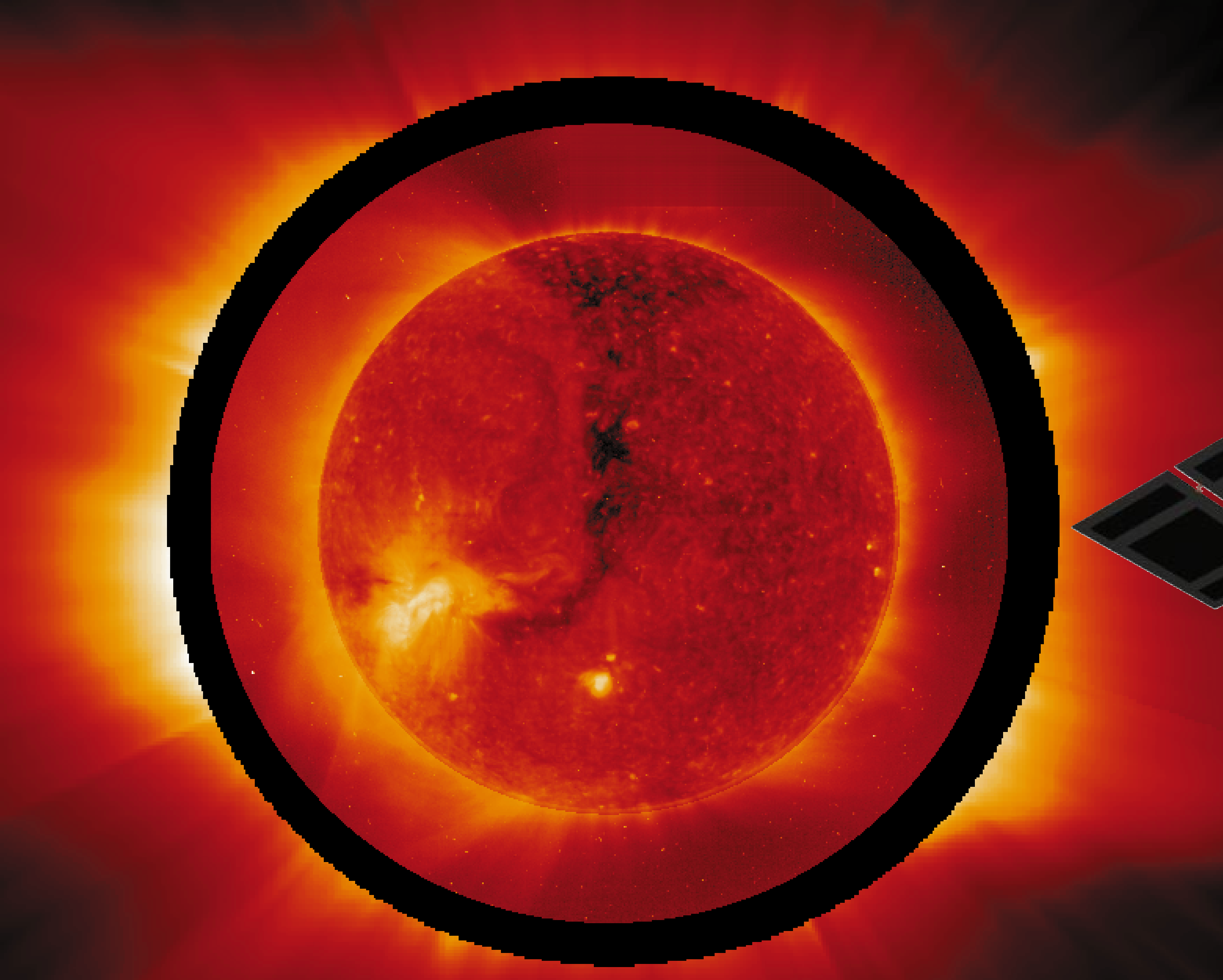
SOHO Reveals the Secrets of the Sun



A powerful new spacecraft—the Solar and Heliospheric Observatory, or SOHO—is now monitoring the sun around the clock, providing new clues about our nearest star

by Kenneth R. Lang

From afar, the sun does not look very complex. To the casual observer, it is just a smooth, uniform ball of gas. Close inspection, however, shows that the star is in constant turmoil—a fact that fuels many fundamental mysteries. For instance, scientists do not understand how the sun generates its magnetic fields, which are responsible for most solar activity, including unpredictable explosions that cause magnetic storms and power blackouts here on Earth. Nor do they know why this magnetism is concentrated into so-called sunspots, dark islands on the sun's surface that are as large as Earth and thousands of times more magnetic. Furthermore, physicists cannot explain why the sun's magnetic activity varies dramatically, waning and intensifying again every 11 years or so.

ESA AND NASA

To solve such puzzles—and better predict the sun's impact on our planet—the European Space Agency (ESA) and the National Aeronautics and Space Administration launched the two-ton Solar and Heliospheric Observatory (SOHO, for short) on December 2, 1995. The spacecraft reached its permanent strategic position—which is called the inner Lagrangian point and is about 1 percent of the way to the sun—on February 14, 1996. There SOHO is balanced between the pull of Earth's gravity and the sun's gravity and so orbits the sun together with Earth. Earlier spacecraft studying the sun orbited Earth, which would regularly obstruct their view. In contrast, SOHO monitors the sun continuously: 12 instruments examine the sun in unprecedented detail. They downlink several thousand images a day through NASA's Deep Space Network antennae to SOHO's Experimenters' Operations Facility at the NASA Goddard Space Flight Center located in Greenbelt, Md.

At the Experimenters' Operations Facility, solar physicists from around the world work together, watching the sun night and day from a room without windows. Many of the unique images they receive move nearly instantaneously to the SOHO home page on the World Wide Web (located at http://sohowww.nascom.nasa.gov). When these pictures first began to arrive, the sun was at the very bottom of its 11-year activity cycle. But SOHO carries enough fuel to continue operating for a decade or more. Thus, it will keep watch over the sun through all its tempestuous seasons—from the recent lull in magnetic activity to its next maximum, which should take place at the end of the century. Already, though, SOHO has offered some astounding findings.

COMPOSITE IMAGE (*left*), taken by two instruments on board SOHO (*above*) and joined at the black circle, reveals the sun's outer atmosphere from the base of the corona to millions of kilometers above the solar surface. Raylike structures appear in the ultraviolet light emitted by oxygen ions flowing away from the sun to form the solar wind (*outside black circle*). The solar wind with the highest speed originates in coronal holes, which appear as dark regions at the north pole (*top*) and across the solar disk (*inside black circle*).

opposite page: COURTESY OF SOHO EIT CONSORTIUM (*inner region*) AND SOHO UVCS CONSORTIUM (*outer region*)

Exploring Unseen Depths

To understand the sun's cycles, we must look deep inside the star, to where its magnetism is generated. One way to explore these unseen depths is by tracing the in-and-out, heaving motions of the sun's outermost visible surface, named the photosphere from the Greek word *photos,* meaning "light." These oscillations, which can be tens of kilometers high and travel a few hundred meters per second, arise from sounds that course through the solar interior. The sounds are trapped inside the sun; they cannot propagate through the near vacuum of space. (Even if they could reach Earth, they are too low for human hearing.) Nevertheless, when these sounds strike the sun's surface and rebound back down, they disturb the gases there, causing them to rise and fall, slowly and rhythmically, with a period of about five minutes. The throbbing motions these sounds create are imperceptible to the naked eye, but SOHO instruments routinely pick them out.

The surface oscillations are the combined effect of about 10 million separate notes—each of which has a unique path of propagation and samples a well-defined section inside the sun. So to trace the star's physical landscape all the way through—from its churning convection zone, the outer 28.7 percent (by radius), into its radiative zone and core—we must determine the precise pitch of all the notes.

The dominant factor affecting each sound is its speed, which in turn depends on the temperature and composition of the solar regions through which it passes. SOHO scientists compute the expected sound speed using a numerical model. They then use relatively small discrepancies between their computer calculations and the observed sound speed to fine-tune the model and establish the sun's radial variation in temperature, density and composition.

At present, theoretical expectations and observations made with SOHO's Michelson Doppler Imager (MDI) telescope are in close agreement, showing a maximum difference of only 0.2 percent. Where these discrepancies occur is, in fact, significant. They suggest that turbulent material is moving in and out just below the convection zone and hint that such mixing motions might occur at the boundary of the energy-generating core—concepts that could be very important for studies of stellar evolution.

For more than three centuries, astronomers have known from watching sunspots that the photosphere rotates faster at the equator than at higher latitudes and that the speed decreases evenly toward each pole. SOHO data confirm that this differential pattern persists through the convection zone. Furthermore, the rotation speed becomes uniform from pole to pole about a third of the way down. Thus, the rotation velocity changes sharply at the base of the convection zone. There the outer parts of the radiative interior, which rotates at one speed, meet the overlying convection zone, which spins faster in its equatorial middle. We now suspect that this thin base layer of rotational shear may be the source of the sun's magnetism.

The MDI telescope on board SOHO has also helped probe the sun's outer shells. Because its lenses are positioned well above Earth's obscuring atmosphere, it can continuously resolve fine detail that cannot always be seen from the ground. For this reason, it has proved particularly useful in time-distance helioseismology, a new technique for revealing the motion of gases just below the photosphere. The method is quite straightforward: the telescope records small periodic changes in the wavelength of light emitted from a million points across the sun every minute. By keeping track of them, it is possible to determine how long it takes for sound waves to skim through the sun's outer layers. This travel time tells of both the temperature and gas flows along the internal path connecting two points on the visible solar surface. If the local temperature is high, sound waves move more quickly—as they do if they travel with the flow of gas.

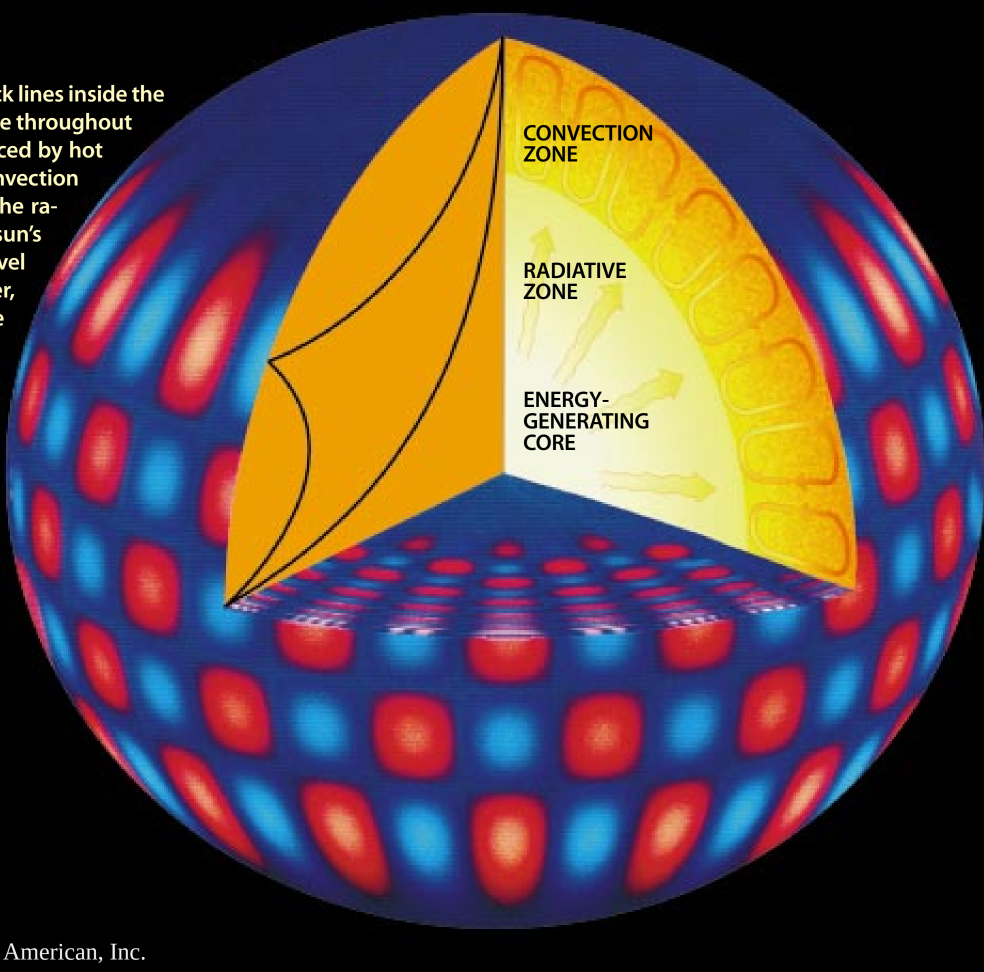
The MDI has provided travel times for sounds crossing thousands of paths, linking myriad surface points. And SOHO scientists have used these data to chart the three-dimensional internal structure and dynamics of the sun, much in the same way that a computed tomographic (CT) scan creates an image of the inside of the brain. They fed the SOHO data to supercomputers to work out temperatures and flow directions along these intersecting paths. Using these techniques during two years of nearly continuous observations, SOHO scientists have discovered vast rivers of hot gas that circulate within the sun.

Completely unexpected currents circle the polar regions of the sun just below the photosphere. They seem to resemble the jet streams high in the atmosphere of Earth, which have a major influence on terrestrial weather. Ringing the sun at about 75 degrees latitude, the solar jet streams are totally inside the sun, 40,000 kilometers (25,000 miles) below the photosphere, and cannot be seen at the visible surface. They move about 10 percent faster than the surrounding gas—about 130 kilometers per hour faster—and they are wide enough to engulf two planet Earths.

The outer layer of the sun, to a depth of at least 25,000 kilometers, is also slowly flowing from the equator to the poles, at a speed of about 90 kilometers per hour. At this rate, an object would be transported from the equator to the pole in little more than a year. Of course, the sun rotates at a much faster rate of about 7,000 kilometers per hour, completing one revolution at the equator in 25.7 days. The combination of differential rotation and poleward flow has been the explanation for the stretched-out shapes of magnetic regions that have migrated toward the poles. The new SOHO MDI observations demonstrate for the first time that the poleward flow reaches deeply into the sun, penetrating at least 12 percent of the convection zone.

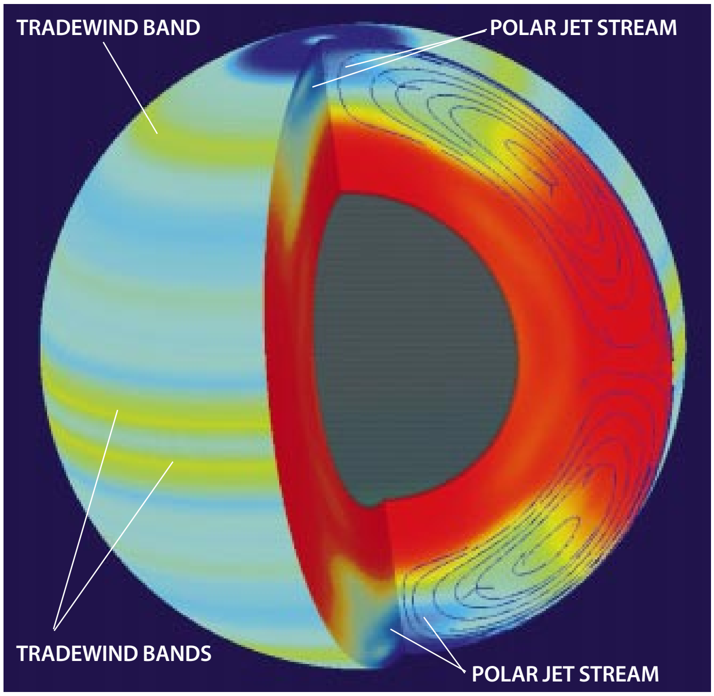
Researchers have also identified internal rivers of gas mov-

SOUND WAVES, represented here by black lines inside the cutaway section, resonate throughout the sun. They are produced by hot gas churning in the convection zone, which lies above the radiative zone and the sun's core. As sound waves travel toward the sun's center, they gain speed and are refracted back out. At the same time, the sun's surface reflects waves traveling outward back in. Thus, the entire star throbs, with regions pulsing in (*red spots*) and out (*blue spots*).



COURTESY OF JACK HARVEY *National Optical Astronomy Observatories;* CROSS SECTIONS BY MICHAEL GOODMAN

SOLAR METEOROLOGY can be seen by looking at internal large-scale flows measured with the MDI instrument on board the SOHO spacecraft from May 1996 to May 1997. Red represents faster than average flows, yellow slower than average and blue slower yet. Yellow bands are deeply rooted zones that move slightly faster than their surroundings; sunspots tend to form at the edges of these zones. The poleward flow is shown as streamlines within the cutaway section. The newly discovered "jet streams" move approximately 10 percent faster than their surroundings.



COURTESY OF PHILIP SCHERRER AND SOHO/SOI TEAM

ing in bands near the equator at different speeds relative to each other in both the northern and southern hemispheres. The solar belts are more than 64,000 kilometers in width and move about 16 kilometers per hour faster than the gases to either side. These broad belts of higher-velocity currents remind one of Earth's equatorial tradewinds and also of Jupiter's colorful, banded atmosphere. The bands are deeply rooted, extending down approximately 19,000 kilometers into the sun. The full extent of the newfound solar meteorology could never have been seen by looking at the visible layer of the solar atmosphere.

The MDI team also investigated horizontal motions at a depth of about 1,400 kilometers and compared them with an overlying magnetic image, also taken by the MDI instrument. They found that strong magnetic concentrations tend to lie in regions where the subsurface gas flow converges. Thus, the churning gas probably forces magnetic fields together and concentrates them, thereby overcoming the outward magnetic pressure that ought to make such localized concentrations expand and disperse.

The Million-Degree Corona

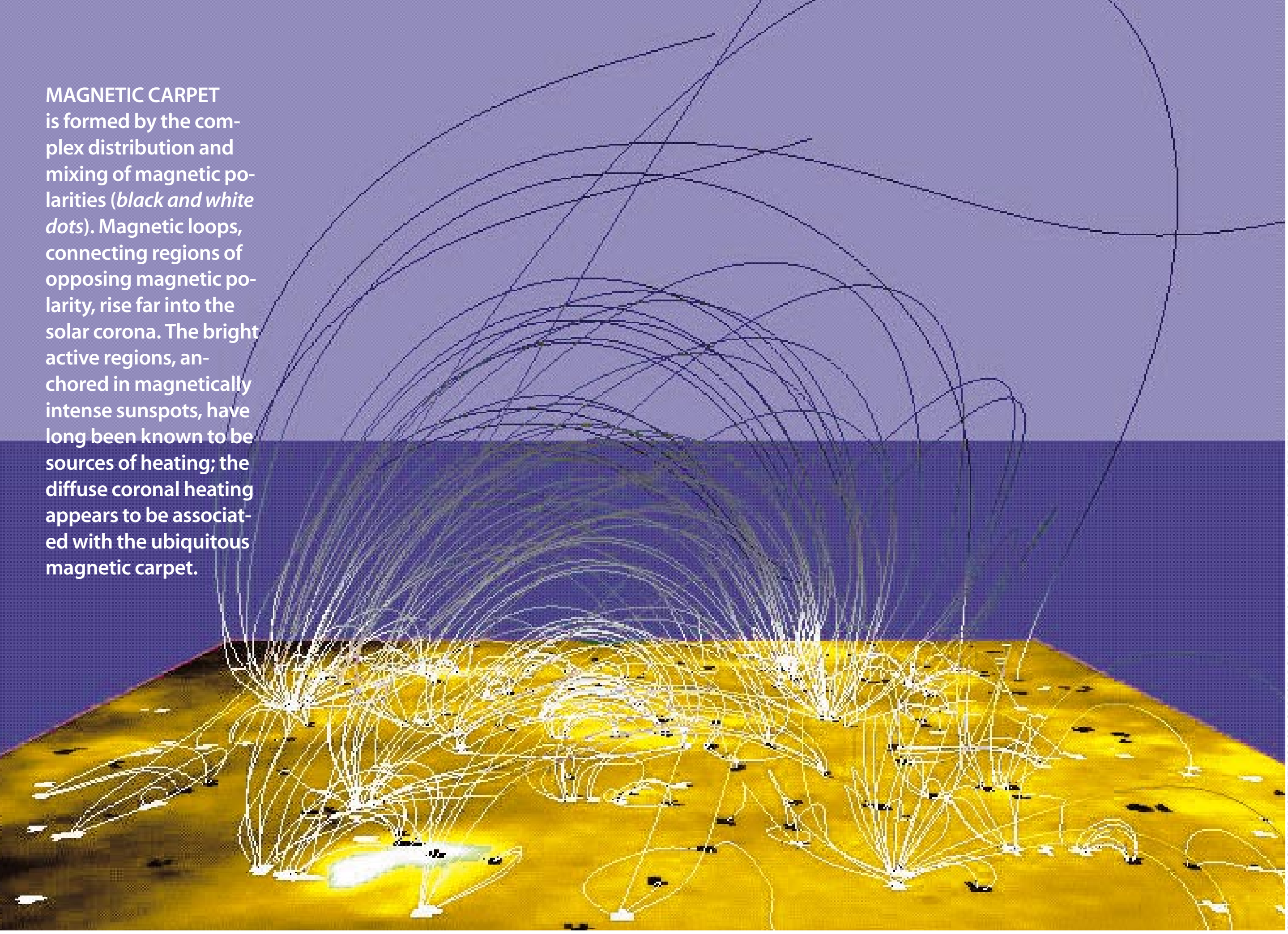
SOHO is also helping scientists explain the solar atmosphere, or corona. The sun's sharp outer rim is illusory. It merely marks the level beyond which solar gas becomes transparent. The invisible corona extends beyond the planets and presents one of the most puzzling paradoxes of solar physics: it is unexpectedly hot, reaching temperatures of more than one million kelvins just above the photosphere; the sun's visible surface is only 5,780 kelvins. Heat simply should not flow outward from a cooler to a hotter region. It violates the second law of thermodynamics and all common sense as well. Thus, there must be some mechanism transporting energy from the photosphere, or below, out to the corona. Both kinetic and magnetic energy can flow from cold to hot regions. So writhing gases and shifting magnetic fields may be accountable.

For studying the corona and identifying its elusive heating mechanism, physicists look at ultraviolet (UV), extreme ultraviolet (EUV) and x-ray radiation. This is because hot material—such as that within the corona—emits most of its energy at these wavelengths. Also, the photosphere is too cool to emit intense radiation at these wavelengths, so it appears dark under the hot gas. Unfortunately, UV, EUV and x-rays are partially or totally absorbed by Earth's atmosphere, and so they must be observed through telescopes in space. SOHO is now measuring radiation at UV and EUV wavelengths using four instruments: the Extreme-ultraviolet Imaging Telescope (EIT), the Solar Ultraviolet Measurements of Emitted Radiation (SUMER), the Coronal Diagnostic Spectrometer (CDS) and the UltraViolet Coronagraph Spectrometer (UVCS).

To map out structures across the solar disk, ranging in temperature from 6,000 to two million kelvins, SOHO makes use of spectral lines. These lines appear when the sun's radiation intensity is displayed as a function of wavelength. The various SOHO instruments locate regions having a specific temperature by tuning into spectral lines emitted by the ions formed there. Atoms in a hotter gas lose more electrons through collisions, and so they become more highly ionized. Because these different ions emit spectral lines at different wavelengths, they serve as a kind of thermometer. We can also infer the speed of the material moving in these regions from the Doppler wavelength changes of the spectral lines that SOHO records.

Ultraviolet radiation has recently revealed that the sun is a vigorous, violent place even when its 11-year activity cycle is in an apparent slump—and this fact may help explain why the corona is so hot. The whole sun seems to sparkle in the UV light emitted by localized bright spots. According to SOHO measurements, these ubiquitous hot spots are formed at a temperature of a million kelvins, and they seem to originate in small, magnetic loops of hot gas found all over the sun, including both its north and south poles. Some of these spots explode and hurl material outward at speeds of hundreds of kilometers per second. SOHO scientists are now studying these bright spots to see if they play an important role in the elusive coronal heating mechanism.

SOHO has provided direct evidence for the transfer of magnetic energy from the sun's visible surface toward the corona above. Images of the photosphere's magnetism, taken with SOHO's MDI, reveal ubiquitous pairs of opposite magnetic polarity, each joined by a magnetic arch that rises above them, like bridges that connect two magnetic islands. Energy flows from these magnetic loops when they interact, producing electrical and magnetic "short circuits." The very strong electric currents in these short circuits can heat the corona to a temperature of several million degrees. Images from the EIT



MAGNETIC CARPET is formed by the complex distribution and mixing of magnetic polarities (*black and white dots*). Magnetic loops, connecting regions of opposing magnetic polarity, rise far into the solar corona. The bright active regions, anchored in magnetically intense sunspots, have long been known to be sources of heating; the diffuse coronal heating appears to be associated with the ubiquitous magnetic carpet.

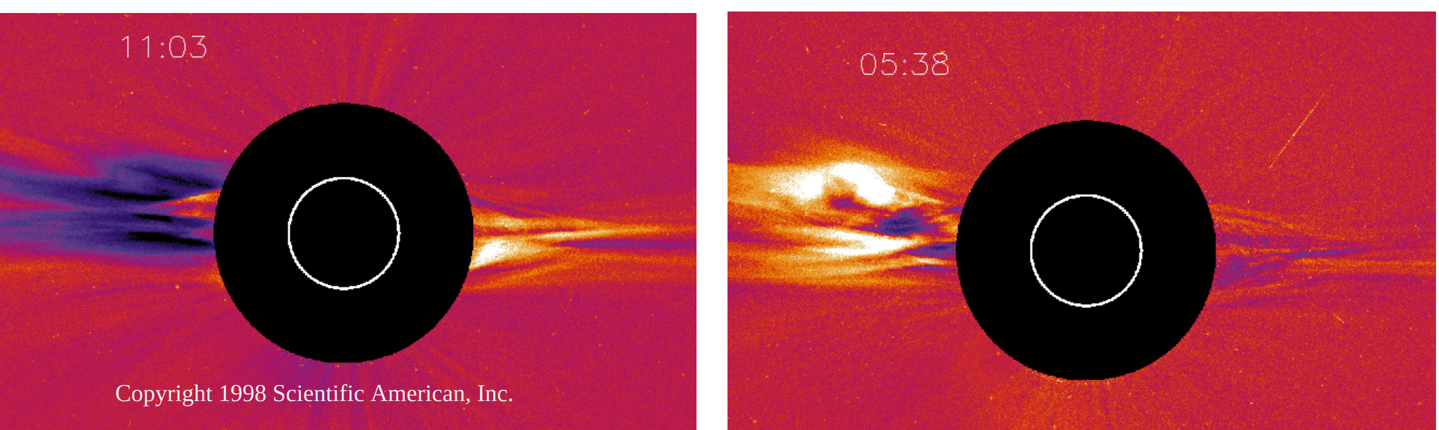
STANFORD-LOCKHEED INSTITUTE FOR SPACE RESEARCH AND NASA GODDARD SPACE FLIGHT CENTER

and CDS instruments on SOHO show the hot gases of the ever-changing corona reacting to the evolving magnetic fields rooted in the solar surface.

To explore changes at higher levels in the sun's atmosphere, SOHO relies on its UVCS and its Large Angle Spectroscopic COronagraph (LASCO). Both instruments use occulting disks to block the photosphere's underlying glare. LASCO detects visible sunlight scattered by electrons in the corona. Initially it revealed a simple corona—one that was highly symmetrical and stable. This corona, viewed during the sun's magnetic lull, exhibited pronounced holes in the north and south. (Coronal holes are extended, low-density, low-temperature regions where EUV and x-ray emissions are abnormally low or absent.)

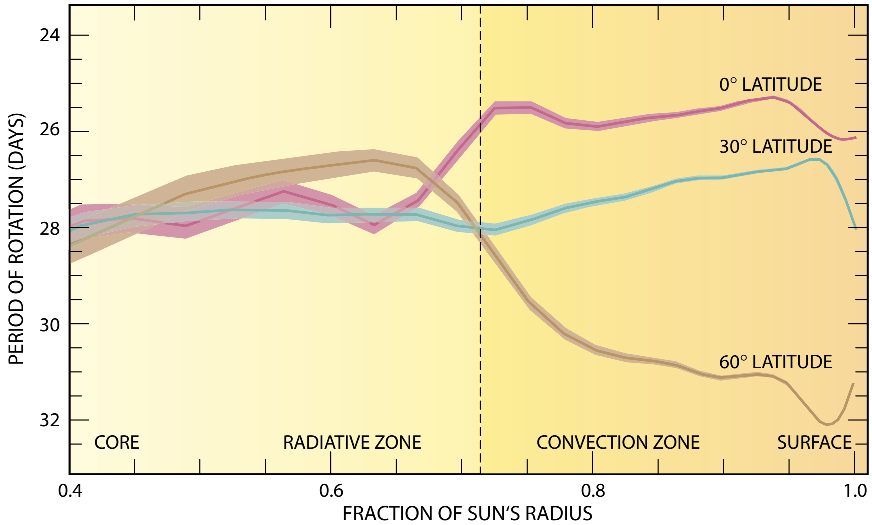
In contrast, the equatorial regions were ringed by straight, flat streamers of outflowing matter. The sun's magnetic field shapes these streamers. At their base, electrified matter is densely concentrated within magnetized loops rooted in the photosphere. Farther out in the corona, the streamers narrow into long stalks that stretch tens of millions of kilometers into space. These extensions confine material at temperatures of about two million kelvins within their elongated magnetic boundaries, creating a belt of hot gas that extends around the sun.

The streamers live up to their name: material seems to flow continuously along their open magnetic fields. Occasionally the coronagraphs record dense concentrations of material moving through an otherwise unchanging streamer—like seeing leaves floating on a moving stream. And sometimes tremendous eruptions, called coronal mass ejections, punctuate the



CORONAL MASS EJECTIONS (*white*), occurring on the east and west sides of the sun, were recorded within hours on the same day by one of SOHO's coronagraphs. The black occulting disk blocks the glare of the sun, whose visible edge is represented here by the white circle.

COURTESY OF SOHO LASCO CONSORTIUM AND GUENTER E. BRUECKNER



MICHAEL GOODMAN, AFTER SOHO SOI/MDI CONSORTIUM AND ALEXANDER G. KOSOVICHEV

INTERNAL ROTATION RATE OF THE SUN at latitudes of zero, 30 and 60 degrees has been inferred using data from the Michelson Doppler Imager. Down to the base of the convection zone, the polar regions spin more slowly than the equatorial ones do. Beyond that, uniform rotation appears to be the norm, although scientists have not yet determined rotation rates within the sun's core.

steady outward flow. These ejections hurl billions of tons of million-degree gases into interplanetary space at speeds of hundreds of kilometers per second. This material often reaches Earth in only two or three days. To almost everyone's astonishment, LASCO found equatorial ejections emitted within hours of each other from opposite sides of the sun.

The coronagraphs have only a side view of the sun and so can barely see material moving to or from Earth. But based on what we can see, we guess that these ejections are global disturbances, extending all the way around the sun. In fact, unexpectedly wide regions of the sun seem to convulse when the star releases coronal mass ejections, at least during the minimum in the 11-year activity cycle. And the coronagraphs have detected that a few days before the ejections, the streamer belt gets brighter, suggesting that more material is accruing there. The pressure and tension of this added material probably build until the streamer belt blows open in the form of an ejection. The entire process is most likely related to a large-scale global reorganization of the sun's magnetic field.

Solar Winds and Beyond

The sun's hot and stormy atmosphere is forever expanding in all directions, filling the solar system with a ceaseless flow—called the solar wind—that contains electrons, ions and magnetic fields. The million-degree corona creates an outward pressure that overcomes the sun's gravitational attraction, enabling this perpetual outward flow. The wind accelerates as it moves away from the sun, like water overflowing a dam. As the corona disperses, it must be replaced by gases welling up from below to feed the wind. Earlier spacecraft measurements, as well as those from Ulysses (launched in 1990), showed that the wind has a fast and a slow component. The fast one moves at about 800 kilometers per second; the slow one travels at half that speed.

The slow component is associated with equatorial regions of the sun, now being scrutinized by LASCO and UVCS. These instruments suggest that the slow component of the solar wind flows out along the stalklike axes of equatorial coronal streamers. The high-speed component pours forth from the polar coronal holes. (Open magnetic fields there allow charged particles to escape the sun's gravitational and magnetic grasp.) SOHO is now investigating whether polar plumes—tall structures rooted in the photosphere that extend into the coronal holes—help to generate this high-speed solar wind.

SOHO's UVCS has examined the spectral emission of hydrogen and heavily charged oxygen ions in the regions where the corona is heated and the solar wind accelerates. And these spectral-line profiles have produced surprising results, revealing a marked difference in the agitation speeds at which hydrogen and oxygen ions move. In polar coronal holes, where the fast solar wind originates, the heavier oxygen is far more agitated, with about 60 times more energy of motion; above two solar radii from the sun's center, oxygen has the higher agitation speed, approaching 500 kilometers per second. Hydrogen, on the other hand, moves at only 250 kilometers per second. In contrast, within equatorial regions, where the slow-speed wind begins, the lighter hydrogen moves faster than the oxygen, as one would expect from a heat-driven wind.

Researchers are now trying to determine why the more massive oxygen ions move at greater speeds in coronal holes. One possibility is that the ions are whirling around magnetic-field lines that stretch from the sun. Information about the heating and acceleration processes is probably retained within the low-density coronal holes, wherein ions rarely collide with electrons. Frequent collisions in high-density streamers might erase any signature of the relevant processes.

SOHO has obtained marvelous results to date. It has revealed features on the mysterious sun never seen before or never seen so clearly. It has provided new insights into fundamental unsolved problems, all the way from the sun's interior to Earth and out to the farthest reaches of the solar wind. Some of its instruments are now poised to resolve several other mysteries. Two of them will soon have looked at the solar oscillations long enough, and deep enough, to determine the temperature and rotation at the sun's center. Moreover, during the next few years, our home star's inner turmoil and related magnetic activity—which can directly affect our daily lives—will increase. SOHO should then offer even greater scientific returns, determining how its threatening eruptions and hot, gusty winds originate and perhaps predicting conditions in the sun's atmosphere. SA

The Author

KENNETH R. LANG is professor of astronomy at Tufts University. His recent illustrated book, *Sun, Earth and Sky,* describes all aspects of the sun and its interactions with Earth. Lang has also written more than 150 professional articles and four additional books, which have been translated into seven languages. Among them is the classic reference *Astrophysical Formulae.* This article updates a version that appeared in *Scientific American* in March 1997.