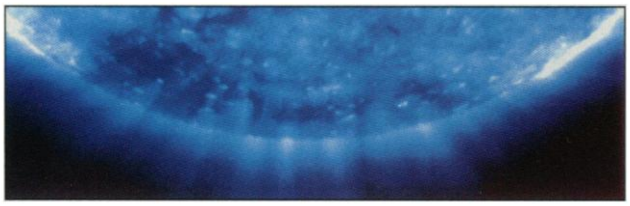
SOLAR PHYSICS

Unruly Sun Emerges in Solar Observatory's First Results

MADISON, WISCONSIN—"A gaze blank and pitiless as the sun" was how William Butler Yeats evoked faceless doom in his poem "The Second Coming." The glare of the sun may still seem pitiless, but it is blank no longer—at least not to solar physicists, and especially not to researchers analyzing the initial torrent of data from the Solar and Heliospheric Observatory (SOHO), a spacecraft that has been returning the sun's glare with a steady gaze of its own since early this year.



SOHO EIT CONSORTIUM

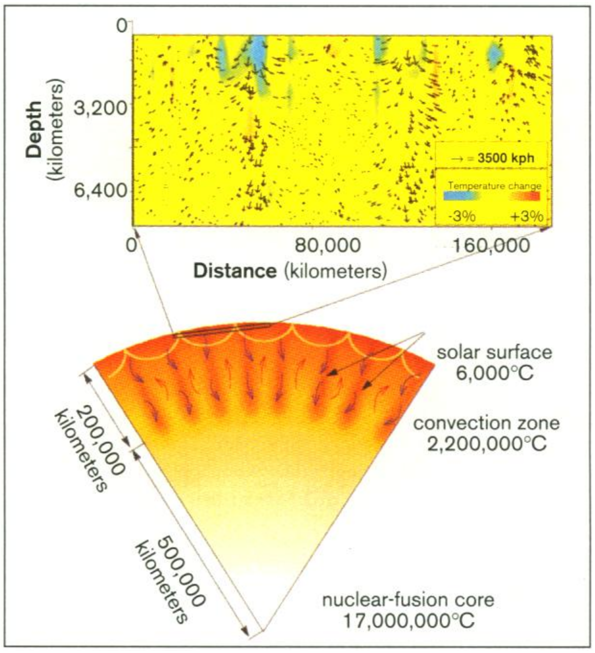
Polar plumes. Jets of hot gas emanate from the sun's south pole in an extreme-ultraviolet image.

SOHO researchers reported at the American Astronomical Society meeting last month that the spacecraft's 12 instruments are revealing a virtual bacchanalia of twisting magnetic field lines and turbulent gases in the sun's surface layers and atmosphere. The sheer level of activity is unexpected for this point in the 11-year cycle of solar activity, when the sun is supposed to be in a lull. And SOHO's detailed look at the commotion has uncovered several mysteries that could portend major revisions in scientists' understanding of the sun. The convection cells that carry energy from the sun's deeper layers to its surface, like the boiling of a pot of soup, seem to have the wrong shape for most theories; small-scale magnetic fields at the solar surface are more active than theorists predicted, and they skitter about in puzzling patterns; and unexpectedly wide regions of the sun convulse when it releases coronal mass ejections (CMEs), occasional eruptions of ionized gases that can trigger magnetic storms on Earth. These and other findings, says Richard Fisher of NASA's Goddard Space Flight Center, "are going to change people's perception of how the solar system works."

Launched last December, SOHO sits at the so-called L_1 Lagrangian point, 1.5 million kilometers from Earth in the direction of the sun, where the gravitational pull of the two bodies is in balance. Because the spacecraft simply hovers there rather than circling the earth, with nary a trace of atmospheric gases to create turbulence, "you've got the calmest view of the sun you could possibly imagine," says Alan Gabriel, director of the Institut d'Astrophysique Spatiale in Orsay, France, a collaborator on the joint European Space Agency/NASA project.

Like nearly all efforts to study the sun, the $1.2 billion spacecraft is limited to the clues it can glean from the sun's surface and atmosphere. But some of those clues point to conditions deep inside. The amplitude and timing of vibrations that shake the sun's surface deliver a report about conditions in the interior, where they originate (*Science*, 31 May, p. 1264). And although the SOHO experiments designed to pick up the deepest waves—those that probe the sun all the way to its core—haven't yielded clear insights yet, theorists' attention has already been captured by evidence from shallower layers.

A SOHO instrument called the Michelson Doppler Imager (MDI) measures slight Doppler shifts in particular wavelengths of light as patches of the surface bob up and down because of pressure waves—sound waves, in effect. Excited by turbulence at the surface, the waves travel through the sun's outer layers and pop up again elsewhere. By measuring the travel times of waves emanating from a particular spot on the surface, the MDI can detect "head winds" or "tail winds" due to convection beneath the surface. The result, says collaborator Thomas Duvall of Goddard, is "views of unprecedented clarity of flows beneath the sun."



T. L. DUVALL JR., A. G. KOSOVICHEV, P. H. SCHERRER, P. N. MILFORD

Seething sun. Lateral circulation beneath the solar surface is shallower than predicted, according to SOHO results *(top)*.

The first 8 hours of data from the MDI's high-resolution mode, in which it zooms in on particular areas rather than looking at the full solar disk, have revealed the anatomy of vast convection cells to depths of 7000 kilometers. The tops of the cells are visible on the sun's surface as so-called supergranules, grainlike areas 20,000 or 30,000 kilometers across where gas flows steadily outward from the center of each cell to its boundaries. But their underpinnings have been mysterious. A few theories predicted cool, narrow "plumes" of downgoing material in the centers of the supergranules, and the MDI has provided tentative confirmation.

But the overall shape of the convection cells is a surprise: Rather than churning the sun to depths of tens of thousands of kilometers as expected, each cell is shallow, like a pancake. Shallow cells could pose a problem for theorists because they would be less efficient than deeper cells at transporting energy outward from the sun's interior. The new picture of the cells will also affect theorists' understanding of how the sun's convective churning generates its magnetic field. The results are still preliminary, however, and with so much at stake, says Duvall, "I think we still need to poke and squeeze things and make sure of what we're seeing."

Magnetic hang-ups. By tracking individual features on the sun's surface, the MDI can also directly measure flows along the surface—like gauging winds in Earth's atmosphere by watching clouds—and follow small-scale magnetic fields, which shift lines in the spectrum of light from the magnetized gases. Because the churning gases are ionized, and hence electrically conductive, they should sweep the magnetic field along, says Goddard's Art Poland, the SOHO project scientist in the United States: "The dogma is that gas pressure dominates the magnetic field."

The MDI results bear out the dogma in the interiors of the supergranules, where the fields seem to follow the gas as it flows out to the supergranule boundaries, says MDI collaborator Alan Title of the Lockheed Palo Alto Research Laboratory in California. But at the edges of the supergranules the field lines get "hung up," refusing to be

Spying On the Sun—on the Cheap

As solar physicists feast on new data from SOHO, the Solar and Heliospheric Observatory (see main text), one crucial part of their observational appetite isn't being satisfied: a craving for high-resolution images of the sun's surface and the tight bundles of magnetic field that swarm across it like spooked wildebeests. These bundles, just tens of kilometers across, may carry the energy responsible for much of the turmoil SOHO is detecting. Yet our view of these features, which often show up as threadlike striations in the hot gases, has been "fleeting" at best, says Eugene Parker of the University of Chicago. Seeing them clearly would require an orbiting solar telescope with a 1-meter mirror. And cost estimates for building such an instrument have ranged up to an impractical $1 billion.

Enter "Solar Lite," a large, low-budget solar telescope conceived by Alan Title of the Lockheed Palo Alto Research Laboratory in California, who thinks it could do the job for well under $100 million. The secret to its low cost is Russian expertise in advanced materials and optics—along with the low wage scale of Russian engineers. Funded by part of an initial $2.2 million grant from NASA, a 1-meter primary mirror and smaller secondary are already under construction at the Vavilov Institute in St. Petersburg, which once built surveillance satellites for the former Soviet Union. If these components live up to expectations, Title and Lockheed colleague Theodore Tarbell hope to win NASA funding for the full mission. Bill Wagner, head of solar physics at NASA, thinks they have a chance. Title is "one of the cleverer people in the business," says Wagner.

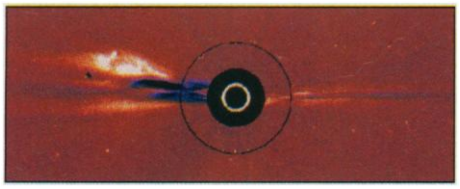
Other solar physicists certainly hope Title succeeds. "We know enough to know that a lot of the essential action goes on at scales below 100 kilometers on the sun," says Parker—processes including the small-scale entangling and reconnection of field lines and the generation of plasma waves. "And if you don't have something at least 1 meter [in aperture], you're not going to see it." SOHO's instruments, with apertures of just a few centimeters, can only see features more than about 1000 kilometers across.

To be rigid enough for a solar telescope, however, a 1-meter mirror made of glass has to be thick and heavy. Advanced ceramics can lighten the weight, but at a large penalty in cost. But the Russian components are being made from a material never before used for an astronomical telescope: silicon carbide, which is not only relatively cheap but also stiff and lightweight. The factor-of-5 weight savings that results "just ripples through the system," says Wagner, leading to lighter supports and servos and a smaller, cheaper rocket to boost the telescope into orbit.

Wagner adds, though, that it remains to be seen whether the optical quality of the silicon carbide components will match that of expensive materials like advanced ceramics. If the Russian components pass those tests, he says, the project will have a shot at receiving the $70 million or so needed to fly it before the end of the decade. And if that mission works, the same concept could be applied to even larger telescopes—up to 3 meters in diameter, more than enough to satisfy the most data-hungry solar physicist. **–J.G.**

dragged along the boundaries to points where the flow of gas converges. Perhaps, says Title, "the field is being replenished along the boundaries by a process we don't understand," such as a mysterious dynamo operating at the surface.

Activity just above the restless solar surface is the focus of another SOHO instrument, the Extreme-ultraviolet Imaging Telescope (EIT). Radiation in that part of the spectrum comes from gases at temperatures between 60,000 and 2.5 million kelvin—the temperatures found at the base of the sun's tenuous atmosphere, the corona. The mechanisms that heat the corona to those temperatures, hundreds of times hotter than the surface, are exactly what the EIT is supposed to investigate. Its early observing program may have provided a clue: dazzling images of so-called polar plumes—rays of hot gas poking into relatively cool, dark regions at the sun's poles. The early data, says Goddard's Joseph Gurman, suggest that the plumes may be the result of loops of magnetic field that burst near the surface, releasing energy and locally heating the corona where the plumes are found. The observations may even shed light on the stunning discovery, by another SOHO instrument, of oxygen ions over the sun's poles that reach temperatures extraordinary even for the corona, 100 million degrees (*Science*, 21 June, p. 1738).



Liftoff. A coronal mass ejection erupts from the sun, artificially eclipsed in this SOHO image.

GUENTER BRUECKNER/NRL

But a fresh puzzle about the corona's behavior has emerged in the first results from the Large-Angle Spectroscopic Coronagraph (LASCO). The device images the corona by blocking the disk of the sun in an artificial eclipse, then detecting the visible sunlight scattered from the thin coronal gases. Along with unprecedented sensitivity, the LASCO can image the full extent of the corona, which stretches millions of kilometers into space, because it has three detectors with overlapping fields of view. As a result, it can capture movies showing how CMEs—million-kilometer-wide bubbles of ionized gas and magnetic fields—erupt from the sun and fly off into space.

Magnetic puzzle. Composite image shows gas flow (arrows) and magnetic field (light and dark regions) on the solar surface. Unexpectedly, points where the flow converges (green) don't collect the most magnetic field.

GEORGE SIMON/NATIONAL SOLAR OBSERVATORY

Theorists don't understand the energy sources for CMEs, although they think that a local magnetic instability somehow spreads, unmooring a large region of magnetic field and the gases it anchors. The LASCO, says team member Ken Dere of the Naval Research Laboratory (NRL), may have torpedoed that view by showing CMEs apparently erupting in synchrony on opposite sides of the sun—behavior, says Dere, that "no one has even hinted at before." The finding, says NRL's Spiro Antiochos, could mean that the magnetic fields threading the CMEs "are ordered on a huge scale." Magnetic fields, he says, are the only plausible way these structures could communicate over such distances. If that's the cause, the eruptions could play a role in the sun's 11-year solar cycle, when the sun generates global fields, then mysteriously sheds them.

As Yeats says elsewhere, "I will ... pluck till time and times are done ... the golden apples of the sun." One group of enthralled scientists has only just started.

–James Glanz