Metallization and Electrical Conductivity of Hydrogen in Jupiter

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Electrical conductivities of molecular hydrogen in Jupiter were calculated by scaling electrical conductivities measured at shock pressures in the range of 10 to 180 gigapascals (0.1 to 1.8 megabars) and temperatures to 4000 kelvin, representative of conditions inside Jupiter. Jupiter's magnetic field is caused by convective dynamo motion of electrically conducting fluid hydrogen. The data imply that Jupiter should become metallic at 140 gigapascals in the fluid, and the electrical conductivity in the jovian molecular envelope at pressures up to metallization is about an order of magnitude larger than expected previously. The large magnetic field is produced in the molecular envelope closer to the surface than previously thought.

Jupiter is the largest planet in our solar system, composed primarily of H (90 atomic %) and He (~10%). Because of its large mass and low thermal conductivity, Jupiter's interior is at high pressures and high temperatures (*1–3*); the pressure and temperature at the center are about 4 TPa and 20,000 K, respectively (*4*). Internal temperatures are well above the calculated melting curve of hydrogen (*5*). Jupiter has an outer molecular hydrogen (H_2) envelope that transforms continuously to a monatomic metallic core, which means that Jupiter has no distinct core-mantle boundary (*6*). It also has the largest magnetic field, which varies from 14 G at the north magnetic pole to 3 G on the magnetic equator (*7*), compared with 0.5 G on Earth. Jupiter's magnetic dipole is 2×10^4 times that of Earth's (*8*).

The magnetic field is produced by the convective motion of electrically conducting hydrogen by dynamo action (*9*). On the basis of calculations of electrical conductivities of dense fluid hydrogen (*10–12*), the magnetic field has been thought to be produced primarily in the monatomic metallic core, as well as in the molecular mantle (*12–14*). However, the relative contribution of each region has been uncertain. Recent shock temperature measurements have led to another model for the pressures, densities, and temperatures in Jupiter (*6, 15*). Electrical conductivity measurements at pressures and temperatures up to 180 GPa and 4000 K have shown that at 140 GPa and 3000 K, hydrogen undergoes a continuous transition from a semiconducting to a metallic molecular fluid (*16*). Here, we derive a scaling relation for electrical conductivity and evaluate it as a function of pressure, density, and temperature in the interior of Jupiter.

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A two-stage, light-gas gun was used to generate high pressures and temperatures (*16, 17*). The technique that we used to measure electrical conductivity was similar to that used in shock temperature measurements (*6*). Highest pressures were achieved with a reverberating shock wave (*16*). Electrical conductivity increased almost four orders of magnitude from 93 to 140 GPa (3000 K) and was essentially constant at 2000 $(\text{ohm·cm})^{-1}$ from 140 to 180 GPa. An electrical conductivity of 2000 $(\text{ohm·cm})^{-1}$ is the same as that of metallic Cs and Rb in the expanded fluid at 2000 K (*18*), where, like hydrogen, these alkali metals undergo a continuous transition from semiconducting to metallic fluids. This agreement indicates that all three elements metallize when the mean free path of electrons becomes comparable with the mean distance between the particles providing the electrons. On the basis of a model for molecular dissociation derived from shock temperature measurements (*6, 15*), the calculated dissociation fraction in those conductivity experiments is 5% at metallization. Thus, electronic conduction in hydrogen is probably caused by electrons delocalized from H_2^+ ions (*19*). For hydrogen the calculated minimum electrical conductivity of a metal is given by (*20*) $\sigma = e^2/3\hbar a$, where e is the charge of an electron, $\hbar = h/2\pi$, (h is Planck's constant), and a is the average distance between particles; the calculated value is 4000 $(\text{ohm·cm})^{-1}$, in good agreement with the experimental value, 2000 $(\text{ohm·cm})^{-1}$. Because hydrogen in shock experiments is in thermal equilibrium (*6*), our conductivity results are applicable to the interior of Jupiter.

In a semiconducting fluid electrical conductivities fit the relation

$$\sigma = \sigma_0(\rho)\exp[-E_g(\rho)/2k_BT] \quad (1)$$

where σ is the electrical conductivity, σ_0 depends on density ρ, $E_g(\rho)$ is the density-dependent mobility gap in energy in the electronic density of states of the fluid, k_B is Boltzmann's constant, and T is temperature. The relation between energy gap E_g and density was derived from recently measured conductivities in two different density ranges (*16, 17*) (Fig. 1). The fit to the data is $E_g = 20.3\rho - 64.7\rho$ in the range $0.13 < \rho < 0.3$ mol cm^{-3} (E_g is in electron volts). Metallization occurs in the fluid at a density of 0.31 mol cm^{-3}, where the band gap is about equal to the temperature (*16*). The electrical conductivity in the metallic fluid is independent of density and temperature within the uncertainty in the measurement (*16*). Conductivities of metallic liquids are known to depend weakly on temperature and density. The prefactors σ_0 determined in the two sets of experiments reported in (*16, 17*) differ by 10^4 at densities of 0.13 and 0.30 mol cm^{-3} (the corresponding pressures differ by a factor of 10). We obtained values of σ_0 at intermediate densities by exponential interpolation of these data:

$$\sigma_0(\rho) = 3.4 \times 10^8 \exp[-44\rho] \quad (2)$$

Equation 2 fits the value of σ_0 determined at 0.13 mol cm^{-3} [1.1×10^6 $(\text{ohm·cm})^{-1}$] and is close to the value obtained near 0.3 mol cm^{-3} [1.4×10^2 $(\text{ohm·cm})^{-1}$], where hydrogen is undergoing a continuous transition from a semiconducting to a metallic fluid, and σ extrapolates to the metallic value of 2000 $(\text{ohm·cm})^{-1}$ at 140 GPa.

The electrical conductivity of monatomic metallic hydrogen was predicted theoretically to be higher, 1×10^5 to 2×10^5 $(\text{ohm·cm})^{-1}$ (*10, 11*), than measured, 2×10^3 $(\text{ohm·cm})^{-1}$, by Weir *et al.* (*16*) at the density and temperature at which they observed metallization (0.31 mol cm^{-3} and 3000 K). The metallic hydrogen conductivity predicted theoretically is expected to be accurate at higher densities above 0.5 mol cm^{-3} (*10, 11*) and is comparable with that of solid alkali metals at room temperature.

States of hydrogen in Jupiter were as-

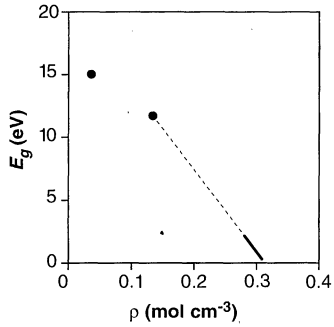

Fig. 1. Plot of the energy gap in the electronic density of states of fluid hydrogen versus molar density ρ. E_g at 0.04 mol cm^{-3} is the value at 1 bar; E_g at 0.13 mol cm^{-3} is from (*17*); the solid line near 0.30 mol cm^{-3} is from (*16*). The dashed line is the linear fit to E_g from (*16*) and (*17*).

sumed to be on an isentrope of hydrogen starting from the surface conditions of Jupiter, 165 K and 1 bar (6). Above 40 GPa this isentrope has a lower temperature than expected previously because internal energy is absorbed in molecular dissociation rather than heating. This dissociative transition from the molecular to the monatomic phase occurs continuously with increasing density at high temperatures. About 10% of the H_2 molecules are dissociated at metallization (4000 K) in Jupiter. Moreover, lower jovian temperatures throughout the interior have been predicted on the basis of a radiative window near the planet's surface (*21, 22*). To demonstrate that electrical conductivities were measured at pressures and temperatures representative of those in Jupiter, we plotted both the hydrogen isentrope (*6*) and the temperatures and pressures achieved in the electrical conductivity measurements (*16, 17*) in Fig. 2.

We calculated the electrical conductivity of hydrogen along the isentrope (Fig. 2) using Eqs. 1 and 2 and the density-dependent E_g (Fig. 1). In Fig. 3 the resulting conductivity is plotted versus pressure along this isentrope. The conductivity was calculated up to 120 GPa, where the electronic energy gap approaches the temperature on the isentrope, and was then extrapolated up to the metallic value of 2000 $(\text{ohm·cm})^{-1}$ at 140 GPa.

For comparison, we also calculated electrical conductivities in the molecular envelope of Jupiter (*12*) using Eq. 1 with $\sigma_0 = 300\ (\text{ohm·cm})^{-1}$, a value typical of a liquid semiconductor (*23*), and different relations of $E_g(\rho)$ at 0 K for H_2 calculated by Freidli and Ashcroft (FA) (*24*) and by Min *et al.* (M) (*25*), along an isentrope of hydrogen calculated by Saumon *et al.* (*26*). These two curves, FA and M (Fig. 3), can only be calculated up to 200 GPa where the temperature on the isentrope is equal to the band gap of the molecular phase. For pressures below 20 GPa, the values for all three models approach a common value (Fig. 3). For pressures above 40 GPa our calculated conductivities are one to two orders of magnitude greater than those calculated according to FA and M. There is no physically meaningful way at present to interpolate from FA and M at 200 GPa in the molecular phase up to the calculated value for the monatomic phase at 300 GPa, denoted as S in Fig. 3. Further theoretical results (*10, 11*) imply that the conductivity of monatomic metallic hydrogen at what was thought to be the core-mantle boundary—300 GPa, 0.65 mol cm^{-3}, and 10,000 K (*4*)—should be $10^5\ (\text{ohm·cm})^{-1}$ (S in Fig. 3).

The metallization pressure of 140 GPa in the fluid given by Weir *et al.* (*16*) is substantially lower than 300 GPa, the typical theoretical value for the solid at 0 K (*27, 28*). This lower pressure implies that hydrogen in Jupiter becomes metallic at about 0.9 of the radius, as predicted by Smoluchowski (*13*), rather than at about 0.8 of the radius for 300 GPa. The measured metallic conductivity is also lower than predicted (*10, 11*). An electrical conductivity as low as 20 $(\text{ohm·cm})^{-1}$ might contribute to the magnetic field of Jupiter because a conductivity of this value is thought to be responsible for producing the magnetic fields of Uranus and Neptune (*29*). A conductivity of 20 $(\text{ohm·cm})^{-1}$ is achieved in Jupiter at 80 GPa (Fig. 3). For these reasons, the external magnetic field of Jupiter would be produced in the molecular envelope substantially closer to the surface, with a metallic conductivity about two orders of magnitude smaller than previously thought.

The above results imply that the magnetic field of Jupiter is produced in the region in which fluid H_2 undergoes a continuous dissociative phase transition. Using the theoretical model for molecular dissociation derived from shock temperature experiments (*15*), we calculate that about 10% of the H_2 molecules are dissociated at metallization in Jupiter (140 GPa and 4000 K). Once hydrogen metallizes, additional changes in electrical conductivity caused by the continuous molecular transition to complete dissociation at higher pressures are expected to be relatively small for an additional two- to threefold increase in pressure. That is, the increase in the electrical conductivity is dominated by the increase in the number of conduction electrons. Once they are all excited to form a metal, further changes in conductivity are expected to be relatively small (about a factor of 2) as density and temperature increase somewhat with an increase in pressure and depth. The sizes of the hydrogen molecule and atom and their initial electronic energy gaps are similar, which suggests that in the mixed-phase regime the two are mutually soluble and form a common mobility gap in their electronic density of states, so that in the regime up to two to three times the observed metallization pressure, the electrical conductivity is about 2000 $(\text{ohm·cm})^{-1}$. At higher pressures and temperatures, at which molecular dissociation becomes complete, we expect the pure monatomic phase to form a metallic plasma (*30*), and we expect the higher conductivity predicted for that state (*10, 11*) to be the case. However, the external magnetic field is caused primarily by a conductivity of about 2000 $(\text{ohm·cm})^{-1}$ in the outermost portion of Jupiter.

It is likely that small amounts of He, the ices, and rock contribute less than 1% to the electrical conductivity in the outermost portion of Jupiter. The electrical conductivities are ionic in the case of the ices and rock. In He the conductivity is electronic but is caused by an electronic band gap larger than that of hydrogen. In addition, the He concentration (~10 atomic % total) is too small to affect the conductivity if the He atoms are in solution and would produce at most a tiny filamentary percolation path if the He atoms phase-separate. These materials would be a small, electrically inert volume fraction within the hydrogen.

It is unlikely that the slope of temperature with pressure of the hydrogen-He mixture is negative, as suggested by Fig. 2 for hydrogen, at least not over an appreciable radial thickness. Helium has a substantially higher temperature than does hydrogen at the same pressure and density because monatomic He cannot absorb internal energy in excited molecular vibrational states; nor

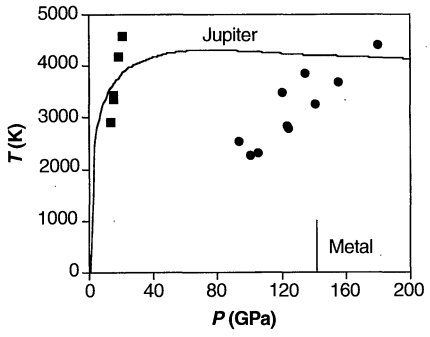

Fig. 2. The solid curve is the isentrope of hydrogen calculated from surface conditions of Jupiter (165 K and 1 bar) plotted as temperature versus pressure (*6*). Circles (*16*) and squares (*17*) represent values for temperatures and pressures at which electrical conductivities have been measured. Metallization of hydrogen in Jupiter occurs at 140 GPa (1.4 Mbar).

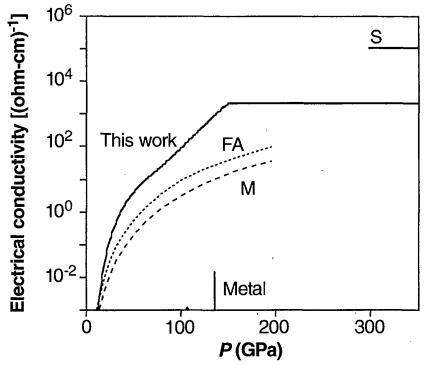

Fig. 3. Electrical conductivities of hydrogen plotted versus pressure along isentropes of hydrogen with an initial temperature of 165 K calculated here and with energy gaps from (*24*) (FA) and (*25*) (M) with an isentrope from (*26*). The theoretical conductivity of the monatomic metallic core (S) was calculated from (*10*) and (*11*).

does He absorb significant internal energy in electronic excitations because its band gap is large compared with the temperature at relevant densities. Thus, He has a positive definite rate of increase of temperature with pressure, which most likely causes a positive total slope of temperature with pressure for the hydrogen-He mixture. In the metallic molecular fluid at 140 GPa and above, temperature variations have a weak effect on the electrical conductivity. In the semiconducting fluid at pressures P of 60 to 140 GPa, only a ~2% increase in temperature is sufficient to increase dT/dP from slightly negative for hydrogen (Fig. 2) to slightly positive for the hydrogen-He mixture. The latter is likely the case because Jupiter contains ~10 atomic % He. Temperature differences of a few percent have a negligible effect on the calculated conductivities (Fig. 3). Thus, the conductivities calculated here are consistent with a positive slope of dT/dP in Jupiter. To produce convection, dT/dP must be positive so that the volume coefficient of thermal expansion is also positive. Jupiter is known to be convective over most of its volume because it has a large external magnetic field. In addition, convective heat transfer to the surface is substantial and is the reason why Jupiter radiates more internal energy than it receives from the sun (*11*). It is possible, however, that Jupiter is convectively quiescent over a radially thin region (6).

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Short-Period Comets: Primordial Bodies or Collisional Fragments?

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Modeling results show that collisions among Edgeworth-Kuiper Belt Objects (EKOs), a vast swarm of small bodies orbiting beyond Neptune, have been a major process affecting this population and its progeny, the short-period comets. Most EKOs larger than about 100 kilometers in diameter survive over the age of the solar system, but at smaller sizes collisional breakup is frequent, producing a cascade of fragments having a power law size-frequency distribution. Collisions are also a plausible mechanism for injecting EKOs 1 to 10 kilometers in diameter into dynamical resonances, where they can be transported into the inner solar system to become short-period comets. The fragmental nature of these comets may explain their physical properties, such as shape, color, and strength.

Comets were recognized as visitors from the outer periphery of the solar system almost half a century ago. Long-period ($P >$ 200 years) comets come from the nearly isotropic Oort cloud, tens of thousands of astronomical units (AU) from the Sun, whereas short-period comets may be derived from the transneptunian, flattened Edgeworth-Kuiper (E-K) Belt, at semimajor axes starting at about 35 AU and extending to 50 AU or beyond (*1*). These two different sources explain the different dynamical features of the two types of comets, in particular the much lower typical inclinations of the short-period group (*2*). Also, both types are plausible remnants of the accumulation of planetesimals in the outer regions of the primordial solar nebula (*3*). As a consequence, comets were considered to be the most primitive small bodies in the solar system: planetesimals from the giant planet zone that have never undergone the thermal and collisional processing that is typical of planets, satellites, and asteroids. This paradigm has been the basis for most recent studies on the structure of comet nuclei and their physical properties (*4*). However, we believe that the primitiveness paradigm is unwarranted for short-period comets derived from the transneptunian region, because significant collisional processing takes place there.

The discovery of the transneptunian object 1992 QB_1 and its successors (*5*) has confirmed the earlier theoretical evidence for a population of bodies beyond the giant planets. By early 1996, 32 objects had been discovered in this zone (besides the Pluto-Charon system). These objects are between 100 and 350 km in diameter, assuming a geometric albedo of 0.04. The total population of EKOs is estimated at (1 to 3) $\times$ 10^4, with diameters between ≈100 and 400 km at distances of 35 to 50 AU from the Sun, based on the total area searched to date. The distribution of eccentricities and inclinations is poorly known, but average values are probably low (≈0.05 for eccentricities and several degrees for inclinations) if the orbits are to be stable over the age of the solar system (6). An even more numerous population (at least ≈10^8 bodies) at diameters of about 20 km is probably present in the same zone, on the basis of results of recent Hubble Space Telescope

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