a shock wave (a steep compression wave) travelling into the undisturbed fluid at a velocity U_s. The velocities U_s and U_p are the experimentally determined quantities. The pressure and density are determined exactly from U_s and U_p by expressions that are derived from the conservation equations for mass and momentum (Rice *et al.*

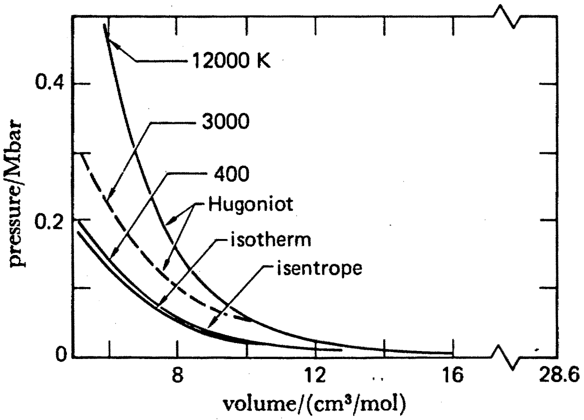

FIGURE 3. Comparison of calculated liquid Hugoniot, liquid isentrope and 0 K isotherm for hydrogen. The dashed curve is a Hugoniot reflected at 10 cm^3/mol. Some temperatures (approximate) are indicated at a common volume 6 cm^3/mol.

1958). For a one-dimensional planar shock wave moving into matter initially at rest

$$P - P_0 = U_s U_p \rho_0, \tag{1}$$

$$\rho/\rho_0 = U_s/(U_s - U_p), \tag{2}$$

where P_0 and ρ_0 are the initial pressure and density ahead of the shock front and P and ρ are the compressed quantities behind the front. These are the Rankine equations. An additional expression, the Hugoniot equation, relating the total energy (E) to the pressure and density, is derived from the energy conservation relation:

$$E - E_0 = \tfrac{1}{2}(P + P_0)\left(\frac{1}{\rho_0} - \frac{1}{\rho}\right). \tag{3}$$

The temperature cannot be obtained directly from the dynamic variables but must be computed from the energy and density by means of an equation of state. Additional diagnostics, such as thermal radiation detectors, are being developed for pyrometric temperature measurements (Lyzenga & Ahrens 1980). The shock process is adiabatic, but highly irreversible. As a result very high temperatures are achieved.

By carrying out a series of shock wave experiments, all starting from the same initial conditions but employing different projectile velocities, a locus of P, V, E points (Hugoniot) can be reached that is defined by equation (3). Figure 3 illustrates a Hugoniot curve calculated for liquid hydrogen (Ross 1974). Shown for comparison are the 0 K isotherm and a liquid isentrope. Calculated temperatures at one volume are also indicated. Note that the Hugoniot has by far the highest pressure and temperature.

By varying the initial density one can obtain a set of different Hugoniots. However, unless the initial state can be varied considerably, the final Hugoniots will not differ sufficiently to justify the extra effort. A considerable variation in the path of the Hugoniot can be achieved by means of reflected-shock experiments shown as a dashed curve in figure 3. In a reflected-shock experiment, the primary shock is passed through the material and then reflected from an anvil (figure 2), such as a brass plate. The reflected wave then compresses the already compressed material to a higher pressure. At the same density, the temperatures along the reflected Hugoniot are lower than those reached by the principal Hugoniot, and tend toward the isentrope. Thus, by carrying out a series of reflected experiments it is possible to extend the range of experimental conditions.

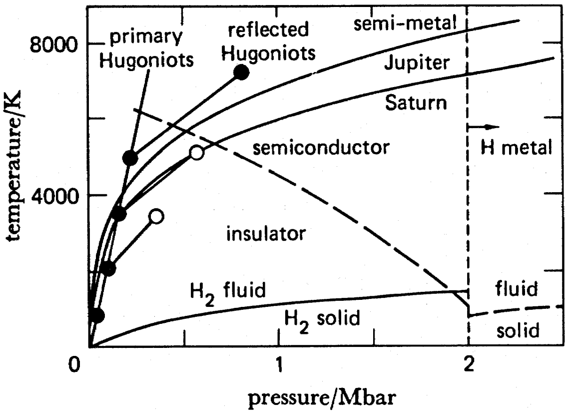

FIGURE 4. Experimental shock wave results, Jupiter and Saturn isentropes (Slattery 1977) and a calculated hydrogen phase diagram. Single shock data up to 210 kbar and reflected points near 800 kbar shown as ●. Two more reflected experiments are planned, ○. Dashed lines indicate the more speculative regions of the phase diagram.

HYDROGEN

The low mean densities of Jupiter and Saturn, 1.3 and 0.7 g/cm^3 respectively, have made it obvious that these planets consist of 90 at. % H, the remainder being almost all helium. The pressure at the core–envelope boundary in Jupiter and Saturn are computed to be about 45 and 10 Mbar, well in excess of recent estimates of the molecular–metallic fluid phase transition in H_2 (2–5 Mbar) (Ross 1974). Jupiter and, to a lesser extent, Saturn are the best observed 'stars' in the universe. That is, their measured physical properties provide more stringent constraints on the theoretical models than do those of any other stellar object, the Sun included.

The accurately known 'structural' data, radius, oblateness, rotation rate and multipole gravitational moments J_2, J_4 and J_6, make it necessary to have an accurate equation of state to build structural models of the current epoch planets. Such models have been constructed for Jupiter by Slattery (1977), Stevenson & Salpeter (1976) and Grossman *et al.* (1980). An equally restrictive task is to model the 'energetics' of the evolving planets, that is, to predict the exact observed current epoch luminosity. The luminosity is available for the Sun. But while the Sun's emission has been constant for 10^{10} years, Jupiter and Saturn have relatively rapidly changing values and are more difficult to predict. This requires evolutionary models that release the planets gravitational energy in precisely the correct manner to arrive at the present luminosity in 4.5×10^9 years. This has been done by Graboske *et al.* (1975). All of these groups used a hydrogen equation of state that made extensive use of earlier L.L.N.L. shock data (Van Thiel *et al.* 1974; Ross 1974).

Recently Nellis & Mitchell (1980) carried out additional and more accurate single shock experiments up to 200 kbar and reflected experiments to about 800 kbar. Two more reflected experiments at lower pressures are planned. To underline the significance of shock data to modelling studies we have, in figure 4, plotted pressure against temperature for computed isentropes of the current epoch models of Jupiter and Saturn (Slattery 1977) along with some shock wave results. The close proximity of the shock data to the planetary isentropes is apparent. Also shown in figure 4 are features of the hydrogen phase diagram to be discussed below. Typically when a Hugoniot and an isentrope originate from the same initial conditions they each progress along very different pressure–temperature paths as demonstrated in figure 3.

However, planetary isentropes originate at very low (atmospheric) density and temperature and as the result of an extended compression range reach pressures and temperatures comparable to those on the high density liquid Hugoniot. This allows us to carry out experiments that sample the region of our primary interest.

In recent years there have been a number of static high pressure measurements on the thermodynamic properties of hydrogen and deuterium. These measurements include 4 K solid isotherms to 25 kbar (Anderson & Swenson 1974), fluid isotherms to 300 K and 20 kbar (Mills *et al.* 1977), and melting curves to 57 kbar at room temperature (Mao & Bell 1979; Mills *et al.* 1980*a*). As mentioned, shock data is now also available on the liquid up to about 800 kbar and about 7000 K. At L.L.N.L. we have a theoretical program to develop models for predicting all of this recent data.

In principle, it should be possible to use the well established methods of quantum mechanics to calculate the forces acting between molecules and then to apply statistical mechanics to calculate thermodynamic properties. Fortunately, the calculation of thermodynamic properties with statistical mechanics has made great strides in the past 10 years and the available methods are sufficiently accurate. However, a satisfactory determination of the forces between molecules currently represents the chief uncertainty. As an alternative to theoretical rigour, it is necessary to search for an effective intermolecular potential that, when used with proven statistical mechanical models, will reproduce the available experimental data. These models can then be used to compute thermodynamic properties. Some care must be taken when extrapolating to regions outside the range of the data from which the potential was determined.

The intermolecular potential that we used is a modification of one first suggested by Silvera & Goldman (1978). They used a very accurate model for molecular solids, to determine a pair potential that fits the solid hydrogen and deuterium data up to 25 kbar. We subsequently used this potential with an accurate theory for the compressed fluid and were able to predict the experimental fluid isotherms from 0 to 20 kbar and 75 to 300 K as well as the melting curve up to 57 kbar (Ross & Young 1980; Young & Ross 1980). The calculation of the melting curves represents an even more severe test of the goodness of the theories because it is necessary to compute both free energies and pressures accurately in both phases. However, to correctly calculate the shock wave data it was necessary to modify the Silvera–Goldman potential at small intermolecular separations. Their potential had been fitted to low temperature data for solids below 25 kbar and does not extrapolate correctly beyond that region. Shock wave data represent a much higher temperature phenomenon where the important interactions occur at small intermolecular separations. This new potential, combined with our fluid theory, now fits the shock data up to about 800 kbar and 7000 K as well as the lower temperature static isotherms. In addition the high temperatures generated in the shock process make it possible to determine the intermolecular potential as spacings comparable to those found in the molecular solid at densities believed to be near the metallic transition. These new theoretical results based on recent data do not differ substantially from the earlier work (Ross 1974). However, they have not yet been applied to a planetary modelling study.

Although metallic hydrogen has never been studied experimentally, extensive computer simulations for a model fluid have been made (Hubbard & Slattery 1971). The equation of state obtained with this model is probably sufficient for isentrope calculations but not for calculating phase transitions (McMahan & Ross 1976).

Using these theories we extended the melting curve of H_2 to pressures of a few megabars and computed the molecular–metallic phase transition by means of a previously published equation of state for the metal. We also approximated the melting curve of the metal by means of hard sphere perturbation theory. These results are included in figure 4 along with the experimental Hugoniots and planetary isentropes. The solid exists only at temperatures too low to be of any concern to planetary models. Most current estimates for the metal transition range from 2 to 5 Mbar. In figure 4 we placed it at the lower value. Phase transitions are perhaps the most difficult properties to calculate accurately as small deficiencies in the theory lead to large uncertainties in pressure. As a result such predictions can be very misleading if taken too seriously by the uninitiated.

One other possibility exists concerning the nature of the metallic transition, that it may not be first order, but is similar to the gradual molecular–metallic transition observed in diatomic iodine (Balchan & Drickamer 1961; Riggleman & Drickamer 1963; Takemura *et al.* 1979). As the pressure is increased the valence electrons in molecular iodine gradually occupy states in the unfilled conduction band leading to a transition continuous in density and pressure. Some preliminary theoretical calculations for a solid at 0 K indicate that this may be so in hydrogen (Ramaker *et al.* 1975; Friedli & Ashcroft 1977). These calculations show that the electron energy gap separating the filled valence band from the unfilled conduction band goes to zero near the volumes typically predicted for the metallic transition. This possibility would lead us to a phase diagram in which molecular hydrogen first changed to an electrically conducting form of the molecule and then at some higher pressure into a monatomic metal. Some indication that this might occur could be drawn from the results of Sharma *et al.* (1980). Using Raman spectroscopy these authors measured the molecular vibrational frequency under pressures of up to 600 kbar. They found that with increasing pressure the frequency increased as expected. But, above 300 kbar the frequency began decreasing. This could be interpreted as the gradual onset of intermolecular bonding. Even if a molecular conducting phase does not appear at low temperature and high density the electron energy gap will have narrowed sufficiently to permit thermal excitation of a significant number of electrons into the conduction band at planetary temperatures. Thus we expect the electrical conductivity along the isentropes to increase from insulator to semiconductor, to semi-metal and then to metal as indicated in figure 4.

All remarks concerning the metallic phase, here or elsewhere, must be viewed as speculation. At present no convincing experimental data exist for its properties or the pressure of its transition.

HELIUM

Static solid and fluid data similar to hydrogen are also available for helium. They include a 4 K isotherm to 25 kbar (Stewart 1956), fluid isotherms to 300 K and 20 kbar and a melting curve up to 115 kbar at room temperature (Mills *et al.* 1980*b*; Besson & Pinceaux 1979). In addition high energy molecular beam data (P. B. Foreman, A. B. Lees & P. K. Rol, personal communication 1979) provide information on the very short range pair interaction. At present there are no shock wave data. Unfortunately, for the material of interest, a mixture of H_2 and He, the only experimental data are for below 10 kbar (Streett 1973). Because of the highly disparate boiling points of H_2 and He, a mixture sample cannot easily be made for shock experiments and it is unlikely that such experiments will be done in the foreseeable future. However, shock results for He, with reasonable estimates of the H_2–He pair interaction, would provide important data for a theory of the molecular mixture.

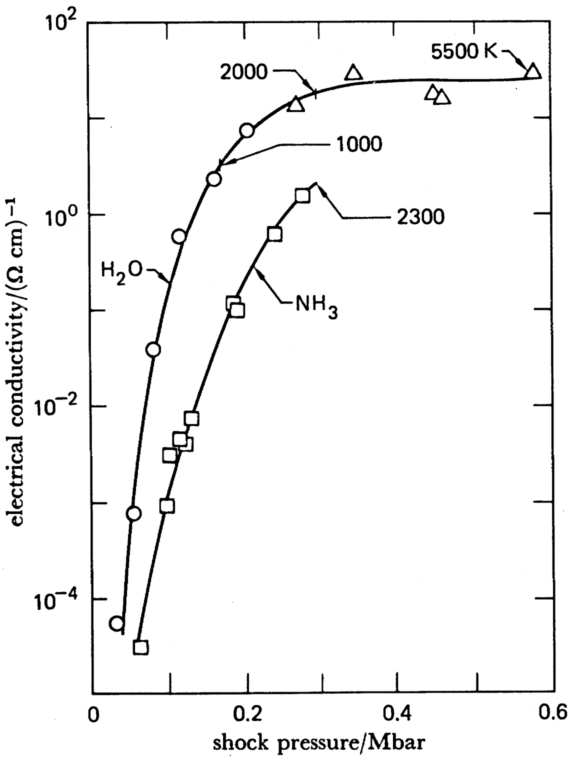

FIGURE 5. Measured electrical conductivities of H_2O and NH_3. Data of Hamann & Linton (1969) and Mitchell *et al.* (1980) for H_2O (△) and NH_3 (□). Shown also are temperatures (approximate) measured for H_2O (Lyzenga & Ahrens 1980) and calculated for NH_3 (Kovel 1973).

THE 'ICES'

The 'ices', H_2O, NH_3 and CH_4, constitute the middle layer in recently proposed three-layer models of Uranus and Neptune (Podolak & Cameron 1975; Hubbard & MacFarlane 1980). The calculated pressures and temperatures in these bodies vary from about 6 Mbar and 7000 K at the inner core–ice boundary, to about 0.2 Mbar and 2200 K at the outer H_2–He boundary. Shock data on these molecules, including electrical conductivities for H_2O and NH_3, have been measured over part of this range. Mitchell & Nellis (1979 and personal communication) compressed liquid H_2O up to 0.82 Mbar in a simple shock experiment, and up to 2.3 Mbar by reflexion. In a separate set of experiments G. Lyzenga *et al.* (personal communication, 1980) measured the temperature up to 0.82 Mbar. The new data result in an equation of state that is considerably softer than any previously used. This leads to evolutionary and structural planetary models for Uranus and Neptune (Hubbard & McFarlane 1980) that agree with observational data, with assumption of only approximate solar abundances of ice and rock.

The electrical conductivity is always of great interest because it can lead to the explanation or prediction of a magnetic field. At present there is one report of possible radio signals from Uranus (Brown 1976) and none from Neptune. Electrical conductivities in shock compressed water were first measured by Hamann & Linton (1969) up to 133 kbar (1.7 g/cm^3) and 1100 K. Recently Mitchell *et al.* (1980) extended these measurements to 590 kbar and 4200 K. Above about 200 kbar the conductivity becomes constant at about 20 to 30 $(\Omega\ \mathrm{cm})^{-1}$. These results are shown in figure 5 along with data for NH_3 to be discussed below. Clearly the processes leading to conductivity (molecular ionization) have become fully saturated. It is interesting to note that Hamann & Linton predicted these results from an analysis of their lower pressure data. They concluded that above 150 to 200 kbar water becomes fully ionized to H_3O^+ and OH^- and is then essentially a molten salt isoelectronic with NH_4F and NaOH. Similar results have been observed in NH_3, as shown in figure 5. Kovel (1973), using explosively driven shock waves investigated the P–V behaviour and electrical conductivity of liquid NH_3 in the pressure range 45 to 282 kbar, with temperatures from 600 to 2300 K. More recently Nellis & Mitchell (1980) extended this range to 630 kbar. The conductivity of NH_3 is always less than H_2O. This is to be expected since the dissociation constant of NH_3 is much smaller. We expect that in the limit of very high pressure the conductivities of the two will converge.

The experimental data for CH_4 are a principal Hugoniot up to 450 kbar and one point that was reflected from 230 to 910 kbar (Nellis *et al.* 1980). No electrical conductivity measurements were made. The theoretical predictions are in agreement up to 230 kbar ($T = 2300$ K) but become too high above this pressure (Ross & Ree 1980). Chemical equilibrium calculations show that above 200 kbar and 2000 K CH_4 is converted into elemental carbon (probably amorphous carbon or diamond powder) and molecular hydrogen. Recent theoretical calculations on Hugoniots of many hydrocarbons (Ree 1979) indicate that the shock heating induces C–H bond scission and that shock compression favours the dissociated carbon atoms to condense into some sort of residues. By considering the hydrocarbons to have been converted to a mixture of condensed carbon and H_2, and using the known equations of state of these materials, it has been possible to compute high density Hugoniots that are in excellent agreement with experiment. The results of similar calculation for CH_4 are also in agreement with the data. Under planetary conditions diamond or carbon residues should be a conducting liquid metal. They could be insoluble and form a separate phase or possibly a fourth layer. In the work of Hubbard & MacFarlane the mass of available carbon is an appreciable 17 % of the total.

To summarize, the results from the shock wave studies indicate that the ice layer in Uranus and Neptune should consist of material that is highly ionized and dissociated, and has an electrical conductivity at least of the order of 30 $(\Omega\ \mathrm{cm})^{-1}$. If sizeable amounts of liquid carbon aggregates are present then the conductivity would be higher.

Iron and the rocky core

The properties of iron, particularly its melting curve and electrical properties at high pressure, are of continuing interest. The equation of state and the electrical conductivities have been studied by shock wave methods. However, all efforts to detect melting have failed because the thermodynamic properties of iron at several megabars vary little in going from solid to liquid. Recently Brown & McQueen (1980) succeeded in measuring the sound velocity by a method sufficiently sensitive to detect changes that they believed must be due to melting. They report that iron melts at 2.5 ± 0.2 Mbar at a calculated temperature of about 5500–6000 K. This is in agreement with the range of predictions mainly based on the Lindemann theory. Before this, Mitchell & Keeler (1968) measured the electrical conductivity of iron to 1.4 Mbar and about 2500 K. Matassov (1977) studied some iron–silicon alloys and Royce (1967) investigated FeNi (20 % (by mass) Ni). The conductivity of these materials varies slowly with pressure and an extrapolation to the reported melting pressure is well within the limits required by dynamo theories for the Earth.

We have extrapolated these melting predictions to the core boundarys temperatures of Uranus, Neptune and Saturn. An extrapolation to Jupiter would be too extensive. We find that in the first two planets any iron is clearly in the solid phase while in Saturn it is very close to the melting line, and possibly liquid. Freezing would provide a mechanism that on evolutionary cooling could provide the additional energy release believed present in that planet and currently attributed to H–He immiscibility.

The modelling of candidate rock core components is more important for the smaller outer Solar System objects than for the giant planets, the rock fraction increasing from 4 % of total mass for Jupiter to perhaps 100 % for Io. Most planetry structural studies use Thomas–Fermi models to compute mixture properties. Hubbard & MacFarlane (1980) have shown that these models disagree completely with shock data for H_2O, and this will be true for all rock–ice systems. Grossman *et al.* (1980) have used high pressure shock data for Fe, Ni, MgO and SiO_2 to constrain empirical equation of state mixture models. Both these studies show that experimentally based equation of state models produce better agreement for planetary models than do the cruder, purely theoretical, models.

Discussion

One compelling feature that has followed from the use of improved equations of state based on shock data is a simplification in the planetary models. Earlier giant planet models, using less accurate equations of state, required assumptions of non-solar compositions, with excess helium, or excess H_2O or other ices being required to give structural models that match observations. With the new experiment-based thermodynamics, Jupiter can be modelled to match all observations in terms of a solar composition. Uranus and Neptune, with solar-composition ice and rock components, now match the observations. Only Saturn is anomalous at present, and the thermodynamics and solubility of H–He mixtures may hold the solution to this discrepancy. Further, there is an emerging consensus that a roughly comparable rock core exists in all the giant planets, arising from the use of improved equations of state.

In their review, Stevenson & Salpeter (1976) listed as the four primary theoretical priorities for modelling giant planet thermodynamics at high pressure and the metallic phase transition: dense H, H_2–He mixture thermodynamics and solubility of He in H; opacity of dense H_2; high pressure and temperature chemistry of core rock and ice components. The current experimental methods are making substantial progress in helping the theoretician and planetary physicist answer these questions.

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