New pictures of the sun reveal a number of surprising and puzzling solar features

By IVARS PETERSON

Of average mass, build and appearance, the sun doesn't have much to distinguish it from untold numbers of other stars. In fact, many astronomers think of the sun as a commonplace star, even a dull one. Nonetheless, says astrophysicist Juri Toomre of the University of Colorado in Boulder, "it has a variety of startling features."

For one thing, as the sun spins on its axis, a point near the equator takes about 25 days to make a round trip, while a point in a polar region requires 33 days to complete a rotation (SN: 1/17/87, p.39). Moreover, some observations hint the sun's core may be rotating as much as three times faster than its surface. No one has yet developed a theory that fully accounts for these unusual motions.

The sun also reverses and rebuilds its magnetic field every 11 years or so. Sunspots — dark blemishes that periodically appear and disappear on the sun's face — mark sites of intense magnetic activity. Their strong magnetic fields block or redirect the normal flow of hot gases to the sun's surface. "But we still don't know what actually causes sunspots," says J.W. Harvey of the National Solar Observatory in Tucson, Ariz.

In addition, the sun quivers and shakes. Like a bell, it resonates at specific frequencies, displaying a characteristic acoustic signature (SN: 6/18/83, p.392). Its surface shows complex patterns of pulsating bulges and depressions produced by a mix of sound waves generated by turbulence at various depths within. Scientists are just beginning to translate these patterns into information about the sun's interior.

Perhaps the sun's most distinctive feature is that it's only about 93 million miles from earth. No other star is so readily accessible to earth-based observers. No other star has such a direct influence on the earth's climate and environment. Even tiny variations in brightness could shift climatic patterns, initiating an ice age or prompting a global ice melt.

During the last decade, the arrival of ever-more-sophisticated instruments and techniques for observing the sun has transformed the discipline. Now, solar physics encompasses much more than counting and mapping sunspots, although that remains an important pursuit. From earth, researchers can track subtle movements of the sun's vast surface — movements slower than an idler's leisurely stroll. They can detect streams of charged particles heated to 1 million°C or pick out the one lithium atom hidden among 100 billion hydrogen atoms.

But these increasingly precise measurements often suggest more puzzles than they solve. The next decade requires even better instruments so that astronomers can see more detail and get a better handle on what the sun is doing. The promise shown by a number of new observational techniques was a major topic at last month's American Astronomical Society meeting in Kansas City, Mo.

Using the characteristic patterns generated by sound waves to study the sun's interior is a little like banging on a block of wood and listening to tell if the block is hollow. However, unlike the vibrations of a wooden block, the sun's oscillations are subtle, typically no faster than 20 feet per minute. And because the sun can vibrate in millions of different ways at once, the resulting patterns are extremely complicated.

Astronomers detect solar surface movements by carefully examining the light absorbed by atoms of a particular element at the sun's surface. These atoms absorb only certain characteristic wavelengths, or colors, of light. By focusing on a single absorption line in the solar spectrum, researchers can detect motion by measuring how much that line's wavelength has shifted from its normal position. For motion toward the observer, the light becomes a little more blue; for

Facing page: White-light image of the sun's corona during the solar eclipse of March 18.

motion away from the observer, it becomes a little more red. Detecting these tiny wavelength shifts is roughly equivalent to tuning a radio to a precision of one part in a billion.

Each of the sun's millions of vibrations arises from a particular region inside the sun. As these sound waves move outward from their sources, they penetrate to different distances and cover different latitude ranges. Eventually they reach the surface, create ripples, then bounce back into the sun's interior.

"The job of the observer is to measure the frequencies of as many different vibrations as possible," Harvey says. "By combining measurements of many vibrations, the structure of the sun can be worked out rather like peeling layers from an onion."

Helioseismology, as this relatively new discipline is called, requires large numbers of precise observations made continuously for days at a time. To meet that requirement, astronomers have journeyed to the Antarctic every summer since 1980 to observe solar oscillations. At the geographic South Pole, they can spend up to three months — if clouds don't intervene — observing a sun that never sets. Past efforts have been successful enough that for the coming season, a team of astronomers plans to operate a telescope equipped with a new detector significantly more sensitive than those previously used at the South Pole.

"The major improvement and prospect for the future is to obtain observations for months or years with few interruptions," Harvey says. One way is to coordinate observations at several sites around the world. As the sun fades from view at one observatory, another observatory takes over.

The most ambitious such project is an international effort now being put together under the direction of the National Solar Observatory and called the Global Oscillation Network Group (GONG). The full network of six stations is scheduled to start operating in 1991, although funding difficulties threaten to delay its completion. When fully operating, GONG will gather data at the rate of one picture per minute for three years.

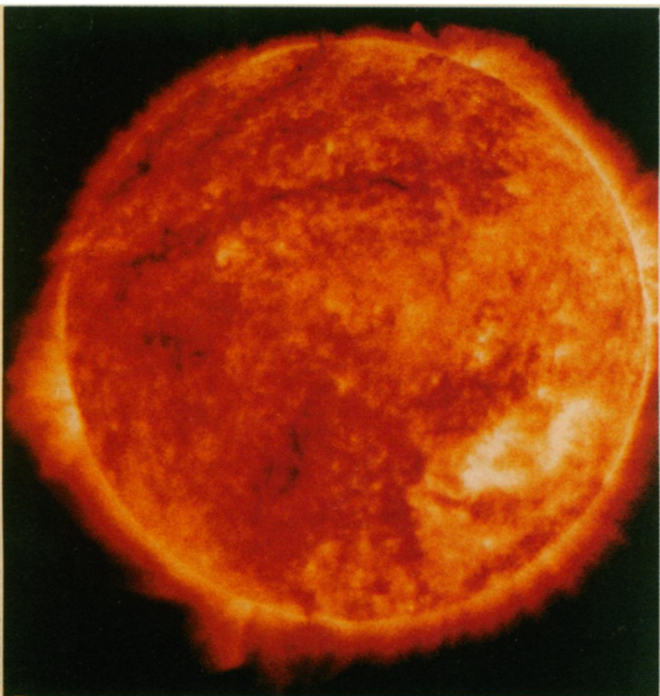
"The GONG project will produce images of the solar oscillations so that tens of thousands of different oscillations can be measured," Harvey says.

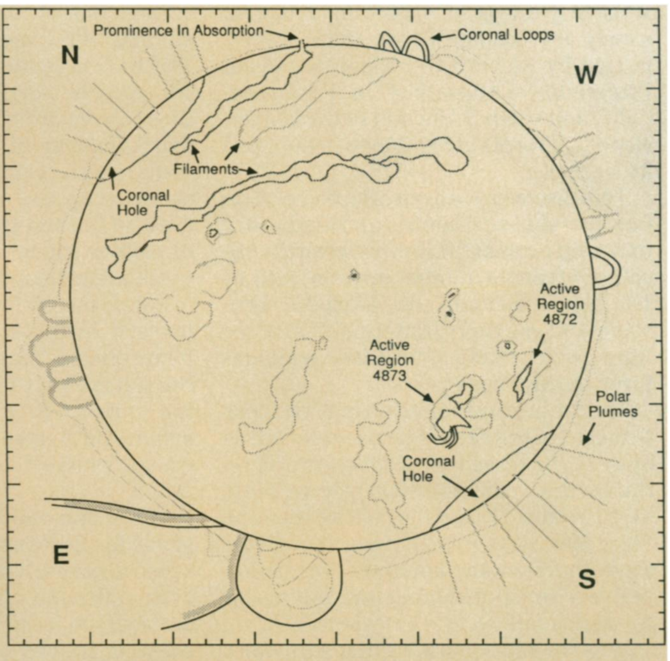
Even better pictures can be obtained from space, where the blurring effect of the earth's atmosphere is absent. Using an instrument intended for another purpose, researchers already have obtained valuable oscillation measurements from the Solar Maximum Mission (Solar Max) satellite, launched in 1980 to study the last solar-cycle peak. However, recent solar activity has heated the earth's atmosphere and caused it to expand. Solar Max, encountering increased drag, will likely fall and burn up sometime in 1990. Future satellites may carry improved instruments for monitoring solar oscillations. NASA is planning several space missions specifically designed for studying various aspects of the sun (SN: 6/25/88, p.406).

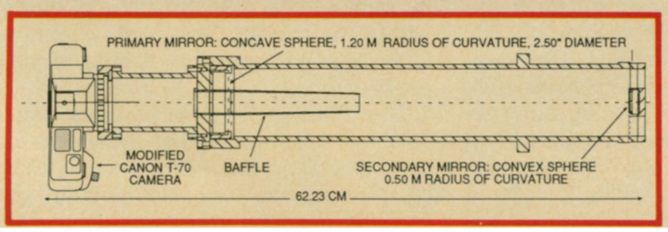
This month, the Soviet Union is expected to launch a spacecraft headed for Mars. That vehicle will carry a Swiss instrument capable of observing solar oscillations during the spacecraft's six-month cruise. The European Space Agency's Solar and Heliospheric Observatory, scheduled for launch in 1994, will carry three helioseismology instruments (SN: 2/22/86, p.119).

With these new sources of data, solar physicists hope to chart the large-scale flows that occur just below the sun's surface and to map how the sun's various layers rotate, all the way to the core. Such motions appear to govern how the sun dissipates heat and changes its magnetic field. These scientists would like to check whether oscillation frequencies shift in response to solar cycles corresponding to reversals of the sun's magnetic field.

Illustrations: Arthur B.C. Walker Jr. et al./Stanford Univ.







This X-ray image (top left) of the inner reaches of the sun's atmosphere was recorded on a special film in a camera attached to a modified Cassegrain telescope (left) aboard a sounding rocket launched last October. The telescope mirrors are coated with thin, alternating layers of molybdenum and silicon, allowing the telescope to operate in parts of the X-ray and ultraviolet spectrum not previously accessible to such instruments. The photograph displays solar emissions corresponding to coronal plasma at 1 million° C. Among the features seen (top right) are magnetically confined loops of hot plasma, coronal plumes and the polar coronal holes.

Moreover, the sun appears to flicker, changing its temperature and brightness slightly, as its surface moves up and down.

"The next decade of helioseismology observations will produce a detailed picture of the internal structure of the sun and of the subsurface structure of solar activity that affects the earth," Harvey says. "We will also learn a great deal more about motions inside the sun."

The major source of information about the sun's brightness has been a special instrument on the Solar Maximum Mission spacecraft. That instrument – a radiometer – has provided useful data since 1980. From that information, scientists have started to develop a picture of subtle variations in the sun's brightness in response to changes in the number of sunspots during solar cycles.

Sunspots, identified by their dark color, appear to reduce the total amount of radiation the sun emits. Radiometer measurements made over periods of days or weeks confirm this decrease in luminosity. But on longer time scales, the pattern turns out to be the other way around. As the number of sunspots decreases, solar output also decreases, dimming the sun by about 0.1 percent. This poses an unexplained paradox for astronomers.

More recent data, covering a period of increasing sunspot activity, show the sun's brightness in visible light is also slowly increasing. Those data are reported by Richard C. Willson of the Jet Propulsion Laboratory in Pasadena, Calif., and Hugh S. Hudson of the University of California at San Diego in the April 28 NATURE.

This discovery of a positive correlation between sunspot number and luminosity may help explain the link between the so-called Maunder minimum from 1645 to 1715, when virtually no sunspots were seen, and northern Europe's "Little Ice Age," which saw record-low temperatures during those years.

The 0.1-percent variation in brightness detected in the satellite measurements is close to the threshold at which effects on the earth's weather are likely to be seen, says Hudson. He and his colleagues hope Solar Max stays in orbit long enough for them to follow the apparent correlation between sunspot number and luminosity through a full cycle – at least to 1991.

Why the sun seems brighter with more sunspots puzzles solar scientists. Says Hudson, "Theoretically, this is hard to understand right now." One possibility is a subtle connection between the sun's pulsations and its magnetic activity, which in turn could affect luminosity.

Solar flares are explosive releases of energy seen as fiery plumes shooting out from the sun. These events, which may last a few minutes or an hour, represent vast outpourings of radiation and particles. Such flares can dramatically affect the earth by increasing the brilliance of auroral displays and disrupting communications. No one knows quite why solar flares occur, but recent theory links them with magnetic fields in the vicinity of sunspots.

High Altitude Observatory/NCAR

Gas in the sun's outer atmosphere can reach temperatures of 2 million° C or more. During the total solar eclipse last March, one instrument recorded green light emitted by iron with 13 electrons removed. Astronomers used a special filter to measure the direction in which this hot, iron-containing gas was flowing. The image was processed so red indicates movement away from the observer while blue material is moving toward the observer. Yellow fringes show no relative motion.

Taeil Bai of Stanford University has studied 1,485 major flares observed from 1955 to 1985. In the May 15 ASTROPHYSICAL JOURNAL, he concludes that almost half those flares are clustered in a relatively small number of "superactive" regions containing large sunspots. These regions seem to appear most often in certain areas of the sun known to be "hot spots," or active zones. More flares occur in these areas than elsewhere.

Bai observed four such hot spots, two in each of the southern and northern hemispheres. These zones rotate around the sun in about 26 days, slightly faster in the southern than in the northern hemisphere. Both rates are slightly faster than the sun's surface rotation rate (SN: 7/4/87, p.4).

These hot spots remain surprisingly stable for decades, says Bai. Such active zones may result from the large columns of fluid flowing upward toward the sun's surface, similar to the flows that produce volcanic activity at certain locations on the earth, such as Hawaii (SN: 10/17/87, p.250).

The occurrence of solar hot spots and their association with flare activity adds to the mystery surrounding what happens in the sun's subsurface convective layer, where large circulating currents carry material from deep within the sun toward the surface. Knowing the nature of these giant convective cells could shed light on the formation of sunspots and solar flares and account for the latitude-dependent irregularities in the sun's rotation rate.

The sun can be regarded as a huge magnetic engine that converts energy-releasing nuclear reactions and large-scale, convective fluid flow into magnetic energy, says Richard R. Fisher of the High Altitude Observatory in Boulder, Colo. One way to study the sun's large-scale magnetic fields is to observe its corona – the outermost reaches of its atmosphere.

A total solar eclipse provides an ideal opportunity for photographing the corona. The moon hides the sun's face, allowing the fainter light of the corona's diaphanous folds and streamers to become apparent. That's what led Fisher and three colleagues to the rooftop of the city hall in General Santos City in the Philippines on March 18. It was a chance to see the corona just as the old solar cycle was fading away and a new one was beginning.

The researchers used three special cameras to document the corona's appearance. One camera, which had a filter suppressing the great variations in the corona's brightness, provided a dramatic look in white light at subtle details in the corona's magnetic structure. A second camera captured parts of the corona glowing at 2 million°C and provided information on the direction of flows within the corona. The third camera, a video system, revealed details of the inner corona.

The Philippines observations were part of a larger scientific collaboration involving observations from a sounding rocket, the Solar Max satellite and various solar observatories. "We collected an unusually rich store of data for this eclipse period," Fisher says.

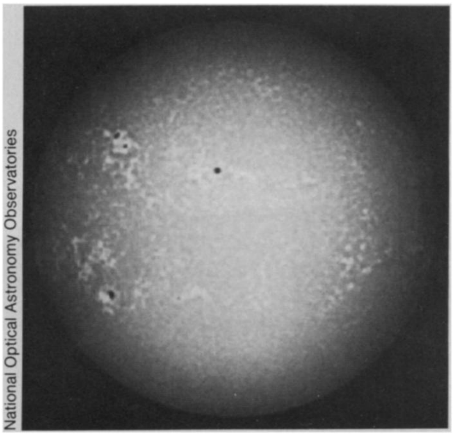
Such combinations of data give new insights into the nature of the forces acting in the solar atmosphere, the flux of mass emitted from the sun, and the temperature distribution of the sun's outer atmosphere. The white-light coronal image is of particular importance because it ties together the different types of observations.

For example, the combination of an X-ray image of the sun obtained by the sounding rocket together with the white-light coronal image (see cover) allows researchers to work out the corona's three-dimensional form. For the first time, they can see the relationship between the corona's structure and variations in the magnetic field across the sun's surface. "We can see where the streamers are rooted," says Fisher.

Researchers also were surprised to find that streamers associated with high-latitude sunspots of the new sunspot cycle are considerably hotter than the streamers coming from older sunspots clustered near the equator. Furthermore, some of the coronal rays seen at relatively high latitudes seem to originate from small regions that are bright X-ray sources.

The most remarkable feature is the bending of the new-cycle streamers toward the equator, says Fisher. That observation implies that the magnetic fields associated with old-cycle sunspots still exert a considerable force toward the equator and away from the poles.

Later in the solar cycle, the number of streamers should increase. At that stage, all the streamers should point radially outward, like spokes in a bicycle wheel, instead of being bent, Fisher says.



National Optical Astronomy Observatories

This image of the sun is one of several thousand solar oscillation observations made from the South Pole during an Antarctic summer. In this case, a filter allows the camera to capture light emitted by calcium atoms. The pattern of light and dark areas provides clues about the sun's complicated motions. From a sequence of such patterns gathered over days, solar scientists can work out the different kinds of oscillations the sun undergoes.

The sun is rapidly approaching a maximum in its current sunspot cycle, which could come as early as the end of 1989. Researchers know from sunspot patterns already observed that it will be quite large in terms of activity and numbers of sunspots. Some of the most active cycles on record have occurred within the last 30 or 40 years.

The month-to-month variation so far has been too erratic for astronomers to predict whether the present cycle will be unprecedentedly large, Fisher says. May was calmer than April, but by June the sun again was picking up sunspots at a good pace.

"We're in a period of adventure with the sun," Toomre says. What's exciting is the prospect of obtaining more detailed and comprehensive views of the sun than ever before.

"The payoff is big," Harvey says. With their array of new instruments and improved observational techniques, solar scientists hope to find answers to some of their questions about the sun and to test in a serious way theories about the structure and evolution of stars. "That's why we go to these extremes," Harvey says.

The sun, for all its averageness, is still largely an enigma. □