LARGE-SCALE SOLAR MAGNETIC FIELDS

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INTRODUCTION

George Ellery Hale detected strong magnetic fields in sunspots in 1908. For some years following that, Hale and his colleagues at Mount Wilson tried to measure what they thought should be a general dipole magnetic field of the Sun. Various numbers were quoted over the years (Hale 1913, Hale et al. 1918), but no firm results ever came from those attempts. Later analysis of the original plates indicates that no dipole field was measurable from them (Stenflo 1970).

In 1952, H. W. Babcock (1953) devised the principle of the modern solar magnetograph. This instrument, by means of a subtraction technique, avoided the major instrumental polarization problems that had plagued earlier instruments and for the first time made possible the accurate measurement of weak longitudinal magnetic fields on the solar surface. Almost all of the magnetic measurements of the photosphere in the last 25 years have been made with instruments using the principle devised by Babcock.

In an early paper, H. W. and H. D. Babcock (1955) demonstrated the existence of more than just a polar field. They found bipolar magnetic configurations associated with active regions and large, weak unipolar magnetic regions in some quiet areas of the Sun. Later work in the 1950s (Leighton 1959, Howard 1959) established that magnetic fields occupied precisely the locations of emission regions in Ca II spectroheliograms, even down to the smallest details (cf Figure 1), and that the dark Hz filaments (prominences seen against the disk) invariably lay between magnetic areas of opposite polarity. These associations confirmed the great importance of magnetic fields to solar activity and laid the basis for later studies of the appearance of active-region magnetic fields and their subsequent decay into large-scale coherent magnetic-field patterns. These expanding field patterns, in conjunction with the supergranulation (Leighton et al. 1962), proved to be important in the establishment and maintenance of the calcium (magnetic) network. This weak network pattern is now generally considered to be maintained by the action of the supergranulation motions. The nature of the large-scale distribution of magnetic
Figure 1 Magnetograms (top) and Ca II K-line spectroheliograms (bottom) for the central area of the solar disk for the dates indicated. All observations are from Mount Wilson. Note the background network pattern and the breakup of the plage and magnetic fields as the region ages.
fields on the solar surface is a result, at least to some extent, of the actions of the supergranular motions and the differential rotation (Schatten et al. 1972).

LARGE-SCALE MAGNETIC SURFACE FEATURES

The Decay of Active Regions

It has long been known that solar active regions, as seen in chromospheric lines, do not form and decay in the same manner. Their formation is generally rapid, and at the end of the growth phase the region is relatively bright, with sharp and well-defined boundaries. The decay of an active region is a slow process of spreading out, weakening, and fragmentation (Butler 1924). The supergranulation motions appear to play an important role in the process of decay.

Figure 1 shows an example of the decay and final dissolution of an active region seen in magnetograms and the Ca II K line. The eroding effects of the supergranular motions are evident. The final death of the region may be defined as occurring when the last emission patches blend with and become indistinguishable from the background chromospheric network (Bumba et al. 1968).

It should be noted that sunspots normally exist only in the earliest stages in the lifetime of an active region. The active region may live on for many weeks or even months after the last sunspot is gone. In the interval following the death of the sunspots, the active region can still be a spectacular phenomenon in the chromosphere. At times solar flares result from such spotless regions (Dodson & Hedeman 1970).

I have noted that active regions do not all decay at the same rate. Some regions decay quite rapidly, and some regions appear to last for much more than the normal lifetime. One factor in determining the lifetime is certainly the size of the region, but the nature of the surrounding fields and the nature of the magnetic connection to subsurface layers could be additional factors. This is an area where more research is needed.

Ephemeral regions (Harvey & Martin 1973, Harvey et al. 1975) are tiny, short-lived active regions without sunspots. They show as bright dots on X-ray pictures (Vaiana et al. 1973). Their latitude distribution is somewhat broader than that of ordinary active regions. They appear to follow, at least roughly, the Hale polarity law seen in active regions, but they have a broader distribution of orientation than do the active regions. Although they may be responsible for bringing to the solar surface a non-negligible fraction of the solar flux that arises from below, it seems unlikely, because of their small sizes and short lifetimes, that they contribute significantly to the large-scale magnetic patterns (Howard 1974c).

The Background Field Pattern

The total effect of the contribution of the decaying magnetic fields from all the active regions on the Sun is the formation of a large-scale pattern of alternating polarities that is remarkably long-lived (Bumba & Howard 1965, 1969). The individual areas of one polarity—but not the same field elements—may last for a year or more. As new regions are born and decay, they often provide additional magnetic
flux to reinforce the existing weak fields. Smaller weak-field areas (a few tens of degrees in longitude) generally have the same polarity on either side of the equator, and may persist for nearly a year. Somewhat larger features, containing predominantly fields of one polarity, may live for up to three years. Figure 2 shows a Mount Wilson magnetic synoptic chart for the period near the most recent activity maximum (1970) and one during 1967, taken at the time of the rise to maximum.

At times scattered fields of the following polarity may combine over a longitude range of 100° or more at a latitude generally greater than that of the normal background field pattern. Such a feature is referred to as a Unipolar Magnetic Region (UMR). None are visible in Figure 2 because they occur preferentially during the decline from activity maximum. A UMR may be seen in Figure 1 of the paper by Bumba & Howard (1965). More recent UMRs, and the largest ones in recent years, may be seen in the southern hemisphere in Carrington rotations 1599 to 1606 (negative polarity), and in the northern hemisphere in rotations 1615 to 1623 (positive polarity). (The Mount Wilson synoptic charts of magnetic fields are published regularly in the I.A.U. Quarterly Bulletin on Solar Activity.)

The Polar Fields

The earliest photoelectric magnetograph measurements (Babcock 1953) were made to measure the “general field” of the Sun, which in those days was assumed to be a N-S dipole field. These earliest measurements indeed showed the existence of magnetic fields in the polar regions that were generally of opposite polarity at the two poles. The resemblance to a true dipole ended there because of the pattern of large-scale fields found at intermediate and low latitudes.

At the next solar maximum (≈1957–58) the two polar fields changed polarity, first the south field and then a year or so later the north field (Babcock 1959).

A few years later the polar fields, which had been fairly strong during the 1950s, weakened considerably (Severny 1971, Howard 1965, 1972), so that the polarity reversal at the next solar maximum was difficult to detect. There is, in fact, some difference in the exact date of the reversal as observed at Kitt Peak and Mount Wilson, although both sets of observations agree that 1. the reversals followed the maximum of solar activity by a year or more, and 2. the reversals at the two poles took place at different times (Gillespie et al. 1973, Howard 1974a).

Sheeley (1976) has traced the history of the polar fields in this century by counting polar faculae on white-light photographs of the Sun taken at Mount Wilson. The polar faculae are known to occur at the concentrations of polar fields; thus the more polar faculae, the stronger is the polar field. Sheeley finds that the number of polar faculae go through a minimum near the maximum of each solar cycle. Figure 3 shows the facular counts for this century. One can see in Figure 3, in agreement with the magnetic results mentioned above, that the faculae decreased in number quite suddenly in the early 1960s. It is also clear from this figure that in general the polar fields reverse a year or two following solar maximum.

It should be emphasized that at least a large percentage and perhaps all of the polar field flux is contained in isolated small strong-field elements. This conclusion comes from direct observations (Howard 1959), from analogy with the low-latitude
Figure 2  Magnetic contour synoptic charts from Mount Wilson data for Carrington rotations 1517 (February 1967) and 1559 (March–April 1970). These are cylindrical equal-area projections. East is at the left and the horizontal lines represent the equator, ±20°, ±40°, and ±60°. The north pole is the line at the top, and the south pole is at the bottom. The date of each observation is given at the bottom of each chart, along with the location of the central meridian at the time of the observation. The vertical dashed lines represent the dividing line between separate days’ observations. No data from more than one day are averaged to make these plots. Solid lines represent positive magnetic fields (magnetic vector toward the observer) and dashed lines represent negative fields. The contours are ±5, 10, 20, 40, 80 G.
Figure 3 The numbers of north and south polar faculae, respectively, during the interval 1906–75. The numbers have been assigned polarities corresponding to the polarities of the associated polar magnetic fields. Also the numbers represent the magnetic flux normal to the entire surface of each polar cap in units of $0.3 \times 10^{21}$ Mx ($\pm 50\%$). For comparison, the sunspot number for the whole solar disk has been plotted with a magnetic polarity assigned that corresponds to that of the following spots in each hemisphere. (From N. R. Sheeley Jr. 1976. Journal of Geophysical Research 81: 3462, copyrighted by American Geophysical Union.)
situation (Howard & Stenflo 1972), and from the generally good agreement between Sheeley's facular counts and the measured polar fields.

The polar fields are not well measured with the solar magnetograph because of the poor angle at which the fields must be viewed. A recent analysis of the Mount Wilson data (Howard 1977a) indicates, however, that the measured magnetic fields near the poles represent fairly well the true average field strengths there. An absolute limit on the underestimation of the polar fields is about a factor of 5. Thus the true average magnetic field strength in the polar regions cannot exceed 5 or 10 G, and is most likely about 1 G. A field of 1 G spread over the polar region contains approximately the same magnetic flux as a large active region ($\approx 4 \times 10^{21}$ Mx).

Giant Regular Structures

A very large-scale ordering of the field distribution has been discussed by Bumba (1970). A giant cell-like pattern, with dimensions of the order of 400,000 km, changes its configuration slowly, but as seen in the fields of the two polarities separately, it maintains a definite cellular shape. Lifetimes of individual cells are several months (Ambrož et al. 1971).

This may represent a giant-scale analogy to the granulation and supergranulation patterns. Simon & Weiss (1968a, b) have suggested that this pattern represents a system of giant convection cells, with dimensions of the order of the depth of the convection zone in the Sun.

Bumba (1976a) has found a good correlation between the polarity of the main body of the giant structures and the interplanetary magnetic field. The ordering of the solar pattern is on about the same scale as the interplanetary sector pattern, and this also leads to a strong indication of a physical connection between the two.

Wagner & Gilliam (1976) have suggested that the large-scale convection cell pattern may be seen in the pattern of filament distribution. For a period in the summer of 1972 during which a simple pattern appeared, the longitudinal wave number they found was 5. The lifetimes of the cells they studied were 2–4 months. On the whole, although a number of indications point to a large-scale cellular pattern of magnetic fields, there is still no firm evidence of the convective nature of these patterns. No large-scale velocity fields have been conclusively associated with the magnetic patterns. However, the velocity amplitude of such motions would be quite small, and their detection will be a difficult task. A large-scale velocity pattern has been detected by Howard & Yoshimura (1976), but it has not yet been possible to demonstrate an association of this pattern with magnetic fields.

Expansion of the Field in Surface Harmonics

Altshuler et al. (1974) have carried out a surface harmonic expansion of the magnetic fields of the Sun, as measured at Mount Wilson, in terms of Legendre polynomials. The data covered the interval 1959–72. A microfilm tabulation of the harmonic coefficients through 1974 has been published recently (Altshuler et al. 1975). The most frequently occurring harmonic is that corresponding to a dipole lying in the plane of the equator. This was particularly true of the most active years of solar cycles no. 19 and 20. The north-south dipole harmonic was prominent only during
DOMINANT SURFACE HARMONIC FOR SOLAR MAGNETIC FIELD
Figure 4 The dominant surface harmonics for the photospheric magnetic field are indicated for the period 1959–72. A black box in the lower right-hand corner of each space indicates harmonics that appear most often among the top 5 in importance. The numbers in the spaces give the number of times the harmonics were dominant. (From Altschuler et al. 1974.)
quiet years. A 4-sector structure was evident at various times, and occasionally a 6-sector structure could be seen. In general the contribution to the field from harmonics between 5 and 9 (the maximum calculated) was very small.

From time to time rather rapid changes (within one rotation) in the contributions of the various harmonics were seen. This indicates that either the polar field is not very deep, or that strong fluid flows connect the photosphere with deeper layers.

Figure 4 shows schematically the dominant surface harmonics for photospheric magnetic fields for the interval 1959–72. The geometrical interpretation of these harmonics is as follows. The harmonic \( P_n^m(\theta) \cos m\phi \) [or \( P_n^m(\theta) \sin m\phi \)] is zero on 2 \( m \) different meridians equally spaced in longitude. If \( m \neq 0 \) there are 2 \( m \) sectors in longitude, \( m \) of positive polarity and \( m \) of negative polarity. The poles of the Sun, in this simplified representation, can have a uniform field only if \( m = 0 \). The quantity \( n - m \) is the number of times the surface harmonic goes through zero between (but not at) the poles. The quantity \( n \) gives the index of the multipole: \( n = 0 \) is a monopole, \( n = 1 \) is a dipole, \( n = 2 \) is a quadrupole, etc.

Naturally the true magnetic-field distribution is much more complicated than can be represented by surface harmonics unless one includes very high-order harmonics. A glance at any synoptic chart will demonstrate this. However, the expansion in Legendre polynomials is a convenient and simple means of describing some of the large-scale characteristics of the field distribution. Whether or not the characterization by this means of, for example, “dipole” or “octupole” components of the field distribution has any bearing on the large-scale subphotospheric structure of the fields is an open question.

The Average Inclination of Magnetic-Field Lines in the Photosphere

Solar magnetographs have so far produced little if any usable transverse Zeeman-effect observations of magnetic fields outside sunspots. In general transverse measurements with solar magnetographs are roughly two orders of magnitude less sensitive than longitudinal measurements, which explains the paucity of transverse field observations. A consequence of this is that from individual observations we get no information about the inclination of magnetic-field lines to the solar surface.

One can, of course, gain information about the average east-west orientation of field lines by comparing observations of the same magnetic fields measured east and west of the central meridian; I have done this in a recent paper (Howard 1974b). Figure 5 shows the variation of the quantity \( \beta \) as a function of time separately for fields of the two polarities in various latitude zones in the northern hemisphere. The quantity \( \beta \) is defined as \( \beta = (|F_E| - |F_W|)/(|F_E| + |F_W|) \), where \( F_E \) is the average magnetic flux measured east of the central meridian over one rotation, and \( F_W \) is the same quantity west of the central meridian. One degree of inclination in the east-west direction corresponds to \( \beta \approx 0.01 \). Positive \( \beta \) represents an inclination leading the rotation, i.e. from east to west with increasing height.

Figure 5 shows that in the northern hemisphere during these years the two polarities started out inclined toward each other (negative was the following polarity in the north at that time), and the inclinations gradually decreased until they were zero, or even slightly reversed by the end of the interval. Svalgaard & Wilcox (1974)
found that the deviations from the average spiral angle of the interplanetary magnetic fields measured near the earth showed a roughly similar behavior in the same interval. The magnetic fields in the southern hemisphere of the Sun were weaker in this interval, and did not show quite such smooth behavior as is seen in Figure 5.

Figure 5  Values of \( \beta \) for the various latitude zones for each polarity separately in the northern hemisphere. Each point connected by the thin lines represents a value derived for one Carrington rotation. The thick lines are 13-rotation running means of the data. The dots along the time axis represent rotations within which two observations were separated by more than 100° in longitude, and thus could be of poor quality. The dashed lines represent missing rotations. (From Howard 1974b.)
The total magnetic flux \( F^T = |F^+| + |F^-| \) for each of the latitude zones studied showed small negative values of \( \beta \), corresponding to an inclination of about 1°, trailing the rotation. A spot check of some areas in 1976 (solar minimum) shows inclinations, at low latitudes, leading the rotation (Howard 1977a).

Cross-correlation coefficients calculated for the magnetic flux of opposite polarities indicate that poleward of 40° latitude in either hemisphere the two polarities behave oppositely, i.e. an increase in the east-west inclination of positive fields is most likely to be accompanied by a decrease in inclination of negative fields. Below 40°, variations in inclination of fields of the two polarities are most likely to be parallel.

THE SOLAR ACTIVITY CYCLE AND THE LARGE-SCALE PATTERNS

The Appearance of the Background Fields Through the Cycle

In Figure 2 one may see magnetic synoptic charts from two phases of the solar activity cycle: the approach to maximum, and maximum. In Figure 6 synoptic charts from Kitt Peak are presented for three times in the cycle.

As one might expect, at the approach to maximum the magnetic fields are concentrated at intermediate latitudes. The level of activity at this time is not high. It is interesting to note the zone within about 10° of the equator, which appears to be free of fields for most of the length of the synoptic chart. This results because of the fact that early in the cycle the active regions occur preferentially at high latitudes. It is not clear why the fields appear to expand mostly in the poleward direction.

As the cycle progresses the stronger magnetic fields are found at lower latitudes, and they occupy more area as the frequency of active regions increases. Near maximum, even the weak maximum of the last cycle (no. 20), the background fields become strong and generally fill up fully a large portion of the solar surface with fields in excess of 5 G. The post-maximum phase is characterized by the appearance of active regions at very low latitudes, a diminution of the level of activity, and the appearance of very large-scale magnetic structures. The synoptic charts close to minimum show very large-scale, weak, and diffuse patterns (Bumba & Howard 1965).

Bumba (1976b), using recent data, has shown that the large-scale patterns are quite similar for the years following maximum in cycles no. 19 and 20. In particular the role of the two polarities is very much the same.

The Variation of the Fields Through the Cycle

Stenflo (1972) and Yoshimura (1976) have examined digitized Mount Wilson magnetograph data over intervals of a cycle or more. Stenflo plotted a series of four-rotation average synoptic charts that showed in a simple form the features described above.

Yoshimura (1976) averaged a large amount of the same data. He divided the data into poloidal and toroidal components. Only the longitudinal fields were observed, but he averaged the fields in longitude to form the poloidal component,
and he subtracted this field at each longitude from the measured field, and called the absolute value of this quantity the toroidal field.

The poloidal field evolution is quite interesting. As the cycle begins, two branches of the poloidal field appear in the mid-latitudes in each hemisphere; one propagates toward the equator and the other toward the poles. This behavior was predicted by Yoshimura’s (1975) theoretical model of the solar cycle which is driven by the dynamo action of global-scale convection. The toroidal component of the field

*Figure 6*  Kitt Peak magnetic synoptic charts for 3 Carrington rotations, 1558 (February–March 1970), 1589 (June 1972), and 1610 (January 1974). In the first two charts, black represents positive magnetic fields and white represents negative magnetic fields. In the third chart the sense is reversed. These represent a time near solar activity maximum (1558), the decline from maximum (1589), and the approach to minimum (1610). (Courtesy of Dr. J. W. Harvey.)
behaved somewhat like the butterfly diagram. Figure 7 shows the variation during the cycle of both the toroidal and poloidal components.

Variations in Magnetic Flux

An inspection of the magnetic flux values separately for each polarity (Howard 1974c) over the interval 1967–73 shows that an increase in the low-latitude flux around activity maximum roughly parallels the sunspot curve. The polar field polarity reversal in each hemisphere is seen to be the result of a wave of magnetic

![Graph showing magnetic field variation](image)

**Figure 7** Evolutionary pattern of poloidal (left) and toroidal (right) magnetic fields on the solar surface. The ordinate is latitude, and the abscissa for each plot represents solar rotations 1432–1620 (1960 through 1974). The toroidal field behaves in much the same manner as the butterfly diagram, i.e. the latitudes of activity decrease as time progresses within the cycle. The contour interval is 0.1 G for these averaged data, and the maximum values are 6.9 G for the toroidal fields and 1.5 G for the poloidal fields. (From Yoshimura 1976).
flux of the appropriate polarity, which requires about one year to move from 40° latitude to the pole. Figure 8 shows the flux situation in the northern hemisphere in this interval.

Among the conclusions in this study was the fact that about 95% of the total magnetic flux of the Sun ($F^T$) is confined to latitudes below 40° in both hemispheres. The flux above 60° represents less than 2% of the total flux. The poleward flux

![Diagram showing magnetic flux](image)

**Figure 8** Positive polarity magnetic flux (solid lines) and negative polarity magnetic flux (dashed lines) in various latitude zones as a function of time in the northern hemisphere of the Sun. Each point represents the daily average over one Carrington rotation. The lowest solid curve is the Zurich full-disk Wolf (sunspot) number, and the lowest dashed curve represents the number of spot groups per quarter in the northern hemisphere. The vertical dashed lines represent three poleward magnetic flux migrations (positive, negative, positive). (From Howard 1974c.)
migrations, which were responsible for the polar field reversals, were accompanied by a poleward migration of filaments (Waldmeier 1973), which are known to separate large-scale magnetic fields of opposite polarities. The filament migration for cycle no. 10 was somewhat anomalous.

Recent work indicates (Howard 1977b) that the total flux at latitudes above 40° has, in the interval 1973–75, increased by a factor of about 2.5; no such increase has appeared in the low-latitude flux. This may be associated with changes in the latitude gradient of differential rotation at high latitudes during the approach to activity minimum (Howard 1976).

The Overall Pattern and its Variations

Svalgaard et al. (1974) have discussed a phenomenological model of the interplay between the very large-scale sector pattern of solar magnetism and the polar field. Referring to their Figure 1, the global-scale north-south neutral line takes on roughly an “S” shape, stretching from the northern to the southern hemisphere. This neutral line is overlaid in the corona by a current sheet that is tilted with respect to the central meridian. The current sheet is visible as a helmet streamer. The locations of helmet streamers in recent years agree with the predictions of this model. Also, the field distribution on the Sun shows such a shape (Svalgaard et al. 1977). The model presents a very much simplified arrangement of large-scale fields, but it predicts well the large-scale characteristics of the coronal and interplanetary magnetic field and the locations of large, long-lived coronal streamers.

Hansen & Hansen (1975, 1977) have used the differential rotation of large-scale surface magnetic features to explain evolutionary and sudden changes in the major structural components of the corona. Magnetic mergers and the large-scale reconnection of magnetic field lines are presumed to occur. No striking changes in the surface field patterns are required to produce these variations in the coronal structure.

There is no doubt that both these models are important in determining the broad characteristics of the corona and interplanetary magnetic fields.

The Magnetic Field of the Sun as a Star

A good correlation has been established (Severny et al. 1970) between the polarities of the magnetic field measured in integrated sunlight and the interplanetary magnetic field displaced by 4½ days to account for the spiral pattern of the interplanetary fields. A recent study (Scherrer et al. 1977) compares the Crimean and Mount Wilson mean field observations over a period of 5 years or so. Because of the weak fields involved and the difficulty of obtaining good integrated sunlight in a large solar telescope, a perfect agreement can scarcely be expected. The cross-correlation coefficient between the two observations is 0.4 and peaks at a 12-hour lag, which represents the longitude difference between the two observatories.

The good agreement between the rather regular sector structure of the interplanetary magnetic fields and the large-scale solar fields is a bit puzzling. The solar sector pattern (Wilcox & Howard 1968, Wilcox & Svalgaard 1974) may represent
a different and separate magnetic structure from that which results from the decay of active regions (Wilcox 1971, Svalgaard et al. 1977).

The Long View

Eddy (1976) has recently provided convincing evidence that the solar cycle has not continued without interruption since the first telescopic observations of sunspots. In the last half of the seventeenth century and early in the eighteenth century (the Maunder Minimum) there was no evidence of a cycle because the level of solar activity was practically zero.

It is not at all clear what the large-scale magnetic fields of the Sun looked like during this interval, although we could surmise that they resembled the last minimum but were two or three orders of magnitude weaker. Nevertheless, a successful theory of the solar activity cycle must be able to explain how it is possible for a gap of many cycles to occur, and then for there to be a long series of cycles such as we have seen since the end of the Maunder Minimum.

MAGNETIC FIELDS IN THE CORONA

It is not practical to measure magnetic fields in the corona; the spectrum lines are much too weak. One may infer magnetic-field structure from the shapes of coronal features seen at the limb or in X-rays and, alternatively, from extrapolations of the measured surface magnetic fields, using generally some approximation to the true coronal situation (Altschuler & Newkirk 1969, Schatten et al. 1969).

Expansion of the Surface Fields

The problem of calculating the magnetic-field configuration in the corona, given the surface field distribution, consists of finding a solution of Laplace’s equation which satisfies the boundary conditions. Schatten et al. (1969) have used a Green’s function to find a solution. Schatten (1968) was able to predict in a satisfactory way the appearance of the corona at the time of a solar eclipse, although such comparisons are inevitably somewhat subjective.

By far the most prolific coronal field calculators are Altschuler, Newkirk, and their collaborators. They solve Laplace’s equation with a Legendre polynomial expansion, which is equivalent to an expansion of the magnetic potential in spherical harmonics. Newkirk et al. (1973) have published a microfilm atlas of coronal magnetic fields from which Figure 9 is one illustration.

The spherical harmonic solution represents a potential field. It should be remembered that transient or rapidly growing or decaying coronal features will probably not be well represented by this technique.

An interesting recent result of the potential field calculations during the time of the Skylab X-ray experiment is that a coronal hole is the locus of open field lines (Levine et al. 1977). Also, coronal holes appear to be the origin of high-speed solar wind streams (Krieger et al. 1973) and geomagnetic activity (Sheeley et al. 1976). A coronal hole may be seen in the X-ray observations, in many far ultraviolet lines, or in $\lambda$ 10830 observations from the ground.
X-ray Coronal Loops

Soft X-ray photographs made by the AS & E S-054 experiment during the Skylab mission (Vaiana et al. 1974, Chase et al. 1977) show many loops connecting various features on the solar surface, some of which cross the equator.

These loops represent some of the magnetic-field lines in the corona. Figure 10 illustrates some of the loops. Sheeley et al. (1975) have shown that a newly emerging region can become interconnected with old fields in the neighborhood. Recent studies (Švestka et al. 1977, Howard & Švestka, 1977) have pointed out a number of characteristics of coronal loops, such as: (a) magnetic-field variations can cause transient brightenings and sharpenings of loops; (b) large loops connecting newly formed regions can form through reconnection of existing field lines; (c) a visible loop connection between two active regions does not result in the influence of the activity in one region on the other; (d) probably the most common way that loops interconnecting two active regions appear is by the brightening of a pre-existing field connection; (e) the basic magnetic interconnections between active regions, once born, live at least as long as both the interconnecting regions exist as distinct magnetic features; (f) individual loops, on the other hand, are visible for only short

Figure 9  Magnetic field lines from a potential field calculation for 1.03 R to 2.5 R. This view is at longitude 300° in Carrington rotation 1417 (13.1 August 1959).
Figure 10. A.S. & E. Skylab X-ray photographs of the Sun on the dates indicated in 1973. Filter 1 has a passband of 2-17 A, and Filter 3 has a passband of 2-32 A and 44-54 A. The loops connecting the two regions cross the solar equator. Note that the loops can change appearance in a matter of hours. (From Svestka et al. 1976.)
times—generally less than one day; (g) newly emerging magnetic flux tends to make some pre-existing field connections visible as loops; (h) the variability in the shapes of loops that are sometimes seen can at times be related to changes in photospheric magnetic field configurations; (i) a complex of activity (Bumba & Howard, 1965) appears to show remarkably ordered behavior, such as simultaneous brightenings of loops connecting different regions, and a characteristic pattern of loops internal and external to the active regions.

CONCLUDING REMARKS

After more than two decades of magnetograph observations, we have learned a great deal about magnetic fields on the solar surface. Perhaps the most fundamental result from this work is that practically every solar feature that can be seen in the photosphere, chromosphere, corona, and beyond to interplanetary space owes its existence in one way or another to the presence of magnetic fields. The one notable exception to this rule is the photospheric granulation pattern, which may be purely hydrodynamic in origin.

Solar activity is, therefore, the result of the motions of magnetic fields in and around the Sun. The Sun, as a result, becomes an interesting laboratory for large-scale magnetohydrodynamic phenomena. The activity cycle becomes a magnetic variation, perhaps a self-regenerating dynamo (cf Weiss 1971).

A number of questions remain to be answered. Among these we should include the following:

1. Is the solar sector magnetism a separate structure from the active-region fields that are seen to weaken, expand, and form the large-scale patterns and polar fields?
2. Can the behavior of magnetic fields at the solar surface be explained using only the random walk resulting from supergranular motions combined with the shearing effects of differential rotation, or are there other factors that contribute?
3. Do the large-scale patterns of magnetic fields represent the manifestation at the solar surface of a global-scale convection?

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