EVOLUTION OF CORONAL AND INTERPLANETARY MAGNETIC FIELDS

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ABSTRACT. Numerous studies have provided the detailed information necessary for a substantive synthesis of the empirical relation between the magnetic field of the sun and the structure of the interplanetary field. We will point out the latest techniques and studies of the global solar magnetic field and its relation to the interplanetary field. The potential to overcome most of the limitations of present methods of analysis exists in techniques of modelling the coronal magnetic field using observed solar data. Such empirical models are, in principle, capable of establishing the connection between a given heliospheric point and its magnetically-connected photospheric point, as well as the physical basis for the connection. We thus find ourselves at a plateau, looking back over a quarter century of empirical synthesis while anticipating a new era of detailed physical investigation on a global scale.

1. INTRODUCTION

1.1 Scientific Themes of Solar-Interplanetary Magnetism

The first synthesis of observations of the solar magnetic field was summarized by Babcock and Babcock in 1955. Using over two years of data from the original Mt. Wilson magnetograph, they were able to point out the dipolar character of the general solar field, and described many of the features of Bipolar Magnetic regions and their association with sunspots, Hale's polarity laws, and enhancements of coronal brightness. The general magnetic field of the sun, however, appeared to them to be confined to the higher latitudes; the field in the equatorial regions did not present a persistent global pattern. In the lower latitudes (between $\pm 50^{\circ}$) the fields were seen as localized and (relatively) transient. Most of these were Bipolar Magnetic regions of varying complexity, but a very few were given the interesting (but later misleading) name "Unipolar Magnetic" (UM) regions:

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> In introducing the term "unipolar," we refer to regions which . . . show . . . almost exclusively one polarity and which are not directly accompanied by adjacent regions of opposite polarity; in most cases it is not at all obvious where the magnetic lines of force emanating from the UM region re-enter the sun.

Because we can now shed much more light on the questions that Babcock and Babcock had to leave unanswered, their paper is an interesting and satisfying gauge of our progress in understanding the structure of the global solar magnetic field. At the same time, however, we are reminded of one of the persistent themes of research in the field of solar-interplanetary magnetism, for Babcock and Babcock noticed that UM regions tended to last for several rotations, and found that one particularly prominent series of geomagnetic storms in 1953 recurred in association with a large unipolar region, with a 2-3 day phase lag. They hypothesized that the UM regions might in fact be the "M" regions suggested by Bartels (1932) as the source of solar particle emissions responsible for recurrent geomagnetic activity.

Another theme of scientific relevance is represented by Alfven (1956), who criticized the then-popular view of the general magnetic field outside the sun as being a dipole on the ground that it was an "unfounded assumption." He pointed out the evidence for currents (in the form of known changes in the electromagnetic field) and reminded his readers that the flowing charges would alter the presumed structure of the field. In the process of developing his critique, he presented a simplified model of the interplanetary magnetic field that is probably the first recognition of the possibility of the opening of dipolar (or more generally potential) lines of force. The model explicitly assumed that the open lines of force are "beamed," or concentrated into restricted areas of the solar surface, and that other portions of the sun are characterized by closed magnetic structures.

Perhaps the most widely referenced early insight into the influence of the structure of the solar magnetic field on the heliosphere is the work of Billings and Roberts (1964). Their schematic suggestion lacks any indication of magnetic polarities, concentrates on an invalid temperature distribution, and does not recognize the global nature of large-scale open field regions. However, it does recognize the role of the solar wind in extending weaker magnetic field lines outward, and presents the issue of the modulation of coronal temperature and density structure by the magnetic field. Billings and Roberts' work has been cited by several authors and has served as the basic framework for more elaborate schematic illustrations of the basic physical processes.

A final key theme that needs to be remembered is the discovery of the sector structure of the interplanetary magnetic field. With the ability to measure the interplanetary field in situ near the earth, Wilcox and Ness (1965) discovered that the averaged (over several hours) magnetic field points predominantly toward or away from the sun for several days at a time, and that this pattern of alternating polarity sectors persists in its general form for times long compared with the time scales on which the obvious manifestations of the photospheric field (i.e., BMRs) change.

These themes, the large-scale polarity regions of the solar photosphere, the possible existence of open magnetic field lines in the corona, and the interplanetary magnetic sector structure, are the basic scientific framework for the continuing study of the way in which the solar magnetic field extends into the heliosphere.

1.2 Scope of This Review

The ability to identify the key scientific themes mentioned above is due to an ongoing synthesis of observational data and theoretical insights. Excellent summaries of this work were given by Dessler (1967) and by Wilcox (1968). The advances at the beginning of this decade, due largely to improved instrumentation and especially to the solar experiments on Skylab, are discussed in the Coronal Hole Workshop volume edited by Zirker (1977) and in a review of the work on the large-scale solar field by Howard (1977).

In this discussion, it is my intent to concentrate on the state of our present physical understanding of the global solar magnetic field and its extension into the interplanetary medium. I do not intend an exhaustive review of the literature, nor a catalog of experimental results. Rather, I wish to reflect a largely coherent understanding of the large-scale processes in the magnetic field (at least above the photosphere), and to emphasize that the period of basic discoveries which have led to this understanding must now be followed by increased theoretical efforts aimed at modelling the physical processes in realistic detail and by careful observations designed to establish a long-term, reliable data base for both empirical analysis and input to theoretical models.

The second section discusses the observational picture of the solar and the interplanetary magnetic field. The correlation between the two fields is interpreted within the framework of the understanding of the global solar magnetic field that has emerged in recent years. Section 3 points out data-based models of the global solar magnetic field that presently exist. The known limitations of each type of model are emphasized. The final section is an overview of the progress in this field, pointing out expectations and needs for the future, as well as providing recommendations for fruitful areas of theoretical and observational pursuit.

2. OBSERVATIONS OF SOLAR AND INTERPLANETARY MAGNETIC FIELDS

2.1 Whole Sun Measurements

Measurements of the mean magnetic field of the sun use integrated light from the full solar disk (the sun seen as a star) and represent the average net line of sight field strength over the disk, with the field value at each point weighted by the intensity of the magnetically sensitive line used to determine the field. In practice this means that points nearer the central portion of the disk contribute most heavily to the measured value. The values obtained also represent averages over some portion of a single day. Such measurements have been carried out since 1968 at the Crimean Astrophysical Observatory, since 1970 at Hale Observatories (Mt. Wilson), and since 1975 at the Stanford Solar Observatory. Studies based on these observations, including intercomparisons, have been published by Severny, et al. (1970), Scherrer, et al. (1977a), and Scherrer, et al. (1977b).

The physical basis of using mean field measurements is that they reflect a (weighted) average of the net solar magnetic flux over large areas of the photosphere. The properties of large-scale patterns in the photospheric field can then be investigated, although the actual net flux and the area over which it is averaged cannot be determined. The observed mean field varies slowly from day to day, with the pattern generally repeating with slow evolution after about 27 days. This is consistent with the interpretation that there are large-scale structures of consistent magnetic polarity and weak average net field strength in the photosphere. Because of the difficulty involved in interpreting mean field measurements directly in terms of photospheric structures, however, their use has been confined almost exclusively to comparisons between solar and interplanetary magnetic structure (see section 2.3, below).

2.2 Spatially Resolved Measurements

The more traditional method of studying the large-scale magnetic field of the sun has been to construct synoptic charts of spatially resolved daily magnetograms. This permits direct investigation of large-scale patterns in the photospheric magnetic field. Examples of studies using this type of data are by Babcock and Babcock (1955), Bumba and Howard (1965, 1966), Wilcox and Howard (1968), Stenflo (1972), and Svalgaard, et al. (1975), all using data from the Mt. Wilson instrument, and by Levine (1979) using measurements from Kitt Peak National Observatory.

Some properties of the large-scale photospheric field are illustrated in Figure 1. These are synoptic charts of the line of sight magnetic field (measured at Kitt Peak) averaged over eleven solar rotations. The only difference between the four panels is the grid size onto which the data are averaged. The emergence of large-scale patterns as the viewing resolution decreases is readily apparent. At

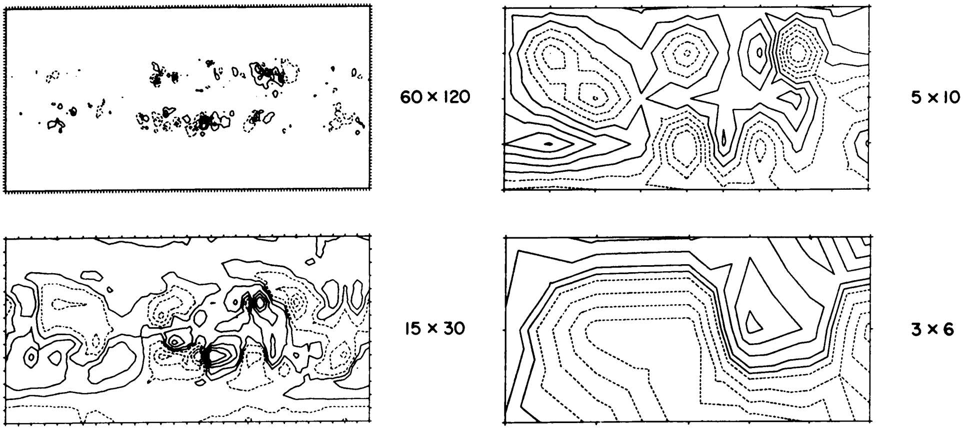

Figure 1. Contour plots of average magnetic field observed over Carrington rotations 1601-1611. The four panels each represent the same data averaged onto grids of different surface resolution. The sizes of the grids used are indicated. Contour levels (+ and -, in gauss) are (60 x 120): 5, 15, 25, 35; (15 x 30): 0, 1, 3, 5, 7; (5 x 10): 0, .4, .8, 1.2, 1.6; (3 x 6): 0, .1, .3, .5, .7 (from Levine, 1979).

its lowest resolution the pattern is remarkably similar to the description of the large-scale field which has been inferred from interplanetary and mean field observations by Svalgaard, et al. (1974, 1975). This phenomenological model is based on the union of the observed structure of the polar caps, with uniform net polarities through most of the solar cycle, and the alternating polarity structure of the lower latitudes, which is inferred from the sector structure of the interplanetary field and the observed mean field of the sun. The result is a single large-scale neutral line which is supposed to separate the largest polarity sectors of the sun. Figure 1 shows that this model is a very good representation of the gross properties of the data, even though the intent of Svalgaard, et al. was to relate the interplanetary sector observations to coronal structure, rather than to "the complicated features found in the photosphere or in the chromosphere."

Because the sector pattern was more readily identifiable when the strong active region fields were removed from their Mt. Wilson data, Svalgaard, et al. (1975) concluded that the photospheric sectors were "not caused or controlled by the strong magnetic fields of active regions." Levine (1977a, 1977b, 1979) has studied the data from Kitt

Peak for Carrington rotations 1601-1611 and its relation to coronal holes. The conclusion of these studies is that active region flux contributes systematically to the maintenance of polarity sectors (and coronal holes, which are related to them). Thus, although the contour levels in the lower resolution panels of Figure 1 are a few gauss or less, the large-scale patterns they outline are not necessarily determined by a weak solar magnetic field component. The appearance of large-scale patterns with weak net fields might be due to the imbalance of stronger fields of opposite polarity. Because of the possibility that solar magnetic fields are concentrated into bundles of high field strength in the photosphere, however, we cannot directly make statements about the large-scale patterns being due to strong fields or weak fields; we can only examine the role of flux which is concentrated vs. flux which is more diffuse. Measured field values which differ represent either actual photospheric fields which are distributed over similar areas and have strengths which differ, or they represent fields of similar strength which cover different areas of the photosphere.

We cannot then say that only diffuse flux or only concentrated flux is responsible for the photospheric polarity pattern. By separately averaging measurements with high average |B| and low average |B|, Levine (1979) showed that evidence of the over-all pattern is present in the averages of both. Many workers (e.g. Bumba and Howard, 1965; Wilcox, 1968; Wilcox, et al. 1969; Severny, et al. 1970; Svalgaard, et al. 1975) have inferred or assumed that the existence of such patterns was due to a weak background field with a strength of a few gauss. The alternative interpretation provided by analysis of the Kitt Peak data (useful in this context because it does not saturate at high field strengths) is that the inclusion of all measured fields does bring out a sector pattern and that the visibility of the pattern is a question of spatial scale rather than of field strength. This strongly suggests that it is the imbalance of field strengths, rather than their absolute value, which establish the systematic pattern. Mean field measurements, even though sensitive to very weak net field strengths, must also include the effects of systematic imbalance of concentrated flux. A weak background field of a few gauss or less, while not excluded, is not necessary to explain the observations.

From the solar point of view we must ask what processes are responsible for the organization of fields with systematic flux imbalance extending to the largest spatial scales. The contribution of concentrated flux can occur in obvious structures like active regions, but the role of the possibly large amount of magnetic flux in Ephemeral Active Regions (Harvey and Martin, 1979; Golub, et al. 1979) cannot be ignored. The long lifetimes of magnetic polarity patterns, compared to the lifetimes of the structures which contribute their flux, reinforce the view (Svalgaard, et al. 1975; Levine, 1977a, 1977b) that the large-scale structure of the solar magnetic field is a fundamental aspect of solar magnetism. (It is interesting to note that Svalgaard, et al. concluded that the photospheric sector pattern is of fundamental importance because they found it to exist independently of the active region fields while Levine came to the same conclusion by noting that there was a systematic component to active region evolution which maintained the photospheric sectors for times much longer than the lifetime of a typical active region.)

In order to improve the study of the influence of the sun on the earth, it will be important to know at what spatial scales the information about the solar magnetic field is propagated to the earth. Smaller features such as the active regions which make the large-scale pattern difficult to detect at high resolution are not directly sensed in the near-earth environment, while the influences of the largest magnetic sectors are known to be detectable and even dominant in the interplanetary field. It is not known in detail at what spatial scales between these extremes the magnetic pattern of the photosphere might occasionally be manifest near 1 A.U., and what processes are responsible for modulating the patterns observed. The crucial role played by the dipole and quadrupole moments of the photospheric field have been emphasized by Schulz (1973). He has shown that the presence of just these two terms is sufficient to produce a warping of the heliomagnetic equator similar to that envisioned in phenomenological models. It is the evolution of these terms, and the presence of higher order multipoles, which must be incorporated into a more satisfactory explanation of the interplanetary magnetic field (see Section 3, below).

2.3 Why Do Solar Polarity Sectors Correlate with the Interplanetary Magnetic Field?

The details of the discovery that the interplanetary magnetic field is organized into sectors of alternating polarity have been reviewed by Wilcox (1968).

By reducing the IMF and solar polarities (mean field or synoptic averages) to Bartels' chart format the similarity of the solar and interplanetary patterns can be made apparent (Scherrer, et al. 1977a; Levine, 1979). A more quantitative measure of the agreement can be obtained by cross-correlating the solar and IMF data sets. Figure 2 shows the results of such a calculation by Severny, et al. (1970) for four months in 1968. The correlation peaks at a lag of 4.5 days. This is interpreted as indicating a transit time of about 4.5 days for the solar wind to bring the solar pattern to the vicinity of the earth, where the IMF measurements are made. As discussed below, however, it is not clear exactly what pattern is being transported by the solar wind, and it is certainly not the entirety of the photospheric pattern that physically maps to the earth.

There are a series of correlation peaks in Figure 2 at 4.5 days plus multiples of 27 days, resulting from the rotation of two slowly evolving patterns. What is surprising is that the peak at 4.5+27 days is larger than the peak at 4.5 days. Subsequently, the peaks decrease slowly in magnitude, which is what would be predicted for the

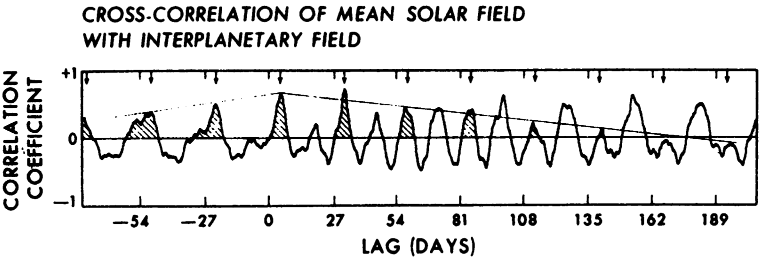

Figure 2. Cross correlation of the direction of the mean solar field with the direction of the interplanetary field during March-June, 1968 (from Severny, _et al_. 1970).

correlation of two slowly evolving patterns as the time lag is increased. The greater magnitude of the second peak was interpreted by Severny, _et al_. as indicating that there was a delay of up to one solar rotation between the appearance of a new magnetic structure in the photosphere and its manifestation in the IMF. A similar conclusion was reached by Schatten, _et al_. (1969). Similarly, Levine, _et al_. (1977) showed that smaller-scale evolutionary changes in the photospheric field took up to one rotation to be reflected in the appearance of coronal holes. Levine (1979) was able to clarify the source of this feature by cross-correlating the IMF with different spatial averages of Kitt Peak data taken in 1973-4. The increased size of the second peak (at 4.5+27 days) was found only for photospheric areas less than 20° in longitudinal extent. Averages over larger regions produced the greatest correlation at a 4.5 day lag, indicating that the evolutionary changes in the IMF are due to photospheric changes which are characteristically much smaller in scale than the largest polarity regions, and that these smaller-scale changes tend to influence the IMF after a time delay greater than several days but less than a full solar rotation.

It is instructive to inquire more deeply into the physical nature of the connection responsible for the statistical correlation of the interplanetary and solar polarity patterns. We can understand why mean field measurements correlate with the IMF by examining Figure 3. This is a contour plot from the study by Levine (1979) showing the cross-correlation of solar and interplanetary polarities where the solar polarities were determined by averaging over different size areas of the Kitt Peak synoptic magnetograms. The correlation is plotted as a function of the latitudinal and longitudinal extent of the photospheric region used to determine each day's solar polarity, and the qualitative features are the same for time lags from three to seven days. It is

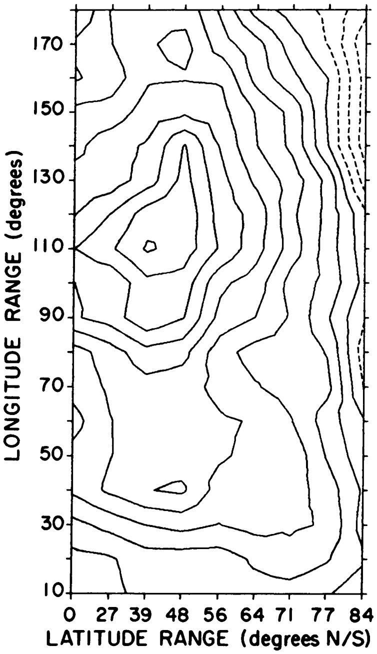

Figure 3. Contour plot of the cross correlation of solar and interplanetary polarities as a function of the size of the photospheric area used to define the solar polarity. Contour levels are from -0.09 to 0.39 in steps of 0.04 (from Levine, 1979).

clear that the maximum correlation occurs when a region of about 100° in longitudinal and latitudinal extent is used on the sun. The mean field measurements fortuitously sample the sun near this spatial scale, although the comparison cannot be exact because of the continuous weighting of the visible disk due to integrating over a varying line intensity in mean field observations vs. the sharp boundaries used to define averages of the Kitt Peak data.

Although Figure 3 helps to explain why mean field measurements are a useful representation of the solar polarity pattern, it does not explain the physical basis for the correlation with the IMF. For example, although the sectors of the IMF are generally traceable to similar sectors in the solar data, the reverse is not always true. There are large-scale polarity patterns in the photosphere which are not manifest near the earth (Levine, 1979). Some of these may be due to the latitudinal extent of the solar polarity regions and to the position of the earth with respect to the ecliptic plane, as described by Hundhausen (1977).

It has also been shown that the pattern of the photospheric field, as measured by its multipole structure, can undergo rapid large-scale rearrangements (Levine, 1977c; Altschuler, et al. 1974) and that these are accompanied by rearrangements of the corona (MacQueen and Poland, 1977). It remains to be seen whether these relatively sudden (i.e., within one solar rotation) reconfigurations of the photosphere and corona are a characteristic or fundamental part of the evolving solar cycle. It might be expected that these rearrangements would be manifest in the interplanetary field only after some delay, if at all, and that this would account for some of the discrepancy between the average photospheric and IMF patterns. Surprisingly, however, it is more nearly the reverse that is the case. The rearrangements of the multipole structure of the photospheric field are not all represented in the photospheric averages, but are evidenced in the evolution of the interplanetary sector structure.

These difficulties are most likely a reflection of the shortcomings of choosing solar polarities by averaging or by mean field measurements. Comparisons using such procedures assume that the entire extent of each large-scale polarity region on the sun can be mapped in interplanetary space. The controlling factors in this process, though, are global and depend on the relative strength of most or all of the large-scale regions on the sun (including the polar regions). It is then not surprising that the analysis of the field in terms of spherical harmonics does show a varying strength of the strongest multipoles which more closely matches the interplanetary pattern during this time of two sectors initially, four sectors briefly, then two sectors again (Levine, 1977c). The interplanetary field is a reflection of the relative strengths as well as of the polarities of large regions of the solar photosphere.

Additionally, explicit empirical models of the sources of interplanetary magnetic flux have supported the "nozzle" theory of the origin of the field, in that the footpoints of open lines of magnetic force tend to concentrate in relatively small portions of photospheric polarity regions (Levine, et al. 1977; Levine 1977a, 1977b, 1978; Burlaga, et al. 1978). Similarly, the phenomenological model of Svalgaard, et al. (1974) explicitly recognizes and attempts to account for magnetic arcades and helmet streamers. These closed structures are directly above the large-scale photospheric neutral lines and form a geometrical barrier to the direct connection of photospheric and interplanetary polarity boundaries. Direct evidence that most of the sun is covered by closed magnetic structures comes from analysis of x-ray observations of the corona (Vaiana, 1976; Vaiana and Rosner, 1978).

Because most of the area of photospheric polarity regions is not likely to connect to interplanetary space, the use of the extent of these regions as tracers of the extent of interplanetary magnetic field sectors is a very simple approximation at best. That this procedure is successful at all is due to the fact that the open field lines concentrated in the photosphere diverge rapidly into the corona where they then tend to reflect the extent (and strength) of the region in which they are rooted. The longitudinal extent of this mapping is largely preserved at 1 A.U., although the latitudinal structure is substantially altered by electromagnetic and dynamical effects (Schulz, 1973; Svalgaard, et al. 1975; Seuss, et al. 1977; Hundhausen, 1977).

3. PHYSICAL MODELS OF THE SOLAR CONNECTION TO THE INTERPLANETARY MEDIUM

As outlined above in Section 2.3, the difficulty with studying the source of the interplanetary magnetic field by observing the sun with little or no spatial resolution is that the physical basis for the correlation of the patterns is never clear in detail. Thus, for example, when four large-scale sectors are observed in the photosphere at a time when there are only two interplanetary sectors the statistical measures cannot help us to decipher the actual mapping.

An ideal procedure would be to establish a connection between each point in the heliosphere and a point on the solar surface using a fully magnetohydrodynamic model of a rotating, magnetized sun and its ionized corona. In practice this is well beyond present capability, for both physical and computational reasons. The important priorities for constructing useful, but admittedly incomplete, models of the extension of the solar magnetic field into the heliosphere are (1) that such models reflect the distribution of magnetic flux at the solar surface in detail, (2) that such models attempt to provide a realistic description of the inner corona, where the influence of closed structures is greatest, and (3) that such models take account of the expansion of the corona and its influence on the magnetic field, i.e., that they include the appropriate mhd effects in each portion of the corona.

Steps toward these goals have been taken and have resulted in substantial progress in understanding the solar-interplanetary connection. Some of the methods now in use or under development are discussed below in Sections 3.1 to 3.4.

3.1 Potential Field Models and Source Surfaces

The potential magnetic field extrapolation technique was developed for the sun by Schatten, et al. (1969) and by Altschuler and Newkirk (1969), and resulting calculated distributions of the large-scale coronal magnetic field were compared with observations of coronal structures with varying degrees of success (Schatten, 1968; Newkirk and Altschuler, 1970; Smith and Schatten, 1970; Smerd and Dulk, 1971; Uchida, et al. 1973). The method is based on a spherical harmonic analysis of solar magnetic field observations taken on a synoptic basis. The basic assumptions are that the field above the photosphere is potential (current-free) and that the line-of-sight component of the model field at the photosphere agrees with the observed line-of-sight field as given by synoptic magnetograms. The presence of currents in the low corona, as well as all short time scale evolution or transient effects, are ignored.

If the harmonic extrapolation of a potential field were not modified, however, all magnetic structures would be closed (except for a finite set of open footpoints with measure zero). So a further provision of all these models is the ability to study the effect of open structures by including a source surface in the mathematical model (Chapman and Bartels, 1940; Schatten, et al. 1969; Altschuler and Newkirk, 1969). The source surface in such models is spherical, concentric to the solar surface, and required to be equipotential, so that the magnetic field has no angular components there and is thus perpendicular to the source surface. In this way the complicated effects of plasma-field interactions that create open structures can be emulated by varying one parameter, the radius of the source surface. Although the source surface is a useful and mathematically simple device, it is not meant to be an exact representation of physical processes and care must be exercised in interpreting its use.

More recently, Altschuler, et al. (1976) have greatly improved this technique by using higher resolution synoptic magnetograms and by increasing the highest principal polynomial index used in the expansion from 9 to 90. An equivalent technique, using Fourier decomposition, was developed by Adams and Pneuman (1976). These newer modelling procedures have been used to investigate the coronal geometry associated with radio storms (Jackson and Levine, 1979; Gergely and Kundu, 1979), the detailed geometry and evolution of coronal holes (Levine, et al. 1977, Levine, 1977a, 1977b), the relation of open magnetic structures in the low corona to solar wind flow (Burlaga, et al. 1978; Levine, 1978), the properties of possibly open field lines within active regions (Svestka, et al. 1977), and the relation of recurrent energetic particle phenomena to coronal structure (Roelof and Levine, 1978). These studies have demonstrated the strong relation of open magnetic structures to active regions, and have emphasized that the sources of magnetic flux in the ecliptic plane can originate over a broad range of photospheric latitudes. This implies that almost all of the solar wind flow in the low corona is significantly non-radial.

An example of the difficulty of applying spherical source surface techniques to the study of solar structures is that investigations of the corona at eclipse (e.g., Altschuler and Newkirk, 1969) or of structures associated with active regions or active region interconnections (Howard and Svestka, 1977; Gergely and Kundu, 1979) usually find the best agreement for a source surface at a distance of about 2.5 solar radii from the center of the sun. Studies of interplanetary structure (Schatten, et al. 1969; Burlaga, et al. 1978; Levine, 1978) and of coronal holes (Levine, 1977a, 1977b), however, have used a source surface radius of about 1.5 solar radii to fit the observations. It is likely that both of these determinations are correct, in the sense that the height at which field lines become open over active regions is higher than it is over coronal holes. This can be expected by noting that the radius at which the solar wind flow speed reaches the local Alfven velocity is defined by a surface where the plasma density times the square of the magnetic field strength is constant. Because both the density and the field strength are larger at a given radius over active regions than over coronal holes, the Alfven radius will be closer to the sun over coronal holes. Attempts to account for this in self-consistent models are discussed in the next two sections.

3.2 Models Including the Effects of Current Sheets

In addition to the difficulty mentioned above, Schatten (1971) noted that both polar plumes and streamers have a significant (and systematic) non-radial orientation. The use of a spherical source surface at which the field is required to be radial cannot produce these effects. Because the plasma pressure is much less than the magnetic field pressure out to many solar radii, Schatten argued that currents could only exist in the inner corona at places where the field was weak, i.e., near neutral sheets. In contrast, source surface models ignore all currents, except for an implied current distribution on the source surface itself.

By using an ingenious trick dependent on the symmetry of the electrostatic Maxwell stress tensor, Schatten was able to devise a relatively simple procedure to account for sheet currents in a self-consistent manner while retaining the boundary condition of observed photospheric fields. His model uses a spherical, heliocentric shell to define the direction of field lines in a potential model with no source surface. At the height of this shell field lines are not necessarily radial; in fact, if the potential field lines were allowed to extend beyond the shell they would all close. However, Schatten's model specifically requires that no closed structures exist above the shell. This opening of field lines is due to an implied distribution of currents, much as in a source surface model, except that in Schatten's model the currents flow on neutral sheets in the region outside the specified shell, and the field distribution can be calculated there. As in a source surface model, there is one free parameter, the radius of the shell, and all closed structures must lie below the shell. The necessity of using shells as low as 1.6 solar radii, however, results in a poor representation of the observed structure directly over large closed regions such as helmet streamers.

Yeh and Pneuman (1977) developed a current sheet model in which the positions and strengths of neutral-line current sheets are determined in an iterative solution to the pressure balance equation, including the effects of coronal expansion. While generalizable in principle, this technique is so numerically intricate that it will be difficult to use it in contexts much more complicated than the example of a photospheric dipole. In that case, however, it agrees very well with a full mhd solution.

3.3 Non-Spherical Source Surface Models

Schulz, et al. (1978) have recently produced a close simulation of mhd behavior by introducing a source surface that is non-spherical. Arguing that an isogauss surface of a potential field solution will have the desired property of being closest to the sun over regions of low average B, they calculate an analytic solution for the case of a photospheric dipole in which the source surface is defined by a constant value of B in a purely dipole field.

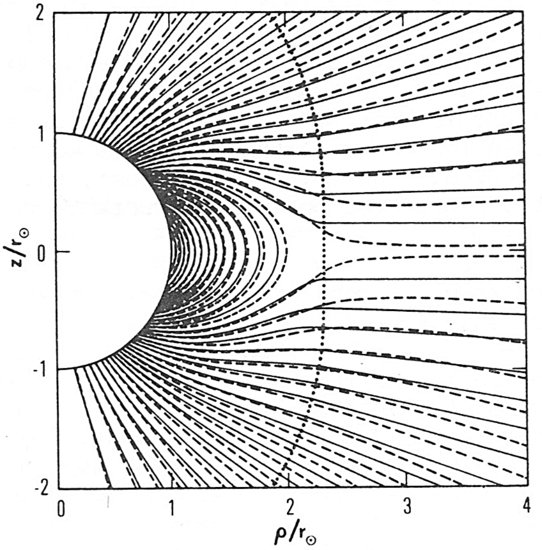

Figure 4. Configuration of magnetic field lines due to an internal solar dipole in the mhd solution of Pneuman and Kopp (1971, dashed lines) and in the non-spherical source surface model of Schulz, et al. (1978, solid lines). The position of the source surface is dotted and has an equatorial radius of 2.3 solar radii and a polar radius of 2.9 solar radii (from Schulz, et al. 1978).

Their example, shown in Figure 4, demonstrates the variation of the source surface radius and also a close agreement with the mhd solution of Pneuman and Kopp (1971) for an isothermal corona over a photospheric dipole. The field lines are deflected systematically equatorward from their equivalent positions in a spherical source surface solution. The exterior solution, produced by extrapolating the field outward normal to the source surface (rather than radially) in a rotating heliosphere, gives a field value at earth that is a few gammas for a one gauss dipole at the sun. This value is not highly dependent on latitude because of the deflection of flux from the polar regions toward the equator. Another important feature of the illustrative model of Schulz, et al. is that the (equatorial) current sheet is highly localized compared with the current distribution implied in a spherical source surface model.

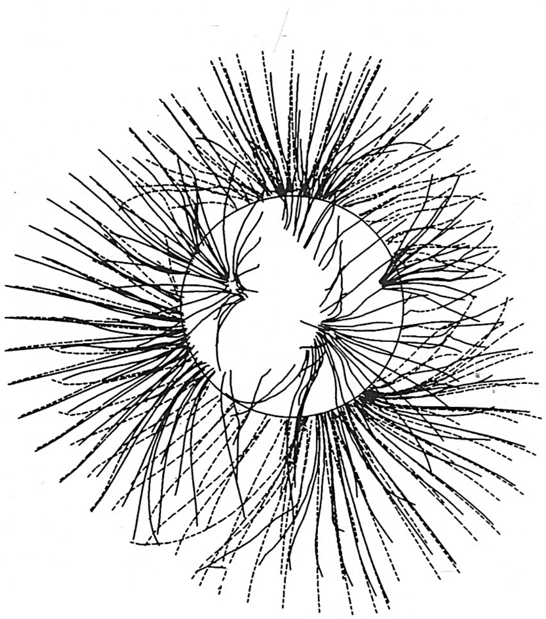

Figure 5. Configuration of magnetic field lines in a non-spherical source surface model being developed by Levine, Schulz, and Frazier. The photospheric data represents Carrington rotation 1601 and the source surface was chosen as an isogauss of the potential solution with no source surface.

It is possible to extend the formalism of Schulz, et al. (1978) for a non-spherical source surface to the analysis of actual photospheric data. This is being studied by Levine, Schulz, and Frazier. The advantages of this type of model are the expected ability to simulate more closely an exact mhd solution, and the provision for specifying any continuous distribution of radius as the source surface. Preliminary results are shown in Figure 5. The source surface was chosen as an isogauss of the potential field model for Carrington rotation 1601 and field lines have been plotted inward from the source surface. The highly non-spherical nature of the source surface is apparent, as is the presence of non-radially oriented coronal structures. Further work on this model, including the exterior solution for the interplanetary field and its evolution, is in progress.

4. OVERVIEW

Although I have attempted to present a coherent view of the structure of the sun's magnetic field and how it might be understood in a degree of detail matching that of the best observations, I have chosen a basically magnetostatic approach. In Section 3 I alluded to the fact that the full problem involved magnetohydrodynamic considerations which at the present time can only be simulated in realistically detailed models. Other approaches to the dynamically coupled problem of solar plasma-field interactions place more emphasis on accounting for all the magnetic stresses to a known degree of accuracy and less emphasis on reproducing observed magnetic fields. The exact mhd solution of Pneuman and Kopp (1971), for example, uses an isothermal corona, has an equatorial field strength at the photosphere half that at the poles, and gives unacceptable flow speeds. Nevertheless, it has proven extremely useful as the only fully nonlinear calculation with which comparisons can be made. An improvement over this calculation, either in terms of physics (e.g., inclusion of thermal conduction and/or a different photospheric field distribution) or of geometry (e.g., relaxation of azimuthal and/or north-south symmetry) would be welcomed. Analyses using mhd approximations, such as those of Suess, et al. (1977) or Nerney and Suess (1975), are applicable only well into the interplanetary medium but have the great advantage of treating the problem self-consistently. Regretfully, there is not sufficient space here to discuss these and other efforts in more detail.

Realistic expectations of progress in studying the structure and evolution of the solar magnetic field are contingent on continuing efforts in three major areas: (1) The synoptic observation of the solar magnetic field with sufficient spatial resolution to discriminate the major sources of magnetic flux. (2) Continued efforts to produce realistic theoretical models of the actual field structure in the low corona and its extension into the interplanetary medium. (3) The development of more mhd models for physically interesting test cases.

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DISCUSSION

Scherrer: You have suggested that the field pattern seen in low resolution observation of the photospheric field and in the interplanetary field has its origin in active regions. Is this consistent with the many year lifetime of the low resolution structure?

Levine: I should clarify that the active regions contribute to the pattern but they do not constitute its only source. As I mentioned, separate averages of concentrated and diffuse flux (essentially including and excluding the active region) both show the photospheric pattern. The data I used to draw this conclusion do not yet cover a time period of years. When that data becomes available, your question will be an important one to investigate. However, even for the time coverage I was able to study there were large-scale structures which lasted much longer than active regions, indicating that some active regions had to have a systematic tendency to reinforce the pattern rather than to destroy it.

Stix: Are there methods available to compute coronal fields with current sheets, which do not require knowledge about the location of these sheets? I mean methods which yield these sheets (e.g., its latitude) together with the surrounding potential field?

Levine: The technique of Schatten which I mentioned results in a model with implied current sheets at all neutral lines outside the shell he uses to define which field lines will be open. The work of Yeh and Pneuman allows specification of the location of current sheets, but only the simplest geometries are tractable. Source surfaces also contain current sheets, although it is only on the non-spherical source surfaces that the current system is well localized. Of course, if you are only interested in the latitude of possible current sheets the positions of neutral surfaces in any potential model will give a good first approximation.

McIntosh: The Stanford solar magnetic-field data can be formatted into synoptic charts of large-scale patterns of neutral lines. These agree closely with the Hα synoptic charts of chromospheric neutral lines. Doesn't this agreement indicate that solar mean field measurements detect solar sector boundaries that originate on, or near, the solar surface?

Levine: The Stanford instrument operates in a mode which produces magnetograms with three arc minute resolution (which are used to make the synoptic charts you mention) and in a mean field mode (this is the data I referred to in my talk). Synoptic charts of their resolved data do agree well with the nuetral lines of the Hα charts, which is to be expected because they both refer to fields near the surface. The mean field measurements also indicate a photospheric pattern. However, because the photospheric neutral line is covered by arcades of coronal loops (visible in X-ray or EUV emission) there can be no direct connection between the photospheric neutral line (sector boundary) and the interplanetary sector boundary. The interplanetary sectors spread like funnels from isolated areas within photospheric sectors. Their boundaries in the outer corona will have longitudes typically near those of the photospheric neutral lines, but their exact position is determined by the relative strengths of the fields in photospheric sectors and by MHD effects in the corona.

Moore: What is your opinion on whether some open field lines may be rooted in the umbras of sunspots?

Levine: The resolution of the numerical techniques used in extrapolating the coronal field is not sufficient to answer this question unambiguously. However, the models and the X-ray data (Švestka, et al. Solar Phys., 55, 359, 1977) are not inconsistent with this possibility. Note, however, that the possibly open structures in active regions tend to be elongated so that only a portion of the field lines could be rooted in a sunspot umbra. Further, if you consider the electrostatics of magnetic multipoles, you will recall that the highest field lines (those which are candidates for opening in the solar analogy) are rooted in the strongest fields.

Pneuman: Referring to the Schulz et al., computation, I think that the model is attractive in that it does incorporate a non-spherical source surface. However, I worry about the physical basis for choosing the surface as an iso-gauss contour. I would think a more appropriate assumption might be to relate the source surface to, perhaps, the Alfven speed which depends upon the solar wind velocity as well as the magnetic field.

Levine: Schulz et al., used an iso-gauss of a dipole field as a non-spherical source surface in order to obtain an analytical solution in a test case which had an appropriate quantitative behavior. This is perfectly acceptable. I agree, however, that other definitions of the source surface should also be explored in realistic cases. This is one goal of our program.