was spectacular beyond all expectation."

J1614 turned out to be the most nearly edge-on binary pulsar yet seen. The data revealed an angle of 89.17 ± 0.02° between the orbital plane's normal and the line of sight. The strength and clarity of the observed signal also benefit from two other fortunate circumstances, one natural, the other instrumental: The companion's mass, 0.500 ± 0.006 $M_\odot$, is three times that of a typical white dwarf in a binary-pulsar system. And the observation owes much to GUPPI, the innovative Green Bank Ultimate Pulsar Processing Instrument installed on the radio telescope shortly before the nine-day observation last March.

Performing ultrahigh-speed computer processing of each pulse as it arrives, GUPPI provides a fourfold improvement in the telescope's timing resolution. It also corrects for signal smearing due to dispersion by interstellar electrons.

As a function of orbital phase in the nine-day circuits of the pulsar and its companion, figure 2 plots the measured delay of the pulse arrivals relative to what one would expect in the absence of the Shapiro effect. The zero of the orbital phase is taken to be the moment when the white dwarf is closest to our line of sight to the pulsar.

Demorest and company took a large fraction of their data near that moment of "orbital conjunction," where one expects the strongest and most rapidly varying Shapiro delay. The cusped curve shows the best theoretical fit to the single-orbit GUPPI measurements plus auxiliary longer-term Doppler data. That fit yields the impressively precise determinations of the two masses and our viewing angle of their orbital plane.

Merging neutron stars

Beyond ruling out most proposed scenarios for exotic matter in neutron stars, the new record mass has other important implications.[2] Among them is a possible answer to the long-standing puzzle of what causes the short-duration minority subclass of gamma-ray bursts (see PHYSICS TODAY, November 2005, page 17). There's much evidence that short GRBs signal the cataclysmic merger of two neutron stars into a black hole. But short GRBs typically last a second or two, which is much too long for the naive dynamical time scale of such mergers.

But now that we know that neutron stars can be heavier than 1.8 $M_\odot$, Özel and company argue, two scenarios for prolonging the GRB become possible: The merged system might be momentarily supported by centrifugal forces that take about a second to dissipate and allow the final collapse. Alternatively, the formation of the black hole might not be delayed, but in the process a massive accretion disk could form and be devoured in something like a second.

Neutron-star mergers are also expected to be a principal source of gravitational-wave signals recorded by ground-based detectors in the near future. A later generation, capable of recording such signals at frequencies beyond a kilohertz, should reveal much about the inner characteristics of the merging neutron stars. But how much can one learn from the lower-frequency components to which LIGO and the next generation of detectors are limited?

In that regard, the existence of 2-$M_\odot$ neutron stars is encouraging. If neutron stars had the highly condensed cores expected for exotic matter, little information about their interiors would be encoded at frequencies below 600 Hz by tidal deformation during a merger. But having largely ruled out such condensed cores, the collaboration concludes that the detection of gravitational waves, even at low frequencies, "will allow accurate measurements of the equation of state of neutron-star matter in the near future."[2]

Bertram Schwarzschild

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Optical measurements probe the pressure and density of water under tension

Little is known about the thermodynamics of the familiar liquid's metastable phases.

It's easy to think of water as a typical liquid, but many aspects of its behavior are highly atypical. For example, its freezing and boiling points are high compared with those of liquids with similarly-sized molecules, and it becomes less dense as it freezes. The unusual behavior is presumed to have something to do with the hydrogen bonds that form between the hydrogen and oxygen atoms of different water molecules, but the details of the connection are not fully known.

To better understand water's anomalous nature, and to test theoretical models that connect its microscopic and macroscopic properties, researchers can study its behavior in metastable liquid phases. Supercooled water is metastable (see the article by Pablo Debenedetti and Eugene Stanley, PHYSICS TODAY, June 2003, page 40), as is water under tension, or negative pressure (see the article by Humphrey Maris and Sébastien Balibar, PHYSICS TODAY, February 2000, page 29).

Just as a spring or rope under tension is stretched beyond its equilibrium length, water under negative pressure is forced to fill a volume larger than it would occupy at zero pressure. Such stretched water could lower its potential energy by partially evaporating, creating a vapor bubble that would allow the remaining liquid to shrink to a smaller volume. But if no bubbles are present already, an energy barrier bars their formation.

Experimental studies of water under tension present mysteries of their own: Different methods of stretching water achieve vastly different maximum tensions before vapor bubbles form. To try to resolve the discrepancy, Balibar, Kristina Davitt, and colleagues at the École Normale Supérieure in Paris measured the equation of state (EOS, the relationship between temperature, pressure, and density) of stretched water.[1] The last time the EOS was measured so extensively was in 1911, when Julius Meyer collected data down to −3.4 megapascals (−34 atmospheres). The Paris researchers measured it down to −26 MPa.

Stretching water

Like a rope, water can sustain only so much tension before it breaks. All sorts of things—impurities, rough patches on the walls, even cosmic rays—can nudge the water over the energy barrier and induce so-called heterogeneous cavitation. Even in an experiment carefully designed to minimize those effects, thermal fluctuations eventually become sufficient to surmount the barrier, at a point called the homogeneous cavitation threshold. At even more negative pressure, there's another thresh-

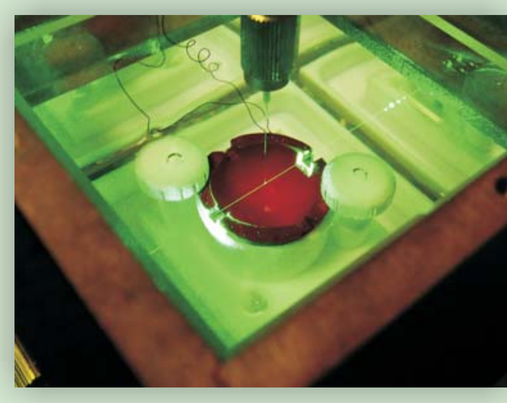

Figure 1. Stretching water with sound. A hemispherical piezoelectric transducer (red) generates intense ultrasound pulses that alternately stretch and compress the water at the sphere's center by tens of megapascals. The water's pressure and density can be derived from two optical measurements using the vertical optical fiber and the horizontal green beam.

old, called the spinodal, at which the barrier to cavitation disappears and the stretched water is no longer metastable but unstable. The spinodal can be studied theoretically but can never be accessed experimentally, since thermal fluctuations are always present.

There are many methods of stretching water. In all but one, even careful experiments achieve tensions of at most −30 MPa. The exception is water trapped in micron-sized pockets (or "inclusions") in natural or synthetic minerals.[2] Researchers heat those samples until the water fills the entire inclusion (whatever air is present becomes dissolved in the water), then lower the temperature until gas bubbles reform. From the temperature measurements, they infer that the water reaches pressures as low as −140 MPa.

But inferring the pressure so far into the metastable regime requires an EOS extrapolated from positive pressures, and the extrapolation might not be accurate. That was the Paris researchers' motivation: If the temperatures and densities measured in the mineral-inclusion experiments actually corresponded to a pressure closer to −30 MPa, there would be no discrepancy.

Experimental EOS data at negative pressure are sparse because the experiments are difficult: It's necessary to determine the stretched water's temperature, density, and pressure simultaneously. Temperature measurements are straightforward; in this case, the researchers kept their system at a constant 23.3 °C. Pressure and density measurements are harder, especially if the metastable state is

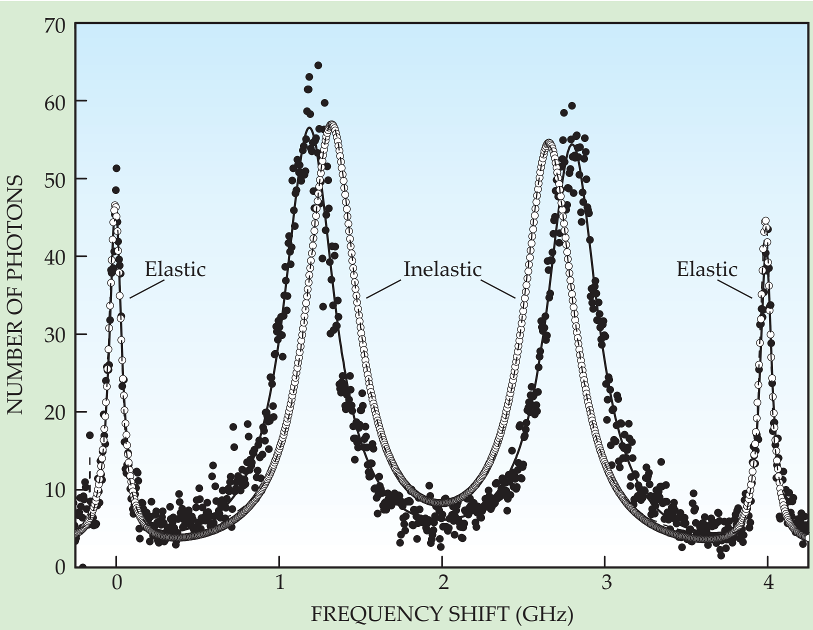

Figure 2. Brillouin scattering spectra for stretched water (black dots) and unstretched water (white circles, scaled to fit). The spectra were taken using a Fabry–Perot interferometer that can't distinguish between frequencies separated by 4 GHz, so the elastic-scattering peak (with zero frequency shift) appears twice. The two inelastic-scattering peaks represent excitation and de-excitation of thermal phonons. (Adapted from ref. 1.)

present for only a short time.

The Paris researchers created negative pressure using an acoustic method developed in the 1980s to study cavitation in liquid helium.[3] The apparatus is shown in figure 1. All acoustic waves consist of alternating regions of high and low pressure. A short burst of ultrasound launched from a hemispherical piezoelectric transducer can produce positive and negative pressures of tens of megapascals at the sphere's center.

By confining the most negative pressure to a small region far from any walls, and by sustaining the tension for a short period of time, the researchers limited the effects of heterogeneous cavitation. Still, they found that bubbles consistently formed at −30 MPa. To be safe, they limited their study to −26 MPa.

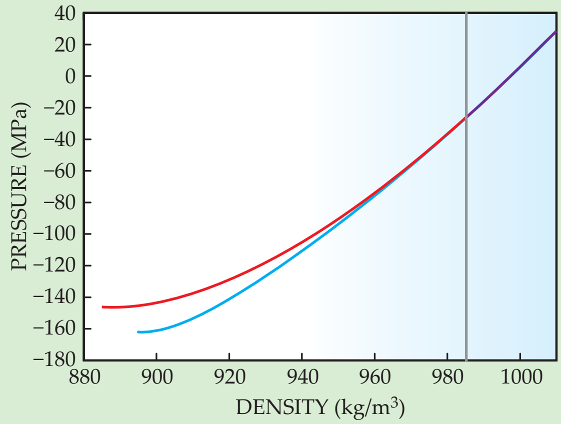

Figure 3. Water's equation of state as measured experimentally (purple) and extrapolated theoretically (red and blue). Although the ultrasound method can't generate tensions beyond −30 MPa before vapor bubbles form, the measured equation of state agrees with models predicting that much greater tensions should be possible. (Adapted from ref. 1.)

Pressure and density

To determine the pressure and density of the water, the researchers used two optical methods. The first, employing a fiber-optic probe hydrophone, measured the density.[4] An optical fiber (positioned vertically in figure 1) extends into the water, with its tip at the acoustic wave's focus. IR light directed down through the fiber is partially reflected when it reaches the tip. The reflected intensity depends on the water's local refractive index, which is a function of the density.

The second optical measurement, Brillouin scattering, used the horizontal green beam in figure 1. Similar in principle to Raman scattering, in which inelastically scattering photons lose or gain energy as they excite or de-excite molecular vibrations, Brillouin scattering involves the excitation and de-excitation of thermal phonons. Those phonons—which are distinct from the applied ultrasound pulse—have energies related to $\partial P/\partial \rho$, the derivative of pressure with respect to density; the energies are revealed in the frequency shifts of the inelastically scattered photons with respect to the elastically scattered photons.

A Brillouin-scattering spectrum for one value of the negative pressure is shown in figure 2. Producing that spectrum—with 50–60 photons at each of the peaks, just enough to reliably determine their locations—required 15 hours of data collection. Keeping the experiment stable enough over that amount of time was a challenge. To check the stability, the researchers also collected data between acoustic pulses and over the positive-pressure half of the acoustic wave—two parts of the phase diagram where the EOS is well known.

Equation of state

Integrating the Brillouin-scattering measurements of $\partial P/\partial \rho$ and combining them with the fiber-optic measurements of ρ gives the pressure–density relationship shown by the purple line at the top right of figure 3. The blue and red curves are the two commonly used model EOSs extended to their respective spinodals.[5] It's no coincidence that both curves flatten out on the low-pressure end. The spinodal is the point at which liquid molecules lose their grip on one another, allowing the liquid to break. At tensions approaching the spinodal, the cohesion of the liquid is starting to break down, so a small change in pressure produces a relatively large change in volume.

The experimental EOS doesn't flatten out, which means that the acoustic method's cavitation threshold is nowhere near the spinodal. It also implies that the temperatures and densities measured in the mineral-inclusion experiments do not, in fact, correspond to pressures near −30 MPa: The mineral-inclusion method really does reach more negative pressures than any other technique, and it's still not clear why.

"We've gone as far as we can with the acoustic method," Davitt explains. "We can't make measurements beyond the cavitation threshold." To extend their experimental EOS to even more negative pressures, she and her colleagues are working on ways to make simultaneous thermodynamic measurements on water in mineral inclusions.

Johanna Miller

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Gamma rays made on Earth have unexpectedly high energies

The as-yet-unexplained observation represents a crossover between astrophysical and atmospheric research.

Terrestrial gamma-ray flashes (TGFs) are the source of the highest-energy nonanthropogenic photons produced on Earth. Associated with thunderstorms—and in fact, with individual lightning discharges—they are presumed to be the bremsstrahlung produced when relativistic electrons, accelerated by the storms' strong electric fields, collide with air molecules some 10–20 km above sea level. The TGFs last up to a few milliseconds and contain photons with energies on the order of MeV.

Now, Marco Tavani, Martino Mari-