

CORONAL MAGNETIC FIELDS AND THE SOLAR WIND *Gordon Newkirk, Jr.*
An invited review

This paper reviews current information on coronal magnetic fields as they bear on problems of the solar wind. Both steady-state fields and coronal transient events are considered. We begin with a brief critique of the methods of calculating coronal magnetic fields including the potential (current free) models, exact solutions for the solar wind and field interaction, and the source surface models. These solutions are compared with the meager quantitative observations which are available at this time. Qualitative comparisons between the shapes of calculated magnetic field lines and the forms visible in the solar corona at several recent eclipses are displayed. These suggest that: (1) coronal streamers develop above extended magnetic arcades which connect unipolar regions of opposite polarity; and (2) loops, arches, and rays in the corona correspond to preferentially filled magnetic tubes in the approximately potential field.

ABSTRACT

Current information regarding the connection of visual coronal forms and such interplanetary features as sector boundaries is still too fragmentary for a definitive analysis. However, it appears that every system of high magnetic arches in the corona can be expected to have a current sheet in the outer corona and to produce a helmet streamer and a sector boundary in the interplanetary field. The accident of perspective has apparently prevented the detection of this relationship between streamers and such geomagnetically significant features of the solar wind as sector boundaries in the past.

Recent observations have partly explained why particular tubes in the approximately potential field present in the corona are preferentially filled with material. Intense knots of field at photospheric levels give rise to elevated densities in the overlying corona, presumably as a result of increased mechanical energy transport into the chromosphere and corona above such regions. Such a mechanism would be expected to produce a mapping of small-scale fluctuations of the magnetic field at photospheric levels well out into the interplanetary medium although their identification in space remains uncertain.

Because of the paucity of information, the evolution of coronal magnetic fields can be discussed only briefly. Magnetic fields and transient events are examined in terms of three categories of phenomena:

1. Events channeled by the ambient field (surges, loop prominences, type III radio bursts, stationary type IV radio bursts, and cosmic ray events)
2. Events in which the ambient field is perturbed significantly (*Disparition Brusque*, Moreton waves, and type II bursts)
3. Mass ejections such as accompany the most violent flares.

Future problems involving magnetic fields in the corona are suggested.

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INTRODUCTION

In the solar corona, we find organized magnetic fields of great variety—from the extended, weak fields of the sector structure to the active region and sunspot fields and the intense but small magnetic pores. These fields play a crucial role in determining the structure of the corona and the solar wind: at a low level they influence the flux of mechanical energy into the corona, and thus determine the distribution of temperature and density. The configuration of the fields in the corona further influences the density distribution and the flow of the inner solar wind and partially accounts for the forms we observe there. Changes wrought in the inner corona are finally reflected in the state of the interplanetary plasma and field, as well as in the rotation of the solar wind.

Coronal fields are also central in the various coronal transient phenomena observed. Several current theories of flares require that the energy of the event be derived from the fields. The shock waves and high energy particles responsible for radio bursts appear to be channeled by the fields. These same fields guide and may be responsible for the storage of solar cosmic rays.

In discussing magnetic fields in the corona we should keep two facts in mind. First, the photospheric fields can be regarded as a boundary condition of our problem—the coronal fields can have only a negligible influence at the photospheric level. Second, it is the large-scale and, unfortunately for our ability to observe them, the weak fields that are most influential in the corona.

MAGNETIC FIELDS IN THE QUIET CORONA

Computations

Since the study of coronal magnetic fields depends almost exclusively on their computation from observed photospheric fields, a brief review of the calculations involved is in order. These all begin with measurements of Zeeman splitting due to the line-of-sight photospheric field B_L . The potential field or modified potential field in the corona is then calculated 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]. The Schmidt technique employs a distribution of monopoles of surface density

$$\sigma(x,y) = kB_n(x,y)$$

where $B_n = B_L$, and arrives at the potential field according to ordinary magnetostatic theory. Techniques for analyzing global fields are identical to those used in

geomagnetism [Chapman and Bartels, 1940] and fit a series of spherical harmonics, which are solutions of the Laplace equation, to the distribution of the line-of-sight field over the entire sun and express the potential field in terms of harmonic coefficients.

The Schmidt program can be used only for heights small with respect to the dimensions of the photospheric area scanned and at points well removed from the borders of that area. On the other hand, the simplicity of the mathematics allows a large number of data points to be processed for detailed analysis of the field above this restricted area. The harmonic expansion, while applicable to larger coronal distances, is limited in the total number of coefficients that can be fitted to the data; with current computers we can incorporate only a rather coarse pattern of the surface fields. Thus, this technique cannot be used to calculate the fine details of the field above an active region. The Schmidt program requires observations near the center of the disk for $B_n(x,y)$, while the harmonic expansion demands the field over the entire sun—a distribution that is frequently a rather uncertain average of the temporally varying fields at the surface.

Neither technique includes the influence of electric currents that may be present in active regions and flow in the corona as a result of the solar wind. Since the latter currents are known to be significant, they must be accounted for in any complete theory. Ideally, we should be able to specify the magnetic field, density, temperature, and velocity at any level in the corona once the spatial distribution of these conditions is known at the top of the chromosphere. Since such a complete solution for a realistic sun is still beyond our resources, we must consider two partial solutions. One, pioneered by Pneuman [1968, 1969] and Pneuman and Kopp [1970, 1971], solves the dynamic, thermal, and magnetic equations for a simple initial field such as that of a dipole. The success of this method is judged by the fact that realistic profiles of coronal streamers result. The model also affords quantitative predictions of such still inaccessible parameters as the temperature and velocity structure within streamers.

A second technique, which can be applied to fields of greater complexity, simulates the effect of the solar wind on the potential field by the introduction of a zero-potential on the sphere $R_w \cong 1.6R_\odot - 2.5R_\odot$, where the wind becomes super-Alfvénic in the physical models. This surface, first introduced by Schatten *et al.*, [1969], forces the higher field lines to become radial at that radius. They are presumed to remain radial above R_w except for the “garden hose” spiraling. (Actually, in

such a model the field closes above R_w , and any comparison of field lines and the corona should be restricted to $R \leq R_w$.) Note that this technique is equivalent to replacing the volume currents, which flow in the corona as a result of the interaction of the solar wind and the field, by a set of surface currents on $R = R_w$.¹ The exact value of R_w is chosen empirically either to match the shape of the calculated field lines to the shape of the corona [$R_w \sim 2.5R_\odot$, Altschuler and Newkirk, 1969], or to bring correspondence between the average magnitude of the field and its frequency spectrum at 1 AU and that projected from $R_w \sim 1.6R_\odot$ [Schatten *et al.*, 1969].

We naturally ask how well the physical solution,

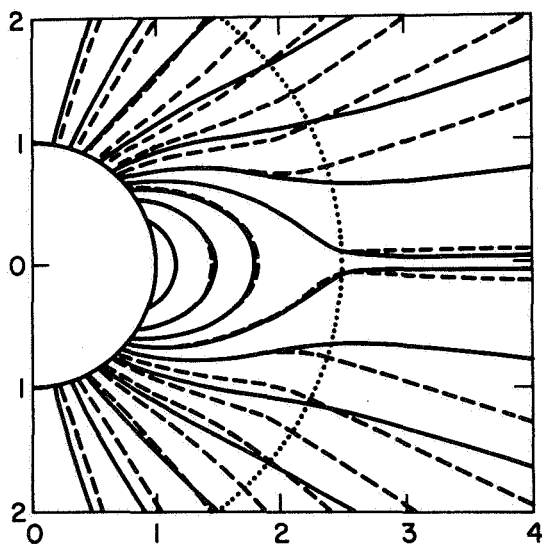


Figure 1. Comparison of the shapes of coronal magnetic field lines calculated for a dipole surface field according to Pneuman and Kopp [1971] (solid lines) and for a potential field (dashed lines) with a zero-potential surface at R_w . The zero-potential solution is not valid above R_w (dotted arc). Foot points for high-latitude field lines are separated for clarity. The super-Alfvénic point in the exact solution occurs at $2.56 R_\odot$ in the streamer.

¹Later in this chapter (p. 44) Schatten describes an algorithm for drawing the field lines that is the equivalent of introducing a current sheet above each magnetic arch that osculates R_w in the pure potential solution. This method gives an improved approximation to the fields beyond R_w . It requires R_w to be set well within the super-Alfvénic point to achieve a match of the field line shapes and the flux transported to 1 AU with those of the physical models.

which can handle only a simple field configuration, compares with the empirical solutions, which can handle complex fields. Figure 1 displays such a comparison for the simple case of a dipole surface field. Within the region of validity of the zero-potential solution, the agreement in the shapes of the field lines appears to be good. Moreover, the flux carried out by the solar wind is the same in the two models. Of course, the value $R_w = 2.49R_\odot$ was chosen to produce good coincidence in the shapes although this value is close to the height of the super-Alfvénic point in the streamer. Thus, we conclude that the zero-potential surface model for more complex photospheric field distributions can also give a good approximation to fields in the corona.

The discrepancy between the value of $R_w = 1.6R_\odot$ chosen by Schatten *et al.* and the $R_w = 2.5R_\odot$ found by Altschuler and Newkirk remains unexplained. This might be due to (1) a difference in the level of solar activity between the two periods examined; (2) the underestimation of the field strength at the source surface by the Green's function method; or (3) an underestimation of the strength of the photospheric fields by the Mt. Wilson magnetograph.²

Observations

True validation of such calculations by a comparison of computed and measured coronal fields is not yet possible. We must rely on statistical information or fields measured in prominences. Figure 2 displays a statistical comparison of the absolute magnitude of the field vs. height. Since the original figure was drawn, the 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 added a few more measures of the absolute magnitude of the field at coronal heights. In the absence of any event-by-event comparison between observed and calculated coronal fields, we compare the observations with three simple models: (1) an R^2 extrapolation from interplanetary space; (2) the Legendre polynomial field above a plage for the surface fields of November 1966; and (3) a

²Note added to proof: J. O. Stenflo has pointed out that the filamentary nature of the photospheric field results in an error in field strengths measured by the 5250Å line of FeI and that the apparent fields must be multiplied by a factor of about 2.5 [Livingston and Harvey, 1969; Stenflo, 1971a]. When this factor is applied, the field strength at 1 AU is best predicted with $R_w = 2.5R_\odot$ [Stenflo, 1971b].

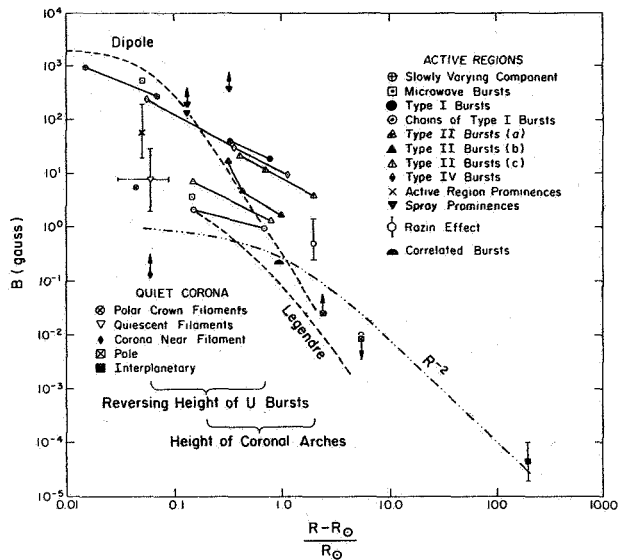


Figure 2. Summary of measurements of magnetic fields in the solar corona compared with (1) R^{-2} extrapolation from interplanetary space, (2) the field above a typical active region using the harmonic expansion method with $N = 9$, and (3) a simple dipole potential model for an active region. Except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

potential dipole model of a plage region. This comparison suggests two conclusions: (1) The Legendre approximation will *not* yield accurate results near active regions (a fact well known); and (2) radio bursts at about $2R_{\odot}$ appear to represent events in which a transient field disturbance is injected into the corona and may be unsuitable as a measure of the ambient magnetic field.

The only comparisons between observed and calculated magnetic fields in coronal space now at our disposal are those for prominence fields [Harvey, 1969; Rust, 1966]. In general, these comparisons show an agreement between the shapes of the fields and currently accepted ideas about the occurrence of prominences within the fields. A discrepancy between the magnitudes of the fields as measured and as calculated appears to be attributable to inaccurate measurement of the surface fields [Rust and Roy, 1971]. Comparison of the shapes of bright coronal emission regions with calculated magnetic fields gives some confidence that the potential field is at least a good first approximation and that the loops, arches, and similar coronal structures constitute magnetic tubes of abnormally high density (fig. 3).

Large-Scale Coronal Density Structures

In comparing the shapes of the calculated field lines with

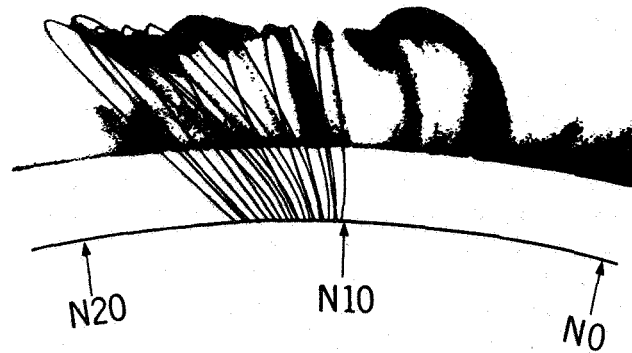


Figure 3. Computed potential field lines for the coronal loops observed in the 5303 \AA line on 2 November 1969. The loops are seen here on an overocculted negative photograph of the corona. The lower arc indicates the level of the chromosphere. Such coronal loops are often nearly identical to the $H\alpha$ loops observed in the same region [Courtesy Rust and Roy, 1971].

larger coronal structures such as streamers we should examine only the general morphology of both features. Our approximate models for the field and the geometrical choice of foot points precludes comparison of the shapes of individual magnetic lines with particular outlines in the corona. Let us examine the pattern of calculated fields present during November 1966 as seen against an $H\alpha$ spectroheliogram and a photograph of the corona (fig. 4). The magnetic fields may be conveniently divided into diverging fields, which are found in close association with plages, low magnetic arcades (LMA), and high magnetic arcades (HMA). A most striking feature of the field is the existence of magnetic arches connecting widely separated active regions. Such arches may well be the lines of communication that give rise to nearly simultaneous radio bursts in separated active regions [Wild, 1969a].

We can conclude from this type of comparison, in which the three-dimensional structure of the corona and the field are known, that coronal streamers form over high magnetic arcades. This conclusion substantiates the concept long used in theoretical models [Kuperus and Tandberg-Hanssen, 1967; Pneuman, 1968; 1969] that streamers develop above the neutral lines separating large-scale adjacent regions of opposite polarity.

Coronal Structure, Sector Boundaries, and Geomagnetic Activity

Hypotheses concerning the correlation between large coronal streamers, interplanetary sector structure, and recurrent geomagnetic storms [Mustel, 1961; 1962a, b;

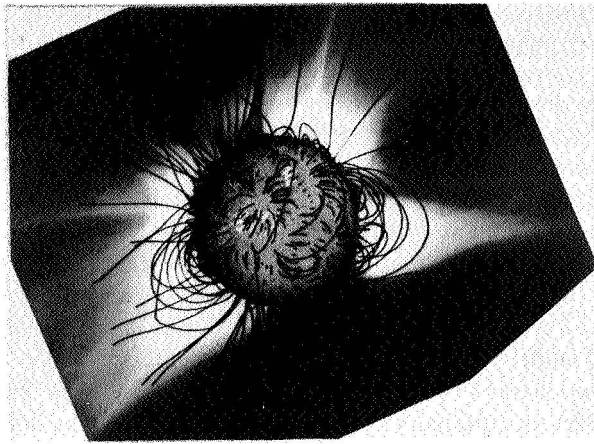


Figure 4. Calculated coronal magnetic field lines (least-mean-square fit to B_L , $R_W = 2.5R_\odot$, corrected for magnetograph saturation), superimposed on the appropriate $H\alpha$ spectroheliogram [courtesy Sacramento Peak Observatory] and a photograph of the corona of 12 November 1966. [Unless otherwise noted, the coronal field maps are based on photosphere magnetic data furnished by R. Howard (Hale Observatories) and obtained in a program supported in part by the Office of Naval Research under contract NR 013-023, N00014-66-C-0239.]

1964] have long lacked conclusive proof. However, several factors suggest that they must be related: (1) current sheets are thought to be required to produce coronal streamers [Pneuman and Kopp, 1971]; (2) each

sector boundary must contain a current sheet; and (3) geomagnetic activity is known to be connected with the passage of a sector boundary at 1 AU. Recent studies suggest that an accident of perspective may have obscured the true connection. One study of this correlation [Bohlin, 1968; 1970a, b] analyzed streamers that had been located both in latitude and longitude and showed that of 12 streamers observed during two periods in 1964 and 1965 only two could be held responsible for recurrent magnetic storms. Both were located so that they might reasonably be expected to intersect the earth. More recently *Couturier and Leblanc* [1970] deduced from radio and emission-line coronal observations that solar wind velocity peaks originate in coronal enhancements. Using similar coronal data *Martres et al.* [1970] determined that the sector boundary originates approximately 14° west of a coronal condensation, a finding in agreement with the conclusion of *Wilcox* [1968] that the sector boundary falls statistically one day west of a stable plage region. Because statistical samples involved in these studies are sparse and because not every enhancement in the low corona appears as a streamer in the outer corona, we should use caution in drawing conclusions regarding the connection of streamers and the interplanetary sector structure.

To examine the problem further let us compare the sector structure boundaries, coronal streamers, and coronal magnetic fields observed in November, 1966. Table 1 gives data on the sector boundaries, which are compared in figure 5 with the coronal structure of the same period. *Newkirk and Altschuler*, [1970] identify

Table 1. Sector boundaries and coronal structure.

Sector Boundary	Date of Sector Boundary Crossing at 1 AU* (1966)	Character of Sector Boundary	CMP at the Sun†	Longitude at the Sun†	Associated Coronal Magnetic Structure	Position of Sector Boundary Compared to Associated Coronal Density Structure
A	Nov. 15.5	field very mixed between these dates	11	280°	LMA	West of enhancement α
B	Nov. 20		15.5	225°		East of enhancement α
C	Nov. 23.5 - 25 (data gaps)	stable	19 - 20.5	$180^\circ - 160^\circ$	LMA & HMA	coincident or west of streamer $\beta - \beta'$
D	Dec. 4.5	stable	30	35°	LMA & HMA	North of streamer δ West of streamer γ

*From *Wilcox and Colburn* [1970]

† Assuming a 4.5 day transit time

such distinctive forms in the calculated coronal magnetic fields as low magnetic arcades, high magnetic arcades, and the various coronal enhancements and streamers.

From our general ideas about the nature of the interplanetary sector structure, we should expect that sector boundaries would coincide with HMAs in the calculated coronal magnetic field. This expectation is well borne out in two of the four cases examined; the only sector boundary for which this coincidence fails completely (B) was developing during the observing period; sector boundary A, which is associated only with an LMA, was also in a state of evolution. Boundaries C and D are of special interest; they were located near the solar limbs of 12 November 1966, and showed exceptional stability.

The position of boundary C is somewhat uncertain because of gaps in the Pioneer 7 magnetic data. It appears associated either with a system of HMAs having its axis approximately parallel to the equator or, if the

earlier CMP date is used, with a similar system having its axis approximately north-south. Identification with the east-west system would require that this sector boundary be definitely associated with streamer β' . Such an identification is suspect, however, because the narrow streamer spike leaves the sun some 20° south of the equator and could hardly be expected to intersect the earth's orbit at 1 AU. Placement of sector boundary C at the western limit suggested by table 1 would associate it with the north-south HMA system and place it in a position consistent with the result of *Martres et al.* [1970]. Boundary D appears to satisfy our hypothesis ideally. It lies along the axis of an HMA system and is some 20° west of coronal enhancement γ . Its connection with coronal streamer δ appears to be largely coincidental. Again, with a southward axial inclination of about 25° , streamer δ could not be expected to intersect the earth's orbit.

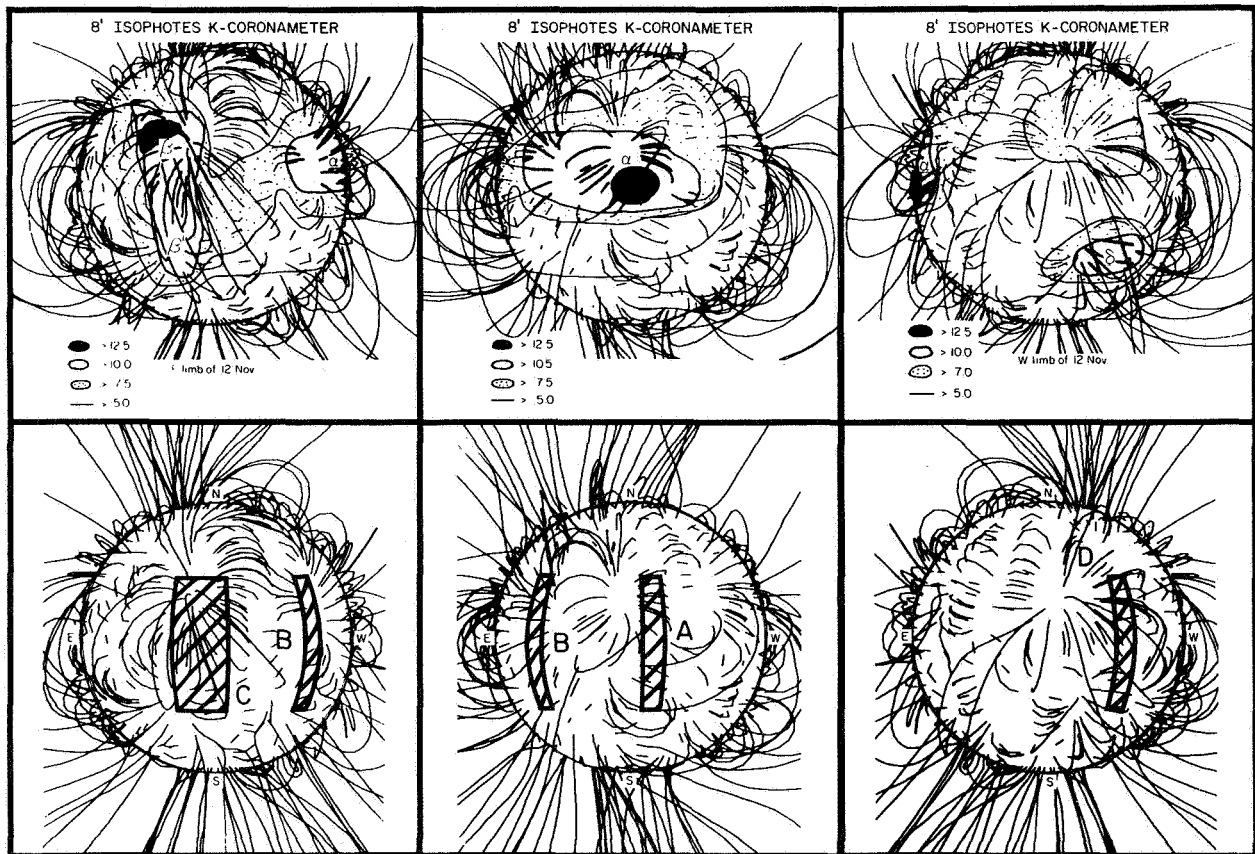


Figure 5. Upper Row: Isopleths of K-coronameter signal (proportional to electron density integrated along the line of sight) for a height of $1.5 R_\odot$ for November 1966, compared with calculated coronal magnetic field lines. At the time of the eclipse of 12 November the east limb was at approximately 180° (central meridian of left figures) and the west limb at 0° (central meridian of right figures). Thus, streamer β' and the low enhancement β were just over the east limb while streamer δ was just over the west limb. Feature a was also an enhancement. Lower Row: Location of the sector boundaries from table 1 compared with calculated coronal magnetic fields.

Taken together these data suggest the overall model schematically represented in figure 6. Here we see an HMA system winding sinuously across the solar surface. A current sheet and a helmet streamer exist above the entire length of the HMA system, while the postulated current sheet contains the axis of the HMA. Clearly, such a sheet will be conspicuous only when viewed edge-on, when it will appear as the spike of a helmet streamer containing a system of concentric arches at its base. In a view normal to the HMA axis the current sheet, which will lie nearly in the plane of the sky, will evade detection. Instead, we shall see the nearly edge-on magnetic arches as divergent rays or a coronal "bush" [Bugoslavskaya, 1949] in the enhancement. However, such a current sheet, since it extends approximately north-south, will probably intersect the earth's orbit and be detected as an interplanetary sector boundary.

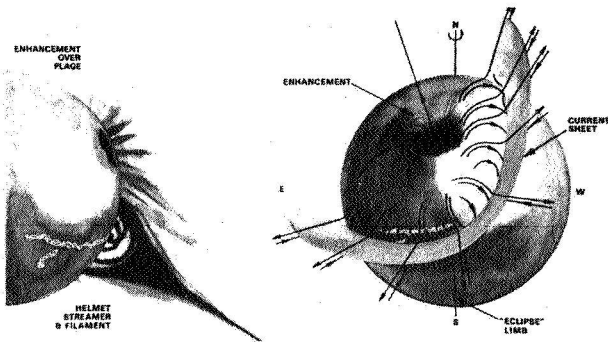


Figure 6. A schematic drawing of the relationship between coronal magnetic fields, the sector boundary, and the coronal density structure. The central meridian of the right drawing corresponds to the limb of the left drawing showing the appearance of the corona. Magnetic arcades in the right drawing are surmounted by a current sheet (sector boundary). A coronal enhancement overlies a plage (not shown). The southern portion of the HMA has its axis along the line of sight so that the current sheet is visible as a typical helmet streamer with coronal arches at its base. The northern portion of the HMA system has its axis in the plane of the sky and appears as a typical coronal bush, or active-region enhancement lying above a plage.

In summary, we suggest that every HMA system can potentially form a coronal streamer with its accompanying current sheet. Only those with axes and current sheets lying approximately along the line-of-sight appear as coronal streamers. Such orientation usually precludes detection of the current sheet as an interplanetary sector boundary at the earth. Streamers with HMA axes lying in a meridian and crossing the equator, on the other hand, are inconspicuous in the optical corona but generally produce sector boundaries at 1 AU.

Fields and 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 transfer of angular momentum into the interplanetary medium. Here we must distinguish the corotation of such features as coronal streamers or sector boundaries in the field from the angular velocity of the ions comprising the features. Observational evidence for the tangential velocity of the corona at 1 AU derives from the orientation of comet tails [Brandt, 1967] and direct detection from space probes [Hundhausen, 1968]. Both techniques yield a tangential velocity of 4 to 10 km/sec, which would require rotation of the corona out to about $15R_{\odot}$ if simple conservation of angular momentum occurred 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 actually lag behind the solar surface at all heights; however, they receive significant angular momentum from the solar magnetic field far out into the interplanetary medium. Except for measurements in interplanetary space, we have no data on the rotation of coronal ions for comparison with these calculations.

The rotation of structures in the corona can be largely independent of the motions of the individual ions. Present information [Hansen et al., 1969] shows that the low coronal enhancements rotate with the large-scale magnetic structures on the surface [Wilcox and Howard, 1970] rather than with active regions. Moreover, these data suggest that the rate of rotation at a given latitude may increase with height as it does in the photosphere [Livingston, 1969]. This apparently anomalous behavior can be explained by the confinement of coronal gas to loops in the magnetic field having their foot points anchored at different latitudes and having different rates of rotation [Pneuman, 1971].

Small-Scale Coronal Density Structures

A comparison of the congruence of the shapes of small-scale features in the corona with the magnetic field lines is almost inevitably restricted to an evaluation of their projected positions and appearances. Considering both figures 4 and 7, we find the agreement to be quite good: open rays, polar plumes, arches, loops, and other structures appear in the corona where they are indicated in the field. However, lest we become too hypnotized by these successes, let us compare some findings from the most recent eclipse (fig. 8). Although there are many coincidences between the shapes of the coronal forms

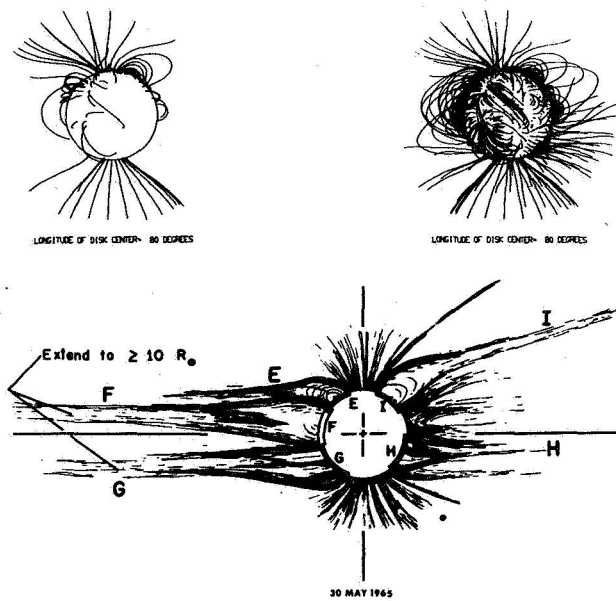


Figure 7. Comparison of the solar corona of 30 May 1965 (drawing from Bohlin, 1968) with the corresponding magnetic maps. Note particularly the similarity between (1) the magnetic and coronal arches in streamer I and (2) the polar magnetic field and polar plumes. The left figure shows strong fields in which are displayed only those field lines originating where $B_L \geq 10\%$ of the maximum line of sight field present at the surface are displayed; the right figure shows weak fields with field lines originating at foot points where $B_L \geq 0.16$ gauss.

and the shapes of the field lines, there are many discrepancies as well. These are particularly sobering when we recall that the surface magnetic data from Mt. Wilson (corrected for magnetograph saturation) and Kitt Peak were compared and found to be in good agreement. Apparently, the surface data for this relatively active period were inadequate because of temporal changes. Of course, undetected large-scale coronal electric current systems may also be modifying the fields. Nevertheless, we conclude that much of the fine-scale density structure visible in the corona corresponds to preferentially filled magnetic tubes that approximately follow the zero-potential model.

The Mapping Hypothesis

Recent work [Schatten *et al.*, 1969] has demonstrated a good correspondence between the interplanetary field and the large-scale pattern of fields present at the solar photosphere or, more correctly, at the source surface $R_w \cong 1.6-2.5R_\odot$. Thus, we conclude that the solar wind originates from a large fraction of the corona and

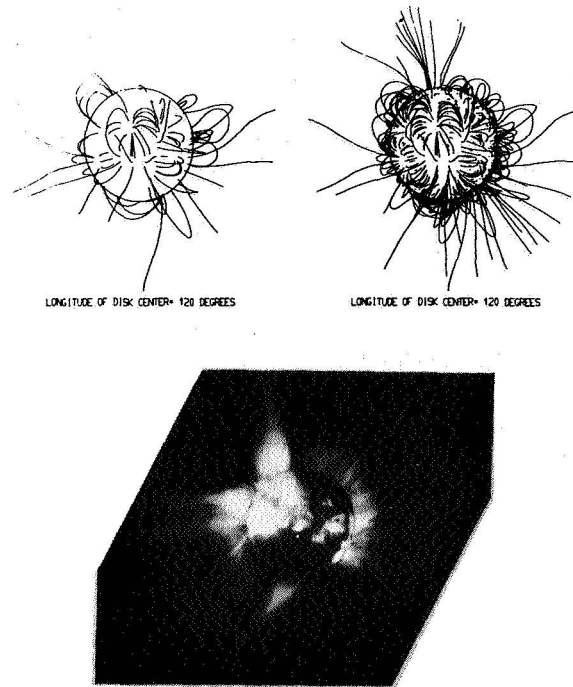


Figure 8. Comparison of the solar corona of 7 March 1970 [outer corona HAO; x-ray corona seen on the disk courtesy Vaiana *et al.*, 1970. *American Science and Engineering*] with the corresponding coronal magnetic maps. The left figure shows strong fields in which are displayed only those field lines originating where $B_L \geq 10\%$ of the maximum line of sight field present at the surface are displayed; the right figure shows weak fields with field lines originating at foot points where $B_L \geq 0.16$ gauss.

that conditions in the interplanetary field reflect or "map" photospheric conditions. We naturally ask if smaller scale structures are mapped in a similar way [Michel, 1967]. The filamentary structure of the corona, which appears to correspond to preferentially filled magnetic tubes, suggests that this is so. Two questions arise: (1) What mechanism singles out particular tubes? (2) How does the presence of such filled tubes influence the outer corona and the solar wind?

To answer the first question, we must examine conditions in the photosphere and chromosphere at the base of such preferred tubes. In a general way we know that elevated coronal density, modified chromospheric structure (plages and supergranulation boundary) and strong magnetic fields appear together on the sun [Billings, 1966; Hansen *et al.*, 1971]. Recently, Noyes *et al.*, [1970] have found that the energy flux in the chromosphere-corona transition above a plage is about five times

as great as that above quiet regions. Data from *Withbroe and Noyes* [1971], figure 9, show that the pressure at the base of the corona varies approximately as $B^{1/2}$ once B exceeds about 4 gauss. These observations are consistent with theoretical conclusions that the presence of strong magnetic fields in the photosphere increases the flux of mechanical energy into the chromosphere and corona and consequently increases the density of the overlying corona [Kulsrud, 1955; Kuperus, 1965, 1969; Kopp and Kuperus, 1968; Kopp, 1968]. Although the exact chromospheric origin of the filled magnetic tubes is now known, indirect inferences [Harvey, 1965; Newkirk and Harvey, 1968] indicate that tubes that appear as polar plumes *do* originate in bright calcium faculae where the chromospheric field is stronger than average.

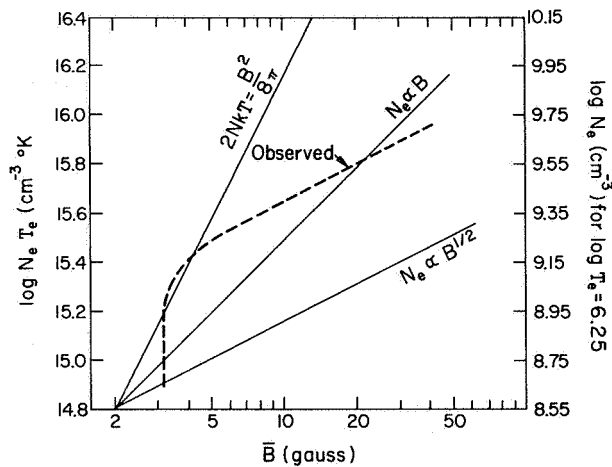


Figure 9. Variation of the pressure at the base of the corona with the strength of the underlying magnetic field as determined from OSO-VI measurements of the MgX(625A) line in active and quiet regions. [Courtesy Withbroe and Noyes, 1971]. The field and coronal data are averaged over an element of approximately one min of arc diameter.

Taken together, these data suggest that the bright coronal rays, plumes, and arches are magnetic tubes containing more material than the average because of high field *strength* at their foot points. The surface fields are generally organized into large patterns each containing a dominant magnetic polarity with a few intense knots of field along the supergranulation boundary. Thus, we should expect the filled tubes to originate at these intense knots and the shapes of the tubes in the corona below $2.5R_{\odot}$ to correspond to the zero-potential field. A simple consideration indicates that the apparently characteristic width of 30,000 km found in many of

these features [Saito, 1958; Ivanchuk, 1968; Newkirk and Harvey, 1968] is probably a reflection of the scale of the supergranulation cells. This is because, in an extended region of uniform polarity, the field lines from a concentrated knot of field in the photosphere expand in the corona to a diameter approximately equal to that of the circulation cell presumed to have concentrated the field (fig. 10). In a region with mixed polarity, diameters equal to the circulation cells cannot be expected, although a type of mapping of the surface conditions by the corona may still occur.

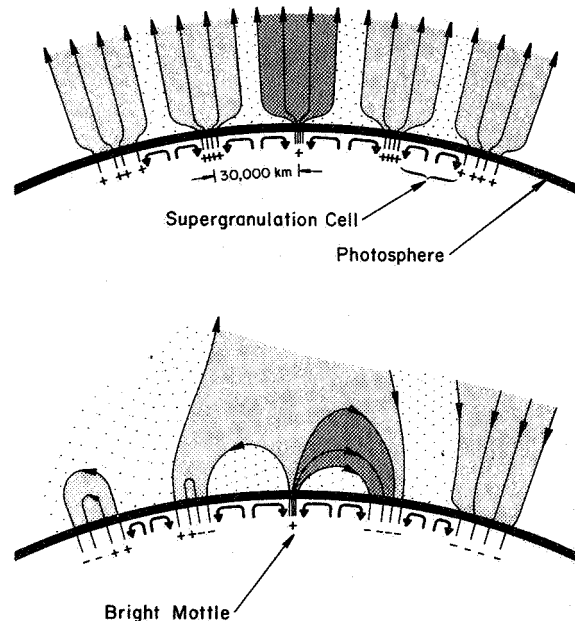


Figure 10. The magnetic field in the corona above the pattern of supergranulation cells, for a region of uniform polarity (top) and for a region of mixed polarity (bottom). The cell circulation is the same in both cases. Intense concentration of the field at the supergranulation border causes an increased density at the base of the overlying corona.

Let us accept, for the moment, the above explanation of why particular magnetic tubes “light up” and examine the consequences of this model for the outer corona and interplanetary medium. Judging from the appearance of rays and polar plumes, one should conclude that such tubes maintain their identity as they are swept up in the general coronal expansion into interplanetary space. Thus, a mapping of relatively small-scale (about 30,000 km) structures in the chromosphere out to the source surface and beyond should occur. Have we any evidence for this other than the examination of eclipse photographs? Discrete radio source occultations [Cohen

and Gunderman, 1969; Hewish and Symonds, 1969; Jokipii and Hollweg, 1970; Lovelace et al. 1970; Hewish, 1971] solar radio burst fine structure [Warwick and Dulk, 1969; Fainberg and Stone, 1970], and spacecraft observations [Jokipii and Coleman, 1968; Hundhausen, 1968] indicate that an intricate filamentary structure exists in both the density and the magnetic field of the outer corona and of interplanetary space. Although much of this filamentary structure doubtless originates in the plasma as waves, shocks, and streaming instabilities, the foregoing discussion suggests that some fraction originates at chromospheric levels. Such density fluctuations in interplanetary space could be expected to be recognized by the condition $(B^2/8\pi) + NkT = \text{const.}$

Identification of such fluctuations in interplanetary space has been somewhat ambiguous. Although tangential discontinuities appear to be conducted past a spacecraft with an average time of about 1 hour or with a size of about 1.3×10^6 km or at any other wavelength [Jokipii and Coleman, 1968; Siscoe et al., 1968]. Presumably, any such characteristic scale has become washed out by the turbulent nature of the interplanetary plasma. However, a search during periods of extremely stable sector structure might be rewarding.

THE EVOLUTION OF CORONAL FIELDS

At the present time little is known regarding the evolution of coronal magnetic fields except through indirect inference. Judging from the evolution of the surface fields, we should expect the coronal and the interplanetary magnetic pattern to reflect the following characteristic times:

1. The characteristic lifetime of about 1 day for the supergranulation network.
2. The development of an active region over about one month.
3. The growth and spreading of unipolar magnetic field regions over one to three months.
4. The lifetime of the photospheric magnetic sector structure of several months to one-half year.

Such patterns of evolution in the corona do appear, although their direct connection with the field has not been conclusively established. For example, the lifetime of polar plumes is estimated to be about one-half day [Waldmeier, 1955]. The evolution of coronal enhancements in concert with the underlying plage is well known [Kiepenheuer, 1953; Hansen et al., 1971]. While the lifetime of coronal streamers [Bohlin, 1970a, b] compares well with that of the unipolar regions, which are believed to be largely responsible, some particularly long-lived streamers appear to be connected to the sector structure fields.

Concerning the field itself, we have only the suggestion [Schatten et al., 1969] that the fields of an active region require about one month to evolve sufficiently to reach the source surface from which they are connected into interplanetary space, and the observation of Valdez and Altschuler [1970] of the opening of coronal field loops near active regions following this occurrence of proton flares. The modulation of the interplanetary field by the large-scale photospheric sector fields is well known [Wilcox et al., 1969].

MAGNETIC FIELDS AND TRANSIENT PHENOMENA

We have examined coronal magnetic fields as if both the fields and the ambient medium were constant in time. This is often not the case. We discuss magnetic fields and transient phenomena in three groups: (1) those in which the coronal fields remain stable and channel the disturbance, (2) those in which a perturbation of the coronal field occurs, and (3) those in which a major disruption of the field occurs. These distinctions are somewhat arbitrary: a given disturbance may be completely channeled at one level and may disrupt the field at another, and practically all transient phenomena in the corona may have ramifications in interplanetary space. Although most of these transient phenomena are associated with solar flares, we shall not discuss the role of magnetic fields in producing flares but simply consider the flare as an accomplished fact and examine several of the accompanying phenomena that occur in the corona and appear to have a direct consequence on the solar wind.

Field-Channeled Phenomena

Surge Prominences These objects represent an organized ejection of material from active regions, usually following flares with an average upward velocity of about 300 km/sec followed by an apparently gravity-induced return to the photosphere along the same trajectory [Tandberg-Hanssen, 1967]. They present a general appearance of being channeled and contained by the field, and the fact that the highest surges contain the weakest fields [Harvey, 1969] emphasizes that they are under magnetic control. The energy density associated with their motion (about 750 ergs/cm^3) when compared to that of the field (table 2) suggests that the most violent surges may disrupt the field. Except for the surge-sprays, to be discussed later, it is questionable whether surges ever permanently escape the sun.

Loop Prominences These post-flare prominences appear in both $H\alpha$ and the 5303 line of the corona (fig. 3) and contain densities of 10^9 to 10^{10} with

temperatures from 4×10^4 to 3×10^7 °K. Their appearance and the data in table 2 suggest that they are under strict magnetic control and have no obvious contact with the interplanetary medium. However, *Jefferies and Orrall* [1965a,b] found it necessary to postulate the presence of 10-keV protons in loop prominences to account for their $H\alpha$ profiles and their duration. They conclude that some of the 10-keV particles produced by flares are stored high in the corona, while others of the same energy are rapidly thermalized [*Culhane et al.*, 1970] and impact on the chromosphere, or are lost to interplanetary space.

Type III Radio Bursts These events are ascribed to the passage through the corona of about 10^{35} electrons per burst in the 10- to 200-keV energy range [*Kundu*, 1965] or about 10^{30} protons per burst in the 50 MeV energy range [*Smith*, 1970a,b]. They have been observed down to 0.6 MHz (at about $40 R_{\odot}$) [*Hartz*, 1969; *Haddock and Graedel*, 1970] and are considered to propagate out along a streamer of abnormally high density. The burst of particles postulated in these mechanisms carry sufficient momentum to distort the magnetic field in the corona above about $2 R_{\odot}$. In fact, *Warwick* [1967] reasons that a typical sequence of bursts may heat the outer corona and thus have an influence on the solar wind. The burst particles required by the second mechanism would be guided by the field out to at least $5 R_{\odot}$. At present the relationship between the trajectories of type III bursts, coronal magnetic fields, and density structures in the corona is largely unknown [*Kai*, 1970]. *Pneuman and Kopp* [1971] have suggested that these bursts are channeled along narrow current sheets and that the conditions inferred from their frequency and duration do not represent the ambient corona at large.

Stationary Type IV Bursts These events are believed to be due to the synchrotron radiation of semirelativistic particles trapped in closed magnetic arches high in the corona [*Kundu*, 1965]. Tentative comparisons [*Smerd and Dulk*, 1971; *Newkirk*, 1971] between the calculated and inferred magnetic arches indicate that this is so. The direct influence of these trapped particles on the solar wind is negligible, although they may provide useful diagnostic information.

High-Energy Particle Events There is ample evidence for the presence of high-energy particles accompanying solar flares. Although such particles cannot be expected to influence coronal magnetic fields or the solar wind directly, they may provide us with useful diagnostic information on outer coronal fields. A current problem is that of the storage of such particles near the sun and their dispersion over longitudes widely separated from the parent flare [*Bryant et al.*, 1965]. This problem has not yet been analyzed using realistic coronal magnetic fields.

Field-Perturbing Phenomena

Disarption Brusque Some of the characteristics of the several phenomena that have been ascribed to waves propagating through the corona appear in table 3. One of the earliest of these to be described was the *disarption brusque* [*d'Azambuja and d'Azambuja* 1948], in which a quiescent prominence far distant from the flare suddenly becomes agitated and erupts. Frequently, the prominence reforms at its original location. On other occasions, the activation of the prominence may show only as a change in its form. Two facts suggest that the disturbance may well be a slow-mode MHD wave guided by the magnetic field: the activation often occurs only in a preferred direction from the flare, and the velocity of propagation

Table 2. Energy density comparison.

High Energy Particles										Thermalized Plasma				
R (R_{\odot})	B (gauss)	$B^2/8\pi$	Type of Event	ϵ (particle $^{-1}$)	N (cm $^{-3}$)	E (ergs)	E V (ergs/cm 3)	References	Location	T_e	N_e (obs)	$2N_e kT$	Reference	
1.03	10^3	4×10^4	Microwave X-ray bursts	100 keV	10^8	10^{12}	10^{12}	<i>Wild</i> [1963]	Immediately above active region (flare)	3×10^7 4×10^8	$< 3 \times 10^{11}$ $10^{11} - 10^{12}$	2.5×10^5 $10^5 - 10^7$	<i>Culhane et al.</i> [1970] <i>Zirin</i> [1970]	
1.15	10^3	4×10^4	Loop prominence	10 keV	2×10^7	5×10^{11}	2×10^{11}	<i>Jefferies & Orrall</i> [1965a,b]	Loops above active region (sporadic coronal condensation)	4×10^8 1.8×10^8	$10^{11} - 10^{12}$ 7×10^9	$10^5 - 10^7$ 1.5	<i>Zirin</i> [1970] <i>Reidy et al.</i> [1968]	
2.0	2×10^3	1.6×10^5	Type III burst	10-200 keV 50 MeV protons	10^8 10^7	2×10^{12} 8×10^{12}	2×10^{11} 8×10^{11}	<i>Kundu</i> [1965] <i>Smith</i> [1970a,b]	Coronal enhancement above active region	1.5×10^8	10^7	4.1×10^5	<i>Newkirk et al.</i> [1969]	
4.0	4×10^3	6.4×10^5	Type IV burst	0.4 MeV	10^7	2.5×10^{12}	10^{12}	<i>Kundu</i> [1965]	Corona above active region	1.3×10^8	6×10^6	2.2×10^5	<i>Newkirk</i> [1967]	

ranges from 100 to 250 km/sec [Dodson and Hedeman, 1964] as would be expected for sonic waves in the corona.

However, this explanation may well be oversimplified. Bruzek [1952] has found evidence for the triggering of the *disparition brusque* by an activity wave that migrates outward from developing sunspot regions at a very slow speed (about 1 km/sec). Perhaps both mechanisms are at work.

Moreton Waves and Type II Bursts Further inspection of table 3 shows several wave-like phenomena with a characteristic propagation speed of the order of 1000 km/sec. In the Moreton wave the disturbance causes short-term oscillations in the chromosphere [Moreton, 1960; Smith and Harvey, 1971], which spread out from the flare over a restricted sector. This disturbance appears directly related to that of "winking filaments," in which a distant filament is caused to oscillate vertically by the disturbance. Three explanations have been offered to account for these observations. In one [Anderson, 1966; Uchida, 1968] a weak Alfvénic shock wave travels from the flare through the corona along magnetic field lines; in the second [Athay and Moreton, 1961] a spray of magnetically guided particles is responsible; in the third [Meyer, 1968] fast-mode MHD waves channeled by refraction remain in the chromosphere and cause the activation. Recently, Uchida [1970] has calculated the coronal propagation of fast-mode MHD waves for several models of an active region.

Before discussing the merits of these mechanisms, let us turn to another phenomenon long associated with coronal waves. Type II radio bursts are interpreted as a shock disturbance moving out through the corona at speeds of about 1000 km/sec. The shock is believed to set off oscillations that emit radio radiation at the local plasma frequency. That such MHD shocks *are* directed by the ambient magnetic field is demonstrated by a comparison (fig. 11) of the field lines calculated from the surface magnetic fields with the wave front of the Type II burst [Kai, 1969b]. In this particular event we see not only the channeling of the shock by the field but also the activation of a distant filament and the generation of a moving Type IV radio burst. The latter is presumed to be caused by the synchrotron radiation of relativistic particles accelerated in the shock front as it moves through the corona.

Have we any visual evidence for these events in the corona? The answer appears to be yes. Movies of the corona in the 5303 Å line [Dunn, 1970] occasionally display a moving "whip" in a previously existing magnetic arch in the corona [Evans, 1957]. Examination of several of these whips [Kleczek, 1963; Bruzek and Demastus, 1970] shows that:

1. The motion begins gradually and rapidly accelerates to velocities in excess of several hundred km/sec.
2. Some motion of the coronal forms can be detected

Table 3. Wave phenomena in the corona.

Phenomenon	Velocity	Type of Wave Inferred	E	Reference
Prominence activation and <i>disparition brusque</i>	~100-250 km/sec (flare-induced)	Magnetically guided sound (slow-mode MHD)	?	Tandberg-Hanssen [1967]
	~1 km/sec (sunspot-induced)	Activity wave		Bruzek [1952]
Winking filaments	500-1500 km/sec	Weak Alfvén shock (along magnetic field lines in Corona)	4×10^{29} ergs	Anderson [1966]
Moreton wave	~1000 km/sec	Fast-mode MHD through chromosphere	$\lesssim 10^{29}$ ergs	Meyer [1968]
Coronal whip	accelerating to several 100 km/sec	Alfvén growing to MHD shock	?	Bruzek and Demastus [1970]
Spray prominences	150-1300 km/sec		10^{31} ergs	Bruzek [1969a,b]
Types II and IV Bursts	~1000 km/sec	MHD shock	10^{29} ergs	D. F. Smith, private communication
Interplanetary shock	700 km/sec at 1 AU but transit time yields 950 km/sec	MHD shock	10^{32} ergs	Ness and Taylor [1969]
			5×10^{31} ergs	Hundhausen et al. [1970]

before the flash phase of the associated flare, although the most rapid acceleration appears to be coincident with the flash phase.

In addition to the characteristics noted by Bruzek and Demastus, we note that there is no evidence for any increase in the density or temperature of the material enveloped by the loops. We conclude that the arch is not being driven out by an explosion from below but that a dramatic disruption of the magnetic field has occurred; the coronal material is simply carried along by the field, which is readjusting to the new configuration with the Alfvén speed.

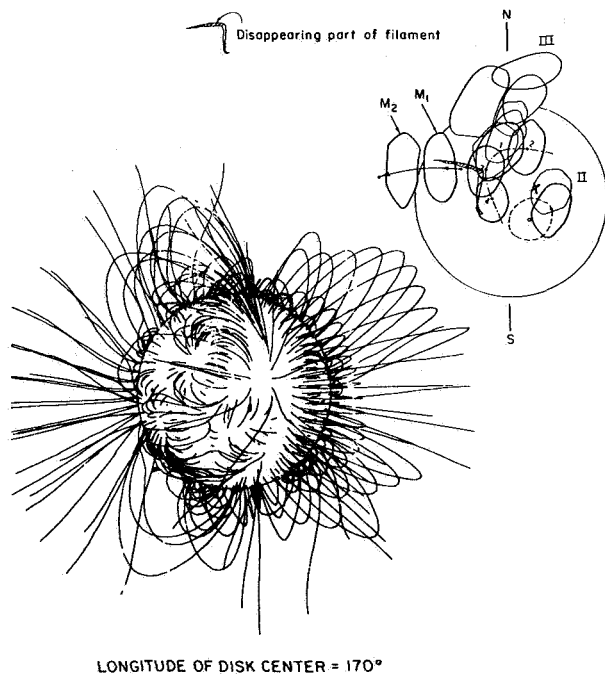
The rapid acceleration and final disruption with velocities of about 1000 km/sec of a previously stable configuration is reminiscent of the behavior of spray prominences [Smith, 1968]. Although there is evidence that such sprays originate in the flare itself, the ejection of previously existing quiescent prominences also occurs [Dodson and Hedeman, 1968]. Some of the material is observed to return to the surface along the legs of the

arch. However, knots are frequently observed that have greater than escape velocity and unquestionably leave the sun.

Apparently, the coronal whips, spray prominences, and type II and type IV bursts [Smerd and Dulk, 1971] are various aspects of the same phenomenon—a developing MHD shock causing rapid readjustment of the coronal magnetic field which may or may not result in significant mass motion.³ Wild [1969b] and Stewart and Sheridan [1970] proposed earlier that the Moreton wave and type II burst were two ramifications of the same disturbance. The sequence of events might well be visualized as follows:⁴

1. The preflare storage of energy in the field, caused by a gradual relocation of the surface magnetic fields, produces a slow motion of the arches visible in 5303 Å and in overlying filaments if any exist.
2. The occurrence of a triggering instability causes a sudden release of magnetic energy at chromospheric levels (the flare), MHD shock, and the subsequent readjustment of the field at Alfvén speeds in the corona (the whip or spray prominence).
3. The shock wave grows as it expands into the corona (production of type II and type IV bursts, high energy particles, postflare X-ray emission).
4. Some of the shock energy returns to the chromosphere far from the flare, given an appropriate field configuration (activation of distant filaments, *disparition brusque*, Moreton wave, triggering of sympathetic flares).
5. The shock escapes into interplanetary space at $v \cong 1000$ km/sec and gradually decelerates to about 700 km/sec at 1 AU.

That such a sequence of events is at least plausible is shown in figures 11 and 12, in which a spray prominence [McCabe and Fisher, 1970] preceded a rapidly moving type IV burst [Riddle, 1970], which could be followed to several solar radii. The disturbance appears to have propagated out along the ambient field lines. Dulk and Altschuler [1971] have examined a similar event and

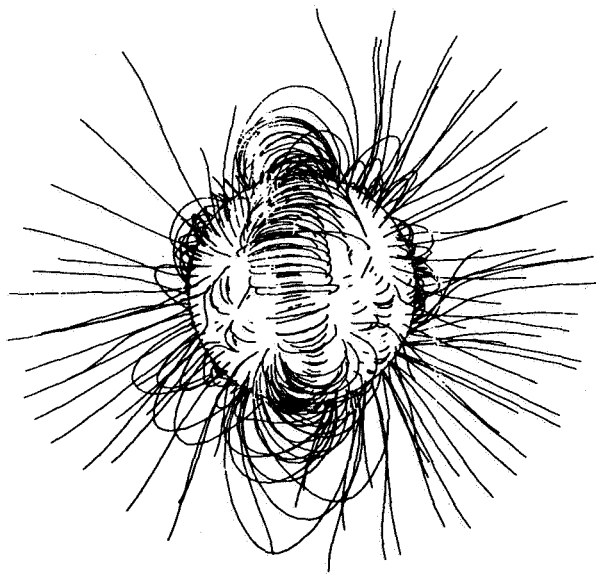


LONGITUDE OF DISK CENTER = 170°

Figure 11. Channeling of a directed shock, which gave rise to a complex of type II (line connecting points 2, 1, 3, 4), moving type IV (M_1 and M_2), and type III (light enclosed regions in north) radio events and a disappearing prominence [Kai, 1969a] by the coronal magnetic field. The flare was at x . Field lines originating at foot points where $B_L \geq 0.16$ gauss are displayed.

³The observation of Orrall and Smith [1961] suggests that the connection may be more complex. On one occasion a spray traversed the corona with no visible influence on the overlying coronal arches.

⁴Recently Kopp [1971] has proposed that the entire phenomenon is caused by a single large shock originating at the photosphere. The ejected spray material is interpreted as part of the chromosphere blown off and acting as the driver gas in the corona.



LONGITUDE OF DISK CENTER = 340 DEGREES

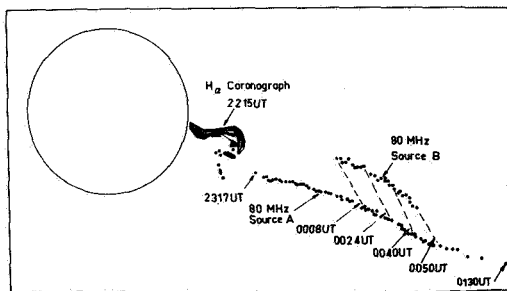


Figure 12. An ejected spray prominence [McCabe and Fisher, 1970] and an associated moving type IV burst [Riddle, 1970] move out along the coronal magnetic field lines. Field lines originating at foot points where $B_L \geq 0.16$ gauss are displayed.

concluded that the ejected plasmoid was, in their case, a ring-current vortex whose poloidal magnetic field contained the mildly relativistic electrons. Similar vortices have been observed optically [Hagen and Neidig, 1970].

Mass Ejections In the previous section we emphasized those phenomena in which waves in the corona were believed to be the principal cause of the disturbance. In other instances the gradual or explosive transport of material may occur. The magnetic fields may channel the flow or, in the most violent cases, be completely disrupted by the material (see table 2). Early observers of the corona ascribed the changes observed in loops and arches either to the motion of an excitation phenomenon or to the gradual filling and emptying of adjacent

magnetic tubes of force. Although spectral measurements [Newkirk, 1957] show that true, macroscopic motions do occur, they are relatively rare. Most of the changes observed appear to be due to the filling mechanism.

The gradual expansion of regions of high density such as coronal enhancements also occurs, although their causal connection with flares is uncertain. Associated with the proton flares of 7 July and 2 September 1966 [Newkirk *et al.*, 1969] the electron density in the corona above the active regions increased by a factor of about two. However, it is impossible to say unambiguously that the flares were the source of the material. On one hand, radio observations [Tanaka *et al.*, 1969] show that a gradual increase in the density began before the proton flare of 7 July 1966. On the other hand, in a few days following each of these flares, the electron density distribution showed a concentration of material below $1.5 R_\odot$ from the center of the sun — a concentration that was not observed in this active region at any other time during its two-month lifetime. The fact that the density bubble appeared to expand at almost the same speed as that reported for the late expansion stages of $H\alpha$ loop prominence systems in general [Bruzek, 1964] and for the loops observed two days following the flare of 7 July [Valnicek *et al.*, 1969], suggests that we may be seeing two aspects of the same phenomenon: a gradual filling of successively higher magnetic loops in the corona. That this material is actually pushing out the loops seems questionable from a comparison of the energy density of the material with that of the field (table 2).

Observations of genuine ejections of coronal material from flares are rather scarce. One such event has been analyzed by Zirin [1966], who determines the following parameters for the coronal cloud:

$$\text{Diameter} \cong 2 \times 10^9 \text{ cm}$$

$$N_e \cong 10^{11} \text{ cm}^{-3}$$

$$T_e \cong 4 \times 10^6 \text{ }^\circ\text{K}$$

$$\text{Total } N \cong 10^{39} \text{ electrons}$$

$$\text{Total mass} \cong 2 \times 10^{15} \text{ gm}$$

Although Zirin states that the material left the flare site "explosively," he does not make clear whether the material was in fact ejected from the corona. The actual expulsion of a considerable mass of material together with the magnetic field to form a temporary magnetic bottle extending out to about $10 R_\odot$ has recently been inferred from satellite occultation observations [Schatten, 1970].

Shock waves observed in interplanetary space afford the most unambiguous evidence for the true ejection of flare material. As summarized by *Hundhausen et al.*, [1970] such shocks have a mean energy of 6.8×10^{31} ergs and a mean mass of flare ejecta of 5×10^{16} gm. A linear relation obtains between the ejected mass (from 3×10^{15} to 3×10^{17} gm) and the shock energy at the sun (from 10^{31} ergs to 3×10^{32} ergs). Flares accompanied by shock events in the corona (type II and IV radio bursts) are most likely to produce interplanetary shocks.

The present picture is anything but clear. We must conclude that the flare injects into its local environment some 10^{41} particles. Of these, some 3×10^{40} may escape into interplanetary space to be observed ultimately at 1 AU as the driver of a shock wave. How this is channeled by the ambient coronal fields is unknown. Another 3×10^{40} particles take up fairly permanent residence in the coronal condensation while the remaining 3×10^{40} particles may ultimately return to the photosphere by the formation and maintenance of the loop prominences [*Jefferies and Orrall, 1965a,b*].

FUTURE PROBLEMS

As mentioned in the first part of the discussion, practically all our conclusions regarding coronal magnetic fields and their relation to optical, radio, and solar wind phenomena are based on the computation of these fields from data at photospheric levels. We desperately need actual measurements of both the magnitude and direction of fields in coronal space to compare with these calculations. Such data will come from several sources. Observations of the degree and orientation of linear polarization of coronal emission lines can yield information on the direction of the field in the inner corona. The Zeeman splitting of the circularly polarized components of these lines is proportional to the line-of-sight field in the same region. Although such measurements are difficult, they are feasible with present-day techniques. At radio wavelengths, the polarization of the slowly varying (thermal) component, the polarization of microwave, type I, and type II bursts, and the frequency distribution of type IV bursts give partial information on both the magnitude and direction of the field at various heights in the corona. The present ambiguity in the interpretation of some of these observations apparent in figure 2 is largely due to a lack of angular resolution in our radio telescopes, the use of unrealistically simple models of the coronal field, and uncertainty as to the exact mechanisms responsible for some of the bursts.

All these factors can be expected to improve rapidly in the next few years as we examine data from the new

radioheliographs, use actually measured surface fields in our calculations, and, generally learn more about radio bursts. It is likely that a combination of several of these types of observations rather than a single technique will be required.

The continued study of the Faraday rotation of the signals which transverse the corona from satellite-borne radio transmitters and natural pulsars hopefully will give a more complete picture of the fields in the outer corona than we have currently.

Also on the observational side, we require detailed information on the chromospheric conditions existing at the feet of the more densely filled magnetic tubes in the corona. Such observations should indicate how the mass and energy flux into the corona is modulated by the presence of magnetic fields at photospheric levels. Given this information, an extension of the exact solutions for the interaction between the field and the solar wind to more complex and realistic field configurations should be attempted. Such an investigation would not only improve our understanding of the density structure of the solar corona as we see it, but also illuminate the role played by the corona in the mapping of chromospheric conditions into the interplanetary medium.

The intriguing question of the connection of visible structures in the corona to conditions in interplanetary space requires additional study. The data currently available are fragmentary. However, with the launching of orbital coronagraphs in the next few years, we should obtain the necessary data to replace conjecture with knowledge.

Although the synoptic development of magnetic field patterns in the photosphere is well known, the consequences of this development on the coronal fields have yet to be investigated. Similarly, the role played by the evolution of these fields on that of the solar corona is unknown.

Earlier we mentioned coronal transient events, particularly those observed at radio wavelengths, as useful diagnostic tools for measuring coronal fields. Such events bear study in their own right. At present we know little about the general relation of the various radio bursts to the ambient magnetic field. Such fundamental questions as whether the disturbances propagate along or normal to the field and the detailed mechanism responsible for some bursts remain uncertain. The magnetic channeling of the shock disturbances responsible for the Moreton waves, winking filaments, and coronal whips has not been conclusively demonstrated. Equally unknown are the roles played by coronal fields in directing shock waves escaping into interplanetary space and in channeling and storing high energy particles.

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P. McIntosh In comparing these sector boundary locations with the computed magnetic fields you mentioned that some of these boundaries were steady, some were unsteady. Could you clarify what you meant by this difference?

G. Newkirk Simply that if you look in the presentation of the interplanetary magnetic field polarities, rotation by rotation that from one rotation to the next the sector boundary may appear, disappear, change sign and be very unsteady. On the other hand, a steady sector boundary will be seen month after month after month in approximately the same position. Now, I admit it is rather daring, on the basis of four events, of which two fit your conception, to draw a whole picture of what the sector boundary and the connection between the magnetic field is, but this is all the data we have.

E. J. Smith I notice that one of the assumptions made in these analyses is that there is no displacement of the corona relative to the photosphere.

DISCUSSION

G. Newkirk Yes, this is rather tacitly assumed. The evidence we have for that is simply the fairly good connection between high density enhancements in the corona and the high magnetic field concentrations which we see in plages, and this is a very well established sort of thing. Now, as to whether or not the angular velocity of the corona and the photosphere match well enough to prevent distortion, the observations suggest that in general the coronal rotation rate is the same as that of the magnetic fields in the underlying photosphere, with one suggestion of a slight acceleration with altitude. That acceleration is apparently due to the fact that the field is anchored at lower latitudes and tends to drag the material along. We are then looking at a place where the characteristic velocity isn't that of the underlying latitude point.

M. Dryer Gordon, in the one sequence in the movie when we saw the material flowing back toward the sun, does that material cause the kind of flare that Hyder has talked about? Do flares result from that material?

G. Newkirk Well, these – you're trying to get me in trouble, aren't you? These loop prominences follow flares. Now, Hyder talks about the impact infall flares and flare-like brightenings. Now, I don't believe he would assume that a loop prominence causes this sort of thing. He is talking more about events which characteristically look a little different than this.

J. M. Wilcox Could you comment on the ejection of material from the lower layers of the solar atmosphere out into the interplanetary medium?

G. Newkirk The general impression you get from seeing these field distribution coronal maps, as well as from seeing coronal events, is that the material is generally collimated rather strongly by the magnetic field. Now, whether or not, for example, one of these type IV moving bursts is the radio evidence of such an ejection we really don't know; but if it is we then have pretty good reason to see how the collimation occurs. That sort of event is collimated by the nearly radial magnetic field. The composition of the polarization of those radio events suggests at least some of them are toroidal magnetic field ejections. So what we have is a sort of smoke ring in the field with actually a current going around and the field containing all these type IV relativistic or mildly relativistic particles. This thing drifts out essentially with the Alfvén speed, and it is apparently associated with the shock wave which eventually arrives out into the interplanetary space.

R. Howard While we're talking about velocities I just want to say that although we see pictures of the upward motion of surges and so on, those who observe velocities on the solar surface in general agree that if there is anything at all characterizes the residual velocity fields over the solar surface, it is that where there are strong magnetic fields the velocities in the photosphere are toward the surface of the sun.

C. P. Sonett I assume that when you are looking with a white light coronagraph you're looking at the Thompson-scattered light from electrons, that in effect measures your plasma density. But there are also observations in H-alpha, which is recombination radiation. Could you clarify the plasma temperature and density structures?

G. Newkirk When you look at the white light coronagraph you are indeed seeing Thompson-scattering from free electrons; that's just the straight electron density. You look in the 5303 line of the corona and you're looking at a material which for you to see has to be of the order of one or two million degrees. And where it's bright, it's high electron density. A feature such as loop prominence which I showed has a very intricate temperature structure, because approximately in the same region you also see H-alpha, which is representative of an electron density that is approximately a factor of a hundred over the ambient corona, and where the temperatures may be only 20, 30, 40 thousand degrees. So you may have a very intricate temperature structure, and just asking what is the plasma density in that thing is something that we can't give you a straight answer to. You've got to ask what the plasma density is at what temperature.