PART I

MAGNETIC STRUCTURE RESPONSIBLE FOR CORONAL DISTURBANCES

MAGNETIC STRUCTURE RESPONSIBLE FOR CORONAL DISTURBANCES: OBSERVATIONS

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Abstract. Coronal disturbances are considered as consequences of the ejection of electric currents (or non-potential magnetic fields) from the photosphere and chromosphere into the corona. It may be that electric currents are generated near neutral lines in the photosphere and are later ejected into the corona.

1. Introduction and Point of View

The corona of the Sun is a tenuous fully-ionized plasma, and therefore extremely responsive to magnetic fields. Indeed, the large-scale inhomogeneous structure of the corona, with streamers, condensations, holes, polar plumes, and helmets, is largely a consequence of the distribution of magnetic field throughout the solar atmosphere.

On occasion, the corona or some part of it becomes disturbed over short time scales. Mass motions, particle accelerations, and changes which affect the density and temperature of the corona are observed over intervals ranging from a few seconds in the case of certain radio and hard X-ray bursts to an hour or so for increased emission in the visible and radio continua and in the soft X-ray bands.

For the purpose of this talk, I will divide coronal disturbances into three different categories:

(1) long-period, or evolutionary, disturbances which persist for several days or more and which are undoubtedly controlled by persistent coronal magnetic fields rooted in the photosphere.

(2) fast disturbances which occur over times ranging from minutes to hours and which probably involve hydromagnetic processes.

(3) impulsive disturbances which occur in a few seconds or less and which are possibly a consequence of particle acceleration processes in certain coronal regions.

Fast and impulsive coronal disturbances are closely related to flare processes and eruptive prominences, thus to changing magnetic fields. Long-period coronal disturbances reflect the large-scale photospheric magnetic field.

These different types of coronal disturbances can affect the Earth's magnetic environment in different ways. Long-period coronal disturbances control the fast streams of solar wind and the interplanetary magnetic sector structure. Fast coronal disturbances may cause strong interplanetary shocks. Impulsive coronal disturbances are an important source of energetic particles and X-rays.

Thus it is difficult and misleading to study coronal disturbances apart from other solar and interplanetary activity. Indeed, all forms of solar and interplanetary activity are consequences of magnetic fields generated initially in the subphotosphere. (In the corona, concentrations of thermal energy from causes unrelated to magnetic fields

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are probably of little importance and will not be discussed.) What we are concerned with basically is the transport of magnetic energy from the subphotosphere to interplanetary space either directly by convection of magnetic field or indirectly in the form of fast particles and mechanical energy. Coronal disturbances are a key link in that chain of physical processes.

The purpose of this conference is to trace in as much detail as possible the emergence of magnetic energy from the photosphere or chromosphere into the corona, and the partition of this energy into mass motions, hydromagnetic waves, shocks, fast particles, and heat. Viewed in this way, coronal disturbances should eventually be useful diagnostic tools to help understand both terrestrial magnetic disturbances and the nature of photospheric activity.

Let me now ask a specific question. Are present observations of coronal disturbances and magnetic fields sufficient to allow us to construct a physical model of a given coronal disturbance? To construct even a crude hydromagnetic model, we need to know the spatial and temporal distributions of the mass density, momentum density, magnetic field, and temperature of the disturbance. Even this information may not be sufficient to understand impulsive bursts, because a hydromagnetic description averages over velocity space and cannot describe non-Maxwellian particle acceleration processes. Since at present we do not have complete observations even of the three-dimensional time-changing magnetic field of a coronal disturbance, we cannot construct a unique physical model.

Consequently, we must make inferences from imperfect data. This means we must use observations together with established physical principles to guess how the magnetic field and the plasma are interacting. In general, we cannot expect a unique model of a coronal disturbance to emerge from this approach. Probably the best thing to do is to classify the observed coronal disturbances and the different physical processes that are likely to be present, and then to see if we can guess at the correspondences between the observations and the physical processes.

Immediately, however, we encounter two difficulties. First we must agree on which observations should be explained, and second we must decide which physical processes are important. These are not trivial problems.

Our ability to observe coronal and solar activity has vastly improved over the past ten years. With satellites, space probes, and orbiting laboratories, we are no longer limited by the Earth's atmosphere. We have observed virtually the entire electromagnetic spectrum from gamma rays to hektometer wavelengths as well as charged particles of all types over a wide energy range. Good spatial resolution in the plane of the sky has become available at wavelengths previously undetectable. At present, we have the immense task of correlating in space and time all the different kinds of observations. Thus there is now so much data and so much detail that a significant problem is to decide which observations to try to explain. On the other hand, just listing the different models that have been proposed for solar flares and prominences will show that agreement among theoreticians, even about the dominant physical processes, is not always present.

In fact, the difficulties faced by both observers and theoreticians derive from the same underlying cause, which is both the curse and the charm of solar physics. What we are concerned with in solar activity is a complex system of interacting fields and particles which can be viewed from many levels of sophistication.

To be rigorous, we must picture a coronal disturbance as a plasma of electrons, several different kinds of ions, and perhaps some neutrals, together with a magnetic field which affects the dynamics of these various plasma particles and is in turn perturbed by their motions. Any given ion may continually change its excitation, ionization, position in space, and velocity. Time changes may occur over the entire plasma and in local regions. The plasma distributions in space and velocity are extremely anisotropic because of gravity, magnetic fields, and boundary conditions on the plasma. Billings (1966) describes how complex a single cubic millimeter of coronal plasma really is.

However, coronal disturbances cannot be as completely chaotic as a microscopic description would imply. If they were, there could not be such easily recognizable coronal events as meter wavelength bursts of types II, III, and IV, eruptive prominences, flare surges, and so on. The very fact that it is possible to classify or define different kinds of coronal events on the basis of observation means that there are certain patterns of interaction between the magnetic field and the plasma that justify a macroscopic or fluid description. This is the reasoning that encourages us to attempt simple models of coronal disturbances on the basis of a few selected observational features.

Of course, a fluid description can also be extremely complicated. If we treat each plasma component as a separate fluid with a mean density, mean velocity, mean temperature, etc., the number of nonlinear partial differential equations that we must solve as a system becomes unmanageable. If we lump all the plasma components together and consider only one conducting fluid with an imbedded magnetic field as in magnetohydrodynamics, we still have several dependent variables such as the magnetic field, the fluid velocity, the density, and the temperature, which are functions of space and time, and constitutive parameters such as viscosity, electrical conductivity, and thermal conductivity, which are often treated as constants but which in fact could be functions of the dependent variables. Boundary conditions are also a problem because a coronal disturbance is not a closed system; it is imbedded in a plasma through which other electromagnetic, plasma, and acoustic waves (or disturbances) are continually propagating. Therefore, even a single-fluid hydromagnetic description of a coronal disturbance is usually so complex that we can obtain neither a numerical solution nor a conceptual picture to compare with observations.

Thus understanding the microscopic physics and being able to write down the equations is not enough in the case of coronal disturbances. To interpret observations we must understand the macroscopic interactive system of field and plasma. This means we must be able to write, solve, and interpret some rather complex closed sets of partial differential equations. At present we cannot properly solve such sets of equations and therefore must either do computations with a few terms or else solve the linearized (small-amplitude) approximations. As a result, except for the simplest cases, we do not yet know all the macroscopic processes and nonlinear feedback chains that may be contained in the plasma equations.

I have just painted a bleak picture primarily to emphasize that interactive plasma systems are sufficiently complex that deciding what physical processes and what observations should be emphasized in a model of a coronal disturbance is not a completely trivial matter. With regard to both the theory and the observations of a coronal disturbance, we must at present be satisfied with incomplete descriptions. An incomplete description, however, is largely a matter of judgement. It runs the risk of over-interpreting some observations while ignoring others, and of imagining physical processes that might not actually occur while neglecting those that are crucial. Moreover, to be interesting it should provide a picture broad enough to incorporate several diverse phenomena from only a few assumptions.

Granted that we must settle for an incomplete description and that the game is risky, I will now assume an optimistic attitude and return to my original goal of classifying the observations of coronal disturbances and a few hopefully relevant physical processes, to see if we can distil some useful concepts from this enormous complexity. There are a large number of ways to classify observations and plasma processes, and I will now commit myself to those at the very lowest level of sophistication.

2. Coronal Disturbances and the Electric Current Picture

If a magnetic field supplies energy which affects the temperature, density, or flow field of the surrounding medium, then the magnetic field must be non-potential, that is, it must have a twist or curl, therefore an electric current. Probably any observable solar phenomenon which can be classified as solar activity (whether in the photosphere, chromosphere, or corona) is a consequence of a non-potential magnetic field, or equivalently, an electric current.

In simple hydromagnetic theory, it does not matter whether phenomena are described in terms of the magnetic field or in terms of the electric current (Gold, 1968). If we emphasize the magnetic field, we can determine the electric current by taking the curl (or rot) of the magnetic field; if we emphasize the electric current, we can determine the vector potential and then the magnetic field by solving a Poisson-type vector equation with suitable boundary conditions.

If, however, the regions of electric current are sufficiently localized, then there is a decided advantage in trying to map the electric current rather than (or in addition to) the magnetic field. This is simply because the electric current regions of the solar atmosphere are the regions where magnetic energy is available for conversion into various kinds of kinetic energy. In fact, the neutral lines of the photospheric magnetic field must parallel the major large-scale electric currents of the Sun's surface. Whenever a neutral line is sharply defined in the photosphere, the photospheric electric current is probably strong and localized. Coronal activity, then, is most likely to originate over or near the photospheric neutral lines.

On the other hand, many coronal disturbances seem to follow the lines of potential (or current-free) magnetic field. Of course, any perturbation or kink in the potential field is equivalent to an electric current in the hydromagnetic sense. Nevertheless, for such coronal disturbances there is no clear advantage in using a current description.

There are also many cases where the magnetic field (**B**) is nearly parallel to the electric current (curl **B**). In this situation there usually is no discernible geometrical symmetry and the problem is difficult both mathematically and conceptually. The force-free field is an example.

The situation may also become quite complex if a broader view of hydromagnetic theory is taken, for example if we use a general Ohm's law, or equivalently, treat the electrons and ions as two separate fluids. Then non-parallel gradients of electron pressure and density may generate electric current. In practice, however, the electric current picture is interchangeable with the magnetic field picture at low frequencies until charge separation becomes important in the plasma.

Here I will emphasize the electric current picture and try to interpret observations of coronal disturbances accordingly. At low frequencies, the electric current picture does not introduce new physics, but hopefully follows a less familiar approach.

Let us now discuss the different ways an electric current may be generated in the corona. Since an electric current (that is, a non-potential magnetic field) in the corona is presumably the cause, effect, or kernel of a coronal disturbance, we are in fact classifying physical processes involved in a coronal disturbance.

Suppose that initially electric currents exist only in the photosphere and that the coronal magnetic field is everywhere current-free or potential. How can we generate an electric current in the corona? Four general ways are listed below.

(1) Perturb the potential field of the corona with coronal forces. Examples of this process are:

(a) Drop or condense matter at the top of a closed potential field line thereby bending it to create an electric current. This is equivalent to the magnetic buoyancy of plasma due to the tension forces of the magnetic field (Kippenhahn and Schlüter, 1957; Brown, 1958; Nakagawa and Malville, 1969; Anzer and Tandberg-Hanssen, 1971; Hildner, 1971; Raadu and Kuperus, 1973).

(b) Pull the potential field outward by forces of the solar wind expansion as in helmet streamers; create a current sheet thereby (Sturrock, 1968; Pneuman and Kopp, 1971).

(c) Set up shear flows in the corona which distort or twist the potential magnetic field.

(d) Create a shock or violent mass motion either parallel or perpendicular to a loop of potential magnetic field thereby causing a large-amplitude perturbation of the potential field lines (Uchida, 1970; Pneuman, 1967; Meyer and Schmidt, 1968; Schatten, 1970).

(2) Perturb the potential field of the corona with photospheric or chromospheric

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motions. Examples of this process might be:

(a) Change the electric current density in the photosphere by expanding or collapsing the electric current cross-section; kinks in the magnetic field (hence electric currents) propagate out at about the Alfvén speed to readjust the field configuration; changes occur in the strength of the potential magnetic field, or equivalently, in the localization of the magnetic flux.

(b) Change the configuration of the electric current in the photosphere by convective motions; meanders or shears in the photospheric electric current region can twist the potential field lines of the corona, thereby generating an electric current (Sturrock and Coppi, 1966; Levine and Nakagawa, 1974).

(c) Move the footpoints of the potential magnetic field by displacement motions or by vortical mass motions; the kinks or twists propagate into the corona at the Alfvén speed; the twisted field (or current) may continue to build up and store energy, or act as a force-free field (Gold, 1964; Anzer, 1968; Stenflo, 1969; Nakagawa and Raadu, 1972); this situation is similar to that of (b).

(d) Create an electric current in the photosphere by means of non-parallel gradients of electron temperature and electron pressure (Kopecky and Kuklin, 1971), and thus cause readjustment of the coronal field.

(3) Create an electric current in the corona by various plasma processes.

(4) Eject a photospheric electric current or electric current filament upward into the corona. Possible methods of doing this are:

(a) Concentrate the photospheric electric current; then magnetic buoyancy should be effective (Parker, 1955).

(b) Concentrate the photospheric electric current into a thin filament; then the region surrounding the current is heated by magnetic diffusion; current becomes buoyant.

(c) Create magnetic forces (that is, antiparallel electric currents) either by reconnection of field lines in the photosphere (Sweet, 1958; Petschek, 1964; Coppi and Friedland, 1971) or by meandering the photospheric electric current thus creating a small area of opposite magnetic polarity in a unipolar photospheric region (Altschuler *et al.*, 1968).

These four general methods of producing a coronal electric current provide a conceptual scheme to describe the prerequisite conditions for a coronal disturbance. Of course, in reality the fluid flow cannot be merely assumed as we have done, but must be considered self-consistently with the magnetic field and other forces. Now let us take a brief panoramic view of the observations of coronal disturbances.

3. Classification of Observations of Coronal Disturbances

Classifying a coronal disturbance by where it appears in the electromagnetic spectrum is probably safest (1) because each spectral region reveals a different parameter domain of the solar plasma and (2) because the sophistication, sensitivity, and resolution of our detection equipment varies greatly over the spectrum. Thus if radiation enhancements observed in different spectral regions are considered different types of coronal disturbances for classification purposes, we need not decide *a priori* whether we are observing (1) a single coronal region in which several different physical processes are operating over a wide range of energy, or (2) separated coronal regions emitting at the same time under different ambient conditions (such as inside or outside a coronal streamer).

Let us list coronal disturbances and associated phenomena according to the spectral range in which they are observed. No attempt is made for completeness, and fast disturbances are emphasized.

(1) Hα measurements (and other strong hydrogen lines):
- (a) brightenings on disk and limb (flares)
- (b) surges, sprays, other ejecta
- (c) active loops, coronal rain
- (d) flare waves (Moreton disturbances)
- (e) disappearing or winking filaments on the disk
- (f) large erupting prominences on the limb (particularly hedgerow)

(2) Monochromatic measurements of coronal emission lines in the visible spectrum:
- (a) expansion of coronal arches: slowly, rapidly, or explosively
- (b) whips: opening of coronal arches
- (c) hot plasma regions at tops of flare loops

(3) White Light Measurements:
- (a) coronal changes over eclipse path
- (b) thin coronal rays or sheets (possibly electric current sheets)
- (c) electron density changes
- (d) moving blobs, mass motions

(4) Measurements at X-ray wavelengths:
- (a) impulsive brightenings
- (b) small hot emission cores in coronal loops or filaments
- (c) EUV flares and ejecta

(5) Radio measurements (millimeter to hektometer wavelengths):
- (a) sharply defined frequency drifts at decimeter and longer wavelengths
- (b) impulsive microwave bursts
- (c) continuum emission
- (d) enhanced emission and proper motions (two-dimensions in plane of sky) at a single frequency (for example 80 MHz)

(6) Non-Electromagnetic Measurements:
  (a) terrestrial ionospheric disturbances
  (b) solar wind enhancements or (shock) discontinuities in speed, density, and magnetic field
  (c) enhancements in number, flux, and energy of fast charged particles (such as protons, electrons, solar cosmic rays)

At this conference these phenomena will be reviewed in detail. Here I will confine my remarks to aspects of these coronal events which concern magnetic fields. Let us now look at the observations, deductions, and inferences regarding the solar magnetic field.

4. Determining the Coronal Magnetic Field (Long-Period Disturbances)

4.1. Coronal emission line polarization

The coronal magnetic field configuration can be inferred (at least in projection over the limb) if we can observe the monochromatic emission from certain magnetically-sensitive coronal lines and determine the distribution of polarization in the plane of the sky. The degree of polarization together with the angle of maximum polarization provide information on the direction (but not the magnitude) of the coronal magnetic field at the position where the emission line radiation originates. Such observations have been made with a coronameter (Charvin, 1965, 1971) and during eclipses (Hyder, 1966; Eddy and Malville, 1967; Hyder *et al.*, 1968; Beckers and Wagner, 1971; Eddy *et al.*, 1973) for various coronal emission lines. To measure the Stokes parameters, new coronameter-type instruments have been built at Meudon (Charvin, 1971), the University of Hawaii (Orrall, 1971), and at HAO (Querfeld, 1973).

The theory of coronal emission line polarization is quite involved (Charvin, 1965; Hyder, 1965; House, 1972). If the three-dimensional coronal magnetic field is known, House (1972) can determine the polarization that should be observed in the plane of the sky. That was in itself a difficult problem. House, Querfeld, and I are now working on a method which we hope will solve the converse problem of determining the coronal magnetic field geometry in three dimensions from daily polarimeter observations. Our plan is to observe the Stokes parameters of a coronal emission line in the plane of the sky over several days and then use regression analysis together with a few assumptions to find the three-dimensional coronal magnetic field configuration that best fits the plane-of-the-sky observations. Some information about the non-static magnetic fields in fast coronal disturbances might also be inferred with such a method.

4.2. Limb prominence fields

Magnetic fields of limb prominences have been determined from measurements of the Zeeman splitting in several strong spectral lines (Tandberg-Hanssen, 1971). Of the quiescent prominences observed, more than half have a mean line-of-sight field strength between 3 and 8 G. The magnetic field appears to enter and leave at the sides, but in the quiescent prominence itself there is a component of the field parallel to the prominence axis. Rust (1966, 1967) and Harvey (1969) found some evidence that stronger fields occur higher in the prominence. Thus from the available measurements, a quiescent prominence appears to illustrate how a magnetic field may support matter. However, the limited spatial resolution of $10'' \times 10''$, or 7.5 Mm in distance on the Sun, does not allow an estimate of the magnetic fields in prominence fine structures. The fine structures of quiescent prominences may indicate a circulation of matter (Dunn, 1960; Engvold, 1972; Tandberg-Hanssen, 1974). Tandberg-Hanssen and Malville are now studying the Climax measurements of magnetic fields in active limb prominences. A new instrument to measure the four Stokes parameters of spectral lines (and hence the magnetic field) in limb prominences is under construction at HAO.

4.3. Other coronal measurements pertaining to magnetic fields

In addition to measurements of the coronal emission line polarization and the Zeeman splitting of prominence lines, other direct information concerning the general configuration of the coronal magnetic field may be obtained from studies of the X-ray loops and structures (Krieger *et al.*, 1971) and from radio measurements (Daigne *et al.*, 1971; Kundu, 1971).

4.4. Current-free fields: small scale (no surface curvature)

At present, however, the coronal magnetic field cannot be determined on a routine basis from measurements of coronal phenomena. Instead, we must calculate the coronal field from measurements of the photospheric field. One way of doing this is to assume that the magnetic field is current-free (or potential) above the photosphere and then to solve a Laplace equation with the measured photospheric magnetic field distribution providing the boundary condition. Since only the line-of-sight photospheric field component can be accurately measured, observations are usually taken as near as possible to disk center so that the measured field is normal to the surface. The current-free approximation provides a mathematically unique solution for the three-dimensional coronal magnetic field. Any observed deviation from the calculated field geometry is an indication of coronal electric currents.

Schmidt (1964) was the first to use detailed measurements of the photospheric magnetic field to trace the current-free coronal field configuration. His program was designed to represent a limited region not exceeding about 200 Mm on a side; therefore, the curvature of the solar surface was not included. The potential magnetic field of the corona calculated by this method has been compared with active and quiescent prominence features above the limb (Rust, 1966; Harvey, 1969; Rust, 1970; Rust and Roy, 1971; Roy, 1972) and with chromospheric Hα filaments (Rayrole and Semel, 1968; Harvey *et al.*, 1971).

Above strong but reasonably static photospheric fields, the predicted coronal potential field is consistent with the coronal loops observed in monochromatic emission as far as 150 Mm from the limb (Rust and Roy, 1971); this agreement appears in spite of the fact that the photospheric magnetic fields of an active region are measured about a week before or after limb passage. Surprisingly, coronal loops formed after a large flare also agree with the potential field configuration (Roy, 1972). This might mean that non-potential fields in the corona can relax rapidly to potential fields after releasing energy which heats or disturbs the plasma. However, there is also the possibility that the flare-loop magnetic fields have highly twisted fine structure and therefore contain electric current.

In the chromosphere, the agreement between the potential field and the direction of the Hα fine structure is often poor (Rayrole and Semel, 1968; Harvey *et al.*, 1971). This indicates that the fine structure of the chromosphere is associated with non-potential or twisted magnetic fields. In fact the very existence of a filamentary structure is good evidence for complex plasma processes and non-potential magnetic fields. Photospheric fields also appear to be filamentary (Howard and Stenflo, 1972; Frazier and Stenflo, 1972) and therefore non-potential on a fine scale.

Programs have recently been devised which use photospheric field measurements to calculate force-free magnetic fields above active regions (Nakagawa and Raadu, 1972). In these calculations, the electric current and the magnetic field are everywhere parallel and have a constant ratio of magnitudes. The derived force-free magnetic fields sometimes are aligned with active filaments of the chromosphere. Again this indicates that chromospheric fields are often twisted, and that the magnetic field and the electric current are not always perpendicular. However, large active-region filaments do seem to lie along the boundary (neutral-line) which separates photospheric regions of opposite magnetic polarity (Howard and Harvey, 1964).

I do not wish here to enter the controversies concerning the orientation of chromospheric features with respect to the magnetic field (Veeder and Zirin, 1970; Frazier, 1972a, b; Zirin, 1972; Foukal and Zirin, 1972; Cheng *et al.*, 1973) except to emphasize that this is an extremely important problem for our purposes because we want to understand how electric currents (or non-potential fields) are created in the photosphere and chromosphere and how they generate coronal disturbances. Undoubtedly changes in the opacity and orientation of chromospheric filaments during the flare process are associated with changes in magnetic fields and electric currents (Zirin and Tanaka, 1973) although the precise mechanism is still not clear. In any case, the measurement of magnetic fields in the photosphere and chromosphere, particularly for the fine scale, is difficult both observationally (Beckers, 1971; Harvey, 1972) and theoretically (Stenflo, 1971). (See also the other related articles in *IAU Symp.* **43**.)

Since the calculated potential field agrees better with large coronal structures than with fine-scale chromospheric features, maps of the potential magnetic field on a global scale should be useful for the study of those coronal disturbances which are guided over long distances by the general field structure. Let us now discuss the potential field of the solar corona on the global scale.

4.5. Current-Free-Fields: Global Scale

Methods have been developed to calculate the current-free coronal magnetic field on a global scale using as data only the measured line-of-sight component of the photospheric magnetic field. In recent years, the mathematical techniques and limitations for such global maps have been discussed in detail in the literature (Newkirk *et al.*, 1968; Schatten *et al.*, 1969; Altschuler and Newkirk, 1969; Schatten, 1971a). Here I will merely make a few general remarks and then discuss applications relevant to coronal disturbances.

The Mt. Wilson data are the only full solar disk magnetic measurements continual over a long period of time. The equipment, the observational techniques, and the method of reduction were described by Howard *et al.* (1967). To obtain the global coronal field in the current-free approximation, the photosphere is first divided into 1080 surface elements of equal area, with 30 zones ($\Delta \sin\lambda = 1/30$ in latitude λ) and 36 sectors ($\Delta\phi = 10°$ in longitude ϕ). For each surface element an average line-of-sight magnetic field is found from the Mt. Wilson data. Corrections for magnetograph saturation are added to those surface elements where strong sunspot fields are present. The average line-of-sight fields of the 1080 equal surface elements are then used to calculate the Legendre coefficients of the harmonic series which solves the Laplace equation and best fits the global photospheric magnetic data (Altschuler and Newkirk, 1969). Once the Legendre coefficients are known, the magnitude and direction of the current-free (potential) coronal magnetic field can be determined at any point in space within about $r = 2.5\ R_0$, beyond which the solar wind dominates.

There are several limitations of this procedure which must be kept in mind. The Mt. Wilson data are restricted to one magnetic component (line-of-sight), to one atmospheric level (the photosphere), and to a relatively small intensity range (0.5 to 100 G). Because of foreshortening effects, the magnetograph measurements are representative of actual fields only near the center of the visible solar disk. Thus photospheric magnetic data for the polar regions are of limited accuracy, and data covering the entire Sun must be collected over at least one complete solar rotation. As a result, any magnetic field fluctuations in the photosphere can be detected only at three to four week intervals. The unavoidable errors in correcting for strong fields and in measuring the photospheric field over an entire solar rotation cause a spurious net monopole component for the global solar field. This spurious monopole contribution is removed by adding a constant to all the line-of-sight field measurements (Altschuler and Newkirk, 1969). The resulting field has no monopole component larger than one part in 10^8. A zero potential surface is also included to make the coronal field radial at $r = 2.5\ R_0$ and thereby simulate the effects of the solar wind.

From a set of Legendre coefficients, we can at present draw four different kinds of maps to help visualize the coronal potential magnetic field.

The first type of map traces the lines of coronal magnetic field from footpoints which are distributed geometrically over the photosphere. One coronal magnetic field line is drawn from each of 648 elements of equal photospheric area (that is, 27 equal divisions in longitude and 24 equal divisions of the north-south axis). Thus this map shows the overall geometry of the coronal magnetic field but does not distinguish strong from weak fields either in the corona or in the photosphere.

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The second type of map shows a particular subset of the field lines which appear in the map of the first type. The photosphere is first partitioned into regions of similar magnetic polarity (unipolar regions). The total number of field lines (a number chosen in advance) is then distributed among the unipolar regions in proportion to the amount of radial magnetic flux. Thus this map shows the coronal distribution of the largest amounts of magnetic flux. Strong fields from small photospheric areas and weak fields from large photospheric areas can appear in this map provided a sufficient amount of flux passes through the unipolar photospheric region.

The third type of map shows the field lines which originate from the photospheric regions of strong magnetic intensity. A grid four times finer with $648 \times 4 = 2592$ elements of equal photospheric area is used. The field strength at the center of each area element is calculated and ranked. Field lines are drawn from the 400 area elements with the strongest calculated magnetic field. Thus this map plots only 15% of the possible field lines and shows how photospheric regions of strong magnetic field influence the solar corona. Strong fields correlate with active regions in the corona such as those appearing in X-ray rocket photographs.

The fourth type of map draws a continuous intensity distribution so that the coronal regions with largest $|\mathbf{B}|$ appear brightest. This map is being used to compare the three-dimensional magnetic field distribution with the three-dimensional density distribution as calculated by Altschuler and Perry (1972) and Perry and Altschuler (1973).

In Figure 1, the first three types of maps are shown for the November 1966 eclipse together with an Hα disk picture. Figure 2 shows these types of maps for the March 1970 eclipse together with the X-ray picture taken by American Science and Engineering (Krieger *et al.*, 1971). Figure 3 is a map of the fourth type for the November 1966 eclipse (devised by R. M. Perry) to show the absolute magnitude of the magnetic field strength. The calculated coronal fields for the November 1966 eclipse correspond well with the global density structure and the strong Hα emission regions (Newkirk and Altschuler, 1970; Newkirk, 1971). Around the time period of the March 1970 eclipse, the Sun's photospheric field changed considerably. Even so, there is some agreement between the strong field map (type 3) and the X-ray emitting regions. It is likely therefore that the X-ray emission occurs where the coronal field is strong. The direct comparison of calculated coronal fields with eclipse photographs (Newkirk, 1971; Schatten, 1971b; Altschuler, 1971) has shown that the global potential field is useful for tracing the inhomogeneous coronal structure, thus for long-period (or evolutionary) disturbances.

5. Fast Coronal Disturbances and Coronal Magnetic Fields

Fast coronal disturbances usually occur in less than an hour and often in a few minutes. They probably involve complex hydromagnetic processes. When we try to conceptualize such processes we generally think of 'static' and 'dynamic' magnetic fields. When static, magnetic fields may (1) store energy and fast particles, (2) guide

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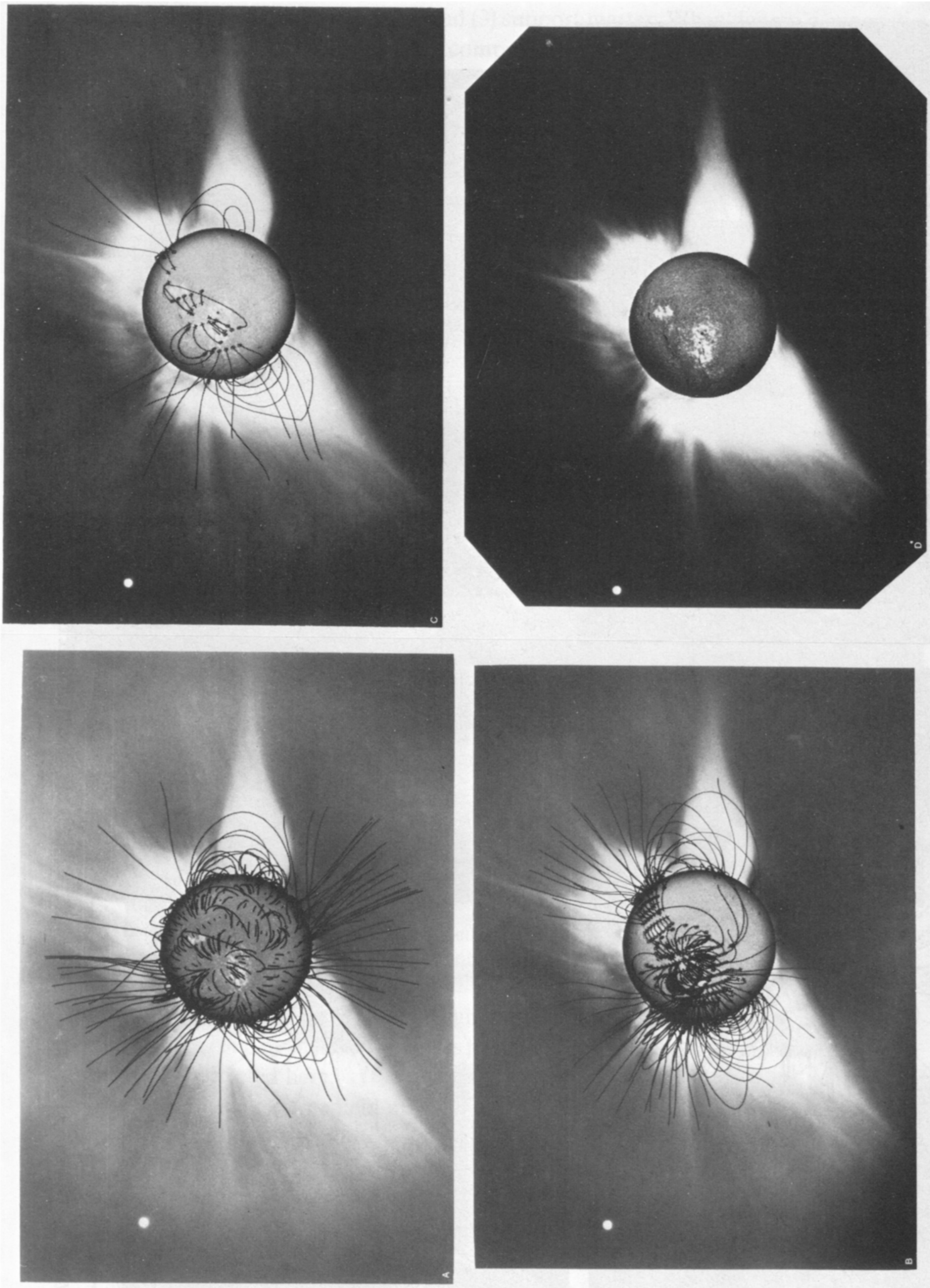

Fig. 1. Global potential magnetic field maps for the November 1966 eclipse. *Upper left*: general field map (type 1). *Upper right*: flux map (type 2). *Lower left*: strong field map (type 3). *Lower right*: eclipse photograph with Hα picture superposed over lunar disk. North is at upper left.

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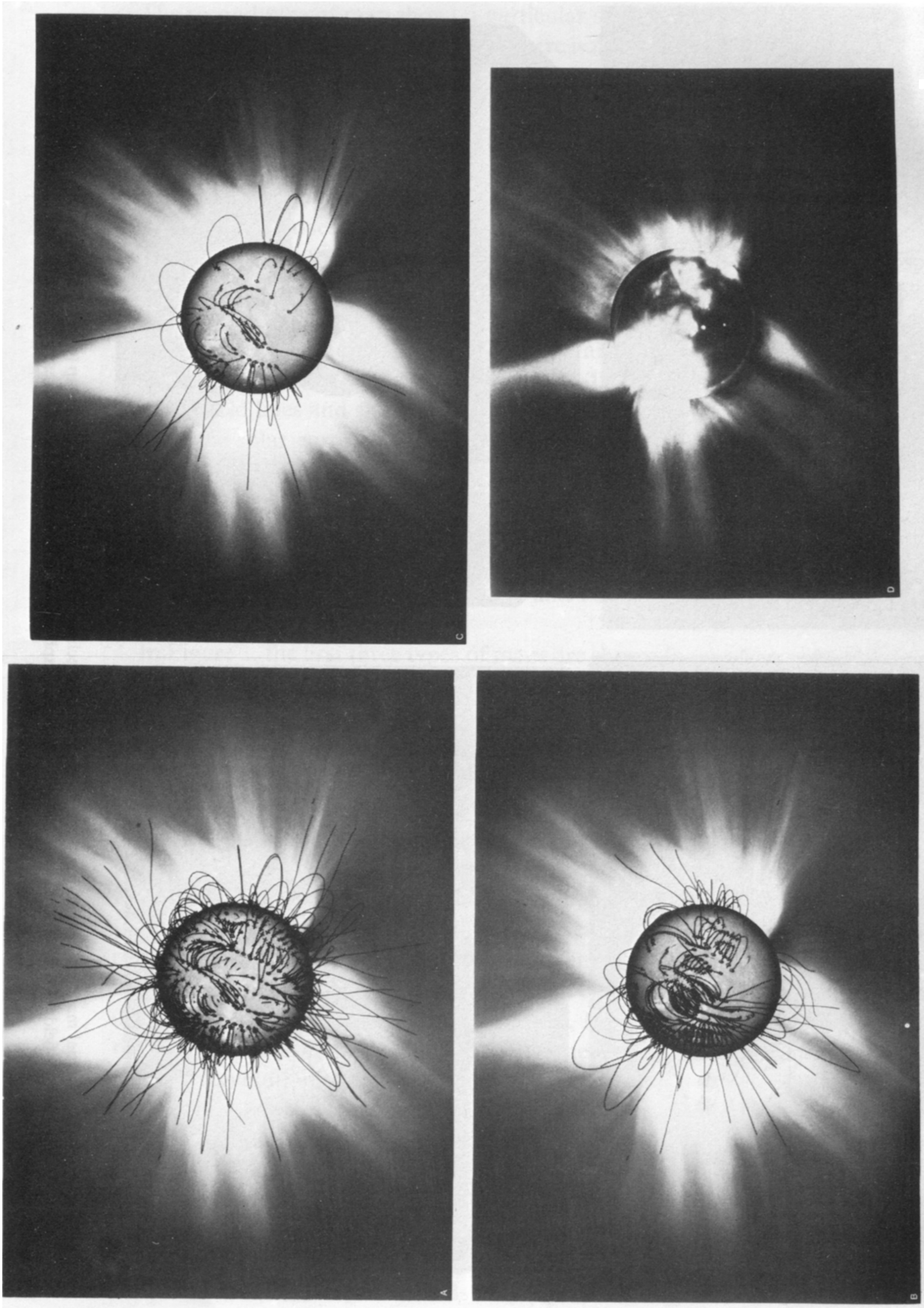

Fig. 2. Global potential magnetic field maps for the March 1970 eclipse. *Upper left*: general field map (type 1). *Upper right*: flux map (type 2). *Lower left*: strong field map (type 3). *Lower right*: eclipse photograph with AS & E rocket X-ray picture superposed over lunar disk. North is at upper right.

disturbances, waves, and heat flow, and (3) support matter. When dynamic, magnetic fields may (1) accelerate particles, (2) compress matter, and (3) set up waves, shocks, and mass motions which in turn feed back changes to the magnetic field configuration.

In terms of the electric current description of Section 2, the 'static' fields correspond to relatively small perturbations of the pre-existing coronal potential field, whereas the 'dynamic' fields usually correspond to the transport of large non-potential magnetic fields (or electric currents) through the corona. Electric currents generated directly in the corona by plasma processes have not been discussed much in the literature and will be neglected here.

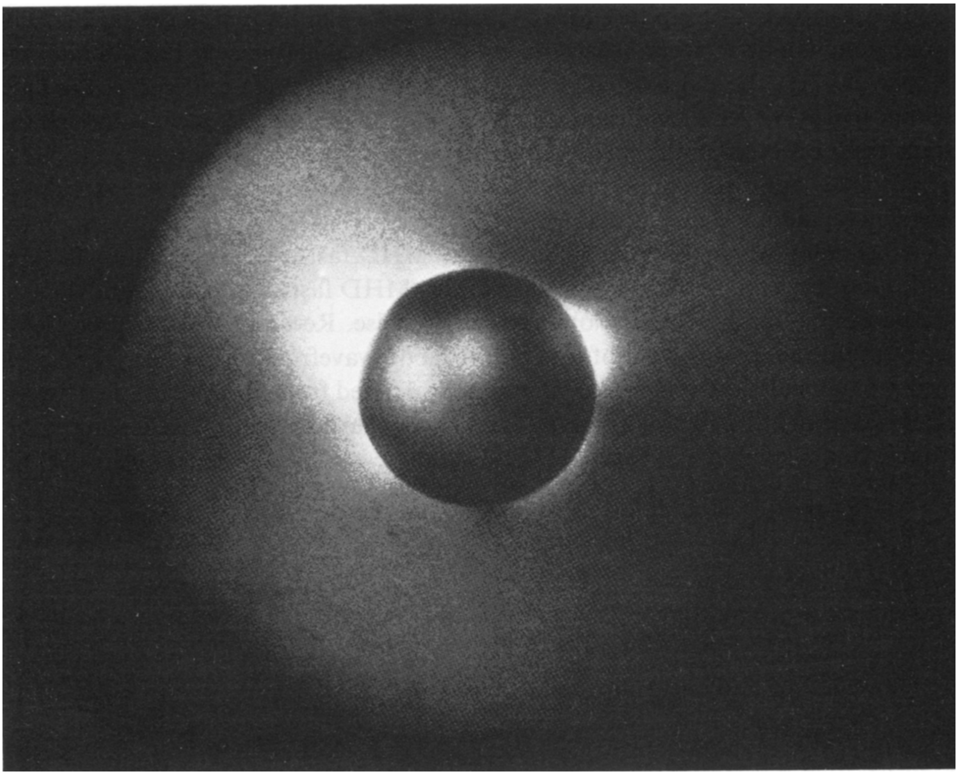

Fig. 3. **Absolute magnitude of global potential magnetic field for November 1966 eclipse. Brightest features have most intense magnetic fields. North is up.**

The global current-free field approximation which we have just discussed in Section 4.5 can be used to study fast coronal disturbances of two extreme types. The first type includes static magnetic fields which guide disturbances over global distances. No permanent changes in the photospheric or coronal field geometries are obvious. The second type includes major dynamic disturbances which alter the large-scale photospheric field and therefore the global coronal field.

Let us first see what can be learned about static (or quasi-static) coronal magnetic fields and the role they play in guiding, focusing, and otherwise controlling coronal disturbances.

5.1. Disturbances guided by magnetic fields

There are several transient phenomena which appear to be guided or controlled by quasi-static coronal fields. These include chromospheric flare waves, certain radio disturbances, and probably fast streams of plasma in the interplanetary medium.

On occasion, a fast (up to 1 Mm s^{-1}) wave pulse can be seen in the Hα chromosphere moving away from a flare region (Moreton and Ramsey, 1960; Smith and Harvey, 1971). The pulse usually remains within some angle centered at the flare, and propagates over a significant fraction of the solar circumference. Although this transient is observed at the chromospheric level, its energy source must propagate as a hydromagnetic disturbance through the corona; in the chromosphere, disturbances are slower and are damped over shorter distances (Anderson, 1966; Meyer, 1968; Uchida, 1968). Apparently the flare emits an MHD fast-mode wavefront which expands into the corona. The intersection of this MHD fast-mode wavefront with the chromosphere then causes the observed wave pulse. Recently Uchida *et al.* (1973) have traced the propagation of MHD fast-mode wavefronts from flare regions by means of (global) potential field configurations derived from magnetograph data and electron density distributions derived from K-coronameter data. An isotropic wavefront was assumed at the source. Figures 4 and 5 show for different flares (1) the

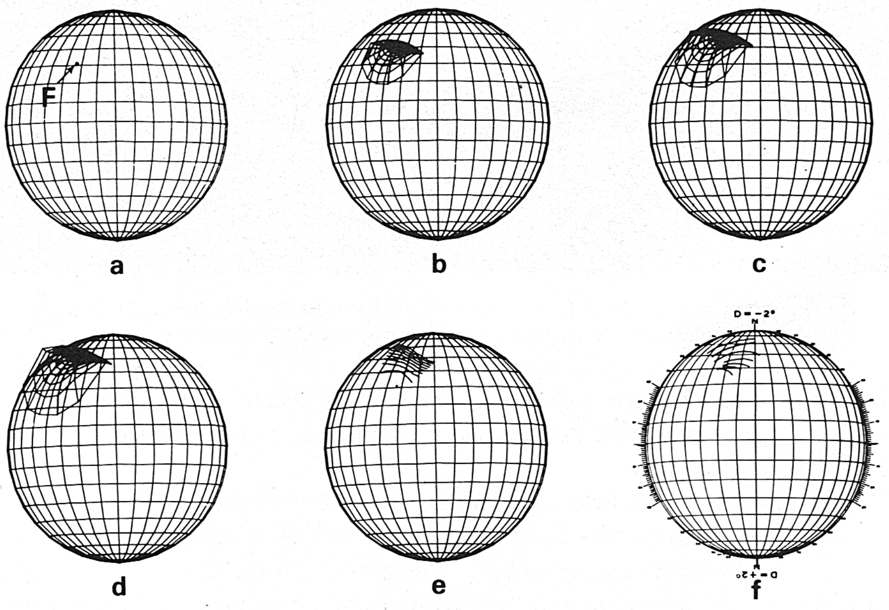

Fig. 4. Calculations for flare wave of 23 May 1967. Diagrams 4a–d show development of coronal wavefront and regions of energy concentration. Diagram 4e shows calculated intersections of the coronal wavefront with the chromosphere at different times. Diagram 4f shows observed positions of the flare wave at different times.

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calculated time development of the coronal wavefront, (2) the calculated intersection of the wavefront with the chromosphere at different times, and (3) the observed chromospheric flare wave at different times. The agreement is remarkable. Thus a chromospheric flare wave is caused by a hydromagnetic fast-mode disturbance which propagates into the corona and concentrates in coronal or chromospheric regions

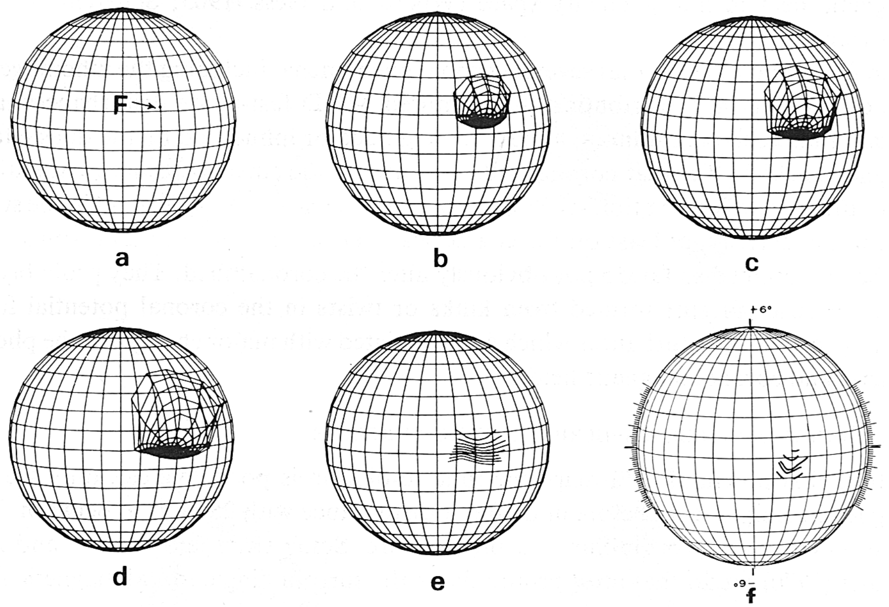

Fig. 5. Calculations for flare wave of 31 July 1967. Diagrams 5a–d show development of coronal wavefront and regions of energy concentration. Diagram 5e shows calculated intersection of the coronal wavefront with the chromosphere at different times. Diagram 5f shows observed positions of the flare waves at different times.

where the Alfvén speed is low. There seems to be some correlation between flare waves and type II radio bursts (Smith and Harvey, 1971; Uchida *et al.*, 1973). Perhaps the type II burst is itself a large-amplitude MHD-fast-mode shock (McLean, 1967), or else a disturbance which originates in a coronal region of low Alfvén speed where MHD fast-mode energy is concentrated.

To determine the magnetic field geometry associated with a radio disturbance, we must accurately locate the radio disturbance at least in the plane of the sky. In general this can be done with interferometry (Wild, 1970). Global maps of the potential magnetic field have been compared with radio data from Culgoora, the University of Maryland, and several other observatories. In general, the results show that fast outwardly-moving radio bursts such as type II, type III, and moving type IV are guided by open field lines (Smerd and Dulk, 1971; Dulk *et al.*, 1971; Dulk and Altschuler, 1971; Kuiper, 1973). Such comparisons are not completely conclusive because we do not know the three-dimensional positions of the radio sources. Moreover, since density gradients are generally small in the corona, their effect on the propagation of radio disturbances is not easy to discern.

The farther we go from the photosphere, the simpler the potential field configuration becomes. Higher harmonics of the photospheric field drop off at higher powers of the radial distance. At $r = 2.5\ R_0$, only the dipole, quadrupole, and sometimes the octupole components are influential. These low harmonic components dominate the magnetic field in interplanetary space (Wilcox and Ness, 1965; Schatten, 1971b; Scherrer *et al.*, 1972).

So far we have shown that several coronal phenomena, including the inhomogeneous coronal density distribution, flare-emitted MHD fast-mode disturbances, and certain radio emitting sources, appear to be guided or influenced by the quasi-static magnetic field of the solar corona as determined by the current-free approximation. Thus theory and observation are beginning to find some common ground in the study of coronal activity, at least on the coarse scale. However, the coronal disturbances we have examined so far do not obviously alter the coronal field. They probably involve electric currents formed from kinks or twists in the coronal potential field. Now let's look at disturbances which are associated with major changes in the photospheric and coronal magnetic fields.

5.2. Eruption of Photospheric Electric Currents

With global potential field maps the time resolution is poor. We can only see the magnetic configuration before and after a disturbance with 28 days in between. The most violent event on the Sun is a proton flare. Some years ago, Valdez and Altschuler (1970) found that after proton flares the surrounding coronal magnetic field seems to decrease in flux and to change from a closed-loop (arcade) structure to an open or diverging field. At that time, we had only (the type 1) maps which plot the general coronal field but do not distinguish strong from weak fields, and (the type 2) maps which give the major flux connections. Now we have a microfilm atlas of the coronal field for the period 1959–1970 which contains maps of both the general field (type 1) and the strong field (type 3) (Newkirk *et al.*, 1972). So in preparing this talk I thought it would be worthwhile to look again at the problem. Figures 6 through 11 show the changes of the global coronal field associated with proton flares. At the top are the strong field maps; at the bottom are the general field maps. As a rule, the magnetic field changes drastically in strength and geometry around the flare region. Low magnetic arcades disappear, or decrease significantly in field strength. Since the low magnetic arcades seen in the strong field maps are caused by strong electric currents flowing in the underlying photosphere, it appears that photospheric electric currents disappear or disintegrate at the time of large flares or shortly thereafter. There are only a few ways that this can be done. The currents can disappear by some very efficient magnetic diffusion process; they can disperse if the electric current expands in cross-sectional area, or branches into many small filaments; they can be pulled below the photosphere, or they can be ejected out of the photosphere into the corona. For changes in the time scale of one solar rotation or less, I am willing to wager that strong and extensive photospheric electric currents can disappear so completely only by being ejected upward from the photosphere. Of course, I do not mean that the electric current must be ejected all at once. It could rise gradually, interact with the chromosphere in some complicated way, and be ejected bit by bit. But somehow strong electric currents do disappear rapidly over rather extensive photospheric regions.

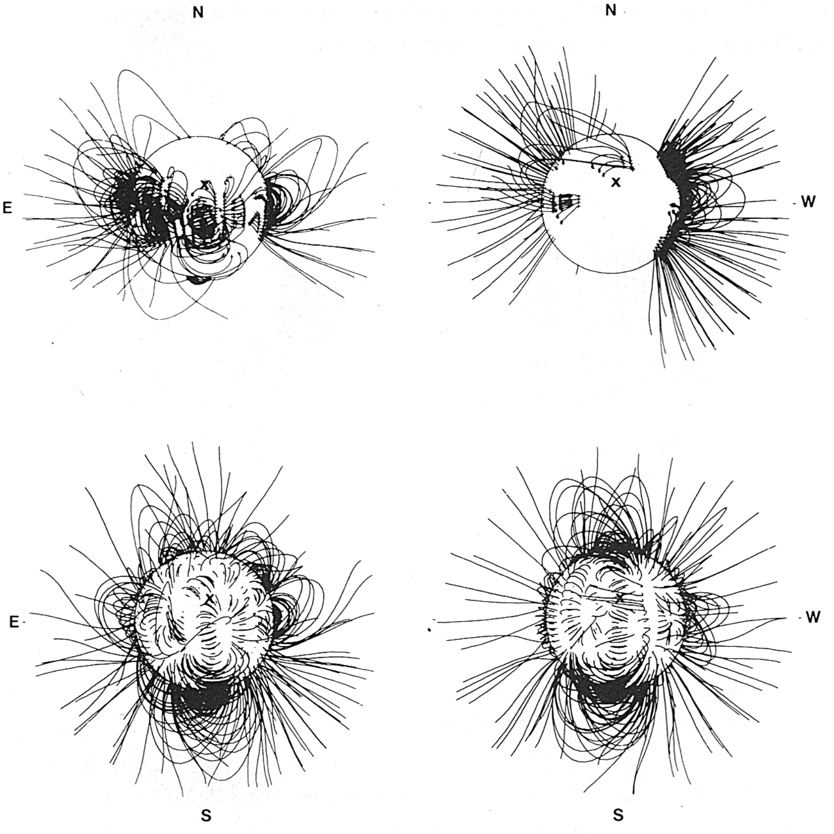

Fig. 6. Changes in calculated coronal magnetic field before and after flare of 29 April 1960. Strong field maps are at top; general field maps are below.

Do we have other evidence that photospheric or chromospheric electric currents are being ejected into the corona? I think we do, and I will try to argue the case. In doing so, I will discuss observations of some of the coronal disturbances listed in Section 3.

If well-defined or localized electric currents are ejected into the corona, we would expect that the accompanying plasma is either hot and dense because of the current pinch effect, or in violent motion because of unbalanced $\mathbf{J} \times \mathbf{B}$ forces.

The hottest and densest plasma regions in the corona are associated with the X-ray filaments or emission cores. Temperatures in such filaments have been put at up-

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wards of 10^7 K. Estimates for the electron density range from 10^{11} to 10^{14} cm^{-3} depending on the assumed volume of the emitting region. Neupert (1971) finds 10^{13} cm^{-3} is sometimes possible. Such dense hot filaments may occur 5 to 50 Mm above the photosphere according to the X-ray pictures of Vaiana and Giacconi (1969) and Krieger *et al.* (1971). During the March 1970 eclipse, Thomas and Neupert (1971) observed that the de-occultation of X-ray emitting regions by the Moon's limb occurred in 0.3 s, corresponding to about 400 km on the Sun. Neupert (1971) believes that the X-ray filaments could be as thin as 16 km.

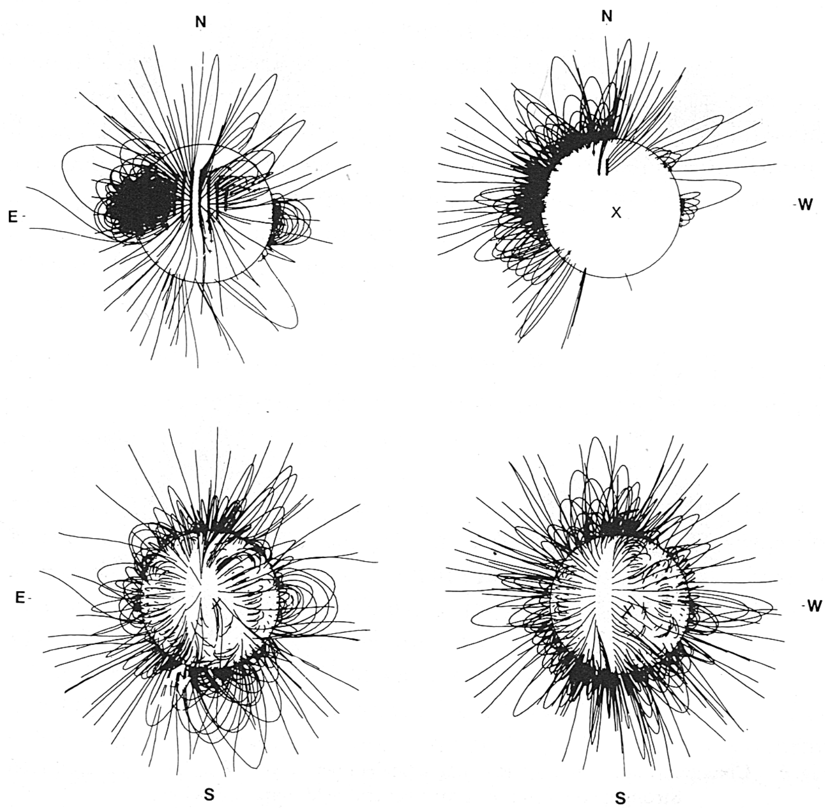

Fig. 7. Changes in calculated coronal magnetic field before and after flares of 4, 6 May 1960. Strong field maps are at top; general field maps are below.

To contain a plasma of 10^{13} cm^{-3} at 10^7 K in the tenuous solar corona requires magnetic fields of about 500 G. If the plasma is held together in a cylinder 100 km in radius, the electric current is about 3×10^{10} A and the current density is about 1 A m^{-2}. Such conditions of temperature, density, and magnetic field permit nuclear reactions to occur. If the electron density were wrong by a factor of 100, the magnetic field and electric current would be wrong only by a factor of 10. In any case, a hot dense plasma cannot be contained for several minutes as a thin filament unless

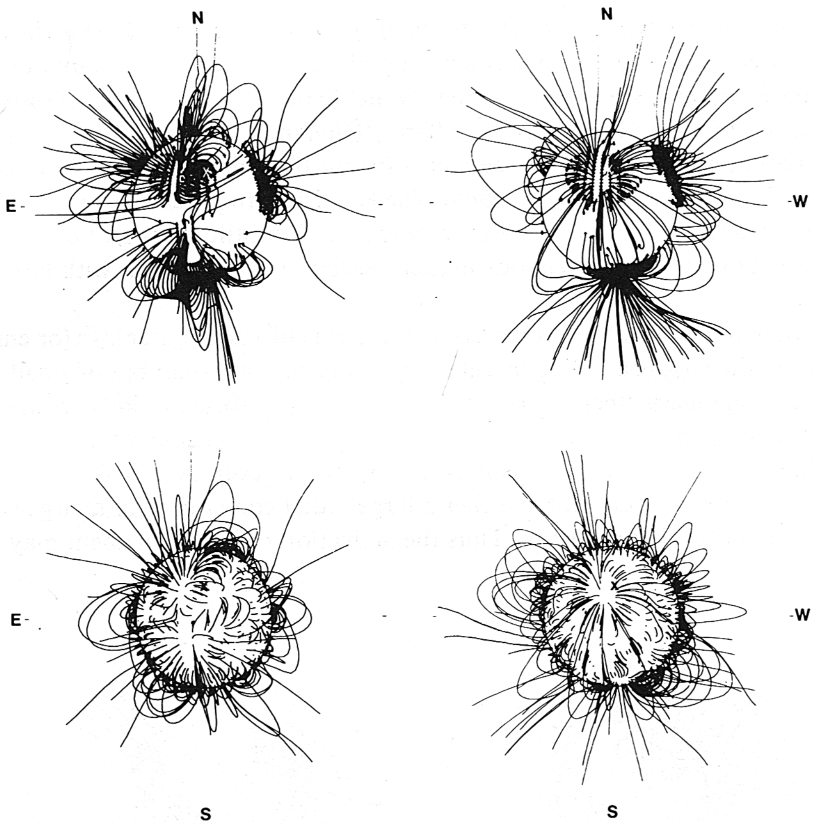

Fig. 8. Changes in calculated coronal magnetic field before and after flare of 24 March 1966. Strong field maps are at top; general field maps are below.

there is a strong electric current along the filament axis. Where could such an electric current originate?

Neupert *et al.* (1974) observed an X-ray loop associated with an importance 1B flare, and found no detectable coronal feature at the flare site before the event. Thus pre-existing coronal material cannot account for the X-ray emission. They found two distinct structures in the X-ray emission: a cooler region (2×10^6–10^7 K) which formed over the Hα flare above the neutral line, and a hot (3×10^7 K) arch about 35 Mm above the Hα flare. The high temperature arch appeared to be more stable in position and lasted about 6 min. They conclude that ionization and heating of chromospheric material must have occurred as the matter moved upward, and that the magnetic field lines must have been closed to provide thermal insulation. Clearly, X-ray flare observations are crucial if we are to observe coronal plasma at temperatures above 5×10^6 K.

Let us now look at a few of the events associated with large flares and prominences that might indicate the ejection into the corona of large electric currents from the photosphere or chromosphere. Most of the flare observations have been made in Hα, a line which shows only the cooler parts of the flare (10^4–10^5 K). Thus in Hα, we would not expect to see hot X-ray emitting plasma but rather mass motions from $\mathbf{J} \times \mathbf{B}$ forces. A few years ago, a special Nobel Symposium was held to discuss the observations of mass motions in solar flares (Öhman, 1968).

Different parts of the flare process are observed on the disk and above the limb (Smith and Smith, 1963; Švestka, 1969). The Hα disk flare primarily shows enhanced densities of active filaments in the chromosphere with little mass motion, while the limb flare shows the more tenuous matter ejected into the corona with large mass motions.

Traditionally, flares have been classified in terms of Hα brightenings (or emission regions) on the solar disk. The brightenings occur first at a number of small points in an active region and then spread along filamentary structures which are at or near the neutral line (which separates photospheric regions of opposite magnetic polarity). According to Severny (1969), the flare brightenings occur over regions where the photospheric electric current has either a large radial component or a large component in the photospheric surface. Thus the activation of a flare filament may corre-

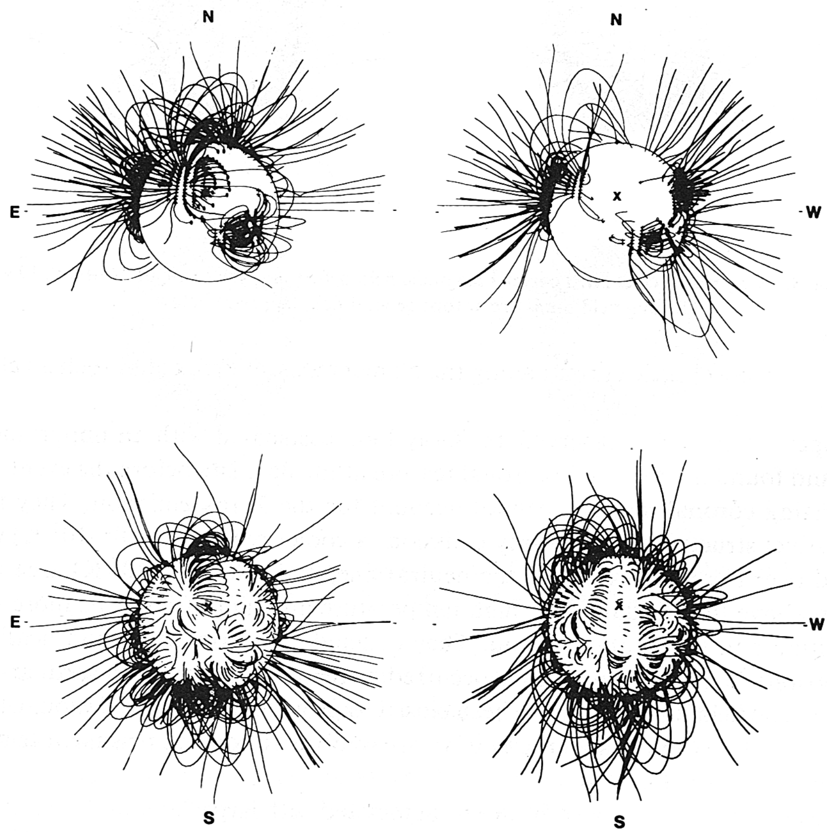

Fig. 9. Changes in calculated coronal magnetic field before and after flare of 18 November 1968. Strong field maps are at top; general field maps are below.

spond to the eruption of an electric current from the photosphere. The dynamical effects that would accompany the rapid elevation of a strong photospheric electric current are complex and violent. Certainly shock waves, adiabatic compression, ionization, and rapid mass motions can be expected. In any case, it is clear that at least chromospheric electric currents are involved in the flare process. The large

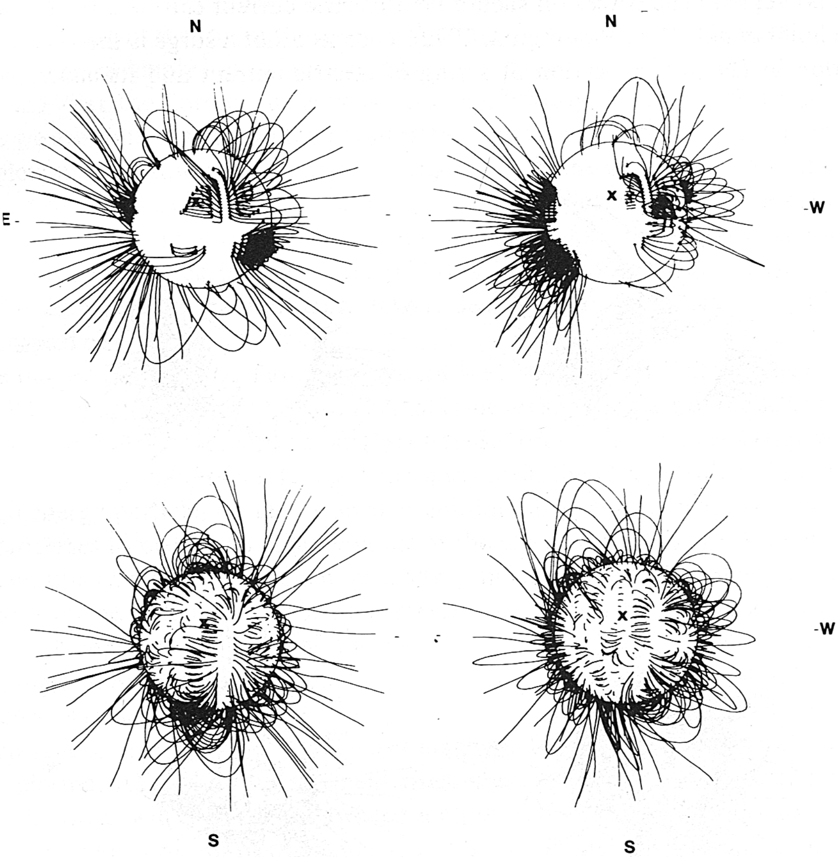

Fig. 10. Changes in calculated coronal magnetic field before and after flare of 29 March 1970. Strong field maps are at top; general field maps are below.

August 1972 flares occurred along a neutral-line filament which was located in a region of strong shear flow (Zirin and Tanaka, 1973). Considerable twists in the smaller filaments, hence presumably electric currents, were also observed.

In addition to the active-region filaments, there are also occasional ejecta or surges into the corona observed in Hα (Macris, 1971). By looking off-center in the Hα line during a disk flare, we can often see evidence for material ejected upward into the corona. Limb observations show flare-associated surges and sprays which correspond to the ejection of matter at about the Alfvén speed. Surges originate in the low chromosphere or photosphere and seem to be associated with small regions of op-

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posite magnetic polarity to that of the nearby sunspot or active surroundings (Rust, 1968; Roy, 1973). Now one of the simplest ways to create antiparallel electric currents with $\mathbf{J} \times \mathbf{B}$ forces directed upward is to take a straight photospheric electric current and create an almost circular bend or meander at some point in the current. This is equivalent to the intrusion of opposite magnetic polarity into a larger unipolar region. The forces on such a bent electric current can be directed upward (Altschuler *et al.*, 1968; Piddington, 1972). I suspect that a surge is the visible manifestation in Hα of the ejection of a ring of electric current and its accompanying

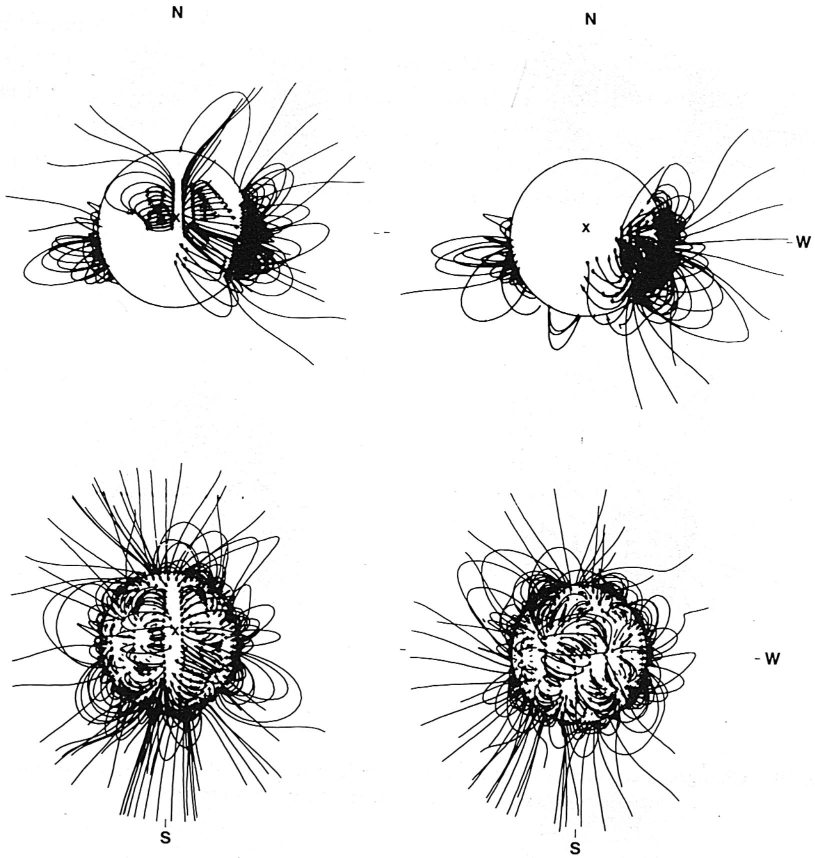

Fig. 11. **Changes in calculated coronal magnetic field before and after flares of 2, 4, 7 August 1972. Strong field maps are at top; general field maps are below.**

plasma into the corona. What we see in Hα is the mass that recombines and leaks out of the current ring.

The most energetic coronal disturbances are undoubtedly the flare loops which are generally associated with large two-ribbon (or proton) flares (Bruzek, 1964). At about flare maximum, coronal loops appear which connect the two chromospheric flare ribbons on the opposite sides of the neutral line. Seen on the limb in Hα light,

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loops appear above previous ones as downstreaming matter flows from Hα knots formed at increasing heights. Thus the loop system grows, reaching heights of 60 Mm or more. Wide Hα profiles indicate internal motions of the order of 1 Mm s^{-1} characteristic of Alfvén speeds. Flare loops are also seen in coronal lines of highly ionized metals, indicating very high temperatures. The most interesting observation is that the high temperature coronal yellow line (λ569.4 nm) of Ca XV is characteristically seen in emission at the top of these loops (Billings, 1966). Moreover, several coronal emission lines of highly ionized metals are all simultaneously enhanced in flare loops, indicating that the coronal density is also significantly enhanced. Billings writes "Thus we are confronted with the paradox that the type of prominence that appears to deplete matter from the corona most vigorously is the one in whose vicinity the corona remains most dense. This paradox strongly indicates that the source of descending material in the prominence is not the corona but the same source that enhances the coronal density." Kleczek (1964) writes "A powerful mechanism must exist for transporting material from lower, denser atmospheric layers during and after some flares."

The mass required for a flare loop system is about 10^{16} gm (Jefferies and Orrall, 1964; Kleczek, 1964) which at 50 Mm height is more than the mass of the surrounding corona. To obtain such a mass we can (1) condense coronal matter over a large volume using magnetic compression, (2) eject the mass from the chromosphere in the form of high energy particles (either at once or continuously) and then allow recombination processes to occur in a small volume at the top of the loop, or (3) carry up hot dense plasma confined in a filament of electric current. Here I will not argue the pros and cons of the different theories, but merely talk about the last. After seeing the results of Neupert *et al.* (1973) on the X-ray flare loop, I have become less cautious about suggesting the eruption from below of electric current filaments which contain hot dense plasma.

A current filament provides the proper magnetic forces to contain and elevate hot dense plasma. As the current filament rises, mass motions induced by the hydromagnetic forces will disperse the twisted magnetic flux into a larger volume. Eventually the electric current of the filament will become too weak either to contain the hot dense plasma or to supply sufficient energy to maintain ionization. As a result, the current filament will dissipate, and the dense plasma will cool by free-free emission, recombine, and flow down along the pre-existing potential field lines, creating the flare loops. The impact of this downfalling material will produce flare ribbons in the chromosphere (see for example, Hyder, 1967).

To lift 10^{15} to 10^{16} gm of ionized plasma to a height of 60 Mm in the corona and then to contain it for some minutes or longer, we could use an electric current of 3×10^{11} A flowing through a filament 1 Mm in radius and about 60 Mm in length. This situation corresponds to a twisted magnetic field of 500 G, a hydrogen density of about 10^{13} cm^{-3}, and a temperature of 10^{7} K. If we assume a filament 10 Mm in radius, we require only 50 G and 10^{11} cm^{-3} for the same temperature, mass, and electric current.

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Now let us briefly discuss other evidence for the ejection of electric currents into the corona.

The eruption or disintegration of large quiescent prominences is clearly associated with twisted magnetic fields even on a macroscopic scale (Valnicek, 1968; Dodson *et al.*, 1972). Beautiful cases of twisting or untwisting erupting prominences have appeared in the literature (Figure 12).

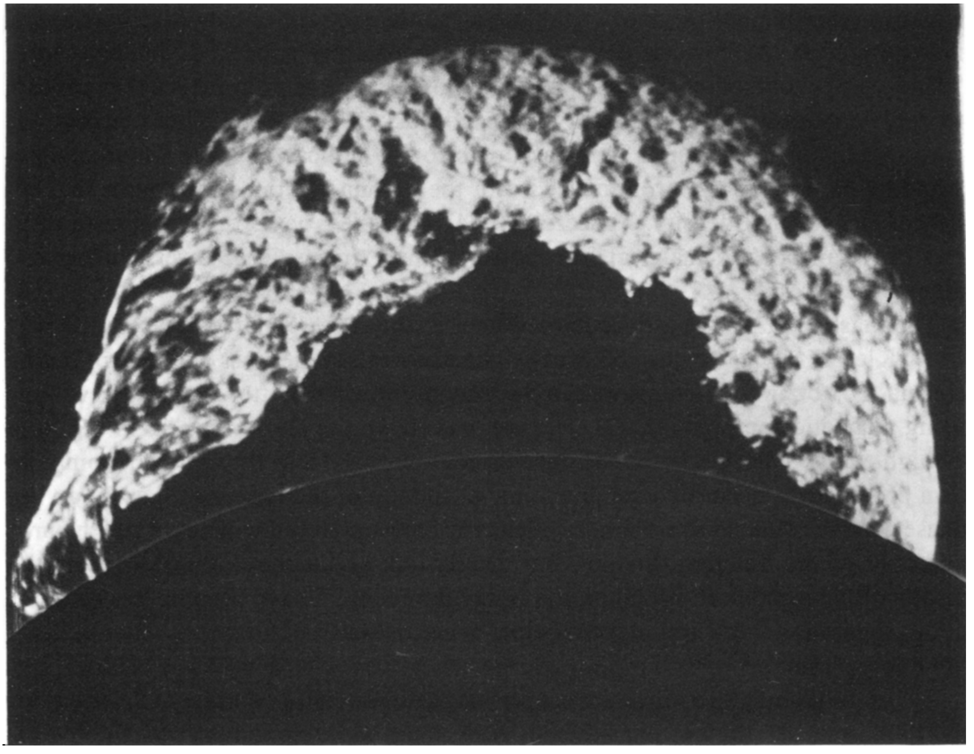

Fig. 12. Famous eruptive prominence of 4 June 1946, photographed by W. O. Roberts at Climax Observatory.

Monochromatic movies of the corona in the green line (λ530.3 nm) show changes at infrequent intervals (Bruzek and Demastus, 1970; Dunn, 1971). Expanding arches are the changes seen most often. Occasionally the whiplike opening of an arch is seen when one of the footpoints appears to disconnect from the photosphere and rise into the corona. Of course, magnetic field lines are solenoidal and cannot be disconnected. What we are seeing, therefore, is an ascending electric current or perhaps current ring, with only one part of the system emitting at the temperature of the coronal green line.

In the radio spectrum, I think a good case can be made that the moving type IV synchrotron-emitting sources contain twisted magnetic fields and therefore electric currents (Riddle, 1970; Smerd and Dulk, 1971; Dulk and Altschuler, 1971).

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Well, I have tried to argue the case that X-ray emitting filaments, the flare loop-prominence system, surges, green-line whips, erupting quiescent prominences, and moving type IV radio bursts are associated with the eruption of electric currents from the chromosphere or the photosphere. Certainly these phenomena are not simple perturbations of the potential magnetic field configuration of the corona.

6. Impulsive Coronal Disturbances and Coronal Magnetic Fields

Let me say a few words about the rapid particle acceleration processes indicated by impulsive X-ray and type III radio bursts. In the tenuous coronal plasma, the Hall Effect becomes important for scale sizes of about 100 m. This means that the magnetic field becomes frozen to the electron plasma component rather than to the fluid as a whole (Pikelner, 1966). Since electrons have little inertia, it is likely that bunches of electrons on the 100 m scale can be accelerated in the corona whenever strong non-potential magnetic fields are present (Altschuler *et al.*, 1973). Undoubtedly, X-ray filaments and flare loops provide such fields.

7. Speculations and Conclusion

Now I will enter further into the realm of pure speculation. Spicules have been called mini-surges. They occur at the boundaries of supergranule cells where the magnetic field is enhanced. Often spiral motions can be seen in spicules (see Öhman, 1968) indicating the presence of twisted magnetic fields or electric currents. Spicules apparently play a key role in the heating and mass balance of the corona. On the basis of present observations (Beckers, 1968), it is not necessary to assume hydromagnetic forces to explain the eruption of spicules (Kuperus and Athay, 1967). Nevertheless, there would be a remarkably simple conceptual scheme if such were the case. We could then say that the entire solar corona is merely a manifestation of electric currents of different sizes and shapes being ejected continually from the chromosphere and photosphere. The 'quiet' corona would then be merely a composite of small coronal disturbances in the form of unresolved filaments of electric current. Perhaps confirming this wild idea is the evidence that coronal holes seem to lie above unipolar photospheric regions, away from the neutral lines and the small magnetic arcades which suggest photospheric electric currents (Altschuler *et al.*, 1972). It would be interesting if the spicule density or intensity were smaller under coronal holes.

Let me now carry this speculation to its dire conclusion. If electric currents are being continually ejected from the photosphere, where are they created? We have already mentioned that low magnetic arcades in the strong potential field maps indicate large photospheric electric currents occur near the neutral line, and that a network of concentrated electric currents may well meander all over the photosphere. The recent observation of Howard (1971) that the velocity field of the photosphere near the neutral line is predominantly downward suggests that neutral lines occur at the boundaries of very large convective cells perhaps 300 Mm in diameter

(Bumba, 1967; Simon and Weiss, 1968; Yoshimura, 1971; Wilson, 1972). If so, then these boundaries would contain gradients of pressure, density, and temperature, not necessarily parallel, thus nonpotential forces which could generate electric currents. This was suggested by Kopecky and Kuklin (1971) at the Paris meeting.

The grand vision that I think may soon evolve from the observations is the following. There are large-scale convective cells on the Sun, say 300 Mm in diameter. At the boundaries of these cells, electric currents are being generated by non-potential forces. Smaller convective cells, the supergranules, might also generate electric current at their boundaries. As all of these electric currents build up in the photosphere, they are continually being ejected in the form of spicules. If large electric currents build up faster than they can be ejected by spicules, then they are ejected as eruptive prominences, surges, or large flares. Surprisingly, the energy of a large flare (10^{31}–10^{32} erg) exceeds the kinetic energy of a photospheric convective cell with a density of 10^{17} cm^{-3}, a diameter of 300 Mm, a depth of 10 Mm, and a mean flow speed of 0.1 km s^{-1}. Thus large flares might disrupt or alter the large-scale circulation of the photosphere at the cell boundaries where electric current is generated. The solar cycle then becomes similar to the conflicting two-population (fox and rabbit) problem of Volterra (Davis, 1962). First the number of current-generating regions begins to increase in the photosphere. Then the number of solar active regions begins to grow, eventually disrupting the current-generating regions. Then the Sun goes quiet until new large-scale cells start generating electric current again.

I began this talk by emphasizing the incredible complexity of the coronal plasma, and have ended with the oversimplified picture that the entire mass of the corona derives from fountains and geysers that eject electric current from the photosphere and chromosphere. But actually, until we solve the appropriate system of differential equations, we cannot determine to what extent the ejected electric currents carry entrapped matter and/or produce waves and shocks. Nevertheless, even a simplified picture, if it is correct, can be useful in both theory and observation. The interesting physics of course lies somewhere between the over-simplified and the hopelessly complex.

Acknowledgements

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Notes added in proof. (1) After studying very high resolution KPNO magnetographs, J. Harvey makes the point that the large 'unipolar' magnetic region is actually a statistical result of almost-equal numbers of small-scale magnetic elements of opposite polarity. Thus, the unipolar regions, neutral lines, and global magnetic flux connections discussed in this paper should be considered large-area averages.

(2) R. G. Athay points out that S. B. Pikelner (1969) provides convincing arguments against a spicule mechanism based on (1) heat flux from the corona and (2) a passive or static magnetic field. The consensus now seems to be that some form of dynamical magnetic field is essential to the spicule mechanism.

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DISCUSSION

Sturrock: The magnetic field representation is simpler for the study of coronal disturbances because of the 'frozen-in' plasma condition. The same does not apply to the current representation.

Altschuler: Correct; I used the electric-current representation here to illustrate *where* in the magnetic-field structure the disturbances occur.

Sturrock: Impulsive disturbances need coronal currents over small length scales (~ 1 km); what is the mechanism?

Altschuler: Small scale is certainly important (see Section 6).

Stewart: K-corona transients occur at times of flare loops; do these occur as two distinct disturbances?

Altschuler: The most difficult problem is to explain how a large mass of solar plasma is carried high into the corona. It is here suggested that this is done by many small, hot filaments (currents). Once up, fragmentation may occur in many ways resulting in many different plasma processes.