THE SUN OUR STAR

The sun is proving to be a star of surprising subtlety and mystery, full of challenges for physicists and astronomers

BY KENDRICK FRAZIER

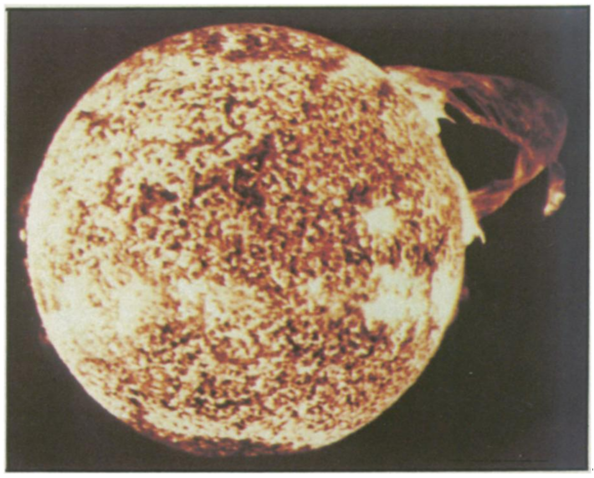
It is one of those little coincidences of history. Just as public interest in the sun as a potential source of practical energy on earth has risen to new heights, scientific interest in the sun as a star full of surprises and mysteries has brought unparalleled vigor to solar astronomy and physics.

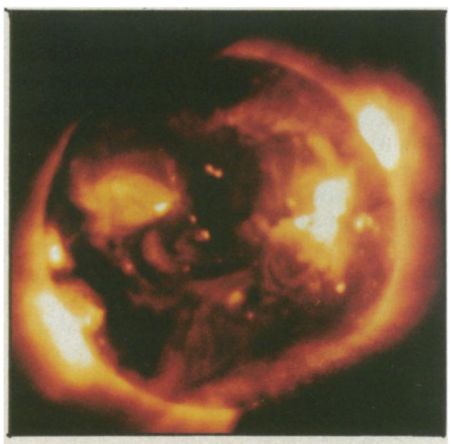
The sun, essential though it is to life on earth, has nevertheless, during much of the recent past, been taken for granted. There it is in the sky every day, shining steadily and constantly, ever dependable. Oh, we knew it went through an 11-year cycle of stronger and then weaker "activity," but that, too, went like clockwork. We were told, accurately, that in virtually every measureable way — lifetime, size, brightness, type — the sun is just an average, typical star, nothing to get excited about. All in all, rather dull. The real stellar frontiers were elsewhere in the galaxy.

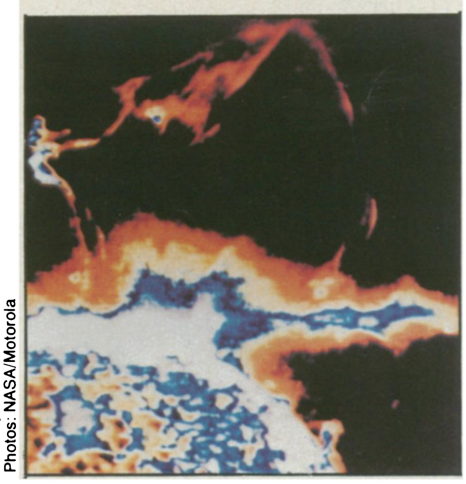
No more. In the 1970s studies of the sun have shown it to be filled with enigma and unanticipated possible variations. At least one longtime mystery has been solved — the source region of recurrent geomagnetic disturbances has been identified with solar features known as coronal holes. New mysteries have arisen. The lack of the expected number of neutrinos reaching earth from the sun's interior has thrown theories about basic stellar processes into confusion. The picture of a regular, constant sun, apart from the long-known 11-year cycle, has been dramatically assaulted from flanks at opposite time scales. Studies of carbon-14 concentrations in tree ring samples and of historical records from around the world indicate that the sun's behavior in the past may have been significantly different from that of today. The data point to gross, irregularly fluctuating changes in solar activity on the scale of hundreds or thousands of years. At the opposite extreme is new evidence that the sun may be undergoing global oscillations on the scale of hours or even minutes (see next page). And all the while scientists ponder ways in which the sun may contribute to climate changes on earth.

Clearly the sun is far more than a source of life-giving heat and energy for earth. It is a star so near that by detailed study we may gain a better understanding of our universe of stars.

The sun's vital statistics, staggering as they are, can be quickly summarized. Nearly 150 million kilometers away (farther than the orbits of Venus, Mercury and Mars but closer than Jupiter and Saturn), its light takes eight minutes to reach the earth. (Slower-moving ionized particles of solar wind take several days.) Its diameter of 1,392,000 km would allow 109 earths to fit across its width. Its mass of 1.99×10^{30} kilograms is 330,000 times the mass of earth. In fact its mass is 745 times that of all the planets of the solar system put together, including giant Jupiter. Different parts of the solar surface rotate at different rates, depending on latitude. The period is 27 days, as seen from earth, in the equatorial regions, up to 31 days near the poles. This differential rotation is proof that the sun is not a solid body.







Photos: NASA/Motorola

Views of the sun (top to bottom): Skylab 4 photo shows 367,000-mile solar flare; X-ray photo reveals coronal holes; and false color image displays solar eruption.

It is, of course, a glowing ball of gas, 90 percent hydrogen, 9 percent helium, 1 percent other elements, powered by nuclear fusions in its hot (16 million degrees K), dense central core. Four hydrogen atoms fuse to become a helium atom in a three-step proton-proton reaction. The resulting helium has slightly less mass (0.7 percent) than the original four hydrogen atoms. It is the conversion of that missing mass to energy that powers the sun and lights our sky. (Although fusion itself happens quickly, the practical release of energy to the sun's surface is a slow process; the solar interior is so opaque to radiation that the energy takes 10 million years or more to work its way outward to the solar surface. Thus, the energy we are now receiving began in events initiated long before the dawn of human history on earth.)

A star the size of the sun should have enough hydrogen to last about 10 billion years. Since the sun has been around for about half that time, it still has about 5 billion years of life left in its present stage. Then when the hydrogen runs low, pressure from fusion will fail to counteract gravity, and the core will contract and heat up, causing the outer layers of the sun to bloat outward. The sun will become a red giant star, probably enveloping the earth and roasting everything on it. Eventually the sun's central regions will contract into a white dwarf star the size of the earth. Nuclear reactions will go out, and the sun will be dead.

Since these unhappy events are still a way off, however, we can safely return to considering the new insights into the sun gained in recent years.

Coronal holes are an outstanding example. By the latter half of the 19th century a relationship between the solar cycle and magnetic disturbances on earth was almost universally accepted. Exceptional activity observed on the surface of the sun was often followed by disturbances in the earth's magnetic field. By 1927, partly due to effects of magnetic phenomena on wireless transmissions, as radio was then called, a recurrent 27-day interval in magnetic disturbance had also been noticed and was gaining considerable scientific attention. These moderate-sized recurrent disturbances were separate from the sporadic, large-scale disturbances.

The recurrent storms tended to appear when the sun was free of any optical sign of activity. The 27-day period seemed to point to an association with the rotation of the sun, and in 1932 Julius Bartels proposed the name M regions (for "magnetically active" and "mysterious") for this still unknown solar source of recurrent storms.

This was the way things stood until the satellite era. The recurrent storms were shown to be associated with high-speed solar wind streams, but the source of these streams on the sun still was not known.

In the 1970s the mystery was solved. Many different lines of inquiry contributed to the solution. The corona is the sun's tenuous outer atmosphere, visible in normal light only at total eclipse. Photographs of the total solar eclipse on March 7, 1970, showed a dark cleft in the sun's corona. Studies reported in 1973 of X-ray solar images made from rockets over a five-year period showed an abundance of holes in the corona, marked by low densities, weak magnetic fields and open, outwardly diverging lines of force. Spectroheliograms in extreme ultraviolet from the OSO-4 orbiting satellite showed holes, and studies of the data revealed them to be low-temperature channels out through the solar atmosphere. Theoretical work showed that high-speed solar wind streams might originate in the regions of the corona having open rather than closed magnetic field lines.

Finally, in 1973 A. S. Krieger and colleagues showed that an observed X-ray

Sun Shakes

BY DIETRICK E. THOMSEN

A number of observations and nonobservations have put the theoretical physics of the sun into a rather shaky state (see accompanying article). The orb we had once thought so regular turns out to be more and more variable and unpredictable. Perhaps it was inevitable that this should come to pass. Our impression of solar regularity may have depended more on our inner need for a dependable celestial parent—living in the neighborhood of a variable star is a bit of a nervous strain — than it did on the facts.

One recent contribution to the solar upheaval, which is still highly controversial, but, if correct, extremely important, is that the sun itself has the shakes, oscillations that go deep into its insides. The observations involve fluctuations in the "limb" or edge of the solar disk observed by Henry A. Hill of the University of Arizona and a number of colleagues working at the Santa Catalina Laboratory for Experimental Relativity by Astrometry, which is located in the Santa Catalina Mountains north of Tucson and operated jointly by the University of Arizona and Wesleyan University.

Hill and his co-workers maintain that these fluctuations represent oscillations in the sun, and furthermore that some of them are "gravity waves," that is up and down motions of the matter of the sun that proceed from deep within the sphere, and not simply pressure waves moving along the surface of the sun. The critics must be convinced first that the observations represent real motions of the solar surface and then that the distinction between gravity waves and pressure waves goes as Hill and his colleagues argue.

The observations had their beginning more than a decade ago in an attempt to find evidence that would distinguish between two rival theories of gravity, that of Einstein and that of Carl H. Brans and Robert F. Dicke. One of the possibly observable differences is that the Brans-Dicke theory should lead to an oblateness of the sun, a slightly longer diameter in the equatorial plane than through the poles. It is from this that the laboratory gets its name, because general relativity is the term for theories that encompass gravity and the relations between space and time and extend to cosmology. The equipment that Hill and his co-workers developed to study the configuration of the edge of the sun has so far never discovered the oblateness that was sought — and the observers have published that result more than once—but it has found these interesting oscillations.

First one must define the edge of the sun. That is not self-evident. There is no sharp boundary. In a certain sense it could be said that all the planets out to Jupiter swim in the outer atmosphere of the sun. The boundary is chosen by a consideration of the light-emitting disk of the sun. There is a narrow outer region through which the brightness falls off very sharply, and the observers choose a point on this fall-off curve, the reasons for which are argued at length in the technical literature, as the edge.

Having observed fluctuations in this edge, the observers must then convince the critics that the fluctuations represent motions of matter in the sun and not changes in the surface brightness that make it look as if the edge has moved nor fluctuations in the earth's atmosphere that make the image shimmer. The observation of the fluctuations repeatedly from day to day under different atmospheric conditions and positions of the sun in the sky tend to rule out these objections, although again the detailed arguments are long and highly technical. In recent months the evidence that the oscillations are real and do belong to the sun has greatly increased, Hill told the European Conference on Solar Physics, which was held in Toulouse in March. Two of the observed vibration modes are identified as gravity waves because of their long periods. Pressure waves in the surface have to have shorter periods.

All of this tends to alter our traditional picture of solar steadiness, and it will have, if and when it is widely accepted, profound effects on the theoretical physics of the sun. The gravity waves are capable of bringing energy out of the sun very fast—in a matter of minutes compared to perhaps millions of years for light. (Light takes that long to get out because it undergoes an astronomical number of absorptions and reradiations on the way.)

The change in the energy transport possibilities will alter the picture of the nuclear reactions that must go on in the interior of the sun to supply the observed flux of energy — especially in the convection zone where heating churns up the solar material. For these reasons the existence of the oscillations may also provide a solution to the solar neutrino problem — why the sun does not produce the flux of neutrinos that would be expected from the thermonuclear reactions that currently accepted theory proposes take place in the sun's interior.

Last, but far from least, these observations lead back through stellar physics to the cosmology with which they began. The sun is a fairly representative star, and if it has such vibrations, a lot of others probably do too. The theory of stellar evolution depends on the energy processes in the stars, so it will apparently have to change. In the end we may be discovering that we do not live in as quiet a corner of the universe as we may have wished. □

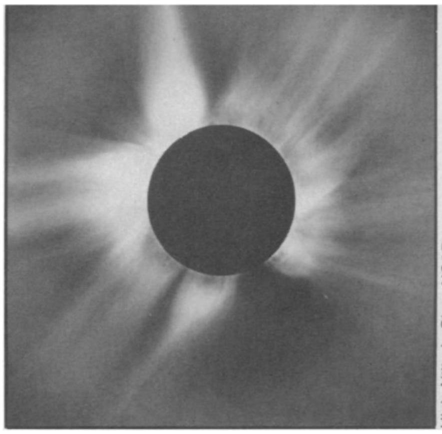
coronal hole was in fact the source of a high-velocity solar wind stream. The discovery has been reconfirmed by a number of observers since. In 1976, for instance, N. R. Sheeley and colleagues reported dramatic correlations between passage of coronal holes and geomagnetic disturbances from 1973 to 1976.

Thus, more than four decades after Bartels gave it the label M-region, the source on the sun of the 27-day recurrent geomagnetic disturbances was finally identified — the coronal hole.

The Skylab missions in 1973 and 1974 were just in time to add immeasureably to understanding of the sun, especially the coronal holes. They showed, among other things, that coronal holes can be abundant (nearly 20 percent of the Skylab-period sun was covered by coronal holes) and are among the most long-lived of solar phenomena (lasting 10 solar rotations or more).

If the confirmation of coronal holes in the 1970s solved one long-discussed problem about the sun, the mystery of the missing neutrinos has deepened throughout the decade to become one of the major unsolved scientific problems of our time. The puzzle has been well covered by SCIENCE NEWS over the years. Suffice it to say that the sun, in some way, is throwing astronomers, astrophysicists and particle physicists a curve. Only about a fourth of the expected number of solar neutrinos — tiny particles produced in the core of the sun as a byproduct of the fusion reaction — have been monitored by a detector a mile beneath the earth in a gold mine in South Dakota. Something is wrong.

The problem has become very troubling. The experiment itself has been checked and rechecked and refined. The nuclear reactions produced in fusions



High Altitude Obs., NCAR

Total solar eclipse, March 1970. Dark cleft at lower right is a coronal hole.

have been measured in laboratories and found to be in accord with theory. Astronomers' ideas about the interior structure of the sun may be wrong. If so, our understanding of the evolution of stars may be in error, and that would have far-reaching consequences.

The apparent neutrino deficit could mean that some of the fusion reactions in the sun's interior have switched off; perhaps it is at heart a variable star. Neutrinos pass through matter so readily that they reach earth from the center of the sun in only minutes, whereas as mentioned earlier the light we are now receiving was generated in the solar interior far in the past. It is conceivable that something has happened in the sun's core in the meantime.

No ready answers await these speculations. The missing solar neutrinos are a genuine and disturbing puzzle.

Another series of discoveries beginning to vastly alter our conception of the sun is the accumulating evidence that the sun has gone through long-term, apparently random changes in activity in the historical past. It began with the confirmation two years ago by John A. Eddy that from A.D. 1645 to 1715, a period now known as the Maunder minimum, no evidence of the 11-year cycle appeared (SN: 3/6/76, p. 154). Few sunspots were recorded. Auroras, related to solar activity, were practically nonexistent. During eclipses coronas were absent or severely weakened. An earlier period of low activity in the 15th century, the Spörer minimum, was also identified.

The historical record was corroborated by carbon-14 evidence in tree rings. Through a series of processes C-14 concentrations are altered by solar activity. C-14 isotopes are created when galactic cosmic rays strike nitrogen atoms in the upper atmosphere. High solar activity tends to shield the earth from cosmic rays. Thus, when solar activity is low, more C-14 is produced and, with a time lag of roughly 40 years, absorbed into tree rings. When solar activity is high, less C-14 is produced and absorbed.

With tree-ring radiocarbon data from Paul Damon of the University of Arizona and research of historical records, Eddy, now senior scientist at the National Center for Atmospheric Research, has established a record of long-term solar variability back to 5,000 B.C., almost halfway to the end of the last glaciation and well beyond the reach of the written word. It turns out that what we thought to be anomalies — like the Maunder minimum — are really quite ordinary.

There have been no fewer than 12 important excursions on a scale of hundreds or thousands of years in the last 5,000 years in which the sun has been both a good deal less active, and probably more active, than anything seen in modern days.

Eddy has given these excursions labels taken from the general historical period in which the anomaly falls. For example, the "Stonehenge" solar maximum occurred from 1870 to 1760 B.C. The "Egyptian" solar minimum, between about 1420 and 1260 B.C., occurred during the Golden Age of the New Kingdom of Ancient Egypt. The "Homeric" minimum immediately following came shortly after the time of Homer. The radiocarbon evidence shows there was a Grecian minimum from 440 to 360 B.C. Eddy suggests this may be why there seems to be no mention of spectacular auroral displays during this era of early Greek interest in science and natural philosophy.

"It now seems quite possible," Eddy says, "that the common 11-year sunspot cycle is but a temporary feature of the most recent solar history, or that it gets switched off and on in a program that seems almost random." This poses, he notes, a quandary new in solar physics. The sun, far from being regular and repeatable, seems to be just the opposite.

"The New Solar Physics tells us that the 11-year cycle is but a ripple on an ocean of great sweeping tides," says Eddy. "It suggests we step back and look instead at the longer-term changes, when the sun

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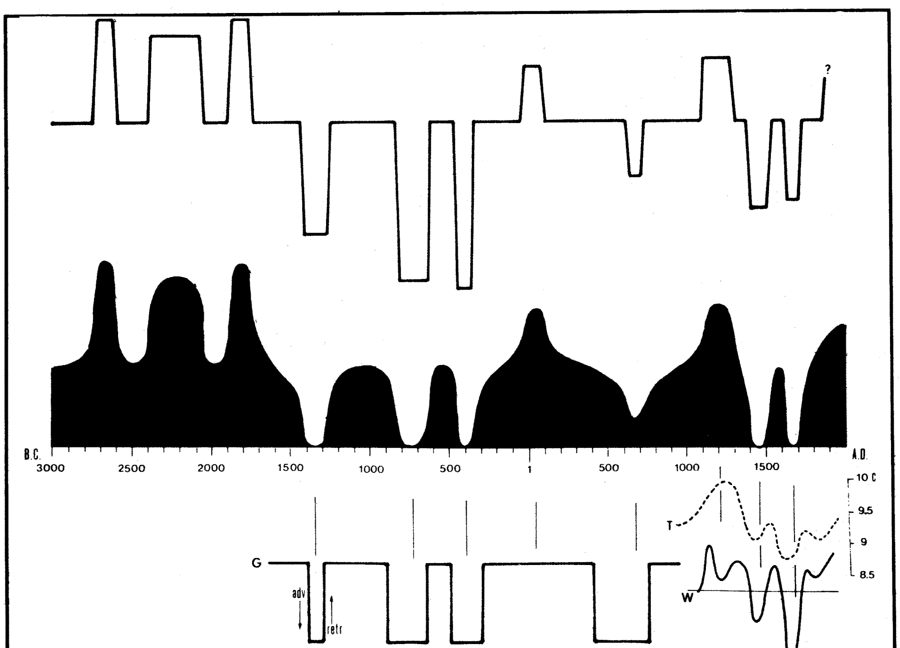

J. A. Eddy

Tree-ring radiocarbon data (top), solar activity (middle) and glacial advance and retreat records suggest a long record of solar variability.

. . . Solar Physics

drifts in and out of eras like the Maunder minimum. It says these changes may be the more fundamental on the sun, the more indicative of changes in the sun's energetic radiative output, and the more important in terrestrial effect."

The newly confirmed solar variability may well have important climatic consequences. It was noted that the Maunder minimum correlated with the time of the so-called Little Ice Age. The Spörer minimum likewise corresponded with a time of cooling. And the Earlier Medieval maximum was a time of warming.

When Eddy compared the earlier solar record with the even earlier climate history, the correspondence was no less striking. He has constructed a graph of glacial advance and retreats since 1500 B.C. plus later historical climate data and compared it with a graph of solar activity reconstructed from the C-14 data. Says Eddy: "The correspondence, feature for feature, is, I think, almost the fit of a key in a lock."

Whenever a dip in solar activity occurs, the climate swings coldward and glaciers advance. When there is a prolonged maximum of solar activity glaciers retreat and the earth warms.

Such statistical correspondences are always controversial in science unless an accepted physical mechanism — the actual cause — is at hand to explain them. Eddy strongly believes that the variations in sunspot number and other solar activity are but a manifestation of a more basic effect — changes in the solar constant. This is a measure of the rate at which solar radiation is received outside the earth's atmosphere at the mean earth-sun distance. In other words, he believes the sun's energy output may vary. Efforts to systematically determine to what degree the solar constant may vary are now underway.

If it turns out that solar variability is a key to climate changes on the scale of a century or a millenium, it would nicely complement the work of James D. Hays and colleagues. In late 1976 they reported strong statistical evidence from deep sea cores that longer-term climatic variations — on the order of 10,000 to 100,000 years — are due to known cyclic variations in the orbit of the earth. Thus in this picture, the shorter-term climatic changes would be related to irregular changes in the sun itself while longer-term ones would be the result of cyclic changes in the orientation and position of the earth with respect to the sun. Nothing is ever so neat, especially in climatology. But it does show the crucial role the sun seems to play in such considerations.

While society turns now to the sun as an increasingly important source of energy for civilization on earth, it also becomes clear that the sun is a star of surprising subtlety and mystery. It presents a magnificent and formidable challenge to late-20th century science. □