outside the core. The experimenters suspect that the Ar emissions stem from the region just outside the opaque plasma core; that's where charged particles near the core's boundary might collide with Ar atoms.

Although the temperatures calculated from the Ar atom emissions are in the same ballpark as those determined from the blackbody-like spectrum seen at shorter wavelengths, Suslick cautions against directly comparing the two. The emissions on which the temperatures are based do not necessarily originate at the same time in the bubble or from the same spatial region. Suslick is collaborating with Putterman on an experiment to pin down the respective emission times.

The temperatures determined from Ar emissions were hotter at higher values of the acoustic driving pressure. By 2.9 bar, the temperature had reached 15 000 K. At even higher pressures, the thermal broadening of the atomic lines hinders any estimate of the temperature.

Why are such atomic emissions not seen when Ar bubbles form in water? The blackbody temperatures of SBSL in water can be higher than those seen in the sulfuric-acid system. Thus, one might expect a plasma to form in a water system as well. Perhaps atomic emissions do occur, but they are blurred by thermal broadening. Or perhaps their appearance in sulfuric acid has to do with the jittery motion: Putterman and Suslick note that atomic emissions have not been seen in single bubbles that are more stationary.

Evidence for a plasma

Flannigan and Suslick argue that Ar atoms are unlikely to be kicked into the 4*s* and 4*p* levels by thermal processes. Rather, they say, it takes collisions with energetic charged particles. That implies the presence of a plasma. Even stronger evidence comes from the sighting of spectral lines corresponding to the excited state, O_2^+. This species, Flannigan and Suslick assert, could have been formed only by collisions with highly energetic charged particles, and not by thermal processes. That's because the dissociation energy of the oxygen molecule is much less than its ionization energy. The sighting of O_2^+ indicates that it must have been hit with a charged particle and ionized before it had a chance to dissociate.

Last year, Putterman and two colleagues at UCLA presented indirect evidence for the formation of a plasma in SBSL. They drove an isolated bubble of xenon in water at a very high frequency to produce such a small bubble that its core was no longer opaque. The group fit the emission spectrum with a thermal bremsstrahlung distribution and estimated a temperature of a million degrees.[7]

The Illinois experiment is a first step toward exploring the inner core of sonoluminescing bubbles. There's still a lot more to learn, such as how dense the plasma core is, how hot it gets, and how its opacity varies with other conditions. The challenge is for experimentalists to learn how to probe the inner core of optically opaque bubbles.

Barbara Goss Levi

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A String-Theory Calculation of Viscosity Could Have Surprising Applications

A deep connection between strings and gauge symmetries enables theorists to address the dynamics of strongly interacting fluids.

At the banquet that concluded the Strings '98 conference held in Santa Barbara, California, some 300 theoretical physicists danced the "Maldacena," a version of the then-popular Macarena. Their giddy behavior was inspired by Juan Maldacena's conjecture that a profound relationship exists between four-dimensional gauge theories and string theories formulated in 10 dimensions.[1]

Maldacena (Institute for Advanced Study in Princeton, New Jersey) had built on work of Steven Gubser, Igor Klebanov, Alexander Polyakov, and many others. In the duality he described, certain problems in gauge theories with strong interactions can be recast as equivalent problems in a theory of weakly interacting strings (see PHYSICS TODAY, August 1998, page 20). Because the behavior of such strings is dominated by massless particles—gravitons in appropriate scenarios—the Maldacena duality relates gauge theories to 10D gravity. With the help of the duality, a battery of novel techniques can be brought to bear on gauge-theory problems that cannot be addressed with perturbation theory.

In 2001, Dam Son of Columbia University and colleagues Giuseppe Policastro and Andrei Starinets from New York University recognized that they could combine the Maldacena duality with hydrodynamics. That marriage enabled them to consider dynamical behavior in one particular plasma.[2] They calculated the plasma's coefficient of shear viscosity, a parameter that describes how forces are transmitted transversely in fluids.

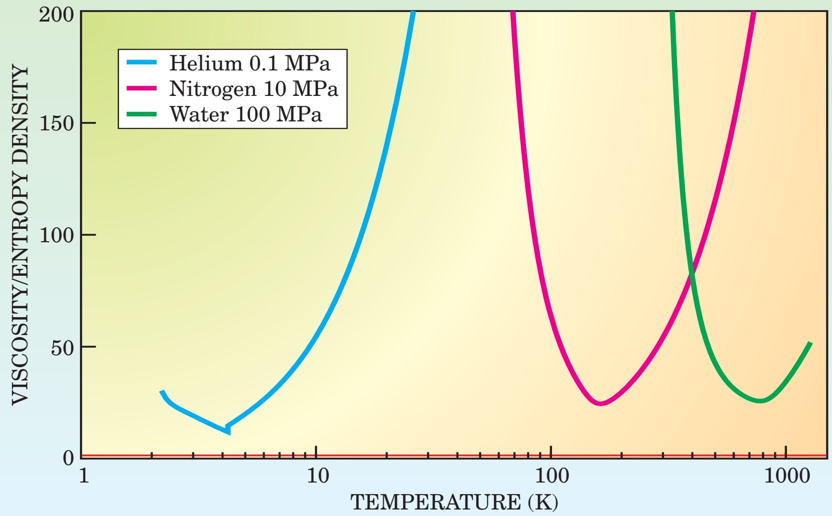
Son (now at the University of Washington, Seattle) and colleagues continuously refined their investigations; in particular, they focused on the ratio of shear viscosity to entropy density. This March, Son, Starinets (now at the Perimeter Institute for Theoretical Physics, Waterloo, Canada), and Pavel Kovtun (Kavli Institute for Theoretical Physics) described a general calculation[3] of the ratio that extended previous results[2,4] and sharpened an earlier conjecture that there exists a lower bound to the ratio for a wide class of fluids.

Shear elegance

Any particular gauge theory is about a specific collection of particles. The particle system has an entropy density s that, in principle, can be calculated by counting the number of states in a small energy slice. The system also has such hydrodynamic parameters as the coefficient of shear viscosity η, which may be defined as follows: Consider a thin layer of fluid lying between two plates with area A, the plates separated by a distance z. Sliding the top plate with a speed v relative to the bottom plate requires the exertion of a force parallel to the plate. That force is proportional to A and v and inversely proportional to z; the proportionality constant is η. The shear viscosity is greater for honey than it is for water.

Son's group and several others considered η/s for a wide variety of gauge theories whose dual string descriptions all involved a 10D spacetime.

Included in the spacetime was a particular class of black holes. The remarkable result is that the ratio is always the same and may be expressed in terms of the Planck and Boltzmann constants: $\eta/s = \hbar/4\pi k_B = 6.08 \times 10^{-13}$ K·s. By any standard this duality ratio is tiny. For comparison, the figure at right shows η/s as a function of temperature for helium, nitrogen, and water.



The ratio of viscosity to entropy density in units of $\hbar/4\pi k_B$ for helium, nitrogen, and water varies with temperature. Visible in the data at around 4 K is the jump at the gas–liquid phase transition for helium. The horizontal red line indicates the temperature-independent quotient for a wide variety of systems that can be related to black holes. It lies well below the curves of the real-world substances at the specified pressures. (Adapted from ref. 3.)

The gauge theories considered by Son don't describe strongly interacting particles in the real world. Nonetheless, results from the Relativistic Heavy Ion Collider (RHIC) and observations of strongly interacting lithium-6 atoms suggest that the extremely low viscosities calculated by Son and others may be more than just a theoretical curiosity.

Located at Brookhaven National Laboratory, RHIC, in its highest-energy experiments, smashes together two countercirculating beams of gold nuclei (see the article by Thomas Ludlam and Larry McLerran, PHYSICS TODAY, October 2003, page 48). According to Peter Steinberg, a physicist at Brookhaven who works on RHIC's PHOBOS experiment, scientists initially thought that the energetic collisions would liberate the quarks and gluons confined in the nuclei; the result would be a quark–gluon plasma that behaved like a gas. But, notes Steinberg, "many of the expectations we had were confounded as we pushed the energies higher and higher." The post-collision medium seems to behave more like a strongly interacting fluid than a gas.[5] And detailed results of RHIC collisions are in excellent accord with the hydrodynamic limit of zero shear viscosity. Theorists are seeing if they can relax the hydrodynamic limit to determine the maximum η/s compatible with RHIC's experimental results.

Degenerate trapped fermions may also interact strongly. John Thomas and colleagues at Duke University created a gas of strongly interacting ^{6}Li atoms in an atomic trap, then watched how the gas expanded after being liberated.[6] The anisotropic explosion they observed is remarkably consistent with the hydrodynamic limit. A subsequent observation of the system's radial breathing mode confirmed the nearly perfect hydrodynamic behavior.[7]

How low can you go?

To calculate η/s, Son and colleagues developed new tools to find η and took advantage of earlier work that had determined s. About 30 years ago, Jacob Bekenstein suggested, and Stephen Hawking confirmed, that 4D black holes have entropy and temperature. The celebrated Bekenstein–Hawking formula reveals that a black hole's entropy is proportional to the area of its event horizon. Son related fluids to 10D black holes that likewise have entropies proportional to their horizon areas. Each such fluid has the same temperature and entropy as the corresponding 10D black hole.

The viscosity calculation is more involved. The key element is the stress–energy tensor, which encodes densities and fluxes of energy and momentum. Part of that coding is η.

The stress–energy tensor is also intimately connected with gravity inasmuch as the matter it describes warps spacetime and leads to gravitational forces. In the language of quantum mechanics, the tensor's coupling to gravitons is analogous to an electric current's coupling to photons in quantum electrodynamics. Using the Maldacena duality, Son and company could relate a fluid's η to an appropriately normalized cross section for gravitons to be absorbed by the dual black hole: In the limit that the gravitons have vanishing energy, the two quantities are proportional.

A standard quantum-mechanical result indicates what one might learn about graviton absorbtion. The quantum-mechanical cross section for low-energy particles to scatter off a hard sphere is equal to the sphere's area. The graviton result is similar: The zero-energy-limit cross section equals the area of the black-hole horizon. In the ratio η/s, the horizon area cancels.

The specific systems that yield the duality value for η/s have vanishing chemical potential. Son and colleagues conjecture that the duality value is a lower bound for η/s in any nonzero-temperature system with vanishing potential. Just what might be said about η/s for systems with nonzero potential is an open question, but the techniques employed by Son and others have a natural extension to that regime. Calculations that include the chemical potential, though, will have to deal with an interesting technical wrinkle: The dual black hole has angular momentum.

Steven K. Blau

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