Compressibility measurements reach white dwarf pressures

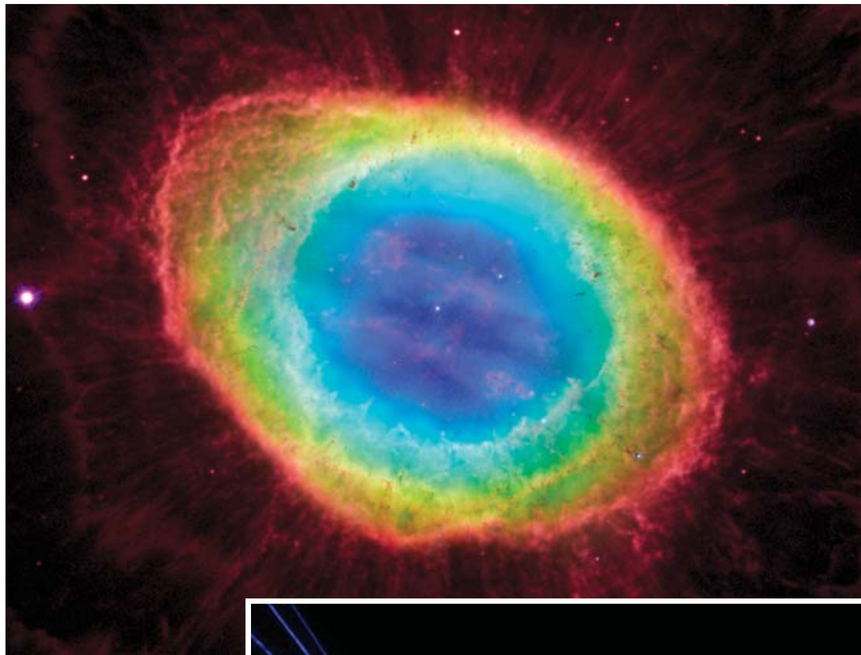
With spherically converging shock waves, researchers can probe material properties under extreme conditions.

Humans have never visited Earth's core or been to the stars. Most of what we know about those exotic environments comes from observations made on or near Earth's surface. We've learned a lot about what's inside our own planet from seismic waves, which propagate differently through the rocky crust and mantle, liquid outer core, and solid inner core. (See, for example, the article by Bruce Buffett, PHYSICS TODAY, November 2013, page 37.)

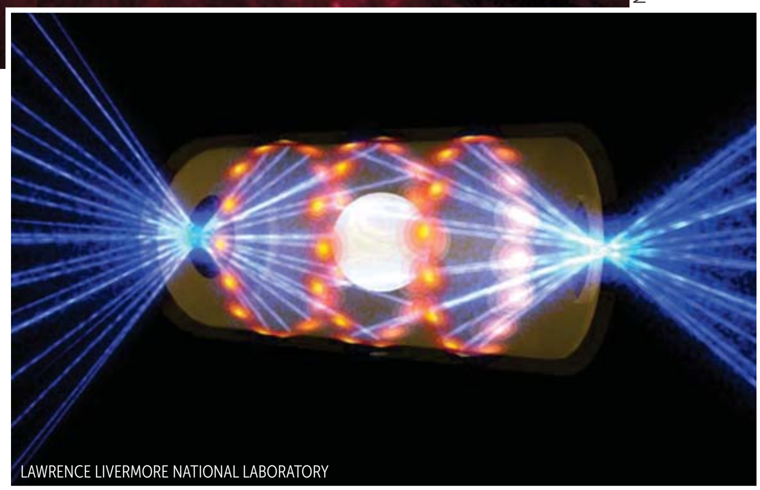
Stars, too, are seismically active, and the pressure and gravity modes that pulse through a star can reveal themselves as periodic brightness variations that, though subtle, are visible from Earth. By analyzing those oscillations, asteroseismologists reconstruct stars' compositions, internal structures, and even evolutionary dynamics. (See the article by Conny Aerts, PHYSICS TODAY, May 2015, page 36.)

But much of the matter inside planets and stars exists in forms unlike anything we encounter on Earth's surface. Chemical bonds start to be ripped apart at pressures above 1 Mbar (a million times the atmospheric pressure at Earth's surface, but less than a third of the pressure at the planet's core, and an even smaller fraction of the pressure inside a star). Above 100 Mbar, or 10 TPa, atoms of carbon and its neighboring elements start to lose even their core electrons. Those changes inevitably influence material properties, such as how much a material compresses in response to additional pressure, and thus complicate the interpretation of asteroseismology measurements.

Now, for the first time in a laboratory experiment, researchers working at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) have measured material compressibility[1] at pressures exceeding 100 Mbar. The team used NIF's powerful lasers (the blue beams in the lower panel of figure 1) to deliver a megajoule of energy in a 5 ns pulse to a solid sphere 2 mm in diameter. The lasers launched a spherical shock wave that converged on the sphere's center and reached pressures up to 450 Mbar.



NASA/ESA/C. R. O'DELL/D. THOMPSON



LAWRENCE LIVERMORE NATIONAL LABORATORY

FIGURE 1. THE PALE DOT at the center of the upper image is a white dwarf, the hot, dense ball of mostly carbon and oxygen left behind when a dying star sheds its outer layers. The National Ignition Facility re-creates white-dwarf conditions in the lab by using lasers (blue beams in the artist's rendering in the lower image) to deliver hundreds of kilojoules of energy to a centimeter-long cavity (dull gold) containing a solid sample (white).

Because the sphere was made of a carbonaceous material, its compression mimicked the conditions in the outer envelope of a carbon-rich white dwarf—the faint, dense remnant of a main-sequence star that has exhausted its hydrogen fuel but has insufficient mass to fuse carbon and oxygen into heavier elements. Like other stars, white dwarfs can pulsate and be probed by asteroseismology (see PHYSICS TODAY, March 2018, page 16), and the convective outer envelope is the region most responsible for their pulsation modes.

Consider a spherical shock wave

Shock-wave experiments have long been used to study materials under extreme

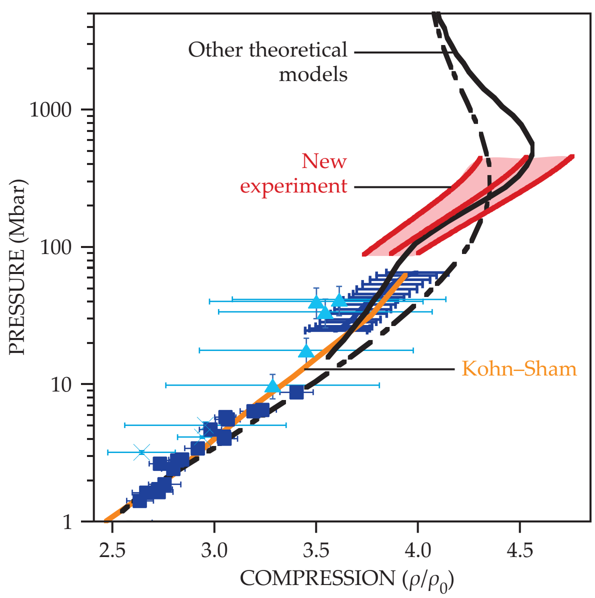


FIGURE 2. SHOCK-WAVE EXPERIMENTS on a hydrocarbon solid show how the material's compression (mass density ρ divided by initial density ρ_0) varies with pressure. Light- and dark-blue data points show the results of previous experiments, mostly based on planar shock waves and in good agreement with Kohn–Sham density functional theory (orange). Above 100 Mbar, carbon starts losing its core electrons, and only other, computationally cheaper theoretical models are feasible (black curves). New work using spherical shock waves, the results of which are shown in red, is the first lab measurement of compressibility in that high-pressure regime. (Adapted from ref. 1.)

conditions. (See the article by Paul Drake, PHYSICS TODAY, June 2010, page 28.) Shock waves—created by lasers, magnets, explosives, or other means—concentrate energy in time, so they can access higher pressures than is possible with static compression. And their behavior is well understood: Conservation of mass and momentum straightforwardly relate the shock propagation speed to the pressure and density of the shocked material. If any two of those three quantities are known, the third can be calculated. Most experiments to date have used planar shock waves that propagate uniformly through a material, so that their speeds, for example, can be extracted from their total transit time over a known distance.

NIF was designed for research on inertial confinement fusion: using lasers to heat and compress a small capsule of frozen hydrogen in the hope of inducing a nuclear reaction that yields more energy than was used to trigger it. Although that mission has yet to succeed, the laser setup is ideal for studying matter at high energy density (see PHYSICS TODAY, February 2017, page 33). And it's already optimized for a spherically symmetric geometry, because the fuel capsules need to be irradiated with equal intensity from all directions. To study spherically converging shock waves, just swap the spherical fuel capsule for a spherical solid sample.

Spherical shock waves have some advantages over planar ones. For one thing, they can reach higher pressures as the shock waves converge on a progressively smaller volume. For another, they make it possible to probe a range of pressures with a single laser shot—and because NIF laser shots take hours to prepare and are in high demand, it's important to get as much information as possible out of each one. On the downside, the shock speed, pressure, and density are all functions of time, so they need to be measured as instantaneous quantities rather than time averages. For a shock wave that takes just 9 ns to traverse the sample's 1 mm radius, that's not easy.

The researchers use x-ray streak radiography to record the x-ray transmission, with the necessary time resolution, through a thin slice across the center of the sphere. Because compressed material blocks x rays more effectively than uncompressed material does, the shock wave's progress is traceable as it closes in on the center of the sphere. From the details of the transmission profile, the researchers solve for the mass density just behind the shock front; from that, they extract the pressure and thus the compressibility curve.

Stars in the lab

Two years ago the NIF researchers published spherical-wave compressibility measurements[2] up to 60 Mbar. For that work, they limited the laser energy to 311 kJ, which simplified the experiment in several ways. Now, to advance to higher pressures, they've tripled the pulse energy—and introduced some experimental complications. For example, they can no longer assume that x-ray attenuation is proportional to mass density. Carbon atoms block x rays because the x rays excite the atoms' core electrons into higher-energy states. But when the pressure rises above 100 Mbar, the atoms start to lose their core electrons, and the x-ray absorption grows less efficient. The researchers had to account for that dependence when solving for the shock-wave pressure and density.

Figure 2 shows the compressibility results. Data from a collection of previous experiments are depicted in light and dark blue. Because most of those experiments used planar shock waves, which probed one pressure at a time, their results are shown as discrete data points, with individual error bars for each. The new spherical-wave experiment measures a range of pressures in a single shot, so its results are shown as a continuous trace surrounded by an error band.

The experiments help to benchmark the theoretical models that researchers currently use to estimate compressibility at high pressures. Kohn–Sham density functional theory, whose compressibility curve is shown in orange, is highly accurate but too computationally costly to use in the pressure regime of the new experiment. At higher pressures, researchers often resort to more approximate models, two examples of which are shown in black. The solid black curve is from a model, also based on density functional theory, that accounts for the electronic shell structure of atoms; it reproduces the experimentally observed inflection point at around 100 Mbar, where core ionization begins. The dashed black curve, from a model that lacks a representation of electronic shells, doesn't agree well with the data.

Even under the high pressure generated in the NIF experiment, the hydrocarbon sample was compressed by less than a factor of five relative to its ambient-pressure density. It's a long way from studying the conditions in the core of a white dwarf, which is orders of magnitude denser than any ordinary solid and resists further compression only through electron degeneracy pressure.

But pinning down the properties of the white dwarf envelope, where electron degeneracy has a more modest influence and densities are closer to those of earthly solids, can still help advance the understanding of the star's interior. Like sound waves in a whispering gallery, seismic waves spend much of their time near the surface of their star or planet. Knowing the material properties of that near-surface region is essential to correctly interpret the signals from those waves in order to probe the internal structure.

Johanna Miller

References

1. A. L. Kritcher et al., *Nature* **584**, 51 (2020).
2. T. Döppner et al., *Phys. Rev. Lett.* **121**, 025001 (2018).

One photon's transmission usefully controls another

To preserve the quantum correlations between two particles of light, researchers mapped the scattering that a photon experienced onto the entangled state.

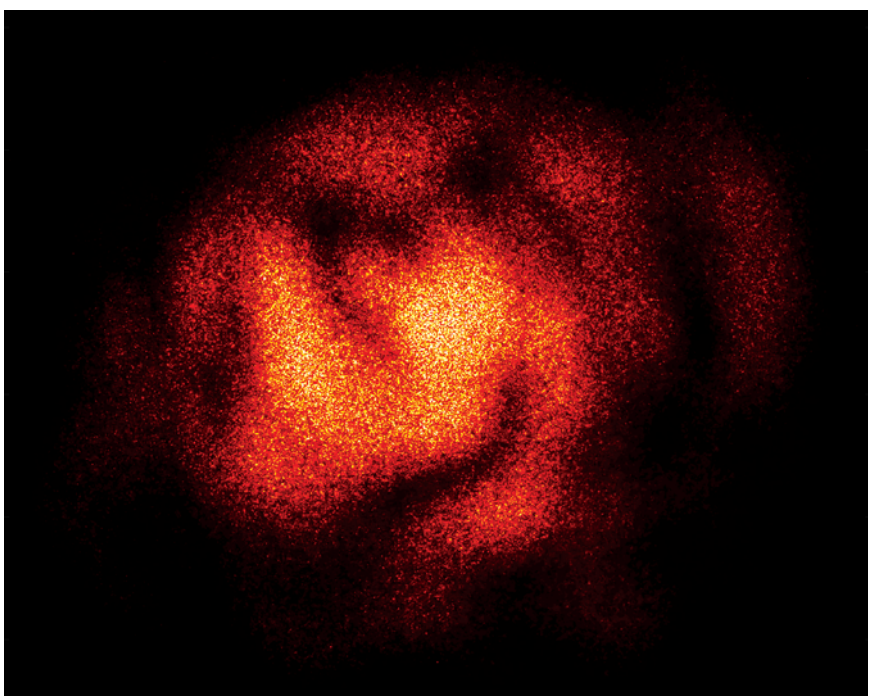


FIGURE 1. THE RED–YELLOW SPECKLE PATTERN formed from light that interferes with itself as it travels through a multimode fiber-optic cable. The effects of such scattering must be corrected for an entangled state to transmit error-free information in a quantum computer. (Image courtesy of Mehul Malik.)

Prime numbers are the keys to encrypting sensitive information (see the Reference Frame by N. David Mermin, Physics Today, April 2007, page 8). If an adversary wanted to decipher a message protected by today's most often-used encoding method, known as RSA encryption, they would need to identify the prime factors of numbers with thousands or tens of thousands of digits. That feat is beyond the capability of classical computers, although not for quantum-based ones.[1]

In a quantum computer, the information stored as zeroes and ones in classical bits can be encoded as a superposition of quantum states in various physical systems, such as trapped ions and large groups of cold, neutral atoms (see the article by Ignacio Cirac and Peter Zoller,