

PHOTOSPHERIC MAGNETIC FIELDS

Robert Howard

An invited review

Our knowledge of the nature of magnetic fields on the solar surface is reviewed. At least a large part of the magnetic flux in the solar surface is confined to small bundles of lines of force within which the field strength is of the order of 500 gauss. Magnetic fields are closely associated with all types of solar activity. Magnetic flux appears at the surface at the clearly defined birth or regeneration of activity of an active region. As the region ages, the magnetic flux migrates to form large-scale patterns and the polar fields. Some manifestations of the large-scale distribution are discussed.

ABSTRACT

INTRODUCTION

Soon after the invention of the spectroheliograph, astronomers observed the beautiful swirling patterns of chromospheric fibrils, and noted their similarity to patterns of iron filings around magnets. *George Ellery Hale* in 1908 was the first person to observe magnetic fields in any astronomical object when he showed that sunspots contain strong fields. Soon after this discovery *Hale* and his co-workers set out to detect a general dipole magnetic field of the sun. After many years of hard work and uncertain results, a value of about 20 gauss for a dipole field was published [*Hale et al.*, 1918]. More years of work were devoted to the problem by the Mount Wilson group without improving the precision of this number. Recent examination of the older plates by *Stenflo* [1971] has shown that the earlier measurements were in error.

Following World War II, improved photoelectric techniques became available, and several attempts were made at photoelectric measurements of solar magnetic fields. Difficulties still remained, however, and it was not until the development of the magnetograph by *H. W. Babcock* [1953] that reliable measurements of weak magnetic fields in the photosphere could be made. Except perhaps for a few scattered observations, the polar fields of the sun were not measured until the 1950 s.

The first *Babcock* magnetograph measured line splitting in the longitudinal Zeeman effect. *Stepanov and Severny* [1962] at the Crimean Astrophysical Observatory were the first to build a magnetograph that uses the transverse Zeeman effect to measure magnetic fields perpendicular to the line of sight. Observatories throughout the world now have magnetographs of one sort or another. By far most measurements of magnetic fields on the sun use only the longitudinal Zeeman effect because of the relatively great difficulties in the measurement of the polarized signal in the transverse effect and in the physical interpretation of the measurements once they are made. Compared with the longitudinal measurements, the transverse measurements depend to a greater extent on an accurate model atmosphere and knowledge of the mechanisms important in the formation of the absorption line [*Beckers*, 1971].

This paper covers several aspects of solar magnetism that are of interest in the study of the interplanetary medium. It is generally believed that magnetic field lines encountered by interplanetary probes originate in the photosphere of the sun or lower. The extent to which the small-scale structural characteristics of the solar magnetic fields extend into interplanetary space is not clear, but certainly the nature of the small-scale photospheric field bears on such problems as possible wave motions in the interplanetary field. On the large scale, the relationship of the distribution of photospheric fields to the interplanetary field sector structure has been the subject of considerable study, results of which are reviewed.

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Finally, some aspects of the rotation rates of various features on the solar surface are of great interest with respect to the possibility of spindown and momentum transfer through the interplanetary field. Recent results in this area are reviewed.

SMALL-SCALE MAGNETIC FIELDS ON THE SUN

Solar physicists are seriously hampered in their observations by the distorting effects of the earth's atmosphere. The smallest area measurements of magnetic field strength that are currently practical cover about 10^6 km² on the sun, and such measurements are possible only under the most favorable conditions of the terrestrial atmosphere. Thus "small-scale" measurements are not small in scale compared with those made in a physics laboratory or in interplanetary space.

It was not until some years after the first magnetograph measurements that it was realized that the magnetic fields in the solar photosphere, when viewed on a small scale, show the same intricate patterns as one sees in the chromospheric emission of the calcium K-line [Leighton, 1959; Howard, 1959]. More recently, attention has been given to the very finest scale features observable. In these studies magnetic fields measured in the photosphere are seen to be clumped into small areas called "gaps" or "knots" [Sheeley, 1967; Beckers and Schröter, 1968]. Figure 1 is a view of solar magnetic fields on a small scale, and figure 2 is a spectrum of some small magnetic features. These small features have areas

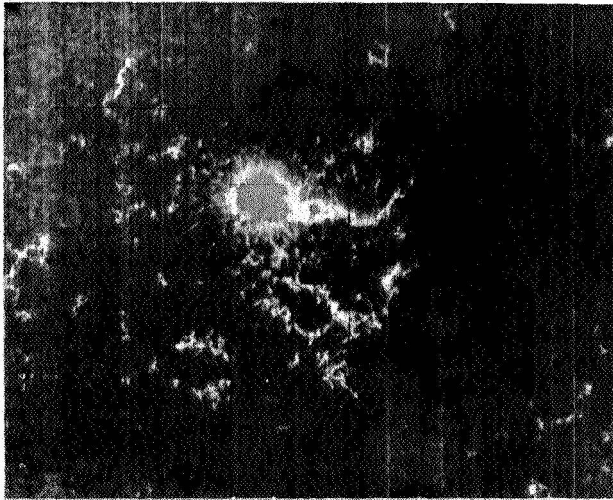


Figure 1. A videomagnetogram of a portion of the solar disk. Polarities are distinguished by either a brighter or darker shade than the background. [Courtesy D. Vrabec, Aerospace Corporation.]

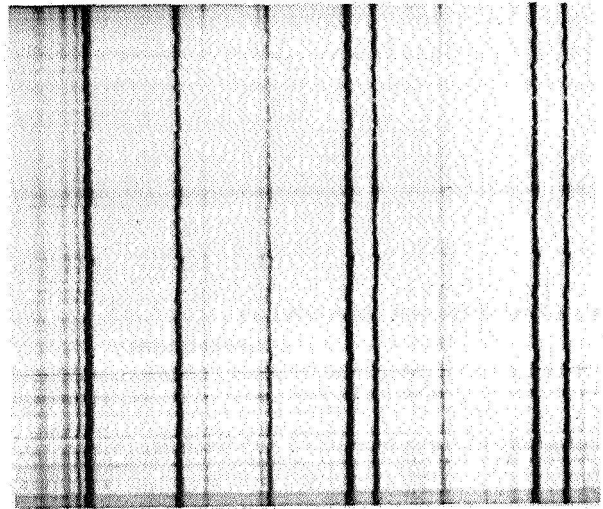


Figure 2. A spectrum of the photosphere in the region of $\lambda 5250$. Note the weakening (gaps) in several places of the absorption lines. [Courtesy N. R. Sheeley, Kitt Peak National Observatory.]

of perhaps slightly less than 10^6 and km² and contain magnetic fields of many hundreds of gauss.

The gaps correspond to long-lived dark intergranular regions in the photosphere, and to bright points in H α or the calcium K_{2,3,2} network in the chromosphere [Sheeley, 1967; Beckers and Schröter, 1968; Abdussamatov and Krat, 1969; Vrabec, 1971]. It has been established that the gaps occur at boundaries of supergranular cells where there is also downward motion [Tanenbaum et al., 1969; Frazier, 1971; Grigorev and Kuklin, 1971]. However, there is some disagreement among observers as to whether there is downward motion associated with magnetic fields [Gopasyuk and Tsap, 1971; Bhatnagar, 1971; Sheeley, 1971]. There are roughly 10 gaps per 100 granules near spots and about one gap per 100 granules far away from spots. The high density of gaps around sunspots suggests that they are an important part of the structure of an active region. The magnetic flux from the gaps of an active region is comparable with that of the sunspots. Sawyer [1971] suggests a higher concentration of field elements.

In recent interesting work that deserves confirmation, Livingston and Harvey [1969] present evidence for the quantization of magnetic flux measured in gaps, which could be explained if all gaps have the same magnetic flux.

Evidence exists for high horizontal gradients in the chromosphere of the order of 17 gauss/km [Title and Andelin, 1971], although vertical gradients, even in

spots, are probably smaller—of the order of 0.5 to 0.8 gauss/km [Abdussamatov, 1971]. In general, fields at different levels in the solar atmosphere have different strengths; sometimes even increasing with height [Tsap, 1971; Harvey and Hall, 1971].

Field concentrations have been observed to move outward from large spots [Sheeley, 1971; Vrabec, 1971]. This may be associated with the well-known Evershed motion. The velocities (1 to 2 km/sec) are about the same as the Evershed velocities, but the features themselves are outside the region generally considered to contain the Evershed motions.

Theoretical considerations [Zwaan, 1967; Weart, 1970] show that the magnetic gaps may be stable features. Musman [1971] has shown by analysis of magnetic and velocity observations that the accumulation of magnetic flux at the boundaries of supergranular cells does not proceed as rapidly as one might expect.

The important question of how much of the solar flux may be concentrated in small bundles of lines of force and how much is spread more or less evenly over large areas of the solar surface has not yet been answered. Certainly at least a large fraction even of the polar magnetic fields is contained in small regions with high field strength.

The measurements of these small gaps are on the borderline of the impossible at all observatories during almost all the available observing time. In the future, satellite telescopes hopefully will clear up many of the problems that face us now. Not only is the earth's atmosphere a problem in small-scale observations, but the sun's atmosphere also presents difficulties. Practically all the spectrum lines commonly used in magnetographs present problems of one sort or another in the measurement of magnetic fields in gaps, even when using only the longitudinal component of the field. Harvey and Livingston [1969] have shown that due to the higher temperature in gaps, the commonly used absorption lines change their profiles—for example, λ_{5250} of FeI weakens considerably (fig. 2) — and since most measurements are made with resolution much lower than the size of the gaps, the measured field does not represent a good average over the magnetograph aperture. This problem has not been resolved, and no one has yet found the ideal line to be used for solar magnetic field measurements.

Several observatories are concentrating their efforts on observations of magnetic fields on the smallest possible scale, using various video techniques to obtain good resolution in time. It is hoped that observations such as that shown in figure 1 will help us to understand the complex processes that make up solar activity on the small scale.

LARGE-SCALE SOLAR MAGNETIC FIELDS

The great bulk of the observational data available for the study of the large-scale magnetic field of the sun comes from the Mount Wilson Observatory. Full-disk magnetic scans of the sun have been obtained there daily starting with the original magnetograph [Babcock, 1953] in Pasadena. In recent years the data have been recorded in digital form, and through the years various technical refinements have been made so that although the principle of operation remains the same, the present instrument is a considerable improvement over the original magnetograph. The angular resolution used in the daily scans is 17 arc sec. The isogauss magnetograms, which are now computer-drawn (fig 3), are published monthly in the bulletin *Solar-Geophysical Data* by the National Oceanic and Atmospheric Administration of the Department of Commerce.

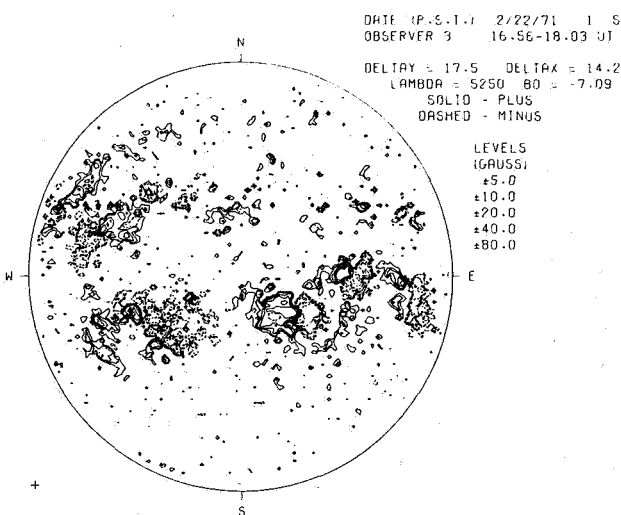


Figure 3. A solar magnetogram from Mt. Wilson. The gauss levels are listed. Solid lines are positive isogauss levels, and dashed lines are negative levels. The angular resolution is 17.5 arc sec.

To examine the magnetic fields of the sun on a large scale, it is convenient to plot them on a global scale. Such a plot is called a synoptic chart (fig 4) and covers the entire surface area of the sun during one rotation in an equal-area projection. Synoptic charts of the sun from the Mount Wilson magnetic data are now published in the International Astronomical Union publication *Quarterly Bulletin on Solar Activity*. The interval from the summer of 1959 to the summer of 1966 was covered in an atlas of synoptic charts published a few years ago [Howard et al., 1967].

On the magnetograms and synoptic charts we see a

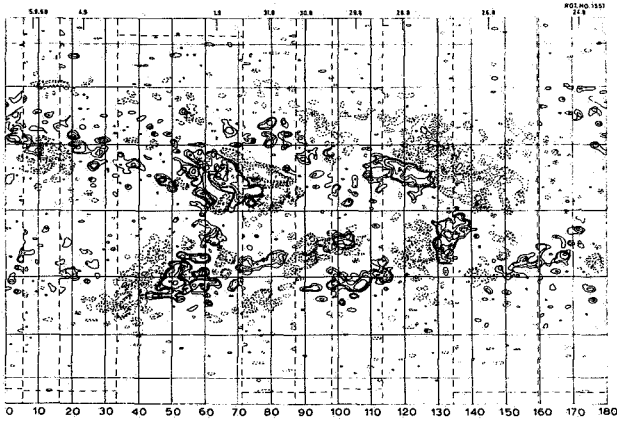


Figure 4. A portion of a synoptic chart of solar magnetic fields from Mt. Wilson data. The levels and resolution are the same as for Figure 3.

number of easily distinguishable features. In general, although sunspots always contain strong magnetic fields, they are not obvious features on the Mount Wilson isogauss maps because they are small compared with the angular resolution of the instrument and because there are obvious large patterns of nonspot fields which dominate the maps. The obvious strong-field features which one sees on the isogauss maps are all active regions. A 20-gauss contour line delineates a calcium plage [Leighton, 1959; Howard, 1959]. The plage fields, seen with the low resolution of the full-disk scan, reach 40 or 50 gauss. The appearance of solar magnetic features on a large scale varies with the level of solar activity. During an active period the most prominent features on solar maps comprise what is known as the "background field pattern" [Bumba and Howard, 1965]. In 1959 this pattern and the active regions, within 4-gauss contour lines, occupied nearly half the surface area of the sun. The pattern is one of the features of alternating polarity inclined to the meridian by the shearing effects of differential rotation. During periods of low solar activity, the background field pattern is extremely weak and generally is lost in noise around 1 or 2 gauss. In the polar regions, the fields measured during the last five years or so are very weak, generally less than 1 gauss. At the time of the last solar maximum the polar fields were somewhat stronger. This weakening of the polar fields is probably due to the lowering of the level of solar activity, as will be discussed below.

In view of the existence of a regular pattern of magnetic fields on the large scale, it seems worthwhile to examine more exactly the flux distribution on the solar surface. In such a study Altschuler *et al.* [1971] analyzed Mount Wilson magnetic field data in terms of surface harmonics. Between 1959 and 1962 the dominant

harmonic corresponded to a dipole lying in the plane of the equator. There was also a significant harmonic in which both solar poles had the same magnetic polarity, opposite to that at the equator. From the end of 1962 through 1964, the harmonic corresponding to four sectors grew dominant as the dipole faded. In 1965 and 1966 the north-south dipole became significant. It is hoped that the analysis can be extended soon to more recent data, which are of better quality than the older data.

The correlation between photospheric and interplanetary magnetic fields is well known [Ness and Wilcox, 1966]. The clear existence of a sector pattern in the interplanetary field [Wilcox and Ness, 1965] implies the existence of some sort of sector pattern in the photospheric magnetic field. Such a pattern has been observed [Wilcox and Howard, 1968]. In the case of the 1964 data, the solar sector boundaries, determined from a cross-correlation analysis with the interplanetary field data, showed a more or less symmetric pattern, stretched by differential rotation, centered on a latitude of $N 15^\circ$. Analyses of subsequent data have shown to a lesser extent the effects of differential rotation [Wilcox *et al.*, 1969; Wilcox, 1971]. However, all these studies seem to show that the equator plays little or no role in the appearance of the pattern; that is, the pattern stretches unchanged across the solar equator. This tendency for the background magnetic field pattern to ignore the equator has been noted by Bumba and Howard [1969] from an inspection of synoptic charts. Wilcox and Ness [1967] have shown that active regions tend to cluster in the preceding portions of solar sectors. Unfortunately, we do not yet know enough about solar activity or solar magnetism (which is, perhaps, the same thing) to be able to answer the important question: Which is the fundamental quantity: the sector or the activity? That is, is the sector there because of the chance clustering of active regions, or are the active regions forced to cluster in the preceding portion of a fundamental, deep rooted structure — the solar sector? It does not now seem likely that a definitive answer to this question will appear within the next few years.

New magnetic flux arrives at the surface of the sun from below at the birth of an active region, or at a rather sharply defined resurgence of activity in an old active region. There is no evidence that magnetic fields come to the surface of the sun in any other manner. The large weak-field features of the background field pattern develop over many weeks or months from the expansion and weakening of remnants of old active region fields [Bumba and Howard, 1965]. Individual features of the background field pattern may persist for many months,

although individual field features are not in general distinguishable for more than a few rotations. The distinction between the *pattern* and the individual field elements is made clear by a study of the rotation of each. The pattern rotates with a period of 27 days at latitudes below about 20° , whereas the individual field elements, when they can be followed, rotate with the rates appropriate for their latitudes [Bumba and Howard, 1969; Wilcox *et al.*, 1970]. In general, the following polarity in each solar hemisphere predominates in a poleward drift of magnetic flux. In each hemisphere a large poleward-moving unipolar region may form at high latitude from the following polarity flux of many active regions. Such unipolar magnetic regions (UMR) may cover more than 180° in longitude at a latitude greater than 60° . It is assumed that this effect during a sunspot cycle builds up the following polarity in the polar regions as the polar field.

The field in the polar regions is weak and variable, and at least largely confined to small bundles of lines of force originating in the polar faculae [Howard, 1965]. A clear reversal of the polar fields was observed at the maximum of cycle 19 by H. D. Babcock [1959]. No such well-defined reversal has been observed yet in cycle 20. It is possible that because of the lower level of activity in the last cycle, the buildup of polar fields is proceeding more slowly than it did in the last cycle. However, the work of Sheeley [1964] in examining old polar faculae data and the well-known periodic migration and disappearance of the polar prominence ring indicate a regular cyclic behavior of the polar magnetic fields at least during this century.

Recent comparisons of the magnetic field of integrated sunlight measured at the Crimean Astrophysical Observatory with the interplanetary magnetic field indicate a very good correlation [Severny *et al.*, 1970] for a period of several months in the spring of 1968. This suggests a very large-scale coherent pattern. More recent results from Mount Wilson measurements (see p.39) indicate that this correlation is not as straightforward as had been believed. It seems possible that the correlation may be a consequence of the large, slowly evolving solar sector pattern.

THE SOLAR ROTATION

In the last few years, interest in the rotation of the sun has increased. The classic work on the differential rotation of sunspots is that of Newton and Nunn [1951]. This is still the standard reference on the subject, although, as Newton and Nunn point out, the observational difficulties in establishing the rotation rate of sunspots are considerable [Ward, 1966]. Attempts early in

this century to establish the rotational velocity of the sun from Doppler shifts of spectral lines gave rather disparate results. [See Howard and Harvey, 1970, for complete references.] One observer [Plaskett, 1916] concluded that the rotational velocity of the sun must vary. The observations were so difficult and the results so varied that very little was done in this field from the early 1930's until a few years ago when accurate line shift measurements became possible with solar magnetographs. Livingston [1969a; 1969b] and Howard and Harvey [1970] have found, using different observing techniques, a rotation rate for the photospheric material that is slower by about 4 percent than that for sunspots. This is a difference of roughly one day per rotation. Fig 5,

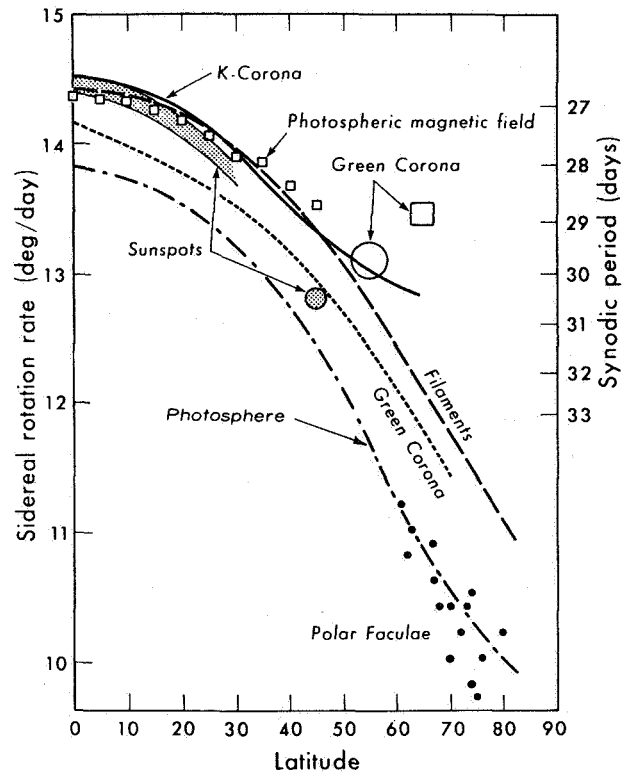


Figure 5. Comparison of various rotation results. K-corona at $1.125 R_\odot$ (solid curve) [Hansen *et al.*, 1969]; photospheric magnetic field (squares) [Wilcox and Howard, 1970]; all sunspots (top of shaded area) [Ward, 1966] recurrent sunspots (bottom of shaded area) [Newton and Nunn, 1951]; high-latitude spots at 45° (shaded circle) [Waldmeier, 1957; Kopecky *et al.*, 1957]; polar faculae (dots) [Muller, 1954; Waldmeier, 1957]; filaments (dashed line) [d'Azambuja and d'Azambuja, 1948; Bruzek, 1961]; green corona (dotted curve) [Trellis, 1957], (circle) [Waldmeier, 1950], (square) [Cooper and Billings, 1962]; photosphere (dot-dashed line) [Howard and Harvey, 1970].

redrawn from *Hansen et al.* [1969], shows a comparison of rotation rates of various solar features. It appears that the spots, the photospheric magnetic fields (outside sunspots), the K-corona, and the filaments maintain roughly the same rotation rates for latitudes below about 15° or 20° . At latitudes higher than this the photospheric magnetic fields, the filaments, and the K-corona maintain a significantly faster rate of rotation than do the spots, while the photospheric material rotates much slower.

Variations in the rotation rates are well-established for the K-corona [*Hansen et al.*, 1969], the photospheric magnetic fields [*Wilcox and Howard*, 1970], and the photospheric material [*Howard and Harvey*, 1970; *Howard*, 1971]. The reason for these variations is not now understood, and as yet no correlation analyses between the various rates have been attempted.

The magnetic fields extending into the interplanetary medium cannot be slowing the photospheric material at the photospheric level because the fields there are rotating about 80 m/sec faster than the gas. The more rapidly rotating magnetic field lines may be connected with more rapidly rotating inner layers of the sun. Note that the filaments and the corona are closely related to the magnetic field structure. It would be puzzling if these features maintained significantly different rotation rates than do the magnetic fields.

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DISCUSSION

E. N. Parker The polar fields of the sun reversed, as I remember, in late 1958. As a consequence there has been a strong psychological feeling that since they are tied to the sunspot cycle, if you add eleven years to late 1958 you get roughly 1969 or 1970—am I correct that the fields have not yet reversed again?

R. Howard I can't answer that with a yes or no. There has not been a clear reversal of magnetic field polarity at the solar poles; at the moment, at least, within the last year or two, the fields at both poles have been slightly negative. However, about a year or a year and a half ago the south pole became somewhat more negative than the north pole. If you define that as a reversal, then there has been a reversal.