Magnetic fields of Uranus and Neptune: Metallic fluid hydrogen

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Abstract. The unusual magnetic fields of Uranus and Neptune (U/N) have been a major scientific issue since their discovery in the 1980s. Based on an extensive database of planetary fluids measured under dynamic compression at pressures and temperatures up to 200 GPa and a few 1000 K, the complex magnetic fields of U/N are made primarily by dynamo convection of metallic fluid hydrogen (MFH) near crossovers from their H-He envelopes to “Ice” cores at ~100 GPa pressures at ~90% of radii of U/N. Because those fields are made close to outer surfaces, non-dipolar magnetic fields can be expected. “Ice” cores are heterogeneous fluid mixtures of nebular Ice and Rock that accreted, sank below the H-He envelopes into the cores, decomposed at high pressures and temperatures and formed new chemical species. Such complex mixtures are expected to have many nucleation sites for convection. Rotational and effective dipolar axes probably have large relative tilts because rotational motions of U/N are weakly coupled to convective motions that make their magnetic fields. “Polar wander” is probably a better descriptor for variations of magnetic field over time than “polar reversal” as for Earth. There is probably little “Ice” in the Ice Giants.

1. Introduction
Dynamic compression achieves extreme pressures P and temperatures T in fluids in the Giant Planets. In the 1970s the Voyager 2 spacecraft departed Earth to visit the Giant Gas Planets Jupiter, Saturn and then on for flybys of the Giant Ice Planets Uranus and Neptune (U/N) [1]. U/N are expected to contain substantial amounts of “ices” H2O, NH3, CH4 etc. Dynamic compression experiments on planetary fluids have been performed intermittently for almost 30 years at the two-stage gun (2SG) at Lawrence Livermore National Laboratory (LLNL). Those experimental measurements are an extensive database for models of interiors of Giant Planets. Metallic fluid H (MFH) is of particular importance because dominant contributions to the unusual fields of U/N are probably made near boundary regions between their Gas envelopes and “Ice” cores at ~100 GPa pressures.

NASAs Voyager 2 spacecraft discovered the non-dipolar and non-axisymmetric magnetic fields of Uranus and Neptune (U/N) in the 1980’s [1]. Those fields are made primarily by degenerate, metallic, fluid H (MFH) [2,3] and are ~2×10^{-5} Tesla [4], comparable to Earth’s. If the measured fields of U/N are force-fit to effective dipolar fields, the effective magnetic axes are tilted 59° and 47° from their respective rotational axes and the effective dipole centers are offset by ~0.33 R_U and ~0.55 R_N, respectively, from the physical centers of U and N. Those fields are illustrated in figure 1. The magnetic fields of Earth, Saturn, Jupiter and its moon Ganymede are dipolar with their magnetic axes aligned within ~10 degrees of their respective rotational axes.
The cause of the non-dipolar non-axisymmetric magnetic fields of U/N has been a major scientific question for decades. Planetary fields are made by dynamos: convection of electrically conducting fluids across lines of magnetic flux [5]. Pressures and temperatures in U/N range up to ~700 GPa and 7000 K near their centers [6,7]. Dynamic compression with a 2SG achieves pressures up to ~300 GPa and several 1000 K, conditions at which the external magnetic fields of U/N are made.

2. Chemical compositions and properties
U/N have similar sizes, densities, magnetic and gravitational fields and probably chemical compositions, although exact compositions are unknown. U/N are composed of [8-10]: (i) Gas, an H-rich mixture of H and He, (ii) Ice, a mixture primarily of H₂O, CH₄, and NH₃, and (iii) Rock, a mix of silicates and Fe/Ni. H and He have solar abundances of about 92 at.% and 7 at.%, respectively [11]. In space “icy” compounds are “nebular”. U/N have masses 14.5 and 17.2 Mₑ, respectively, where Mₑ is mass of Earth. Total mass of the Giant Planets Jupiter, Saturn, Uranus and Neptune is 445 Mₑ. Total mass of the Rocky Planets Earth, Venus, Mars and Mercury is 2.0 Mₑ. Most mass of the solar system is MFH. Experiments on planetary fluids began when Voyager 2 departed Saturn for U/N [12,13].

3. Dynamic compression experiments
The vast majority of measured properties of fluids at high planetary P/Ts have been made under dynamic compression. MFH has been made by impact of a plate onto a cryogenic sample holder containing liquid H₂ or D₂ at 20 K. The impactor was accelerated to velocities as high as 7 km/s with a 2SG and to higher velocities in four experiments at Sandia National Laboratories Albuquerque (SNLA). H₂ samples in the 2SG experiments were 25 mm in diameter and 0.5 mm or more thick.

Historically dynamic compression has been achieved by a single step-increase in pressure that rises in ~ps and ~nm. The sharp rise is called the front of a shock wave, which travels at supersonic velocity in the medium ahead of the front. Supersonic velocity causes the front to “snow-plow” material ahead of it, which compresses rapidly and adiabatically generating dissipation as T and entropy S. Recently, higher density ρ and lower T have been achieved by quasi-isentropic (QI) compression by tailoring rise time of the wave front to be longer than that of a shock [14]. An isentrope is the limit of a large number of weak shocks [15].

Pressure tuning is illustrated in figure 2. A Hugoniot is the locus of points along the pressure-density curve in right panel, each point of which is achieved by a single jump from given initial pressure to a higher pressure. Multiple shocks lengthen time to achieve maximum pressure, as illustrated in the left panel. A ramp wave (not shown) increases pressure continuously from zero or a relatively small initial shock pressure. The effect of a ramp is similar to that of multiple-shocks.
Multiple-shock (MS) compression of liquid H₂ was achieved in the holder in figure 3 to achieve MFH at 140 GPa. Liquid H₂ was contained between two disks of sapphire (single-crystal Al₂O₃). This assembly is a cylindrically symmetric Al cryostat (liquid-H₂ coolant chambers not shown). Two current and two voltage probes are inserted from the right side of the sample holder. Photographs of the facility and sample holder are published [16]. Right panel in figure 3 indicates more than 8 shocks reverberated in liquid H₂ to make MFH. Model calculations with ideal-gas EOS [17] show 9 shocks produce an isentrope starting from the first shock state on the Hugoniot up to maximum pressure. That is, the calculated MS P(t) curve in figure 3 produces the corresponding MS P(ρ) curve in figure 2.

![Graph](image)

Figure 2. Illustration of affect on pressure-density states achieved by sharp jump to Hugoniot pressure versus multiple shocks to same final pressure. Dotted horizontal lines are same Hugoniot pressure in both figures.

Figure 3. Experiment to measure conductivity of MFH at pressures P_f. Sample is liquid H₂ at 20 K. Impactor launched by 2SG is about to impact sample holder. Right: calculated pressure history of shock reverberations at midpoint of liquid H₂ layer made in place by condensing H₂ gas. Copyright 1999 by the American Physical Society.

4. **Hydrogen: Two-stage light-gas gun**

The advantage of measuring the pressure dependence of electrical conductivities of fluid H is their values and radial dependences in U/N are known to estimate the radial positions in U/N at which their external magnetic fields are made. MFH is degenerate condensed matter with T/T_F<<1, where T_F is Fermi temperature. At final temperatures of ~2000 K quantum differences between fluid H and D are negligible. However, different ρ and T are achieved because quantum differences at 20 K between H₂ and D₂ cause different initial number densities. Hydrogen samples “rang-up” to maximum pressure P_i in Al₂O₃ in each of ten experiments in ~100 ns [18-21]. P_f in each experiment was determined experimentally by measuring impactor velocity and determining P_f with shock-impedance matching [20]. Measured electrical resistivities versus P_f are plotted in figure 4. Conductivity reaches that of MFH (~2000/(Ω·cm)) at 140 GPa, 0.64 mol H/cm³ (9-fold compressed H density in liquid H₂), ~2600
K and $T_F = 220,000$ K. This density of MFH is essentially metallization density predicted by WH, 0.62 mol H/cm$^3$ [22]. Similar hydrogen conductivities were measured by Fortov et al [23].

Measured resistivities of fluid H in figure 4 indicate a semiconductor from 93 GPa to 140 GPa, above which conductivity is $\sim 2000/(\Omega \cdot \text{cm})$, typical of strong-scattering metals with minimum metallic conductivity (MMC). Metallization density $\rho_{\text{met}}$ was chosen simply as the density at which mobility gap $E_{\text{gap}}(\rho) \to k_B T$, where $k_B$ is Boltzmann’s constant. Mobility gap $E_{\text{gap}}(\rho)$ was obtained by fitting measured conductivities to the standard expression for a thermally activated semiconductor. $E_{\text{gap}}(\rho)$ was assumed linear between 90 GPa and 124 GPa, a range away from the nonmetal-metal transition at 140 GPa in which values of $E_{\text{gap}}(\rho)$ are positive. MFH is probably monatomic [14].

Figure 4. Measured electrical resistivities of fluid D and H versus multiple-shock pressure $P_f$ determined experimentally by shock-impedance matching in each of 10 experiments. Copyright 1999 by the American Physical Society.

Because neither $\rho$ nor $T$ could be measured, they were calculated with an EOS of D$_2$/H$_2$ developed with a substantial body of previously measured experimental data. The initial shock in each reverberation is on the Hugoniot. The EOS was derived with: (i) measured Hugoniot data [24], (ii) measured single (Hugoniot)- and double-shock temperatures [25] and (iii) peak pressure in hydrogen obtained experimentally by shock-impedance matching each conductivity experiment [20]. 40% of each calculated temperature was caused by measured Hugoniot temperatures [25]. To determine systematic sensitivity of $\rho_{\text{met}}$ to hydrogen EOS, a second EOS developed by Kerley was also used to calculate $\rho_{\text{met}}$. Two values of $\rho_{\text{met}}$ using both sets of $(\rho,T)$ values were determined from $E_{\text{gap}}(\rho_{\text{met}}) \approx k_B T$. Although ten values of $E_{\text{gap}}(\rho)$ differ by $\sim 20\%$ between the two EOS models, the two $\rho_{\text{met}}$ values differ by 2%, sufficient to determine $\rho_{\text{met}} = 0.64$ mol H/cm$^3$ [20].

5. Wigner and Huntington’s prediction
In 1935 Wigner and Huntington (WH) predicted the density of a first-order dissociative transition from insulating H$_2$ to metallic H at density $\rho_{\text{met}}=0.62$ mole H/cm$^3$ [22] at which static pressure is 73 GPa at 300 K [26]. A metallic solid phase of H$_2$ has yet to be observed at static pressures approaching the 400 GPa range. In contrast dynamic compression deposits sufficient T and S to dissociate H$_2$ to H in a cross over that completes at WH’s predicted metallic density by overlap of 1s$^1$ wave functions on adjacent atoms at temperatures cold enough to make degenerate condensed matter ($T<<T_F$) [27].

6. Deuterium: Z Accelerator
Liquid D$_2$ has been compressed quasi-isentropically in two stages by current-generated magnetic pressure in 4 experiments at the Z Accelerator [28]. The first stage generated three shocks by reverberation in liquid-D$_2$. The second stage then drove a ramp wave that compressed deuterium
isentropically up to ~300 GPa at temperatures in the range 800 K to 1700 K. Diagnostics were optical VISAR signals to measure velocity histories v(t), which were used to derive P(t) in deuterium that generated v(t), using a hydrodynamic computer code. ρ(t) and T(t) were calculated theoretically. Calculated Ts were nearly constant between 150 GPa and 300 GPa, a surprising and unusual observation that warrants temperature measurements. Despite this unusual reported behavior of T(P), no experimental or systematic uncertainties in P and T are given. Reflectivities were measured up to ~300 GPa at which reflectivity of fluid D increases abruptly to ~45%, which suggests an electrical conductivity of a few 10^5 S/m, as measured for MFH with a 2SG. This Z transition at 300 GPa is claimed to be first-order at substantial finite temperatures. Other transitions of fluid hydrogen achieved under dynamic compression are observed as crossovers at finite temperatures. The nature of this transition at 300 GPa needs to be determined experimentally. For example, could this observation of transparency be caused by dynamics of the longitudinal density distribution of fluid D, its corresponding longitudinal distribution of optical depth and the bright illumination laser used in the reflectivity measurement? D reflectivity decreases rapidly by orders of magnitude below the transition.

H densities are greater than 1.0 mol H/cm^3 at 300 GPa, factors of ~2 and ~60% greater than P and ρ on completion of the crossover at 140 GPa at the 2SG. These substantial differences indicate the transitions in the Z and 2SG experiments are different transitions. Agreement in metallic H conductivities in both experiments implies both measured strong-scattering MMCs. The P/T states of the Z experiments are sufficiently below estimates of T(P) adiabats of Giant Planets that the transition observed at Z probably makes negligible contribution to external magnetic fields of the Giant Planets.

7. Ices: Two-stage light-gas gun

Experiments have been performed on many small-molecular liquids under single- and multiple-shock compression [16]. Multiple-shock compression achieves relatively high pressures, densities and low temperatures with respect to single-shock compression [14]. Trends in those measurements are used as a basis for speculation on the nature of the interiors of UN, which might produce their unusual magnetic fields. Liquids investigated under multiple-shock compression include H_2/D_2 [19-21], O_2 [29,30], N_2 [30], H_2O [31,32], and Synthetic Uranus (SU) [7]. SU is a single-phase liquid mixture of polar molecules H_2O, NH_3, and C_3H_8O (isopropanol). Liquids investigated under single-shock compression include He [33], H_2/D_2 [24,25,34-37], N_2 [38-41], O_2 [38,42], CO [43], CO_2 [44], air [44] CH_4 [43,45-47], NH_3 [13,46], H_2O [13,48,49], C_6H_6 [50,51], CH_3 [47, 50] and SU [52]. Measured properties indicate small-molecular fluids decompose below ~100 GPa and a few 1000 K. Measured electrical conductivities of liquid H_2, N_2, O_2 and H_2O under QI multiple-shock compression are plotted in Fig. 5. Conductivity of SU is within a factor of 2 of that of H_2O [7]. Conductivity curves of fluid H, N and O are similar because they are dominated by disorder scattering, which depends weakly on element. Figure 5 implies MFH, N, and O have similar electronic structures and are mutually soluble. Chemical ionization of H_2O causes positive protons to dominate conductivity below ~30 GPa. At higher pressures it appears electron carriers delocalize from OH^- ions with increasing pressure, which causes electrical conductivity to increase slowly with increasing pressure. Thus, once accreted, nebular molecules sink to depths in the Cores and decomposed nebular molecules re-react to form new chemical species. Also at depths in UN at pressures above ~300 GPa most species might be monatomic because ρ and T might be too high for chemical bonds to exist.
8. Planetary fluids: Static compression

Using a pulsed-heating technique Deemyad and Silvera measured melting temperatures of hydrogen in the pressure range 50 to 80 GPa with a maximum of 1050 K at 65 GPa [53]. Dzyabura et al. achieved pressures and temperatures in the ranges 1000 K to 1700 K at 119 GPa and 900 K to 1500 K at 125 GPa [54]. Those states are comparable to semiconducting ones under dynamic compression [20]. The melting curve of water ice has been measured in the range 20-90 GPa with melt temperatures between 1000 K and 2400 K [55]. Melting temperatures of water have also been measured at lower pressures as well [56,57]. Chemically ionized H₂O is observed up to 56 GPa and 1500 K [58]. Decomposition and reaction of ices to form new species have been observed with spectroscopic measurements in NH₃ [59] and CH₄ [60] at P/Ts up to 60 GPa and 2500 K and 80 GPa and 2000 K, respectively.

9. Interior picture of Uranus and Neptune

Voyager 2 measured gravitational moments, which lead to radial density distributions [61]. This process depends on the EOS of fluids in U/N with large systematic errors. Densities increase from zero at \( R_U/R_N \) up to \( \sim 0.6 \text{ g/cm}^3 \) at radii of \( \sim 90\% \, R_U/R_N \). Densities then increase to \( \sim 4-5 \text{ g/cm}^3 \) near planetary centers. Lighter outer regions are Gas envelopes; heavier inner regions are Ice/Rock cores. Measured pressure dependence of electrical conductivities of fluid H suggest radii at which fields are made, which suggests a likely explanation for the shapes of those fields. At depths below H-rich envelopes, details of P/Ts of whichever nebular molecules accreted and decomposed to form U/N are not needed to conclude that resulting mixtures probably make relatively small contributions to the planetary fields, which are coupled weakly to dominant contributions made by convection of MFH.

Conductivities of fluid H at 93 GPa and \( \sim 1500 \text{ K} \) reach 2000/(\( \Omega \)-cm) at 140 GPa, 0.64 g/cm³ and \( \sim 2600 \text{ K} \). 2000/(\( \Omega \)-cm) is 100 times larger than 20/(\( \Omega \)-cm) measured for “Ices” and thought to cause magnetic fields of U/N prior to Voyager 2 [62]. The crossover in fluid H to MFH probably occurs in P/T intervals as much as \( \sim 100 \text{ GPa} \) and \( \sim 1500 \text{ K} \). Because gravitational moments are delocalized constraints and although 0.6 g/cm³ [61] might be caused by Gas mixed with Rock, it is reasonable to expect that at 0.6 g/cm³ in H-rich U/N pressure is \( \sim 100 \text{ GPa} \) near bottoms of envelopes and tops of cores. A similar estimate is based on measurements at static pressures. At 0.6 g/cm³, pressure of solid H₂ is 73 GPa [26]. At \( \sim 2000 \text{ K} \) H₂ is dissociated or nearly so, which means more particles to increase thermal pressure caused by temperatures up to \( \sim 3000 \text{ K} \). Decomposed “Ice” probably has substantial fractions of MFH, which likely exists in cores out to \( \sim 0.9 \, R_U \). Unreacted N and O formed on decomposition of Ices are probably soluble in MFH. Dynamos probably make dominant contributions to the magnetic fields by convection of fluid H from lower envelopes down into outer cores.
Voyager 2 implies the fields of U/N are made relatively close to their outer surfaces [63,64]. A dipolar field falls off with distance r as 1/r^3. Multi-polar fields fall off faster than 1/r^3 and are more likely to be observed if made relatively close to outer surfaces. Fields of U/N are probably made at radii as large as ~0.9 R_U/R_N. Earth’s dipolar field is made in convecting fluid Fe outer core at ~0.5 R_E.

A clue to finding the cause of non-axisymmetric fields of U/N is why Earth’s field is axisymmetric. Small deviations from axial symmetry might be caused by fluctuations in convective flows that generates Earth’s magnetic field, which is not perfectly dipolar, and its dipole axis wanders over time and periodically magnetic North and South poles reverse in times short compared to times dipole axis points North or South [65]. Because rotational motion (RM) of Earth is strongly coupled into convective dynamo (CD) motions of its fluid-Fe outer core, planetary R-M stabilizes convective motions that generate a dipolar magnetic field. If a convective fluctuation occurs which tends to destabilize a given dipolar axis, then strong RM-CD coupling either drives convective motions that essentially restore the initial orientation or CD fluctuations that drive the initial magnetic axes out of orientational equilibrium are so strong that RM-CD coupling eventually drives the dipolar axis into an alignment anti-parallel to its initial one.

Recent analysis of deep-Earth seismic signals supports this picture. Earth has a strong, solid mantle that rotates with constant angular velocity, except that strong RM-CD coupling causes tiny variations in the length of a day observed for 130 years. Possible interactions mechanisms that cause field reversal include surface roughness of ~0.5 km on inner radius (~3500 km) of Earth’s mantle [66].

U/N do not have solid mantles to strongly influence convective fluid motions in their cores and thus magnetic fields. Fluid H-He envelopes have little strength. However, complex fluid mixtures in the cores of U/N are probably heterogeneous [3], implying relatively active convective cores, with many nucleation sites for convection. Thus local convective dynamo motions of fluids that produce the magnetic fields are essentially decoupled from global rotational motions, as is implied by Fig. 1. The dynamos of U/N would then be relatively free to wander as local convective fluctuations dictate. Thus, tilt angles and center-offsets of their fields would vary slowly over the age of the Solar System. “Polar wander” is probably a better term for the magnetic fields of U/N than “polar reversal” for Earth.

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