THE MAGNETIC FIELD STRUCTURE IN THE ACTIVE SOLAR CORONA

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Abstract. The structure of the magnetic field of the active solar corona is discussed with reference to optical and radio observations of the solar atmosphere. Eclipse observations provide evidence of fine scale structures in the solar atmosphere that appear to relate to the coronal magnetic field. The coronal magnetic field used for comparison is that field calculated from potential theory: the influence of solar activity upon the potential theory field is discussed with reference to observations of the Faraday rotation of a microwave signal from Pioneer 6 as it was occulted by the solar atmosphere. Evidence has been found suggesting the existence of expanding magnetic bottles located at 10 $R_\odot$ above flaring active regions. The dynamics of these events is discussed. It is further suggested that these magnetic bottles are an important component in the solar corona.

I would like to discuss optical and radio observations of the corona and their relation to the magnetic field in the active corona.

First I would like to mention briefly the inactive corona for reference. Gordon Newkirk has described the research relating the computed coronal magnetic field to the observed features in the visible corona at the time of an eclipse.

Some of the basic physics involved in the structuring processes of the solar corona may be understood by referring to Figure 1. This figure illustrates the energy densities of various components of the solar atmosphere as a function of distance above the photosphere. The energy curves shown are to be interpreted from a somewhat qualitative viewpoint in that temporal and spatial variations may significantly alter these curves. Nevertheless the curves do show the relative importance of various components of the corona. Close to the Sun both the total magnetic field and the transverse magnetic field predominate indicating a force-free field configuration results. Beyond about 0.6 $R_\odot$ the plasma thermal energy density supersedes the transverse field energy density. This allows the plasma to stream away from the Sun carrying the magnetic field. The supersonic point is about 3 $R_\odot$. The Alfvén point is between 20 and 30 $R_\odot$. This is where the flow energy density exceeds the field energy density and thus the flow is super-Alfvénic and escape of the plasma is inevitable. This point will be important later.

The second figure is a schematic showing the magnetic field in the solar corona as it extends outward to 1 AU. Region 1 represents the photosphere where the magnetic fields are essentially held rigidly due to the large amount of plasma present and rotate with the Sun. Region 2 represents the inner corona where the magnetic field energy density supersedes the plasma energy density. Thus the magnetic field determines the geometry and thus the plasma rotates with the field lines. The large-scale field lines obey the current-free field equations and thus form arches and rays. At about 0.6 $R_\odot$ the plasma energy density supersedes the transverse field energy and thus

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currents flow which cause the magnetic field to form an open field configuration and allow the plasma to escape. This field is then stretched into an Archimedes spiral. This was predicted by Parker and observed on many spacecraft experiments.

Comparisons of field calculations with observations of coronal structure from eclipse photographs adds support to these ideas. Figure 3 shows a comparison of a drawing based upon field calculations with a photograph of the November 12, 1966

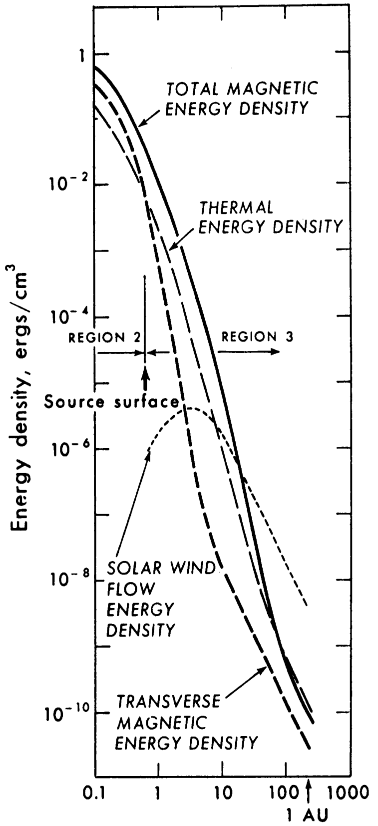

Fig. 1. The coronal energy density of the total magnetic field, transverse magnetic field, thermal motion, and solar wind flow versus distance above the photosphere. In Region 2 the magnetic field dominates the structure. On the source surface currents flow which allow the field to be transported by the solar wind.

eclipse. The Sun was not yet very active. There is fairly good agreement of many of the large scale features.

I would now like to discuss one aspect, perhaps the most significant of the influence of solar activity upon coronal magnetic field structure. This is the expulsion of magnetic flux from the inner corona by flare activity. The influence of a flare upon the coronal field occurs primarily from the creation of a hotter denser plasma expanding outward

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from the flare region. We shall therefore discuss the manner in which the coronal magnetic field reacts to this change.

A unique experiment conducted by Gerry Levy and others at the Jet Propulsion Laboratory allowed observations of the coronal magnetic field from 4 to 16 $R_\odot$ that enabled an interpretation of the interaction. Figure 4 shows the geometry involved in the experiment. Levy *et al.* (1969) measured the Faraday rotation of the microwave signal transmitted by Pioneer 6 as it passed through the solar corona to Earth.

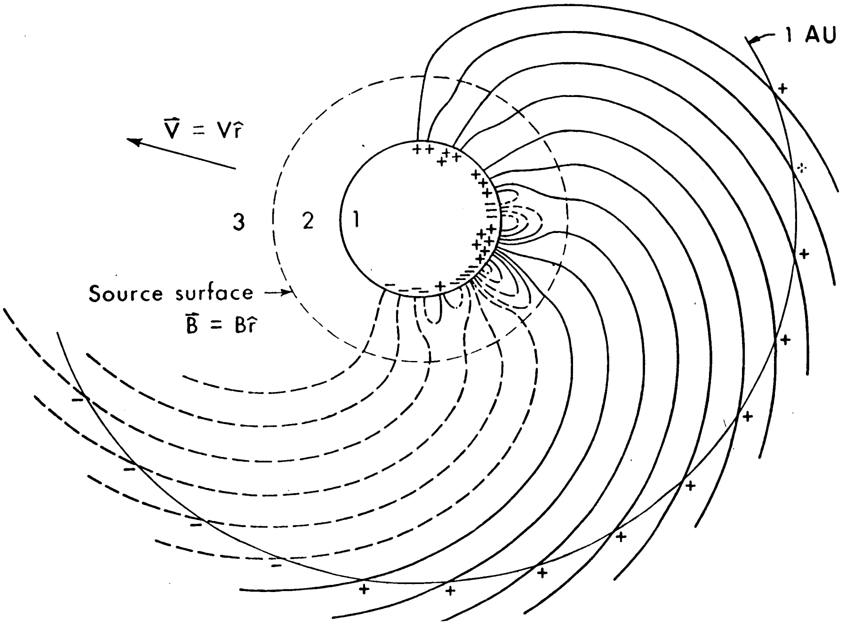
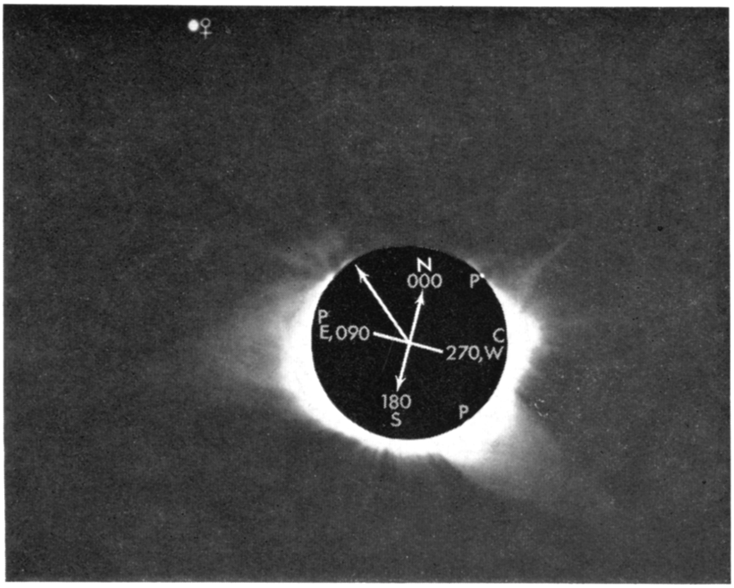


Fig. 2. Schematic representation of the source surface model. The photospheric magnetic field is measured in Region 1 at Mount Wilson Observatory. Closed field lines (loops) exist in Region 2. The field in this region is calculated from potential theory. Currents flowing near the source surface eliminate the transverse components of the magnetic field, and the solar wind extends the source surface magnetic field into interplanetary space. The magnetic field is then observed by spacecraft near 1 AU.

In this figure the undisturbed coronal magnetic field pattern is shown as suggested by the coronal models of Altschuler and Newkirk (1968), and Schatten *et al.* (1968). Solid lines indicate away from the Sun magnetic field and dashed lines indicate toward the Sun field. Close to the Sun (within approximately a solar radius), the magnetic field may form closed loops but beyond this distance a Parker type Archimedean spiral geometry is thought to occur on average. In the absence of any disturbance the signal to Earth from Pioneer 6 passes through the open field geometry.

This Faraday rotation experiment provides a measure of the line integral of the electron density times the component of the magnetic field along the line of sight from the spacecraft to Earth. Levy *et al.* (1969) report three transient phenomena with



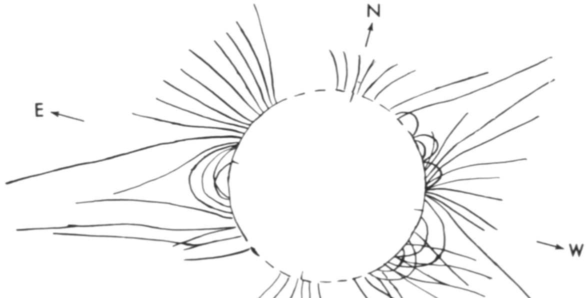


Fig. 3. Photograph of the corona of November 12, 1966 by S. Smith – NASA Ames Research Center (top). Drawing of the magnetic structure of the corona from source surface potential theory (bottom).

Faraday rotations on the order of 40° with a duration approximately two hours. These Faraday rotation signals were observed when the distances from the Sun to the Pioneer 6-Earth line of sight were 6, 9 and 11 $R_{\odot}$.

A possible model for producing the Faraday rotation observed by Pioneer 6 but allowing the interplanetary sector pattern to remain intact is shown in Figure 5.

A flare of importance 1 or a subflare occurs in the active region resulting in the heated coronal plasma expanding to produce the magnetic field configuration shown here. This field configuration is similar to that proposed by Gold (1959) for a solar outburst reaching 1 AU. In this case the heated plasma expands the looped coronal magnetic field past the Pioneer 6 Earth line of sight at about 10 $R_{\odot}$. The tension in the magnetic field, however, may prevent the coronal plasma from escaping further into interplanetary space. Let us now examine the observation of Levy *et al.*, that suggest this hypothesis.

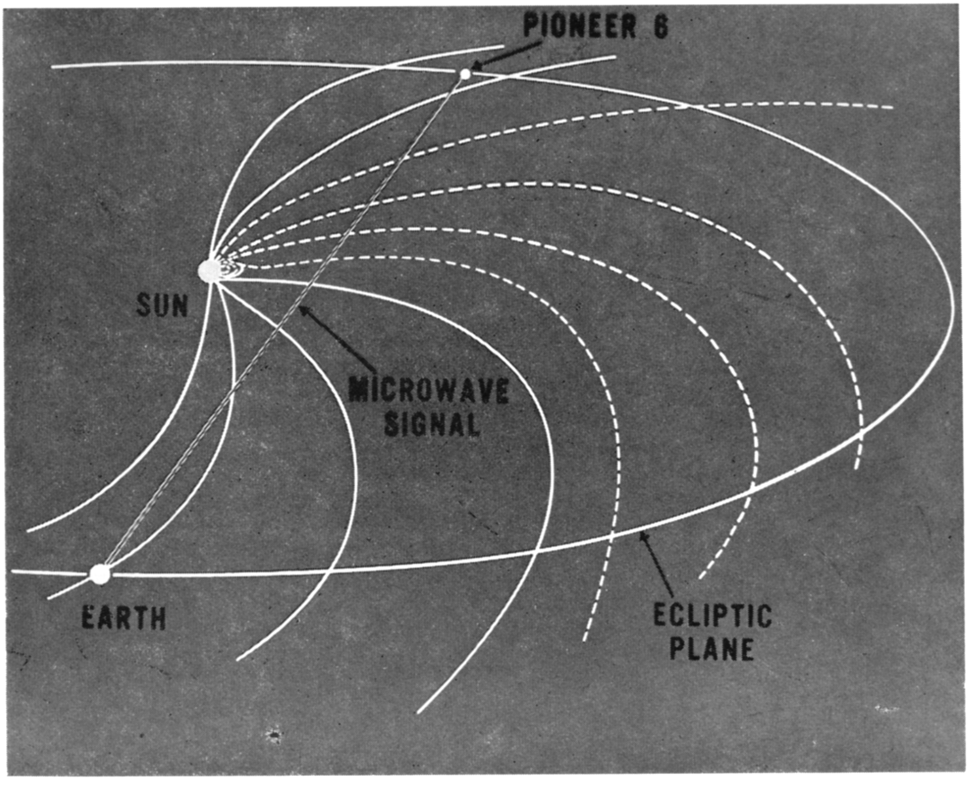


Fig. 4. Sketch of coronal and interplanetary magnetic field and the geometry V involved in the Pioneer 6 Faraday rotation experiment. See text.

Figure 6 from Levy *et al.*, shows the polarization angle of the radio signal in degrees versus universal time on November 4, 1968. The spacecraft was transmitting its signal at a polarization angle of 90°. The background Faraday rotation is due to the effects of the ionosphere and the corona. Approximate velocities of transport of the coronal material are calculated by dividing the distance from the Sun to the Pioneer 6-Earth line-of-sight by the time between the prior flare and the observed Faraday event. Velocities of about 200 km/s are obtained. Using this speed and the average 2 hr duration of the observed Faraday rotation effect one can find an approximate value for the dimension of the region moving past the line of sight. A value of two solar

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radii is thus obtained for the thickness of the region. It is interesting that J. P. Wild has reported at this meeting large-scale flare ejections using observations from the Culgoora radioheliograph.

Further insight into the dynamics of the phenomena associated with these coronal disturbances may be obtained by considering their effect on the interplanetary medium.

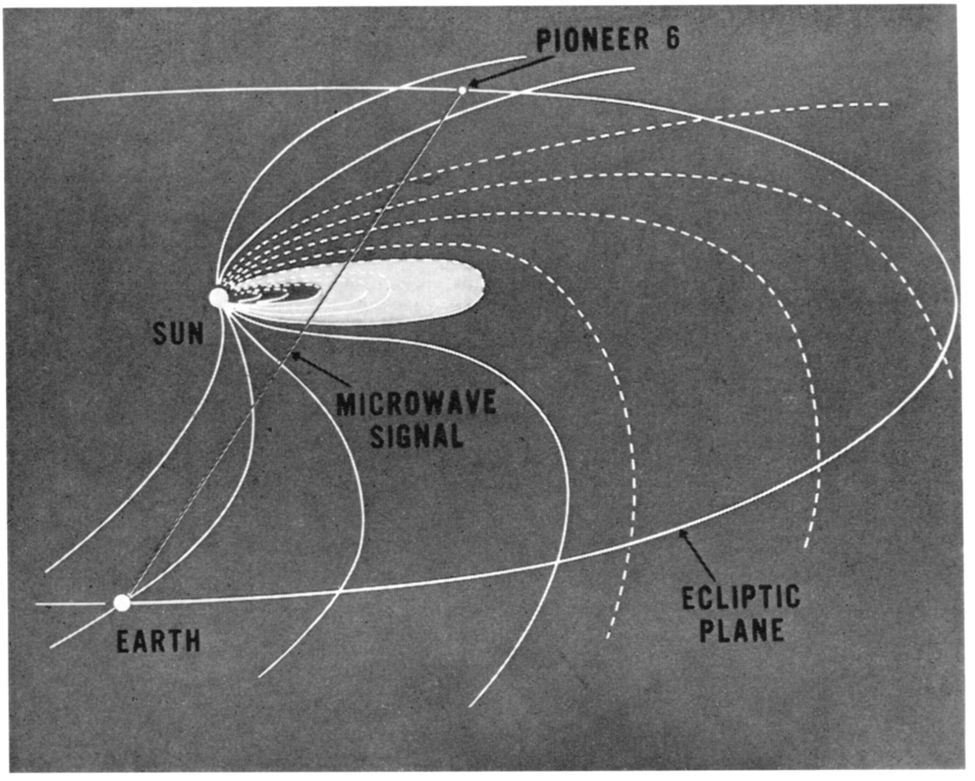

Fig. 5. Sketch showing an interpretation by Schatten of the magnetic field for the events observed on November 4, November 8, and November 12, 1968. The light shaded looped field region indicates the area affecting the Faraday rotation measurements for the 3 events.

The sector pattern, it appears, relates more to the background field and is usually not affected by most solar flares occurring within active regions. This was shown by Wilcox and Severny (1969) in their solar field interplanetary field correlations. Another example to show this is that an average of 17 flares of importance 1 or greater occurred on the Sun with 30 degrees of central meridian per 27 day solar rotation during the last quarter of 1968. Whereas only a few disruptions in the sector pattern each 27 day period are noted for this time. Thus it is expected that events of the type observed with Pioneer 6 at about 10 $R_\odot$ do not usually affect the interplanetary magnetic field pattern at 1 AU. In addition, the Faraday rotation returns to background level after each event has ended suggesting no permanent influence on the field beyond about $10\,R_{\odot}$.

Figure 7 shows magnetograms of the Sun obtained from the Mount Wilson Observatory 7 days prior to each of the three events. Thus due to the effects of solar rotation, central meridian in these magnetograms corresponds to the west limb at the three events. The three regions thought responsible for the events are labelled by their McMath plage number. Regions 9747 and 9754 were simple bipolar magnetic regions oriented with the positive flux (solid contours) following (eastward of) the negative flux. This orientation is of the proper sense to produce the Faraday rotation observed,

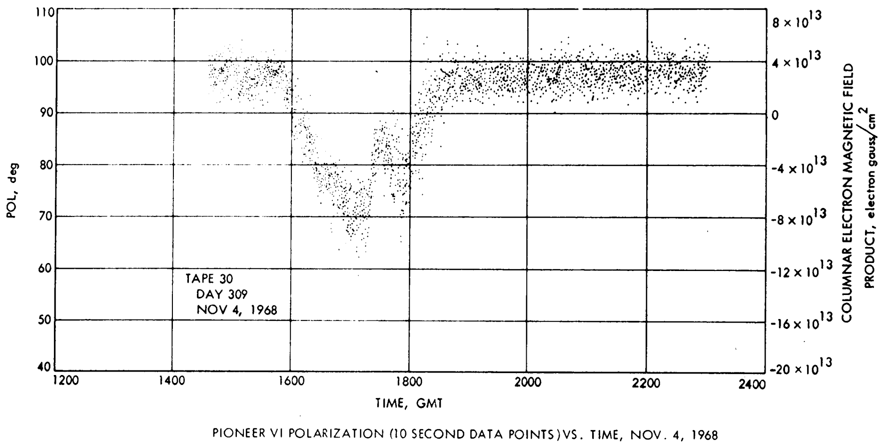

Fig. 6. Observations of Levy *et al.* (1969) of the Faraday rotation of the microwave signal observed from Pioneer 6 on November 4, 1968. The signal was transmitted at a 90° angle from the ecliptic. The background effect is due to the steady-state corona and the Earth's ionosphere.

if the model previously outlined is correct. Region 9740 is a magnetic region with a more complex field configuration. The field arrangement does have positive flux following negative flux and hence could also produce the observed Faraday rotation in accordance with the model.

These regions contain approximately 3×10^{21} G cm^2 of magnetic flux. If this flux is spread through a meridional cross-section perpendicular to the flux loop one can estimate the field strength in the region where the Faraday rotation occurs. A 0.02 G field strength at $10\,R_{\odot}$ results. A proton and electron density of $2.0 \times 10^4/\text{cm}^3$ is assumed. Enhanced coronal densities near this value are found near solar maximum at these distances from the Sun. The coronal plasma at $10\,R_{\odot}$ would thus have an Alfvén velocity of 330 km/s. This is slightly greater than the 200 km/s speed of transport of the plasma calculated from delay times. Thus the magnetic field can transport the force necessary to retain the expanding coronal plasma.

The expected Faraday rotation can then be calculated. A degree of rotation results from about 4×10^{12} eG/cm^2. Allowing an azimuthal extent of 30°, the line integral

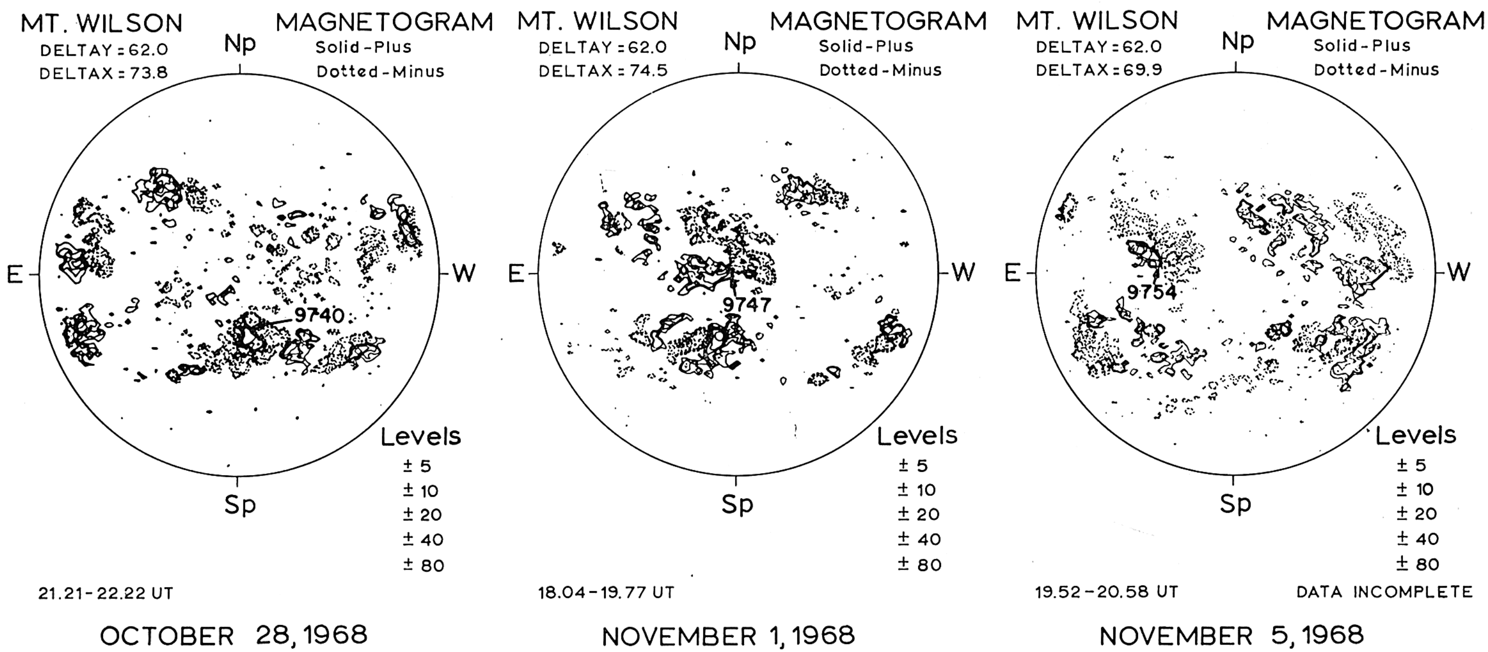

Fig. 7. Magnetograms of the Sun on October 28, November 1 and November 5, 1968. Solid lines indicate away from the Sun magnetic field and dashed lines indicate toward the Sun magnetic field. Contour levels are 5, 10, 20, 40 and 80 G.

of $N\mathbf{B}\cdot\mathrm{d}\mathbf{l}$ is approximately 1.3×10^{14} G/cm^2. Hence approximately 33° of Faraday rotation should occur as the signal from Pioneer 6 passes through the solar corona. The observed Faraday rotation is from 30 to 40° in each of the three events. Thus the proposed model is consistent both in sign with the observed photospheric field and in magnitude with the observed Faraday rotation.

If an adiabatic expansion of the flare heated coronal gas is allowed, one can consider the variation in gas pressure relative to magnetic pressure as expansion occurs to gain a qualitative understanding of the dynamics. The adiabatic gas pressure varies as $P_G \propto V^{-\gamma} = V^{-5/3} \propto L^{-5}$, where V represents volume and L is a characteristic dimension of the system. The magnetic pressure varies as $Pm \propto B^2 \propto L^{-4}$ if the field varies as an inverse square with distance as it would if the plasma expands radially into a conical shape. Thus the gas pressure falls off more rapidly than the magnetic tension and at some distance the field can retain the plasma. If, however, coronal heating occurs thereby increasing the plasma pressure, or the hot coronal plasma expands past the Alfvén point which is about 20–30 $R_\odot$, the expansion can continue to 1 AU. This would be the case in large flares associated with terrestrial effects. In the current investigation it is suggested that although the coronal plasma is expanding with a supersonic velocity, the Alfvén velocity exceeds the expansion rate and escape can thus be prevented by the magnetic field.

After a balance between plasma pressure and magnetic pressure develops, the coronal gas cools by radiative losses and conduction, mostly in the lower corona, and the field configuration slowly returns to its initial state.

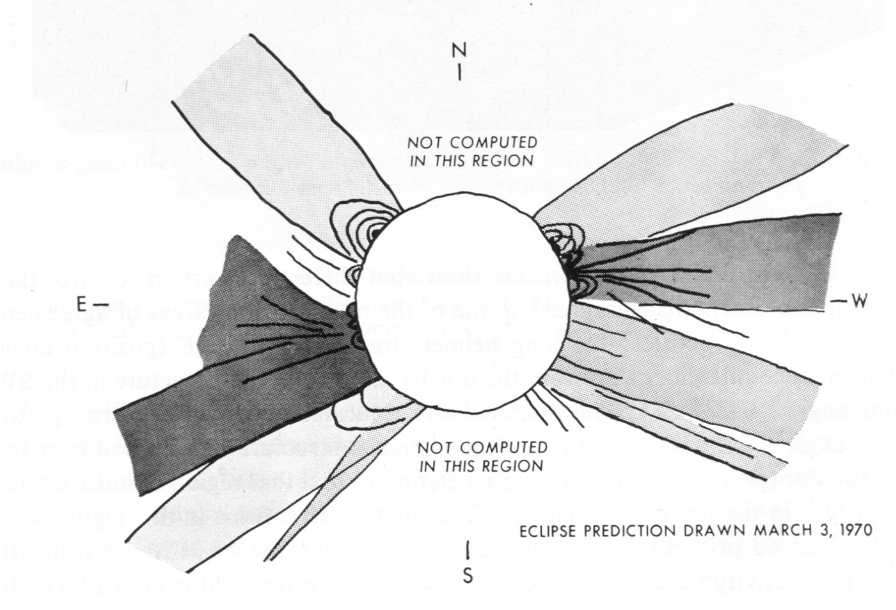

Fig. 8. Prediction of the coronal magnetic field structure for the March 7, 1970 solar eclipse. Compare with Figures 9 and 10.

Thus it appears that even moderate solar activity may influence the coronal magnetic field structure. We shall now examine the recent March 7, 1970 solar eclipse (total over Mexico, the United States and Canada) for effects of solar activity upon coronal field structure.

Figure 8 shows a prediction of the structure of the corona at the March 7, 1970 eclipse and Figure 9 shows a photograph of the corona during the eclipse. The photo was obtained with a radial transmission filter by Sheldon Smith. Waldmeier (1970) as well as Smith and Schatten (1970) compared the prediction with observations of coronal

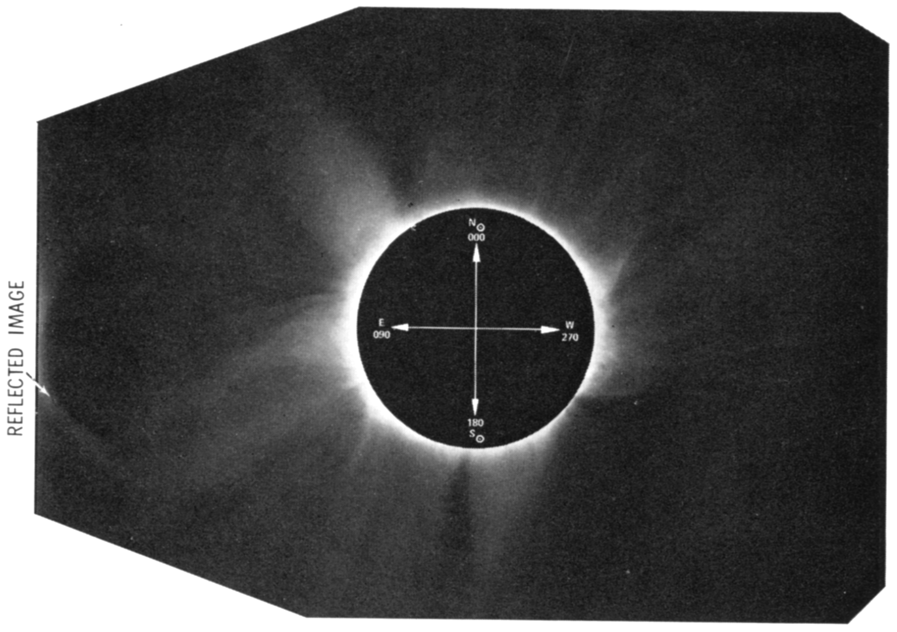

Fig. 9. Photograph of the corona during the total solar eclipse of March, 7, 1970 using a radial transmission filter by Smith and Weinstein. See also Figure 10.

structure. In both findings comparisons show that there were certain features that agreed well and others that disagreed. Some of the more obvious areas of agreement are the following structures: the long helmet streamer in the NE (position angle 30–70, degrees counterclockwise from the north), short ray open structure in the SW (position angle 210–230), a system of nested arches located above the western equator (position angle 292); and a streamer without helmet structure located south of the eastern equator (position angle 100). Waldmeier notes that that region of most serious discrepancy is in the southwest quadrant. The photospheric fields in this region were not well observed prior to the eclipse due to inclement weather at Mt. Wilson. In addition new activity developed there just prior to the eclipse. Martin *et al.* (1970) report in *Nature* that on the SW limb an active region began developing on the preceding day around 1700 UT.

Smith and Schatten point out that the regions of disagreement are ususally associated with fan shaped structures. These are located near the equator on the east and west limbs (position angle 109–122, 268–283). These fan shaped structures could be a visible manifestation of the flare ejected plasma just discussed. The structure of the regions is that of a concave outward series of rays emanating from a small region near the limb. This is just the shape that would characterize flare ejected field and plasma.

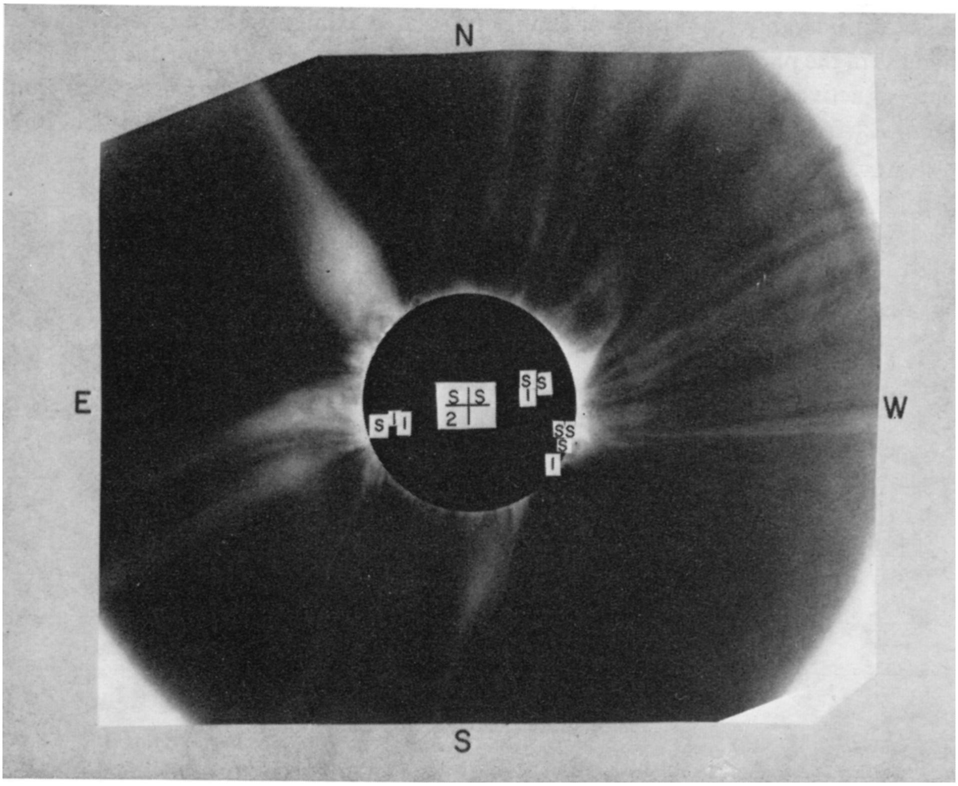

Fig. 10. Photograph of the March 7, 1970 solar eclipse by Laffineur and Koutchmy. Superposed are the flares that occurred on the visible side of the Sun 12 hr prior to the solar eclipse. The letter '*S*' indicates a subflare, a 1 indicates an importance 1 flare and a 2 indicates an importance 2 flare.

Figure 10 shows superposed upon a photo of the corona by Serge Koutchmy all the flares and subflares listed in the *ESSA Bulletin on Solar Geophysical Data* 12 hours prior to the solar eclipse. If the flare ejected plasma emanates radially, the eastern fan structure may be explained very well. The fan structure on the west limb also appears close to active regions recently flaring. In fact it may be the region Martin *et al.* observed.

I would now like to present evidence that these coronal magnetic bottles produced by small flares are not uncommon. First I shall note a few relevant observations. One

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feature of the active corona we have seen is the large number of apparently open-rayed structures. The interplanetary magnetic field near the ecliptic does not increase in magnitude from solar minimum to solar maximum as shown in Figure 11. This figure shows the magnetic field magnitude and direction as observed by Ness near solar minimum (top) and near solar maximum (bottom). Note that the field magnitude (the top graph) is near five gamma at both times (1 gamma equals 10^{-5}G). This indicates that roughly the same number of field lines are leaving the outer corona and extending to 1 AU at solar minimum and at solar maximum. The photospheric field varies considerably from solar minimum to solar maximum. There is a substantial increase in the photospheric field strength from minimum to maximum due to the presence of active regions. The predominantly open structure of the inner corona from 1 to 4 $R_\odot$ from the eclipse observations indicates most of these aditional field lines

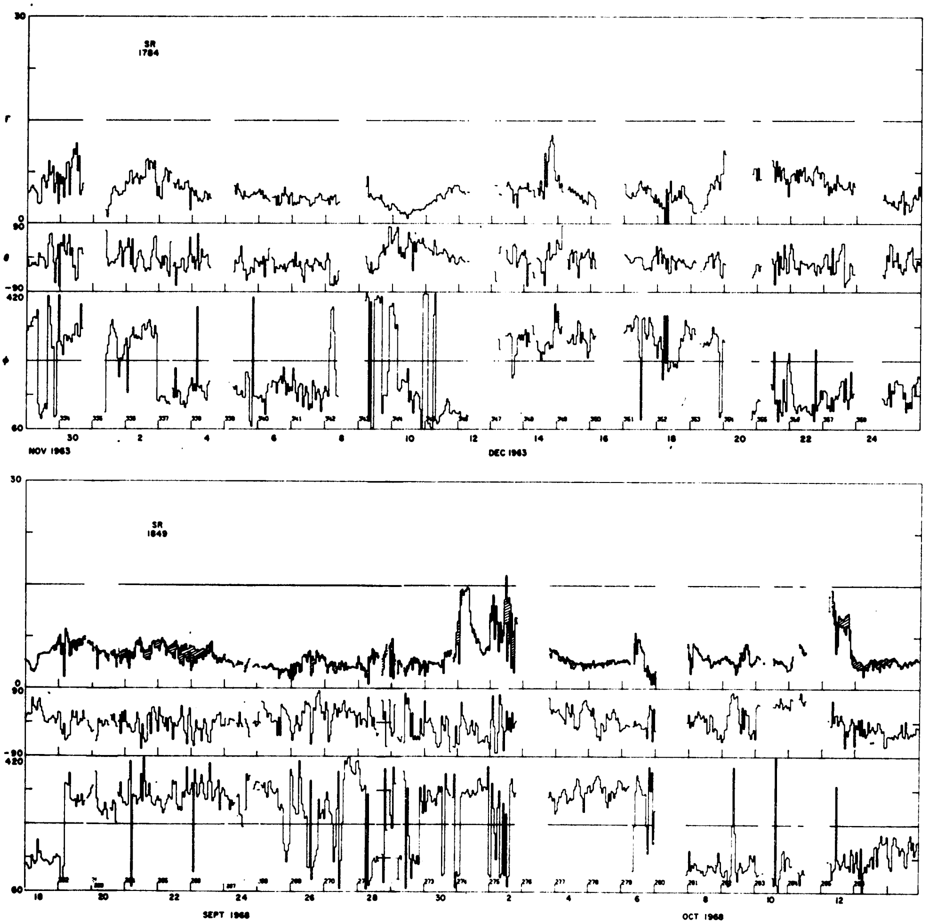

Fig. 11. The observed interplanetary magnetic field at 1 AU for 1963 (top) and 1968 (bottom). The first graph is field magnitude in gammas (1 gamma equals 10^{-5} G). Beneath this are the solar ecliptic field direction angles. Note that field magnitude shows very little change with solar cycle.

leave the inner corona; the constant interplanetary field magnitude throughout the solar cycle indicates the additional field lines do not reach 1 AU and in fact do not reach the Alfvén point at 20–30 $R_{\odot}$ as they would then be convected to 1 AU by the solar wind where they are not seen. Thus much of the additional field at solar maximum may reside in magnetic bottles located at 10 to 20 $R_{\odot}$. Flares may be responsible for this new field configuration. A suggested field topology of the active solar corona is thus illustrated in Figure 12 in a logarithmic polar coordinate graph.

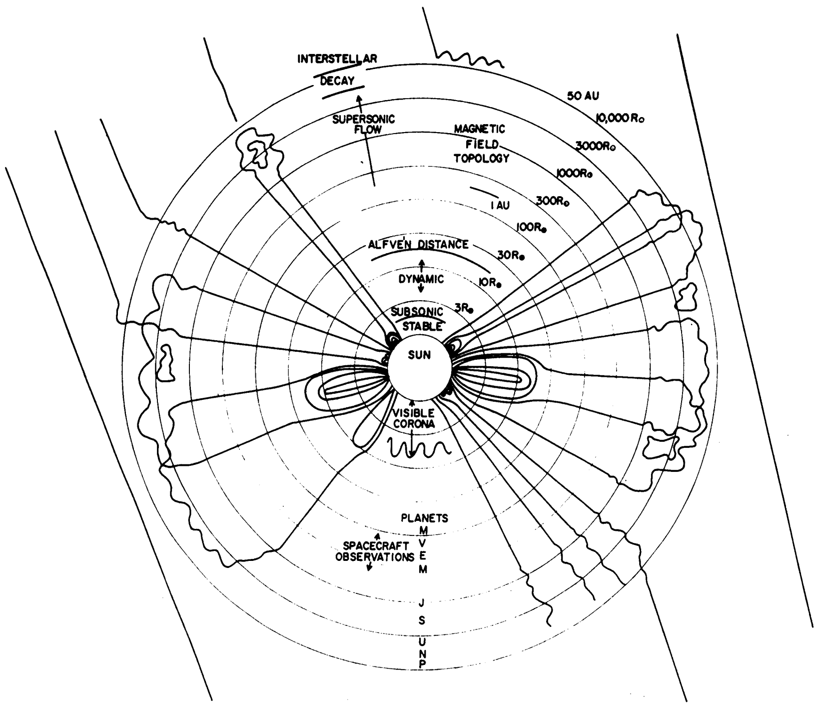

Fig. 12. Magnitude field topology in the solar system. Stable loops form above magnetic regions beneath 2 $R_{\odot}$. Flare ejected loops exist below 20 $R_{\odot}$. The field is then convected out to the heliospheric boundary at about 50 AU. The sector structure and the spiral structure are not shown for clarity.

Mostly we are concerned with the central region. Close to the Sun, the corona is stable and inactive coronal magnetic loops may form in accordance with the magnetic field calculations. These loops rotate rigidly with the Sun. Larger field loops are ejected by small flares. The inner portion of these loops is in the visible corona and appears as radial rays emanating from a common location. This region is labeled Dynamic as these bottles expand when flare energy is released and contract when cooling. The bottle may extend out to anywhere between 5 and 20 or 30 $R_{\odot}$. This outer portion of the bottle in general would not be observed. Beyond 20 $R_{\odot}$ the field lines are open and form Archimedes spirals. These, as well as the sector structure, are not shown for clarity.

Occasional field loops will emanate from the Sun and exist in this region but they will quickly be convected out by the supersonic solar wind. At about 50 AU the field lines presumably merge and the local instellar field predominates.

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Discussion

Meyer: One is worried a little bit about the lateral equilibrium in your model of a magnetic bottle. When such a bottle is pulled out radially with a velocity of 200 km/s, but on the other hand conserves an inside Alfvénic velocity of 300 km/s, the configuration would have time enough to set itself into equilibrium with the weak lateral pressures of the normal solar wind magnetic field, which are an order of magnitude smaller than the field strengths you infer for your bottle. Thus one should expect a considerable lateral expansion together with the radial motion. Consequently, the fields inside the bottle should in effect be much smaller than would be inferred from purely radial motion, in fact of the order of the field strength in the surrounding ordinary solar wind.

Schatten: Your argument is interesting. However, one may allow the tension in the magnetic bottle to provide the force that prevents lateral expansion. In carrying out the calculations, I used a 30 degree lateral spread. This would be correct to a factor of 3 in any case.

Maltby: Is there any indication of Faraday depolarization in the radio observation. If so an interpretation with magnetic field perturbation may be more feasible.

Schatten: Gerry Levy *et al.* measured the depolarization Doppler shift, angle polarization, and other quantities that relate to the signal. It is the Faraday rotation of the angle of polarization that relates directly to the field component along the line of sight. Weakening of the signal and other processes other than Faraday rotation do not change the direction of polarization. They tracked the signal from 16 to 4 $R_\odot$ at which time the noise from the Sun obscured the signal. The angle of polarization was adequately tracked *throughout* the three events so as to eliminate the possibility of loss of signal as the cause of the change.