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Unusual Magnetic Fields of Neptune and Uranus

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Abstract

A large database has been measured for likely fluids in Uranus and Neptune (U/N) at pressures and temperatures up to 180 GPa and a few 1000 K. Those data yield an explanation of why magnetic fields of U/N and Earth are so different. Fields of U/N are made at 90% of their outer radii and thus have non-dipolar contributions. Earth has a strong rotating rock mantle that couples its rotation into its Fe-rich fluid outer core. In contrast Uranus and Neptune have no such mechanism and so magnetic field geometries of U/N are free to wander unconstrained.

1. Introduction

NASA's Voyager 2 spacecraft flew by Uranus and Neptune (U/N) and measured their magnetic and gravitational fields [1]. The gravity data detected two layers in each, a low-density envelop composed mostly of H and He and a high density core [2] composed of planetary "Ice", a fluid mostly of H_2O, NH_3, and CH_4, plus Rock. Magnetic-field intensities of U/N are comparable to Earth's. Spatial dependences of those fields are non-dipolar and non-axisymmetric, unlike Earth's nearly dipolar and nearly axisymmetric magnetic field.

If the measured magnetic fields of U/N are force-fit to dipoles, those effective magnetic axes are tilted 59^0 and 47^0 from their respective rotational axes and their effective dipole centers are offset by 33% and 55% of their respective radii. The reason why magnetic fields of Earth and of U/N differ so greatly has been a major unresolved question. The purpose of this paper is to report a model based on experimental data measured on Earth and Voyager 2 observations, which provides a likely explanation of why those planetary field geometries are so different.

2. Basic Ideas

Planetary magnetic fields are made by dynamos: convective paths of electrically conducting fluids across lines of magnetic force. To determine why magnetic fields are as they are, one needs to consider measured electrical conductivities and equations of state of likely constituent fluids at pressures P and temperatures T at which planetary magnetic fields are made and likely coupling mechanisms between layers of materials that might affect convective flows. An extensive experimental database for fluid H_2, O_2, N_2, H_2O, NH_3, CH_4, the "Icy" mixture Synthetic Uranus, CO, CO_2, and several hydrocarbons has been *measured* up to P and T of 180 GPa (1.8×10^6 bar) and several 1000 K under dynamic compression with experimental lifetimes of 100 ns, more than sufficient to obtain thermal equilibrium in dense fluids [3,4]

Those dynamic compression results were measured at Lawrence Livermore National Laboratory, starting in 1980 when Voyager 2 headed for U/N on departing Saturn. Extreme P/Ts were generated by impact at velocities up to 7 km/s generated with a two-stage gas gun. Liquid samples were contained in small cryostats at 20 K for liquid H_2, for example. Measured electrical conductivities indicate fluid H is semiconducting from 93 to 140 GPa and a poor metal from 140 to 180 GPa with electrical conductivity of 2000/(ohm-cm). Corresponding calculated Ts range from 1700 to 2600 K at pressures from 93 to 140 GPa and then up to 2900 K at 180 GPa [5]. "Icy" molecules that accrete during formation of U/N decompose at high interior P/T above ~100 GPa.

The facts that the magnetic field of Earth is dipolar and nearly aligned with its axis of rotation and that the magnetic fields of U/N are neither implies that Earth's field is made primarily by convective loops strongly coupled to planetary rotation; the convective loops of U/N are virtually decoupled from planetary rotation. The dipolar field of Earth implies its external magnetic field is made deep in that planet [6]; Fe-rich convecting fluid extends only up to the Core-Mantle Boundary (CMB) at half the outer radius of Earth. Because dense conducting fluid H is a good electrical conductor above 90 GPa at about 90% the outer radii of U/N, the external magnetic fields of U/N are made relatively close to their outer surfaces. Thus, their magnetic fields are expected to have non-dipolar contributions [6] as observed.

The coupling of Earth's Fe-rich fluid outer core to Earth's rotation has been demonstrated by Hide et al [7]. Small decay of the length of a day over 150 years can be understood by an interaction at the CMB. Earth has a strong, rock mantle that rotates at nearly constant angular velocity, which is expected to form current loops in convecting Fe-rich fluid such that Earth's magnetization is generated to nearly align itself along its rotational axis. Several possible interactions might cause coupling between Earth's strong, rock mantle across its relatively sharp CMB, one of which is an estimated surface roughness of less than 0.5 km on the inner radius of the Earth's mantle (3500 km) [7].

Tendency for Earth's magnetic field to orient along its axis of rotation derives from the fact that potential energy of interaction between magnetization M produced by current flowing in a loop in an external magnetic field B is minimized when M and B point in the same direction. For a spherical ensemble of convective loops rotating at constant angular velocity about an axis of rotation, magnetic field at any one loop is the vector sum of magnetic fields produced by all the other convective loops.

U/N have weak fluid H-He envelops and weak fluid cores. In this case convective dynamo motions are expected to be weakly coupled to global rotational motions of U/N. Thus, the dynamos of U/N would be relatively free to wander as local conditions dictate. In this case effective tilt angles and effective center-offsets of their magnetic fields would be expected to vary slowly and unconstrained over the age of the Solar System. "Polar wander" is a good descriptor for the time dependence of magnetic fields of U/N.

3. Summary and Conclusions

Based on a substantial database measured over three decades for numerous representative planetary fluids at high *P/T* generated with a two-stage light-gas gun, the non-dipolar non-axisymmetric magnetic fields of Uranus and Neptune are (i) made primarily by degenerate metallic fluid H (MFH) at or near crossovers from H-He envelopes to "Ice" cores at ~100 GPa (Mbar) pressures and ~90% the radii of U/N; (ii) numerous likely planetary fluids investigated experimentally decompose at *P*/*T* above ~100 GPa or less and few 1000 K; (iii) thus there probably is little molecular nebular "Ice" in the Ice Giants; (iv) electrical conductivity of MFH is up to a factor of 100 larger than conductivity of "Ices" thought previously to make the magnetic fields of U/N (20/(ohm-cm) [8]); (v) because those magnetic fields are made close to outer surfaces, non-dipolar magnetic fields can be expected as observed; (vi) "Ice" cores are a heterogeneous mixture of nebular Ice and Rock that accreted, sank below the H-He envelopes into the cores in which nebular materials decomposed at high *P/T* and probably re-reacted to form new chemical species; (vii) those magnetic fields are probably non-axisymmetric because rotational motions of U/N are weakly coupled to convective motions that make their magnetic fields. For U/N "polar wander" is a good descriptor for variations of magnetic field over time.

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