MAGNETIC STRUCTURE RESPONSIBLE FOR CORONAL DISTURBANCES: THEORY

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Abstract. Due to the strong coupling between the coronal material and magnetic fields, magnetic structures are probably intimately involved, either actively or passively, in virtually all coronal disturbances. The purpose of this paper is to put into perspective the various roles magnetic fields can play in both exciting and guiding these observed transient phenomena. A discussion of our present theoretical concepts relevant to this subject can be conveniently divided into four categories.

We begin by discussing our present understanding of how the gross magnetic structure of the corona is determined. Important considerations here are the tendency for the coronal field to seek its lowest energy state, the effect of convection on the field, and the influence of the solar wind. Secondly, we investigate magnetic structures which reside in elevated energy states (higher than the energy of an equivalent potential field) as well as disturbances which appear to be related to changes in these configurations. Thirdly, the role of the field in guiding coronal disturbances is considered. This is evident for bulk motions (sprays, surges, flare loops, green line events, etc.), wave motions (flare associated waves, Alfvén waves), as well as for individual particle phenomena. Lastly, a special class of magnetic structures which seem to be constantly associated with coronal activity are discussed. These are the magnetic discontinuities such as neutral sheets and current sheets. In this context, the magnetic neutral point and associated reconnection phenomena are considered.

1. Introduction

Certainly the most illuminating observation of the solar corona is a white light photograph taken during a total eclipse (see Figure 1). Despite the difficulties in attempting to visually deconvolve line-of-sight effects, one can learn much about the gross magnetic structure and even its effect upon the distribution of coronal material. For example, in the lower corona below about 2 $R_{\odot}$, the density structure reveals closed magnetic field lines evidently bottling up the coronal gas which, in the absence of the field would rapidly escape into interplanetary space. The magnetic structure in other places appears to be open permitting outward expansion. This drain of material and energy can result in a significant decrease in density there, causing those regions to appear less bright than the closed regions.

In the lowest part of the corona, the magnetic field energy density is at least comparable to the thermal energy density and, in some regions, probably greater. This fact, however, does not insure any interaction between the field and the coronal gas. It is the high electrical conductivity resulting from the high coronal temperature, so effectively coupling the material with the field, which is primary responsible for all coronal hydromagnetic effects. The magnetic Reynolds number appropriate for coronal conditions is of the order of 10^{10}–10^{14} indicating that there can be virtually no motion of material across field lines.** This conclusion is observationally verified

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** A magnetic Reynolds number equal to one corresponds to a condition where diffusion across field lines and the 'freezing-in' effect are of roughly equal importance.

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by the apparently close correspondence between density structure and field structure.

Another important consequence of its high temperature is the high thermal conductivity of the corona. As pointed out by Chapman (1957), thermal conduction is so effective that, if the corona were static, the resulting temperature distribution would be so flat that the coronal temperature would fall by only a factor of about 5 between

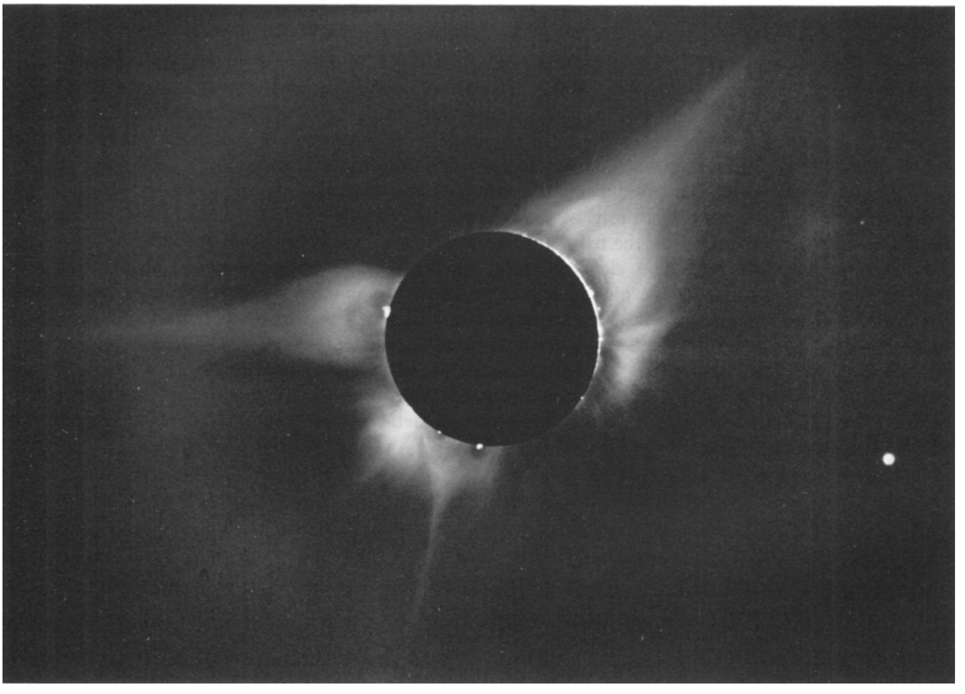

Fig. 1. The solar corona as observed during the 12 November 1966 eclipse. The bright points at the bases of the large helmet streamers are quiescent prominences (courtesy G. Newkirk Jr.).

the Sun and the Earth. A temperature profile of this type can, in fact, be shown to be incompatible with a static corona and, consequently, expansion must take place. The result is a solar wind, a now observationally well documented condition of the interplanetary medium. Another interesting aspect of the thermal conductivity is that it is essentially zero for heat conduction across field lines. This results in non-uniform heating effects which, along with the solar wind, stresses the magnetic fields – giving rise to the possibility of impulsive phenomena.

One unfortunate property of an eclipse photograph is that it is at best only a snapshot. Consequently, little information about coronal transients can be obtained from these pictures. Other evidence, however, suggests that the corona is continually in a disturbed state. For example, type III bursts seem to be constantly taking place and observations of the solar wind at 1 AU reveal temporal variations in interplanetary properties on a time-scale of hours. On the other hand, transients observed in the green line, λ5303, are quite rare and type II and IV bursts seem to associate only with the largest flares.

Magnetic fields sometime play a passive role in impulsive events such as, for example, the fields overlying the sites of flares and eruptive prominences. Usually, however, the field configuration and its changes are either instrumental in producing an event or play a role in guiding bulk motions and individual particles involved in the disturbance. The multitude of disturbances which respond to changes in magnetic configuration all seem to be most readily understood in terms of a very few basic physical mechanisms. For example, convection and other motions in the deeper layers transport field lines in such a way that potential field configurations are not always attainable. Consequently, the field can reside in higher energy states which often are either metastable or unstable. Also, again due to the high electrical conductivity of the corona, magnetic discontinuities such as neutral sheets, current sheets and neutral points are present. Reconnection of field lines at these sites is becoming an increasingly more attractive explanation for a great variety of impulsive solar phenomena.

2. Tendency for the Coronal Magnetic Field to Reside in Its Lowest Energy State

If the Sun had no corona or a cool non-conducting corona, the coronal magnetic field would, of course, just be a potential field ($\nabla \times \mathbf{B} = \nabla \cdot \mathbf{B} = 0$) and, if the net flux through the Sun were zero, all field lines would be closed. But the convection zone produces a hot corona which, in turn, couples strongly with the field. It is this coupling and the resultant tug-of-war between fluid and magnetic forces that gives the corona its characteristic appearance. All deviations of the coronal field from its corresponding potential configuration can be ultimately traced to convection. Convective motions not only tangle the field lines setting up strong electric currents but also produce the solar wind which completely dominates the field beyond about $2.5\,R_\odot$. The appearances of the polar plumes (Bugoslavskaya, 1950; Van de Hulst, 1950), the over-all flattening of the corona toward the equator during solar minimum, and the observational results of Babcock and Babcock (Babcock and Babcock, 1955; H. D. Babcock, 1959; H. W. Babcock, 1961) has, in the past, suggested to solar astronomers that the Sun's magnetic field, when viewed on the largest scale, resembles that of a dipole with its axis oriented roughly along the axis of rotation. Although more recent higher resolution eclipse photographs and magnetograms have shown that the magnetic fields are generally much more complicated than a simple dipole, there is some evidence that the large-scale fields in the inner corona (as inferred from the brightness structure) do appear to resemble those appropriate for a current-free atmosphere. Support for this comes from a comparison of a computed potential field model using Mt. Wilson magnetograph data covering the period during the November, 1966 eclipse* (Altschuler and Newkirk, 1969). The correspondence be-

* Large-scale twisted force-free fields, for example, are not generally observed.

tween the calculated field lines and the general appearance of the corona was quite good. A similar comparison with the corona during the eclipse of March, 1970, however, was not so satisfactory (Newkirk, 1971), however, this could have been due to a higher level of solar activity during this period violating the steady state assumption inherent in the theory. Also, since the corona is generally believed to be hotter during the maximum phase of the solar cycle, the field may have been more non-potential due to the increased importance of gas pressure forces.

The first model to compare magnetic fields calculated by potential theory with observations was constructed by Schmidt (1964). This model employed rectangular coordinates and, consequently, was valid only for structures whose general dimensions were small as compared to a solar radius. Subsequently, more accurate potential field models were developed by Newkirk *et al.* (1968), Schatten *et al.* (1969), and Altschuler and Newkirk (1969). More recently Schatten (1971) has developed a model in which the field current-free everywhere except at discontinuous surfaces (neutral sheets) over which the polarity of the field changes abruptly. Since in Schatten's model the quantity $B^2/8\pi$ is always continuous across these surfaces it is still valid only in the limit of vanishing gas pressure (since, in general, $P+B^2/8\pi$ should be the conserved quantity). However, comparisons of both Newkirk and Altschuler's model (Newkirk, 1972a) and Schatten's sheet current model (Schatten, 1971) with an appropriate MHD solution using the same boundary conditions (Pneuman and Kopp, 1971) are favorable at low levels for the case when the gas pressure at the coronal base is assumed to be independent of latitude.*

That some caution must be excercised when applying potential theory to actual coronal conditions is borne out by the following consideration. Since, in general, $\nabla\times\mathbf{B}=4\pi\,\mathbf{j}$, the approximation $\nabla\times\mathbf{B}\approx 0$ requires that

$$|\nabla\times\mathbf{B}|\ll|\mathbf{B}|/L_b, \tag{1}$$

where L_b is the scale over which $\mathbf{B}$ spatially varies. If pressure and magnetic forces roughly balance in the low corona, then we also have

$$|\nabla\times\mathbf{B}|\approx\frac{4\pi P}{|B|\,L_p}, \tag{2}$$

L_p being the scale for horizontal pressure variations. Combining Equations (1) and (2), the requirement for validity of potential theory is,

$$P\ll\frac{B^2}{4\pi}\;\frac{L_p}{L_b}\;. \tag{3}$$

Hence Equation (3) could be invalid in places where the gas pressure varies rapidly from place to place over the coronal base (eclipse observations do suggest filamentary structure in the lower corona). Even in the absence of this consideration one notes

* If this were not the case, horizontal pressure gradients might produce significant deviations from potential theory.

that, for $N_e = 2 \times 10^8$ and $T = 1.5 \times 10^6$, the ratio of $B^2/4\pi P$ is about one for a field strength of one gauss. Thus, it is not entirely clear that pressure forces really are negligible in the lower corona.

In addition to the above, two other mechanisms negate the possibility for the coronal magnetic fields to be completely potential. These are the effect of convection on the field and the influence of the overall coronal expansion or solar wind. Both these influences introduce stresses into the field configuration and, hence, are of importance in understanding the mechanisms which could underly coronal disturbances.

3. Magnetic Structures in Elevated Energy States

Beneath about the middle chromosphere, the fluid forces dominate the magnetic field and, as a consequence, field lines can be twisted, tangled, compressed, and, in general, transported in quite an arbitrary manner depending on the fluid motion. Since the coronal field remains tied to this subphotospheric field, it is also transported. The material in the corona is tied intimately to the field however and each field line retains an identity. As a consequence, direct transformation from one topology to another (such as to that of the potential configuration) cannot always occur. If then the magnetic energy density in the corona is large as compared to that in the gas and a potential configuration is topologically unattainable, the field must be either force-free or, as an alternative, potential but with certain regions where sheet currents are present. An example of the latter is shown in Figure 2. Suppose, in a medium of infinite conductivity, a simple bipolar region, labeled (1), exists. Now, further suppose that a second bipolar region (2) emerges beneath (1). If reconnection is not allowed, the resultant configuration will be that of Figure 2a. Configurations (1) and (2) can be potential-like individually but a sheet current will exist between them. Figure 2b

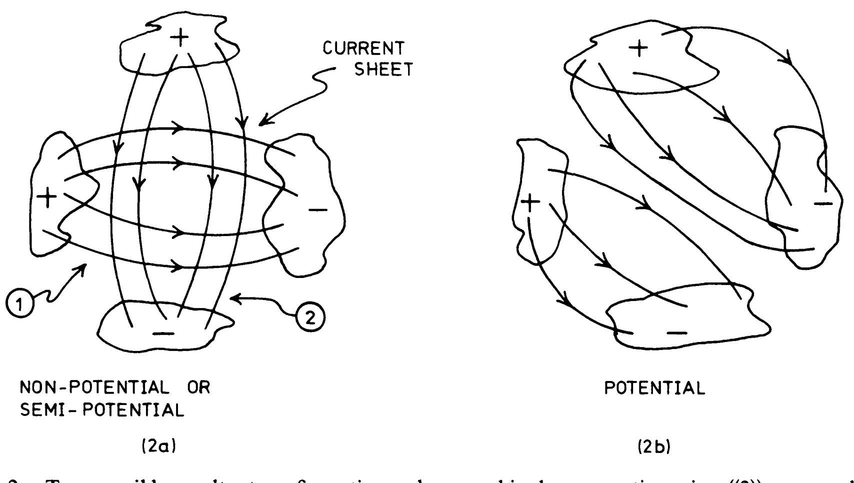

Fig. 2. Two possible resultant configurations when one bipolar magnetic region ((2)) emerges beneath another ((1)). In (2a), reconnection is not permitted and the two flux ropes remain intact with a sheet current separating them. Figure (2b) shows the resulting potential configuration if reconnection occurs easily.

shows the completely potential configuration which cannot be reached without reconnection.

The fact that the chromospheric fields inferred from Hα (Veeder and Zirin, 1970; Zirin, 1972) appear so complicated and the coronal fields relatively much simpler (see Figure 1) suggest that as magnetic flux is transported outward from the convection zone a large amount of simplification has taken place. This implies an energy release mechanism capable of motivating coronal disturbances or even heating the corona on a continuous basis.

3.1. Force-free fields

The importance of force-free fields as a possible exciter of coronal disturbances is obvious. Firstly, this type of structure is expected in at least some regions of the corona and, secondly, the energy density in a force-free field is always higher than that of an equivalent potential field, providing available energy for disturbances. Barnes and Sturrock (1972), for example, have suggested that the transformation from a closed force-free configuration to an open configuration could provide the necessary energy for a solar flare.

A force-free field configuration satisfies the equation

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \tag{4}$$

$$\nabla \alpha \cdot \mathbf{B} = 0, \tag{5}$$

where α is an arbitrary scalar. Solution of these equations under various assumptions have been discussed by many authors (see Boström (1972) for a comprehensive review). The physical interpretation of the results of these analyses has been rather speculative. More recently, however, comparison of fields calculated from force-free theory with observations near sunspots (Nakagawa *et al.*, 1971) and with chromospheric fibrils and filaments as observed in Hα (Raadu and Nakagawa, 1971; Nakagawa and Raadu, 1972) have been encouraging. In essentially all these models, however, the assumption $\alpha = \text{const}$ is employed, an assumption which is physically difficult to justify. Further investigation for the cases $\alpha \neq \text{const}$ would certainly be fruitful. For example, Low (1973) has recently computed solutions for nonconstant α including resistive diffusion. He fiinds that the field may evolve slowly for an extended period of time, then abruptly develop steep gradients and pass into an explosive phase. A process which may have application to solar flares and eruptive prominences.

In contrast to potential fields, the energy in a force-free configuration can be steadily increased by motion of the foot points. This has been demonstrated by Raadu (1972) for the simple example of differential rotation acting upon a quadrapole field. Assuming the field remained force-free as the footpoints were sheared, Raadu found that the field energy was increased by 25% in only one solar rotation. In addition, the field configuration expanded outward during this period. Although the motion considered here is particularly simple, shearing motions are always occurring in the convective zone. Hence, these results could have significant implications for coronal disturbances such as expanding magnetic arches. bottles, etc.

3.2. Prominences

Historically, the name prominence has been applied to almost any bright protuberance observed in Hα on the limb, whether transient or steady state. In order to understand the physics of these structures and their changes, however, we must clearly differentiate between two types – those associated with active regions and flares such as surges, loop prominences, flare loops, etc. and the so-called quiescent prominences residing usually towards the poles away from active regions under helmet streamers (note the bright points at the base of the helmet streamers in Figure 1). It is questionable whether these two classes of configurations have the same origins or explanations and, consequently, they should be considered separately.

Loop prominences and surges do not seem to be due to alterations in local magnetic structure but rather the result of ejected material from an underlying disturbance such as a flare. The main difference between the two phenomena can be interpreted in terms of the field geometry previously overlying the disturbance. Surges occurring where the field lines are either open or extend over large distances and loop prominences where closed loops directly overlie the disturbance. Surges travel upward rather fast, about 300 km s^{-1} and generally return along more-or-less the same trajectory (Tandberg-Hanssen, 1967). Loop prominences show a great variation in their motion. Some appear to expand extremely slowly – perhaps at 10 km s^{-1} (Bruzek, 1964) but exhibit broad wings in Hα indicating energetic internal motions. Other expand explosively with velocities exceeding 100 km s^{-1} thus separating loop prominences into two distinct classes (Bruzek and Demastus, 1970). Perhaps the cases of slow expansion, since actual deceleration of material is observed (Bruzek and Demastus, 1970), give evidence for magnetic inhibition of the outward motion. Another possibility is that these apparently slow moving prominences do not expand at all but merely reflect an excitation process repeated through successfully higher levels in the solar atmosphere (Goldsmith, 1971) or, according to Schmidt (1969), they could be the result of a slow reconnection of lines of force torn apart by the flare. Perhaps the coronal and interplanetary manifestations of the rapidly expanding loop prominence systems are to be seen in the moving type IV radio bursts and the 'magnetic bottles' observed at 1 AU. Both these phenomena reflect closed field geometries and seem to be always associated with flare activity although all flares certainly do not produce loop prominences or type IV emission.

The mechanism producing type IV radio bursts is now generally accepted to be synchrotron emission (Boishot and Denisse, 1957), however, the magnetic structures associated with these large-scale disturbances are still not fully understood. Observations suggest that they can be of several varieties each of which suggests different physical mechanisms. Some appear to be associated with an advancing shock front (Kai, 1970a; Stewart and Sheridan, 1972, Stewart *et al.*, 1970) occurring generally after a type II burst. Others can be interpreted as an expanding magnetic arch containing trapped electrons while wtill others look like ejected plasma blobs moving radially outward to great heights at uniform velocity (Riddle, 1970). These 'blobs' have been suggested to have a self-contained field structure and move out along the open field lines of the large-scale coronal field (Smerd and Dulk, 1971; Dulk and Altschuler, 1971).

The possibility of magnetic bottles in the interplanetary medium was first suggested by Gold (1963) to explain the Forbusch decrease in galactic cosmic rays observed at the Earth following a large flare. Since then Schatten *et al.* (1968) reported an observation of a magnetic tongue at 1 AU which occurred in connection with a new active region and the birth of a new interplanetary sector. Also, Schatten (1970), from the Faraday rotation of a radio source, inferred a bottle traveling out to 10 $R_{\odot}$ at a velocity of about 200 km s^{-1} (see Figure 3). Another interesting argument for the existence of magnetic bottles as far out as the orbit of Earth is based upon the anomalously low temperatures in the solar wind following interplanetary shock waves (Montgomery *et al.*, 1972; Gosling *et al.*, 1973). These low temperatures could result if the driver gas behind the shock is inclosed in a magnetic geometry which prohibits thermal conduction from the inner corona. The closed field lines of an isolated bottle would provide such a geometry. It seems as though another possible explanation for this phenomena, however, is that the flare ejecta volume could expand outward more rapidly than the r^2 increase of the normal solar wind. If this were the case, simple adiabatic cooling due to overexpansion would produce lower temperatures in these regions. In summary then, there seems to be a great deal of evidence, from observations both in the inner corona and in the interplanetary medium, for closed magnetic loops being expelled from the Sun. One final question is whether these loops remain tied to the solar surface and, perhaps, even return after the disturbance or whether reconnection occurs producing isolated bubbles which can then move freely outward without reverse magnetic forces. As we shall see later, reconnection rates appropriate for these conditions are extremely uncertain so that this question, for the moment, must remain unanswered.

Quiescent prominences are located away from active regions under helmet streamers and appear in Hα on the disc as long thin east-west oriented filaments. They also seem to undergo a general poleward migration on the time-scale of a solar cycle (Lockyer, 1931; d'Azambuja and d'Azambuja, 1948; Hyder, 1965). Contrary to their name, these interesting structures do become involved in coronal disturbances. They differ from the active region prominences, not only in their location but that they seem to undergo some fundamental change in their own structure rather than passively react to the forces of another disturbance. This indicates that energy conversion takes place within the prominence itself.

Most older theories of quiescent prominences are similar to the Kippenhahn and Schluter (1957) and Dungey (1958) concepts of a gas supported against gravity by the sagging lines of force of a magnetic field (see Figure 4).* Observations of the photo-

* See Tandberg-Hanssen (1974) for a comprehensive review of older theories of quiescent prominences.

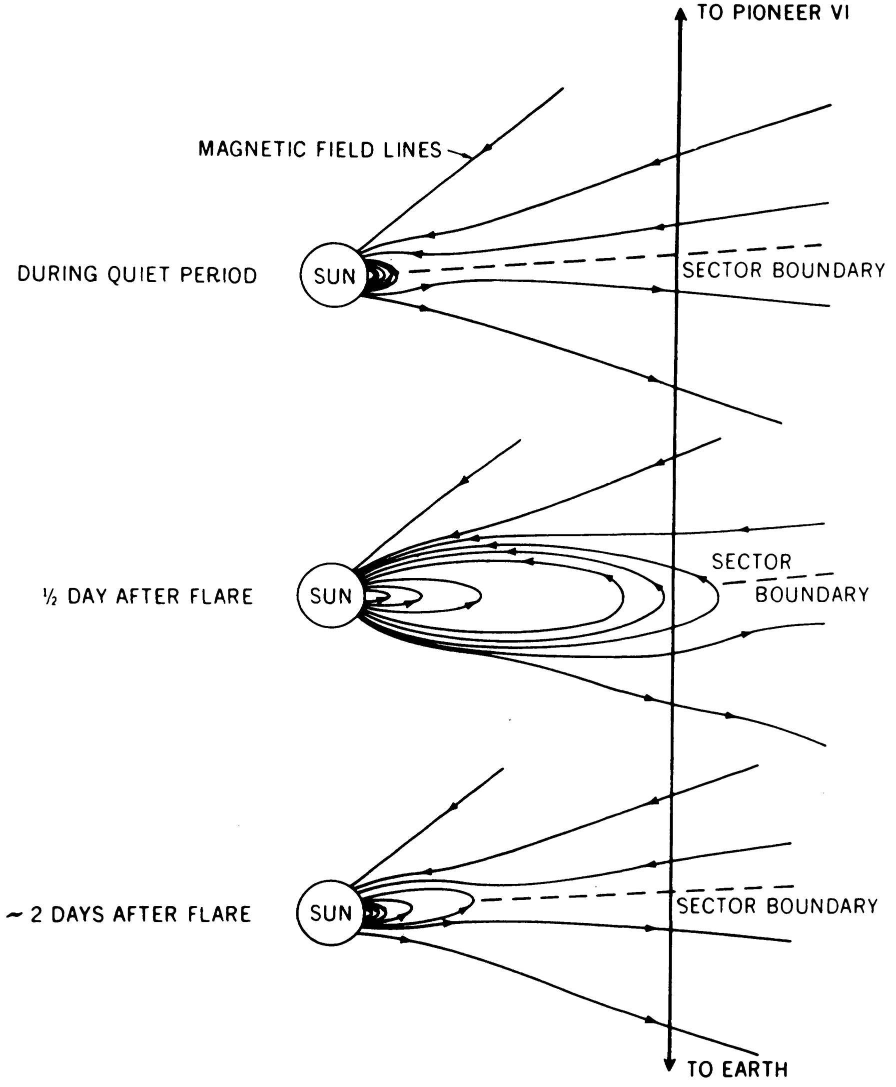

Fig. 3. View from the north of a proposed magnetic bottle observed by Pioneer VI (from Schatten, 1970).

spheric field pattern beneath these prominences by Rust (1970) tend to confirm this hypothesis. Anzer and Tandberg-Hanssen (1970) suppose that quiescent prominences have a helical structure produced by two current systems, one in the photosphere and one along the cylindrical prominence.* Other recent models (Anzer, 1972; Kuperus and Tandberg-Hanssen, 1967; Raadu and Kuperus, 1973) also employ sheet currents of various configurations.

* The classic prominence eruption of June 4, 1946 does give the appearance of untwisting helical lines of force.

Most theories of quiescent prominences assume the prominence is formed by condensation from the corona through a thermal instability (Kleczek, 1957, 1958; Lust and Zirin, 1960; Uchida, 1963; Kuperus and Tandberg-Hanssen, 1967; Raju, 1968, Nakagawa, 1970; Hildner, 1971). Another possibility is that they are the natural consequence of the energy balance requirements at the base of hlmet streamers, i.e.,

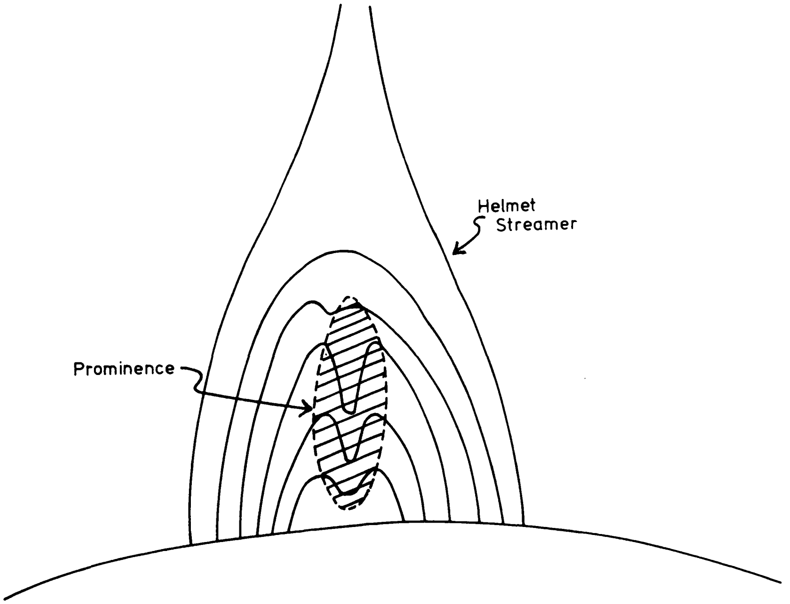

Fig. 4. Kieppenhahn-Schluter model of a quiescent prominence. Here, the dense material is supported against gravity by the sagging lines of force shown in the center portion of the helmet.

that they are necessary in order to balance radiative losses with mechanical heating from below (Pneuman, 1972).

Since quiescent prominences can persist over many solar rotations, we can tentatively conclude that they are *not* unstable. However, they do occasionally disrupt or explosively disappear one or more times either for no apparent reason or due to a triggering wave from a distant flare site (Dodson and Hedeman, 1964) or developing sunspot region (Bruzek, 1952). These sudden disappearances, called *Disparition Brusques* (d'Azambuja and d'Azambuja, 1948) are usually followed by a reappearance of the prominence some time later.*

This type of behavior suggests the quiescent prominence is a *metastable* configuaration – stable to infinitessimal perturbation but not those of sufficient magnitude. Two quite different explanations which could account for this come to mind. One is that some type of change takes place in the underlying magnetic field pattern which excites a reconnection process. Rust (1970), for example, suppose that a flux

* Garcia *et al.* (1971) has indicated that this might not always be the case. If so, the implication toward the theories of these structures are important.

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loop of opposite polarity to the field in the prominence emerges from below (see Figure 5). This creates an unstable neutral point configuration and explosive reconnection begins to take place. If, on the other hand, the very existence of the prominence depends upon energy balance considerations then one might speculate that a significant violation of these requirements could also disrupt the system. If, for some reason, the radiative losses from the prominence were temporarily inhibited leaving the incoming mechanical energy flux unaltered, then the closed field lines above the prominence would bottle-up the mechanical energy flux in a manner similar to that suggested by Pneuman (1967) as a possible flare mechanism. If this were the case, the

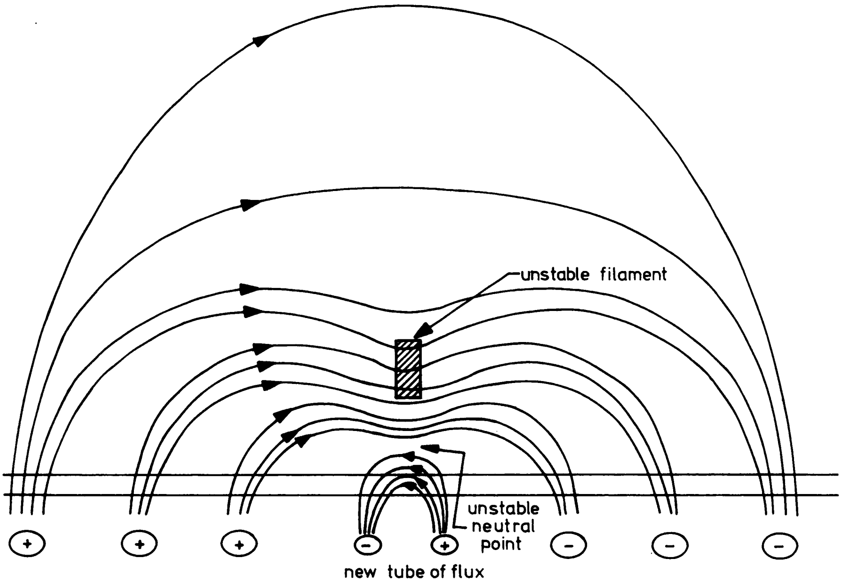

Fig. 5. Unstable neutral point created by the emergence of a new bipolar flux loop beneath a quiescent prominence (from Rust, 1970).

energy content in the prominence would increase until it became equal to that of the restraining fields at which point expansion would begin. This condition can be mathematically expressed as

$$qA_0t = \frac{B^2}{8\pi} A_0 L,$$

where q is the incoming mechanical flux, A_0 the cross-sectional area at the base of the prominence, B the field strength, L the length of the prominence, and t the time. Hence,

$$t = \frac{B^2 L}{8\pi q}.$$

Taking 1 G $< B <$ 50 G, $L = 0.1\ R_\odot$, and $q = 4 \times 10^5$ erg cm^{-2} s^{-1} we find that t ranges from about 10 min to several days. Hence, energy balance considerations could conceivably be important.

3.3. Interaction of the solar wind with coronal magnetic fields

Although the existence of a solar wind has been known for only about 15 years, an especially astute eclipse observer could have predicted it many years ago merely from the general appearance of the large-scale coronal features. For example, the form of the helmet streamers and the overall radial configuration of the corona beyond about 2 $R_\odot$ can be consistent only with a general expansion. We will not dwell upon the many interesting observational as well as theoretical aspects of solar wind physics here (see Hundhausen (1972) for a review of the subject) but will concentrate upon its relevance in shaping the coronal magnetic field configurations. The solar wind introduces stresses in the large-scale fields, the relief of which could provide energy for coronal disturbances.

The most important influence of the solar wind upon the coronal magnetic field is that it divides the corona into magnetically closed and open regions. Each of these regions is expected to have entirely different physical characteristics due chiefly to influence of the geometry upon the energy balance mechanisms (Pneuman, 1973).

Closed magnetic regions cannot suffer an outward conductive heat loss since heat conduction across field lines is difficult in the corona. Also, as opposed to the open regions, they do not lose energy carried by expansion. As a result, the temperature and density are significantly elevated in the closed regions. The so-called 'coronal holes' (Withbroe *et al.*, 1972; Altschuler and Perry, 1972; Altschuler *et al.*, 1972) are probably just open field lines being constantly drained of their energy content by the solar wind and thermal conduction (Pneuman 1973).* The recurrent high speed streams commonly observed at 1 AU seem to correlate well with these low density open field line regions (Wilcox, 1968; Hundhausen, 1972; Pneuman, 1973; Noci, 1973; Krieger *et al.*, 1973). These streams are sometimes associated with recurrent geomagnetic activity (e.g. Chapman and Bartels, 1940) and provide evidence for the disturbing influence of the solar wind upon the Earth's magnetic field.

When viewed on the large scale, the solar wind appears to be stable. This contention is supported by theory (Parker, 1965, 1966; Carovillano and King, 1966; Jockers, 1968) as well as observation. Small-scale instabilities and disturbances of various kinds, however, are constantly present. Alfvén waves are observed at 1 AU (Coleman, 1967;Unti and Neugebauer, 1968; Belcher and Davis, 1971) and have been invoked to provide momentum to the solar wind (Hollweg, 1971a, b, 1973; Belcher, 1971; Alazraki and Couturier, 1971). These waves could have been produced by the supergranulation network (Hollweg, 1972a, b) and traveled outward along open field lines with very little dissipation. Small-scale disturbances, however, do not appear to influence the corona as a whole. In order to gain insight into the potential large scale changes in the inner corona resulting from the solar wind, we must examine the helmet

* A sample calculation shows that, even for uniform base conditions, a density enhancement of a factor of ten between the closed and open regions can be produced at 2.5 $R_\odot$ through these mechanisms.

streamers where most of the energy and mass of the inner corona resides. Those configurations clearly are stressed by the coronal expansion and, thus, reside in an elevated magnetic energy state relative to that of a potential field. Such elevated slates are always suspect when searching for the origins of coronal distrubances.

Streamers appear both over active regions and, at higher latitudes, over quiescent prominences, the latter being both larger and more stable. They are, of course, associated with bipolar magnetic regions on the Sun and, depending upon how high the coronal temperature is, can be either completely open (Parker, 1964a; Pneuman, 1969) or contain regions of closed loops at their base (Pneuman, 1968). In both open streamers and helmet streamers the density is enhanced over the background by a factor of 2–10 (Schmidt, 1953; Michard, 1954; Hepburn, 1955; Saito, 1959; Saito and Billings, 1964; Saito and Owaki, 1967; Leblanc, 1970; Newkirk *et al.*, 1970; Koutchmy, 1971) with the enhancement increasing outward.* This density enhancement is a result of greater energy losses adjacent to the streamer. These losses produce a relatively lower temperature there than in the streamer and, through the scale height effect, a much larger difference in density (Pneuman and Kopp, 1970; Pneuman, 1973).

Streamers containing closed loops, called helmet streamers, appear to be more commonly observed in the corona than open streamers and are probably more relevant to the subject of coronal disturbances. The chief interest in the helmet streamer, shown schematically in Figure 6, lies in the cusp-type neutral point at the

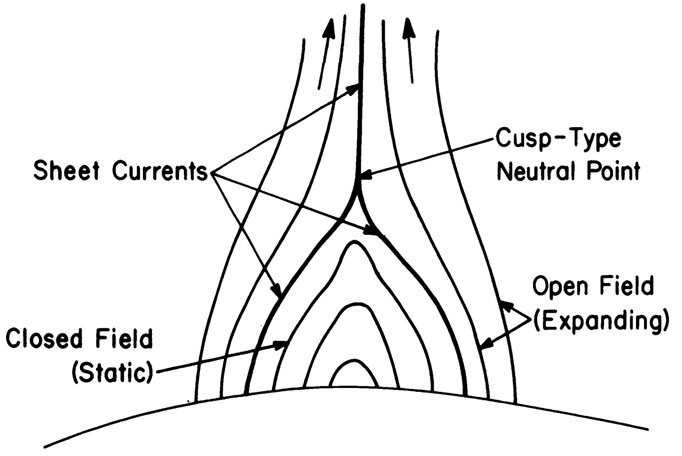

Fig. 6. Schematic of a typical helmet streamer (from Pneuman and Kopp, 1971). Note the 'cusp-type' neutral point and the sheet currents both above and below.

top of the closed loops, the neutral sheet above, and in the sheet currents below the neutral point between the open and closed regions (Pneuman and Kopp, 1971).

On the whole, the helmet seems to be a reasonably stable configuration persisting usually for several rotations (Hansen *et al.*, 1969, 1972; Bohlin, 1970a, b, 1971). Evidently they evolve in accordance with the changes in their underlying field

* See Newkirk (1967) for a comprehensive review of coronal observations.

structure. This picture is consistent with the apparent stability of the sector structure (Wilcox and Ness, 1965, 1967; Wilcox, 1968) assuming sector boundaries are the interplanetary extension of the actual sheets lying above helmet streamers (Wilcox, 1968; Newkirk, 1972a; Hundhausen, 1972). However, sudden disappearances or displacements do occur and the physical reasons underlying these disruptions are not understood. Five possibilities immediately suggest themselves. Firstly, the streamer could be blown out by an eruption of the underlying prominence. Secondly, some basic reorientation of the photospheric and chromospheric field may take place (such as reconnection or the relaxation of a force-free configuration) requiring a major readjustment of the coronal configuration. Thirdly, the streamer itself may be in a *metastable* state and undergo an explosive change due to an outside disturbance such as from a distant flare site.* A fourth mechanism may be that physical conditions in the corona may change such as an increase in temperature requiring a transformation from a closed to open configuration. This can occur for a relatively small change in temperature (Pneuman, 1968) and, once the streamer has opened, the density will rapidly decline giving the appearance of a void in the corona where a streamer once existed. Finally, since outward expansion and thermal conduction are prohibited in the helmet, all the energy dissipated by waves there must be radiated away. If this can't be accomplished, the helmet must expand.

Other transient phenomena associated with streamers perhaps related to the above are the apparent day-to-day changes in streamer locations and orientations observed in white light (Tousey, 1972). Although these changes have been attributed to basic physical changes in the corona, this phenomena could be one of perspective. For example, we expect the neutral sheets above streamers to be quite thin (Pneuman, 1972) due to the high conductivity of coronal material. Suppose the corona consists of a network of thin sheets in the vicinity of which the high density material is located. Since the brightness reflects an integral of density along the line of sight, the material will then be most visible when the plane of the sheet lies along the line of sight and essentially invisible when perpendicular to it. If these surfaces are curved, then the planes which appear bright could either shift about considerably or even flicker in and out of view on a rather short time scale. For example, if t_r is the time scale for solar rotation (≈ 27 days), and l the sheet thickness, then the time scale for this phenomena could be as short as $(l/R_{\odot})\, t_r$. For a sheet 1000 km thick, this time is only about an hour.

The overall stability of the helmet streamer configuration has not been investigated. However, the stability of the neutral sheet overlying the streamer has been studied and will be discussed in Section 5. The tearing mode instability is relevant here (Kuperus and Tandberg-Hanssen, 1967; Raadu and Kuperus, 1973), the inception of which may be responsible for the acceleration of electrons responsible for type III bursts (Sturrock, 1966, 1968, 1972). Another interesting type of instability, suggested recently

* Recently, Hansen (1973) has reported three separate observations of a coronal 'twitch' in which the axis of a large helmet streamer was displaced (rotated about its base) by about 5° as the result of a distant flare. Since this flare was accompanied by a type II and moving type IV burst, it is likely that this displacement could be produced by a traveling hydromagnetic shock.

by Cowling (1973), involves the discontinuity in pressure between the open and closed field lines with the larger pressure existing in the closed region. Cowling sees a possible discrepancy in the fact that the large gas pressure in the closed tubes is unable to break open the field lines for the material to escape whereas the smaller pressure outside is able to keep them from closing. He suggests there may be an instability near the top of the arches of closed flux tubes with the tubes becoming filled with plasma, bursting open, and then reclosing after losing their mass and heat content.

4. Role of Magnetic Fields in Guiding Coronal Disturbances

In some regions of the corona the condition $B^2/8\pi > P$ is satisfied and it is in these regions where we expect coronal fields to be effective in constraining particles and waves to move along field lines. We arbitrarily divide these types of disturbances into 3 classes – bulk motions, or those which exhibit continuum properties, wave motions, and individual particles events.

4.1. Bulk motions

The role of the magnetic field in surges is obvious. The surge is evidently produced by some underlying disturbance. Ejected material merely flows outward along the lines of force and generally falls back when its kinetic energy is spent. Loop prom-nences also show motion along the field. It is perplexing that this motion is always downward with the estimated mass falling on the cromosphere much greater than what would be supplied from the corona. Chromospheric brightenings are associated with this falling material motion which have been likened to the flare mechanism (Hyder, 1967a, b). Chromospheric spicules resemble miniature surges in many ways also seem to be a field channeled phenomena. They appear at the boundaries of super-granulation cells where the flow from the cells converges. It is easy to imagine this flow compressing the field lines and setting up strong vertical motions. This process has been evoked in many spicule theories (Ferraro and Plumpton, 1958; Weymann and Howard, 1958; Osterbrock, 1961; Parker, 1964b). Since, neglecting dissipation, ϱv^3 (ϱ being the density and v the velocity) will tend to be constant with height, we find for a vertical field ($B = \text{const}$) that $V \approx \varrho^{-1/3}$. Since the density decreases exponentially, large velocities can result high in the chromosphere.

Among the less obvious mechanisms for producing bulk motions along magnetic field lines is one suggested by Meyer and Schmidt (1968) applicable to closed loops. Although they have used this mechanism only to explain the Evershed motion near sunspots, it may very well be applicable to a great variety of field channeled flow phenomena observed in the corona. Consider a flux tube with both feet rooted in the deeper layers (see Figure 7a). If the temperature of the tube is uniform, it can easily be shown that the gas can be in hydrostatic equilibrium only if the pressure at the base of the tube are equal ($P_1 = P_2$). If not, a flow will be initiated from the higher pressure footpoint to the lower. Although for modest differences in pressure, the total mass flow may not be large, the velocities can be appreciable.

Considering a symmetric flux tube, Figure 7b shows the various possible solutions of the momentum equation for the steady state velocity profile. The only solution which yields $P=P_1$ at the left footpoint and P_2 at the right is one which begins a curve C and terminates on curve D. As can be seen however, there is no continuous solution linking these two curves, the reason being that the flow cannot pass continuously

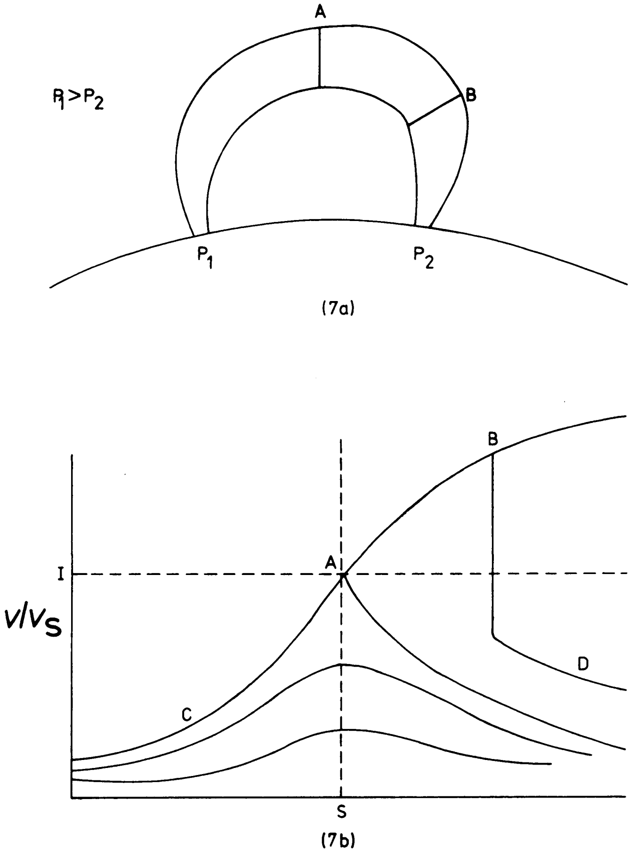

Fig. 7. A possible guiding role of coronal magnetic fields proposed by Meyer and Schmidt (1968). Figure (7a) shows a flux loop with two different gas pressures at its footpoints. As shown in (7b), the resultant flow becomes supersonic at the top of the loop (A) then undergoes a shock transition to subsonic flow at point B.

from a supersonic velocity to a subsonic velocity. The only solution yielding $P=P_1$ at the left and $P=P_2$ at the right is one where the velocity begins on curve C, passes through the sound speed at the top of the loop (point A), then undergoes a shock transition to curve D at point B. In this mechanism, the shocked gas is of higher density and *always* downward moving. It should be more visible and may explain why loop prominence material is only observed when moving downward. The increase in density be the shock can, of course, be only up to a factor of about four – probably not enough to explain the observations.* It should be kept in mind that this theory is a *steady-state* theory. It is more likely that the pressures at the base of closed loops are continuously fluctuating and the resulting mass motions may be more modest.

Another interesting type of coronal event which seems to be field-guided in a certain sense are the so-called 'coronal whips'. In this case mass doesn't appear to be flowing along field lines but, instead, is pulled rapidly through the corona in a whipping fashion by a readjustment of the whole field structure, the entire process beginning gradually and accelerating to velocities of about 100 km s^{-1} (Evans, 1957; Kleczek, 1963; Bruzek and Demastus, 1970; Dunn, 1970). This is clearly produced by a rapid large-scale change in the coronal field structure rather than by the coronal material and probably reveals the after effects of a reconnection process. For example, consider the configuration shown in Figure 8. At the top a loop structure in shown moving toward open field lines of opposite polarity. Eventually, reconnection will

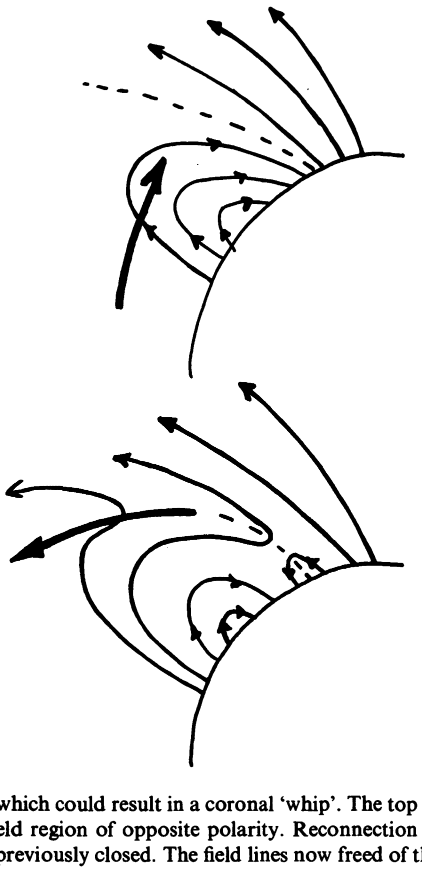

Fig. 8. A possible situation which could result in a coronal 'whip'. The top figure shows a bipolar region encroaching upon an open field region of opposite polarity. Reconnection at the base between the two regions then opens field lines previously closed. The field lines now freed of their photospheric connection can 'whip' out into the corona at approximately the Alfvén speed.

* On the other hand, further compression of the material after being shocked is also certainly possible.

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begin to occur freeing the photospheric connection of one side of the loops. Once, released, these noe open field lines will whip out into the corona at approximately the Alfvén speed carrying their load of coronal material along.

4.2. Wave motions

The contention that the solar corona is heated by waves emanating from the convective zone must at present be considered without observational support. Although attempts have been made to observe coherent disturbances which propagate and dissipate in the low corona, results so far have been inconclusive. Indirect evidence, however, is available from observations of Alfvén waves at 1 AU (Belcher and Davis, 1971) and recently observed coherent oscillations in plage regions (Bhatnager and Tanaka, 1972) which may reflect resonant Alfvén waves trapped in closed magnetic field lines (Pneuman, 1968).

Certainly the most spectacular wave disturbances on the Sun are associated with flares. These disturbances, seen in Hα, are observed to move outward in the chromosphere from the flare site at velocities of the order of 1000 km s^{-1} (Moreton, 1960) and have been of great interest to solar observers (Atahy and Moreton, 1961; Anderson, 1966, Dodson and Hedeman, 1968). The good time correlation between these 'Moreton waves' in the chromosphere and type II radio bursts observed in the corona strongly suggest that these two events are caused by the same shock wave leaving the flare site (Moreton, 1964; Ramsey and Smith, 1966; Wild, 1969).

Considering sonic and Alfvénic velocities appropriate for the chromosphere, Meyer (1968) has argued that a shock traveling there with a velocity of $\approx 10^3$ km s^{-1} would have a mach number of more than 10 and would thus exhibit large wave amplitude and strong dissipation. These difficulties disappear if the Moreton wave is considered to be a coronal phenomenon, the sound and Alfvén velocities being much higher there.

This concept has been amplified by Uchida (1968) in which the disturbance is considered to be a fast-mode MHD wavefront propagating from the flare region into the corona. The chromospheric manifestation is likened to that of a 'sweeping-skirt' of the coronal disturbance. Using a general ray tracing technique (eikonal equation), Uchida *et al.* (1973) have calculated the development of the fast-mode MHD wavefront in the corona in which the Alfvén velocity is computed from potential magnetic field theory (Altschuler and Newkirk, 1969) and deconvoluted density profiles obtained from *K*-coronameter data (Altschuler and Perry, 1972). In general, the wave focuses toward regions of low Alfvén speed so that most of the energy tends toward places where either the magnetic field is weak or the density is high. This brings up an interesting point regarding the neutral sheets above helmet streamers. There, the Alfvén speed goes to zero (or very nearly so) suggesting that these locations may be very effective in concentrating the energy in this type of coronal disturbance.

It is important to note that fast mode MHD waves *do not*, in general, follow field lines. The direction of propagation of these disturbances is sensitive to the distribution of Alfvén speed, not the field direction. Other investigations, on the other hand, have claimed a channeling of the type II shock along open more-or-less radial field lines (Kai, 1969; Dulk *et al.*, 1972).

One shortcoming in all these analyses is that the energy density involved with these type II and IV events is probably so high that the pre-existing field configuration is completely disrupted. Hence, any magnetic field model based upon the pre-existing photospheric magnetic fields could be extremely unrealistic.

4.3. Magnetic fields and individual particles

Perhaps the most common solar event which is essentially an individual particle phenomenon is the type III radio burst. These occur more commonly than flares and are apparently produced by a stream of energetic electrons travelling outward through the corona at a significant fraction of the speed of light exciting plasma oscillations at progressively higher levels. They have recently been observed far from the Sun at distances approaching 1 AU (Hartz, 1964, 1969; Slysh, 1967a, b; Alexander *et al.*, 1969; Haddock and Graedel, 1970; Fainberg and Stone, 1970a, b, 1971).

The coronal densities inferred from type III burst analyses have been consistently high (Newkirk, 1967; Fainberg and Stone, 1971). This, in addition to their apparent association with filaments seen in Hα (McLean, 1969, 1970), has led to the suggestion that the netral sheets associated with coronal streamers are the location of these outward travelling electron streams (Kai, 1970b; Weiss and Wild, 1964). This idea is strengthened by the apparent low degree of circular polarization of the bursts (Kai, 1970b) indicating a weak magnetic field such as could occur very near the neutral sheet of a streamer. Also, Sturrock (1968) has proposed that reconnection at the neutral point at the top of a helmet could be the acceleration site of these particles. One drawback of the neutral sheet hypothesis, however, is that these coronal structures probably contain transverse magnetic fields (Pneuman, 1972). If so, electrons can neither escape along the axis of the sheet nor pull the field lines outward with them (Smith and Pneuman, 1972) They could presumably travel just outside the sheet however.

A great variety of radio emission seems to be associated with closed loop structures in the lower corona. For example, 'U' bursts are evidently the direct counterpart of type III bursts. In this case, the electrons travel along closed field lines rather than open evidenced by the reverse frquency drift and their limited extent in height, their maximum observed height corresponding roughly to the highest observed closed loops in the white light corona. Type V emission also is caused by electrons spiraling back and forth along closed field lines producing broad band continuum radiation (Weiss and Stewart, 1965). They follow type III bursts (about 10% of them) and the radiation is believed to be due to synchrotron emission. Figure 9 is a schematic of a possible field configuration which could be responsible for all three of these phenomena.

The source characteristic of type I noise storms and stationary type IV bursts appear almost indistinbuishable (Kai, 1970b; Wild *et al.*, 1963), both consisting of a narrow band burst component superimposed on a broad band continuum. In the type I storm, the narrow band component is most prominent, while in the stationary type IV the continuum dominates. Type I storms are associated with sunspots and active regions, seem to occur in bipolar fields (Lartos-Jarry, 1970), and are quite persistent. The association of these radio regions with the interplanetary sector structure has been investigated by Sakurai and Stone (1971) (see Figure 10). They found, for the period 13 March to 21 August, 1968, that the number of type I centers was the same as the

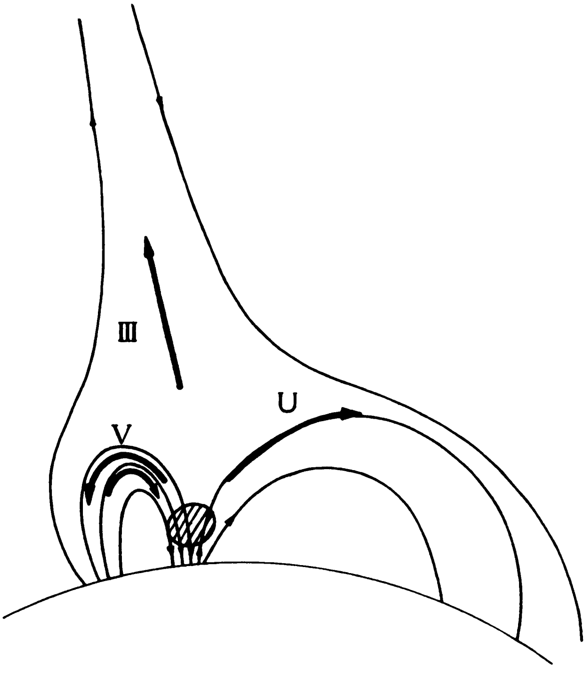

Fig. 9. Possible magnetic field configuration which is consistent with type III, V, and U bursts (from Wild and Smerd, 1972).

number of sector boundaries with the passage of a sector boundary delayed by about 5 days after the central meridian passage of the type I regions.

The overall problem of particle storage in magnetic fields is still quite unsettled. That containment in closed field regions does occur is suggested by X-ray photographs of the lower corona (see Figure 11). The bright arches are attributed to thermal bremsstrahlung and gyro-synchrotron emission of trapped electrons (Benz and Gold, 1971). One peculiar aspect of this subject is the apparent emission of energetic particles (≈ 10 MeV protons) from active regions for days and even weeks following a major flare (Fan *et al.*, 1968; Lin *et al.*, 1968; Krimigis, 1969; Krimigis and Verzariu, 1971). Since stable closed loops probably exist to a maximum height of about 2–2.5 $R_\odot$, the density must always be high in the storage regions. It is therefore difficult to understand why these particles don't quickly lose their energy by coulomb collisions with the ambient coronal gas (Ahluwalia, 1972). On the basis of considerations such as these, a continuously operating acceleration mechanism may be indicated (Newkirk, 1972a).

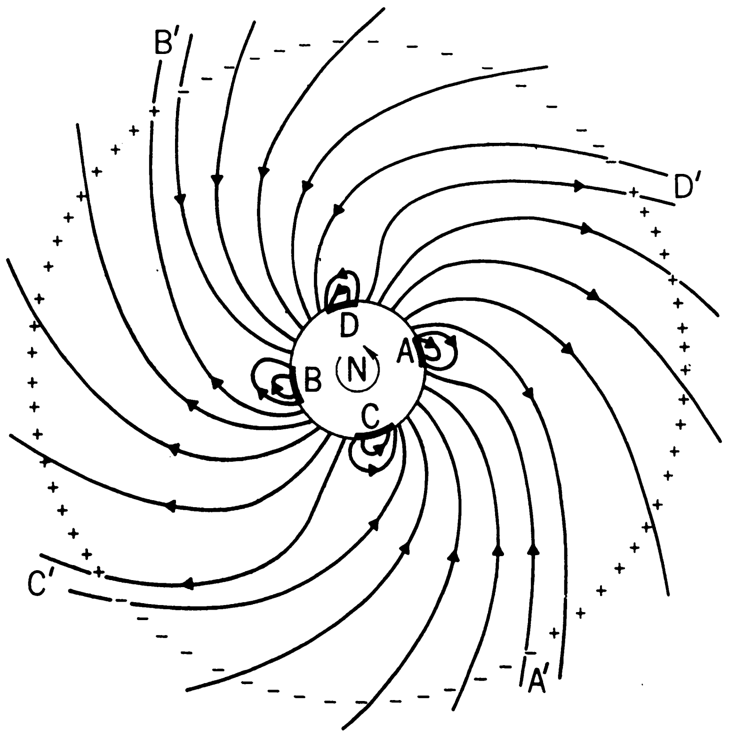

Fig. 10. Relationship between bipolar magnetic regions on the Sun, as inferred from type I storm centers, and the interplanetary sector structure (from Sakurai and Stone, 1971).

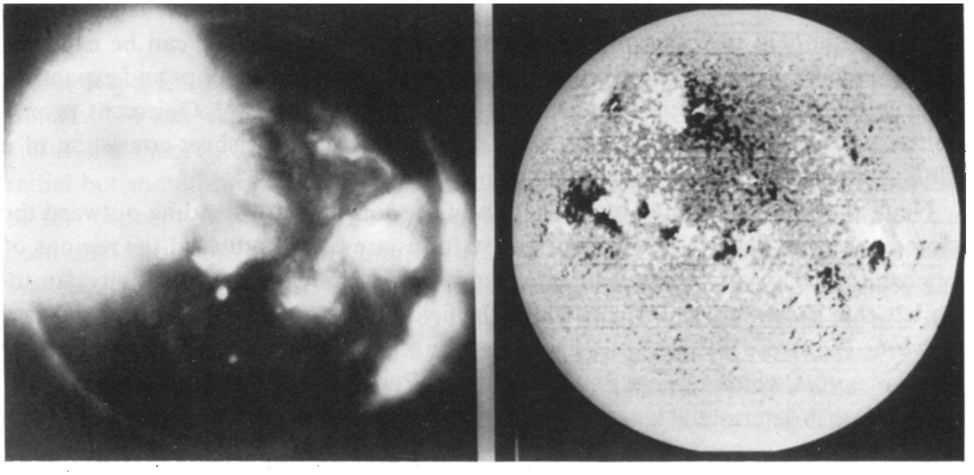

Fig. 11. Concurrent photographs of the Sun for the period covering the 1970 March 7 eclipse. On the left is shown the coronal X-ray emission and, on the right, the polarity pattern of the photospheric magnetic field (taken from Krieger *et al.*, 1970). Note the one-to-one correspondence between bright X-ray sources and bipolar magnetic regions.

5. Magnetic Discontinuities and Reconnection

In the crudest sense, we can estimate that a typical time scale for a magnetic disturbance in a conducting medium of density ϱ where the magnetic field strength is B will be

$$t \propto \frac{l\sqrt{\varrho}}{B},$$

where l is the typical length scale of the region where the disturbance originates. This is just the time required for an Alfvén wave to traverse the distance l. Since our main interest here is in fact coronal transitory phenomena, we search for physical situations where this time is comparatively short. Hence, regions of strong magnetic field, low density, or small characteristic lengths are relevant here. Our attention in this section is turned to those regions where l is small – such as the neutral sheets and current sheets. In spite of the lack of direct observations of these structures in the corona, they are fully expected because of the extremely high electrical conductivity of the medium.

5.1. Current sheets and neutral sheets

Magnetohydrodynamic discontinuities (other than shocks) are commonly observed in the solar wind at 1 AU (Burlaga, 1968, 1969; Siscoe *et al.*, 1968; Burlaga and Ness, 1968, 1969). Direct observations on the Sun or in the inner corona, however, are scant.* Due to their extreme thinness this is to be expected and, hopefully, more observations will be forthcoming from the ATM coronagraph experiments. Neutral sheets are expected above the helmet structures in coronal streamers (Sturrock and Smith, 1968; Pneuman and Kopp, 1971; Endler, 1971) and between adjacent coronal loop systems of opposite polarity such as shown in Figure 12. Current sheets, where the magnetic field is discontinuous but does not reverse polarity, can be expected almost anywhere but especially on the boundary between closed loops and expanding solar wind regions (Pneuman and Kopp, 1971; Endler, 1971).** Quiescent prominences also could possibily be the manifestation of a current sheet consisting of a kink in the magnetic field (Anzer, 1972).

Neutral sheets are formed by the action of the solar wind distending outward the closed magnetic fields of the Sun. As these loops are pulled outward the regions of opposite polarity approach each other and, in the limit of zero resistivity, an infinitely thin sheet develops across which the field polarity reverses. In the actual case however (non-zero resistivity), this sheet contains distended stationary magnetic tongues across which plasma flow takes place (Pneuman, 1972). The equilibrium of the tongues is determined by a balance between the pressure gradient tending to pull

* From a study of old eclipse plates, Eddy (1973) has recently reported an observation of a coronal neutral sheet (1922 eclipse) originating between two coronal helmets.

** Thermal conduction and expansion produce a gas pressure in the open region which is much lower than in the adjacent closed region. Since $P + B^2/8\pi$ must be the same on both sides of the interface, a corresponding discontinuity in B must be present requiring a current sheet.

the loop outward and the reverse $\mathbf{J}\times\mathbf{B}$ force (see Figure 13). Defining a magnetic Reynolds number $R_m = (4\pi/c^2)\,\sigma r_0 v_s$, σ being the electrical conductivity, r_0 the solar radius, and v_s the sound speed, the sheet thickness, transverse magnetic field, and expansion velocity in the sheet are proportional to $R_m^{-1/3}$ whereas the electric current density in the sheet varies as $R_m^{1/3}$. Assuming the sheet cross-section were radial and

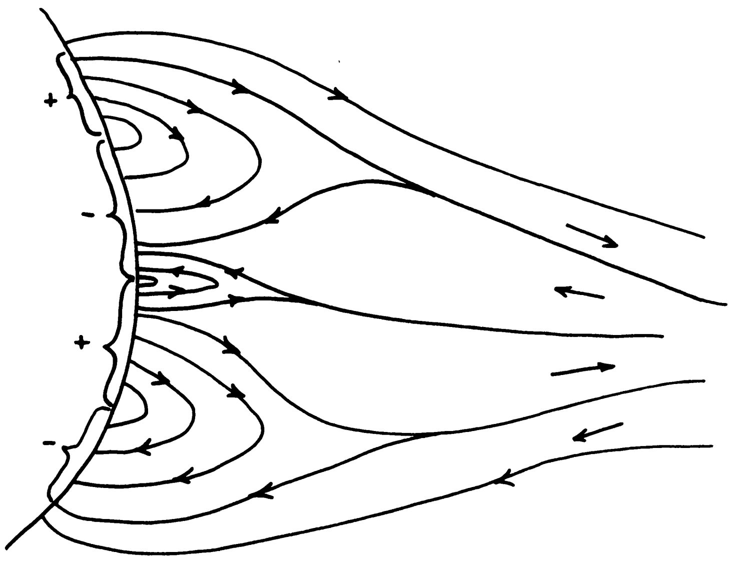

Fig. 12. Resultant field configuration over two bipolar regions of opposing polarity. Here, three current sheets are formed by the solar wind. Because of magnetic forces, these sheets may merge at greater heights. A configuration such as this could produce the neutral sheet seen in the 1922 eclipse (Eddy, 1973) and is the logical result of the action of the solar wind on the magnetic field geometry proposed by Sweet (see Figure 15).

evaluating σ for a current carried by ions perpendicular to the field, thicknesses as small as 500 km were estimated. This, however, is expected to be a lower limit since additional theoretical considerations lead to the expectations that the sheet is not radial but should broaden as one proceeds downward in the corona.* An extension of this concept, incorporating more sophisticated mathematical assumptions, has been carried out by Priest and Smith (1972). In considering these simplified physical models, it should of course be kept in mind that differences in solar wind speed and direction from one side of the sheet to the other could produce a highly sheared and distorted configuration differing drastically from the simple symmetric case.

Although the stability of current sheets in the corona has not been studied, neutral sheets have received some attention. The particular instability suspected in these structures is the tearing mode first suggested by Furth *et al.* (1963). In this instability, reconnection of field lines takes place along the sheet due to finite conductivity effects. Such an instability has been proposed as a mechanism for the formation of quiescent

* The results of Eddy's (Eddy, 1973) observation seems to bear this out.

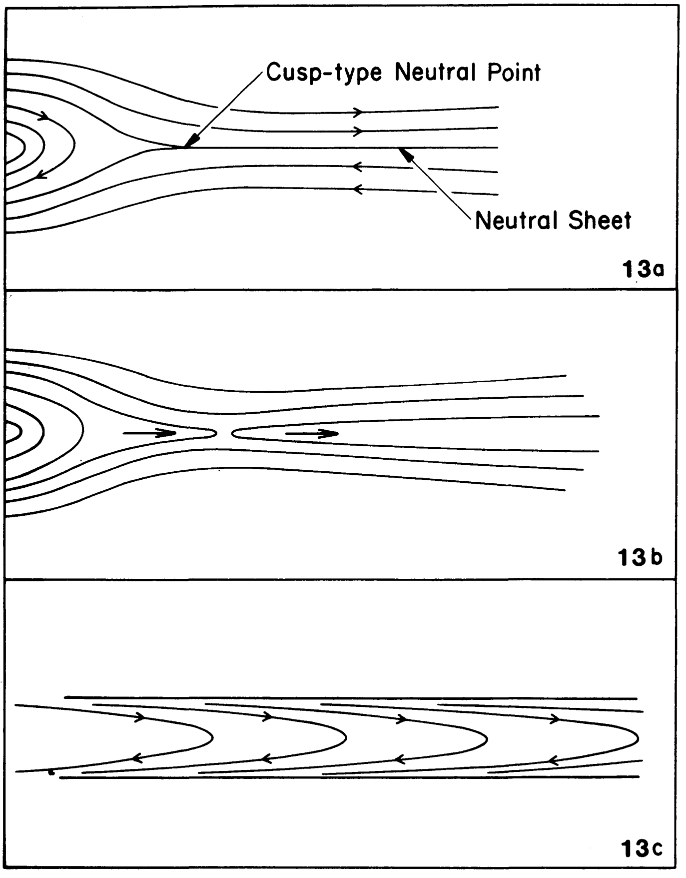

Fig. 13. Schematic of a typical helmet streamer showing how the neutral sheet topology could be developed by finite conductivity effects. (a) Streamer field line topology for the case $\sigma = \infty$ showing the neutral point and current sheet of zero thickness. (b) When finite conductivity is introduced, reconnection of open field lines can occur at the neutral point forming the above shown oppositely directed loops. Arrows denote the subsequent motion of these field lines due to pressure forces. The outer loop is expelled to infinity whereas the inner one expands to a stationary position determined by the reverse $\mathbf{J} \times \mathbf{B}$ force. (c) Resulting topology of field lines in the neutral plane is one of enormously distended magnetic tongues with plasma diffusion taking place across the field (from Pneuman, 1972).

prominences (Kuperus and Tandberg-Hanssen, 1967; Raadu and Kuperus, 1973). In these models, the neutral sheet is assumed thermally unstable giving rise to compression and cooling of material to form the prominences by condensation from the corona. Recent observations however suggest that a coronal origin cannot account for the observed amount of material in prominences (Saito and Tandberg-Hanssen, 1973). If this is so, such a mechanism must be reconsidered.

Although theoretical analyses of the tearing mode instability have shown mixed conclusions (Northrup and Birmingham, 1970; Smith and Raadu, 1972; Coppi and Friedland, 1971; Biskamp and Schlindler, 1971), two considerations lead us to suspect that neutral sheets in the solar corona are stable, at least to gross destruction. Firstly, the long lifetimes of helmet streamers, the stability of the sector structure at 1 AU and of the geomagnetic tail observationally attest to their persistence. Secondly, a neutral sheet such as that pictured in Figure 13 cannot be topologically affected by an infinitesimal displacement as opposed to a sheet that does not contain a transverse magnetic field. This suggests that a disturbance of finite amplitude is necessary to disrupt the sheet – i.e., the configuration could be *metastable*.

An important aspect of neutral sheets to the subject of coronal disturbances is their possible role in guiding both particles and waves. The relevance of these structures to the type III radio burst phenomena and in focusing flare produced MHD waves has already been pointed out. In addition, Bumba and Obridko (1969) have suggested that proton flare activity associated with Bartel's active longitudes occurs in the neighborhood of the sector boundaries of the interplanetary magnetic field. Hence, neutral sheets could be the 'tracks' along which energetic particles travel from the Sun to the Earth. In addition to their guiding role, neutral sheets have been considered in theories of solar flares (Sweet, 1958; Severny, 1958, 1961, 1962a, b; Jaggi, 1964; Sturrock, 1966), prominence formation (Kuperus and Tandberg-Hanssen, 1967; Raadu and Kuperus, 1973) and chromospheric spicules (Uchida, 1969; Pikel'ner, 1969).

5.2. Magnetic neutral points and reconnection phenomena

Magnetic reconnection at neutral points is believed to be at the root of much solar transient phenomena. Because this process seems to be the most efficient way of converting magnetic energy to other forms, it is often invoked in solar flare theories (Sweet, 1958; Severny, 1958, 1961, 1962a, b; Parker, 1963; Carmichael, 1964; Petschek, 1964; Sturrock, 1966, 1968, 1972; Krivsky, 1968) as well as those involving chromospheric spicules (Pikel'ner, 1969; Uchida, 1969) and prominence disruption (Rust, 1970). It is likely that the so-called 'coronal whips' and other observed transients in λ5303 are due to readjustment following magnetic reconnection. According to most theories of the solar cycle, reconnection must take place to explain the observed changes in polarity of the polar field.

Overall coronal evolution is also critically dependent upon how fast field lines can reconnect in the corona – a question that cannot be conclusively answered at the present time. For example, if reconnection rates are rapid as compared to the time scales for evolution of the surface fields, then a *unique* coronal configuration exists for given boundary conditions at the coronal base. If, on the other hand, reconnection is difficult, then the state of the coronal magnetic fields and gas will depend upon the complete time history of the surface changes. This consideration is critical to the overall problem of solar-interplanetary modeling.

Reconnection can occur only at neutral points. Therefore some discussion of their geometry is appropriate here. The 'X-type' neutral point (Dungey, 1953, 1958) (shown schematically in Figure 14) has received the most theoretical interest because of its relevance to flare theories. This configuration can exist between two sunspot pairs as depicted in Figure 15 (Sweet, 1958) or wherever fields of opposite polarity approach each other preferentially at one location.

Three other types of neutral points are possible where field lines undergo a transition from a closed to open configuration such as at the top of coronal helmets. These are the 'Y-type', 'T-type' and 'γ' or 'cusp-type' (Sturrock and Smith, 1968). These are

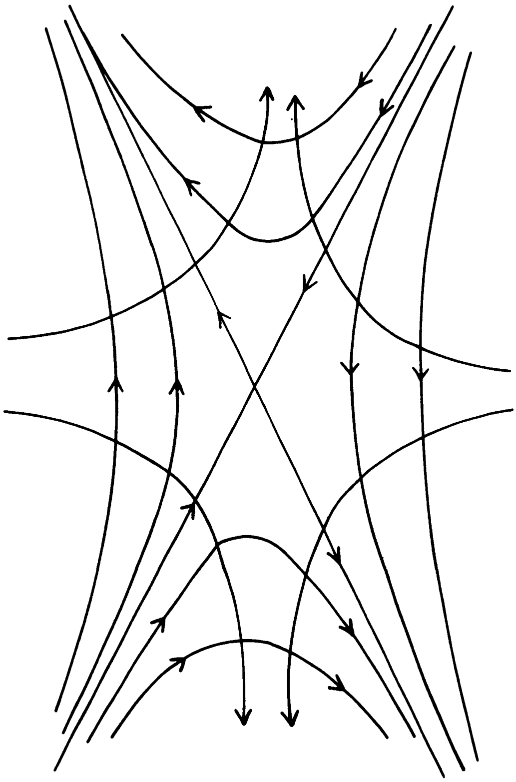

Fig. 14. Schematic of X-type neutral point. The field lines are brought toward the neutral point from the left and right by the flow. After reconnection, they are expelled to the top and bottom.

shown in Figure 16 and each results from a different type of pressure jump between the open and closed regions. If, as seems to be the case, the gas pressure outside the helmet is lower than inside, both the 'Y' and 'T' neutral points can probably be ruled out in the solar corona (Pneuman and Kopp, 1971). The 'Y-type' cannot occur since the field vanishes when approaching the neutral points from all directions and there is consequently no way to balance the pressure jump (since $P + B^2/8\pi$ must be continuous). In the 'T-type', the field vanishes in the open region but not in the closed and the jump in B is of the wrong sign. The only type consistent with the expected mechanical forces is the 'cusp type' in which the field goes to zero approaching the neutral point from the inside but does not vanish on open field lines.

Having reduced the possible neutral point configuration in the corona to two

('X-type' and 'cusp-type') let us now examine the reconnection process. Although reconnection at 'cusp-type' neutral points has received some attention (Kuperus and Tandberg-Hanssen, 1967; Sturrock, 1966, 1968, 1972; Raadu and Kuperus, 1973) the 'X-type' configuration is the usual one considered in theoretical analyses. Moreover, the reconnection processes is essentially the same for both since time dependent reconnection at a cusp would result locally in an X-type geometry.

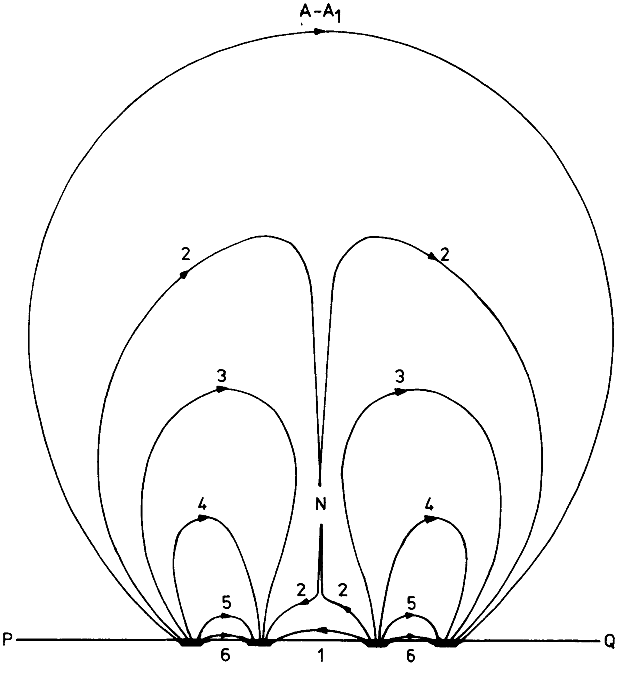

Fig. 15. Neutral point configuration proposed by Sweet (1958) as a model for solar flares.

Early analyses of magnetic reconnection at an 'X-type' neutral point were based upon ordinary dissipation due to the finite conductivity of the plasma. An externally imposed flow approaches the neutral point and, after reconnection took place the fluid was ejected along the axis at essentially the sound speed.

For pressure equilibrium, the sound speed is taken to be equal to the Alfvén speed outside the region. The rate of annihilation is controlled by two factors – the diffusion time and the time required to expel the fluid. This leads to a characteristic reconnection velocity

$$v_d = \left(\frac{B_0}{\sqrt{4\pi\varrho}} \frac{c^2}{4\pi\sigma L} \right)^{1/2},$$

where B_0 is the ambient field outside the boundary, ϱ the density inside and L the

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characteristic length of the reconnection region. Using reasonable values for these quantities, one can easily verify that the characteristic times obtained through this mechanism are much too long to account for explosive phenomena in the chromosphere and corona. Attempts to alleviate this difficulty have involved corregated neutral surfaces (Parker, 1963) in which the characteristic dimension be reduced and one-dimensional time dependent models (Dungey, 1958; Severny, 1958) in which a nonstationary collapse toward the neutral surface occurs.

In an entirely different mechanism, introduced by Petschek (1964), the magnetic field is annihilated by the propagation of Alfvén waves. The magnetic energy here is directly converted into the kinetic energy of the upward moving plasma. In Petschek's

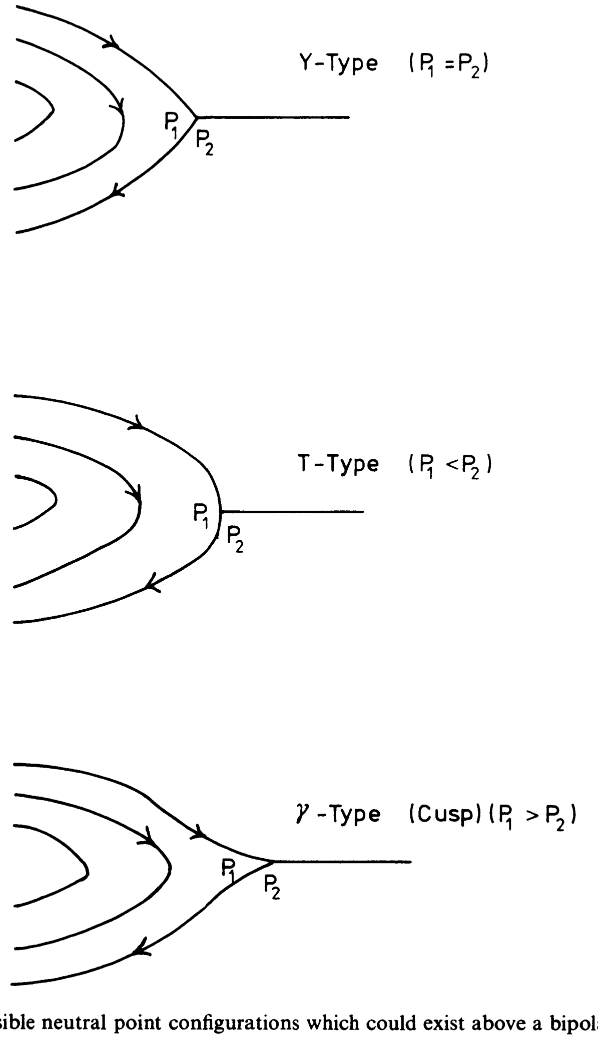

Fig. 16. Three possible neutral point configurations which could exist above a bipolar magnetic region (Sturrock and Smith, 1968). Due to the expected mechanical forces, however, the first two can probably be ruled out.

mechanism, the characteristic velocity is proportional to $(ln\ R_m)^{-1}$ (R_m being the effective magnetic Reynolds number) rather than $R_m^{-1/2}$. In spite of some criticism of the model (Green and Sweet, 1967; Petschek and Thorne, 1967; Priest, 1972), this offers a significant reduction in annihilation time which may be able to account for the observed transient phenomena. Even more in the direction of reduced dissipation times, Yeh and Axford (1970) and Sonnerup (1970) have argued that reconnection is completely independent of the electrical conductivity. Once the input velocity is specified by external conditions, the conductivity just determines the size of the region of annihilation. Hence, reconnection can occur with any speed up to the Alfvén speed.* Instabilities have also been evoked to reduce the reconnection time. For example, Parker (1973) contends that the fluid can escape rapidly from the annihilation region via the interchange and kink instabilities and also finds reconnection speeds of the order of the Alfvén velocity.

In summary, then, the search through the years seems to be toward faster reconnection rates – rates that can now be said to be fully consistent with the observed time scales of coronal disturbances. Processes based upon reconnection alone, however, appear to require very special circumstances to work. If the reconnection rate is too slow, short time scales are not obtained. If, on the other hand, reconnection is too rapid, the event will not be explosive. It is not entirely clear, therefore, that large-scale changes in field topology on a short time scale can be explained by reconnection alone – especially if the region of dissipation is small. For this type of process, the rapid relaxation of a stressed field configuration may be a more attractive explanation.

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* Recently Priest (1973) has re-examined this mechanism and concludes that the fastest reconnection rate is about an order of magnitude smaller.

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DISCUSSION

Dryer: The interpretation that led to the suggestion that a closed 'magnetic bottle' had been observed may not be correct; the observations can also be explained without involving closed fields. Also, enhancements at 1 AU have been observed without the corresponding enhancement in B_r which would occur in a 'bottle'. The white light observations certainly suggest a 'bottle' but we are not yet certain that closed magnetic fields are involved.

Pneuman: Another explanation could be that the ejected plasma flows out from the Sun in a much wider angle than the r^2 expansion of the solar wind. This could result in an anomalously low temperature by adiabatic cooling due to overexpansion.

Schatten: What characterizes 'coronal holes'?

Pneuman: In my opinion they are regions of open field lines where the solar wind flows resulting in a drain in energy content due to thermal conduction and expansion. Calculations, using this hypothesis, show that density differences of a factor of ten and temperature differences of a factor of about two can be expected between closed and open regions.

Schmidt: In defense of 'magnetic bottles', I should note that the cool electrons seem to flow in from both directions as would be expected.

Mullaly: Decimetre (21, 43 cm) bright region auto-correlations show persistence of stable magnetic fields in the corona for ~year. The possibility remains that the persistent regions may be 'holes' rather than 'bright' regions.

Newkirk: Similar persistence of some coronal features has been known for some time.

Smith: As correctly pointed out by Parker, none of the analyses of reconnection to date can tell what determines the rate of reconnection. Thus, all analyses which have increased the reconnection rate have done so by guessing, and you must accept these analyses pretty much on faith.

Dryer: A recent paper (*J. Plasma Phys.*) by Fukao and Tsuda provided this kind of computation for the diffusion region with finite electrical conductivity. They found the Yeh and Axford suggestion, that (for situations where the proton gyro radius is small relative to the diffusion region's scale size) the reconnection rate is independent of the conditions within the diffusion region and depends only on the external boundary conditions, is valid.

Smith: Tsuda obtained the result which he did because he set the problem up that way. His analysis was also a steady-state analysis and thus gives us no new information about what determines the rate of reconnection.

Dryer: I believe you are referring to their earlier paper. They have recently published a time-dependent solution.

Zirin: Filaments lie *along* field lines; this does not seem compatible with Kippenhahn-Schlüter model.

Pneuman: How certain is it that magnetic-field is directed along the filament?

Zirin: I am sure it is.

Meyer: Kippenhahn and Schlüter showed that any stable prominence supporting field configuration must *already* contain a trough even before the filament material has settled into this trough. The filament material will bring its own magnetic field with it. The natural configuration which that process will produce is then one in which the magnetic field of the heavy filament gas lies along the trough. Thus, the magnetic field of the filament gas is along the filament, the supporting field is, however, across.