MEETING BRIEFS

Plasma Physicists Seek New Uses for the Legacy of Fusion

LOUISVILLE, KENTUCKY—On 6–10 November, plasma physicists gathered here for their first major meeting since Congress decimated funding for fusion-energy research. Organizers noted optimistically that attendance had dropped only 10% from 1994. There was a more genuinely hopeful sign among the papers and posters, however. The 1285 physicists in attendance are eagerly applying hardware and concepts developed over decades of fusion research to new tasks—everything from spacecraft propulsion to understanding magnetic fields in the cosmos.

Sounding Out a New Dynamo

Magnetic fields seem to be the universe's ultimate weed, sprouting spontaneously in galaxies, stars, and planetary cores—wherever there is a conductive plasma or liquid metal. Just where they come from is a puzzle: It takes an organized, large-scale electric current to generate a field, and there's no obvious source of current in any of these objects. Dynamo theorists, who study how magnetic fields arise, thought they had one thing straight: Fluctuating electric fields—created by effects such as heat-driven convection, fluid buoyancy, or energetic plasma instabilities—ultimately drive the "cells" of current that add up to produce the large-scale magnetic field. But this picture just got a new twist.

New measurements presented at the conference by Hantao Ji, who recently moved from the University of Wisconsin to the Princeton Plasma Physics Laboratory, imply that those currents can be generated by something as simple as pressure fluctuations, analogous to sound waves in an ordinary gas. That proposal would amount to a major extension of dynamo theory, says Scott Robertson of the University of Colorado, Boulder: "You ask, 'Is it all driven by the same mechanism?' Ji [in his talk] was saying, 'No—it's not the same.' That's heavy stuff."

The new insight into how plasmas can generate magnetic fields comes from a child of the fusion program, a device called the reversed-field pinch (RFP). RFPs were originally thought up as a way to confine a hot plasma long enough for its ions to fuse, producing energy (*Science*, 14 July, p. 154), but they have also turned out to be a good laboratory system for studying how magnetic fields can spontaneously take root in a plasma. The basic setup is a donut-shaped container with current-carrying coils wrapped the short way around the donut. These coils create a "toroidal" magnetic field—a field looping the long way through the donut.

When plasma gets dumped into the container, however, this field spontaneously begins to twist away from the toroidal direction, at an angle that increases toward the container's walls. At the wall itself, the field actually reverses its direction, creating a toroidal component of the field oriented in the opposite direction from the field applied by the coils. This configuration gives the device its name—and also keeps fusion plasmas securely imprisoned.

The plasma's turbulent motion is the immediate cause of this new, spontaneous field, says Stewart Prager of the University of Wisconsin, a collaborator in the experiments. As each packet of conductive plasma moves through the existing magnetic field, it generates a tiny current. If these fluid elements simply sloshed back and forth, the currents would average to zero. But the kind of turbulence found in an RFP generates small-scale magnetic fluctuations as well as small-scale motions. The plasma's jitter and the magnetic fluctuations act in phase to generate a net, large-scale current, producing a new large-scale magnetic field—the dynamo field that creates the twist.

What shakes the plasma in the first place, according to dynamo theory, is a fluctuating electric field, generated in the RFP by fine-scale instabilities—in effect, tiny electrical storms driven by the plasma's internal energy. Working with RFPs at the University of Tokyo, the University of Wisconsin, and the Electrotechnical Laboratory in Tsukuba, Japan, Ji and co-workers set out to test this picture. They began by measuring the small-scale electric and magnetic fluctuations to see if they had the correct magnitudes and phases to produce the observed large-scale dynamo fields. But the observations "didn't match up," says Ji.

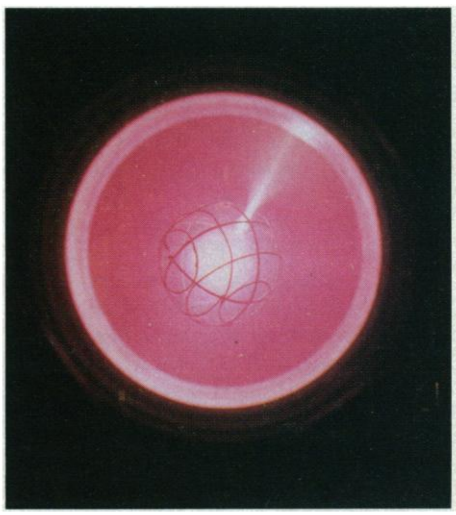
Ji speculated that the missing element might be pressure fluctuations—a phenomenon dynamo theorists have neglected, because so much of plasmas' behavior depends on electric and magnetic fields rather than on pressure. Ji realized, however, that sufficiently strong pressure fluctuations, possibly caused by new instabilities, could play the role of an electric field in knocking the fluid elements about. "This time it was a success," he says, as the probes showed that the pressure and magnetic fluctuations together could generate the dynamo field. Further measurements showed that the standard dynamo worked fine when the plasma was tenuous, but the new effect took over in denser plasmas. This dividing line is an observation that theorists have yet to explain.

Could the new dynamo have wider implications in a universe that is overgrown with magnetic fields? Katia Ferrière, a theorist who studies astrophysical dynamos at the Observatoire Midi-Pyrénées in Toulouse, France, points out that simple arguments about the strength of turbulence at different size scales suggest that such pressure fluctuations should be small in settings like the galaxy and the interior of the sun. Nevertheless, she says the new effect "is impossible to rule out" based on existing observations. Ji, for his part, is scouring the astrophysical literature for any hints that the effect could help explain why magnetic fields cling to the cosmos like kudzu.

Move Over, Wernher von Braun

In *The Evolution of Useful Things*, the engineer Henry Petroski marveled at "the almost limitless functions to which a single form can lead." Petroski was writing about the humble paper clip, but several presentations at the plasma conference show that the same may hold for much grander devices—reactors meant to confine a plasma while its ions fuse, generating energy. At least two such devices might find potential new uses in spacecraft propulsion.

Plasma-powered rockets may well turn out to be as far-fetched as fusion reactors have been accused of being. But while one scheme is admittedly visionary, aiming at fusion-powered spaceships, the other aims at a comparatively down-to-earth application: low-power thrusters, driven by electric cur-



YIBIN GU

Ball of fire. Ions jet from a 4-cm metal cage in what could be a prototype satellite thruster.

rent rather than fusion, for maneuvering satellites. Either way, researchers note that, in a time of sharp cutbacks in the fusion program, they have little to lose by proposing imaginative new uses for their technology. "My strategy is, we'll concentrate on [propulsion and] anything else I can think of now," says George Miley, director of the Fusion Studies Laboratory at the University of Illinois, Urbana-Champaign.

Working plasma thrusters, proposed for use on next-generation communications satellites, already exist, based on flat, electrically charged grids that draw beams of ions through a nozzle. These devices, however, tend to be short-lived, as the ions erode the fine mesh. But at the plasma physics meeting, Miley proposed that a fusion device invented by ITT's Philo Farnsworth—better known as the principal inventor of television—can provide a sturdier alternative. As modified by Farnsworth's co-worker Robert L. Hirsch, now president of Energy Technology Collaborative in Washington, D.C., the fusion device consists of a metal cage carrying a strong negative charge, which confines a low-pressure cloud of plasma that, Hirsch hoped, would serve as fusion fuel.

In this scheme, the symmetric negative charge would drive beams of positively charged ions into the cage's center, where they would collide and fuse. Unfortunately, says Hirsch, the fusion community has long favored schemes to use electric rather than magnetic fields to confine plasmas, and Department of Energy support for studies of the device's fusion potential has dwindled. But in the meantime, Miley found that even if the device has no chance of achieving fusion, it can serve as a thruster.

The cages for his fusion experiments were "all made by students—and it's a little bit tricky, because [the cages] have to be quite symmetrical," Miley explains. When a student wound a cage with one hole slightly larger than the others, the plasma unexpectedly started squirting only out of that hole—probably because of the near-perfect symmetry of electric potentials elsewhere in the cage. "We didn't think 'this is a thruster' at the time," says Miley, but the idea came to him as he was searching for new projects for his lab.

"When opportunity knocks, it's good to pay attention," says Hirsch. "That's what George is doing." The inertial electrostatic thruster, as Miley calls it, would rely on energy siphoned from the cage's bias voltage. Like other plasma thrusters, it would use propellant sparingly, making it useful for low-thrust, long-lifetime applications like maneuvering a communications satellite. And it should also last longer than existing flat ion thrusters, because the ions are channeled through an opening in the cage.

Terry Kammash, a professor of nuclear engineering at the University of Michigan, is plotting a more ambitious future for an erstwhile fusion machine. The device, called the magnetic mirror, actually functions more like a leaky bottle. It consists of current-carrying coils arranged in a cylinder, which generate a large bundle of magnetic-field lines inside the cylinder. At two points, stronger currents encircling the cylinder constrict the field lines, creating choke points that reflect ions following the field lines. The effect partly confines a hot plasma to the region between the constrictions, encouraging it to fuse. The mirror-fusion program "died on the vine" when it didn't live up to initial hopes, says Kammash.

But Kammash wants to make a virtue of the mirror machine's leakiness. Working at very high plasma densities, Kammash envisions making one end of a mirror leakier than the other and igniting a fusion reaction inside it. Plasma squirting out the leakier end would push the rocket. Kammash and his Michigan colleague Myoung-Jae Lee, who presented results in Louisville, calculate that such a machine, weighing about 500 metric tons and measuring less than 100 meters in length, could make a round-trip, crewed flight to Mars in a few months—compared to several years for a chemical rocket.

The fusion thruster "has characteristics that are quite nice as far as something you'd want to explore the solar system with," says William Emrich, a senior engineer at the National Aeronautics and Space Administration's Marshall Space Flight Center in Huntsville, Alabama. The rocket could be assembled in orbit, and its fuel weight would be "minuscule" compared to that of other rockets, Emrich says, adding, "You could go to Pluto with no problem."

How to Detonate a Plasma

More than a decade ago, Princeton University plasma theorist Russel Kulsrud shook his head and summarized the problem this way: "I don't understand why things go bang."

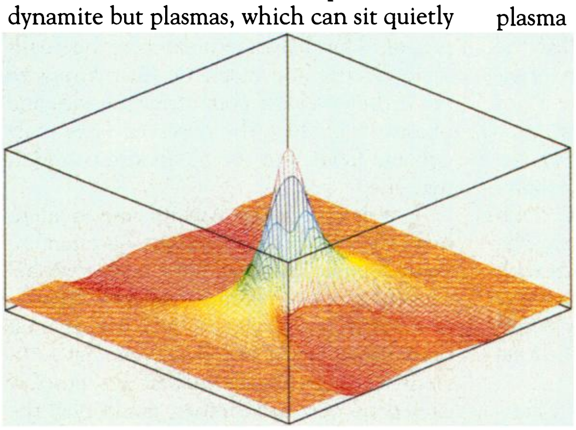
He didn't mean familiar explosives like dynamite but plasmas, which can sit quietly for long periods and then detonate for no apparent reason. In the sun's corona, for example, huge arches of plasma rise above the sun's surface, apparently stable, until the structure suddenly erupts in the catastrophic events called coronal mass ejections. Likewise, in the donut-shaped fusion devices called tokamaks, a hot, confined plasma can suddenly "disrupt," hurling itself against the vessel's walls. Theoretical calculations generally show that if a quiescent plasma passes an instability threshold—say, as more material is poured into a cage of magnetic fields—the plasma should shiver and then rearrange itself to become stable again. But theorists simply may not have followed the plasma's contortions for long enough to see the explosion.

At the Louisville conference, Steve Cowley of the University of California, Los Angeles, a former student of Kulsrud's, presented theoretical work that takes that extra step and may go a long way toward explaining why things go bang. Working with a model of a plasma confined by magnetic field lines, which become "stretchy" when plasma gets loaded onto them, Cowley has found that a narrow, marginally unstable bundle of lines can undergo explosive contortions. Although the field lines try to snap back at first, Cowley found that, like overstretched elastic, they eventually lose their resiliency and give up the fight. The result is a "blast wave" effect that progressively destabilizes the rest of the plasma.

"What Steve has done is to find a concrete, three-dimensional, physical situation in which this phenomenon occurs," says Ravi Sudan of Cornell University. The calculation considers an instability that might develop in a magnetic arch on the sun, in which a thin bundle of field lines, loaded with relatively tenuous plasma, starts to bob upward through overlying, denser plasma. Because the endpoints of the field lines are fixed, as they are on the sun, the lines stretch like rubber bands. In the traditional picture they eventually resist the instability and snap back. But Cowley's nonlinear calculations show that as the field stretches even further, plasma expands in the deforming bundle, forming bulging, unstable "fingers" of instability. As the fingers thicken, the magnetic field weakens and loses its ability to snap back, resulting in explosive growth and launching a blast wave through the plasma.

Cowley points out that similar instabilities develop in many explosively unstable plasmas. Although he cautions that the calculations must still be carefully compared to data from tokamaks and the sun, Cowley says, "this could be why things go bang."

–James Glanz



STEVE COWLEY

Out of control. A fingerlike instability in a plasma begins its runaway growth in new theoretical calculations.