either the formation of oxygen radicals or their effects. Bredesen and his colleagues found that Bcl-2 seems to protect cells not only from apoptotic death, which may be triggered by modest amounts of oxygen radicals, but also from the nonprogrammed necrotic death that occurs under conditions that normally make oxygen radical levels soar. If those results hold up, they could widen the potential for eventual therapeutic uses of Bcl-2, since the death of cells during strokes, trauma, and some degenerative diseases may be predominantly necrotic.

While some cell death researchers are excited by the oxygen-radical connection, others are skeptical. "It's getting a lot of hype at the moment, but I must confess I don't find it very convincing," says Raff, of University College, London, who notes that apoptosis aims to take cells apart "neatly, and in minutes." Reactive oxygen radicals, he thinks, seem "a little too uncontrolled" to kick off that kind of process.

Washington University's Johnson says he finds the reactive oxygen link "intriguing" but also a bit unsettling. And he points out that there are alternative biochemical means through which Bcl-2 may be working: For example, a team at Onyx Pharmaceuticals in Richmond, California, recently reported that Bcl-2 associates with a protein called R-ras, which is related to the *ras* oncogene product, and is thought to be involved in intracellular signaling in ways that are as yet unknown.

Bcl-2 and ICE are clearly only two parts of the cell death puzzle, and while the clues they provide are important pieces to have on the table, the puzzle will not be complete until researchers fill in the story of how cell surface molecules receive the death command and transmit its message to the cell. Others are also following up leads suggesting that cell death may have some elements in common with the cell-division cycle.

Ultimately, researchers may find that they can manipulate cell death, turning it on to destroy cancer cells or turning it off to prevent the loss of neurons in neurodegenerative disease. But for now, the main goal is to find all the puzzle pieces. "We're not to the point yet where everything makes sense," says Washington University's Johnson, "but I think we've got a lot of the pieces that will turn out to be important."

–Marcia Barinaga

Additional Reading

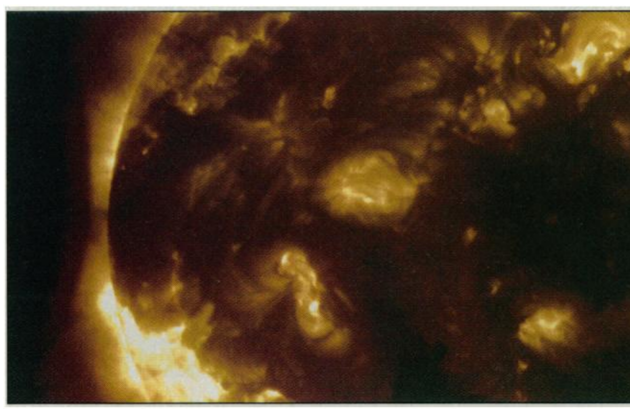
M. Miura, H. Zhu, R. Rotello, E. Hartwieg and J. Yuan, "Induction of Apoptosis in Fibroblasts by IL-1 Beta-Converting Enzyme, a Mammalian Homolog of the *C. elegans* Cell Death Gene *ced-3*," *Cell* **75**, 653 (1993).

Z. Oltvai, C. Milliman, and S. Korsmeyer, "Bcl-2 Heterodimerizes in vivo With a Conserved Homolog, Bax, That Accelerates Programed Cell Death," *Cell* **74**, 609 (1993).

SPACE PHYSICS

Solar Physicists Peer Into a Mysterious Furnace

During a total eclipse, the solar corona is an awesome sight: a halo that streams out into space for several times the sun's diameter. The spectacle is more than awesome, though; it's a brazen challenge to astrophysicists. This halo of glowing gas can fight off the sun's gravitational pull and extend so far into space only by maintaining a temperature of several million degrees Kelvin—200 times hotter than the solar surface. The very existence of the corona thus seems to flout standard thermodynamics, which predicts that temperatures will drop off with distance from the sun's energy-producing core, just as the air in an old farmhouse cools as you move away from the stove. "The question is, Why on earth is [the corona] there?" says solar physicist Keith Strong of the Lockheed Palo Alto Research Laboratories.



LEON GOLUB

Close scrutiny. An x-ray image made at the onset of an eclipse reveals fine structure in the magnetic loops, suggesting that the corona might be heated by electrical resistance.

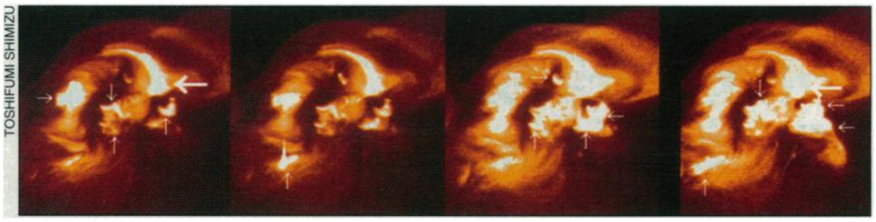
Somehow, most researchers believe, mechanical energy from the churning of the sun's outer layers gets pumped up into the corona and turned into heat. Learning how this happens would not only solve a key riddle posed by the sun and other stars; it would also unmask the driving force of the solar wind, an extension of the corona that affects terrestrial matters such as communications and, some researchers speculate, even the weather. With so much at stake, solar physicists have had no shortage of theories. But until recently, they had few facts to test those theories against. Now, says Jack Zirker of the National Solar Observatory, new space-based observations of the sun are starting to take researchers "into the guts of the physical processes."

Once there, researchers hope to pick out the best of a series of proposed mechanisms, many of which center on the bundles of magnetic field lines that arch over the sun's surface. Pockets of turbulence in the bundles or wavelike motions in the lines might generate heat; "nanoflares"—sparklike releases of magnetic energy from the bundles—might heat the corona by spewing high-energy particles; electric currents flowing along the field lines could turn them into giant toaster filaments. To tell these mechanisms apart, researchers need detailed images of the magnetic bundles, which are outlined by hot, x-ray-emitting gas.

Such images are now arriving from two new instruments, the Soft X-Ray Telescope (SXT) on board the Japanese satellite Yohkoh and the Normal Incidence X-Ray Telescope (NIXT), flown on sounding rockets by Leon Golub of the Harvard-Smithsonian Center for Astrophysics and his colleagues. The SXT, which has been watching the sun since Yohkoh's launch in August 1991, can take pictures in much quicker succession than previous instruments, yielding movies that reveal bursts of heating. NIXT takes only snapshots, but it can reveal detail three times finer than SXT. While the new images haven't pointed to a clear winner among the competing theories, a vision of heating by electric currents seems to be on the upswing, while a long-time favorite, nanoflares, appears to be fading.

Proposed and developed by Eugene Parker of the University of Chicago during the 1980s, the nanoflares theory holds that as the footpoints of the magnetic bundles shuffle around on the solar surface, the field lines in the bundles get stretched and braided—something like maypole streamers wound up by disorderly dancers. The process is "like stretching rubber bands," says Roger Kopp of Los Alamos National Laboratory, and it results in a buildup of magnetic energy. Parker suggested that this energy gets released when adjacent field lines suddenly reconnect, releasing tension. When the process takes place on a large scale, it is thought to power solar flares. Large flares are too rare to heat the corona, but Parker proposed that tiny bursts of reconnection take place a few times a second in each bundle, triggering enough nanoflares to heat the corona.

Nanoflares and their effects on the bundles would be too faint and small for earlier instruments to have spotted them. But researchers hoped the SXT's high-resolution x-ray movies might be able to capture the most vigorous of them. As it turned out, the SXT reaches its limits of resolution just above the needed sensitivity. But by recording the frequency of "microflares"—the very faintest visible flashes and sparks—and extrapolating downward, Toshifumi Shimizu of the University of Tokyo's Institute of Astronomy and his collaborators set out to estimate nanoflare frequency. The result: When Shimizu extrapolates downward from the point where the brightenings get lost in a diffuse x-ray background, the results suggest, he says, that "the transient energy releases...are not a significant contribution to the heating."



Microflares. Yohkoh images made minutes apart capture transient brightenings.

If the finding holds up, says Peter Cargill of the Naval Research Laboratory, it poses "a serious, serious problem" for the nanoflare concept. But Jason Porter, a solar observer at the Marshall Space Flight Center, thinks Shimizu might be "systematically underestimating" the numbers by sampling with x-rays instead of ultraviolet light, which might reveal cooler and fainter microflare events. Shimizu himself leaves the door open a crack by acknowledging that the diffuse background might consist of nanoflares that run together because they happen so often.

Images from NIXT, however, suggest that another mechanism may play a bigger role in heating the corona: strong electric currents forced along the bundles by magnetic activity at the surface. The key evidence, says Golub, is the slim, tubular appearance of the magnetic bundles in the detailed NIXT images. To explain that shape, says Golub, "you have to assume current." Electric current would generate spiraling magnetic fields that would wrap around the bundles, preventing them from bulging.

Steady currents looping through the corona in magnetic filaments could heat the thin gases by electrical resistance—the same principle at work in a toaster. And NIXT's high-resolution images lend extra support for the idea by revealing that the hot gases outlining the tubes seem to be divided into fine threads. Researchers know that in order for such currents to heat a plasma efficiently, they must flow along narrow filaments or sheets. So far, however, Golub can't prove that current actually flows along the fine structures he sees. What would bolster the toaster-filament theory still further would be evidence of the instabilities that such finely divided currents should set off within the magnetic loops. Each instability would be manifested, says Golub, as "a thin thread of brightness which then fattens to fill the loop."

To detect these and other signatures of electric currents, Golub and his colleague will need to move from NIXT's snapshots of the corona to videos that could reveal equally fine detail. Two proposed satellites, called TRACE (for Transition Region and Coronal Explorer) and SWATH (for Space Weather and Terrestrial Hazards) would carry NIXT-like instruments. Because these telescopes would be in orbit, they would share SXT's ability to take many images in succession. Meanwhile, another version of NIXT will fly on the Solar and Heliospheric Observing Mission (SOHO), scheduled for launch in 1995. Several other instruments on SOHO will be able to look at the cooler, lower regions of the corona that are critical in many heating theories, and at the solar wind.

If those instruments can't solve the mystery of what heats the corona, additional clues might be waiting at the solar surface, on scales too small to be seen by the ground-based solar telescopes that researchers have relied on for their understanding of the sun's churning. To map the fine-scale turbulence that braids the magnetic bundles in the corona, says Parker, would require "a one-meter or bigger [solar] telescope above the atmosphere"—something that hasn't even made it onto anyone's drawing board. And there's always the possibility that, in focusing on the magnetic bundles, solar physicists have been following the wrong scent (see box). If that's the case, the corona may be taunting solar physicists for some time to come.

–James Glanz

James Glanz is a science writer in Chicago.

Another Way to Light a Fire

Most solar physicists trying to explain how the sun's corona is heated to 200 times the temperature of its visible surface—in apparent defiance of thermodynamics—look for ways to turn the churning of the solar surface into a heat source (see main text). But Jack Scudder of the University of Iowa thinks there's no need to search for elaborate ways to funnel this energy upward and dump it into the coronal particles. He thinks the particles have all the energy they need before they ever get to the corona.

Like any gas, the plasma at the base of the corona consists of particles of many different energies, Scudder notes. The sun's intense gravity, he says, confines slower-moving, lower-energy particles to a layer near the surface; only the higher-energy—hotter—particles can rise far above the solar surface. This "filtering," he says, could produce a rapid increase in temperature with height.

For all its simplicity, this mechanism isn't winning over Scudder's peers. That's because he has to make one major assumption about the particles' velocity distribution close to the solar surface: an unusual abundance of particles at the high-energy end of the distribution. Without these high-energy "tails," the filtering would yield too few hot particles to boost the temperature.

Scudder believes that the heat-driven churning in the sun's surface layers could readily produce a plasma that has an unusually large fraction of very-high-energy particles. But Jack Zirker of the National Solar Observatory doesn't see it that way. "He's got a good deal of work to show how [the tails] could be produced." Adds the University of Chicago's Eugene Parker, a pioneer in the study of the corona, "Nobody knows what would produce the hot particles" near the sun. And if the plasma has no tails, says Zirker, the mechanism is "like saying if pigs had wings they could fly."

Scudder counters that satellite observations have revealed hot tails in the solar wind, which originates in the corona. And no one is rejecting his theory out of hand, especially since it has shown an uncanny ability to predict aspects of the heating with which other theories have struggled—for example, the observation that the loops of plasma seen arching upward from the bright regions near sunspots are hottest at the top. In Scudder's picture, the highest temperatures would naturally occur at the highest altitudes, where the greatest number of slow particles have been filtered out. But until Scudder can find a convincing way to pin tails on his plasma, most of his colleagues looking for a coronal heat source are opting for plausibility over elegance.

–J.G.