Physics

Physics **5**, 25 (2012)

Viewpoint

Seeing Deep Inside Icy Giant Planets

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Published February 27, 2012

Magnetically accelerated metal plates are used to compress water to high pressures and temperatures like those inside Neptune and Uranus, permitting measurements that aid in the development of models of planetary interiors.

Subject Areas: **Materials Science, Geophysics**

A Viewpoint on:
Probing the Interiors of the Ice Giants: Shock Compression of Water to 700 GPa and 3.8 g/cm3
M. D. Knudson, M. P. Desjarlais, R. W. Lemke, T. R. Mattsson, M. French, N. Nettelmann, and R. Redmer
Phys. Rev. Lett. **108**, 091102 (2012) – Published February 27, 2012

Water is one of the most abundant molecules in "icy" planets and moons in our solar system and probably in extrasolar planets, such as icy "super Earths" with masses from ~ 2 to 10 times the mass of Earth, and "hot Neptunes" with masses comparable to or smaller that than the mass of Neptune, which is 15 times the mass of Earth. Planetary "ice" is a mixture of H_2O, CH_4, and NH_3, whether frozen solid on the surface or as a fluid in the hot interior of an "icy" planet or moon. Ice in Neptune and Uranus, for example, exists only as a fluid. Ice is mostly H_2O, and generally treated as such, which is why the equation of state (EOS) of water is so important for modeling icy planets [1]. Because of their large sizes and low thermal conductivities, planetary interior pressures range up to several 100 gigapascals (GPa) and temperatures of several 1000 K [2]. As reported in *Physical Review Letters*, Marcus Knudson at Sandia National Laboratories, New Mexico, and colleagues have now made substantial advances in probing the properties of water under such conditions [3].

Researchers at Los Alamos National Laboratory developed an EOS of water at high pressure and temperature decades ago, which is one of many EOS's archived in a database called Sesame. Sesame was started with relatively little experimental data and is used widely for planetary modeling. Initial shock data for water extended up to a maximum pressure of ~ 40 GPa. Interior pressures in both Neptune and Uranus are ~ 600 GPa and are much higher in many newly discovered icy planets. Because of recent advances in shock-compression techniques, experimentalists can now measure EOS data of H_2O at pressures and temperatures up to those in the cores of the icy giant planets Neptune and Uranus. Knudson *et al.* have made such measurements, and they have used their data to construct an EOS of water that can now be used by the planetary physics and chemistry community to construct accurate models of deep interiors of icy planets and moons.

More specifically, space flyby missions to Neptune and Uranus have measured their gravitational fields, from which mass-density distributions are derived. By knowing accurate EOS models for various likely constituents, the combination of models that best matches measured total planetary mass and mass distribution, provide a good indication of the likely chemical composition of the interiors. At present this technique works only for a few general classes of materials, namely light material (H-He), medium-weight material (ice, rock, and their mixtures), and heavy material (Fe). This selection process is aided by knowledge of whether or not a planet has a magnetic field, which is discussed below.

For the past 55 years, extreme pressures, densities, internal energies, and temperatures have been achieved in water by hypervelocity impact and by irradiation with an intense radiation pulse. These energy sources produce fast, high-pressure pulses in highly condensed matter, often within less than a nanosecond (ns) and last for ~ 10 to ~ 100 ns, depending on the source. These time scales are sufficiently long to achieve thermal equilibrium in most materials and sufficiently brief that the process is adiabatic (heat of compression is retained during experimental lifetime). In addition, corrosion by ionic fluids so produced has insufficient time to occur. Hydrodynamic waves produced by such fast processes are called shock waves. Energy deposited in these fast processes goes into compression and into dissipation in the forms of heating and disorder. The locus of states produced by a sequence of shock pressures in a material with fixed initial density is called a shock-compression curve, or a Rankine-Hugoniot curve, or simply a Hugoniot. Uniform shock states are achieved throughout the bulk sample, or uniform values can be obtained by modest corrections to measured data.

Knudson *et al.* achieved high shock pressures with

DOI: 10.1103/Physics.5.25
URL: http://link.aps.org/doi/10.1103/Physics.5.25

impacts and measured EOS data points of water up to 700 GPa. In a Hugoniot EOS experiment, initial material densities, velocities of impactor, the shock wave induced by impact, and the velocity of mass just behind the shock front are measured. Knudson measured these quantities with optical interferometry. Basically, velocity is proportional to the number of interferometric fringes measured. Shock pressure, density, and internal energy are then calculated from measured initial mass densities and velocities by conservation of momentum, mass, and energy, respectively, across the front of a shock wave. The conservation equations are called the Rankine-Hugoniot equations [4]. Temperature of shock-compressed matter is determined experimentally by measurements of gray-body thermal-emission spectra, provided the medium in front of a thermally radiating shock front is sufficiently transparent, or it is calculated theoretically.

Knudson *et al.* also measured optical reflectivity of a laser beam reflected from a moving shock front. Electrical conductivity of shock-compressed water can then be estimated from measured reflectivities. Electrical conductivities of water are needed to calculate planetary magnetic fields by magnetohydrodynamic dynamo calculations of fields produced by convecting, conducting fluid water mixed with rock [1]. At extreme pressures and temperatures in planets, water dissociates into several chemical species. Thus, in general, if a planet has a magnetic field, it has a constituent of its interior that is conductive and perhaps metallic at interior pressures and temperatures. This latter condition also facilitates identification of likely chemical constituents of planets.

The magnitude and lifetime of a shock wave generated by impact depend sensitively on the velocity, density, and aspect ratio (diameter/thickness) of an impactor plate. Its aspect ratio should be sufficiently large to eliminate edge effects during experimental lifetime, which is determined by impactor size and mass. Impactor mass is important because it affects kinetic energy imparted to an impactor and the fraction of kinetic energy that goes into velocity. Achievement of ever-higher shock pressures by impact has required a series of shock drivers with ever-higher kinetic energies or radiation intensities.

Historically, water has been single-shocked to 40 GPa with planar shock waves generated with chemical explosives [5], to 80 GPa with a two-stage light-gas gun [4, 6], to 1400 GPa with underground nuclear explosions [7, 8], and to 800 GPa with a pulsed giant laser by Lawrence Livermore National Laboratory at the Omega Laser [9]. Now, this work of Knudson *et al.* pushes to 700 GPa with a giant pulsed electrical current at the Z Accelerator at Sandia National Laboratories [10]. Today, only giant pulsed lasers and impactor plates accelerated with the Z machine to velocities above $\sim$ 10 km/s can achieve shock pressures above a few 100 GPa in water. The Z machine has achieved not only very high pressures but also small experimental error bars on pressure, compression, and energy, which essentially eliminate previous ambiguities concerning the correct Hugoniot of water in this newly accessible regime. Knudson's small error bars are a major contribution of this work.

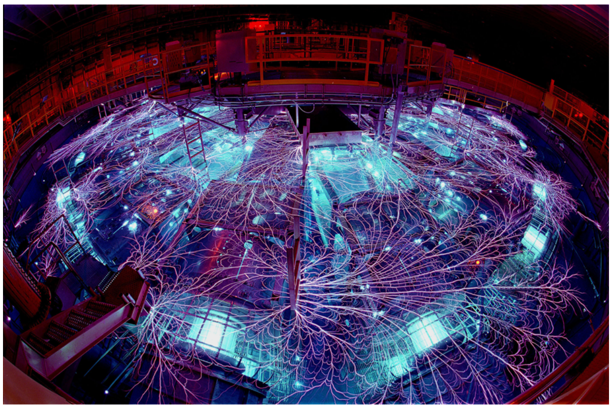

FIG. 1: The Z Accelerator at Sandia National Laboratories, which is 34 m in diameter and 7 m high. A capacitor bank, just inside the outer diameter, can be charged to 22 megajoules to generate a current pulse with a peak of $\sim$ 25 mega-amps and a rise time of $\sim$ 100 to 500 ns. Important thicknesses of the aluminum and quartz drive plates and water samples (see supplemental information in Ref. [3]) were a few 100 microns; the rear quartz window was a few mm thick. The sparking in the figure is caused by some power leakage from fast switches. (R. Montoya/Sandia National Laboratory)

Highest shock pressure was generated by impact onto a sample holder of a 2.0-gram aluminum plate travelling at a velocity of 27 km/s and a kinetic energy of $\sim$ 0.7 megajoules. The Z Accelerator, shown in Fig.1, produces a current pulse behind the impactor that rises to a peak current of $\sim$ 20 mega-amps in $\sim$ 100 ns. The pulsed magnetic field not only produces a magnetic pressure on the rear surface of the impactor plate, it also heats the impactor plate by magnetic flux diffusion. The limiting magnetic drive pressure is $\sim$ 250 GPa because it is produced by a current pulse that maintains the aluminum layer near the impact surface as a solid. This minimizes heating of the impactor behind the solid regime, which keeps the impact surface flat and stable. The result is a density variation that does not compromise use of the Hugoniot equations and fast hydrodynamics to interpret measured velocities in terms of thermodynamic variables.

Knudson's EOS of shock-compressed water will lead to improved modeling of deep interiors of icy planets both within and beyond our solar system, and demonstrates a strong likelihood that many icy planets outside our solar system have magnetic fields. His reflectivities are $\sim$ 0.1 at $\sim$ 150 GPa and range up to $\sim$ 0.22 at higher pressures and temperatures. These reflectivities of a fluid correspond to electrical conductivities typical of poor metals (minimum conductivity of a metal), which are optimum values for supporting planetary magnetic fields [1].

Interesting work for the future includes (i) measuring the complex index of refraction of shocked water and other planetary fluids to be able to derive more accu-

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URL: http://link.aps.org/doi/10.1103/Physics.5.25

rate values of electrical conductivities from reflectivity measurements; (ii) determining experimentally relative contributions to optical emission from shocked fluid and shocked windows containing the fluids; and (iii) measuring temperatures of single and double-shocked water.

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About the Author

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William Nellis is an Associate of the Department of Physics at Harvard University. His research deals primarily with shock compression of fluids and solids, including the making of metallic fluid hydrogen at 140$extrmGPa$ and tenfold compressed liquid-$extrmH_2$ density. He obtained his Ph.D. from Iowa State University in 1968, where he measured electrical and thermal resistivities of rare-earth single crystals. He then was a postdoctoral researcher in the Materials Science Division at Argonne National Laboratory, where he measured electrical and magnetic properties of actinide ordered and disordered alloys. In 1973 he went to Lawrence Livermore National Laboratory where he investigated condensed matter at extreme pressures and temperatures achieved by shock compression and was Head of the High Pressure Sciences Center in the Institute of Geophysics and Planetary Physics. Since retiring from LLNL he has been at Harvard University. He is a Fellow of the American Physical Society and holds the American Physical Society's Duvall Award for Shock Compression of Condensed Matter. He also holds the Bridgeman Award of the the International Association for High Pressure Science and Technology (AIRAPT) and is a Past-President of that association.

DOI: 10.1103/Physics.5.25
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