INTRODUCTORY REVIEW OF SOLAR ACTIVITY

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Abstract

An abbreviated review is given of the properties of the sun that must be considered in context with solar activity. The terrestrial and space responses associated with solar activity are due entirely to spectacular changes of several orders of magnitude in relatively minor components of the solar energy output. The solar atmosphere can be divided into three principal regions in ascending order from the visible solar surface: photosphere, chromosphere, and corona. These regions are described in their quiet state as the environment for all forms of solar activity. It is emphasized that solar activity is the result of magnetic field activity concentrated in localized centers that display sunspots in the photosphere, bright plage in the chromosphere, and hot condensations in the corona. Properties of solar flares are summarized in terms of physical parameters derived from both optical and nonoptical observations.

The Sun as a Star

The sun is a common run-of-the-mill star, a globe of gas 1.4x10⁸ km in diameter. It is powered by nuclear reactions in the core which convert 4.4x10⁶ metric tons of mass/sec to 4x10³³ erg/sec. This energy leaks out from the core by radiative transfer into a convective layer that carries it to the surface, where it escapes primarily as optical and infrared radiation. The radiative flux is about 6x10¹⁰ erg-cm⁻²-sec⁻¹ at the surface. This primary energy flow is practically unaffected by solar activity, quantitatively. However, in addition to the optical and infrared flux, there is a small steady flow

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of about $10^6$ erg-cm$^{-2}$-sec$^{-1}$ composed of extreme ultraviolet and x-radiation, radio radiation, and particles, mainly those of the solar wind. The terrestrial and space responses associated with solar activity are due entirely to spectacular changes of several orders of magnitude in these relatively minor components of the solar energy output.

**Solar Atmosphere**

The observable region of the sun is the transparent solar atmosphere that rests on a white surface where the combination of temperatures and density favors the formation of negative hydrogen ions. They form an opaque fog through which we cannot see. The temperature here is about 6400$^\circ$K, and the surface radiates the continuous background of the solar spectrum. Above this observational floor is the photosphere, about 350 km thick, where the atoms absorb their characteristic wavelengths and produce most of the thousands of dark absorption lines of the solar spectrum. The photosphere merges into the overlying chromosphere, some 2000 km thick, with no physical discontinuities. As we proceed upward through the photosphere and lower chromosphere, the temperature decreases. At about 350 km above the white surface, it reaches a minimum value of about 4300$^\circ$K and from there rises with a steadily increasing gradient to much higher temperatures, the exact value of which depends upon where one wants to draw the line. The chromosphere terminates abruptly in the extraordinary chromosphere-corona transition layer, which is a good facsimile of a temperature and density discontinuity. The exact temperature profile of the transition layer is still unknown, but it is clear that temperature rises from 50,000$^\circ$K in something like 100 km. Above this level, the curve probably flattens out, and the temperature reaches the relatively isothermal coronal level of about $1.5 \times 10^6$ in a few thousand kilometers. The corona reaches out from the transition layer with a slowly declining temperature and density until it merges with the interstellar background far beyond the earth's orbit (Billings, 1966). It is in a state of steady expansion. The outward streaming coronal material constitutes the solar wind that passes the earth at some 400 km/sec with a temperature of about $3.5 \times 10^5$K. It drains material away from the sun at a rate of about $10^{13}$ hydrogen atoms or $10^{-13}$ g/cm$^2$ of the solar surface each second.

**Quiet Sun**

The so-called quiet sun is in a steady state of quiet mass motions that dwarf the most violent terrestrial hurricanes. It is a steady state in the sense that its statistical description
is the same at different places and times. When we look at the white surface, we find that it has a marked granular structure shown in Fig. 1. The bright granules, about 1000 km in diameter, are the tops of hot convective columns resembling cumulus clouds of negative hydrogen ions. There are larger convective cells, known as supergranulation, about 30,000 km in diameter which are not evident in photographs of the white surface. They were discovered by the outward motion of the material from the centers of the supergranule cells and have since been found to be outlined by the well-known coarse network of the chromosphere. These two scales of convection which reach the surface in cells of 1000 and 30,000-km diameter, with nothing in between, are one of the puzzles of modern solar physics. The

Fig. 1 Granulation of the solar surface photographed in white light with the Sacramento Peak Tower telescope at 30-in aperture. The width of the figure equals 35,000 km on the sun.
whole process is a basic one, since it is the means by which the vast bulk of solar energy reaches the surface.

The quiet photosphere is also the scene of vigorous activity. Figure 2 shows some lines of the solar spectrum which originate in the photosphere. They were taken with a sharply defined image of the sun projected on the slit of a stigmatic spectrograph. Thus, each point along the line corresponds to a point on the sun. Note that the wiggles in the different lines are practically identical. They are, in fact, Doppler displacements due to vertical mass motions in the photosphere. If we watch any one point for a while, we find that it oscillates vertically in a 5-min period with a velocity amplitude that varies from about 0.3 at low levels to more than 1.0 km/sec in the lower chromosphere.

The chromosphere is a very inhomogeneous layer characterized by the mottled background of Fig. 3 and shot through by spicules (Fig. 4) that rise through the transition layer and probably feed material into the corona to replace the losses in the solar wind.

![Image](https://example.com/image.jpg)

**Fig. 2** Three of the absorption lines of the solar spectrum showing Doppler shifts in wavelength due to local vertical velocities in the photosphere. Photographed with coelostat and 12-in horizontal telescope.
Fig. 3 Quiet and active sun in Hα light. The bright patches are plages in the active centers. Note their arrangement in two latitude belts, the sunspot zones. The dark features are prominences in projection against the disk. Photographs from 4-in flare patrol telescopes.

Fig. 4 Spicules photographed in the Hα line of hydrogen at the solar limb. The width of the figure equals 93,000 km on the sun. Photographed with the Sacramento Peak Tower Telescope at 20-in aperture.
The corona, which has a very high temperature and low density (about 5x10^-17 g·cm^-3), is also very inhomogeneous. The inhomogeneities are on a very much larger scale than those of the chromosphere. They are so pronounced that any "average" characteristics of the corona are nearly meaningless.

This, very briefly, is the character of the quiet solar atmosphere, the environment of all forms of solar activity, which is the real subject of this introduction. The other papers in this volume will describe specific active features in far more detail. However, it is hoped that this paper will provide an integrating framework that will relate the various features and fit them into the whole picture. More detailed descriptions of the solar atmosphere can be found in texts by Zirin (1966) and Tandberg-Hanssen (1967).

Solar Magnetic Fields

Before considering the different kinds of solar activity, it is important to realize the basic role played by magnetic fields. The whole solar atmosphere is a plasma of very high electrical conductivity permeated by magnetic fields. Naturally the two interact. Because of the high conductivity of the plasma, the field is "frozen into" the gas. This means that the only permitted relative motion between the gas and the field is along the field lines. If there is any transverse motion, the gas and the field lines must move together. The gas and field are related like a cluster of beads on elastic threads. The beads can move freely along the threads, but in any other direction, beads and threads must move together.

Both the gas and the magnetic field have internal energy that manifests itself as gas pressure, proportional to the product of temperature and the number of atoms per cubic centimeter, and magnetic pressure, proportional to the square of the field strength. In and below the photosphere, where field strengths are in the 10-gauss class, the magnetic pressure is very much less than the gas pressure, and the magnetic field exerts practically no restraint on the gas motion. The turbulent convective motions must twist the fields into complicated tangles, and, since the field lines in the higher layers are continuous with those below, they must be profoundly influenced. In the active centers, however, the field strengths rise to thousands of gauss, and the situation is reversed. The gas is confined by a very rigid magnetic structure and can move with only one degree of freedom along the field lines. When some external influence causes the field configuration to change, the material must change with it. In a general way,
it probably is fair to say that solar activity is interaction of solar material with fields in those regions where the magnetic pressure dominates the gas pressure, and the vigor of the phenomena increases as the ratio of the two increases. The point is that, in studying solar activity, we are, in fact, seeing the results of magnetic activity. Therefore, there will be a great deal about solar magnetic fields in subsequent papers in this volume. However, the processes by which magnetic activity produces the various active features are still far from being well understood.

Solar Activity

Most of the phenomena that we call solar activity originate in the active centers that are shown conspicuously in Fig. 3, and on a larger scale in Fig. 5. These are regions of the

![Image](image.png)

**Fig. 5** Typical active center in Hα light, showing a sunspot group, fragmented plages, and the complex pattern of dark fibrils and filaments ordered by the strong magnetic field of the center. Photograph from Sacramento Peak Tower Telescope at 20-in aperture.
solar atmosphere where the magnetic fields are strong and mag-
netic pressure exceeds gas pressure. They are most numerous in
the sunspot zones between 10° and 30° lat. in both hemispheres.
The active centers display a variety of phenomena, some of
which change slowly during the life of a center (which may be
anything from a few hours to several months) and others that
vary rapidly.

The principal slowly changing phenomena are the sunspots,
plages, and an overlying coronal condensation. Figure 6 is a
large-scale white-light photograph of a typical simple spot,
with a characteristic dark umbra surrounded by the sharply de-
 fined and radially structured penumbra. The surrounding granu-
lation of the quiet sun sometimes appears smaller immediately
adjacent to the spots. Figure 7 is a photograph of a very com-
plex sunspot group in a highly active center, the kind most
likely to produce fast activity. The sunspots invariably clus-
ter in the areas of greatest field strength, simply because
they are the inevitable results of very strong fields (Bray and
Loughhead, 1965). The field cuts the circulation path of nor-
mal subphotospheric convection and suppresses it. Hence, no
convective energy is brought to the surface, and the area cools
off by radiation, becoming relatively dark. Around the sun-
spots in regions of intermediate field strength, where convec-
tion continues but material is confined, we find the bright
chromospheric plages, shown in Fig. 3. On a larger scale, they
show the complex structure of the bright areas in Fig. 5. Just
why they are bright, and how they deviate from the normal

Fig. 6 A typical simple sun-
spot in the granula-
tion field of the
quiet photosphere
photographed in white
light with a 6-in
patrol telescope.
Note the complicated
radial structure of
the gray penumbra,
surrounding the dark
umbra. The entire
spot subtends an
angle of 46 arc secs,
equivalent to
33,000 km on the sun.
Fig. 7 A very complex sunspot group characteristic of a vigorous active center. The spots at left have typical radially filamented penumbrae, but those in the center have been distorted by the complicated magnetic field. Tower telescope at 20-in aperture.

Chromosphere in temperature and density, we are not really sure. But there can be no doubt that the plages are regions of enhanced field strength of 200–500 gauss.

Over the typical active center is a dome of extra dense coronal material. Its relation to the active center magnetic field is not yet clear, but the arch systems that are often visible probably lie along the field lines. If so, they
delineate the field pattern in coronal space very usefully, since direct measurements of this field are presently very difficult.

The prominences are clouds of glowing gas suspended in the magnetic fields high above the chromosphere in coronal space. The quiescent prominences include the largest ones, and appear against the disk in absorption as long rosy dark filaments like those visible in Fig. 3. Figure 8 shows a typically structured small one at the limb, bright against the dark sky background. This type appears to originate in the active centers, and drift away from them during their lifetimes, which may be as long as several months. The most active of the prominences, however, live only a few hours and are directly related to the active centers. The two most important types, surges and loops, appear in Figs. 9 and 10.

Solar Flares

Most of the rapidly changing phenomena of active centers are associated with the flares, which are easily the most spectacular of all the varieties of solar activity. The existence of

Fig. 8 A quiescent prominence, part of a long filament that disappears over the limb at the left. Note the vertical filamentary structure in the middle portion, terminating in a sharp bright arc at the bottom. This is a very common configuration. Photographed with the Sacramento Peak Tower Telescope at 30-in aperture.
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Fig. 9 A flare-associated surge prominence in Hα light photographed with the Sacramento Peak Tower Telescope at 30-in aperture during mediocre seeing. The flare, in its declining phase, is visible at the base of the surge. Normally the material moves out at 100-200 km/sec, and returns to the sun along the same path, presumably an active center magnetic flux tube.

the flares was first discovered by optical observations in the light of the Hα line of hydrogen, long before we were looking at the sun in radio wavelengths or in the XUV spectrum. Hence, it has become habitual to define a flare in terms of optical appearance, although it is now clear that this misses very significant parts of the total phenomenon.

The optical flare normally appears as a sudden brightening of the Hα line (and a number of other lines) in an irregular patch within an active center. Its brightness increases rapidly as the area expands until it reaches its peak in a few minutes. Then, it fades more slowly until it finally disappears and leaves the active center in very nearly its original configuration. Flares vary in size from the smallest detectable areas to things exceeding 100,000 km in their longest dimensions. Generally, the larger a flare is, the longer it lasts, with durations from 3 or 4 min up to 2 or 3 hr. The rapidity of
Fig. 10  A system of loop prominences in Hα light, some of which are seen edge-on. The material rains down from the top on both sides of a loop in fine filaments. The nucleus at the top is always a region of very high excitation, often surrounded by abnormally hot coronal material. Photographed with 16-in coronograph during poor seeing.

the brightening phase varies a great deal. Some of the large flares have an "explosive phase" during which they reach peak brightness in a minute or two, and spend most of their lives in a relatively slow decline. These are the ones that are most likely to emit the radiations that produce geophysical responses. Figure 11 shows the early stages of development of an explosive flare. The two-ribbon structure, as well as the total rise time of about 20 min with a short explosive phase, is characteristic of normal flare behavior.

This kind of optically visible activity usually takes place in the chromosphere, below the transition layer. Observations of the sun from the ground in radio frequencies (Kundu, 1965) and from above the atmosphere in the XUV spectrum, have enlarged our picture of flares enormously. Both of these radiations originate at levels in the solar atmosphere above the optically observed region, and both are emitted by processes that are optically invisible. Photographs of flares in x-rays show structural features that are different but clearly related to those seen in the Hα line. One of these appears in the center of the sun in Fig. 12. Since the x-rays originate at higher levels and at much higher temperatures than the visible radiations, we infer that the flare has a large vertical structure extending into the lower corona. Generally, large parts of the flare are considerably hotter than the normal corona, and these
Fig. 11 Development of a typical large flare on August 28, 1966. Note the characteristic two-ribbon pattern. In later stages, a system of loop prominences spanning the gap between the ribbons often forms a tunnel-shaped configuration. Mt. Wilson Observatory photograph.

are the regions that emit the x-rays and particles that provoke terrestrial responses. In addition to thermal components with temperatures measured in the tens of millions of degrees, we find superthermal x-ray pulses indicating momentary temperatures as high as a billion degrees. Particles detected by the
Fig. 12 A large flare near the center of the solar disk photographed in x-rays by a rocketborne x-ray camera. Reproduced by courtesy of American Science and Engineering, Inc.

radio observations are accelerated over an enormous range of energies from a few hundred Kev to an occasional Gev, and shock waves spread out through the corona with velocities in excess of 1000 km/sec.

In addition to all of these energetic phenomena, flares are often accompanied or followed by the appearance of optically visible surges and loop prominences, shown in Figs. 9 and 10. some of them require energy comparable with that of the flare itself. The loops, in particular, differ radically from the garden variety of prominences in their highly ordered
configurations. They apparently follow magnetic flux tubes
over the active centers and are useful indices to the shapes
of the magnetic fields.

We assume that the energy released in a flare is drawn from
the magnetic field of the active center. A really large flare
will release something like $10^{32}$ erg during its life of a
couple of hours. The magnetic field of a vigorous active cen-
ter contains perhaps 10 times this energy and is the only ade-
quate source of energy known. But we do not know how this mag-
netic energy is converted to the heat and particle accelera-
tions that we observe, or the kinetic and potential energy of
the surges and loop prominences. These are certainly among the
most interesting and urgent problems in the whole field of
solar physics today.

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