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# Recent Solar Research

## Results from new methods of observation prove the sun to be a beautifully complex astronomical body.

Robert Howard

Spots on the surface of the sun have been sketched and counted for several centuries, but it was not until the last part of the nineteenth century that advances in physics made possible the first serious scientific study of the sun. Some physical effects, such as the Doppler shift of spectral lines, found some of their first applications in studies of the sun (*1*). In addition, advances in the art of photography in the last century were quickly applied to studies of the solar surface and, later, of the corona at eclipse (*2*).

George Ellery Hale may be considered the father of modern solar physics (*3*). He founded the Mount Wilson Observatory (originally named the Mount Wilson Solar Observatory), and among his many accomplishments may be listed the discovery of magnetic fields in sunspots (*4*) and of the reversal of polarities of sunspot magnetic fields in alternate solar cycles (*5*), and the invention of the spectroheliograph (*6*), an instrument for photographing the sun in a very narrow wavelength band. This device remains an important tool in solar research in spite of the increasing use of narrow-band filters.

In the early decades of this century advances were made in understanding the nature of the solar atmosphere, and after the development of radiative transfer theory considerable progress was made in determining the abundance of the chemical elements in the sun (*7*). Most of this work was applicable to both the sun and the stars, but the sun was particularly appropriate for the study of a stellar atmosphere because of the possibility of accurately measuring the limb darkening and the influence of small-scale features. Much of the current interest in solar abundances is on the part of stellar astronomers who are interested in galactic or cosmic abundance differences in stellar evolution.

In the late 1930's it was realized that the corona of the sun, which had been seen at solar eclipses on many occasions, was an extremely hot gas—over a million degrees Kelvin. Emission lines that had been ascribed to a hypothetical element, coronium, were recognized as being those of very highly ionized atoms of known elements (*8*).

In more recent decades many advances in our understanding of the sun have resulted in part from advances in magnetohydrodynamics and plasma physics. The sun is a giant sphere of ionized gas, at the surface of which magnetic fields display characteristic and often approximately repeatable behavior. Most solar physicists believe that the magnetic field is a fundamental element in solar activity, but it is only in the last 20 years that any magnetic fields on the solar surface outside the strong sunspot fields have been reliably measured (*9*).

In an article of this length it is not possible to present a complete picture of the present state of our knowledge in a field as large and as rapidly developing as solar physics. Instead I will try to describe many aspects of the field and give some recent results.

### The Sun as a Source of Activity

Sunspots are the most obvious manifestation of solar activity (*10*). However, each active region on the sun has sunspots associated with it generally for only a small fraction of its lifetime, when it has sunspots at all. The active region is characterized by bright emission at chromospheric layers, as seen in the stronger absorption lines such as the hydrogen H$\alpha$ line at 6563 angstroms. In addition, dark "filaments" seen in the chromospheric lines often lie over active regions and frequently are found outside active regions as well. The larger filaments may be seen above the limb of the sun in chromospheric spectrum lines as prominences. Figure 1 is a high-resolution H$\alpha$ filtergram (band pass 0.1 Å) of an active region, and shows the bright plage of the region, filaments, and the smaller fibrils.

The various phenomena that make up an active region are closely linked to the presence of a magnetic field in the surface layers of the sun (*11*). The bright plage of an active region, especially as seen in the K line of doubly ionized calcium (Ca II), is very closely correlated with the presence of predominantly radial magnetic fields (*12*). Figure 2 is a full-disk Ca K spectroheliogram. It is generally assumed that the chromosphere is hotter in the presence of a vertical magnetic field because Alfvén waves, which originate in convective motions in the photosphere below, travel along the lines of force and dump energy in the form of heat into the chromosphere and corona (*13*). Prominences are believed to represent condensations of ionized material in relatively stable, roughly horizontal configurations of magnetic field lines in the corona high above

Dr. Howard is a staff member of the Hale Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena 91101.

the photosphere (*14*); however, the exact nature of the support of this material and the precise configuration of the field lines are not known (*15*). A remarkably detailed photograph of a prominence is shown on the cover. Prominences lie approximately along the dividing line between the two magnetic polarities in active regions, and later also as the plage fields spread out and migrate poleward. The "polar crown" prominences, which are observed at high solar latitudes near the maximum of the activity cycle, are assumed to be related to the presence of polar magnetic fields (*16*), although no definite connection has been established.

The "supergranulation" (*17*) is a large-scale (30,000-kilometer) circulation pattern seen in photospheric and chromospheric absorption lines. The circulation consists of a horizontal flow (approximately 0.5 kilometer per second) outward from the center of the supergranular cells. There is evidence for upward motion at the centers of the cells and downward motion at the edges. Presumably the circulation pattern is completed by horizontal inward motion beneath the photosphere. Magnetic fields are found to be concentrated at the boundaries of supergranular cells and are assumed to have been swept there by the motion. In Fig. 2 the calcium network may be seen as an arrangement of small emission fragments at the boundaries of roughly regular, close-packed cells with dimensions of about 30,000 km. This pattern covers essentially the whole solar surface outside plages and spots. These emission points represent the presence of magnetic fields, and the calcium network represents the boundaries of the supergranular pattern.

Fig. 1. An Hα filtergram of an active region near the limb of the sun on 22 May 1970. A small flare is in progress, and above it both bright and dark surges extend upward far into the corona. The whirled fibril structure of the chromosphere may be seen surrounding the active region. The black areas near the flare are sunspots. [Big Bear Solar Observatory, California; courtesy of Dr. H. Zirin]

Magnetic fields appear at the solar surface at the first appearance of a new active region. There is evidence that the field lines in a new region come from below the solar surface and for a time result in looped fibrils, as seen in Hα filtergrams (*18*). Frequently, small active regions are formed that do not grow large and do not have spots associated with them. Nevertheless, the magnetic field strengths involved are relatively large—many hundreds of gauss—and the appearance in the chromosphere of such fields is unmistakable to an experienced observer. There is no evidence for any gradual appearance of magnetic flux at the solar surface. The large-scale weak patterns, which will be discussed below, all had their origin in the strong fields of active regions.

Larger active regions generally have sunspots associated with them early in their lifetimes. As a region ages the spots disappear and the plage, representing the close-packed magnetic fields, begins to disperse. The action of nearby supergranular cells is believed to "erode" the concentrated plage magnetic fields. The result of the supergranular motions and the differential (with latitude) rotation is to spread the magnetic flux over very large areas of the solar surface, even to the poles of the sun (*19*). Figure 3 shows a recent magnetic observation of the full solar disk. Such observations are made daily at the Mount Wilson Observatory.

The nature of the solar activity cycle is not understood. Some models have been proposed (*20*), but these are largely phenomenological. It is not likely that in the near future our knowledge of conditions below the solar surface or our ability to solve complicated large-scale problems in magnetohydrodynamics will improve sufficiently to allow any sort of exact solution to the problem of the solar activity cycle. The migration of large-scale magnetic field patterns on the solar surface, resulting in the buildup and periodic reversal of the polar fields of the sun (*21*), is certainly an important clue to the mechanism of the solar cycle.

The large-scale magnetic fields of the sun have been analyzed in terms of surface harmonics by using the Mount Wilson measurements. At times a significant harmonic is a dipole lying in the plane of the equator. Also significant at times is a harmonic in which both solar poles have the same magnetic polarity (*22*). Such methods are limited by problems, among them the fact that from the earth we cannot measure all parts of the solar surface with equal reliability. Nevertheless, this is an important way of seeing the large-scale distribution of magnetic fields in a quantitative fashion.

Calculations of magnetic field configurations in the corona have been made by using measurements of the photospheric magnetic field and assuming that the coronal fields are potential fields (current-free) (*23, 24*). Figure 4 is such a plot of field lines above the solar surface on a particular date. The correspondence between such plots and coronal features seen at eclipse is rather good.

There is an excellent correlation between the polarity of the interplanetary magnetic field seen near the earth and the predominant polarity of the solar magnetic fields over a broad zone of latitudes around the equator, when one takes account of the 4½-day lag introduced by the Archimedes spiral shape of the interplanetary field lines (*25*). The interplanetary field tends to be grouped into broad sectors in solar longitude within which the field is nearly all of one polarity (*26*). Such a broad-sector pattern must also exist in some fashion on the solar surface, although it is largely masked by the magnetic fields of active regions. A variation of a component of the earth's magnetic field at any time, measured at a high geomagnetic latitude, has been shown to correlate very well with the polarity of the interplanetary magnetic field (*27*). Thus, since geomagnetic data are available for some decades, it is possible, in principle, to trace back the characteristics of the interplanetary and solar magnetic fields.

The nature of the small-scale magnetic fields on the solar surface has been examined in detail, and one important conclusion is that practically all the magnetic flux on the sun outside sunspots is confined to many small, more or less vertical bundles of lines of force within which the magnetic field strength is approximately several hundred gauss (*28*). There is some evidence that all these magnetic concentrations have the same magnetic flux (*29*). The magnetic fields at the photospheric level outside sunspots are approximately radial to the sun, although the preceding and following magnetic polarities are tilted a few degrees toward each other in each hemisphere. Also both polarities are tilted slightly to trail the rotation (*30*).

Solar rotation has become a subject of increased interest. The variation of the rotation rate with solar latitude has been known for a long time, but only in the last few years has it been generally recognized that the rotation rate of the photospheric material varies with time and that the average rate is slower by about 5 percent than the sunspot rotation rate (*31*). The non-sunspot magnetic fields on the solar surface rotate with a rate that is close to, but at high latitudes significantly faster than, that of the spot rotation (*32*). There is evidence that the higher layers of the solar atmosphere rotate faster than the photosphere (*33*). Figure 5 is a comparison of various rotation rates. In general, phenomena associated with the magnetic field cluster together on the diagram, and these features plow through the slower nonfield photospheric material, gaining at a rate of about 1 day per rotation or about 0.1 km/sec.

There is evidence from measures of solar oblateness that the core of the sun rotates very rapidly—perhaps with a period of about 1 day (*34*). This observation is an extremely difficult one, and confirmation of this exciting result is needed.

One of the most important manifestations of solar activity is the solar flare phenomenon. Although not all solar physicists agree on the definition of a flare (*35*), it will suffice here to define it as a sudden release of a large amount of energy in a relatively small volume above the solar surface. The largest flares represent more than $10^{32}$ ergs—counting x-rays, ultraviolet light, visible light, and particles—released in a few minutes of time. This may be compared with the total energy output of the sun, which is about $4 \times 10^{33}$ erg/sec. In spite of the great energy involved, only a few flares per century are seen in white light.

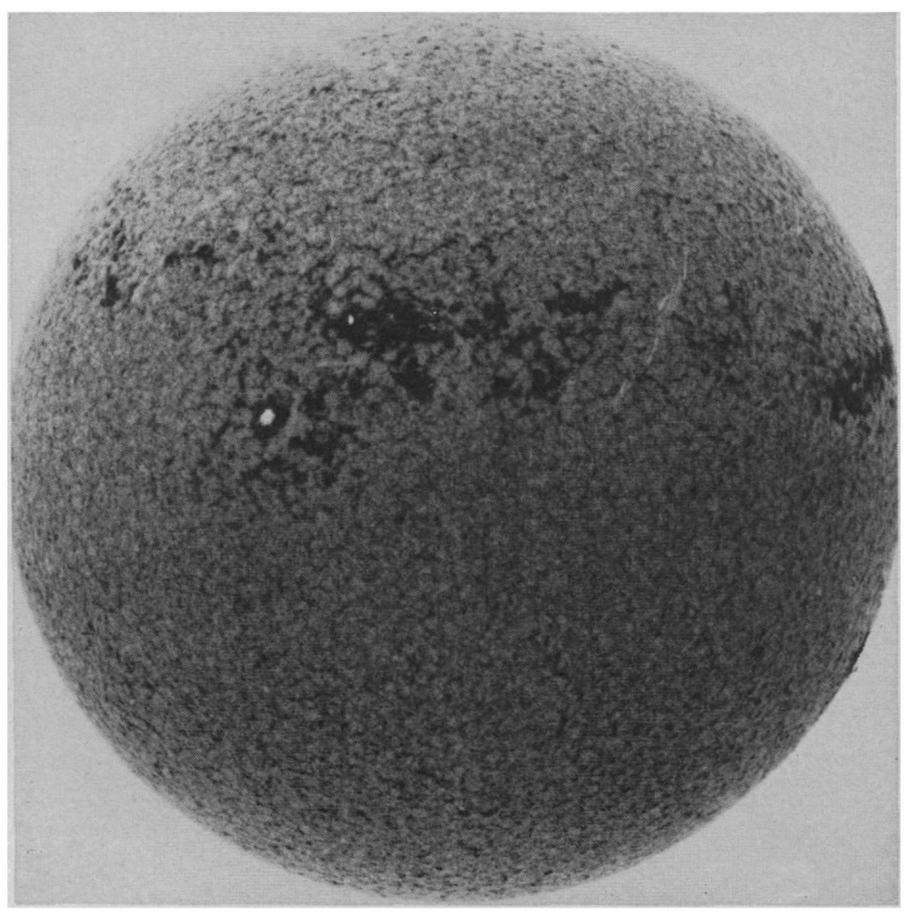

Fig. 2. A Ca K line spectroheliogram of the solar disk taken at the Mount Wilson Observatory on 18 October 1966. A few of the larger sunspots may be seen as white features on this photographic negative. The plages are dark areas. A large filament may be seen as a bright wispy line above and to the right of the center of the disk. A large polar crown filament may be seen near the north (top) of the disk. The calcium network pattern is an arrangement of dark spots outside active regions. Near active regions the emission in the network boundaries is enhanced.

Individual flares, like individual auto accidents, are unpredictable except in a statistical sense. As you must have at least one auto to have an auto accident, so you must have magnetic fields in active regions (but not necessarily sunspots) to have a solar flare. An auto accident is more likely if a driver is inebriated, and a flare is more likely if the magnetic field configuration is complicated. Considerable effort goes into flare prediction because of the great importance of the effects of flares in the field of communications. Most solar physicists agree that confident predictions of individual flare events will not be possible for many years, if, indeed, they will ever be possible.

Flares are observed in the x-ray range by means of instruments in satellites and rockets (*36*). The bulk of the emission of soft x-rays from flares comes from a very small volume located at a maximum of the magnetic field gradient. The temperature derived from this thermal radiation is between 4 $\times 10^6$ and $10 \times 10^6$ °K. The emission of hard x-rays from flares is nonthermal in origin and may result from bremsstrahlung radiation from particles accelerated to high energies. The mechanism for the acceleration of these particles is not known.

The particle emission from large flares represents an appreciable fraction of the total energy released. Part of this energy is seen in the form of low-energy cosmic rays. The largest of the flares produce cosmic rays that are detectable by neutron monitors at ground level on the earth, which requires energies greater than 1 billion electron volts (*37*). Low-energy plasma streams, moving at a rate of about 1000 km/sec, may result from large flares, and at times cause geomagnetic storms and auroras.

Radio radiation from flares in the centimeter range is closely correlated with the x-ray bursts. In the meter range the picture is more complex. There are several types of bursts associated with flares, including a "slow drift" (type II), which is characterized by a gradual drift of radio emission of high intensity to lower frequencies, representing an outward motion of about 1000 km/sec. The "fast drift" (type III) burst is a very rapid change from low to high frequencies. Radioheliograph observations confirm that the source moves through the corona along open magnetic field lines with a speed of about 100,000 km/sec (*38*). The cause of these bursts is thought to be streams of very energetic electrons or protons. Type IV bursts are characterized by broad-band emission moving outward with speeds up to 1000 km/sec. Results from high-resolution observations confirm that these bursts, which are polarized, represent an outward motion that is connected with an expanding magnetic arch or is along open magnetic field lines (*39*). Synchrotron radiation is probably responsible for type IV radio emission.

There are difficult theoretical problems in understanding the flare phenomenon (*40*). One must first find a means of storing a great deal of energy in the chromosphere or the corona, and then find a mechanism for the sudden release of this energy. Although numerous flare theories have been proposed, including a recent suggestion that a flare is an electric discharge (*41*), there is no concensus among solar physicists on this important matter. It may be that the several types of flares observed represent several different magnetic or plasma instabilities. We are certainly very far from a confident understanding of the mechanisms of solar flares and particle acceleration.

Although some manifestations of solar activity have been observed for centuries, interest has increased in this field in recent years because it is now possible to make accurate observations of magnetic and velocity fields on the sun and in interplanetary space, x-ray and ultraviolet radiation from flares and active regions, and particles ejected from the sun. In all these areas we have only scratched the surface so far in our investigations; a great deal more remains to be discovered about solar activity.

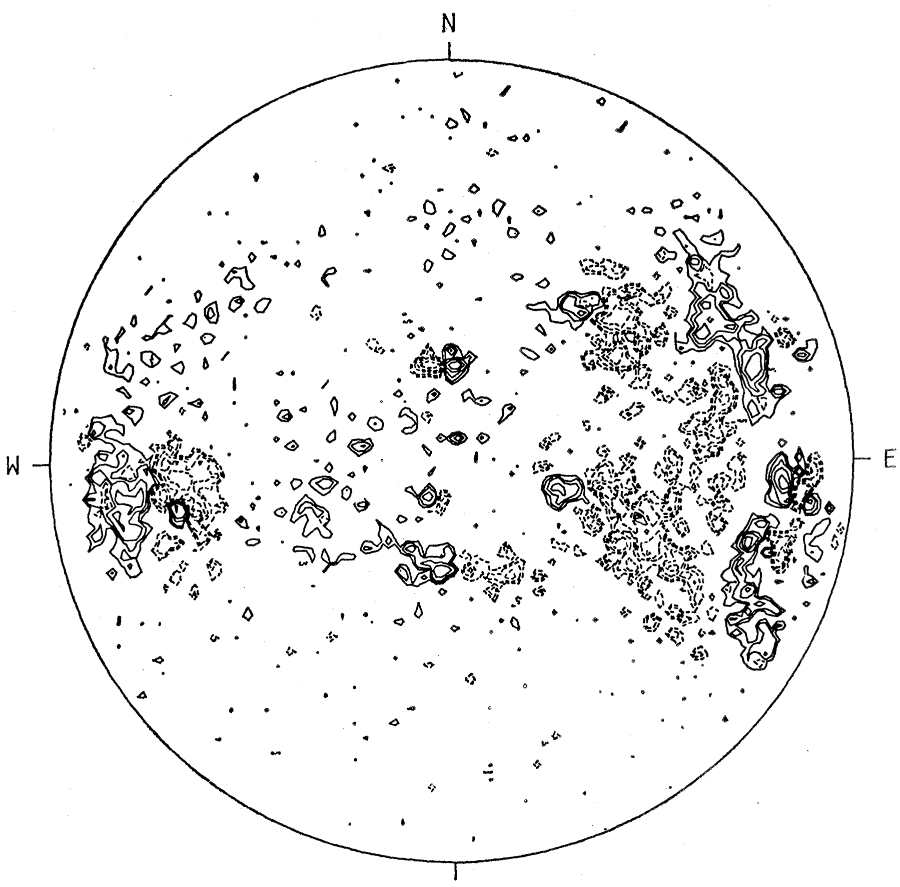


Fig. 3. A solar magnetogram from the Mount Wilson Observatory for 7 April 1972. Solid isogauss lines represent positive magnetic fields (magnetic vector toward the observer), and dashed lines represent negative fields. The magnetic levels are plus and minus 5, 10, 20, 40, and 80 gauss. The north and south (*N* and *S*) markers define the rotation axis of the sun. Rotation is from east (*E*) to west (*W*). The angular resolution of the observation is about 17 arc seconds (14,000 km).

## The Sun as a Physical Laboratory

Since the earliest days of astrophysics it has been obvious that without an accurate model of normal physical conditions in the solar atmosphere, little progress can be made in theoretical in-

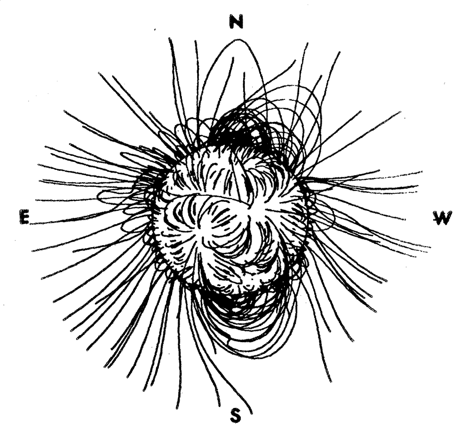


Fig. 4. Magnetic fields in the solar corona calculated from photospheric fields measured over the whole surface of the sun. These fields are calculated with the assumption that there is a potential (current-free) field throughout the corona. The field lines originate where the field (over areas of 10° by 10°) is 0.08 gauss or more. This figure is from the High Altitude Observatory and the Hale Observatories, and is one page from an atlas of magnetic fields in the solar corona (*24*).

terpretations of the transient phenomena that make up solar activity. Much effort has gone into working out models of the temperature and density distributions in the solar atmosphere from the low photosphere to the outer corona, and of the heating and support of the quiet chromosphere and the corona. Rocket and satellite results from the x-ray and ultraviolet end of the spectrum have aided greatly in such studies because radiation from these wavelengths originates in the chromosphere and the corona.

In order to describe the solar atmosphere one has to solve the basic equation of radiative transfer. To do this properly in the case of spectral lines, it is necessary to know the important reactions between atoms and the radiation field and between atoms and other atoms in collisions (*42*). In practice, it is difficult to treat in detail atoms with more than two levels, and often many simplifying assumptions must be made. For parts of the solar atmosphere where continuous radiation originates, this continuous radiation (and its variations from center to limb) may be used to derive a model. This refers almost exclusively to the solar photosphere. An international conference in 1967 adopted a standard atmosphere based on observations of the continuum (*43*). The ephemeral nature of all such models is indicated by the fact that a newer model has already supplanted that one (*44*). The newer model includes recent observations in the ultraviolet which refer to the temperature minimum—the transition zone between the photosphere and the chromosphere.

These models refer to an atmosphere that is uniform in horizontal extent. The solar atmosphere is clearly not uniform in this way, but models are generally made uniform because this is by far the easiest way to handle the problem, and the expectation is that the uniform model will represent average conditions. The inhomogeneity of the "quiet" solar surface is a great obstacle in our path toward an understanding of the atmosphere.

The lower levels of the photosphere are convectively unstable, and the resulting convection gives rise to the granulation pattern seen in high-resolution white light photographs. The temperature decreases outward from about 6400°K at the top of the convection zone to a minimum of about 4200°K some 500 km higher up. The corresponding densities go from $3.2 \times 10^{-7}$ to $2.8 \times 10^{-9}$ gram per cubic centimeter. The density decreases very rapidly above this. In the next 2000 km or so the density drops to $10^{-13}$ g/cm$^3$.

The chromosphere is the transition zone between the photosphere, which is at about 5000°K, and the corona, at about $2 \times 10^6$ °K. Bright lines from the corona may be seen at eclipse, parts of the ultraviolet spectrum show chromospheric structure, and the stronger absorption lines in the visible part of the spectrum show us chromospheric structure as well (see Figs. 1 and 2).

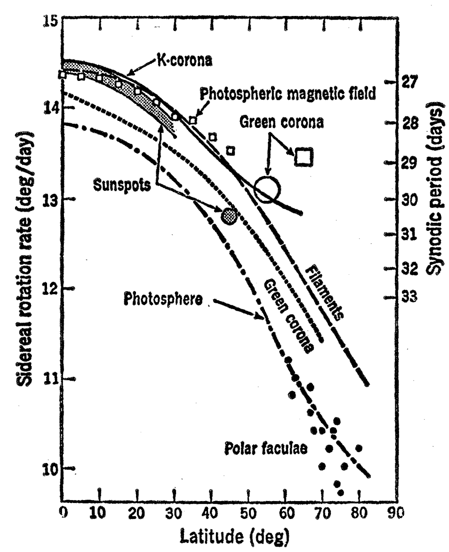


Fig. 5. Various solar rotation rates as a function of latitude. The polar faculae are small, bright emission regions seen near the poles of the sun in integrated sunlight. For details see (*32*).

This is a thin and elusive layer. The thickness of this region up to where the temperature reaches 10,000°K cannot exceed 2000 km (*45*). This is less than 3 arc seconds in projection at the distance of the sun. The region above 10,000°K is even more elusive. For example, the temperature rise from 100,000° to 200,000°K is believed to take place in about 20 km (*46*). The chromosphere is not a quiet uniform gas. There are violent motions, especially in the upper part of the chromosphere. Spicules shoot up into the corona at supersonic speeds. The many violent writhing motions seen in H$\alpha$ chromospheric movies represent great upheavals in the chromosphere. Thus, it becomes very difficult to describe a "model" atmosphere in this region. It appears from observations of forbidden lines and continua at eclipse that the corona, at $2 \times 10^6$ °K, extends in some places to within a few thousand kilometers of the photosphere. Recent ultraviolet data confirm this (*47*). The chromosphere is dynamically somewhat like a thin oil film on a turbulent splashing water surface.

The temperature of the corona well above the chromosphere is about $2 \times 10^6$ °K, as stated above. This value is derived from intensity ratios of ultraviolet emission lines obtained from the Orbiting Solar Observatory (*48*). A similar temperature may be derived from Doppler broadening of emission lines. This temperature is fairly uniform in quiet regions, and small-scale variations evident in the coronal structure are due primarily to density fluctuations. A normal density for the coronal gas 2 arc minutes above the limb is $10^8$ cm$^{-3}$. Above active regions in the low corona the density may be increased by a factor of 5, and the temperature may be higher by $1 \times 10^6$ or $2 \times 10^6$ °K.

Spacecraft observations of the coronal plasma near the earth also give direct evidence for the high coronal temperature. To some extent the high coronal temperature affects the ionization state of the solar wind. Oxygen in highly ionized states, O VI and O VII, is observed near the earth where the electron temperature is actually much too low to produce such states (*49*).

One of the great unsolved problems of solar physics is the nature of the mechanism (or mechanisms) for heating the solar chromosphere and corona. It was pointed out many years ago that thermal conduction must be very efficient in the corona, so it is necessary only to explain the heating of the chromosphere and lower corona (*50*). In the lower photosphere there is a great deal of material in motion with speeds of 1 or 2 km/sec. In the chromosphere (where the density is lower by a factor of $10^6$) even more violent motions are observed. Although the exact mechanisms are not known, it is believed that mechanical energy is transmitted upward, perhaps as shock waves (*51*). This energy is dissipated principally in the corona.

In recent years it has been possible to obtain soft x-ray photographs of the sun from grazing-incidence telescopes carried by rockets. Figure 6 shows an example (*52*) for 7 March 1970 in the wavelength range from 3 to 60 Å. The looped structures delineate magnetic lines of force low in the corona. At times tubes of lines of force appear to connect different active regions, even sometimes across the equator.

Because of the very high thermal conductivity of the coronal plasma the radial temperature gradient is quite small; the temperature varies as the $-2/7$ power of the distance from the sun. Since the acceleration of gravity varies as the inverse square of the distance, the corona cannot be in hydrostatic equilibrium—the gas pressure at infinity is greater than zero. The result is a constantly expanding corona (*53*). This solar wind has at the earth an average velocity of about 500 km/sec and a particle density between 1 and 10 $cm^{-3}$. The velocity is highly variable and correlates well with geomagnetic activity.

We see that the solar atmosphere is an extremely interesting physical laboratory. Complex physical interactions take place that we cannot hope to simulate in experiments on earth. Observations have improved greatly in quality and scope, and they remain well ahead of theories to explain them. Our star is a fascinating and complex object.

## The Sun as a Star

As stars go, our sun is a rather prosaic dwarf of spectral type G. Stars of this class have effective temperatures around 6000°K. On the stellar color-magnitude diagram the sun lies near the main sequence, which is the first stopping place for stars in their evolutionary development. The sun is quiet and well-behaved compared to some of its more gigantic or bombastic relatives.

If the sun were observed as a distant star, its rotation rate (about 1.9 km/sec at the equator) could be detected only at the very highest stellar spectroscopic dispersions, and the 5 percent variations observed in this rate would pass entirely undetected. Many stars show very rapid rotations, some as high as 450 km/sec (*54*).

The magnetic fields seen in integrated sunlight (*55*) are about two orders of magnitude weaker than the smallest fields that can be detected in stellar measurements. Solar magnetic fields integrated over the disk rarely exceed 1 gauss, whereas the largest fields measured in integrated light from stars are around 35 kgauss. It is not known whether the magnetic stars show an exaggerated form of solar activity or whether some entirely different mechanisms are responsible for their magnetic variability.

Studies of the magnetic field in integrated sunlight indicate that the magnetic field of the sun observed as a star correlates well with the interplanetary field observed at the earth (*56*). There is evidence that at times the magnetic field integrated over a smaller central area of the sun correlates better with the interplanetary field than does the field integrated over the whole solar disk (*57*). Such correlations may indicate that the solar field is not projected directly to interplanetary space, but rather that a "source surface" exists high above the solar photosphere from which the interplanetary fields are mapped (*58*).

Evidence is beginning to accumulate to support the hypothesis that some classes of stars have activity cycles similar to that of the sun (*59*). These are detected by observing variations in Ca K line emission. Such variations are only marginally observable in integrated solar spectra at stellar dispersions.

The sun has probably slowed in rotation considerably since it was formed, and its chromosphere and corona have become more quiet. Astronomers believe that the loss of angular momentum to the solar wind has been sufficient to decrease the solar rotation rate significantly in the sun's lifetime (*60*). Younger solar-type stars have higher rotation rates and more active chromospheres than do older solar-type stars (*61*).

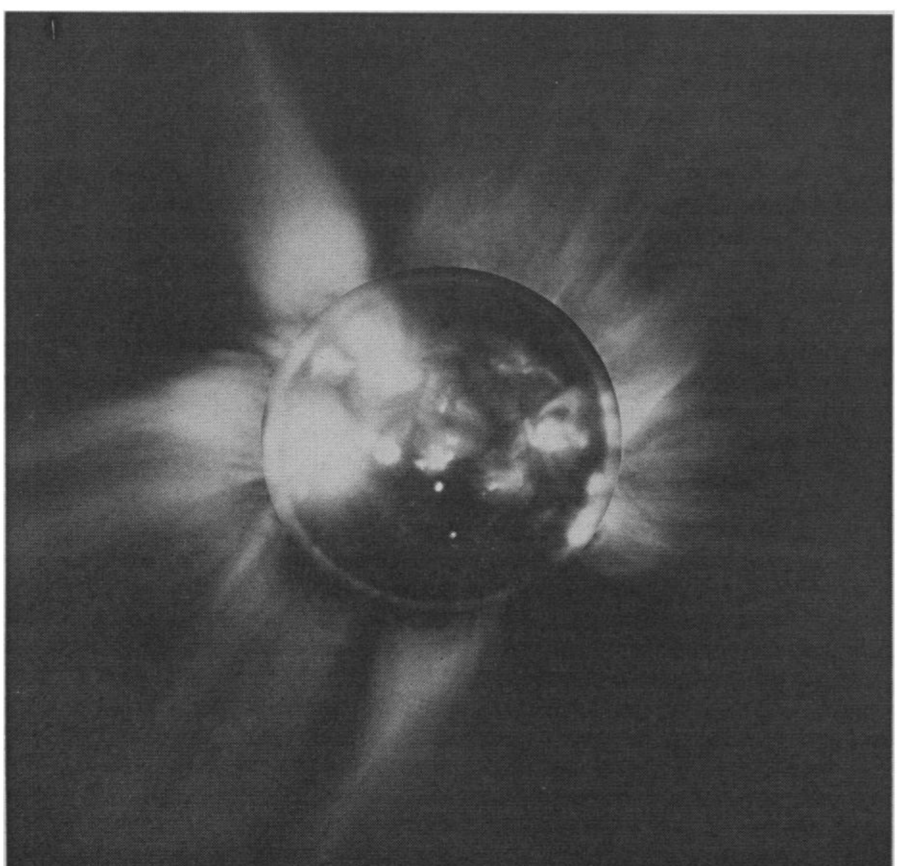

Fig. 6. A print of the solar corona on 7 March 1970, composed of an x-ray exposure in the wave bands from 3 to 36 Å and 44 to 64 Å and an eclipse photograph taken with a radial density gradient filter by G. Newkirk. [Courtesy of the Solar Physics Group, American Science and Engineering, Cambridge, Massachusetts, and the High Altitude Observatory, Boulder, Colorado]

The sun is an important data point for studies of stars and stellar evolution. We can at times extrapolate solar phenomena to explain effects on other stars, but the sun stands as a reminder that many phenomena may pass unnoticed in stellar studies because we cannot see the disks of stars. Much progress is being made in our understanding of the sun, which is a vital link in learning about the universe.

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