PART VI

OPTICAL AND RADIO OBSERVATIONS OF LARGE SCALE MAGNETIC FIELDS ON THE SUN

LARGE SCALE SOLAR MAGNETIC FIELDS AND THEIR CONSEQUENCES

GORDON NEWKIRK, JR.

High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colo., U.S.A.*

Abstract. The general properties of large scale solar magnetic fields are reviewed. In order of size these are: (1) Active region, generally bipolar fields with a lifetime of about two solar rotations. These are characterized by fields of several hundred G and display differential rotation similar to that found for the photosphere. (2) UM regions which appear to be the remnants of active region fields dispersed by the action of supergranulation convection and distorted by differential rotation. These are characterized by fields of a few tens of gauss and have lifetimes of several solar rotations. (3) The polar fields which are built up over the solar cycle by the preferential migration of a given polarity towards the poles. The poloidal fields are of a few gauss in magnitude and reverse sign in about 22 yr. (4) The large scale sector fields. These appear closely related to the interplanetary sector structure, cover tens of degrees in longitude, and stretch across the equator with the *same* polarity. This pattern endures for periods of up to a year or more, is *not* distorted by differential rotation, and has a rotation period of about 27 days. The presence of these long enduring sector fields may be related to the phenomenon of active solar longitudes. The consequences of large scale fields are examined with particular emphasis on the effects displayed by the corona. Calculated magnetic field patterns in the corona are compared with the density structure of the corona with the conclusion that: (1) Small scale structures in the corona, such as rays, arches, and loops, reflect the shape of the field and appear as magnetic tubes of force preferentially filled with more coronal plasma than the background. (2) Coronal density enhancements appear over plages where the field strength and presumably the mechanical energy transport into the corona are higher than normal. (3) Coronal streamers form above the 'neutral line' between extended UM regions of opposite polarity. The role played by coronal magnetic fields in transient events is also discussed. Some examples are: (1) The location of Proton Flares in open, diverging configurations of the field. (2) The expulsion of 'magnetic bottles' into the interplanetary medium by solar flares. (3) The relation of Type IV radio bursts to the ambient field configuration. (4) The guiding of Type II burst exciters by the ambient magnetic field. (5) The magnetic connection between widely separated active regions which display correlated radio bursts.

1. Introduction

The suspicion that the Sun maintained a general magnetic field was first stimulated by the similarity of the shape of the solar corona at sunspot minimum to that of the field lines around a bar magnet (Bigelow, 1889; Störmer, 1911). A brief history of our knowledge of large scale fields shows that this suspicion was to remain unsubstantiated for many years. Following his pioneering work (Hale, 1908) which demonstrated the presence of magnetic fields in sunspots, Hale (1913) turned his newly developed equipment to the detection of a dipole field of the Sun. In spite of great care taken to avoid systematic errors and the averaging of a great number of photographic observations of magnetically sensitive lines, the derived value of 50 G for the field at the poles was, as we now know, erroneous (Stenflo, 1970). In fact, subsequent observations at Mt. Wilson gave values of the polar magnetic field between zero and 50 G and, thus, cast doubt on the existence of such a field.

---

* The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Howard (ed.), Solar Magnetic Fields, 547–568. All Rights Reserved.

Following the application of photoelectric techniques to the problem, several investigators (von Klüber, 1951; Thiessen, 1952; Kiepenheuer, 1953; Babcock and Babcock, 1953) were able to show that the Sun did, indeed, have a polar field of magnitude 1–2 G. Continuous observation (Babcock and Babcock, 1955) of the magnetic field distribution over the entire disk of the Sun for several years not only confirmed the existence of a general polar field but also revealed two general types of low latitude fields: the bipolar regions (BMR) associated with active regions and the unipolar regions (UM), which were believed to be the long sought 'M' regions responsible for recurrent geomagnetic storms. The well documented weakening and subsequent reversal of the polar field during the sunspot maximum of 1958-59 (Babcock, H. D., 1959) led H. W. Babcock (1961) to formulate a qualitative model of the solar cycle which was based on a suggestion of Cowling (1953). The success of this model is well known to us all.

2. General Description of Large Scale Fields

The past decade has brought a remarkable increase in the sensitivity of solar magnetographs and a subsequent revision of our earlier ideas of large scale magnetic structures (Howard, 1967). Bumba and Howard (1965) found that weak magnetic fields pervade nearly the entire surface of the Sun and that this background field contains a persistent pattern of UM regions which lasts for many rotations. These extended regions (Figure 1) appear to consist of the weak, expanded fields of old active regions (Howard, 1967) and their shape is largely determined by the shearing produced by differential rotation. Leighton (1964) has suggested that the initially compact fields of an active region are gradually eroded by the motions within the constantly changing pattern of supergranulation cells and spread to widespread areas of the solar surface. The random dispersal of these fields, coupled with the differential rotation, produces, in his model, a shape for a UM region quite similar to that observed (Figure 2). The preferential transport of following polarity toward the pole accounts for the reversal of the polar fields.

Leighton (1969) has expanded his investigation to produce a model of the solar cycle in which the presence and dispersal of large scale magnetic fields play a crucial role. This model extends the earlier work of Babcock (1961) and Leighton (1964) to include a semi-quantitative treatment of the amplification, eruption to the surface, and spreading of magnetic field. Since the analysis requires the *ad hoc* assumption of several parameters, such as the critical field magnitude which causes eruption of a flux tube and the depth dependence of differential rotation, this work must be a considered midway between Babcock's pioneering qualitative model and a full scale solution of the hydromagnetic equations. One of the first attempts to formulate the full solution will be presented at this meeting by Nakagawa (1970).

Thus, many of the features of large scale solar magnetic fields are well observed and appear to be understandable in terms of theoretical models which are simple only in comparison to the complexity of the problem. However, recently we have become aware

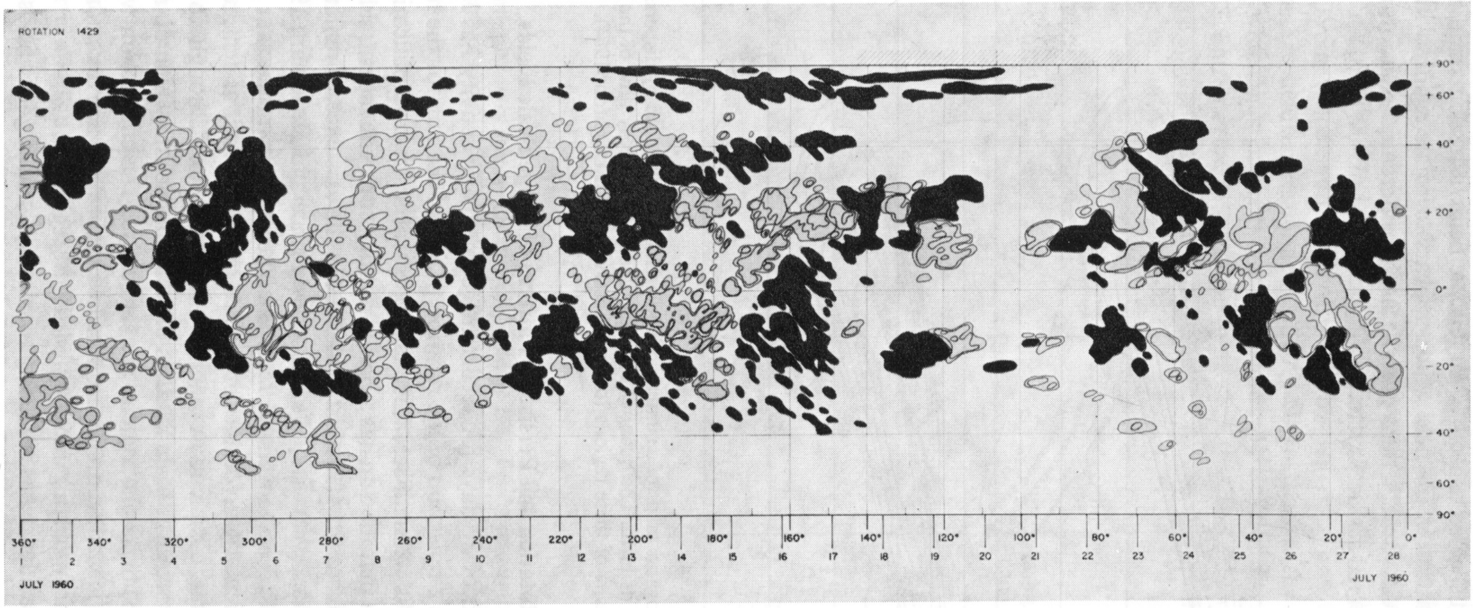

Fig. 1. A magnetic map of the entire solar surface dramatically displays the extended UM regions which result from the dispersal of the compact regions associated with active regions (courtesy Howard *et al.*, 1967).

of some other unsuspected aspects of large scale fields. Most outstanding is the existence of a gross pattern in the field which appears to rotate rigidly with a period of approximately 27 days rather than partake in the differential rotation characteristic of the directly observed surface layers.

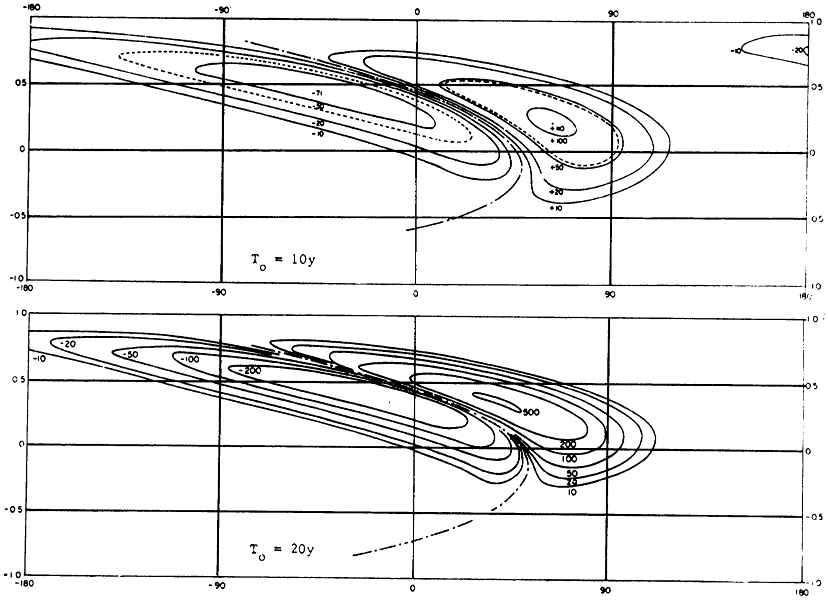

Fig. 2. Calculated isogauss maps of a simulated bipolar source influenced by dispersal and differential rotation $\frac{1}{2}$ yr after its birth. The quantity T_0 is the fundamental decay time of the field. Compare the shape of these regions to those observed (from Leighton, 1964).

3. Rotation and Persistent Patterns of Large Scale Fields

The synodic period of 27 days for recurrent geomagnetic activity has long been interpreted simply as a reflection of the rotation period of the Sun for the mean latitude of active regions. As we shall see, this may represent an oversimplification. The first concrete suggestion that the Sun has a rigidly rotating core with measurable effect at the photosphere came from the statistical evidence for the existence of remarkably active Carrington longitudes (Warwick, 1965; Dodson-Prince and Hedeman, 1968; Sawyer, 1968; Švestka, 1968; Van Hoven *et al.*, 1969). These papers noted that certain solar longitudes are particularly favorable for the production of various symptoms of solar activity such as flares, cosmic ray events on the Earth, etc. Although not *prima facie* evidence that there are large scale features of solar magnetism which do not share the differential rotation, these phenomena are suggestive. The connection with the large scale magnetic field is made more secure when we realize that active regions frequently erupt within previously existing and long-lived UM regions.

A second line of evidence has come from the analysis of magnetic fields measured in interplanetary space. Early investigations of this field (Ness and Wilcox, 1965) showed that it had, at least during periods of low solar activity, a remarkably simple sector structure (Figure 3) with the field generally directed toward or away from the Sun over sectors of 60° to 90° in longitude. This discovery was quickly followed (Ness and Wilcox, 1966; Wilcox and Howard, 1968) by the realization that the polarity of the interplanetary field corresponded rather well to that of the large scale photospheric field which has passed central meridian 4½ days earlier. The concept was extended by Schatten *et al.* (1969) who suggested that the field in the solar corona below a 'source sphere' with a radius of 1.6 to 2.5 R_0 was essentially the potential field distribution, while the field pattern at the 'source sphere' was mapped by the solar wind out into interplanetary space.

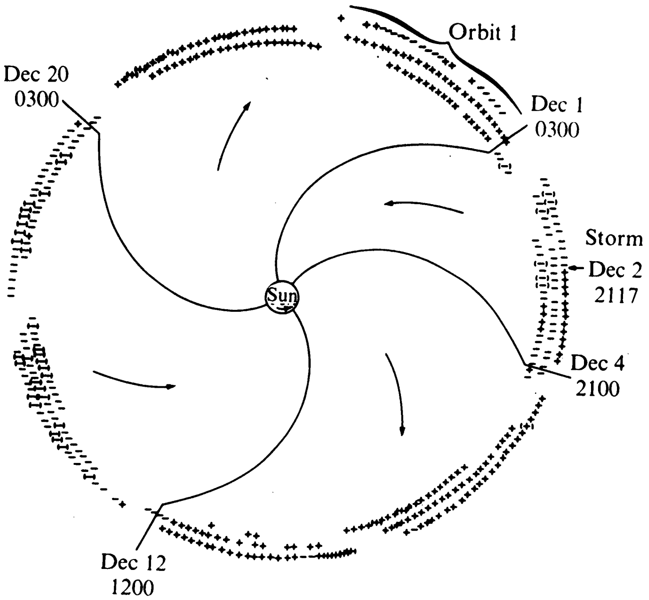

Fig. 3. The interplanetary sector structure observed by IMP-I is representative of one of the largest patterns of organization of the solar magnetic field (from Ness and Wilcox, 1965).

In an attempt to discover the solar origin of the interplanetary field, Wilcox and Howard (1970) determined the rotation rate of the photospheric fields detected on Mt. Wilson magnetograms and found that at low latitudes the rotation rate of the magnetic patterns is the same as that of sunspots. At higher latitudes, the pattern rotates at a rate consistent with that found for prominences and the corona (Hansen *et al.*, 1970). However, we must conclude that these patterns are not primarily responsible for the interplanetary sector structure. The surface fields associated with the sector boundary projected back on the Sun appear to rotate rigidly and have the *same* polarity north and south of the equator (Schatten *et al.*, 1969) (Figure 4). Apparently, the interplanetary field is dominated by very large scale, weak fields which were not

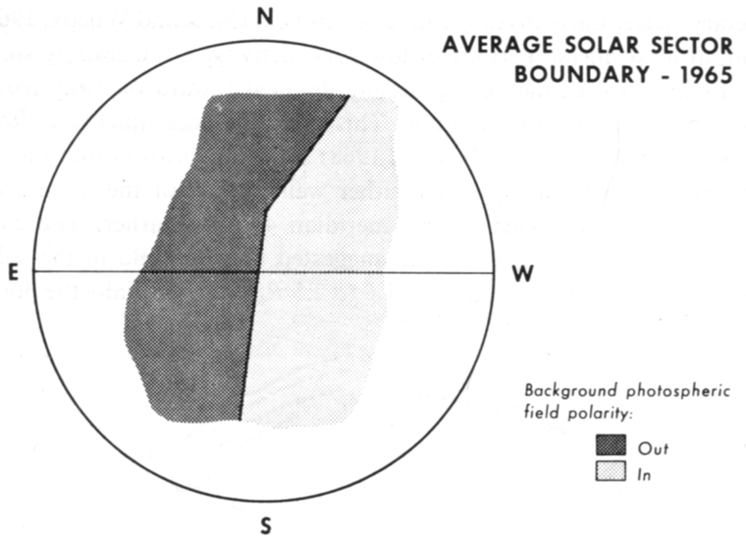

Fig. 4. The average background photospheric field associated with the sector boundaries observed during 1965 and projected back on the solar disk. On each side of the boundary the weak photospheric background field is predominantly of the same polarity. This weak pattern extends across the equator and does not appear to be sheared by differential rotation (from Schatten, *et al.*, 1969).

dominant in the Wilcox and Howard analysis. (They did not distinguish rotation rate according to field strength or the scale of the pattern.)

These very large scale, weak fields do show up in the hemispheric average of the field, which is closely related to the interplanetary field (Wilcox *et al.*, 1969; Severny *et al.*, 1970). They also appear in long term synoptic observations as shown by the analysis of Bumba and Howard (1969), which reveals not only the familiar, transient active regions which evidence the differential rotation, but also extended regions which occupy ten's of degrees in longitude and which have a rotation period of about 27 days. These extended regions persist for many months or years and stretch up to 20° on either side of the equator with the *same polarity*. A recent, statistical analysis of an equally long time series (Wilcox *et al.*, 1970) confirms these characteristics of the persistent, large scale pattern of the weak (~ 1 G) background field (Figure 5) as does the harmonic analysis (Altschuler *et al.*, 1971) to be described later today.

4. Consequences of Large Scale Solar Magnetic Fields

We have already touched on probably the most profound aspect of large scale fields – their central role in the solar cycle. Of course, these fields make their presence known by other ways than on our magnetographs. The extended weak field regions can be outlined by the practiced eye on calcium spectroheliograms (Howard and Harvey, 1964; Veeder and Zirin, 1970). They are undoubtedly responsible for the appearance of white light faculae over the poles during activity minimum (Waldmeier, 1955; Howard, 1959). The occurrence of filaments along the interface between regions of opposite polarity has been well documented (Howard, 1959). Of course, magnetic fields in the corona are, by and large, dominated by the large scale surface fields and we shall devote the remainder of the discussion to various aspects of coronal fields.

A. CORONAL MAGNETIC FIELDS

Unlike other areas of solar physics the study of coronal magnetic fields has had to rely almost exclusively upon calculation. Perhaps a brief review of such calculations is in order. They all begin with measures of the photospheric field and then, either in rectangular coordinates (Schmidt, 1964) over a volume small with respect to the Sun, or in spherical coordinates over a large volume (Newkirk *et al.*, 1968; Schatten *et al.*, 1969; Altschuler and Newkirk, 1969) calculate the potential field present. Without discussing the differences in the various mathematical techniques used in such calculations, we note that they share a common deficiency in either ignoring the electric

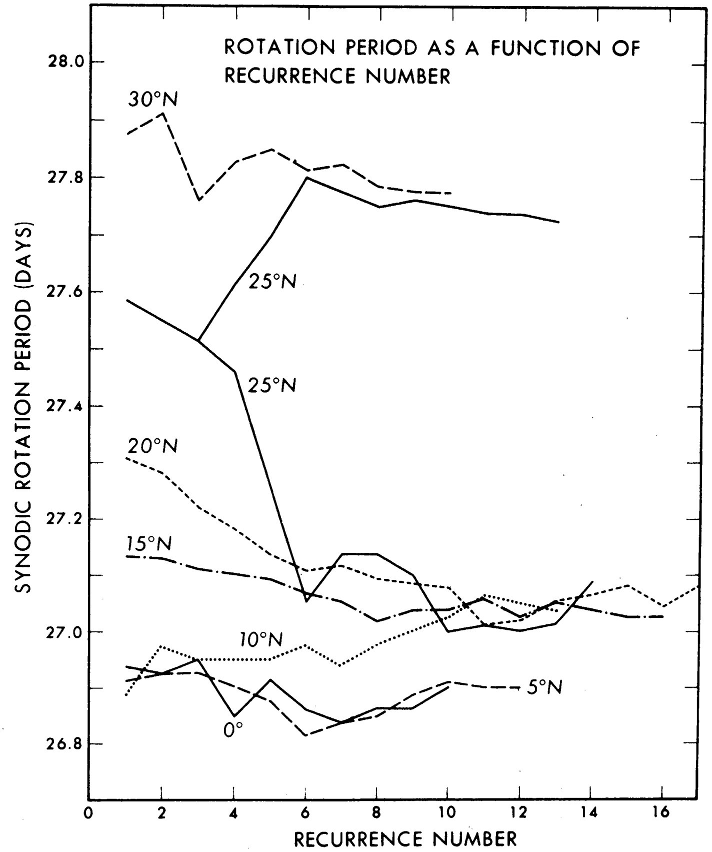

Fig. 5. The synodic rotation rate of solar magnetic fields from an autocorrelation analysis of eight years of Mt. Wilson data. Individual curves are for particular latitude zones. The very persistent features which can be followed through many recurrences have a period of 27 days with little indication of differential rotation (from Wilcox *et al.*, 1970).

currents which occur in the solar wind or incorporating them only by means of the rather crude technique of a zero potential surface or source surface. Moreover, the calculations requiring measurements of the field distribution over the entire photosphere are forced to use time averages of unknown accuracy.

Methods of checking these calculations are unfortunately scarce (Newkirk, 1967; Takakura, 1966) except where direct detection of the Zeeman splitting in prominences can be made (Severny and Zirin, 1961; Rust, 1966, Harvey, 1969; Tandberg-Hanssen, 1970). Analyses of the Razin effect in a single radio burst (Boischot and Clavelier, 1967; Ramaty and Lingenfelter, 1968; Bohlin and Simon, 1969) and of the weak polarization in some correlated bursts (Kai, 1969a) have, in the last few years, added a few more measures (Figure 6) of the magnitude of the field at ~2 $R_{\odot}$. In the absence of any event by event comparison between observed and calculated coronal fields we compare the observations with three simple models: (1) a R^{-2} extrapolation from interplanetary space, (2) the Legendre polynomial field above a plage for the surface fields of November 1966, and (3) a potential dipole model of a plage region. This comparison suggests two cautions: (1) the Legendre approximation will not yield

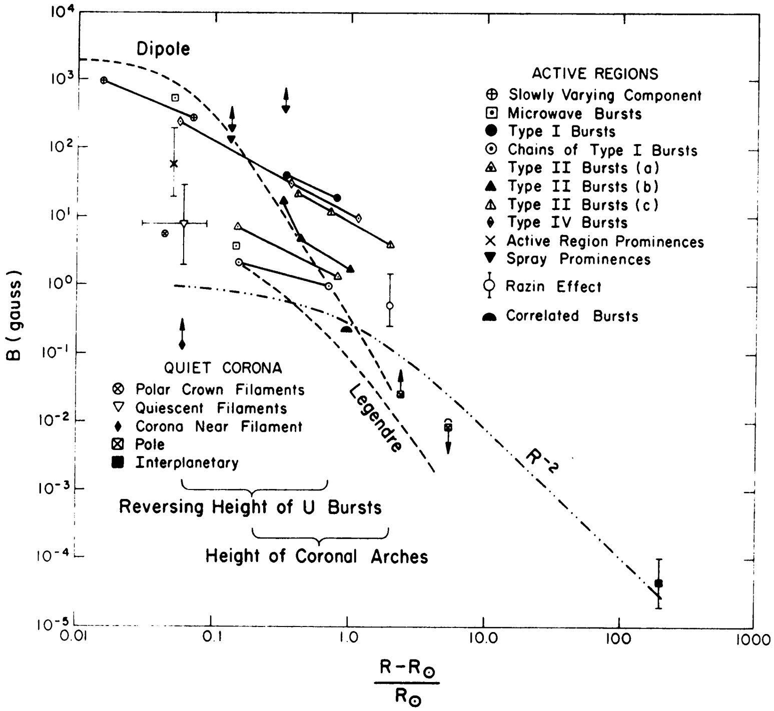

Fig. 6. Summary of measures of magnetic fields in the solar corona compared to (1) R^{-2} extrapolation from interplanetary space, (2) the field above a typical active region using the harmonic expansion method with $N=9$, and (3) a simple dipole potential model for an active region. Except for the Razin effect and the correlated burst measurements, all other references are to be found in Newkirk, 1967.

accurate results near active regions (a fact well known) and (2) radio bursts at $\sim 2\ R_\odot$ may well represent events in which a transient field disturbance is ejected into the corona and may be unsuitable as a measure of the quiet (i.e. current-free) magnetic field.

In fact, the only comparison between observed and calculated fields now at our disposal is in prominences (Harvey, 1969; Rust, 1966) which show, in general, an agreement between the shapes of the fields and currently accepted ideas for the occurrence of prominences within the fields. However, in active prominences, particularly, the measured fields are in excess of those calculated by a factor of five. The origin of this discrepancy is unknown. Similarly, comparison of the shapes of bright coronal emission regions and those of the calculated magnetic fields (Rust, 1970) gives some confidence that the potential field is a good first approximation and that the coronal loops delineate magnetic tubes of abnormally high material density.

B. MAGNETIC FIELDS AND THE SHAPE OF THE CORONA

This brings us to the important question of the influence of large scale magnetic fields on the shape of the solar corona. Although magnetic structures as small as 30000 km may affect such features as polar plumes (Saito, 1965; Newkirk and Harvey, 1968; Ivanchuk, 1968), in general only the extended fields will have major influence in the corona. The investigation of the relation between the magnetic field and the density structure of the corona has followed two lines. One is to compare the calculated fields with the known shape of the corona (Newkirk *et al.*, 1968; Bohlin, 1968; Schatten, 1968; Altschuler and Newkirk, 1969; Newkirk *et al.*, 1970; Newkirk and Altschuler, 1970). Whether the comparison is intended as a prediction (Schatten, 1970a) or as a *post facto* analysis, the method is basically the same. The second line of attack is to use a simplified distribution of the field and to solve the hydromagnetic and solar wind equations simultaneously (Pneuman, 1968; Pneuman, 1969; Pneuman and Kopp, 1970) to determine the resultant distribution of material, the field, the velocity structure, and the energy flow in the modified corona. We shall discuss some examples of both approaches.

To begin, we first examine the pattern of calculated coronal fields present during a typical period as seen against an Hα spectroheliogram (Figure 7). The magnetic fields may be conveniently divided into (1) Diverging Fields which are found in close association with plages, (2) Low Magnetic Arcades and (3) High Magnetic Arcades. Perhaps, most striking is the existence of magnetic arches connecting widely separated active regions. Such arches may well be the lines of communication which give rise to nearly simultaneous radio bursts in separated active regions (Wild, 1969a). In view of the close correlation between the positions of plages and coronal density enhancements, it is not surprising to find a similar correlation between such enhancements and the Diverging Field patterns. Comparing the overall structure of the corona with the field as in Figure 8, we find that coronal streamers appear to form over the High Magnetic Arcades. This is illustrated in Figure 8 by the superposition of the K-coronameter isophotes of a streamer, identified on the 12 November 1966 eclipse photograph on the coronal magnetic map. This substantiates the idea long used in theoretical models (Kuperus and Tandberg-Hanssen, 1967; Pneuman, 1968, 1969) *that streamers develop above the neutral line separating regions of opposite polarity.*

An examination of the relationship between the shapes of small scale features in the corona and of the magnetic field lines is almost inevitably restricted to an evaluation of their *projected* positions and appearances. Returning to the 1966 eclipse (Figure 8), we find that the agreement is quite good – we find open rays, arches, loops, etc. in the corona where they are indicated in the field. A similar conclusion is reached by examination of the most recent eclipse (Figure 9) as well as the 1965 eclipse (Figure 10). *Thus, we conclude that much of the fine structure visible in the corona is simply a mapping of magnetic tubes in the approximately potential field above the photosphere.*

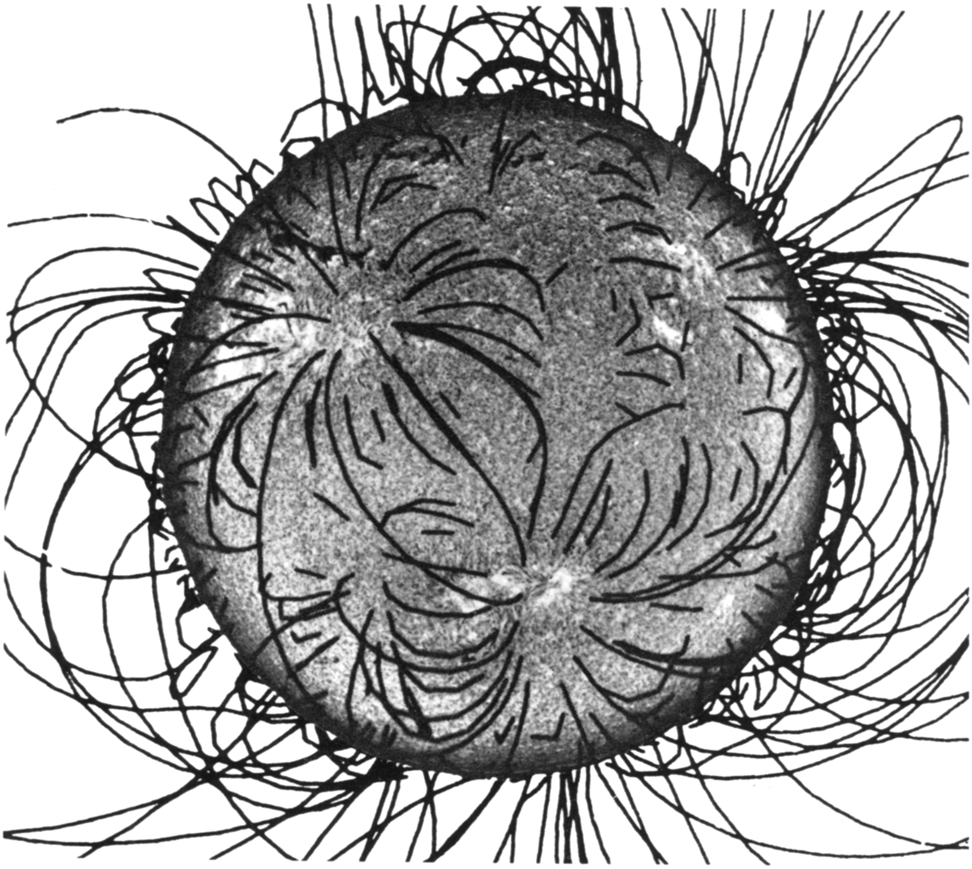

Fig. 7. Superposition of coronal field map (least-mean-square fit to B_L, $R_W = \infty$, corrected for magnetograph saturation) and the corresponding Ha filtergram (Sacramento Peak Observatory).

As an example of the more theoretical approach I cite the work of Pneuman (1968, 1969) and Pneuman and Kopp (1970). They assume a simple distribution of field as

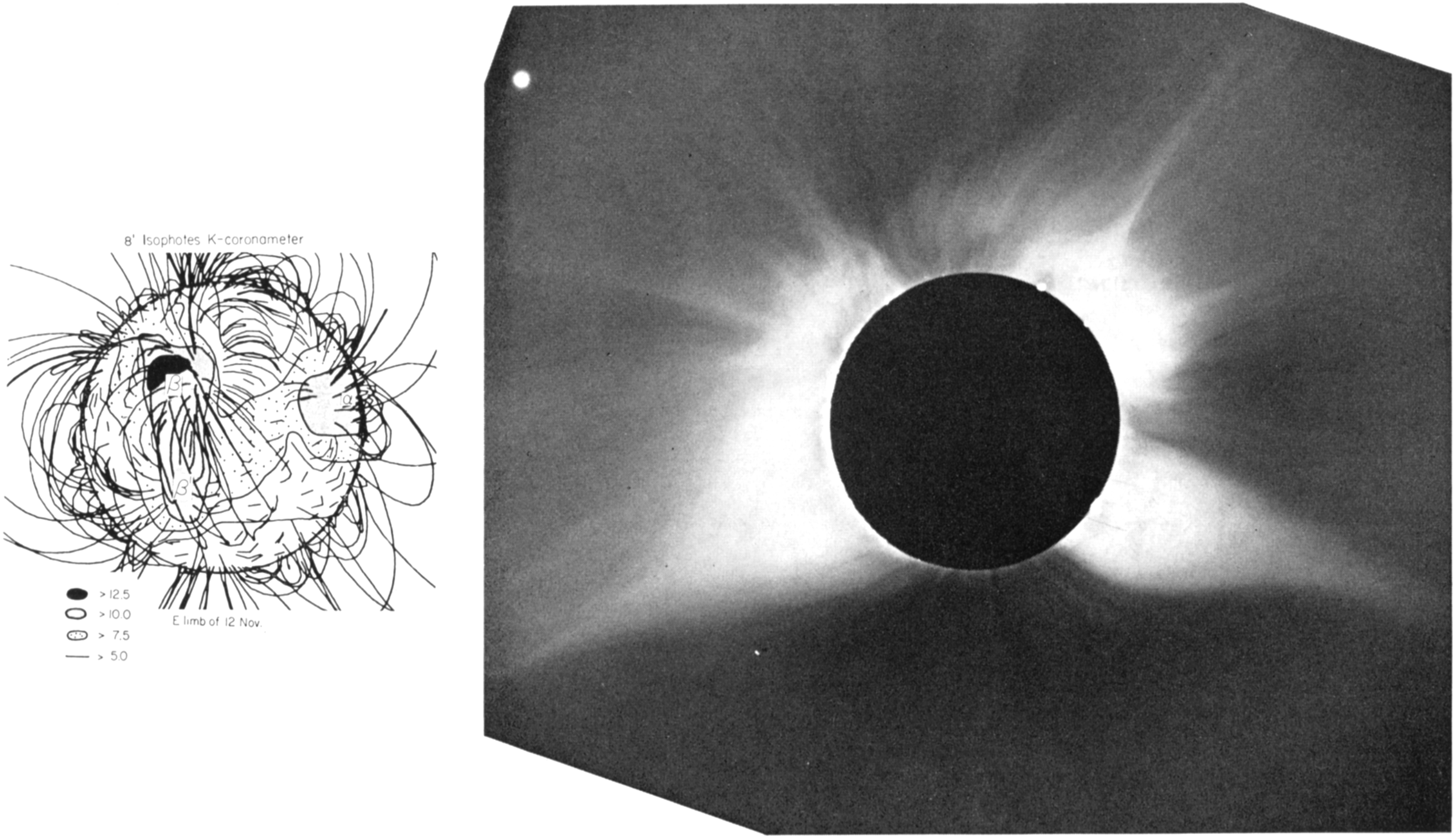

Fig. 8. Comparison of K-coronameter isophotes at 1.5 $R_\odot$ and a coronal magnetic field map (left)with the eclipse corona of 12 November 1966 (right). The central meridian of the magnetic map corresponds to the east limb (left) at the time of the eclipse and the line-of-sight proceeds from right to left across the map. Corresponding arches and rays can be easily located in the field and in the corona.

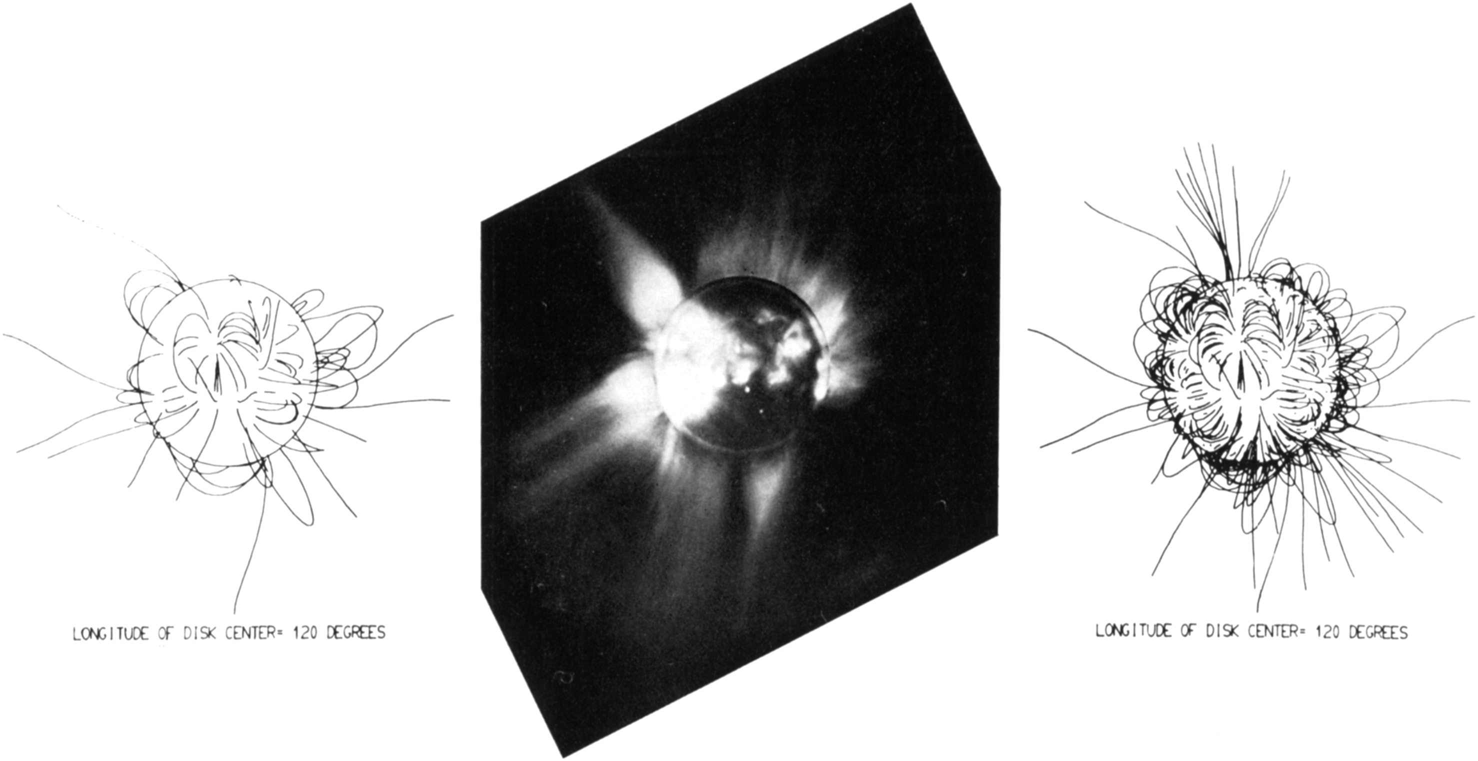

Fig. 9. Comparison of the solar corona of 7 March 1970 (outer corona HAO; X-ray corona seen on the disk courtesy Vaiana *et al.*, 1970, American Science and Engineering) with the corresponding coronal magnetic maps. In this and subsequent coronal magnetic displays, the weak field map on the right shows field lines originating at foot points where $B_L \geqslant 0.16$ G while in the strong field map at the left only field lines originating where $B_L \geqslant 10\%$ of the maximum line-of-sight field present at the surface are displayed.

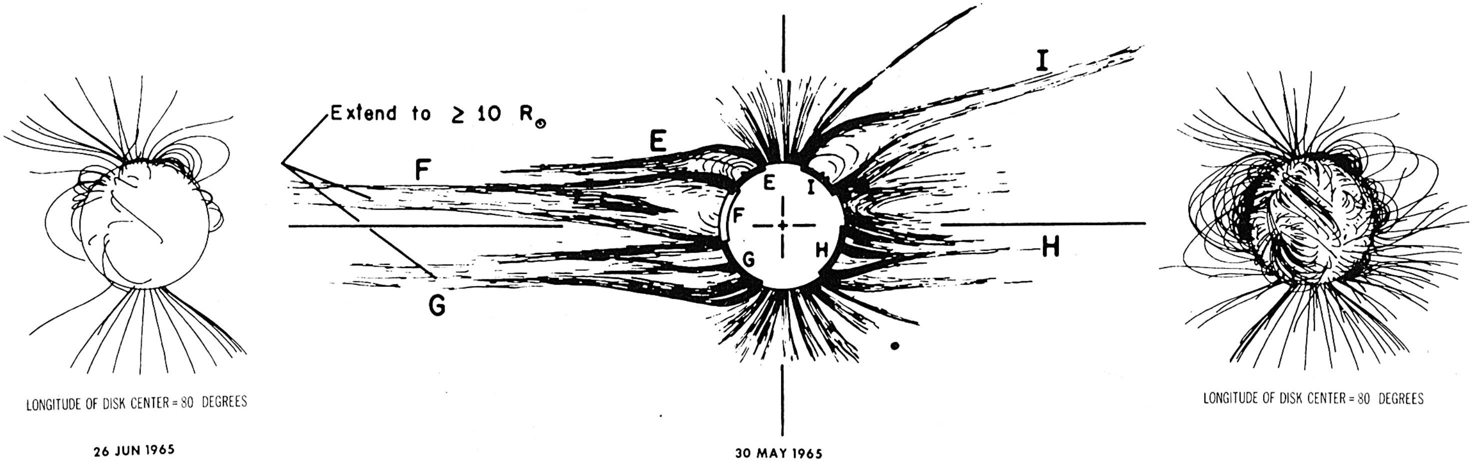

Fig. 10. Comparison of the solar corona of 30 May 1965 (drawing from Bohlin, 1968) with the corresponding magnetic maps. Note particularly the similarity between (1) the magnetic and coronal arches in streamer I and (2) the polar magnetic field and polar plumes (see caption Figure 9).

well as pressure equilibrium at the base of the corona. The hydromagnetic and energy transport equations are then solved iteratively to arrive at a model for the streamer which includes such parameters as:

(1) the profile of the boundary between streamer and interstreamer;
(2) the axial enhancement;
(3) the temperature profile; and
(4) the velocity structure.

At least for those parameters which can be measured, the agreement between the model and the structure of the corona is impressive. Such models are important because they allow us to see how the visible structures in the corona are molded by the magnetic field and how they influence the structure and dynamics of the interplanetary medium.

C. INFLUENCE ON CORONAL ROTATION

In addition to influencing the distribution of material and the expansion velocity of the solar corona, large scale magnetic fields clearly determine the rotation and the angular momentum of the interplanetary medium. Here we must take care to distinguish between the corotation of a feature such as a coronal streamer or a sector boundary and the angular velocity of the ions comprising the feature. Observational evidence for the tangential velocity of the corona at 1 AU comes to us from the orientation of comet tails (Brandt, 1967) and direct detection from space probes (Hundhausen, 1968). Both techniques yield a tangential velocity of 4–10 km/s, which would require rigid rotation of the corona out to $\sim 15\ R_\odot$ if conservation of angular momentum were to hold in the remainder of interplanetary space. Theoretical analyses (Pneuman, 1966; Weber and Davis, 1967; Modisette, 1967; Brandt *et al.*, 1969) show this concept to be vastly oversimplified. Coronal ions, while lagging behind the solar surface at all heights, receive significant angular momentum from the solar magnetic field from the surface to large distances out into the interplanetary medium. We have no data on the rotation of the inner corona to compare with these calculations.

The rotation of *structures* in the corona can be entirely independent of the motions of the individual ions. Present information (Hansen *et al.*, 1970) shows that the low coronal enhancements rotate with the large scale magnetic structures (Wilcox and Howard, 1970) rather than with active regions. Moreover, these data suggest that, at a given latitude, the rate of rotation may *increase* with height in a manner similar to that found in the photosphere (Livingston, 1969). This apparently anomalous phenomenon may be explained (Pneuman, 1971) by the confinement of coronal gas within magnetic loops which have their foot points anchored at different latitudes with different rates of rotation.

D. CORONAL MAGNETIC FIELDS AND TRANSIENT EVENTS

Thus far we have discussed the large scale magnetic field and its influence as if the field were constant in time. Clearly, this is not the case, and we now examine several types of transient events which appear intimately connected with magnetic fields.

One such phenomenon is associated with solar cosmic rays, which imply (1) a more or less direct channel for the escape of the particles from the flare region into interplanetary space and (2) storage and/or continuous generation of particles at the Sun for a period of many days (Fan *et al.*, 1968). An examination of the coronal magnetic field associated with a proton flare (Valdez and Altschuler, 1970) (Figure 11) suggests that the channel of direct escape may be found in the Diverging Fields asociated with every active region and that storage may occur in some of the closed loops connected with most active regions. That a proton flare may be associated with a permanent disruption of the large scale fields is shown by comparing Figures 11 and 12. Figure 12

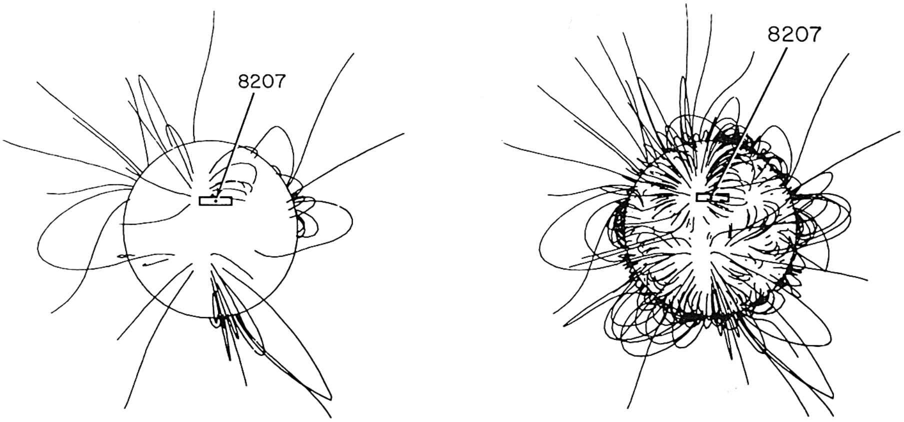

Fig. 11. Coronal magnetic maps for the Proton Flare of 16 April 1966 (Valdez and Altschuler, 1970) based on surface data taken *before* the occurrence of the flare. The location of the flare is marked with a rectangle (see caption Figure 9).

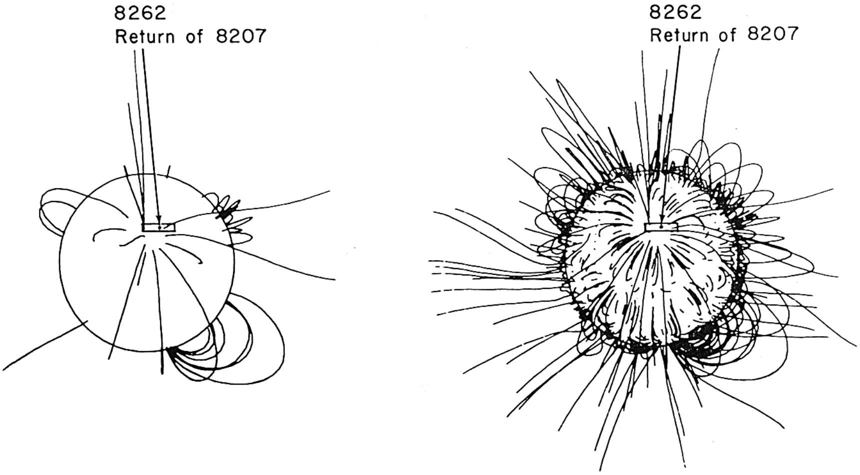

Fig. 12. Coronal magnetic maps for the Proton Flare of 16 April 1966 (Valdez and Altschuler, 1970) based on surface data taken *after* the occurrence of the flare. The location of the flare is marked with a rectangle (see caption Figure 9).

shows the same region as Figure 11 but one solar rotation later, after a proton flare. Note that the previously closed magnetic loops are open after the event. The fact that the open field lines appear in the current-free approximation indicates that a readjustment of the surface fields has occurred.

Radio occultation observations, either of natural sources (Dennison, 1970) or of satellite-borne transmitters (Levy *et al.*, 1969) give evidence for impulsive changes in the large scale magnetic field near the Sun. Transient changes in the angular broadening of the occulted Crab nebula with a time scale down to minutes may be due to streamers or other coronal features of magnetic origin intruding into the line-of-sight. A comparison of such observations with the calculated coronal fields has yet to be made. In the case of a spacecraft transmitter (Schatten, 1970b) (Figure 13), transient changes in the Faraday rotation were interpreted as a 'magnetic bottle' intruding into the line-of-sight at 10 $R_\odot$ after ejection by an observed flare. The observed direction of

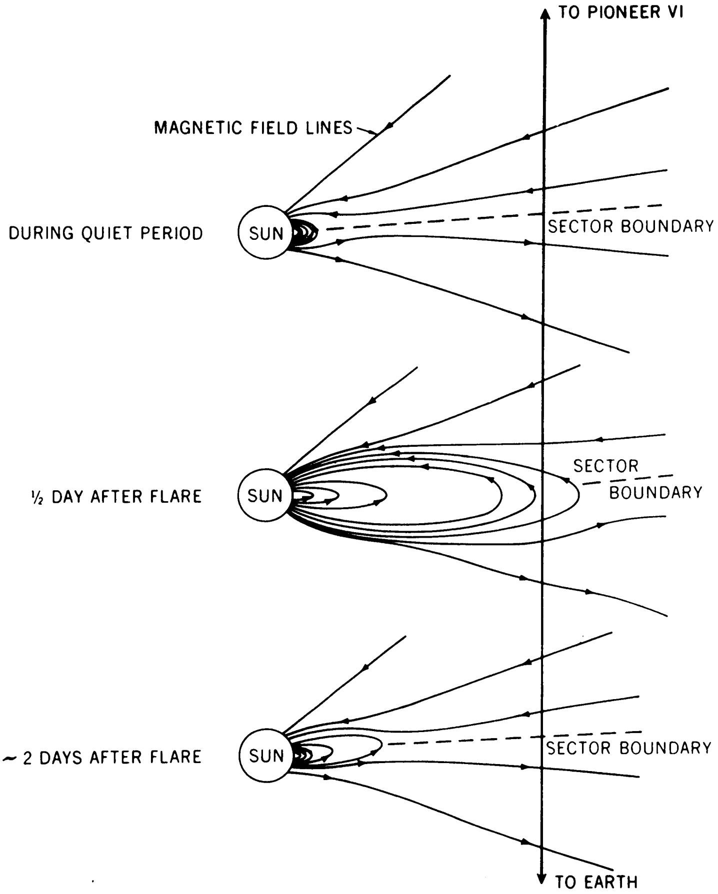

Fig. 13. Inferred geometry of the 'magnetic bottle' envisioned by Schatten (1970b) to account for the post flare transient change in Faraday rotation observed by Pioneer VI.

Faraday rotation was found to be consistent with the calculated fields in the lower magnetic arch which presubably expanded into the line-of-sight. Because the disturbing density and field both exceeded the ambient value by an order of magnitude, we appear to have an example of a true intrusion of a magnetic bottle rather than a minor perturbation of the previously existing corona.

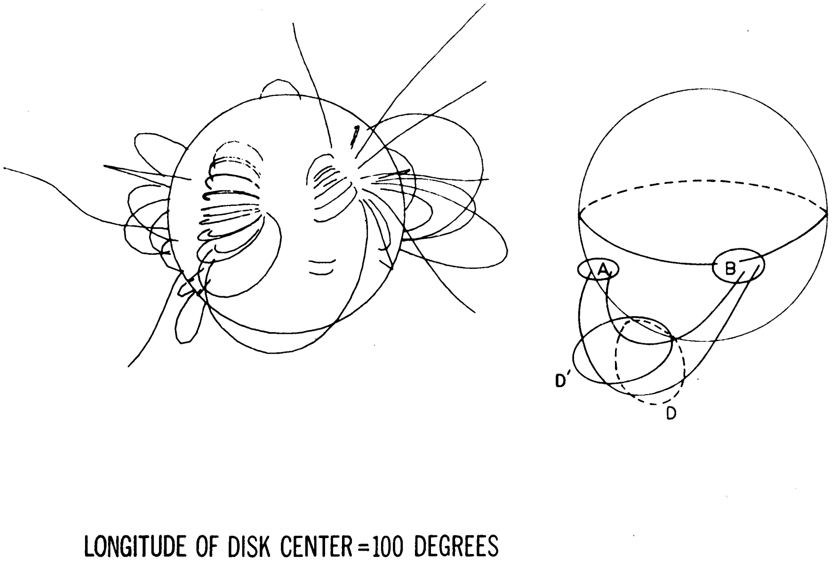

Fig. 14. Comparison of the magnetic arch inferred by Dulk (1970) from the radio bursts of 29–30 August 1969 (right) with the calculated magnetic map (left). Only field lines originating at foot points where $B_L \geqslant 10\%$ of the maximum line-of-sight field present at the surface are displayed.

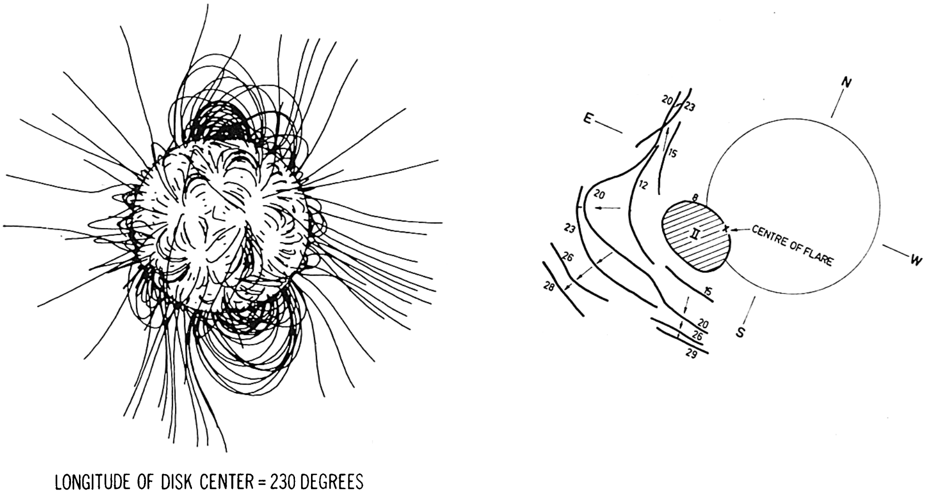

Fig. 15. Comparison of the successive positions of a rising Type IV burst (Kai, 1969b) with the corresponding coronal map. Field lines originating at foot points where $B_L \geqslant 0.16$ G are displayed.

Comparisons of radioheliograph observations of various radio bursts with corresponding magnetic maps have been made only recently and thus no detailed analyses can be reported. However, a brief examination of some of the data suggests that we have some exciting discoveries in store for us.

One of the most energetic of radio events is the Type IV burst believed to be due

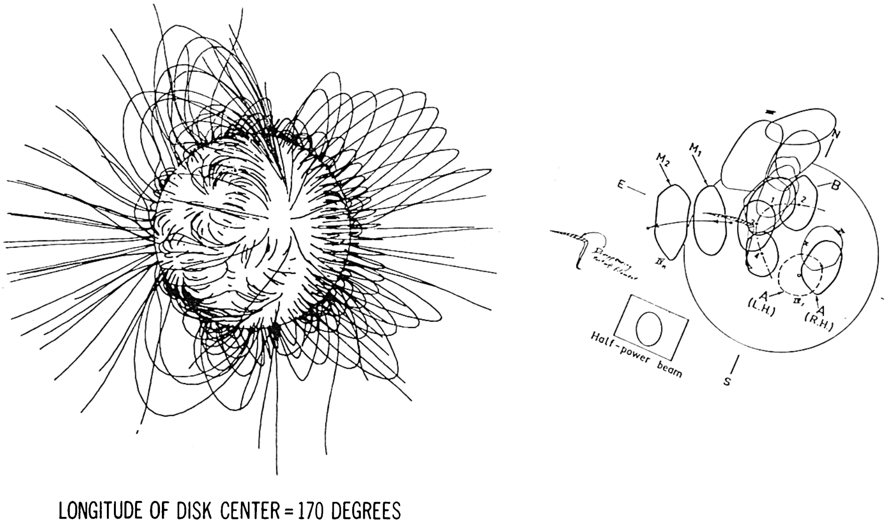

Fig. 16. Channeling of a directed shock, which gave rise to a complex of Type II, Type IV and Type III radio events and a disappearing prominence (Kai, 1969a), by the coronal magnetic field. Field lines originating at foot points where $B_L \geqslant 0.16$ G are displayed.

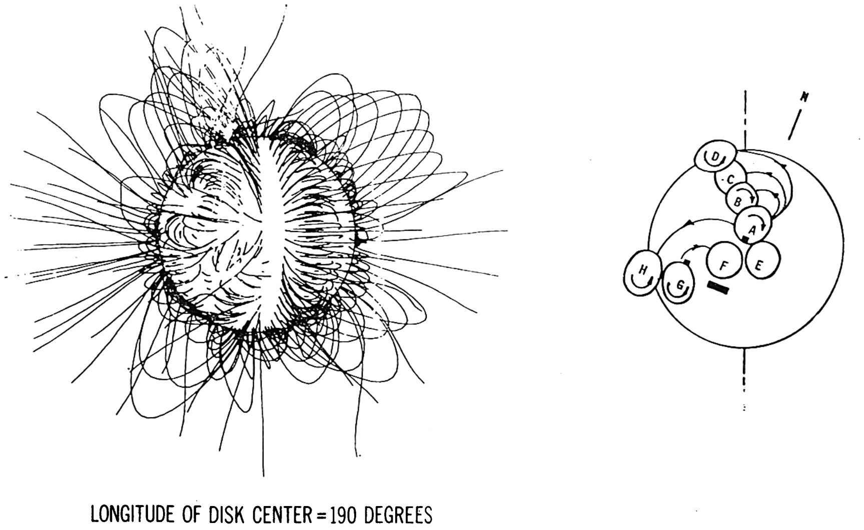

Fig. 17. Correlated radio bursts (Wild, 1970) between various centers (*A*, *B*, etc.) connected by curved lines in the radioheliograms (right) appear to be connected by magnetic arches in the magnetic map (left). Field lines originating at foot points where $B_L \geqslant 0.16$ G are displayed.

to synchrotron radiation from mildly relativistic electrons. A comparison between radioheliograph observations (Wild, 1970) of several of these bursts and the calculated magnetic fields in the corona (Smerd and Dulk, 1970; Newkirk, 1970) shows that various subclasses of the Type IV bursts appear to be influenced by the field in different ways. In one subclass (see Smerd and Dulk, 1970, Figure 12) we see a loop of Type IV emission (Wild, 1969b), which was associated with the flare (X) under the low magnetic loops. Smerd and Dulk (1970) interpret this event as the expansion of the low magnetic loops in which high energy particles are trapped. Alternatively, we might imagine a shock disturbance propagating along the Diverging Fields which proceed to the east from the general region of the flare; however, the slow source speed (<400 km/s) and high polarization are drawbacks to this interpretation.

From the detailed analysis of another burst Dulk (1970) has inferred the presence (Figure 14, right) of a magnetic arch in which the particles are trapped to produce the Type IV burst (D) at the top. That such a loop is a fairly permanent feature of the field is suggested by the comparison with the magnetic map (Figure 14, left).

In another expanding Type IV burst (Kai, 1969b) (Figure 15) the expansion appears to have occurred outward *along* the field lines. Here we may have evidence that the initiating shock wave, which may be responsible for the acceleration of the particles, has been guided by the field and that the moving burst is really the moving shock front. However, since we have not established the coincidence of the burst and the field in three dimensions, this conclusion may be premature (Smerd and Dulk, 1970).

A final moving Type IV (Riddle, 1970) was accompanied by the expulsion of a spray prominence (McCabe and Fisher, 1970). Both the prominence and the burst appear to have been conducted out along the magnetic field (see Smerd and Dulk, 1970, Figure 14). Riddle has suggested that this particular radio event may represent a vortex ejected from below.

Magnetic fields also appear directly responsible for guiding other types of radio disturbances. Kai (1969a) has reported a Type II burst which proceeded from a flare in only one direction and was followed by the disruption of a filament and a slowly moving Type IV. Inspection of Figure 16 strongly suggests that the channeling of the disturbance was, indeed, magnetic.

It has been suggested (Wild, 1970) that correlated radio bursts occur when high magnetic arches connecting widely separated regions conduct a triggering disturbance back and forth between the burst locations. Figure 17 suggests that this is actually the case, although channels for the southern group of correlated bursts are not nearly so obvious as those for the northern group.

5. Prospects and Problems

We have seen that the consequences of large scale solar magnetic fields appear in a variety of forms. Such fields are of primary importance in understanding the fundamental mechanisms underlying the solar cycle. Moreover, they appear to determine the density structure and rotation of the corona as well as its projection out into the interplanetary medium. It is only the large scale features of the field which have an influence on the solar wind as it eventually reaches the Earth. In addition, our present information suggests that it is the large scale fields which act as the guiding force for a variety of impulsive events in the outer solar atmosphere such as radio bursts and cosmic rays and may well act as the container for the storage of cosmic rays over many days.

Many of these suggestions are speculative to say the least and much work remains to be done. However, many questions regarding the basic nature of large scale fields also persist. Their meridional structure and apparent rigid rotation does not fit comfortably into any of the theoretical models now receiving current attention. The evolution of these large, weak regions of field is known only in its bare outlines as is their connection to the density, velocity and magnetic structure of the corona and interplanetary medium.

I suggest that one of the most critical needs at the present time is for more, daily, accurate full disk magnetograms so that the growth and evolution of the large scale structures may be followed for many years. Also, we need observations relating directly to magnetic fields in the outer corona as well as synoptic observations of the corona itself and the transient events which penetrate it. Observations of the magnetic field in the lower corona and in prominences are also needed. In the theoretical area we require the diagnostic tools which utilize the observations and yield information on magnetic fields – I mention coronal emission line polarization and radio burst excitation and polarization as two examples. Finally, the existence and behavior of the large scale fields must ultimately have a theoretical interpretation which not only describes what we observe but explains their origin.

Note added in proof: The coronal magnetic field maps presented in this paper are based on photospheric magnetograph data furnished by R. Howard (Hale Observatories) and obtained in a program supported in part by the Office of Naval Research under contract NR 013-230, N000 14-66-C-0239.

References

Altschuler, M. D. and Newkirk, G., Jr.: 1969, *Solar Phys.* **9**, 131.
Altschuler, M. D., Newkirk, G., Jr., Trotter, D. E., and Howard, R.: 1971, this volume, p. 588.
Babcock, H. D.: 1959, *Astrophys. J.* **130**, 364.
Babcock, H. W.: 1961, *Astrophys. J.* **133**, 572.
Babcock, H. W. and Babcock, H. D.: 1953, in *The Sun*, (ed. by G. P. Kuiper) p. 704.
Babcock, H. W. and Babcock, H. D.: 1955, *Astrophys. J.* **121**, 349.
Bigelow, F. H.: 1889, *The Solar Corona*, Smithsonian Institute, Washington D.C.
Bohlin, J. D.: 1968, Ph.D. Thesis, Department of Astro-Geophysics, University of Colorado.
Bohlin, J. D. and Simon, M.: 1969, *Solar Phys.* **9**, 183.
Boischot, A. and Clavelier, B.: 1967, *Astrophys. Letters* **1**, 7.
Brandt, J. C.: 1967, *Astrophys. J.* **147**, 201.
Brandt, J. C., Wolff, C., and Cassinelli, Joseph: 1969, *Astrophys. J.* **156**, 1117.
Bumba, V. and Howard, R.: 1965, *Astrophys. J.* **141**, 1502.
Bumba, V. and Howard, R.: 1969, *Solar Phys.* **7**, 28.
Cowling, T. G.: 1953, in *The Sun*, (ed. by G. P. Kuiper) p. 565.

Dennison, P. A.: 1970, Private Communication.

Dodson-Prince, H. W. and Hedeman, E. R.: 1968, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, 56.

Dulk, G. A.: 1970, submitted to *Australian J. Phys.*

Fan, C. Y., Pick, M., Pyle, R., Simpson, J. A., and Smith, D. R.: 1968, *J. Geophys. Res.* **73**, 1555.

Hale, G. E.: 1908, *Astrophys. J.* **28**, 315.

Hale, G. E.: 1913, *Astrophys. J.* **38**, 27.

Hansen, R. T., Hansen, S. F., and Loomis, H. G.: 1970, *Solar Phys.* **10**, 135.

Harvey, J. W.: 1969, Ph.D. Thesis, Department of Astro-Geophysics, University of Colorado.

Howard, R.: 1959, *Astrophys. J.* **130**, 193.

Howard, R.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 1.

Howard, R., Bumba V., and Smith, S. F.: 1967, *Atlas of Solar Magnetic Fields*, Carnegie Institute of Washington, Publication 626.

Howard, R. and Harvey, J. W.: 1964, *Astrophys. J.* **139**, 1328.

Hundhausen, A. J.: 1968, *Space Sci. Rev.* **8**, 690.

Ivanchuk, V. I.: 1968, *Problems in Cosmic Physics*, p. 129.

Kai, K.: 1969a, *Proc. Astron. Soc. Australian* **1**, 186.

Kai, K.: 1969b, *Solar Phys.* **10**, 460.

Kiepenheuer, K. O.: 1953, Proc. **9**, Volta Conference, Rome, 1.

Krieger, A. S., Vaiana, G. S., and Van Speybroeck, L. P.: 1971, this volume, p. 397.

Kuperus, M. and Tandberg-Hanssen, E.: 1967, *Solar Phys.* **2**, 39.

Leighton, R. B.: 1964, *Astrophys. J.* **140**, 1547.

Leighton. R. B.: 1969, *Astrophys. J.* **156**, 1.

Levy, G. S., Sata, T., Seidel, B. L., Stelzried, C. T., Ohlson, J. E., and Rusch, W. V. T.: 1969, *Science* **166**, 596.

Livingston, W. C.: 1969, *Solar Phys.* **9**, 448.

McCabe, M. K. and Fisher, R. R.: 1970, *Solar Phys.* **14**, 212.

Modisette, J. L.: 1967, *J. Geophys. Res.* **72**, 1521.

Nakagawa, Y.: 1971, this volume, p. 25.

Ness, N. F. and Wilcox, J. M.: 1965, *Science* **152**, 161.

Ness, N. F. and Wilcox, J. M.: 1966, *Astrophys. J.* **143**, 23.

Newkirk, G. Jr.: 1967, *Ann. Rev. Astrophys. J.* **5**, 213.

Newkirk, G., Jr.: 1970, in Macris (ed.), *Physics of the Solar Corona*, NATO Advanced Study Institute on Physics of the Solar Corona, Greece.

Newkirk, G. Jr., Altschuler, M. D., and Harvey, J.: 1968, in K. O. Kiepenheuer (ed.), 'Structure and Development of Solar Active Regions', *IAU Symp.* **35**, 379.

Newkirk, G. Jr. and Altschuler, M. D.: 1970, *Solar Phys.* **13**, 131.

Newkirk, G. Jr. and Harvey, J. W.: 1968, *Solar Phys.* **3**, 321.

Newkirk, G. Jr., Schmahl, E. J., and Deupree, R. G.: 1970, *Solar Phys.* **15**, 15.

Pneuman, G. W.: 1966, *Astrophys. J.* **145**, 242.

Pneuman, G. W.: 1968, *Solar Phys.* **3**, 578.

Pneuman, G. W.: 1969, *Solar Phys.* **6**, 255.

Pneuman, G. W.: 1971, *Solar Phys.*, in press.

Pneuman, G. W. and Kopp, Roger: 1970, *Solar Phys.* **13**, 176.

Ramaty, R. and Lingenfelter, R. E.: 1968, *Solar Phys.* **5**, 531.

Riddle, A. C.: 1970, *Solar Phys.* **13**,448.

Rust, D.: 1966, Ph.D. Thesis, Department of Astro-Geophysics, University of Colorado.

Rust, D. M. and Roy, J.-R.: 1971, this volume, p. 569.

Saito, K.: 1965, *Publ. Astron. Soc. Japan* **17**, 1.

Sawyer, C.: 1968, *Ann. Rev. Astron. Astrophys.* **6**, 115.

Schatten, K. H.: 1968, *Nature* **220**, 1211.

Scahtten, K. H.: 1970a, *Nature* **226**, 251.

Schatten, K. H.: 1970b, *Solar Phys.* **12**, 484.

Schatten, K. H., Wilcox, J. M., and Ness, N. F.: 1969, *Solar Phys.* **6**, 442.

Schmidt, H. U.: 1964, in *NASA Symposium on Physics of Solar Flares*, p. 107.

Severny, A., Wilcox, J. M., Scherrer, P. H., and Colburn, D. S.: 1970, Univ. Calif, Berkeley, Preprint Series 11, Issue 36.

Severny, A. and Zirin, H.: 1961, *Observatory* **81**, 155.

Smerd, S. F. and Dulk, G. A.: 1971, this volume, p. 616.

Stenflo, J. O.: 1970, *Solar Phys.* **13**, 42.

Störmer, K.: 1911, *Compt. Rend. Acad. Sci. Paris* **152**, 425.

Švestka, Z.: 1968, *Solar Phys.* **4**, 18.

Takakura, T.: 1966, *Space Sci. Rev.* **5**, 80.

Tandberg-Hanssen, E.: 1971, this volume, p. 192.

Thiessen, G.: 1952, *Z. Astrophys.* **30**, 185.

Valdez, J. and Altschuler, M. D.: 1970, *Solar Phys.* **15**, 446.

VanHoven, Gerard, Sturrock, P. A., and Switzer, Paul: 1969, AAS Meeting, Pasadena, California.

Veeder, G. J. and Zirin, H.: 1970, *Solar Phys.* **12**, 391.

Von Klüber, H.: 1951, *Observatory* **71**, 9.

Waldmeier, M.: 1955, *Z. Astrophys.* **38**, 37.

Warwick, C. S.: 1965, *Astrophys. J.* **141**, 500.

Weber, E. J. and Davis, L. Jr.: 1967, *Astrophys. J.* **148**, 217.

Wilcox, J. M. and Howard, R.: 1968, *Solar Phys.* **5**, 564.

Wilcox, J. M. and Howard, R.: 1970, *Solar Phys.* **13**, 251.

Wilcox, J. M., Schatten, K. H., Tanenbaum, A., and Howard, R.: 1970, Univ. Calif. Berkeley, Preprint Series 11, Issue 22.

Wilcox, J. M., Severny, A., and Colburn, D. S.: 1969, *Nature* **224**, 353.

Wild, J. P.: 1969a, *Proc. Astron. Soc. Austral.* **1**, 181.

Wild, J. P.: 1969b, *Solar Phys.* **9**, 260.

Wild, J. P.: 1970, *Proc. Astron. Soc. Austral.* **1**, 365.

Discussion

Schatten: Jan Stenflo and I discussed the fact that if the photospheric fields are measured to be 2 or 3 times too small, then a 'source surface' or zero potential surface more in accord with your observations of 2.5 or 3 $R_\odot$ would be appropriate. This would not change the calculated polarities much but would substantially weaken the 'source surface' field relative to the photospheric field and so could bring them into agreement with the larger photospheric fields suggested.

Newkirk: Then apparently we are in agreement that the source surface should be at 2 to 2.5 $R_\odot$ during 1966 although its height undoubtedly depends upon the solar cycle.