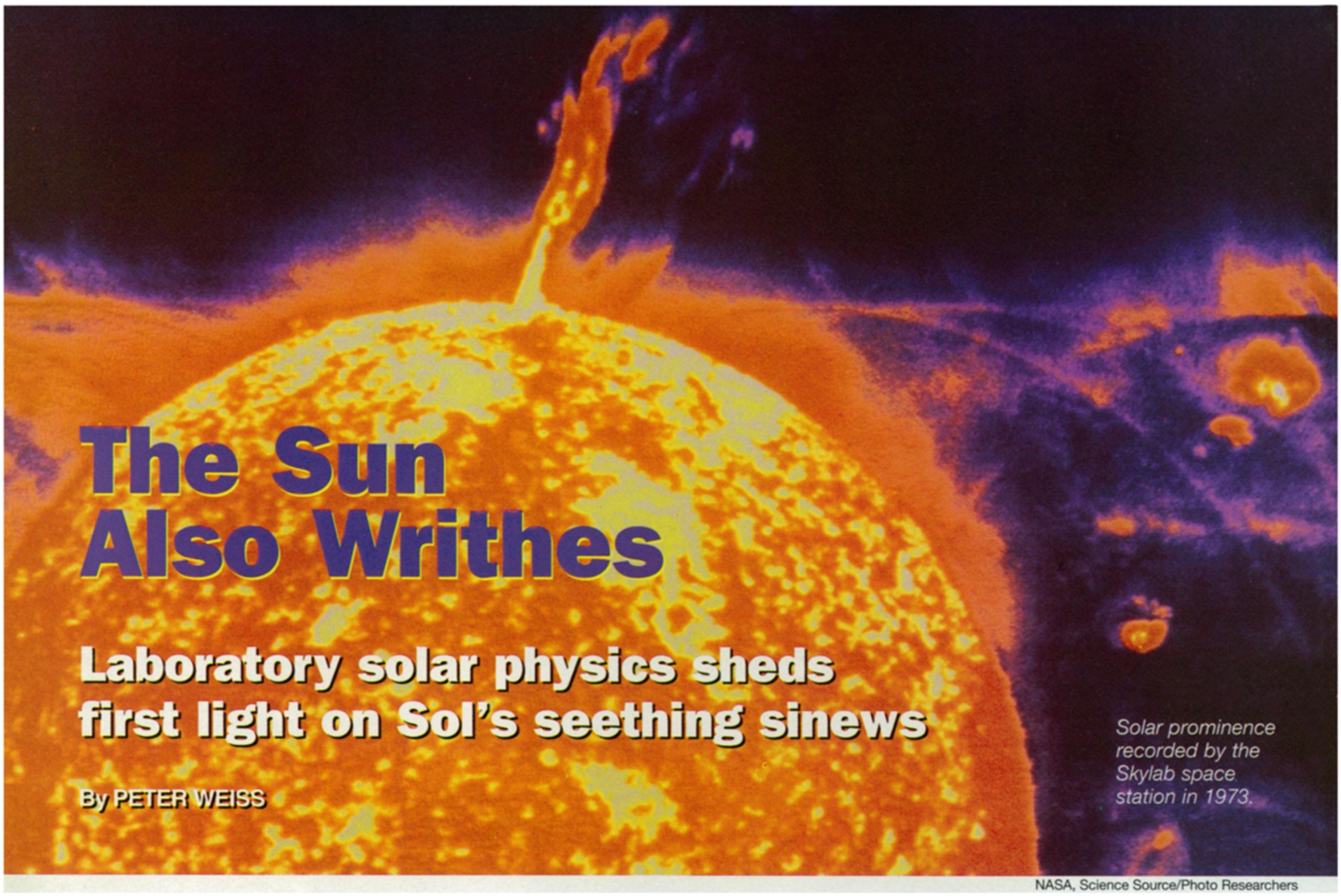


The Sun Also Writhes

Laboratory solar physics sheds first light on Sol's seething sinews

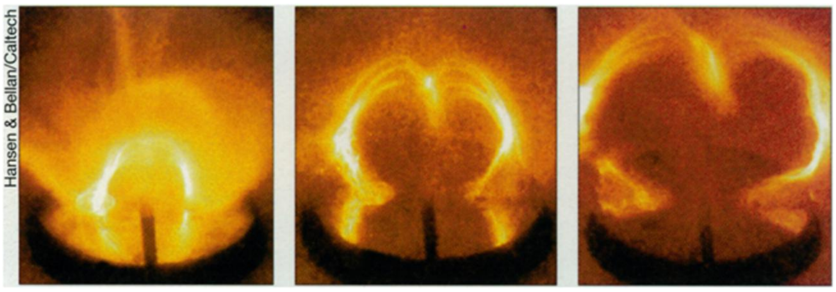
By PETER WEISS

Solar prominence recorded by the Skylab space station in 1973.

NASA, Science Source/Photo Researchers

Paul Bellan creates tiny solar eruptions in his laboratory. He admits that they're not true miniatures of events on the sun. Yet they are faithful enough, he believes, to provide new clues to some important solar mysteries.

The sun is a huge ball of gases—but not electrically neutral gases as in Earth's atmosphere. Nuclear fusion at the core of the sun creates conditions of astounding heat, fast-moving particles, and mighty electric and magnetic fields. These forces shear the electrons from atoms in ordinary gases, transforming the gases into clouds of charged particles called plasmas.



Hansen & Bellan/Caltech

A laboratory-simulated solar prominence the size of a teapot handle wells up from the end of a horseshoe-shaped magnet. Electric currents going through this plasma, which is at roughly 150,000°C, generate repulsive forces that make the arc swell and then fly apart.

Plasmas exhibit extraordinarily complex behavior not seen in other fluids. Scientists have been studying them in the laboratory for decades in pursuit of nuclear fusion as a commercial energy source. Recently, Bellan, who is at the California Institute of Technology, and a small cadre of other plasma physicists have begun to apply their laboratory methods to the study of the sun.

Many intriguing solar features arise from plasma's peculiar behavior. Tumultuous conditions sculpt the plasma at the sun's surface into huge arches of fluid flame known as solar prominences. In the intensely hot outer atmosphere, or corona, collisions of huge blobs of plasma fuel enormous jets of energy called solar flares, which often fire far into space.

In other spectacular discharges called coronal mass ejections, the corona sloughs off not just energy but also huge billows of hot plasma, sending billions of tons of the sun itself into space. These ion clouds sometimes crash into Earth with sorry consequences for satellites and power grids (SN: 3/6/99, p. 150). One such speeding plasma bomb hammered Earth's magnetic field in March 1989, causing electromagnetic disruptions that blacked out the Canadian province of Quebec. Another January 1997 mass ejection may have fried an AT&T satellite (SN: 2/1/97, p. 68).

These and many other features of the sun are poorly understood because solar measurements are sparse and theories of plasma physics are imperfect. "Often in solar physics, you are stuck trying to infer from an incomplete set of measurements why things occur," says Richard Canfield of Montana State University in Bozeman.

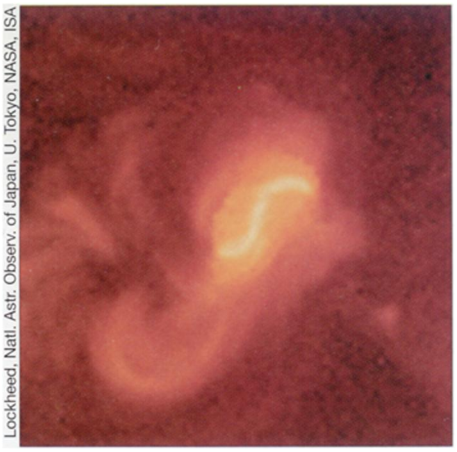
The only tools available for solar study have been ground-based telescopes and satellites. Canfield and his fellow observers "can't stick in a probe and actually make a measurement like you could in a laboratory," he says.

Skeptical at first that a device that fits in a laboratory could yield anything meaningful about a realm as vast as the sun, many solar observers are now finding themselves pleasantly surprised.

They admit that such laboratory experiments are yielding new insights into solar phenomena on multiple levels—

from the looping plasmas on the sun's face to the rushing torrents of plasma believed to flow in its depths. The lab scientists are also tackling fundamental aspects of plasma behavior that may have a bearing on a range of solar features.

"I believe [the laboratory experiments are] going to lead eventually to a much clearer understanding of solar activity," says David Rust, a solar observer at Johns Hopkins University Applied Physics Laboratory in Laurel, Md.



Lockheed, Natl. Astr. Observ. of Japan, U. Tokyo, NASA, ISA

Strands of solar plasma contort into bright, hot S shapes before eruptions. The Yohkoh satellite snapped an X-ray picture of this S on April 24, 1993.

During an experiment in Bellan's lab, the naked eye sees a single pink flash. A high-speed camera, however, shows a miniature, glowing arch expanding from the end of a horseshoe-shaped magnet. The curve builds, wavers, twists, and then dissipates into the surrounding vacuum—all in a matter of microseconds.

There's no comparison in grandeur between such pip-squeak arcs and the mighty solar prominences that Bellan is trying to replicate. The sun's contorted arches of plasma as hot as tens of thousands of degrees Celsius can tower up to 100,000 kilometers above the churning solar surface (SN: 1/4/97, p. 4). They also can linger for days or weeks. Nonetheless, a variety of shared characteristics makes the resemblance good enough, Bellan says.

In his experiments, Bellan zaps puffs of hydrogen gas with hundreds of megawatts of electricity to transform the gas into plasma and to make the arcs twist in response to their own magnetic forces, as many of their big solar cousins do.

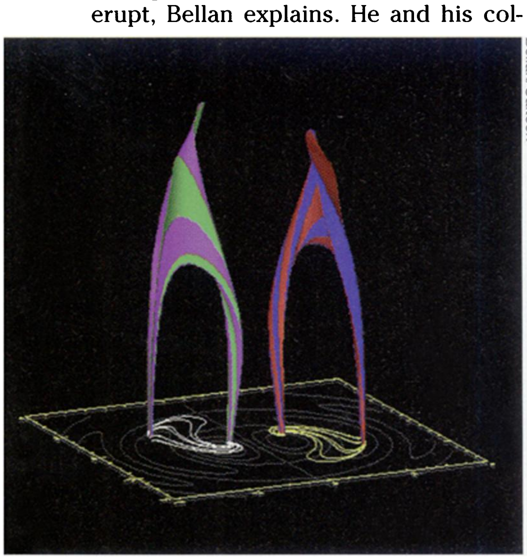
"We can actually duplicate something going on in the sun that people thought [was explained by] a very different physics," he says.

The simulations may shed new light on how prominences arise, contort, and erupt, Bellan explains. He and his colleague Freddy Hansen reported their work last November at the American Physical Society's Division of Plasma Physics meeting in New Orleans.

The simulations have already led them to a new, well-received model for the formation of bright, S-shaped features on the solar surface that appear to lead to solar eruptions within hours or days (SN: 3/13/99, p. 164). In a 1996 study of some 50 such filaments seen in satellite observations, researchers led by Rust concluded that the S shapes were top-down views of extraordinarily hot, twisted prominences. Some scientists suspect that if prominences get too twisted, they become unstable and erupt.

In a model developed by Bellan, a plasma's own magnetic forces produce the S shapes, which also appear in computer simulations of his lab arches. The magnetic forces twist the plasma until its current flows parallel to its magnetic field lines, Bellan explains.

Some researchers, such as John T. Gosling at Los Alamos (N.M.) National Laboratory, however, don't agree that the S is a contorted prominence. Data collected from erupting solar plasma ejected into space have shown that prominences within it remain at their typical temperatures, he says. The S shapes, however, appear to reach coronal temperatures of 1 to 2 million degrees. In observing the S's, "I think we're probably looking down at material surrounding the prominence, rather than the prominence itself," he comments.



Bellan/Caltech

At high electric currents, arches in these computer-simulated plasmas project in two dimensions as S-shapes or mirror-image S shapes, indicating severe twisting caused by self-generated magnetic fields.

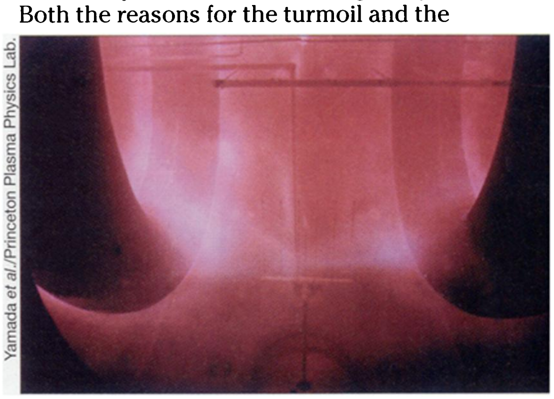
Whether on the sun or in a laboratory, plasmas flow in a complicated manner that taxes the ability of scientists to model and predict their course. The complexity arises from the fundamental interdependence of electricity and magnetism. When a plasma moves, an electric current flows—by definition—because the particles of the plasma are charged. But current flow creates a magnetic field, and magnetic forces act on moving charges. So, a moving plasma pushes itself around and by doing so creates new forces that push it yet some more.

In the sun's deep interior, scientists believe, such turbulence somehow generates a huge, orderly river of current—the solar dynamo—that creates the star's magnetic field. Variability in this dynamo probably also drives the 11-year cycle of surface activity.

Researchers at the University of Wisconsin-Madison have reproduced that smooth stream of charge in a laboratory plasma. When they create a hydrogen plasma held by magnetic forces inside a doughnut-shaped vessel, tumultuous magnetic fluctuations "like splashing in a bathtub" arise spontaneously, says Wisconsin's Stewart C. Prager.

To measure the fluctuations, the Wisconsin researchers salt their plasma with carbon atoms that they use as tracers. Then, by observing shifts in the wavelength of the radiation emitted by the plasma-heated tracers, the scientists determine plasma motions. Magnetic sensors studding the outside of the vessel, which is about 5 meters in diameter, also reveal the shifting magnetic-field directions inside.

"These magnetic fluctuations, we believe, lead to the dynamo effect in our laboratory and in the sun," Prager says. Both the reasons for the turmoil and the way it produces an orderly electric flow are the quarry of the research group he leads.



Yamada et al./Princeton Plasma Physics Lab.

Glowing pink plasma rapidly heats as invisible magnetic field lines break and reconnect around current-carrying coils (darker bands) in a laboratory chamber.

For solar science, deeper understanding of plasmas is the ultimate aim. For fusion energy research, however, the scientists also hope to find a way to banish the dynamo effect from reactors because it diverts energy that could otherwise heat the plasma and sustain fusion reactions.

Even a plasma in the lab remains difficult to study. Developing the technologies for measuring their hot, highly charged, magnetized plasma has proven challenging and time-consuming. Five years ago, the researchers were able to take readings only at the fringes of the plasma. In the May Physics of Plasmas, they will describe finally probing the 5-million-degree core.

Another fundamental solar mechanism yielding to laboratory study is magnetic reconnection, which is the breaking and reattaching of magnetic field lines that have snapped after twisting, stretching, or crossing other lines. To observe reconnection, Masaaki Yamada and his colleagues at the Princeton Plasma Physics Laboratory in New Jersey are slamming together pairs of doughnut-shaped plasma clouds known as spheromaks.

Prager et al./University of Wisconsin

The thick metal walls of vacuum vessels like this one make it possible for scientists to study plasmas heated to solar temperatures in the laboratory.

The phenomenon is attracting interest from solar and fusion researchers because it may be accompanied by powerful energy releases and therefore play a key role in features of the sun. Some scientists suggest that reconnection accounts for the mysteriously high temperature of the corona. At more than a million degrees, the corona blazes at 200 times the temperature of the solar surface (SN: 11/8/97, p. 295). Reconnection may also energize solar flares, which explode from the corona. They typically attain temperatures in the tens of millions of degrees.

Fusion researchers—Yamada's group counts among them—also recognize magnetic reconnection as an important aspect of reactor plasmas that may be useful in boosting plasma temperatures.

Although suspecting that reconnection plays a leading role in the solar drama, theorists have struggled for decades to explain how. Plasmas, especially on the sun, are wispy gases, but the magnetic fields threading through them make them behave as if they were viscous fluids, flowing and intermingling slowly. According to the classical theory of plasmas, magnetic field lines cannot reconnect or, at best, can do so only at a stately pace because of this viscosity. This model is obviously incomplete because it would require millions of years for solar flares to release the energy they expel in minutes or hours.

To resolve the dilemma, researchers have proposed revisions to the classical picture. They postulate that the reconnections occur under extraordinary conditions of electric current flow, perhaps accompanied by shock waves, at the narrow boundaries where magnetic fields with opposite directions clash. Until Yamada's group began its experiments 3 years ago, no one had attempted to detect such conditions.

The results of the Princeton experiments don't quite match any of the theories of reconnection advanced so far, Yamada explains. As described in the April 13, 1998 Physical Review Letters, he and his colleagues see reconnection taking place at a pace much faster than classical theory would allow but still only a hundredth of the rate required to explain solar flares. Also, within the turmoil of the spheromaks' collision, they see no evidence of shock waves.

Uncertain how to explain their findings, the Princeton researchers suggest that they may have discovered a new phenomenon that none of the previous theories included. It's a turbulence in the plasma that would increase interactions between plasma particles and thereby promote reconnections.

The researchers have recently enjoyed some confirmation of the relevance of their lab work to actual circumstances in space. They measured the thickness of the narrow boundary where two, magnetically opposite plasmas collide and cancel each other's magnetic fields. The as-yet-unpublished measurement is in keeping with satellite readings from the region of space where the magnetic fields of the sun and Earth meet, Yamada says.

As the fields of solar physics and fusion research meet and begin to blend, both disciplines are getting a shot of energy. Fusion scientists are awakening to the sun as a place to test the theories developed for their reactors. And, for solar observers, lab experiments are filling in details lost across the 150 million km of space between sun and Earth.

"The laboratory work brings an air of reality," solar observer Canfield says. "It really holds your feet to the fire." □