The solar cycle

The mysteries of the 11-year period of sunspot activity are yielding to new approaches, such as magnetic-dynamo modeling and a seismology that can detect photosphere pulsations as small as a few meters in amplitude.

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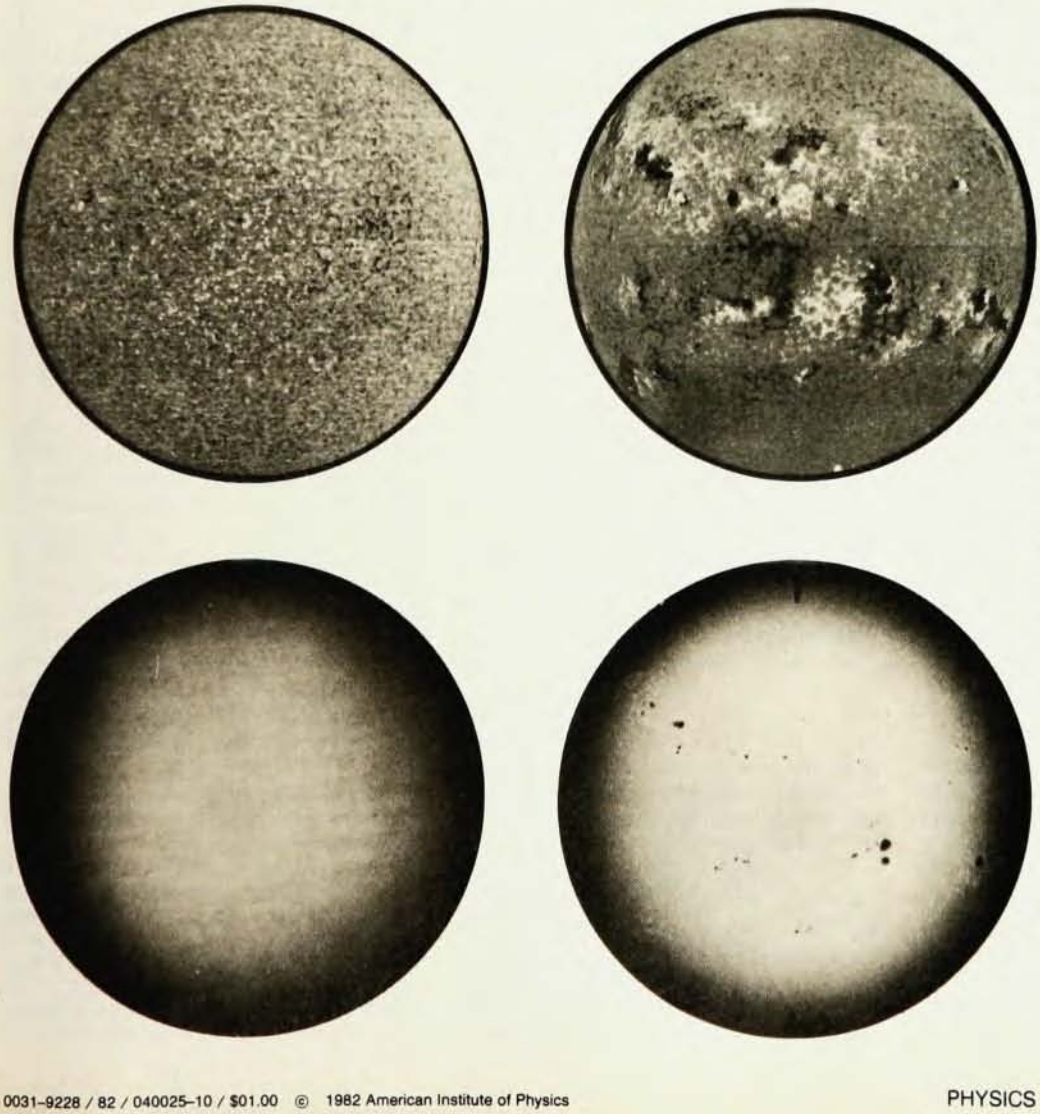
and Kendrick Frazier

Nearly 140 years have elapsed since the German apothecary and amateur astronomer Samuel Heinrich Schwabe reported discovery of the solar cycle. "From my earlier observations," Schwabe wrote in 1843, "it appears that there is a certain periodicity in the appearance of sunspots and this theory seems more and more probable from the results of this year." Schwabe had been looking for new planets crossing the Sun's disk. The day-to-day records of sunspots he kept for 18 years as part of that search led him to realize that solar behavior is cyclic.

Solar physics has come a long way since Schwabe's time. Yet the most fundamental questions about the nature of the solar cycle remain unanswered, and new ones have arisen in the past five years. Solar scientists believe that the 1980s may well bring significant advances in the study of the fundamental mechanisms responsible for solar activity. It is an exciting and urgent goal, one made possible by new theoretical insights into the nature of the cycle, new methods for studying the solar magnetic dynamo, and new observational tools for "viewing" the interior structure of the Sun.

In both popular and scientific usage the "solar cycle" refers to the roughly 11-year period with which sunspots occur, and to the drift of the sunspot zones toward the equator over the same period, even though a wide variety of other phenomena on the Sun has the



Full disk magnetograms of the Sun (top) and corresponding white-light photographs (bottom). In a magnetogram, regions of magnetic field appear light or dark according to magnetic polarity. In white-light photographs, only sunspot regions are obvious. The variation of sunspots and intense magnetic fields with the solar cycle is illustrated by comparison of the images on the left (made 28 February 1976, just after minimum) with the images on the right (made 10 December 1979, near maximum). (White-light photographs courtesy of R. Howard, Mount Wilson Observatory. Magnetograms courtesy of J. Harvey, Kitt Peak National Observatory.) Figure 1

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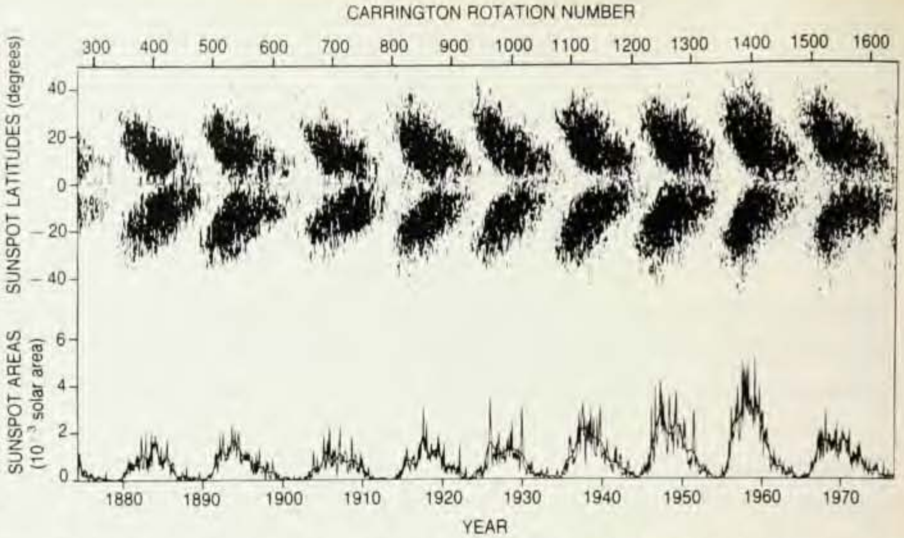
same periodicity (see figures 1 and 2). In a sense, sunspots are merely the most easily observed indicator, or proxy, of underlying solar activity.

Since the early part of this century when the astronomer George Ellery Hale observed the Zeeman splitting of lines in the Sun's spectrum, we have known that sunspots are areas of magnetic field of intensity up to 4500 gauss, which are darker as a consequence of their lower temperature—4400 K as opposed to the 6100 K of the solar photosphere. The magnetic field is believed to bring about the reduced temperature by inhibiting the convective flow of energy from below.

Sensitive modern observations[1] of the magnetic field at the photosphere (the apparent surface of the Sun) further emphasize that the solar cycle is fundamentally a magnetic one. For example, magnetograms such as those shown in figure 1 reveal the presence of magnetic fields not just in sunspots but over vast areas of the apparently "quiet" solar surface, where there is a mean field of only 1 to 2 gauss.[2] The magnetic flux in these large-scale regions appears to originate in the sunspot latitudes. The flux evolves in a manner that suggests it represents the debris remaining after fluid motions in layers beneath the photosphere have caused sunspots to dissipate. High spatial resolution in any one of these areas, in which the same sign of the average field may extend coherently over tens of degrees of the solar surface, reveals a network of intense knots of field of the order of 2000 gauss separated by apparently field-free areas. The scale of the field-free regions—about 30 000 km in diameter—corresponds to that of rising convective cells in the uppermost layers of the Sun. This indicates that the outward flow at the top of each convective cell has pushed the field toward the cell boundaries, concentrating it where the fluid descends. However, the presence of knots of both polarities in regions where one polarity dominates suggests that the fields are both concentrated and tangled by subsurface motions. Also sprinkled liberally across the solar surface are small magnetic dipoles or ephemeral active regions, which appear to make little contribution to the net magnetic flux.

Cycles

As far as is known, all solar magnetic fields follow a cycle of approximately 22-years duration. That the "fundamental" cycle has a period twice that found in the waxing and waning of sunspots was a second important discovery of Hale, who noticed that the individual sunspots comprising an identifiable group organized themselves into a simple, coherent pattern of magnetic polarity.



Maunder "butterfly" diagram of sunspot positions and plot of total sunspot area as a function of time. In the upper plot, vertical lines show the range in latitude of sunspots for the given dates. The cyclic trend in sunspot location, from high to low latitude, is apparent. The lower part of the figure gives the total area occupied by sunspots in thousandths of the area of the solar disk, plotted against date or solar rotation number. (Reproduced, with permission, from data supplied by the Science Research Council, Great Britain.) Figure 2

During one 11-year cycle, for example, the westernmost members of a group may display positive polarity in the northern hemisphere and negative polarity in the southern hemisphere. This magnetic organization generally obtains for all spot groups of the given 11-year cycle, from the appearance of the first groups at high latitude to the disappearance of the last spots of the cycle at low latitude. However, during the next 11-year cycle the sense of the polarity is reversed and the westernmost members in the northern hemisphere have negative polarity.

A similar reversal is displayed by the diffuse, large-scale fields when a cap of one magnetic sign appears near one pole and a cap of the opposite magnetic sign appears near the opposite pole just after sunspot maximum. The polar magnetic regions expand in area until at sunspot minimum they reach to within 50° to 60° of the equator.

As sunspot activity again increases, extensive regions carrying magnetic polarities opposite from the incumbent polar fields migrate to high latitudes from the sunspot zones. The polar caps shrink as their magnetic flux is gradually neutralized by these migrating fields and finally disappear around sunspot maximum. About the same time a complicated and highly variable pattern of large-scale fields dominates the lower latitudes.

As sunspot activity wanes, the poleward-migrating fields begin to coalesce to form polar caps of opposite sign from those of the previous half-cycle. By the next solar minimum, large-scale fields at low latitude have subsided and the polar fields have again reached their greatest extent. Due to the influence of the large-scale fields, the total magnetic flux emerging from the solar surface varies by only about a factor of three over the solar cycle in contrast to the variation by some three orders of magnitude in sunspot area. Observations do not support the proposal that the magnetic flux is constant during the cycle.

Were the solar cycle as regular as the above oversimplified description implies, there might be hope that simple theoretical models could explain its operation. However, departures from the zero-order description are of major importance and may provide the crucial clues to understanding the mechanisms responsible for the cycle. A few examples suffice. The irregularity of the interval between sunspot cycles has confounded researchers for decades. The reversal of the poloidal field around sunspot maximum is anything but regular. The magnetic field regions at opposite poles may fade at such different rates that only a single cap of polar field remains for upwards of a year. Conversely, both polar caps may carry magnetic fields of the same sign for months. Although at times the global magnetic field may approximate

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a magnetic dipole, more often than not its axis is inclined 20° to 30° to the axis of rotation.

The magnetic dynamo

Although the phenomenology of solar magnetism is extremely complex, researchers have made progress in interpreting at least its main features. The most generally accepted theory springs from ideas proposed more than two decades ago to explain the behavior of the large-scale solar magnetic fields, which had been under consistent observation only since the early 1950s.

Dynamo theory,[3–8] as it is now called, depends upon two facts: that the Sun rotates and that it possesses a convective envelope. Models of the interior structure of the Sun show that the nuclear fusion processes that supply the power for its luminosity are restricted to a central core, whose radius is at most about one-fourth the solar radius. Surrounding the core is an envelope through which the energy gradually leaks by radiative diffusion. However, in a shell comprising roughly the outer one-quarter to one-third of the radius, the material is sufficiently opaque that practically all energy is transported further upwards by the vertical circulation of convective eddies. Solar scientists believe that it is in this convection zone that the Sun's magnetic fields are generated. (It is also pertinent to note that the presence of a convection zone is considered to be the *sine qua non* for the existence of a hot chromosphere, corona and solar wind, driven by either mechanical energy or the energy of magnetic field annihilation.)

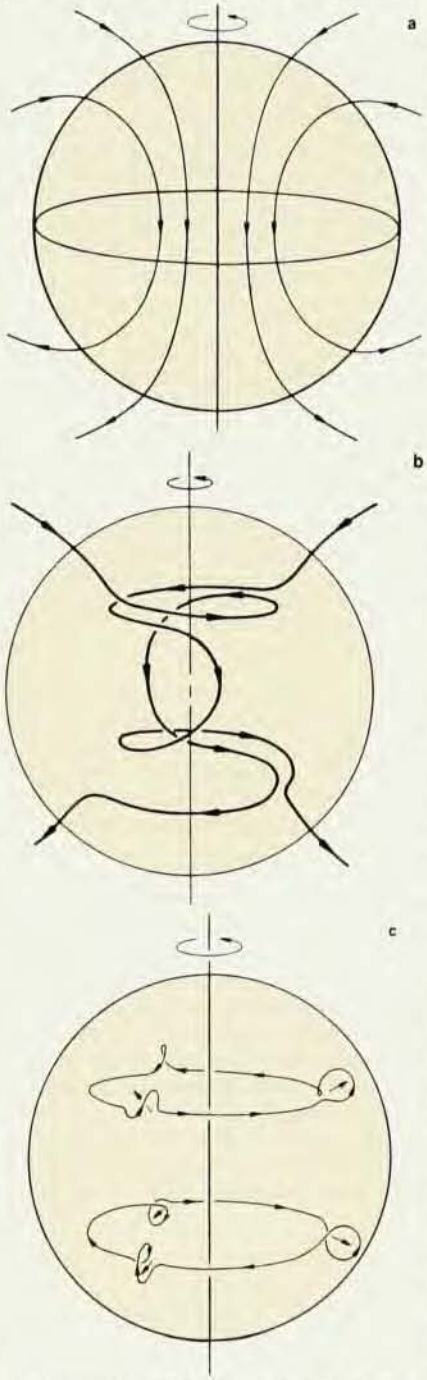
Two factors combine with the convective motions present beneath the surface of the Sun to drive the solar magnetic dynamo.

▶ First, the coupling between convection and rotation produces differential rotation in which the period at the equator (about 25 days) is shorter than the period at higher latitudes (about 29 days at 60°).

▶ Second, the gas composing the solar interior is a very good electrical conductor—a property that "freezes" the magnetic field to a particular parcel of material as it moves about.

Modern theory indicates that these properties permit two process to occur that are responsible for the operation of the solar dynamo, which we can think of as an irregular oscillator. We can visualize the mechanism most easily by following the cycle from the initial state of poloidal field of one polarity through the development of the poloidal field of the reverse polarity.

First, differential rotation stretches the initially poloidal (north–south) field (figure 3a), wraps it around the Sun and creates an amplified toroidal field (figure 3b), which is brought to the surface by convection or tends to float to the surface as a result of magnetic buoyancy. (The density in a magnetic flux tube buried beneath the surface is lower than that in the ambient gas as a consequence of the pressure $B^2/8\pi$ exerted by the field in the tube; the net upward force is referred to as magnetic buoyancy). Second, rising or sinking columns in the convective zone twist as they rise or sink as a result of Coriolis acceleration and impart this twist to the field (figure 3c).



Hypothesized mechanism of the solar magnetic cycle. In the dynamo believed to be responsible for the cycle, the interaction of convection and differential rotation stretches an initially poloidal solar magnetic field (**a**) to produce a toroidal field (**b**). The twist of rising convective cells produces a small poloidal field component from the toroidal field (**c**). The integrated effect of many such cells and the dominance of rising cells eventually reestablish the poloidal field and the cycle continues. (From reference 5.) Figure 3

It would first appear that the oppositely directed twists of rising and sinking elements would exactly cancel. That would be the case in a homogeneous, horizontal fluid. In the solar convection zone, however, the angle between the rotation vector at a given point and the direction of gravity varies with latitude to produce a net twist in the magnetic field. This is depicted in figure 3c, where the twist is imparted to a rising element. This net twist and the destruction of closely packed, oppositely directed fields by turbulent diffusion convert the initially toroidal, or azimuthal, field into a new poloidal one of opposite sign.

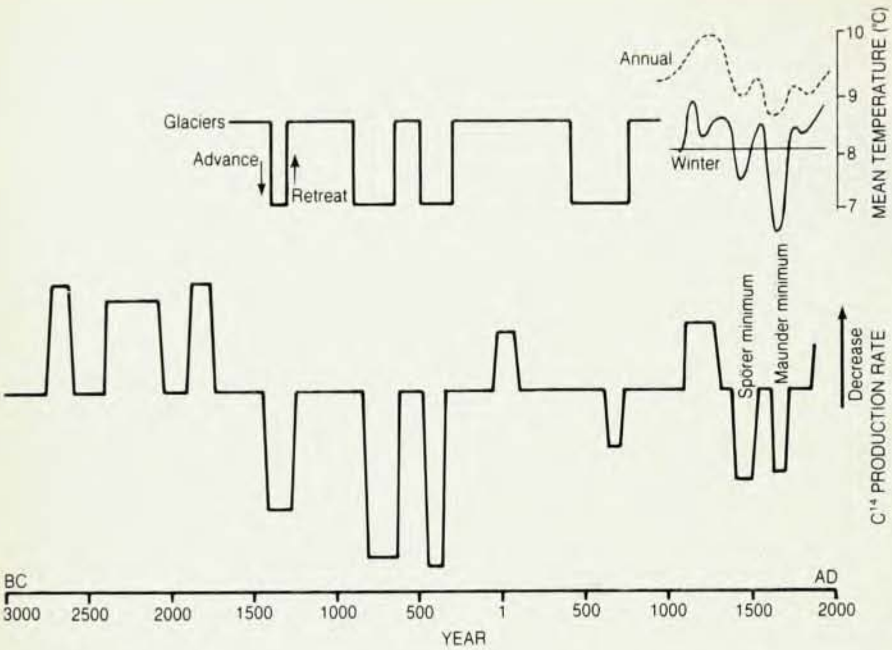
The cycle continues as differential rotation stretches this new poloidal field into a new toroidal field, and the process repeats. Thus, we may view the solar cycle as an engine in which differential rotation and convection drive an oscillation between two (toroidal and poloidal) field geometries and magnetic polarities.

Researchers have made extensive study of the generation of magnetic fields by the dynamo process.[3–8] To do this, they have constructed both kinematic models, in which they calculate the dynamo action of a specified field of fluid motions, and dynamic models, in which they calculate the fluid motions and their dynamo action from first principles.

▶ Kinematic models have met with considerable success in describing such general aspects of the solar cycle as the "butterfly diagram" (figure 2) and the reversal of the magnetic polarity of the general field. However, such models must be "tuned" by fixing several parameters with no *a priori* knowledge of whether the values chosen apply to the Sun or even represent a dynamically consistent set.

▶ Dynamic models, which to date have not included the presence of ropes of intense magnetic field, produce reversals of the magnetic field similar to those observed on the Sun. However, the period of the reversal is far too short. In addition, the rate at which magnetic flux is destroyed by small-scale turbulence—a critical parameter in all dynamos—must be assumed without much physical justification.

Other aspects of the theory of convective dynamos are even less satisfactory. For example, the gradient of angular rotation rate with depth in the convection zone enters as one of the critical free parameters in the kinematic models. Dynamic models must for practical purposes be limited, at present, to in-



Solar activity and climate? Lower curve, based on tree-ring data, represents the rate of production of carbon-14 by cosmic-ray bombardment of the upper atmosphere. This production varies inversely with solar activity. Plotted above are measures of mean European climate: the advance and retreat of Alpine glaciers, historical inferences of mean annual temperature and the recorded severity of northern European winters. The temporal coincidence of low solar activity and cool European climate suggests a causal connection between long-term solar behavior and climate, although other data indicate a more complex relationship. (From ref. 14.) Figure 4

compressible fluids. Moreover, current dynamic models yield a gradient of the rotation rate of *opposite sign* from that required by the kinematic models to mimic the solar cycle! Apparently some essential physics is lacking in the models.

Likewise, the well-established propensity of solar magnetic fields to clump together into bundles of high intensity to form sunspots and smaller magnetic structures has yet to be incorporated into either class of dynamo models, both of which have limited spatial resolution on the Sun. In fact, the presumed presence of ropes of intense magnetic field throughout the convection zone has led some investigators to question the fundamental premise of all dynamo theory—that the magnetic fields are moved more or less passively about by the fluid motions in the convection zone. They argue, instead, that the fluid in the convection zone would simply flow around the tubes of intense magnetic field.

A clock in the Sun?

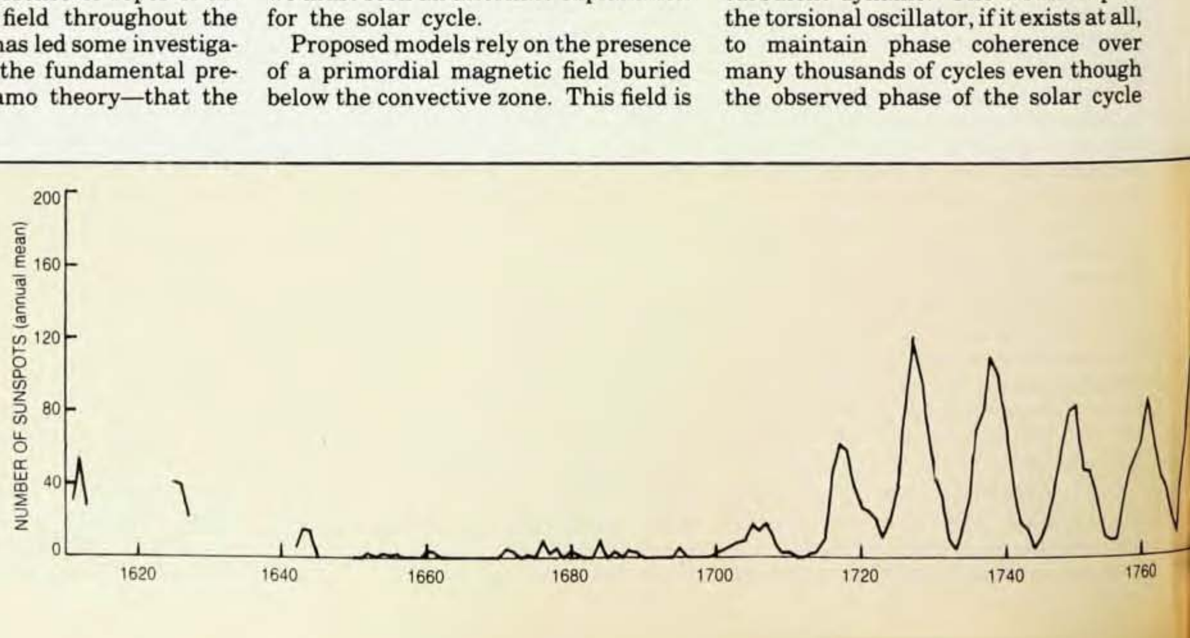
Carried to its extreme, this argument leads us to conclude that not only does the convective dynamo fail to predict the presence of tubes of intense magnetic field but also that the existence of these intense fields so reduces the efficiency of the convective dynamo that we must seek an alternate explanation for the solar cycle.

Proposed models rely on the presence of a primordial magnetic field buried below the convective zone. This field is believed to be a remnant of an original field created by the action of a convective dynamo that operated during the collapse of the proto-sun—the Sun before its central temperature rose to the point where thermonuclear reactions could occur.

Differential rotation in the zone of interaction between the radiative envelope and the convection zone amplifies the toroidal fields in a way similar to that shown in figure 3. When the field reaches a sufficiently high intensity, magnetic buoyancy forces the flux tubes to the surface, where they appear as sunspots. The reversal of the field is explained by the torsional oscillation of a thin layer in the interaction zone, in which the wrap-up of the field reverses every 11 years. The irregularity of the sunspot cycle is ascribed to the variations in time required by the tubes of magnetic flux to float to the surface through the turbulent convection zone.

While the primordial-field models may be attractive in providing an explanation for the intense magnetic fields of sunspots, current work on the topic has produced challenging speculations but has not yet yielded a detailed, quantitative theory; and these models leave out important details. For example, although a primordial magnetic field may well be buried deep in the Sun, the postulated torsional oscillator would run down in a few thousand years without a continuous supply of energy. The physical mechanism that maintains the oscillation has yet to be quantitatively specified.

One might expect that the degree of long-term regularity of the solar cycle would allow us to distinguish between the two classes of models because the primordial field models contain a regular oscillator embedded deep in the interior while the dynamo models oscillate by virtue of the somewhat irregular regeneration of the field by the turbulent dynamo. One would expect the torsional oscillator, if it exists at all, to maintain phase coherence over many thousands of cycles even though the observed phase of the solar cycle



would be distorted by variations in the time required for the flux tubes to rise to the surface. In contrast, the regenerative process of the turbulent dynamo produces a broad range of periods even though the mean period may be well defined. Its relatively short "memory" implies that the phases of two cycles that are separated by more than a characteristic correlation time should be randomly related.

Attempts to use the number of sunspots to test whether or not an accurate clock is responsible for the solar cycle have so far proved inconclusive.[9] Sufficient data simply do not exist. The more or less continuous record of sunspot observations extends back less than 400 years, and the bandwidth displayed by the solar cycle indicates that the correlation time is several hundred years. A reliable assessment of whether phase coherence obtains would require observation covering many correlation times—that is, several thousand years.

Prehistoric solar activity

Solar astronomers agree that, whether or not they ever resolve the question of long-term phase coherence, any acceptable model of the solar cycle must explain the long-term behavior of solar activity. But just what were the characteristics of the cycle one, ten or a hundred thousand years ago? Although pre-telescopic observations of sunspots are recorded in Chinese dynastic histories as far back as 28 BC, the allegorical style of these accounts and the infrequency of the sightings precludes their use for quantitative comparisons with theory. Indirect, historical indicators of past solar activity, such as European records of auroral displays, suffer from much the same difficulty. What we require is a physical measure of pre-telescopic solar behavior.

The solar cycle modulation of galactic cosmic rays arriving at the Earth provides us with just such a quantitative, albeit indirect, scale of past solar activity. Research over the last forty years[10] has given us extensive documentation of an anticorrelation between solar activity and cosmic ray flux, although the detailed mechanisms producing this modulation are poorly understood.[11] Galactic cosmic rays impinging on the upper atmosphere produce a wide variety of radiogenic isotopes. And many of the spallation-generated products are sufficiently rare in the crust of the Earth and in the lower atmosphere that we can identify those that we find as having been caused by cosmic rays in the upper atmosphere. Some of these products are removed from the atmosphere rather rapidly and are sequestered in tree rings, sea sediments and polar ice, where they form a permanent record of the rate of production of the isotope (or of the galactic cosmic-ray flux) and, by inference, solar activity. To decipher the record we need an independent method of dating a particular tree ring or layer of ice, and we must know the Earth's magnetic field in the past. However, we can solve these problems in principle.

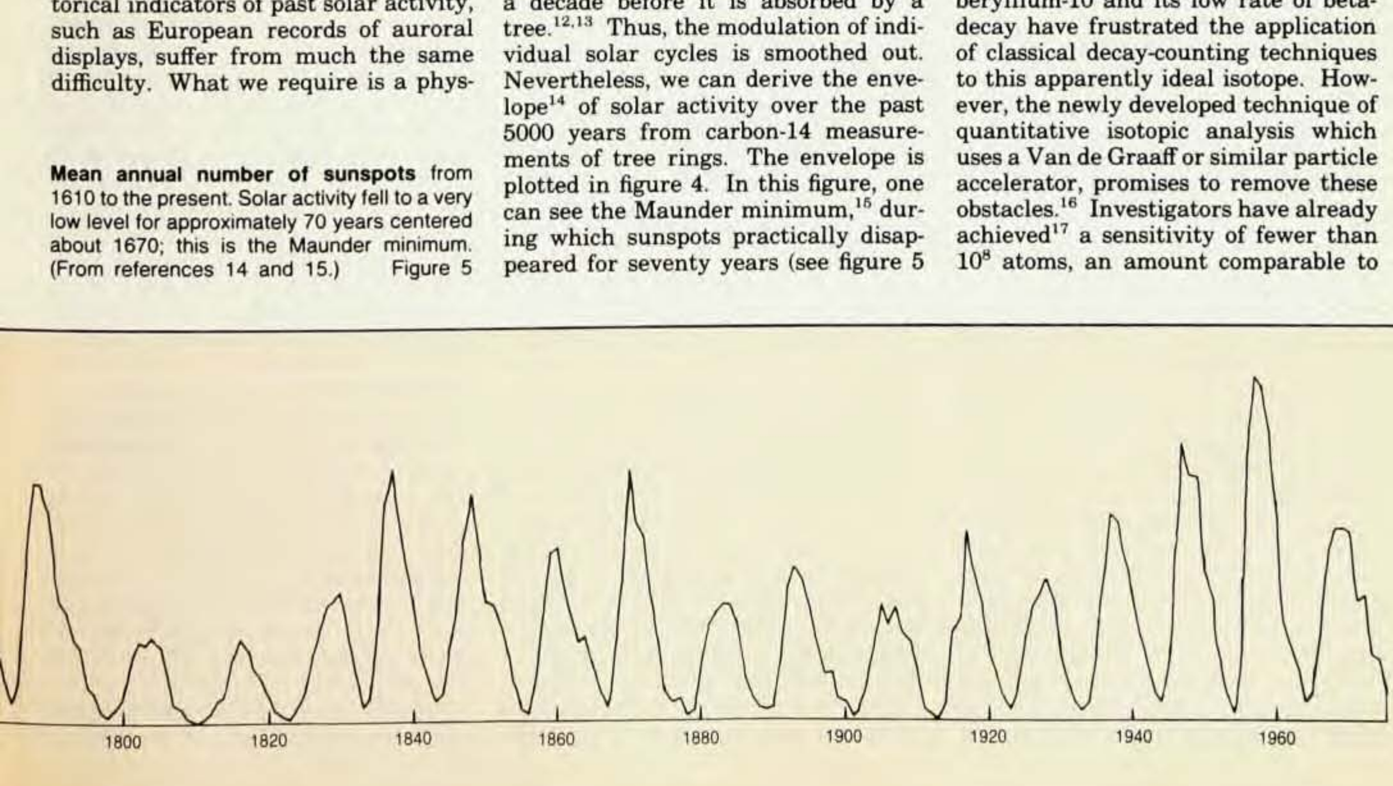
Carbon-14. Most of our current information on long-past solar activity comes from the analysis of carbon-14, which has the advantage that well-established radioactive decay techniques can detect it in the laboratory and the disadvantage that it resides in the atmosphere and oceans for the order of a decade before it is absorbed by a tree.[12,13] Thus, the modulation of individual solar cycles is smoothed out. Nevertheless, we can derive the envelope[14] of solar activity over the past 5000 years from carbon-14 measurements of tree rings. The envelope is plotted in figure 4. In this figure, one can see the Maunder minimum,[15] during which sunspots practically disappeared for seventy years (see figure 5 for greater detail). The Spörer minimum, whose existence is corroborated by the paucity of recorded aurorae during the middle fifteenth century, is also visible. The data on aurorae and the detailed comparison of C^{14} deposition rate with solar activity since the invention of the telescope give us confidence that the C^{14} production rate does, indeed, serve as a proxy of fluctuations in the ten- to twenty-year average of solar activity.

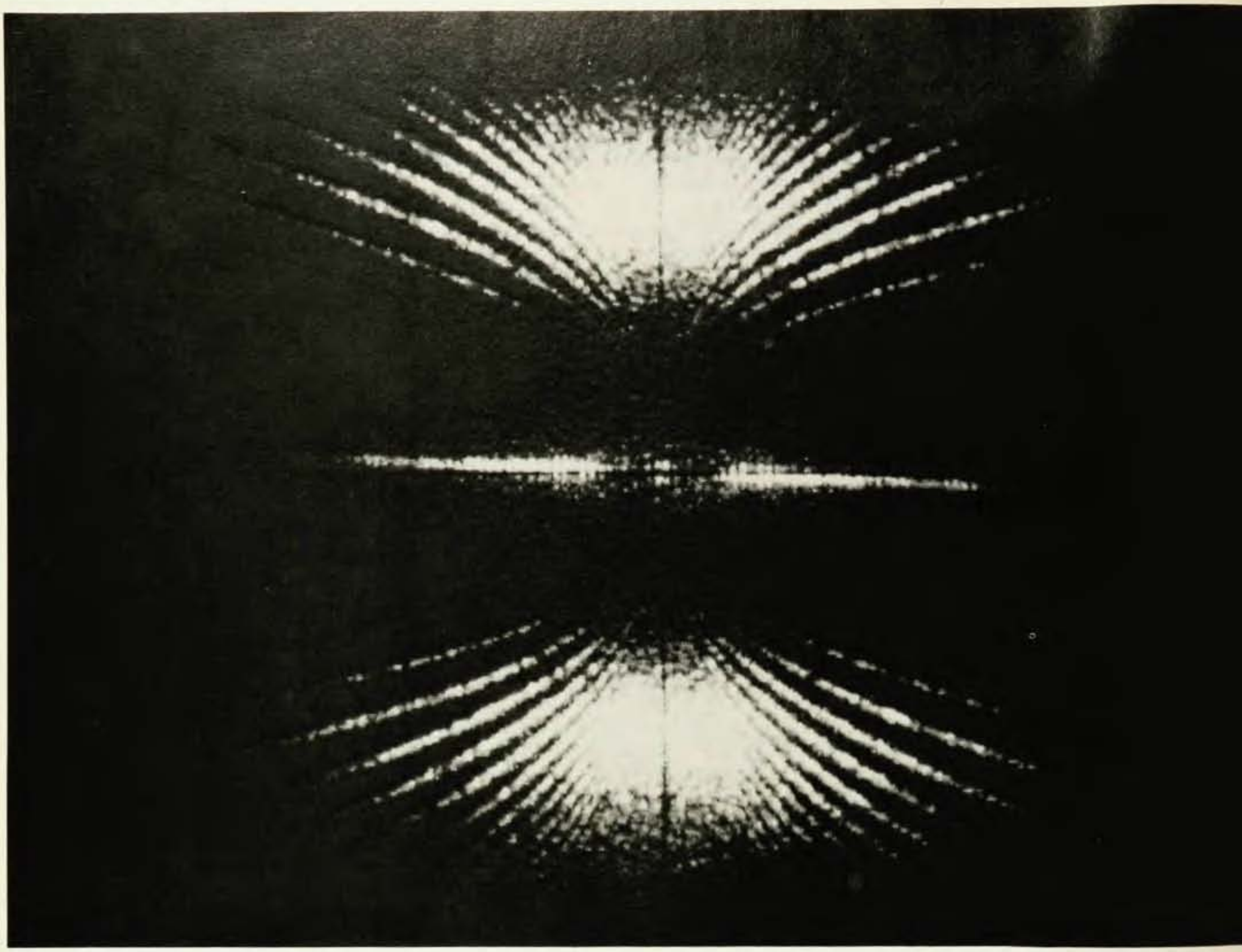
Figure 4 shows that during several intervals over the past millenia, solar activity was much greater or much less than that seen during the epoch of scientific observation. No obvious periodicity appears in the long-term variations—a fact that may be difficult for the primordial-magnetic-field models to explain.

Beryllium-10. Unfortunately, the long residence time of carbon-14 in the atmosphere and ocean reservoirs obscures the individual solar cycles over the five millennia and prevents us from determining whether the phase is accurately maintained through a Maunder-like minimum. However, beryllium-10 may be a proxy with a higher time resolution and a longer time span. This radiogenic isotope has the intrinsic advantage that it reaches the Earth's surface in about a year as a minor constituent of aerosols that are purged from the atmosphere by precipitation. Thus, it should carry the signature of individual cycles of solar activity, and its longer half-life of 2×10^6 years should enable us to follow solar activity as far back as our samples and knowledge of the geomagnetic field allow.

Unfortunately, the low abundance of beryllium-10 and its low rate of beta-decay have frustrated the application of classical decay-counting techniques to this apparently ideal isotope. However, the newly developed technique of quantitative isotopic analysis which uses a Van de Graaff or similar particle accelerator, promises to remove these obstacles.[16] Investigators have already achieved[17] a sensitivity of fewer than 10^8 atoms, an amount comparable to

Mean annual number of sunspots from 1610 to the present. Solar activity fell to a very low level for approximately 70 years centered about 1670; this is the Maunder minimum. (From references 14 and 15.) Figure 5





the beryllium-10 content of a practical ice core or sea sediment sample. Other researchers have recovered marine sediment samples containing an undisturbed record dating back at least 100 000 years, and there exist ice cores extending back several thousands of years. Application of the new methods of analysis to these samples will add an entirely new dimension to the study of solar activity.

Deuterium. Although the study of radiogenic isotopes as proxies of solar activity may extend our knowledge of past solar behavior back many years, uncertainty about the variations of the Earth's magnetic field will probably make the record illegible beyond a few tens of thousands of years. We may well ask if variations in other quantities might also establish indelible records of past solar activity.

We may eventually be able to use other sequestered isotopes, such as deuterium in tree rings, as proxies of different aspects of solar activity. In this case, the ratio of D^2 to H^1 is related to the mean surface temperature of the Earth at the time of deposition and shows an apparent periodicity of 22 years. However, no one has yet made a convincing argument that this fluctuation is related to the solar cycle. One may speculate that solar luminosity varies with the 22-year magnetic cycle or that there is some complex coupling between the sign of the Sun's poloidal field and terrestrial climate. Without the elementary demonstration that the ratio of deuterium to hydrogen sequestered in tree rings replicates the well-established solar behavior since 1610, one cannot use these isotopes as indicators of past solar activity.

Do chemical, as opposed to isotopic, records of past solar activity exist? Although the responsible mechanism is completely unknown, there appears to be a direct relation between solar activity and the abundance of nitrate ions in Antarctic ice. If this correlation survives further scrutiny, and if solar scientists can establish a credible chain of events relating solar activity and the presence of nitrate ions in snow, then we may have in hand a readily exploitable proxy of solar behavior over the last ten thousand years.

The "identification" of the sunspot period in geological deposits has intrigued investigators for 50 years. The variation of the thickness or color of glacially-deposited layered sediments with a "period" of about 11 layers may imply that the solar cycle existed in much its present state as far back as late Precambrian times, 700 million years ago. However, this conclusion must remain tentative, at best, in the absence of convincing evidence that the 11-year cycle influences climate. We should note that there is also some uncertainty in the identification of the bands of such sediments as annual deposits.

Solar seismology

Important though the prehistory of solar activity may be, our understanding of the fundamental mechanism responsible for the solar cycle finally rests on our knowledge of the structure and dynamics of the interior. To pursue this knowledge, we need new tools, and perhaps the most revolutionary of these will be solar seismology—so named by analogy with its terrestrial counterpart.

Geophysicists probe the internal structure of the Earth by analyzing

Diagnostic diagram of oscillations of the solar surface. Spectroscopic measurements show that small elements of the photosphere rise and fall cyclically with a period of about 5 minutes. The bright ridges indicate the spatial frequency (k, horizontal axis) and temporal frequency (ω, vertical axis) of the higher-amplitude oscillations, which result from the natural resonance of acoustic or pressure waves trapped below the surface of the Sun. On the horizontal axis spatial frequency ranges from zero at the center to 316 cycles per solar diameter at the left and right. On the vertical axis temporal frequency ranges from zero at the center to 0.5 cycle per minute at the top and bottom. Based on observations made at Kitt Peak National Observatory by T. Duvall Jr, J. Harvey and E. Rhodes Jr. Figure 6

free oscillations that are set off by earthquakes and propagate both along the surface and through the interior. Although we have yet to see on the Sun the exact analog of these impulsive disturbances, there are global oscillations of the surface of the Sun—stimulated by convective motions in the interior—that we can analyze in much the same fashion.

The analysis depends upon the fact that all mechanical bodies—and the Sun is no exception—can oscillate with characteristic frequencies. For the Sun, two mechanisms of oscillation are important.

▶ Pressure waves, consisting of alternate compressions and rarefactions, owe their existence to the restoring force produced by the elasticity of the solar material.

▶ Gravity waves require a variation of density with depth and are created when a parcel of fluid is displaced from its equilibrium position; gravity provides the restoring force. Long waves on the surface of a body of water are, of course, a common example of the gravity mode of oscillation.

Both the spherical geometry and the extreme range in pressure and temperature within the Sun militate against a simple description of its characteristic oscillations. However, the theory is well-developed and shows that one can specify the normal modes in terms of three characteristic numbers: a radial eigennumber, which specifies the number of nodes present between the center and the surface, and two angular eigennumbers. At the surface, the effect of the interior oscillations is to produce standing waves of wavenumber k and temporal frequency ω. Of course, the exact values of k and ω taken on by a particular oscillation depend intimately upon the density, temperature and dynamical structure of the Sun—a dependence that gives the method of analysis extraordinary power. Thus one can compare the locations of various modes in the k–ω plane (figure 6), as predicted by a model of the solar interior, with their observed locations to affect improvements in the model.

The analysis requires the unambiguous identification of the modes—a task complicated by the large number of modes. Comparing the 10^7 possible pressure-wave modes of the Sun with the approximately 600 lines present in the very complex optical spectrum of an iron arc puts the problem in perspective! Fortunately, the initial analysis is simplified by the fact that each radial eigenmode has a characteristic signature in the k–ω plane (see figure 6), with such factors as the azimuthal eigennumber and the influence of rotation entering as fine structure within each radial mode.

Precise Doppler measurements of the radial velocities of small patches of the solar surface are the raw material for such studies. In fact, the observation that small areas—4000 to 15 000 km in diameter—of the solar surface oscillate with a period of about 5 minutes preceded by some fifteen years the insight that these were coherent, global oscillations. By analyzing the motion within an extended area of the solar surface we can produce a power spectrum in k and ω, as shown in figure 6, and identify the characteristic ridges, each of which corresponds to pressure-wave resonances of low radial order and high azimuthal degree. In the figure, the faint, curved ridge closest to the horizontal axis represents the fundamental mode; the next ridge above is the next higher mode, and so on. Spatial frequencies are reflected into the left half-plane for esthetic appeal only; negative and positive temporal frequencies distinguish between waves propagating eastward and westward across the Sun.

The asymmetry of the patterns in temporal frequency is a measure of solar rotation at some distance below the surface, where the oscillations are formed. Although the low-order modes are most sensitive to conditions in the outer several percent of the Sun, comparison of the predicted and observed ridges in their power spectrum indicates that the depth of the convection zone is about 30% of the radius as compared to the 15 to 25% predicted by previously accepted solar models. Thus, solar scientists have established by relatively direct means a parameter that is critical in the operation of the solar dynamo and in the interior structure of the Sun and other stars.

Minute solar pulsations

Doppler measurements made with the integrated light of the full solar disk also reveal pulsations, although they naturally select lower harmonic modes in which a large fraction of the solar surface moves coherently. The velocities involved in such pulsations are small—in some cases less than 10 cm/sec, which corresponds to a total amplitude at the solar surface of only about 5 meters. Thus, to collect data whose signal-to-noise ratio and frequency resolution are high enough to allow identification of the modes, one must make long and uninterrupted strings of observations. Such observations of the full solar disk led to the discovery of a discrete array of pressure-wave oscillations with modes of high radial order, a mean period of about 5 minutes, and individual "lines" separated by 68 μHz.

The quest for long observing runs has taken astronomers to the South Pole, where, in 200 hours of nearly continuous recording during the Austral summer, they obtained the finest data yet (figure 7). Preliminary analysis indicates that these data will yield an unambiguous identification of some of the modes, and that the oscillations remain coherent over about two days (other data indicate coherence over weeks). Unlike the modes with many azimuthal nodes, these low-azimuthal harmonics are quite sensitive to conditions deep in the Sun. Comparison of the theoretical and observed frequencies of the modes promises to afford a new determination of another parameter—the abundance of helium—critical to our understanding of the interior structure and evolution of the Sun and other stars and important to the resolution of such mysteries as the low output of solar neutrinos.

Recent data from observations of oscillations in integrated sunlight, accumulated for a total duration of 28 days, indicate a rotational splitting of 0.75 μHz in the modes of low spatial frequency in the azimuthal direction. Some researchers believe these observations imply that the core of the Sun is rotating 2 to 9 times faster than the surface, with the exact value dependent upon the size of the rapidly spinning core. Clearly, the interaction of such a core with the convection zone would have a major influence on the solar dynamo.

Researchers have observed only a small portion of the pulsation spectrum of the Sun, and this has made it particularly difficult to identify oscillations with periods between five minutes and a few hours. But measurements of the solar diameter with a precision of about a millisecond of arc do show apparently stable fluctuations with periods of 5 to 60 minutes. However, some researchers wonder whether these oscillations originate on the Sun because the refraction effects of the terrestrial atmosphere are larger than the small amplitude of the oscillations.

Groups at the Crimean Astrophysical Observatory, the University of Birmingham and Stanford University have independently reported an oscillation of the entire photosphere with a still longer period of 2 hours 40 minutes and a velocity-amplitude of less than a meter per second. The apparent phase coherence of this oscillation over many months argues for its solar origin. However, the data remain to be subjected to rigorous statistical analysis.

We expect such long-period oscillations to be dominated by gravity waves. Once these oscillations are confirmed and identified as to mode, they will offer excellent information on the Sun's deep interior. For example, calculations show that oscillations with periods of about 48 minutes would differ in period by about 2% if the Sun's interior had been mixed rather than stratified during its 4.5 billion years of evolution. Thus, the question of whether the Sun underwent episodes of interior mixing, which some believe to be the origin of dramatic revolutions in the Earth's climate, may be resolved by studying minute pulsations of the Sun.

Solar seismology is still in its infancy, but we can now see much of its potential. We must deal with two problems, however, if we are to establish with any reliability such critical parameters as the rotation rate in the interior and the presence of stratification.

▶ Although theory indicates that the longer-period modes, which are sensitive to conditions in the deep interior, are coherent over many thousands of cycles, unexpected perturbations may destroy that coherence. Thus, the Sun itself may prevent us from measuring the various modes with sufficient accuracy to differentiate between competing models of its interior structure.

▶ We will eventually need very long strings of extremely precise observations, free from the disturbing influences of refraction in the Earth's atmosphere and the interruption produced by nightfall and cloudiness. Space platforms appear to be the only means of securing the final requisite frequency resolution and freedom from spurious signals.

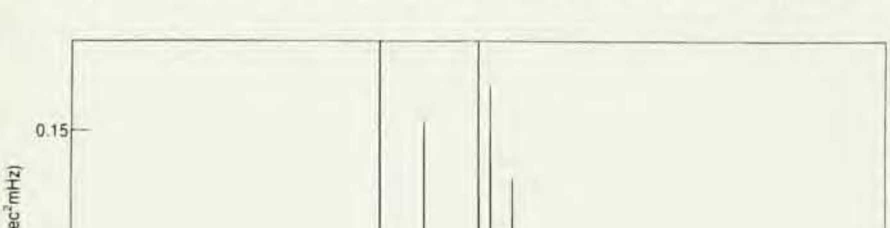
Surface dynamics

Astronomers look forward to the time when solar seismology becomes a sufficiently precise tool to reveal fluid motions deep in the solar interior. However, the large-scale circulation in the convection zone must inevitably be reflected in the flow at the surface, so the measurement of surface motions will provide other invaluable clues for understanding the interior. We may consider differential rotation to be merely the largest in scale and largest in amplitude of an entire spectrum of surface flows; meridional circulation and giant cells, with amplitudes of only a few meters per second, are predicted to exist also. Meridional circulation has been observed, although the small amplitudes of the giant cells are below the currently observable limit. Work is now under way to develop highly stabilized solar spectrographs capable of detecting such large-scale, low-velocity motion in the photosphere.

Uncovering the relationship between magnetic fields and velocity fields on the surface of the Sun will be particularly important for understanding the origin of the magnetic cycle. Fluid motions play sharply contrasting roles in maintaining the magnetic fields of the dynamo models and the primordial-field models. In the primordial-field models, the torsional oscillation responsible for the reversal of the field is buried deep in the Sun, and fluid motions in the convection zone and at the surface play only a secondary role in transporting the field. In contrast, fluid motions are *the* primary agent for generating and transporting the field in the dynamo models. Detailed numerical models of the turbulent, convective dynamo predict specific relationships between the magnetic fields and the surface motions. Observations in the coming years will provide an invaluable test of these models.

Although the turbulent dynamo model has yet to be subjected to such a test, long-term averages of entire zones of latitude reveal unexpected aspects of the large-scale circulation. Investigators recently found narrow zones of faster and slower than average rotation superposed on the solar rotation, which smoothly decreases from equator to pole. At any given phase of the solar cycle there are one or two fast zones between equator and pole, symmetrically situated in each hemisphere. Interestingly, these zones drift from pole to equator in about 11 years and the region of maximum velocity-shear coincides with the mean location of emerging sunspots.

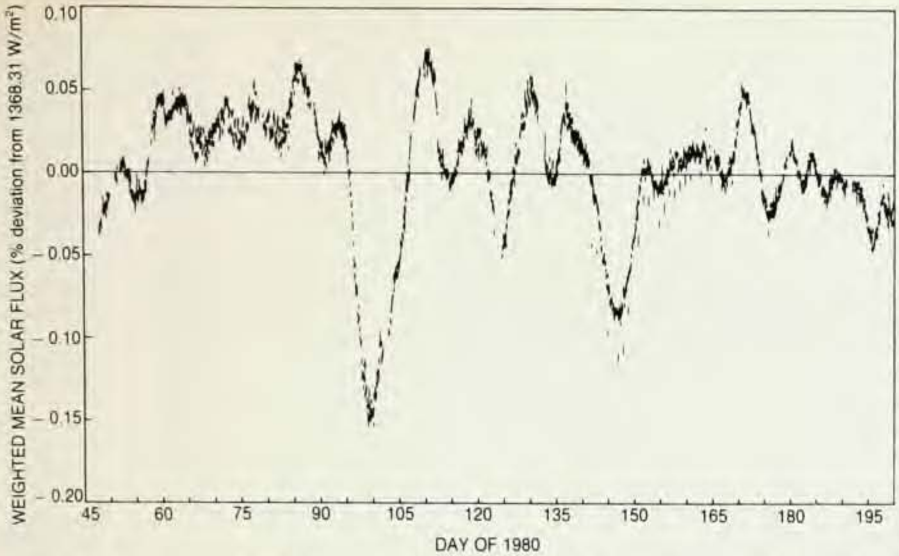
The interpretation of this new phenomenon is still tentative. The fast and slow zones may represent nothing more than the flow produced by the Lorentz force generated as solar plasma encounters the intense magnetic fields of the sunspot latitudes. On the other hand, they may be a symptom of a second-order reaction between magnetic fields and fluid motions, that has not yet been included in the dynamo models. Or they may be the surface manifestation of a deep-seated torsional oscillation. In any case, the small velocity shear involved in the fast and slow zones (about 0.1 m/sec deg) compared to that encountered in differential rotation (5 to 10 m/sec deg), suggests that the former is not the primary source of energy used by the Sun to generate magnetic fields.



Power spectrum of the Doppler velocity of the full solar disk shows a rich spectrum of "lines" separated by about 68 microHz. These oscillations correspond to low azimuthal harmonics of solar pulsations with many nodes between the center and the surface. The small peaks around 2.4 mHz represent global oscillations with a velocity amplitude of approximately 10 cm/sec and correspond to a total motion of the surface of the photosphere of about 5 meters. This spectrum is the result of five days of continuous observation at the South Pole. (From a figure courtesy of G. Grec, E. Fossat and M. Pomerantz.) Figure 7

Luminosity variations

During the solar cycle there are fluctuations in the Sun's output of x rays, radio waves and ultraviolet radiation as well as in its emission of solar wind plasma and energetic particles.[23] All these variations have one feature in common—they occur as a consequence of magnetic fields in the upper layers of



Total solar luminosity at the Earth's orbit shows fluctuations that correlate with the passage of sunspots across the visible disk. The solar flux, measured by a cavity radiometer on the Solar Maximum Mission, is shown as a percentage variation about the weighted mean for the first 153 days of the Mission. Individual points represent the mean irradiance for the sunlit portion of one orbit; vertical bars through each point represent the standard errors of these orbital means. The large decreases near days 100 and 145 are concomitant with the passage of large sunspot areas across the solar disk. The weighted mean irradiance for the period is 1368.31 W/m^2 at 1 astronomical unit. (From R. C. Willson, C. H. Duncan, J. Geist, Science **207**, 177, 1980; provided through courtesy of the Jet Propulsion Laboratory, Caltech.) Figure 8

the solar atmosphere. But we do not expect any of the mechanisms responsible for these emissions to have any direct effect back on the generation of the magnetic fields.

In contrast, the integrated luminosity of the Sun dominates all other outputs by a factor of a million. Since more than half the energy radiated into space is supplied by convective transport, we should not be surprised to find a tight coupling of the three important factors—efficiency of convection, total luminosity and magnetic cycle.

The question of whether the luminosity of the Sun actually does vary with the solar cycle has intrigued scientists ever since the intrinsic variability of other stars was recognized and equipment for the quantitative measurement of solar radiant flux became available late in the last century. However, because Charles G. Abbott's monumental 35-year series of observations of total solar radiant flux—the so-called solar "constant"—failed to reveal any convincing variation, the topic became unfashionable and was completely shunned by astrophysicists and all but a handful of meteorologists for over 20 years. Hindsight shows that uncertainties in the transmission of the atmosphere and inadequacies in basic radiometric technique limited Abbott's accuracy to no better than 1% to 2%.

Stimulated by major advances in radiometric technique, by the ability of satellites to make long-term observations and by the realization that a fraction of a percent change in solar luminosity can have significant climatological effects, the scientific community has found renewed interest in the total solar luminosity. The active-cavity radiometer aboard the Solar Maximum Mission, for example, has a precision of better than 10^{-4} and has revealed previously unknown fluctuations in solar luminosity that correlate with the passage of sunspots across the visible disk (figure 8).

Whether these modern observations will show a variation of the solar constant with the solar cycle, and whether this will be of an amplitude to be of climatological importance, only time will tell. However, the presence (or absence) of such variations at any level will provide yet another important constraint on models of the cycle itself. In addition, with sensitive measurements we may be able to decide whether such long-term variations in solar activity as indicated by the carbon-14 record are accompanied by changes in the solar constant.

Cycles on other stars

Astrophysicists will continue to look elsewhere in the galaxy for insights into solar variability—past, present and future. In his pioneering work, Olin C. Wilson demonstrated that the intensity of the H and K emission lines of ionized calcium in the chromospheres of stars with masses comparable to that of the Sun varies cyclically with periods of seven to fourteen years. From an analogy with the Sun, we know that such emission lines are due to a modification of the structure of the stellar atmospheres by magnetic fields. Thus, we can follow these stellar magnetic cycles by tracing their spectroscopic signatures.

By following the activity cycles of many stars we can get a good perspective of long-term changes of activity because a "snapshot" of only a decade or so catches stars in different stages of their long-term variations. For example, it has long been known that the loss of angular momentum through stellar winds causes the rotation rate of solar-type stars to decrease with age. However, astronomers recently discovered that a more-or-less regular variability appears in stars only after their rotation rates and magnetically stimulated chromospheric radiation have dwindled. This occurs in early middle age for such stars—after the passage of about 5×10^8 years.

Stars younger than this display chromospheric emission lines many times brighter than would the Sun at a similar distance and thus are presumed to have much larger magnetic fluxes. However, the variations in the fluxes are extremely irregular with no trace of a dominant period in the currently available data.

Stars past early middle age have regular cycles similar to those of the Sun. The abruptness of the transition from irregular to periodic magnetic activity as these stars age and lose angular momentum is important. Some researchers take it as evidence for a discontinuous transition of the stellar dynamos from the complex field morphology, produced by a "multiple-mode" dynamo, to the simpler morphology produced by the single-mode dynamo considered responsible for solar activity.

Evidence is also accumulating on other aspects of stellar activity long familiar on the Sun—chromospheres, flares, spots and coronae.[24] We can expect the study of these phenomena to reveal much about the nature of the solar cycle. Likewise, the new tools now emerging for the study of the Sun—tools such as solar seismology, the analysis of surface dynamics, and detailed dynamo models—will give insight into the much broader question of stellar activity.

These new developments will have applications to other questions: Over what range of stellar mass do stars maintain activity cycles? Is stellar activity a general property of such stars or only a transitory phase in their evolution? What is the cause of the wide fluctuations in the level of activity shown by the Sun over the last several thousand years? What is the role of magnetic activity in stellar evolution? We may finally see answers to these fundamental questions.

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