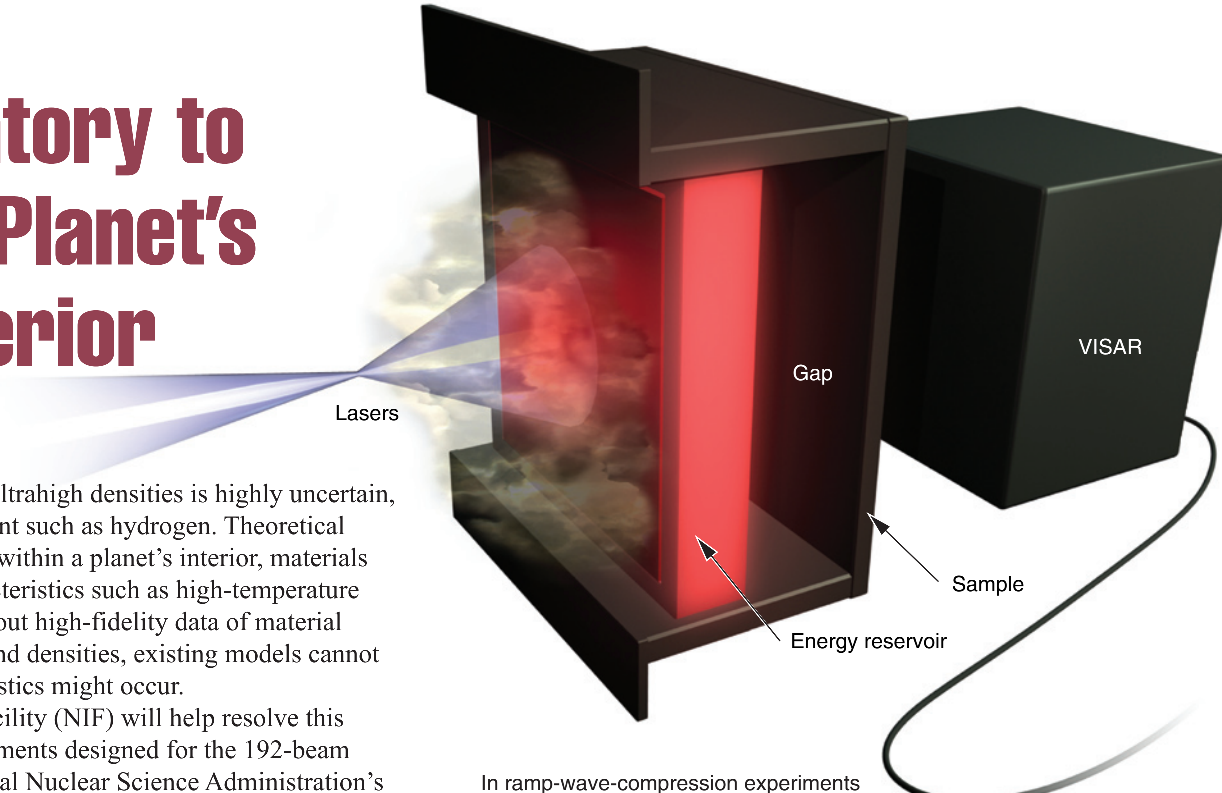
A Laboratory to Probe a Planet's Deep Interior



In ramp-wave-compression experiments planned for the National Ignition Facility (NIF), a laser pulse focuses onto an energy reservoir and condenses the material, creating a plasma piston that compresses the test sample. A diagnostic called VISAR (Velocity Interferometer System for Any Reflector) measures the velocity of multiple sample interfaces as a function of time.

MATERIAL behavior at ultrahigh densities is highly uncertain, even for a simple element such as hydrogen. Theoretical research indicates that deep within a planet's interior, materials could exhibit unusual characteristics such as high-temperature superconductivity. Yet, without high-fidelity data of material behavior at high pressures and densities, existing models cannot predict why those characteristics might occur.

The National Ignition Facility (NIF) will help resolve this problem. Most of the experiments designed for the 192-beam laser will support the National Nuclear Science Administration's Stockpile Stewardship Program. In addition, a portion of NIF shots will explore basic science research in various fields, including astrophysics. These experiments will allow researchers to characterize materials at the extreme densities and pressures typical of the deep interiors of solar and extrasolar giant planets.

Material Behavior Deep within a Planet

The first shock-physics experiments planned for NIF will explore planet formation and structure. For this research, Livermore physicists Peter Celliers, Jon Eggert, Damien Hicks, Ray Smith, and Gilbert Collins in the Physics and Advanced Technologies Directorate are collaborating with Raymond Jeanloz from the University of California at Berkeley, Thomas Duffy from Princeton University, Russell Hemley from the Carnegie Institution, Yogendra Gupta from Washington State University, and Paul Loubeyre from Université Pierre et Marie Curie in France as well as with colleagues from other Laboratory directorates. The researchers plan to study the phase state (fluid or solid) that elemental hydrogen assumes when subjected to extreme heat and pressure. "To better understand the evolution, structure, and internal chemistry of solar and extrasolar planets, we must accurately predict the properties of hydrogen at extreme density and temperature," says Celliers. "NIF will replicate the conditions needed to characterize this element in a laboratory setting."

Planets in the solar system exhibit matter in various ordinary and exotic states. For example, on Earth, when hydrogen and oxygen combine to form water, the compound can take the form of a gas (steam), a fluid (water), or a solid (ice). Water can also exist in the exotic realm. If extreme changes in pressure or temperature occur, the molecular bonds between hydrogen and oxygen can stretch, break, and reconnect in unexpected forms that do not resemble the ordinary states of steam, water, and ice.

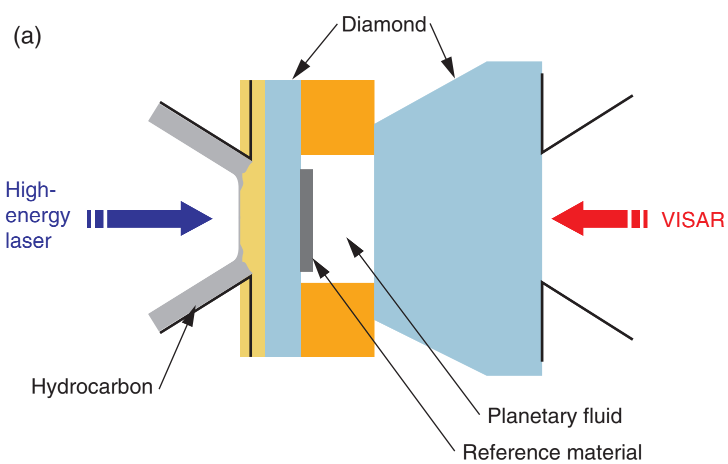
This transitional behavior is difficult to observe and challenging to create or predict. The same is true with other exotic states of matter such as metallic hydrogen or metallized diamond, which have been demonstrated in quantum molecular dynamics simulations and may occur naturally in a giant planet such as Jupiter. Results from experiments at NIF can help researchers better model and predict the changes occurring in these materials.

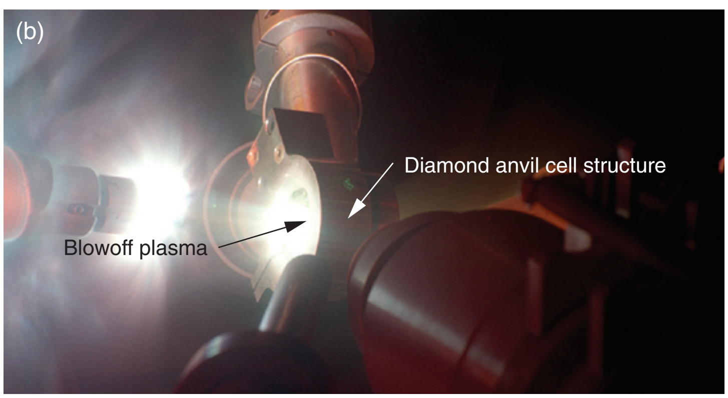
Squeezing Matter to Extremes

To replicate these phase states, the Livermore team plans to stage a series of ramp-wave-compression (RWC) experiments. RWC experiments increase the pressure applied to a sample without inducing a shock wave. (See *S&TR*, March 2007, pp. 23–25.) By precisely shaping the pressure pulse, the team will be able to compress test materials up to 2,500 gigapascals, or 2.5×10^{12} pascals. By comparison, air pressure at sea level is 100,000 pascals.

For example, in one experimental design, laser beams will heat a carbon-based energy reservoir, which will then unload its energy in the form of a plasma piston that shocklessly compresses samples of differing thicknesses. The research team will then measure each sample's velocity profile and use those data to determine the material's equation of state. Equations of state express the thermodynamic relationship between pressure, temperature, and volume for a given sample and are essential for generating reliable computational models of material behavior. With the RWC technique, a sample will remain relatively cool and solid with nearly constant entropy, even under very high pressure.

"The RWC experiments will allow us to inspect condensed matter in states that are similar to those occurring in the deep interiors of planets," says Collins. "These experiments will require the full energy of NIF. The data acquired will help us accurately model the structure and evolution of the giant planets."





(a) The diamond anvil cell experiments at NIF will apply a strong laser-produced shock to a precompressed sample of planetary fluid. A VISAR diagnostic will record the shock velocity of the sample and the reference material, which researchers will use to extract the density and pressure of the shocked precompressed sample. (b) A time-integrated photograph from an experiment on the OMEGA laser shows a strong shock applied to a precompressed sample of helium held between two diamonds.

Shock-Compressing a Precompressed Fluid

Another technique for examining materials under extreme densities is to launch strong shocks in planetlike fluids that are already compressed to an initial high state of pressure and density. This precompressed state is achieved in a diamond anvil cell (DAC). Precompression allows researchers to tune the sample's initial density and thus the final states that can be achieved with strong shocks. "By applying a strong shock to a precompressed sample," says Collins, "we can re-create the deep interior states of solar and extrasolar giant planets."

In a DAC, a support structure holds two diamonds that squeeze a planetary fluid sample contained inside a washer. The diamond on the drive side of the target is thin, so the laser-produced shock remains strong and planar as it transits through the diamond. The diamond's thickness determines the initial precompressed pressure. Because NIF will have outstanding pulse-shaping capability and so much energy, the diamond on the drive side can be much larger than those used in experiments on lower-energy facilities. The sample's initial density and pressure can thus be higher.

To prevent the sample from being heated before the shock, the Livermore team will use a preheat barrier to absorb the high-energy x rays. An ultrafast diagnostic called VISAR (Velocity Interferometer System for Any Reflector) works like a speedometer for shocks, recording the shock velocity of the sample and reference material. "From these data, we will extract the density and pressure of the shocked precompressed sample," says Collins. "We will also use the optical emission from the shock front to measure shock temperature."

Benefits for Basic and Applied Science

In addition to answering questions about planet formation and structure, results from these experiments will benefit the Laboratory's national security missions. The extreme conditions in a planet's deep interior also occur during a nuclear weapon detonation, so data on material behavior at ultrahigh temperatures and pressures can be applied to Livermore's stockpile stewardship research. Examining the behavior of ultradense matter will also help scientists better understand how matter compresses and heats on the way to thermonuclear ignition and burn.

By replicating these extreme environments in NIF experiments, scientists will have the tools needed to model the exotic worlds they can never visit.

—Alane L. Alchorn

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