The Variable Sun

Its steady warmth and brightness are illusory; the sun's output of radiation and particles varies. Systematic observations are beginning to unveil the causes of these changes and their effects on the earth

by Peter V. Foukal

To someone lying on the beach or taking a daytime stroll, the blazing sun seems constant and unchanging. Actually, the sun is a variable star. The well-known 11-year "sunspot cycle"—which is thought to be now near its peak—is but one aspect of a complex, 22-year magnetic fluctuation during which the sun varies in its output of visible and ultraviolet light, X rays and charged particles. These fluctuations can heat and expand the earth's upper atmosphere, cause auroras, knock out power lines, alter the planet's ozone layer and perhaps influence climate. Even this cyclic variation cannot be considered reliable, because the sun has exhibited quite different patterns of behavior as recently as the 17th century, and there is good reason to expect that its behavior will change again.

This possibility is of more than academic interest, because any major change in the sun's luminosity or even in its level of activity could affect the habitability of the earth. Current discussions of possible changes in the global environment tend to focus on the effects of human activities, such as the climatic implications of accumulating greenhouse gases and the destruction of ozone by chlorofluorocarbons. Understanding and quantifying these effects demands an awareness of other causes of environmental change, particularly long-term variations in the sun's emission of light and charged particles. Investigators are working to determine more accurately the connections between conditions on the sun and those on the earth and to predict—or determine if it is even possible to predict—the future course of solar variability.

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The first indication that such predictions might be possible appeared in 1843, when Heinrich S. Schwabe, a German apothecary and amateur solar observer, announced that the number of dark spots visible on the solar disk seemed to vary in a regular, roughly 10-year cycle. Schwabe's evidence for a sunspot cycle came to the notice of J. Rudolf Wolf, who became the director of the newly established Zurich Observatory in 1855. At Zurich, Wolf tracked the daily sunspot number based on reports from an international network of observers; he also compiled a history of the sunspot number based on records from the previous 150 years. Wolf found a corrected average period of about 11.1 years for the sunspot cycle, although both the period and amplitude varied considerably from cycle to cycle.

A graph of the sunspot cycle from 1610 to the present reveals that the sunspot number has oscillated without interruption since about 1715 [*see illustration on page 28*]. During the 13 cycles of reliable data collected since 1848, the cycle's length has varied between about 10 and 12 years. The cycle's amplitude has been even less regular, ranging from an annual mean spot number of about 45 in 1804 and 1818 to a peak of roughly 190 in 1957. The present cycle may produce the highest sunspot number and overall level of activity yet recorded, judging from its current behavior.

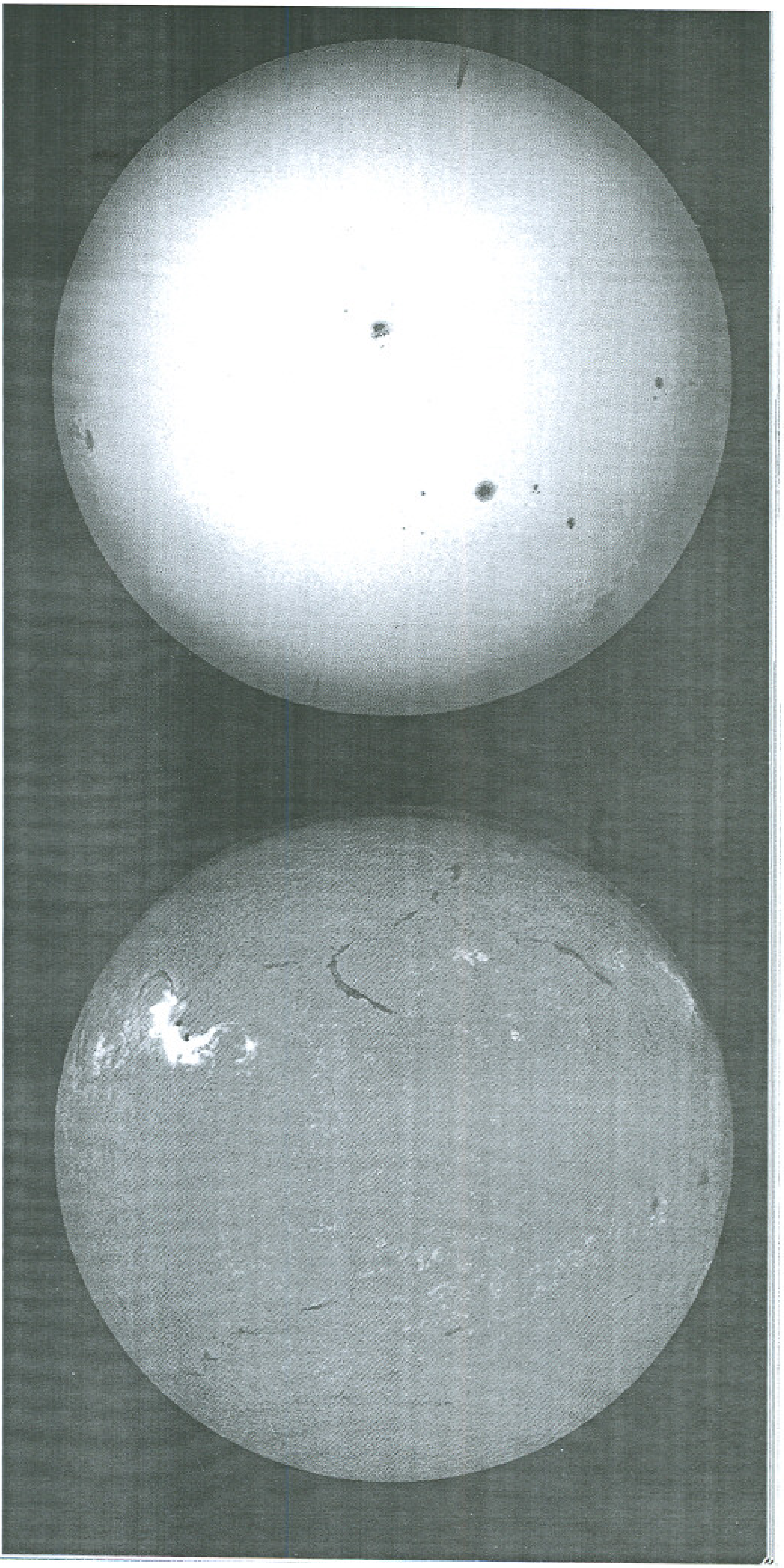
The regular variations of the sunspot cycle are notably absent for the years from 1645 to 1715, when very few sunspots were observed. This period of depressed solar activity is known as the Maunder minimum, named after the British solar astronomer E. Walter Maunder, who did much to draw attention to it in the late 19th and early 20th centuries. Astronomers initially tended to ignore Maunder's findings or to attribute them to the crude telescopes and poor observational techniques of the age.

Recently, though, John A. Eddy, a solar astronomer at the University Corporation for Atmospheric Research in Boulder, Colorado, has accumulated convincing evidence that the dearth of sunspots documented by Maunder was a real and rather remarkable aspect of solar behavior [see "The Case of the Missing Sunspots," by John A. Eddy; SCIENTIFIC AMERICAN, May, 1977]. The Maunder minimum occurred during the most severe portion of a period of unusually cold weather, known as the Little Ice Age, which extended roughly from the 16th to the 18th centuries; the possible connection between these events is intriguing but still speculative. The Maunder minimum and the small peaks in the solar cycles at the beginning of the 19th century may explain why more than two centuries passed between the first European sunspot observations—which were made around 1610, shortly after the invention of the telescope, by Galileo and others—and Schwabe's discovery of the 11-year cycle.

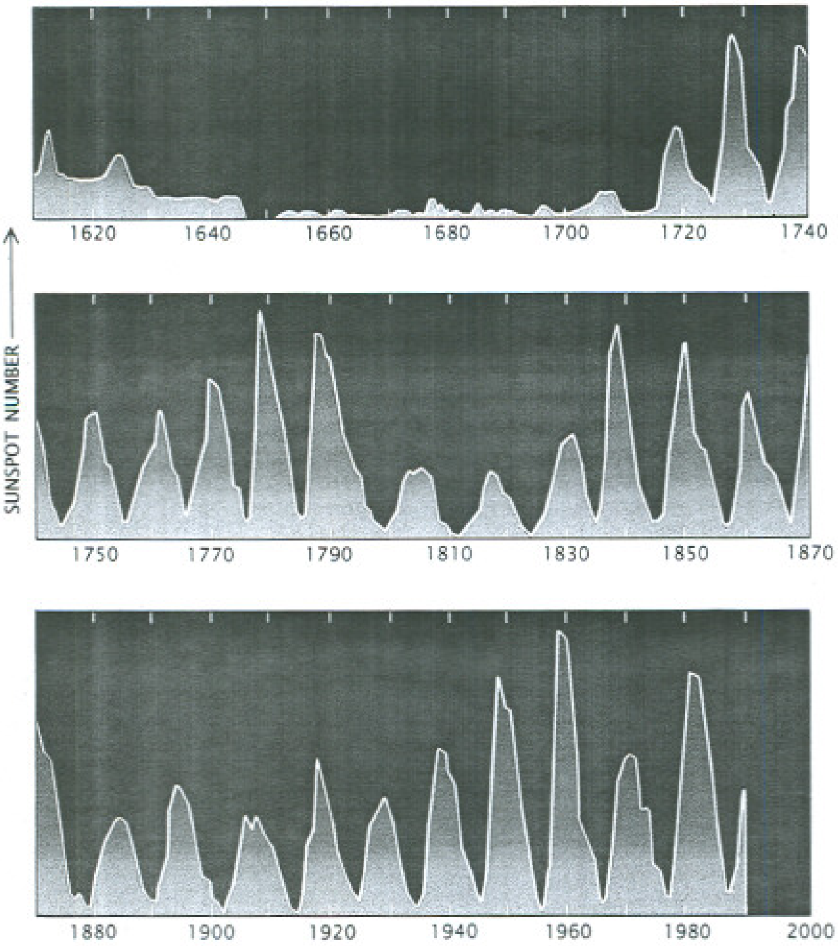
The 11-year variation of sunspot number is now known to be merely the most visible aspect of a profound oscillation of the sun's magnetic field that affects many other aspects of the sun's surface and atmosphere and possibly its deepest interior as well. George Ellery Hale and his collaborators at the Mount Wilson Observatory in California found the first evidence of solar magnetic oscillation in their measurements of sunspot spectra. They discovered that certain absorption lines in the spectra were broadened and polarized much like lines in laboratory spectra of magnetized gases, which had been studied by the Dutch physicist Pieter Zeeman. By analyzing this "Zeeman effect," they determined that the strength of the magnetic fields around sunspots is between 2,000 and 3,000 gauss, thousands of times stronger than the earth's field. They also showed that most spots occur in paired groupings that resemble giant magnetic dipoles (a bar magnet is one example of a dipole) and that are usually oriented roughly parallel to the solar equator.

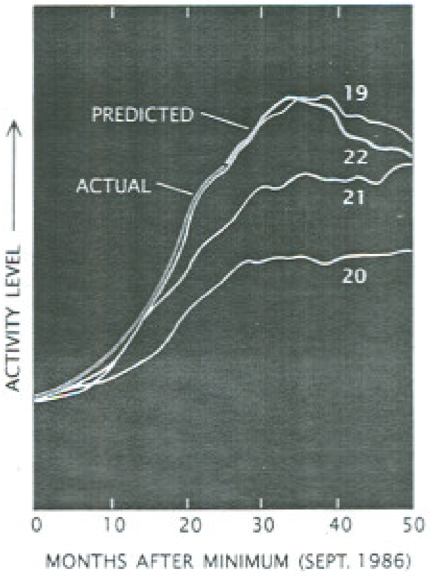
In 1912 Hale announced that the magnetic polarity of these sunspot dipoles had switched sign in the first spots of the new cycle that began that year. By 1924 he had collected enough observations to announce that this switch in polarity occurred at each activity minimum and was a basic feature of the sunspot cycle. He concluded that the 11-year cycle of sunspot number is actually half of a 22-year solar magnetic cycle, during which the polarity of sunspot groups reverses twice, hence returning to its original state.

Much more sensitive measurements of the sun's magnetic field are now made on a daily basis with the magnetograph, which was developed by Harold D. and Horace W. Babcock at Mount Wilson in 1951. One surprising finding extracted from such magnetograms, and from other evidence, is that the sun's surface magnetism is confined to small regions of intense magnetic field that cover only a few percent of the total area of the photosphere, the layer that forms the sun's visible surface. The largest areas of a single magnetic polarity are the sites of spot formation; smaller areas, ranging in size down to the resolution



TWO VIEWS OF THE SUN reveal complex processes beneath its mottled appearance. A visible-light photograph (*top*) shows sunspots and bright areas called faculae on the sun's "surface," or photosphere. Photographs made in a red wavelength emitted by hydrogen capture details in the hotter, higher-altitude region called the chromosphere (*bottom*). A bright flare, or solar eruption, can be seen. Dark filaments of relatively cool, dense gas are suspended by magnetic forces. Powerful magnetic fields determine much of the sun's outer structure.





SOLAR CYCLE manifests itself in the changing number of spots on the sun's visible surface (*left*). The dearth of spots between about 1645 and 1715, known as the Maunder minimum, appears to coincide with an era of unusually cold weather. The current cycle, cycle 22, is predicted to reach its peak this month; it has already surpassed the level of activity of the two previous cycles and may exceed cycle 19, the largest ever recorded (*above*).

limit of the most detailed magnetograms (about 200 kilometers), appear bright in most wavelengths of radiation. These especially luminous areas of the solar surface are called faculae (Latin for "little torches"); they were first seen early in the 17th century.

Hale and his collaborators tried inconclusively to observe the magnetic field near the sun's poles in an effort to determine if the sun had a global dipole field analogous to the earth's magnetic field. More sensitive measurements during the past 20 years indicate that the fields around the north and south solar poles are indeed usually, but not always, opposite in polarity and that they switch sign around the time of peak activity.

These observations also have revealed that the geometry of the sun's magnetic field is far more complicated than that of the earth's field, which can be reasonably modeled as a dipole magnet. The sun's field at low latitudes can be visualized as a series of field lines or magnetic tubes wrapped around the sun roughly parallel to its equator, submerged below the solar surface. Where these toruslike field lines emerge above the surface, they form looping stitches of magnetic field that extend into the outer layers of the solar atmosphere, sometimes reaching millions of kilometers out toward the planets before connecting back to the sun. Active regions, visible as spots and faculae, appear where these lines intersect the photosphere.

The mechanism that causes the solar magnetic cycle remains poorly understood, although it has been the focus of intense research during the past half-century. Astronomers generally agree that the observed changes in the sun's magnetism are caused by the motions of solar plasma forced across existing magnetic fields. Plasma is highly ionized gas—that is, gas in which many electrons have been stripped from their nuclei—and so is electrically conductive. Motions in the solar plasma induce both a current in the plasma and an associated magnetic field, which in turn intensifies the original field.

Unlike a solid body such as the earth, the sun's outer regions do not rotate at the same angular rate at all latitudes, a feature first demonstrated by the British astronomer Richard C. Carrington around 1860. The sun's equatorial regions complete one rotation in about 25 days, roughly 25 percent faster than the poles; there is a reasonably smooth variation in between. This differential rotation is probably a key factor in driving the dynamo that maintains the sun's magnetic field. A field line initially extending directly along the surface between the solar poles and constrained to move with the surface plasma would be progressively stretched by the faster equatorial rotation. After a few solar rotations, the line would be wound almost parallel to the equator. This deformation of the field lines probably accounts for the geometry of the solar magnetic field and for the east-west orientation of sunspot groups [*see illustration on page 30*]. The stretching of magnetic field lines increases their intensity to the high values measured in sunspots.

The eruption of magnetic flux from the sun is believed to be partially responsible for the change in polarity of the sunspot fields between cycles. As the magnetic tubes that give rise to active regions emerge from the sun's interior, their magnetic flux eventually disperses across the solar surface. At the same time, the flux is pushed outward into higher layers of the solar atmosphere by new magnetic fields, which rise from below as a result of the sun's differential rotation. The result is a shedding of the old flux that somehow removes the original polarity and leaves the new flux with a net excess of the opposite polarity.

The combination of the shedding of "old" magnetic field by eruption and dispersal and the generation of new field by differential rotation is probably sufficient to explain the solar magnetic cycle, but little is known about the process by which the sun rids itself of the old polarity. Computer simulations of the dynamics of solar-plasma motions and of their interactions with the magnetic field have difficulty producing the 11-year cycle in conjunction with the sun's differential rotation. A major uncertainty has been the nature of the sun's internal rotation, which was essentially unknown until recently. Observations of the sun's global oscillations [see "Helioseismology," by John W. Leibacher, Robert W. Noyes, Juri Toomre and Roger K. Ulrich; SCIENTIFIC AMERICAN, September, 1985] are providing a window into the interior of the sun, making it possible to analyze the depth profile of solar rotation and to calculate its influence on the solar dynamo. Recent findings indicate that the outer 30 percent of the sun's interior rotates differentially, much as its surface does. This suggests that much of the dynamo action in the sun may take place far below the surface.

Although astronomers still remain far from a comprehensive understanding of the sun's magnetic oscillations, measurement of the magnetic cycle's effects on key solar outputs would in itself be an important advance. Climatologists would be quite satisfied to know the amplitude and characteristic time scales of solar-luminosity changes even if the astrophysical explanation of the changes had to wait. Fortunately, substantial progress has been made in the past few years in this kind of empirical understanding of the sun's behavior.

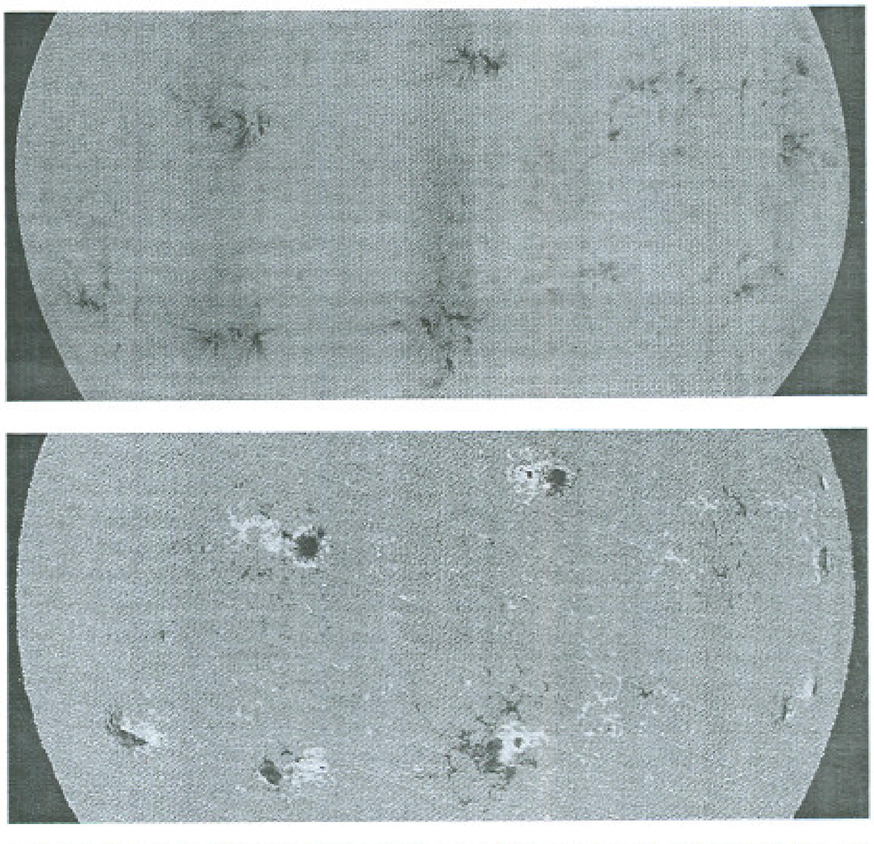
One important advance has been the discovery of cyclic variations in the sun's total light output, known as the total solar irradiance, or—ironically—the solar "constant." The vagaries of the earth's atmosphere have made measurement of the solar constant notoriously difficult, but satellite instruments now reveal that it varies by as much as .2 percent over time scales of weeks. This relatively short-term variation is caused by the passage of dark sunspots and bright faculae across the solar disk as the sun executes its approximately monthly rotation.

These short-term fluctuations were first identified clearly—in data obtained in 1980 with radiometers flown on the *Solar Maximum Mission* (*SMM*) and *Nimbus 7* satellites—by Richard C. Willson of the Jet Propulsion Laboratory in Pasadena, Calif., and John H. Hickey of the Eppley Laboratory in Newport, R. I., respectively. It was harder to identify longer-term changes in the solar constant over the course of the sunspot cycle, because these variations have turned out to be on the order of .1 percent; slow changes in radiometer calibration at this level were difficult to rule out. Convincing evidence finally arrived when readings from both radiometers, which had been falling along with the sun's decreasing activity level since 1980, flattened out in 1986 and began to rise in 1987 as the sun moved into its current cycle and increased its activity.

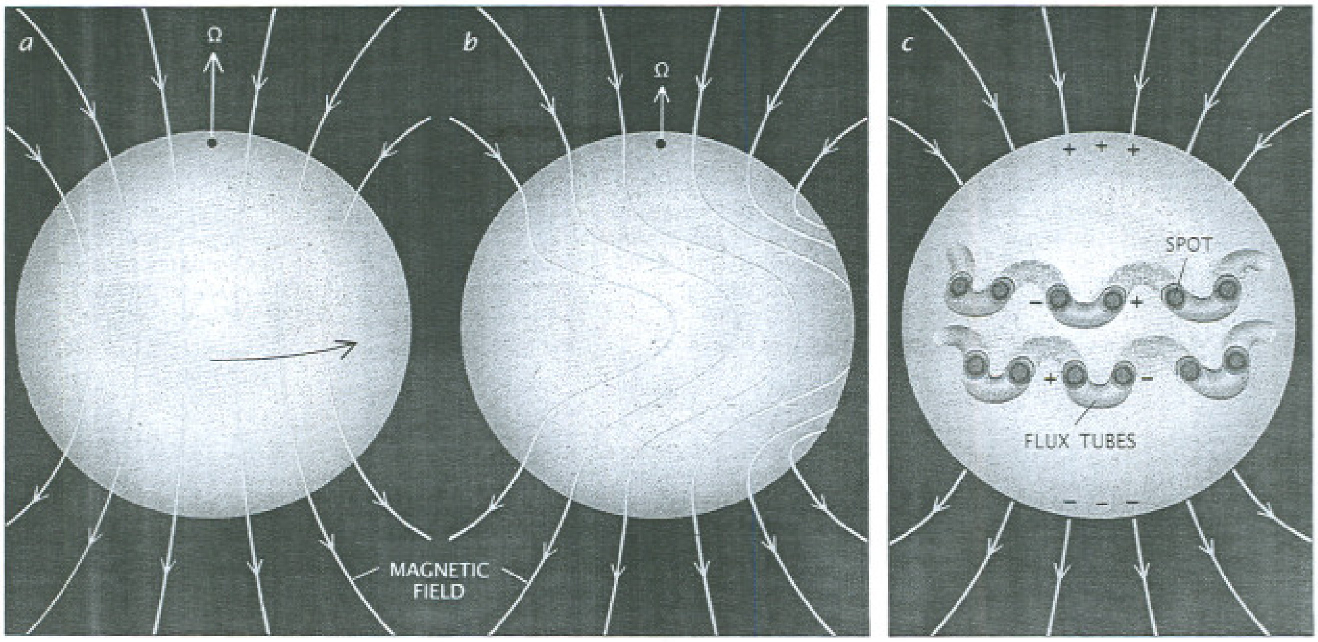
Data from the two satellites indicate that the sun's brightness decreased by about .1 percent between the peak of solar activity in 1981 and its minimum in mid-1986. Surprisingly, the sun grew more luminous as the number of sunspots on its surface grew larger. Analysis of this behavior by Judith L. Lean of the Naval Research Laboratory and myself indicates that the increase in photospheric area covered by bright faculae outweighs the increase in area of dark spots as solar activity increases.

Do these changes in the solar constant affect the earth's weather or climate? It is fairly simple to calculate the effect of variations of solar irradiance on the earth's global mean temperature. Present-day climate models suggest that the size of the effect is well below .1 kelvin. This is a small fraction of the global-warming effect (typically several tenths of a degree) that is expected from the measured increase in the concentration of atmospheric carbon dioxide during the past few decades.

The measurements of solar irradiance made from space so far extend



MAGNETIC FIELD LINES trap huge streamers of hot, ionized gas in the solar atmosphere, or corona. These appear as dark lines in photographs of the sun made in short-wavelength ultraviolet light (*top*). The largest streamers emanate from sunspots. A magnetic image of the sun made at the same time reveals the intense magnetic fields associated with the streamers (*bottom*). Dark and light areas represent opposite magnetic polarities; the strongest fields occur in bipolar active regions.



DIFFERENTIAL ROTATION of the sun is believed to drive the solar magnetic cycle. The solar surface drags existing magnetic field lines along with it as the sun rotates. A complete rotation requires about 25 days near the sun's equator and about 28 days at midlatitudes; over several rotations, a field line that initially followed a straight north-south path (*a*) winds up, stretches horizontally and intensifies (*b*). Sunspots appear where the most intense tubes of magnetic flux emerge at the surface; the points of emergence and reentry of the tubes have opposite polarities (*c*). Sunspots usually form in pairs at similar latitudes because they follow the horizontal stretching of the magnetic field near the surface. Sunspot pairs are huge magnetic dipoles; their orientation in the Northern Hemisphere is opposite to that in the Southern Hemisphere.

over barely one sunspot cycle. Current information is insufficient to tell whether larger solar-irradiance variations occur, perhaps in conjunction with slower variations in solar activity such as the one that produced the Maunder minimum. It has been estimated that during the Little Ice Age global mean temperatures dipped by as much as about .5 kelvin below the long-term average, enough to precipitate a period of significant glacial advance and to cause a series of failed crops in Europe. If the cooling were a result of a change in the sun's luminosity, it would have required a dip in the solar irradiance of between .2 and .5 percent acting over several decades, according to calculations based on standard climate models. A dedicated program of highly precise irradiance monitoring from outer space could detect long-term changes in the sun's luminosity and enable astronomers to determine whether a future lull in solar activity is likely to lead to another extended period of global cooling.

Over the years numerous attempts have been made to find links between the solar cycle and terrestrial weather. The eminent British astronomer Sir William Herschel guessed (correctly!) that the sun is brightest during sunspot maxima, and he mused that the resulting higher temperatures would improve the wheat crop and cause prices to drop. In 1801 he announced that the price of wheat was indeed correlated with the sunspot cycle. The correlation vanished, however, and Herschel turned his attention to other matters. Many other apparent "links" have been similarly short-lived, and all suffer from the fact that they are statistical rather than causal connections; nobody has yet demonstrated a plausible mechanism whereby such tiny variations in the solar constant could have an appreciable effect at the earth's surface.

Yet the quest persists. In 1987 Karin Labitzke of the Free University of Berlin reported the most convincing link yet found. She discovered that the occurrence of mid-winter warmings in the U.S. and Western Europe has correlated remarkably well with the solar cycle over the past 40 years, provided the switch in direction of stratospheric winds roughly every two years is taken into account. The relation she found has withstood repeated statistical tests, and it correctly predicted the warming that accounted for the very mild winter of 1988-89 in the U.K. and Western Europe. An unambiguous and physically explicable connection between solar and climatic variability would represent a tremendous advance in the understanding of the relation between the earth and its star.

The scope of solar variability extends far beyond changes in the appearance and brightness of the photosphere. The magnetic cycle also affects the progressively higher layers of the solar atmosphere, known as the chromosphere, corona and solar wind. The plasma temperature in these regions actually exceeds that of the photosphere even though they are farther from the sun's nuclear heat source. Because the energy losses from these tenuous plasmas are very low, extremely high temperatures—up to millions of degrees—can be maintained by relatively small inputs of energy. This energy is probably derived from the dissipation of sound waves produced by the churning of the photosphere and of electric currents associated with magnetic fields at or below the photosphere.

These hot outer layers of the sun's atmosphere are responsible for the sun's highly variable emissions of X rays and of extreme ultraviolet radiation (EUV), or the wavelengths between about 100 and 1,000 angstrom units (one angstrom unit is 10^{-10} meters). The chromosphere also emits a substantial fraction of the sun's ultraviolet radiation at wavelengths between about 1,600 and 3,200 angstroms and probably accounts for most of the variability in these radiations. Solar X rays have less impact on terrestrial life than UV and EUV emissions, which are of concern because they significantly affect the earth's atmosphere.

The cause of the variability in EUV radiation seems clear from analysis of observations obtained from solar telescopes on *Skylab* in 1973–74 and from more recent satellites such as *SMM*. Intense, locally closed dipole magnetic fields in active regions act as magnetic "cages" that prevent the escape of hot coronal plasma from the sun's gravitational attraction. This trapped plasma is about 10 times denser than that in the quiet surrounding areas, and the denser plasma radiates much more intensely in the EUV. Active regions are therefore the major source of solar EUV emissions, and these emissions rise and fall along with the changes in the solar-activity cycle.

The sun's EUV output variation over the course of an entire 11-year sunspot cycle has not yet been measured successfully. It is a challenge to design spectrometers and detectors for this spectral range and to ensure that their calibration will remain sufficiently steady under powerful EUV irradiation in space to identify reliably slow changes of even several tens of percent. Measurements in the prominent hydrogen emission line at 1,216 angstroms (the Lyman alpha line) indicate a variation in intensity of about a factor of two.

The rapid rise of the current solar cycle has produced a dramatic increase in the solar EUV flux, raising concerns at the National Aeronautics and Space Administration about the orbital lifetimes of the Hubble Space Telescope and the Long Duration Exposure Facility (LDEF), a massive orbiting platform containing 57 zero-gravity experiments. The problem is atmospheric drag: during periods of high solar activity, the increased EUV heating of the earth's upper atmosphere above about 100 kilometers can cause temperatures in the ionosphere to soar to almost three times the values encountered at periods of low activity. These higher temperatures in turn enable the atmosphere to support a gas density as much as 50 times higher at an altitude of 600 kilometers, where the space telescope is supposed to orbit. The greater atmospheric density would lead to increased drag and a much shorter orbital lifetime before a reboost by the space shuttle would be necessary for the $1-billion telescope. NASA has therefore asked solar astronomers to predict both the magnitude of the current cycle's activity and its time of maximum in an effort to choose the best launch date for the space telescope and to plan for the recent shuttle retrieval of the LDEF.

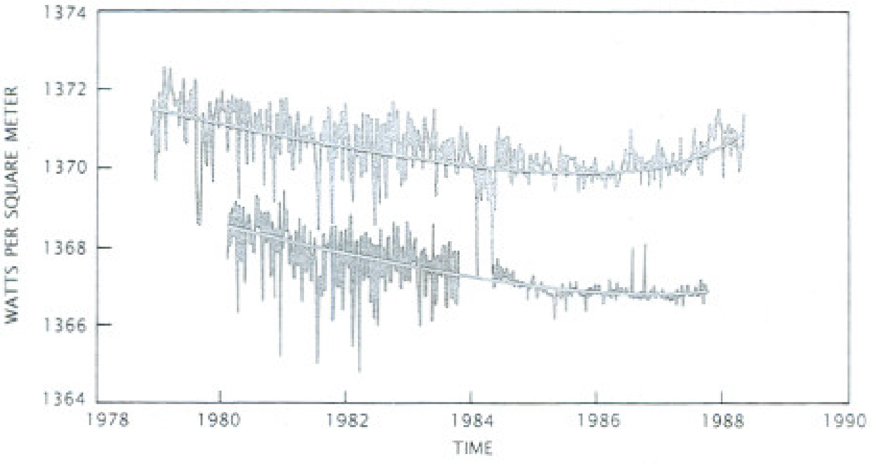
Measuring the sun's 11-year variation is somewhat easier in the ultraviolet than it is in the EUV, and during the past decade more effort has been devoted to observations in ultraviolet wavelengths because they directly affect the earth's ozone layer. Data from the *Nimbus 7* and *Solar Mesosphere Explorer* satellites clearly show a 27-day variation (caused by the sun's rotation) at wavelengths shorter than about 3,000 angstroms. The amplitude of the 11-year solar-cycle variation in the UV is elusive because of calibration difficulties, but it seems to range from as much as 20 percent around 1,500 angstroms to only 1 or 2 percent at wavelengths longer than 2,500 angstroms.

Current models of ozone production indicate that these changes in solar UV emissions might cause a variation of from 1 to 2 percent in total global ozone. This could account for much of the global decrease in stratospheric ozone measured by satellites between 1978 and 1985, a period of mostly declining solar activity. The effects of the solar cycle clearly must be taken into account in attempts to identify the cause of this ozone decrease and the longer-term decrease measured by ground-based instruments between 1969 and 1986. The slow decrease in global ozone is less dramatic than the more recently identified hole in the ozone layer over the Antarctic, but, if this decrease continues, it will be even more serious.

The sun's output of charged particles, which depends primarily on conditions in the layers above the photosphere, also changes over the course of the solar cycle. The most important of these particles in terms of their impact on terrestrial systems are the high-energy protons that are occasionally spewed out by explosions in the solar corona. The earth is also affected by the more general outpouring of coronal plasma called the solar wind.

The high-energy solar protons observed at the earth range in energy from about 10 million to 10 billion electron volts (for comparison, a photon of visible light has an energy of about two electron volts). The most energetic protons travel at close to the speed of light and arrive at the earth about eight minutes after certain of the largest solar flares have occurred. These flares are huge eruptions in solar-active regions; they cause these regions to grow dramatically brighter in X rays and in EUV. Flares are thought to derive their energy from the rapid annihilation of the intense magnetic fields, which heats the plasma and produces powerful electric fields that accelerate charged particles.

Large proton events are of concern to commercial airlines, particularly those flying along polar routes, where the earth's magnetic field lines curve



FLICKERING of the sun was recorded by radiometers on two satellites, *Nimbus 7* (*blue*) and *Solar Maximum Mission* (*red*). Short-term decreases in solar output produced the sharp spikes in the *SMM* data, and most of those seen in the *Nimbus 7* data, which also included some instrument noise. On the average (*yellow line*), the sun shone brightest at the time of maximum sunspot activity. Apparently the greater number of bright faculae at maximum activity outweighed the effect of dark spots.

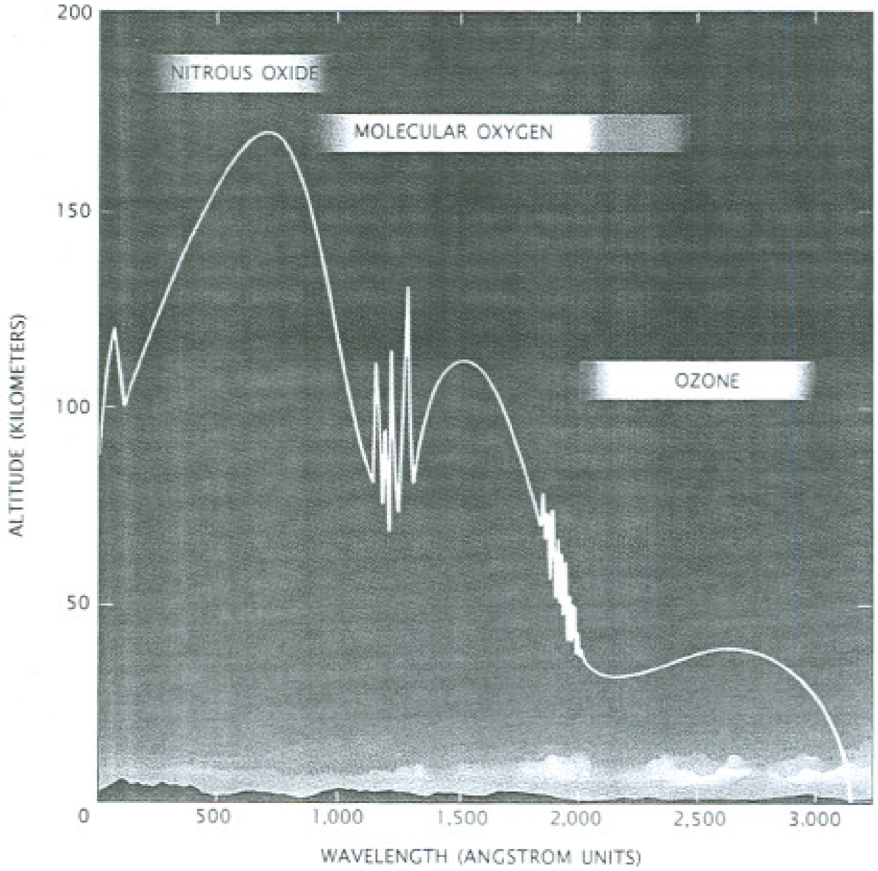
down to the surface and allow charged particles to penetrate to low altitudes, exposing passengers to elevated levels of radiation. These events pose a more serious threat to astronauts, especially those who may fly on polar-orbiting satellites. Proton events also have been implicated in the failure of computer systems; last August one such event temporarily shut down the Toronto stock exchange. Only a few dozen such large flares occur during a solar cycle, but their frequency is much higher near sunspot maxima than it is near minima.

Variations in the continuous flow of solar-wind plasma past the earth give rise to a quite different class of interactions. This relatively low-energy plasma can be visualized as the "overflow" of the solar corona, which is too hot to be entirely contained by the inward pull of the sun's gravitational field. The solar wind is excluded from the immediate vicinity of the earth by the planet's magnetic field, which exerts an electromagnetic force on charged particles attempting to cross the earth's field lines; the volume around the earth from which the bulk of the solar wind is excluded is called the magnetosphere. Flares and other magnetic eruptions in the solar atmosphere lead to disruptions in the solar wind that alter the plasma pressure exerted on the magnetosphere.

The resulting fluctuations in the geomagnetic field are typically only .1 percent of its roughly one-gauss intensity. But the electric currents they can induce in large-scale conductors at the earth's surface, such as power-line networks and oil pipelines, can have dramatic effects. For instance, on March 13, 1989, a powerful geomagnetic storm caused by flares associated with one of the largest spots ever observed knocked out electricity throughout the province of Quebec.

Such potent geomagnetic storms are caused in part by the flares that erupt in active regions of the sun, and so these storms increase in frequency along with sunspot number during the magnetic cycle. The steadier outflow of the solar wind seems to originate from areas of the corona outside active regions, where the sun's magnetic field lines stretch outward to the earth and beyond, thereby creating a path along which charged particles can travel relatively unencumbered.

In some regions of the sun, the open field-line configuration allows charged particles in the solar wind to escape quite easily. This results in areas of depleted coronal plasma, or "coronal holes." Holes are always present near the solar poles, but they can also evolve at lower latitudes. Low-latitude holes produce high-velocity solar-wind streams that can spray the earth directly and recurrently as the sun rotates. The appearance of holes is linked to the solar cycle, but with a different sort of modulation than is observed for sunspots. Although the data are limited to less than two full solar cycles, it appears that the largest low-latitude holes develop during the declining phase of a cycle, so that their contribution to geomagnetic activity is greatest a few years after the peak sunspot number.



PENETRATION DEPTH of solar radiation through the earth's atmosphere varies according to its wavelength. The graph shows the altitudes at which about half of a given radiation is absorbed. Fortunately for life, nitrous oxide in the thin atmosphere more than 50 kilometers above the earth's surface blocks the sun's highly variable, short-wavelength ultraviolet emissions. At lower altitudes, ozone and molecular oxygen absorb longer-wavelength ultraviolet rays, which are also harmful to life. Changes in the sun's ultraviolet emissions affect the structure of the ozone layer.

The many ways in which solar variability affects the terrestrial environment underscore how useful it would be to be able to predict the size and timing of the next sunspot maximum. Present attempts at prediction are extremely limited because they rely on empirical rules derived from the behavior of past cycles. Nevertheless, these rules have provided some useful estimates of the current cycle—cycle 22—and have been useful for NASA's calculations of orbital lifetimes. It appears from current behavior that this cycle will equal or exceed the activity level of the largest cycle reliably recorded: cycle 19, which peaked in 1957.

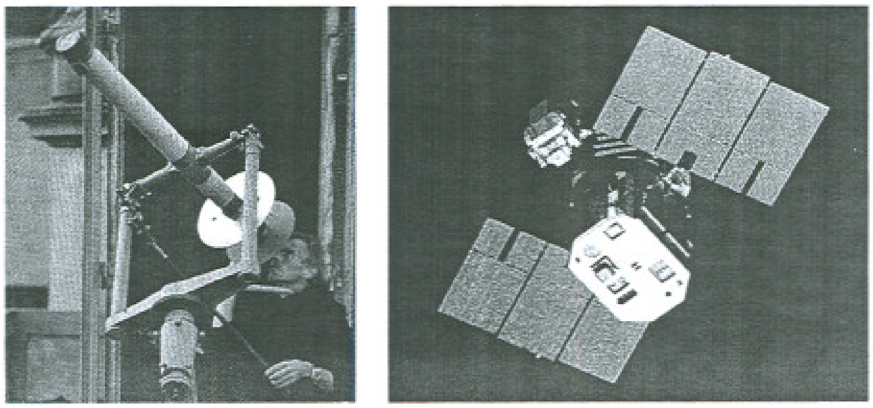
The ability to predict future solar activity depends critically on knowledge of past activity. Several sources of information stretch farther into the past than the first telescopic observations of spots in 1610. Naked-eye observations of large sunspots extend back to at least the fourth century B.C., although before Galileo's time, spots were usually thought to be planets or other nonsolar phenomena crossing the solar disk. Auroras visible at low latitudes are caused primarily by solar flares; aurora observations have proved to be a less ambiguous means of inferring past solar behavior.

A particularly long record of solar activity is hidden in the historical abundances of carbon 14, a radioactive isotope of ordinary carbon 12. The production of C-14 in the earth's atmosphere is determined by the flux of high-energy particles known as galactic cosmic rays, which are produced by energetic processes outside the solar system. The ability of these cosmic rays to penetrate into the solar system is decreased by the strength and geometry of magnetic fields carried out from the sun by the solar wind at high solar-activity levels. In the course of photosynthesis, plants take up C-14 along with other isotopes of carbon and incorporate it into their structure. Solar-activity levels over the past two millennia can be estimated by studying the relative abundance of C-14 in the tree rings of old, but still living, trees; the ages of the rings can be calculated simply by counting back from the present.

The results of ancient spot observations, auroral sightings and C-14 data were brought together in 1976 in Eddy's groundbreaking study. Eddy determined beyond a reasonable doubt that the Maunder minimum coincided with dramatic reductions in the level of solar activity, as indicated by the paucity of auroras and by high C-14 levels. He and others have shown further that such episodes of abnormally low solar activity lasting many decades are a fairly common aspect of solar behavior—another episode, the Spörer minimum, occurred between about 1450 and 1550. On the other hand, an extended period of high solar activity between about 1100 and 1250 coincided with relatively warm weather that seems to have made Viking migrations to Greenland and the New World possible. The historical record indicates that another lull in solar activity might reasonably be expected in the next century.

Another source of evidence regarding the "normal" behavior of the solar cycle, and of the sun's variability in the distant past, comes from observations of other stars similar in mass to the sun. In a pioneering study published in 1976, Olin C. Wilson of the Mount Wilson Observatory showed that chromospheric emissions observable in visible light from many such stars show cyclic variations over periods similar to that of the solar cycle. This provided the first strong evidence that magnetic-activity cycles are a common feature of stars resembling the sun in mass and age (and so also in size and temperature). Measurements of stellar-light curves are also providing tentative indications of differential rotation in these stars.

Studies of stars much younger than the sun show how intense and variable the sun's ultraviolet and total light outputs might have been billions of years ago, when life first appeared on the earth. These studies reveal that the level of a star's photospheric and chromospheric activity, and of its coronal X-ray emission, correlates quite closely with its rate of rotation. Younger stars generally rotate faster than older ones and therefore are more intense and variable in UV light and X rays; they also tend to vary more in total luminosity. One recent and unexpected finding is that younger stars seem to be fainter during periods of high activity, implying that, for them, the effect of "starspots" overwhelms that of faculae—the reverse of the case for the sun.



SOLAR TELESCOPES have grown increasingly complex. In the 1850's J. Rudolf Wolf made the first systematic measurements of the sunspot cycle using a small refracting telescope that is still operating at the Zurich Observatory (*left*). In the 1980's the *Solar Maximum Mission* satellite (*right*) performed delicate measurements of the sun's atmospheric structure and variable radiations. The satellite crashed to the earth on December 2, 1989; its orbit decayed because of the expansion of the earth's upper atmosphere caused by the high levels of solar activity that it was monitoring.

Is it realistic to expect that astronomers will ever be able to make long-term predictions about the behavior of the sun? There may be fundamental restrictions on the possibility of such predictions if the processes driving the solar cycle are nonlinear. Nonlinear systems do not behave in the predictable manner of simple oscillators, such as a pendulum; relatively straightforward feedback of an "effect" on its "cause" can lead to bewilderingly complex behavior. Even when their behavior is governed by a well-understood set of forces, nonlinear oscillators can be so sensitive to initial conditions that predictions extending substantially into the future become impossible.

In the 1950's, while he was studying long-range weather forecasting, Edward N. Lorenz of the Massachusetts Institute of Technology made important contributions to the study of nonlinear behavior. He showed that feedback between various mechanisms in the atmosphere makes prediction of future weather conditions difficult because current pressure, temperature and winds must be known with impossible accuracy in order to predict precisely more than several days into the future. Analysis of the dynamics of the solar cycle suggests that its fairly regular behavior between about 1700 and the present as well as its disappearance for about six 11-year periods between 1645 and 1715 may be characteristic of a nonlinear oscillator.

Research now under way should help establish whether the solar-activity cycle is predictable, at least in principle, or whether it is chaotic. Even if the solar cycle is unpredictable, comprehending the possible relations between slow changes in solar activity and climate will be important in unraveling the earth's past climatic record—and in preparing us for variations that can be expected in the centuries to come.

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