10^{49} ergs. So, in principle, a magnetar could afford several hundred giant flares in a lifetime. But as the magnetar cools with age, says the theory, the diffusion of flux lines through the interior and crust slows down, leaving a still strongly magnetized but now inactive relic after a few times ten thousand years.

Aftermath

In just 0.2 seconds, SGR 1806–20 radiated as much energy as the Sun does in 300 000 years. Its subsequent output over the next minutes and weeks was less showy, but nonetheless instructive. The 6-minute oscillating tail in soft gammas and x rays had a blackbody spectral temperature of about 10 keV. The spike's blackbody temperature, by contrast, was several hundred keV. The tail is thought to emanate from a localized hot plasma of electron–positron pairs, in equilibrium with gammas, trapped by the magnetic field anchored to the surface.

As SGR 1806–20 rotates, the trapped fireball comes in and out of view. Hence the periodicity. All three giant flares have shown such oscillating tails. To the extent that *Swift* can detect the tails at intergalactic distances, one could readily distinguish distant magnetar flares from unrelated short gamma bursts.

What about longer-lasting afterglows? The radio-telescope team led by Bryan Gaensler (Harvard–Smithsonian Center for Astrophysics) has been monitoring the 27 December flare's radio afterglow since 3 January with the Very Large Array in New Mexico and the Australia Telescope Compact Array.[4] They found a radio nebula, several hundred times brighter than that generated by the 1998 giant flare, expanding around SGR 1806–20 at about ⅓ the speed of light. The nebula's emission faded steadily until about three weeks after the flare, when it unexpectedly rebrightened for a week or so before resuming its wane.[8]

Gaensler and company tentatively attribute the afterglow to moderately relativistic protons, ejected by the flare, that drive a shock front through ambient material surrounding the star. The radio signal would be synchrotron radiation from shock-accelerated electrons in the interstellar medium and the ejecta, spiraling around magnetic field lines.

The radio nebula's relatively modest expansion velocity makes significant relativistic beaming of the giant flare's radio or gamma-ray output unlikely. If the flare were narrowly beamed, serendipitously in our direction, one would have to reduce estimates of its total luminosity.

"The rebrightening of the radio nebula is particularly informative," says Gaensler. "Because it manifests the deceleration of the ejecta after a coasting phase, it lets us estimate the total mass of material ejected by the giant flare." That estimate, 10^{24}–10^{25} grams, implies that something like the top 50 meters of the star's crust were blown off. (The outer crust's density, about 10^8 g/cm^3, is much lower than the nuclear density of the interior.) The crust ejection, he points out, had to be spotty. A uniform cover of ejecta would have created an atmosphere too opaque for the tail to be seen.[8]

Magnetars promise a first look at the exotic physics of magnetic fields beyond the critical quantum-electrodynamic field strength $B_c = m^2c^3/\hbar e = 4 \times 10^{13}$ G, where m and e are the electron mass and charge. Above B_c, electrons gyrate relativistically even in their lowest Landau (cyclotron-orbit) states. The vacuum itself becomes strongly birefringent, and x-ray photons can split and merge without interacting with matter.

Bertram Schwarzschild

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Evidence for a Plasma Inside a Sonoluminescing Bubble

The exceptionally bright light emitted by an acoustically vibrated bubble of argon gas in sulfuric acid helps illuminate the extreme conditions within a collapsed bubble.

Send a high-intensity ultrasound wave through a container of liquid, and it's not surprising to find that the alternating cycles of acoustic compression and rarefaction create micron-sized bubbles in the liquid and cause them to successively expand and contract. What *is* mysterious is to see those bubbles emit light. Somehow, the energy dispersed in an acoustic wavefield becomes sufficiently concentrated to produce visible light.

Multiple-bubble sonoluminescence (MBSL) was first seen in the 1930s, but in recent decades researchers have learned to produce and control a stable single bubble. Single-bubble sonoluminescence (SBSL) has allowed them to study in detail the dynamics of bubble cavitation. Experiments soon revealed other remarkable features: The bursts of light are as short as a few tens of picoseconds and the time between successive pulses can be synchronized to within a few parts in 10^{11}. (See the articles in PHYSICS TODAY by Lawrence A. Crum, September 1994, page 22, and by Detlef Lohse, February 2003, page 36.)

Most of the current theoretical models[1] of SBSL predict that the gas bubble will collapse very rapidly to an extremely small radius and that, under some circumstances, the gas within an inner core will form an opaque plasma. That picture has now been strengthened by a recent experiment done by David Flannigan and Kenneth Suslick at the University of Illinois, Urbana-Champaign.[2] They provide evidence for the gas-phase light emission from ions, signaling the formation of a plasma.

The Illinois experiment also demonstrates the promise of studying SBSL with argon bubbles in concentrated sulfuric acid. The light emission, as seen in figure 1, was 3000 times as intense as that from the well-studied system of argon in water. "It's as bright as a light bulb," remarked Lawrence Crum of the University of Washington, who had tried sulfuric acid in his own lab after learning about Flannigan and Suslick's work.

Perhaps because of the increased intensity, Flannigan and Suslick found discrete spectral lines not seen in a water system. From those lines, they were able to make a firmer estimate than previously possible of the temperature outside the plasma core. Consistent with earlier estimates, the new experiment finds that the bubble temperature rises above 15 000 K, several times hotter than the surface of the Sun. No doubt, it's hotter still in the bubble's core, but the opacity prevents one from probing inside.

Theorist William Moss of Lawrence Livermore National Laboratory is excited to see theory and experiment

Figure 1. A bubble of argon in sulfuric acid glows brightly in the experimental flask. (Photo courtesy of Kenneth Suslick, University of Illinois.)

pointing in the same direction. Not only is there now evidence for the long-anticipated plasma in SBSL, but there are also some signs that the light-emitting region within the bubble is as small as 200 nm in radius.[3] Moss and his Livermore colleagues had predicted in 1999 that the light emissions in a water system come from the surface of an optically thick region of about the same radius.[4]

Sulfuric acid, not water

Flannigan and Suslick tried to form single bubbles in sulfuric acid and other liquids with low vapor pressures in the hope of getting brighter emissions than with water. A group from the Istituto Elettrotecnico Nazionale Galileo Ferraris in Turin, Italy, had already reported a few-fold increase in intensity using sulfuric acid.[5] The Illinois team was able to push that brightness much higher.

One reason to expect the increased brightness[6] is that sulfuric acid is more viscous than water. The higher viscosity helps keep the bubbles both stable and spherical as they oscillate. Furthermore, sulfuric acid's low vapor pressure prevents most of the acid from evaporating into the bubble's interior. Thus, the bubble should consist almost entirely of atoms of argon that had been dissolved in the sulfuric acid. Because Ar atoms have no vibrational or rotational degrees of freedom, most of the cavitation energy should go into kinetic energy. Additionally, the high viscosity and low vapor pressures somehow combine to let researchers drive bubbles at much higher acoustic pressures (above 5 bar) than is possible with bubbles formed in water.

Seth Putterman of UCLA is not convinced that the lower vapor pressure can fully account for the increased brightness. He thinks the brightness might have something to do with the bubble dynamics. Unlike the very stationary bubbles in most SBSL studies, the bubble in the Illinois experiment has a jittery motion.

In studies of SBSL using argon or xenon in water, the emission spectrum has been rather featureless. The temperature within those bubbles has been estimated by fitting the spectrum to a blackbody temperature, or sometimes to the spectral distribution expected from bremsstrahlung. Such estimates have not been very satisfactory because they are model dependent.

In MBSL, researchers routinely see both the continuum and discrete spectral lines. The spectral lines give a handle on the temperature because they correspond to chemical species that form only at high temperatures. By knowing the temperature dependence of the reaction rates that produce these species, experimenters have estimated the temperatures reached during cavity collapse to be around 5000 K.

For SBSL in sulfuric acid, Flannigan and Suslick found both the blackbody-like continuum typical of SBSL in water and a series of discrete spectral lines at longer wavelengths, as seen in figure 2a. The spectral lines, which are shown in figure 2b with the underlying continuum subtracted, correspond to transitions between highly excited states of Ar. In particular, the lines correspond to jumps between the 4*p* states (13.1–13.5 eV above the ground state) and the 4*s* states (11.5–11.8 eV) of the Ar atom.

To populate those excited states requires collisions with high-energy particles, such as electrons. Such particles would most likely come from the high-energy tail of some Boltzmann distribution. By studying the relative population of excited atomic states, Flannigan and Suslick calculated the effective temperature of the bubble

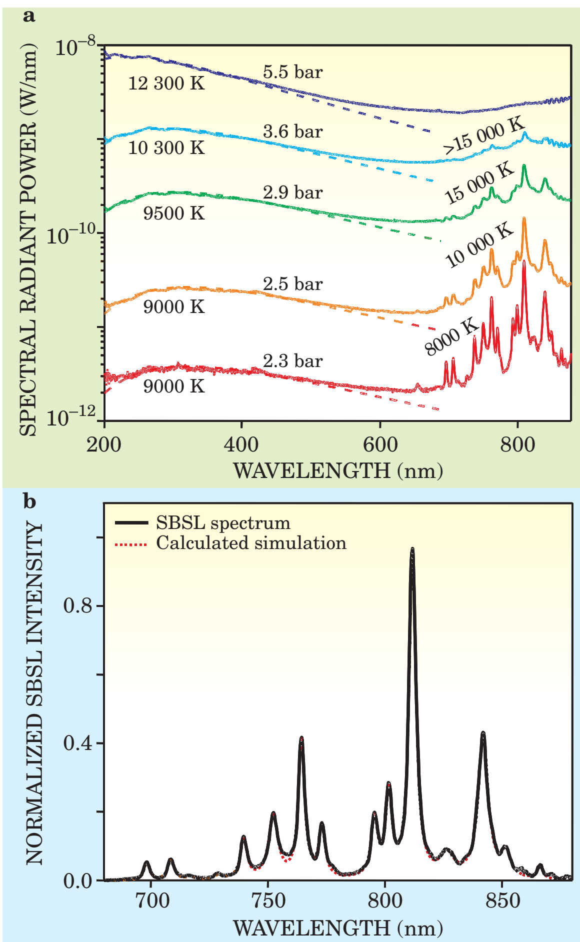

Figure 2. Emissions from a sonoluminescing bubble testify to the presence of a plasma. Spectral peaks seen at wavelengths longer than 650 nm correspond to transitions between excited states of argon that are likely to have been populated by collisions with energetic charged particles, and not thermally excited. **(a)** Spectra at five different acoustic pressures. Temperatures at short wavelengths are estimated from blackbody fits (dashed lines); those at higher wavelengths from the relative population of Ar's excited states. **(b)** The Ar line emission at 2.8 bar with the continuum subtracted (solid line) nicely fits the simulations (dotted). Lines correspond to transitions between 4*p* and 4*s* states of Ar. (Adapted from ref. 2.)

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.