THE PHYSICS OF THE SUN AND THE GATEWAY TO THE STARS

The Sun is stranger than you think, displaying mysterious manifestations of the familiar laws of physics and posing new problems with every major advance in exploratory measurement.

Eugene N. Parker

A pedestrian star like the Sun is, in actuality, a physics laboratory we could never build. The Sun is basically a thermonuclear core enclosed in an opaque shroud that insulates the high temperature (10^7 K, or 1 keV) from the cold universe outside. The core is brighter than ten supernovas at maximum light, but the enclosing shroud turns back all but one part in 2×10^{11} of the thermal radiation, which is largely x rays of 10–50 nm wavelength. We see only the miniscule 4×10^{26} J/s that leak out. The outward journey of the energy from the core to the surface takes about a million years, illustrating again the immense opacity and thermal capacity of the shroud.

So the Sun is an object of extremes, and becomes even more remarkable when studied at high magnification from our vantage point at Earth. About 10^{-5} of the outflowing energy is diverted into magnetic fields that produce a variety of exotic effects, including the coronal mass ejection, the flare, the million degree corona, the solar wind, and the x-ray emission (see figure 1). These small diversions of energy are of particular interest to the physicist because they represent unanticipated manifestations of the familiar laws of physics that carry names such as Newton, Ampère, Faraday, Maxwell, Boltzmann, and Lorentz. Recalling that the physical manifestations of these basic principles are traditionally studied in the terrestrial laboratory, we should not be surprised if additional processes turn up on astronomical scales, such as supersonic expansion of the strongly bound solar corona and the nearly complete tying of a magnetic field to the swirling ionized gas in the regions of solar convection, providing unlimited distortion and extension of the field, and continually generating additional magnetic field. The relaxation of the deformed magnetic field to static equilibrium in the solar atmosphere creates surfaces of tangential discontinuity (current sheets) in the field,[1] with the associated explosive dissipation of magnetic free energy that we see as flares, microflares, and nanoflares (see PHYSICS TODAY, July 1987, page 36). Another unanticipated effect is the inexplicable formation of the magnetic sunspots. The list goes on and on.

We expect that these phenomena can be explained within the framework of the familiar laboratory laws of physics, although the observed neutrino emission is evidently a fascinating exception[2] (see PHYSICS TODAY, July 1996, page 30). All in all, the Sun becomes our great physics laboratory in the sky. All other stars are too distant for detailed observation, and we expect that most of them are exotic in the same way as the Sun, so the Sun becomes the gateway to the stars.

This brief article outlines some of the Sun's more conspicuous challenges to physics. To appreciate each example one must understand the context in which it occurs, and so I will outline here the essential physics as it arises in the outflow of thermal energy from the thermonuclear core through the opaque shroud to the surface of the Sun.

Energy flow

The outflow of heat from the core, which is at 10^7 K, begins as radiative transfer; the familiar thermal conductivity by free electrons is negligible. The temperature declines outward to about 2×10^6 K at a radius of 500 000 km, which is 5/7 of the way to the surface at 700 000 km. At that temperature the radiative transport has declined to the point where it cannot keep up with the heat coming up from below, and the gas is set into convective motion, like the water in a pot on a hot stove. Convective heat transport takes over in the levels above and stirs the heat up to the visible surface through what is called the convective zone.

The convection represents a crude heat engine, converting about 1% of the thermal energy flux into kinetic energy of the turbulent convection. The kinetic energy is dissipated back into heat in a characteristic convective (eddy) turnover time, of course, but not before about 10^{-4}–10^{-3} of the kinetic energy has been converted into magnetic field. And that is where the exotic activity of the Sun begins. As already noted, the magnetic fields are carried and deformed in the convective flows, ultimately producing coronal mass ejections, flares, and so on. Detailed descriptions of these diverse phenomena can be found in

EUGENE PARKER *retired in 1995 as S. Chandrasekhar Distinguished Service Professor in the Enrico Fermi Institute and the departments of physics and astronomy at the University of Chicago.*

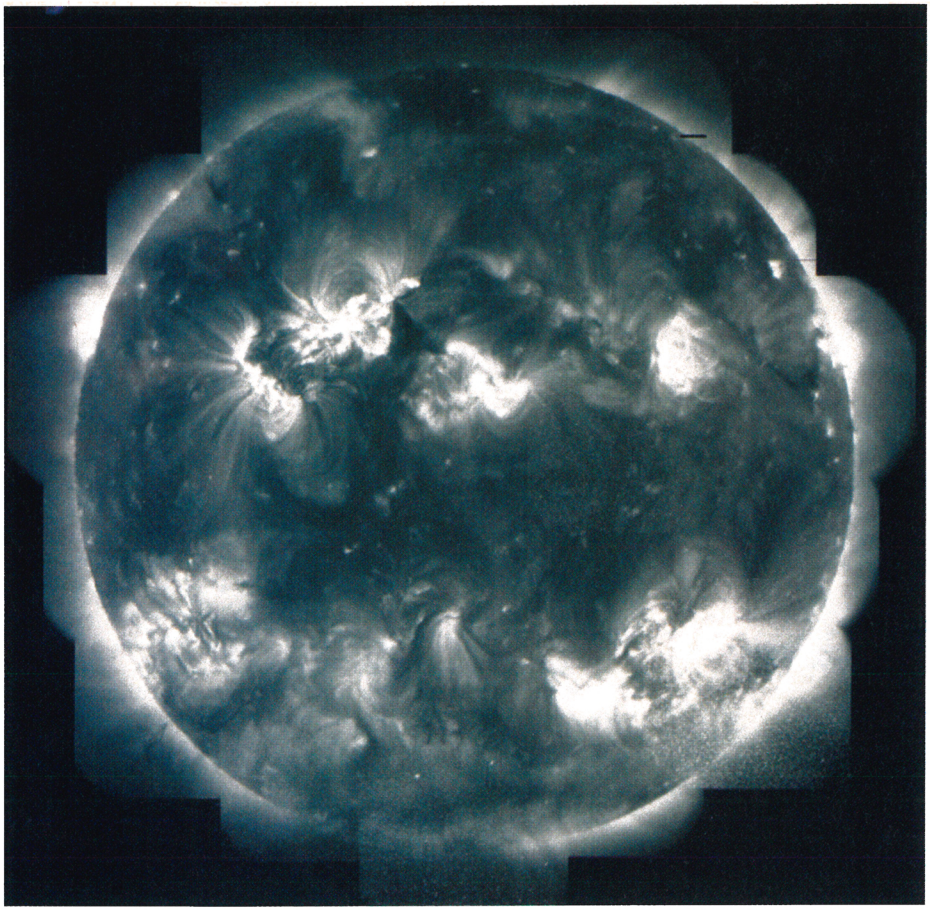

FIGURE 1. X-RAY PICTURE of the Sun in iron-XII, 17:08 UTC 11 August 1998, showing the gas density at 1.5×10^6 K trapped in the bipolar magnetic fields of active regions. The picture was made by the NASA/Transition Region and Coronal Explorer (TRACE) spacecraft, which is a project of the Stanford–Lockheed Institute for Space Research and the Explorer Project at Goddard Space Flight Center.

the literature, but that shouldn't obscure the fact that we understand only limited aspects of the physics and are challenged to uncover the rest.

The thermal Sun

The basic thermal structure of the Sun seems to be pretty well in hand.[2] The degree to which the gas is an impediment to radiative transfer—that is, its opacity—has been calculated in detail. That calculation is greatly complicated by the important role of heavy ions with one or more bound electrons, and by the extreme density (115 g/cm^3 at the center), which causes problems such as overlapping wave functions. The assumption is that the elemental abundances throughout the interior of the Sun are the same as observed at the surface, adjusted for the continuing production of helium in the thermonuclear core and for the diffusion and gravitational settling of the heavier ions. The result is a theoretical model of the solar interior in which the calculated speed of sound matches the speed of sound obtained from helioseismology to within the estimated observational uncertainties of about one part in 500. This puts to rest any conjectures about exotic elemental abundances hidden in the stable radiative interior of the Sun. Such concerns were raised when the very low intensity of neutrinos from the thermonuclear core was first established. It is now pretty clear that the neutrino deficit is a consequence of complications in neutrino physics (see PHYSICS TODAY, August 1998, page 17); the Sun is currently being used as a neutrino factory to study the problem (see PHYSICS TODAY, July 1996, page 30).

Helioseismology and the Sun's rotation

Helioseismology has made possible enormous advances in our understanding of the physics of the Sun (see PHYSICS TODAY, October 1995, page 32), opening up the interior of the Sun to direct probing and measurement. In the simplest terms, the Sun is a thermally stratified ball of ionized gas, possessing thousands of internal echoing acoustic modes. The speed of sound increases downward into the Sun, so the lower side of an acoustic wave front travels faster than the upper side, refracting the wave and heading it back toward the surface—the acoustic equivalent of total internal reflection. The more nearly vertical the acoustic ray vector, the deeper the turn-around level. Upon approaching the surface, the refracted wave encounters a steep gradient in the density and speed of sound, reflecting it back into the Sun. Thus, an acoustic wave is trapped between the surface and the deep refractive turnaround point.

The period of each acoustic mode depends upon the depth of penetration and is given by the sound travel time along the ray path. The ray path and travel time can be computed from the theoretical model of the solar interior and compared with the hundreds of periods found by Doppler analysis of the jiggling surface of the Sun. This comparison provides a precision test of the theoretical model, as already noted.

However, helioseismology can determine more than the speed of sound as a function of radius, because the rotation of the Sun splits each acoustic mode into two states. A detailed analysis of the observed splitting at each latitude provides a map of the rotation profile of the solar interior.[3] The surface of the Sun is observed directly and shows a rotation period of 25 days at the equator, increasing to about 35 days at both poles. Helioseismology shows that, apart from a thin layer at the surface, the rotation period is nearly independent of depth downward through the convective zone (to a depth of 200 000 km), depending only on latitude in essentially the same form as the visible surface. In contrast, the radiative interior, below the convective zone, rotates nearly rigidly with an intermediate period. Thus, there is a strong shear layer at the base of the convective zone, with the convective zone rotating faster than the radiative interior at low latitudes and slower at high latitudes.

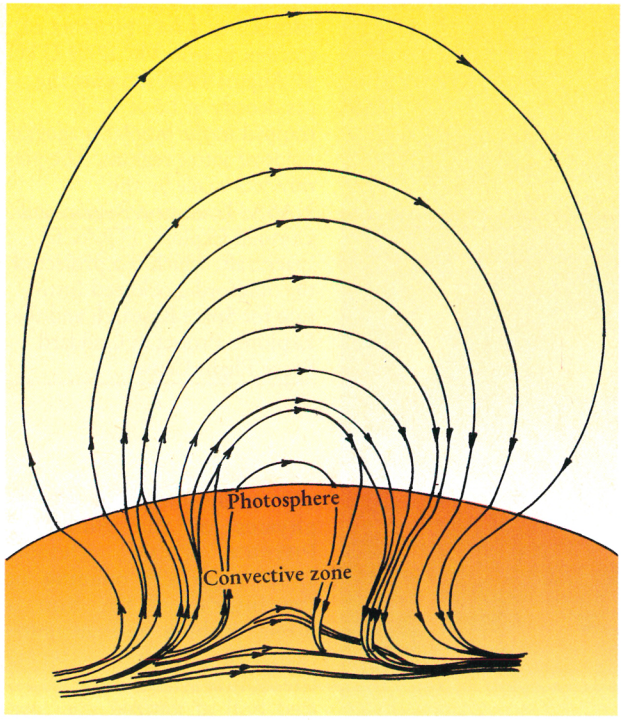

FIGURE 2. LARGE-SCALE STRUCTURE of a bipolar magnetic field, formed by the successive emergence of Ω loops from the general azimuthal field at the base of the Sun's convective zone.

We presume that this remarkable rotation profile is driven by the convection, so it looks like a problem in classical hydrodymanics. However, it turns out to be an extraordinarily difficult problem, because the convection is turbulent (the Reynolds number is on the order of 10^{12}) and, perhaps worse, the convective zone is vertically stratified. The density at the base of the convective zone is 0.2 gm/cm^3; at the top of the convective zone, at the visible surface, it is 10^6 times smaller. A factor of 10^6 represents 14 factors of e—that is, 14 density scale heights, each of which is a dynamical problem in itself, because the convective cells are limited in vertical extent to about one scale height. The bottom line is that contemporary supercomputers, if efficiently coded, can handle up to five scale heights. This treatment of the problem, unfortunately, provides a rotation profile that is unlike that inferred from helioseismology. We may expect that one day an adequate calculation will provide the observed rotation profile. Or it may be that the conventional representation of the turbulence, based on the simple mixing-length concept, is inadequate in the stratified Sun. The essential point is that we do not yet understand the physics of the nonuniform rotation of the Sun.

On the other hand, we know the form of the nonuniform rotation, so we can move on to the next phase, which is the generation of magnetic field in the Sun. Here again, as we shall see, we come up against a baffling problem in physics.

Magnetic fields

Spectroscopic observations of the magnetic fields at the Sun's surface (based on the Zeeman effect) show polar fields of about 10^{-3} T at latitudes above about ±55°, in at one pole and out at the other. At lower latitudes the situation is more complicated, with the buoyant rising of east–west—that is, azimuthal or toroidal—magnetic fields from somewhere deep in the convective zone. Magnetic fields are intrinsically buoyant because they provide pressure without significant mass. Thus a horizontal magnetic field somewhere down in the convective zone develops upward bulges, descriptively termed Ω loops. The bulges emerge through the surface of the Sun (see figure 2), forming bipolar magnetic regions, or magnetic active regions, with lengths up to 200 000 km. The bipolar fields have opposite signs on opposite sides of the equator, and the sign of the fields reverses from one 11-year cycle to the next. The polar fields reverse near sunspot maximum, when spot formation is in low latitudes, within about 10 degrees of the equator. The x-ray emission, shown in figure 1, is produced by the million-degree gas trapped in the bipolar fields.

Sunspots form where the field exits or enters the Sun, and it is in these bipolar magnetic regions that the coronal mass ejections and flares occur. The magnetic field is typically 0.01 T, weaker at the edges and stronger in the vicinity of sunspots. Observations show fresh flux bundles (Ω loops) emerging every few days, continually replenishing the bipolar field, which otherwise is inclined to fade away in times on the order of a month.[4] The fields are typically 10^{-3} T in the regions between the bipolar fields.

Sunspots and their associated bipolar fields (the 0.2–0.3 T sunspot fields were first detected almost a century ago[5]) appear first at middle latitudes, ±40°. New spots continually form from fresh emerging Ω loops. The individual spot may last a couple of days or a week or two. The sunspot formation belts move toward the equator over the next 10 years. The amazing fact is that some of the emerging flux is observed to cluster and compress to form the intense field of the sunspot in opposition to the large magnetic pressure and tension ($B^2/8\pi \sim 4$ N/cm^2). One can only assume that the compression is driven by a powerful converging flow of gas beneath the surface. So we are back to hydrodynamics that we do not understand.

Magnetic field generation

How does this magnetic evolution come about? Solar gases are not intrinsically magnetic. However, being fully ionized except for a thin layer at the visible surface, the gases are excellent conductors of electricity. That means they cannot sustain any significant electric field in their own moving frame of reference.

If there can be no electric field in the moving gas, then the magnetic field cannot move relative to the gas, because to do so would induce an electric field in the gas. So the magnetic field is tied to the gas and carried bodily along with the convective motion. Fortunately, the two essential steps for magnetic field generation are quite simple. First, the weak polar, or poloidal, field is sheared by the nonuniform rotation, drawing out the field lines in the azimuthal direction. The Sun spins around many times (about 150) in 11 years, with the result that the azimuthal magnetic field component builds up to an intensity far in excess of the weak poloidal field.

The second step in field generation involves the convection, which is cyclonic as a consequence of the rotation of the Sun, so that a rising, expanding, convective cell may be presumed to rotate a little less rapidly than its surroundings, while a downdraft becomes increasingly compact and rotates a little more rapidly. These convective cells make upward and downward bulges in the azimuthal field and then rotate those bulges into the meridional plane. Figure 3 shows the general scheme of things, the final result being that the rotated bulges in the

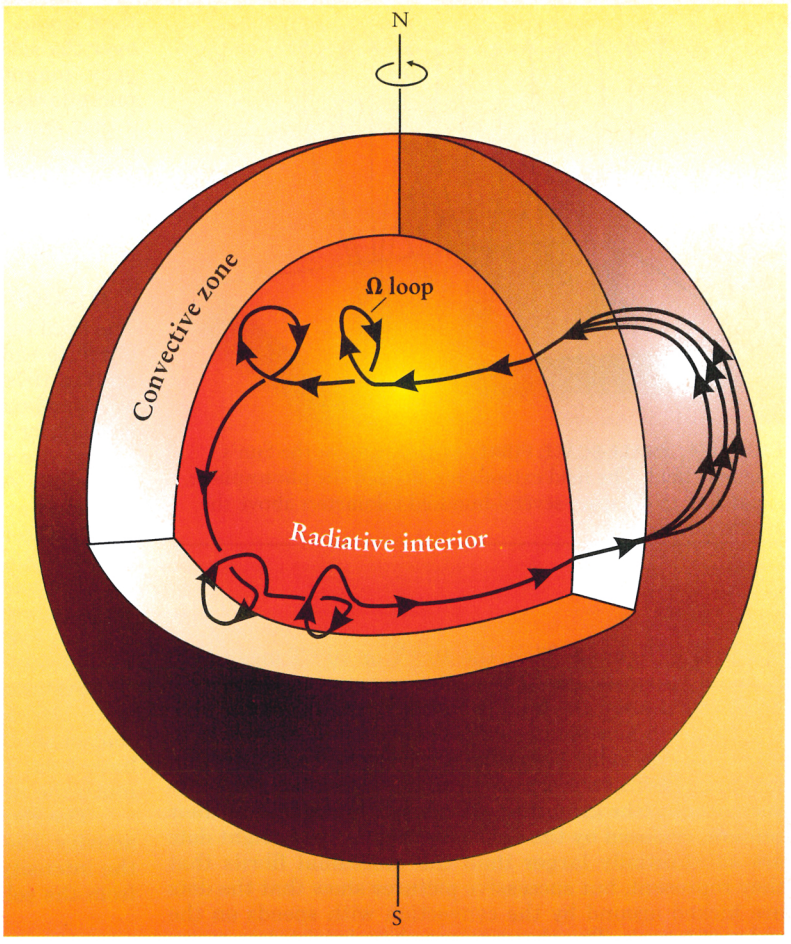

FIGURE 3. OCTANT OF THE SUN'S convective zone cut away to show schematically a poloidal loop of magnetic field. The loop, in a meridional plane (on the right), is sheared by the strong gradient in angular velocity at the base of the convective zone to produce intense bands of azimuthal field. Cyclonic updrafts lift intense twisted Ω loops (on the left) that add to the magnetic meridional circulation of the poloidal field on the low-latitude side and cancel the circulation on the high-latitude side, thereby increasing the total poloidal magnetic flux and moving the location of the azimuthal field toward the equator.

azimuthal magnetic field represent a net circulation of magnetic field in the meridional planes, soon smoothed by diffusion into a general large-scale circulation of field. That is, of course, precisely the nature of the poloidal field with which we started. So the result is a net strengthening of the magnetic field.[6]

Detailed numerical simulations of these processes—the solar dynamo—duplicate the magnetic field variations observed at the surface, and the first thought is that we now understand how the magnetic fields of the Sun, and by inference, those of other stars, are created.

However, a critical look at the theoretical solar dynamo and at the observed magnetic fields on the Sun raises two major difficulties. First, the operation of the dynamo is predicated on the notion of turbulent diffusion of the magnetic field. Second, the field is observed to have an intense, small-scale fibril structure.

Turbulent diffusion

The production and destruction of the solar magnetic field on an 11-year basis requires that the field diffuse over distances on the order of 200 000 km in 11 years. An effective diffusion coefficient η provides a characteristic diffusion distance $(4\eta t)^{1/2}$ in a time t, so η must be on the order of 3×10^{11} cm^2/s. The electrical resistivity of the 10^6 K gas in the convective zone provides a coefficient η of only about 10^4 cm^2/s. So the idea, based on the conventional mixing-length concept, has been that the turbulent diffusion of magnetic field provides an effective diffusion coefficient on the order of 0.1 λv, where λ is the scale of the dominant eddies, or convective cells, and v is the characteristic velocity of the eddies. The estimated values $\lambda \sim 4 \times 10^9$ cm and $v \sim 10^3$ cm/s in the lower convective zone provide $\eta \sim 4 \times 10^{11}$ cm^2/s. This convenient coincidence of numbers has been accepted for many years, providing successful models of the solar dynamo.

However, an inventory of the magnetic flux emerging in a bipolar magnetic active region over a period of six months sometimes shows a total as large as 3×10^{15} Wb. So much flux implies mean azimuthal fields on the order of 0.2–0.3 T or more below the active region. Such fields are as strong as the convection (that is, $B^2/8\pi \sim \frac{1}{2}\rho v^2$) and would stoutly resist being drawn out into the long thin filaments into which, for instance, a puff of smoke is drawn by turbulent diffusion. But the concept of turbulent diffusion of magnetic field is based on direct analogy with the diffusion of a puff of smoke.

So we do not understand diffusion of magnetic field, without which the dynamo does not work. The Sun seems to know how to make it work, but we do not. But that is only the beginning of our ignorance.

It was announced recently that precision analysis of space-based and ground-based helioseismic data shows balanced counter-rotating oscillations of a thin layer immediately above and immediately below the base of the convective zone.[7] The amplitude of the oscillations is about 18 m/s and the period varies from about 1.3 years at the equator to 1 year at 60 degrees latitude. This location places the two shells where it is believed the poloidal field is sheared by the nonuniform rotation to produce the azimuthal field, and it would appear that the angular momentum is transferred between the two thin counter-rotating shells by the Maxwell stresses in the combined poloidal and azimuthal magnetic fields. We are impressed once again with the seemingly unlimited variety of phenomena that turn up with our advancing ability to probe the Sun.

Fibril magnetic fields

Some clever scientific detective work about 30 years ago revealed that the 10^{-3} T and 10^{-2} T fields in the visible surface of the Sun are really composed of widely separated, intense (0.15 T), small (100-km diameter) magnetic flux bundles, or fibrils.[8] The individual fibril is too small to be resolved, so the magnetograph simply records the mean field strength, consisting of the 0.15 T fibrils and the negligible field throughout the broad spaces between fibrils,

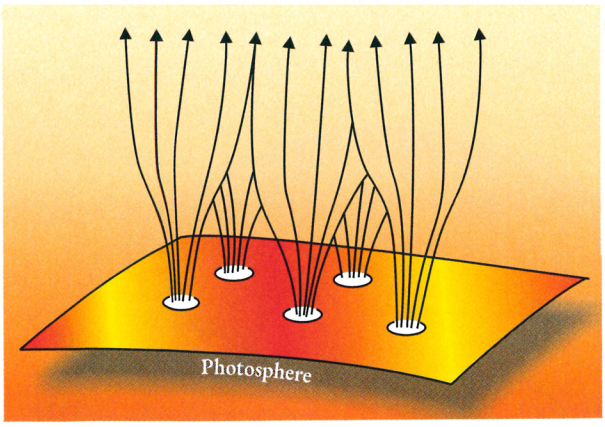

FIGURE 4. SMALL-SCALE FIBRIL STRUCTURE of the Sun's magnetic field. The field extends up through the photosphere, expanding to fill space several hundred kilometers above the visible surface.

sketched in figure 4. Thus the 10^{-3} T or 10^{-2} T mean field is merely a statement of the spacing between the fibrils. The fibril state of the field is without explanation.

Figure 5 is a picture with the best telescopic resolution available today, about 0.3 arc seconds. The individual magnetic fibrils show up as the bright dots among the convective cells (the granules), with bright upwelling at their centers, enclosed by the dark downdrafts. The bright dots are substantially larger than the individual fibrils that they represent, but successive pictures show that the dots are kicked around by the convection with speeds on the order of 1 km/s. The observations show bright dots merging and separating, indicating some sort of interaction of the fibrils. The nature of the interaction between two fibrils depends on whether the magnetic fields of those fibrils have the same or opposite sense and on the degree of twisting of each fibril, neither of which is known. The essential point is that contact between opposite field components can lead to rapid, and even explosive, dissipation of magnetic energy, and we know little or nothing about what actually occurs.

Observations

Fortunately, adaptive optics has progressed to the point where it is now feasible to build a telescope that can see clearly through the roiling terrestrial atmosphere to resolve the individual fibrils and study the gas motion, magnetic field, and temperature variations within and around the fibrils. The telescope would need an aperture of about 4 m to gather enough light to run high dispersion spectroscopy at rapid cadence to follow the small-scale variations of the fibrils. We might call it the "solar microscope" or the "advanced solar telescope." The instrument is essential for studying the emergence, structure, interactions, and disappearance of the fibrils, the astonishing sandwich structure of the sunspot penumbra (composed of alternate vertical slabs of horizontal and inclined magnetic field), the small-scale structure of flares, prominences, the curious bright patches that appear in regions of strong magnetic field (faculae and plages), and the ephemeral active regions.

The ephemeral active regions represent another set of bipolar magnetic regions appearing on the surface of the Sun. They are small magnetic bipoles, with lengths less than about 20 000 km, that appear broadly distributed over the solar surface, and vary only a little with the 11-year magnetic cycle. They produce small flares, or microflares, as distinct from the larger flares of 10^{21}–10^{25} J that appear in the regular bipolar active regions. Their origin is not clear.

One can see that there are whole classes of solar phenomena that defy understanding, and this situation will continue until improved observational instruments give us some idea of the structure of these marvels.

Variations in solar brightness

The total luminosity of the Sun varies with time. The first absolute radiometer flew on the NASA Nimbus 7 spacecraft in 1978. The instrument saw the luminosity come up over a maximum in 1979 at the peak of the magnetic activity, or sunspot cycle, and subsequently decline by almost two parts in a thousand through the sunspot minimum of 1986, and rise a little more than one part in a thousand over the maximum in 1990, and so on (see figure 6). The measurements were corroborated by radiometers on spacecraft launched in the succeeding years.[9] We do not understand why the luminosity varies with the magnetic activity. It may be that the continual buoyant rise of Ω loops stirs the convective zone enough to enhance the delivery of heat to the surface.

Systematic monitoring of several solar-type stars since 1960 shows magnetic activity cycles comparable to that of the Sun. The luminosities of some of those stars have been monitored for about 15 years, and they show much the same variation as the magnetic activity.[10]

The Earth holds a lot of information about past solar activity. The rate of production of ^{14}C depends directly on the intensity of cosmic rays, which are partially excluded from the solar system by the outward sweep of magnetic

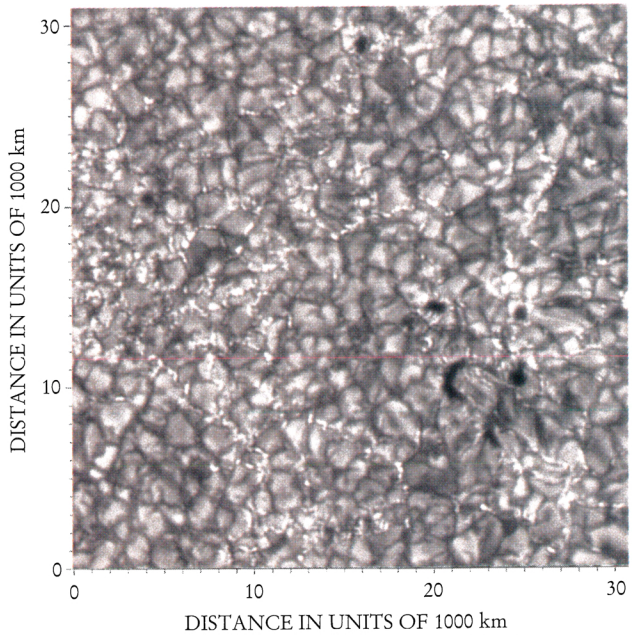

FIGURE 5. UNRESOLVED MAGNETIC FIBRILS. The fibrils appear as bright blobs, about 200 km across. They move about in the dark lanes (downdrafts) between upwelling convective cells (granules), which have characteristic diameters of 1000 km. The picture was taken by Thomas Berger at the Swedish Vacuum Tower Telescope at Las Palmas, Gran Canaria, Spain (the Canary Islands).

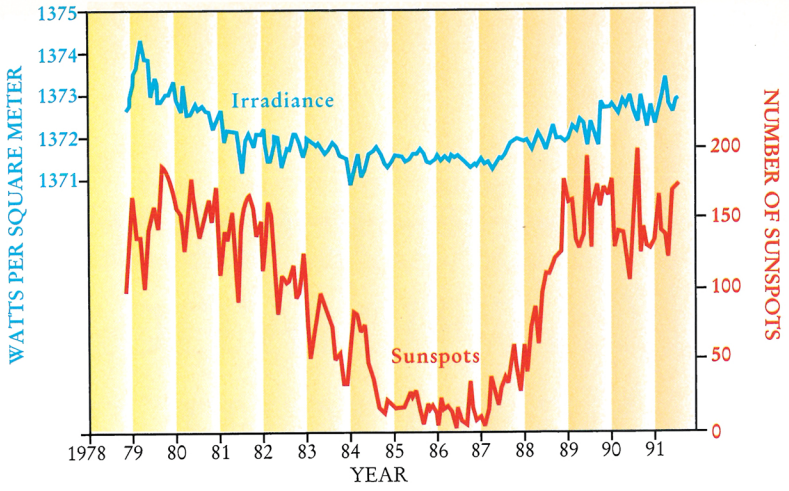

FIGURE 6. LUMINOSITY AND MAGNETIC activity. The upper curve shows the Sun's monthly mean irradiance, recorded by the NASA Nimbus 7 spacecraft. The lower curve shows the sunspot numbers. The correlation between these quantities is evident, but not at all understood. (From ref. 14.)

fields in the solar wind. Thus the cosmic ray intensity and ^{14}C production vary oppositely to the general level of solar activity.

The ^{14}C record shows that over the last 70 centuries, the Sun has been without normal activity for 10 centuries and hyperactive for 8 centuries.[11] The other 52 centuries were variable but more or less "normal." The most recent quiescent period was from 1645 to 1715, first recognized from the sunspot record in 1896 and subsequently called the Maunder Minimum after its discoverer. The 12th century Medieval Maximum is the most recent epoch of hyperactivity, and one can only guess how the Sun behaved at that time. Such periods of abnormal activity are without explanation, as are the variations within the so-called normal centuries. The empirical relation between the total luminosity and magnetic activity, based on many solar-type stars, suggests that the Sun was fainter during the Maunder Minimum by 0.4 ± 0.2 percent and perhaps brighter by a comparable amount during the Medieval Maximum.[10] It is not surprising, then, that the mean annual temperature in the northern temperate zone was lower than normal by 1–2 °C during the Maunder Minimum and higher by 1–2 °C during the Medieval Maximum.[11] The fractional change in temperature is comparable to the fractional change in solar brightness, and so it appears that the Sun is the driver of the climate. The consequences for agriculture were severe during both periods, the Maunder Minimum being disastrous in northern Europe and China, and the Medieval Maximum disastrous in the semi-arid regions, such as what is now the southwestern US.

The general level of solar activity doubled or tripled from 1900 to 1950. That estimate is based on sunspot numbers and on the intensity of geomagnetic activity, which is driven by the impact of the solar wind and its magnetic fields against the geomagnetic field.[12] This increase suggests an increase in solar luminosity by perhaps one part in two thousand, and it is interesting to see that the mean temperature in the northern temperate zone, as well as the surface sea water temperatures, rose during the same period. Warmer seas, of course, reduce the rate at which atmospheric carbon dioxide is absorbed into the oceans. It appears that the global warming since 1950 is in part a consequence of the continuing increase in solar brightness, seriously aggravated by the extravagant burning of fossil fuel.[13] So the mystery of variations in the total luminosity of the Sun is part of the complicated picture of global warming.

Clearly, we have yet to understand some important physics of the Sun and stars. Some day we may well understand more. For now, though, classical physics, which is the basis for the mysterious effects, still has many secrets for us to discover.

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