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.

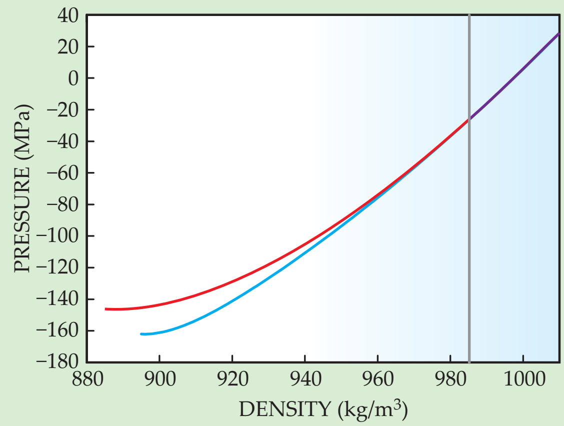

Figure 3. Water's equation of state as measured experimentally (purple) and extrapolated theoretically (red and blue). Although the ultrasound method can't generate tensions beyond −30 MPa before vapor bubbles form, the measured equation of state agrees with models predicting that much greater tensions 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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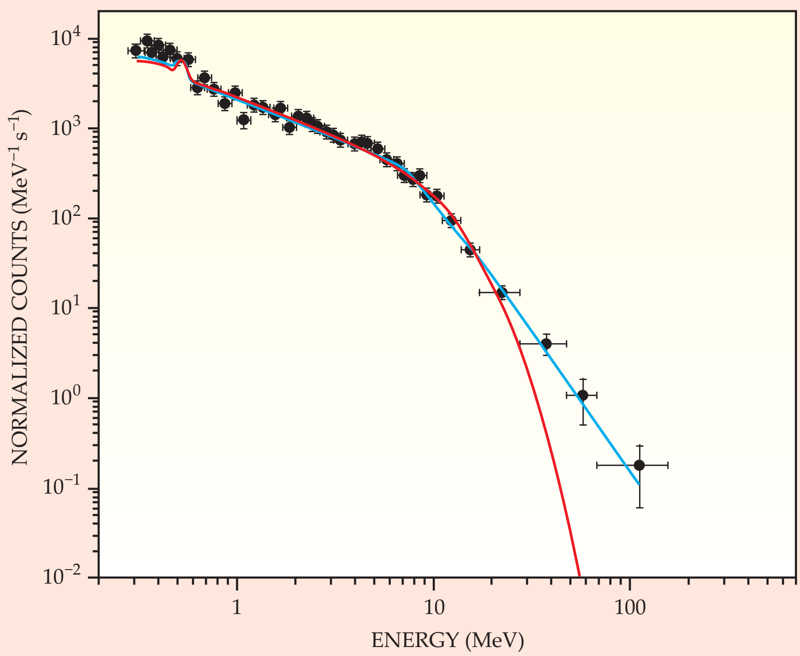
Gamma rays made on Earth have unexpectedly high energies

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-



Energy spectrum for terrestrial gamma-ray flashes. The red line, a theoretical prediction based on a relativistic runaway electron avalanche, follows a power law at low energy and an exponential decay at high energy. The black dots are derived from data collected by the *AGILE* satellite. The blue line, a fit to those data, follows a broken power law, with different exponents for low and high energies. (Adapted from ref. 1.)

saldi, Claudo Labandi, Fabio Fuscino, and others working with data from the Italian Space Agency's *AGILE* satellite find that TGFs are even more energetic than previously thought, with a significant number of photons having energies of 100 MeV and likely even higher.[1] "I think it's safe to say that all the theorists will be absolutely stumped, at least for a while," says David Smith of the University of California, Santa Cruz. "We thought that the energy spectrum was the one thing we understood and could explain well."

Relativistic runaway

A free atmospheric electron starting from rest would have a tough time accelerating to relativistic speed. Even in the electric field of a thunderstorm, which can reach hundreds of kilovolts per meter, collisions with air molecules would decrease its energy faster than the field could increase it. But if an electron is already traveling very fast, it sees the passing molecules with much smaller scattering cross sections, so it builds up even more speed as it zips through the field. When it does collide with air molecules, it releases additional electrons, a few of which have enough kinetic energy to be accelerated by the field as well, so the number of fast-moving electrons increases exponentially.

That process, called a relativistic runaway electron avalanche (RREA), is the mechanism attributed to lightning discharges. (See the article by Alexander Gurevich and Kirill Zybin, Physics Today, May 2005, page 37.) The fast seed particle that starts it all may be a cosmic ray. Ordinary plasma discharges, of the kind that you feel when you touch a doorknob on a dry day, proceed by a different mechanism, which requires a field much stronger than is present in a storm.

The same RREA mechanism is likely to be involved in producing TGFs. Monte Carlo simulations[2] of RREAs in air yield spectra like the red line in the figure: a power-law decline at the low-energy end, interrupted by an exponential cutoff somewhere around 7 MeV.

High-energy tail

Launched in 2007, *AGILE* was designed for astrophysical research. Its onboard hardware and software were tailored for the observation of cosmic gamma-ray bursts. But its sensitivity to fast time scales and high photon energies make it ideal for TGF viewing as well.

Based on data from 130 TGFs collected over a 20-month period, the observed spectrum (black dots in the

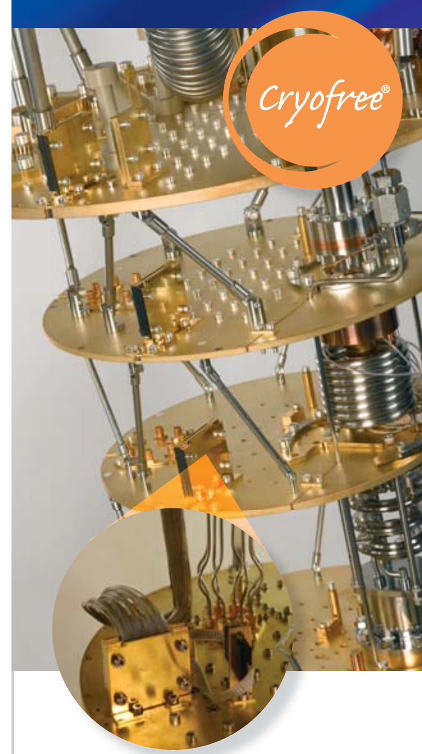


figure on page 17) is well fitted at the high-energy end by a second power law (blue line) that extends at least to 100 MeV with no sign of an exponential cutoff. But in the RREA model, 100-MeV electrons—which are required to produce 100-MeV photons—must have had a long history of flying through the field, colliding with air molecules, and releasing electrons with energies at the low end of the spectrum. "What's impossible to explain in the current model," says Smith, "is that there are so many high-energy photons without a lot more low-energy photons than appear to be there." **Johanna Miller**

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Exploring the extremes of turbulence

Two experiments yield similar data but tell different stories about momentum transport at high Reynolds numbers.

Force a fluid gently and it responds in orderly fashion—points within the fluid trace out smooth, parallel streamlines at steady speeds in what is known as laminar flow. In fact, the response is so orderly that, absent significant diffusion, reversal of the forcing returns each point to its original location.

But disturb the fluid more vigorously so that the Reynolds number—the ratio of inertial to viscous forces—becomes large, and the well-organized flow gives way to the chaotic whirls and eddies of turbulence, with each point subject to abrupt and unpredictable changes in direction and speed. Both flow regimes are beholden to the same Navier–Stokes equations. But whereas laminar flow is easily understood and modeled, turbulent flow is among the most mysterious phenomena in fluid mechanics.

Now, two independent experiments—one by Detlef Lohse and colleagues at the University of Twente in the Netherlands,[1] the other by Daniel Lathrop and Matthew Paoletti at the University of Maryland, College Park[2]—shed new light on turbulence. The data, gathered from previously unexplored regions of the turbulent flow parameter space, could provide insight into fundamental questions of transport phenomena, from the lab scale to the astronomical.

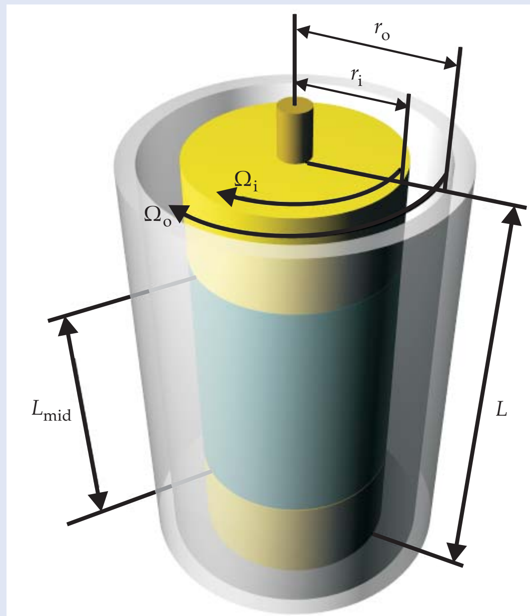

Figure 1. A Taylor–Couette cell. Water fills the gap between concentric cylinders, which are rotated with angular velocities Ω_i and Ω_o. To minimize the role of end effects, the new experiments measured only the torque on the middle length of the inner cylinder, L_{mid}. (Adapted from D. P. M. van Gils et al., http://arxiv.org/abs/1011.1572.)

Spin control

The groups' experiments have much in common. Both teams studied Taylor–Couette flows, in which fluid is sheared between concentric, rotating cylinders, as shown in Figure 1. Their devices were also similarly proportioned: Each team's cylinders were about 1 m tall. Lohse and company's had radii of 20 and 30 cm; Lathrop and Paoletti's, 16 and 22 cm. The teams gathered information about angular momentum transport by measuring the torque required to rotate the inner cylinder at a fixed rate.

Most crucial from a hydrodynamics perspective, however, were the high rotation rates each team could achieve—around 600 rpm for the outer cylinder, which could rotate in either direction, and 1200 rpm for the inner cylinder. When water fills the intracylinder gap, as it did in both teams' experiments, those high rotation rates translate to Reynolds numbers on the order of 10^6. (Flows in pipes become turbulent at Reynolds numbers around 4×10^3.) That surpasses the Reynolds numbers of 10^5 achieved in 1936 by Fritz Wendt, whose experiments, curiously, had remained par excellence in the Taylor–Couette literature for nearly 75 years.

It comes as little surprise, then, that the two teams, exploring similar Taylor–Couette parameter space with similar devices, retrieved similar data. But the stories that those data tell, like the motivations behind the experiments, are quite different.

Ultimate turbulence

Lohse and company were inspired by similarities underlying Taylor–Couette and Rayleigh–Bénard flows, the latter consisting of a fluid confined between two horizontal plates and heated from below (see the article by Leo Kadanoff, PHYSICS TODAY, August 2001, page 34). Though at first glance the relationship between the two might seem tenuous, there are strong physical parallels.

If the temperature difference in a Rayleigh–Bénard cell is slight, heat transfer from the bottom to the top plate is entirely conductive. If the difference grows, thermal expansion causes the fluid near the hot plate to float upward, carrying heat with it, while the cooler, denser fluid above sinks. At large temperature gradients—that is, when the Rayleigh number *Ra*, the ratio of temperature-induced buoyant forces to viscous forces, becomes large—those convection currents become turbulent.

Likewise, if the inner cylinder of a Taylor–Couette cell is rotated slowly, angular momentum is transferred to the outer wall via laminar shear. Rotate the inner cylinder faster, though, and the outward-pulling centrifugal forces, which are greatest near the fast-spinning inner cylinder, destabilize the system—an effect known as the Rayleigh instabil-