1991ApJ...381..306M

THE ASTROPHYSICAL JOURNAL, 381:306–312, 1991 November 1

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NEUTRALIZED AND UNNEUTRALIZED CURRENT PATTERNS IN THE SOLAR CORONA

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Received 1991 February 11; accepted 1991 May 8

ABSTRACT

Observations of the vector magnetic field at the photosphere suggest that there is a net current flowing through the corona along coronal magnetic loops from one footpoint to the other. There is also evidence that flare kernels correlate with regions of high current. The absence of any apparent return current through the corona is inconsistent with this current being generated by stresses in the photosphere or in subphotospheric layers after the loop has emerged from below the photosphere. The possibility that a return current is present and has escaped detection is discussed. If there is no return current, then a rethinking of several widely accepted ideas on solar magnetic fields and their role in solar flares is required.

Subject headings: hydrodynamics — Sun: corona — Sun: flares

1. INTRODUCTION

Observations of the vector magnetic field in solar active regions provide sufficient information to determine the vertical component of curl $\boldsymbol{B}$ and hence to identify the vertical component of the current flowing from below the photosphere into the corona (e.g., Moreton & Severy 1968; Krall et al. 1982; Gray et al. 1987; Ding et al. 1987; Lin & Gaizauskas 1987; Hagyard 1989; Canfield et al. 1990). The observed currents I are up to several times 10^{12} A in an active region. In principle, such observations could provide critical tests of theories of solar flares. For example, coronal storage models for flares (e.g., Sturrock 1980) involve storage of energy in a nonpotential component of the coronal magnetic field, with this energy being released explosively during a flare. Any specific form of this nonpotential component, such as a twist or a shear in the coronal magnetic field, implies a particular distribution of vertical current in the photosphere, and an implication is that this current should be reduced as a result a flare. However, the data on the vector magnetic field do not provide unambiguous support for coronal storage models for flares, and some of the implications of these data have been ignored. One such implication is emphasized in this paper: the data suggest that flaring flux tubes carry a current that flows from one footpoint to the other with no evidence for a return current through the corona. Such an unneutralized coronal current pattern is inconsistent with the current pattern implied by coronal storage models, and it is incompatible with the widely adopted picture of the coronal magnetic field in terms of isolated magnetic flux tubes. In this paper the case is argued that the currents are indeed unneutralized. Either these arguments must be refuted (and the return current identified in the data) or a significant rethinking of some widely held ideas relating to solar flux tubes will be required.

In § 2 it is argued that currents generated by photospheric or subphotospheric stresses after a magnetic flux tube emerges are neutralized, in the sense that both a direct current and a return current flow through the corona. In § 3 observations of the vector magnetic field in the photosphere or chromosphere and the implied current distributions are discussed. The implied currents are unneutralized in the sense that there is only one current path through the corona. This current must close along a return path below the photosphere. The possibility that a return current through the corona is present but has escaped detection is then considered. In § 4 it is pointed out why unneutralized currents, which are invoked in some models for solar phenomena, are inconsistent with several widely favored ideas, notably coronal storage models for flares and the concept of an isolated flux tube.

2. THE PREDICTED CURRENT PATTERN FOR STRESSES FIELDS

In coronal storage models for solar flares it is assumed that after the flux tube, or arcade of flux tubes, emerges from below the photosphere, subphotospheric motions produce stresses that are stored in a nonpotential component of the coronal magnetic field. Suppose that when a flux tube first emerges there is no current flowing along its axis. It is now argued that the current pattern generated as a result of a stress imposed subsequent to the emergence of the flux tube is neutralized. First, however, let us define what is meant by neutralized and unneutralized coronal current patterns in this context.

In the following discussion "current" refers only to the component of current along the axis of the flux tube. Specifically, in an idealized cylindrical geometry, a current-carrying flux tube has a current flowing along the axis. In contrast, an idealized, isolated, cylindrical flux tube that is not current-carrying, in the sense used here, still has an azimuthal current flowing in a sheath or surface layer around the flux tube. Such surface currents are ignored in the present discussion.

Imagine a vertical surface that intersects the photosphere at the neutral line, which separates the regions of opposite magnetic polarity in the photosphere and where the vertical component B_z of the magnetic field $\boldsymbol{B}$ vanishes. In the absence of any current there is no flow of charge across this surface either above or below the photosphere. Even if a current is to flow as a result of stresses subsequently imposed on the flux tube, charge continuity requires that the net flow of charge across this surface must continue to be zero. There are two ways in which a current that subsequently flows through the corona might close. First, there may be a direct and a return path both through the corona, so that the net current crossing the imaginary surface above the photosphere remains equal to zero. This is referred to as a *neutralized* coronal current pattern. Second, the current may close along a return path below the

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photosphere. The coronal current then flows from a footpoint on one site to a footpoint on the other side of the neutral line with no return current path above the photosphere. This is referred to as an *unneutralized* coronal current pattern.

2.1. *Neutralized Current Patterns*

There are two idealized types of stress: a twist and a shear. An idealized twist involves a rotation of one footpoint relative to the other. An idealized shear involves a displacement parallel to the neutral line of one footpoint relative to the other. In both cases the current that is generated flows across field lines in the subphotospheric region where the stress is imposed. This region is called a *dynamo* region. This cross-field current is such that the associated $\boldsymbol{J} \times \boldsymbol{B}$ force balances the imposed stress and the inertial of the plasma. The resulting current pattern is neutralized. Specifically, the current flows across the field lines at one footpoint in response to the stress, and closes by flowing through the corona along one set field lines, across the field lines at the other footpoint and back along another set of field lines through the corona. The $\boldsymbol{J} \times \boldsymbol{B}$ force at the second footpoint must be balanced either by a compensating stress or by plasma inertia in a front propagating downward at the Alfvén speed.

An idealized example of the implied vertical component of the current density J_z in the photosphere is illustrated in Figure 1 for several twisted flux tubes. In a cylindrical model for a field that is being twisted, the sign of J_z depends on the radial gradient of the azimuthal velocity v_ϕ of the plasma flow, and so changes sign at the radius at which v_ϕ is a maximum. An idealized current for a sheared field is illustrated in Figure 2. The important qualitative point is that in both cases there are pairs of regions with opposite signs of J_z on each side of the neutral line. Conversely, a current pattern that has only one region of current flow on one side of the neutral line and one region of oppositely directed current flow on the other side of the neutral line is necessarily unneutralized.

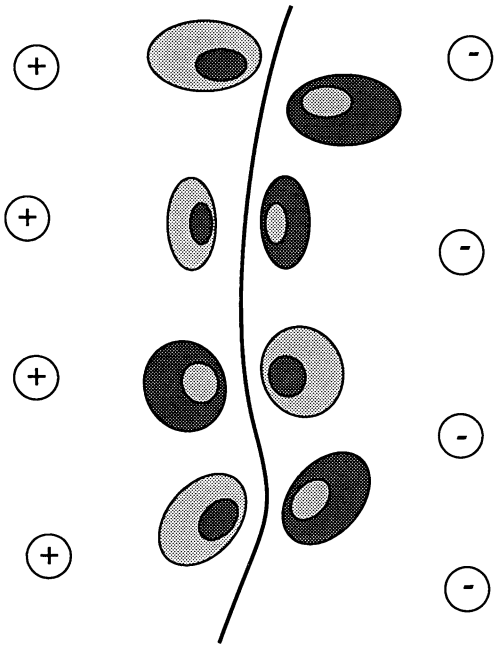

FIG. 1.—Idealized photospheric current pattern for a neutralized coronal current pattern corresponding to several twisted loops; the plus and minus signs represent the sign of B_z, and the solid line represents the neutral line. Light and dark shaded regions correspond to opposite signs of J_z. One loop is shown with a twist in the opposite direction to the others.

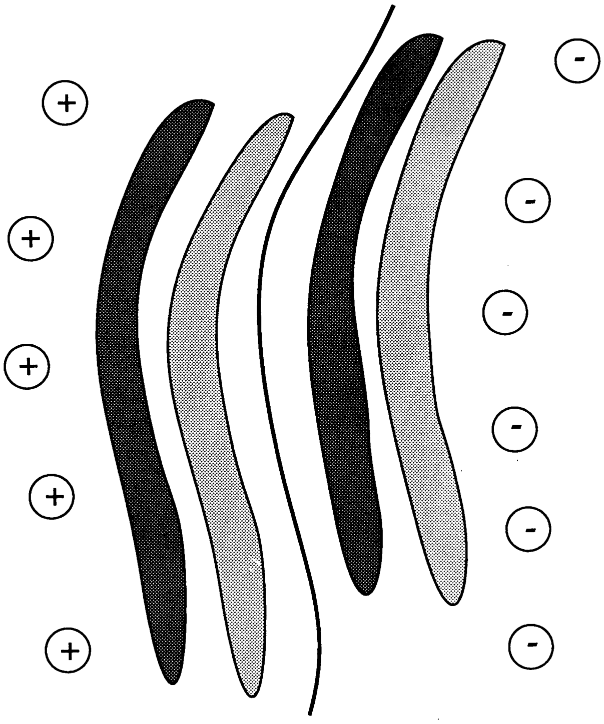

FIG. 2.—As for Fig. 1 but for a sheared field

2.2. *Surface Current Layers*

Although the neutralized current patterns illustrated in Figures 1 and 2 are implicit in most models for twisted or sheared coronal fields, the requirement that there be a return current is not emphasized in the literature. Indeed few authors consider the implied global current pattern. An exception is Spicer (1982) who drew currents closing in the photosphere and flowing along two separate paths through the corona. An idealized example is illustrated in Figure 3.

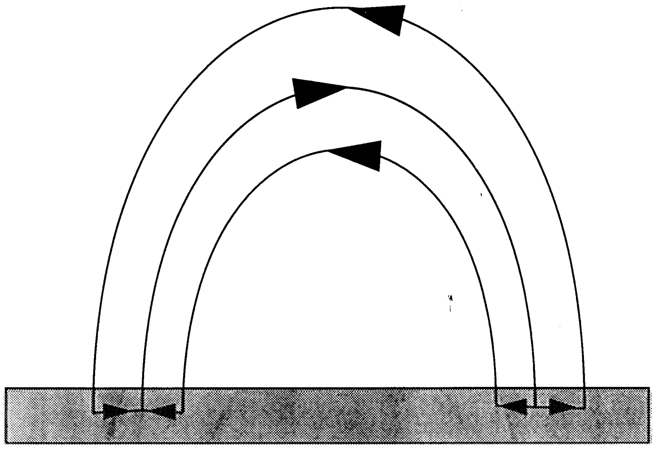

FIG. 3.—Idealized model that simulates the current pattern in the corona for a single neutralized twisted flux loop. Central line represents a body current inside the flux loop with return currents on the surface. Current closes across the field lines in two dynamo regions.

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Consider a twisted, isolated, cylindrical flux tube, for example, as discussed by Parker (1979). By implication the field drops to zero at the surface of the cylinder. This discontinuity in ***B*** implies a singularity in curl ***B***, and hence in ***J***, which correspond to a current on the surface of the cylinder. The surface current may be separated into (1) an azimuthal component that is required to account for the discontinuity in the axial component of the magnetic field, and (2) an axial component that cancels the azimuthal component of the magnetic field. The axial component of the surface current provides the return current. Of course, a singular return current is an idealization, and any return current must flow in a current channel of nonzero width. The cases of thick and thin return current channels are discussed in § 3.

2.3. *Unneutralized Current Patterns in Circuit Models*

In most models for solar magnetic fields that are stressed, a return current is involved, either explicitly or implicitly, but there are some exceptions. In electric circuit models applied to flares (e.g., Alfvén & Carlqvist 1967; Alfvén 1977), to filaments (e.g., Kuperus & Raadu 1974; van Tend & Kuperus 1978; Martens 1987), to loop transients (e.g., Anzer 1978) and to the heating of solar flux tubes (e.g., Ionson 1985) the circuits drawn correspond to unneutralized currents in that there is one current path through the corona and another current path in or below the photosphere. There appears to be no theory for how such unneutralized current patterns could be set up after the magnetic loop emerges from below the photosphere. However, as discussed below, the vector magnetic field observations seem to imply that coronal currents are indeed unneutralized.

3. THE OBSERVED CURRENT PATTERN

The photospheric current distribution derived from the measured vector magnetic field favors an interpretation in terms of an unneutralized coronal current pattern. After describing the observations briefly here, the question of whether there could be an undetected neutralized current is considered.

3.1. *Photospheric Current Distribution*

Two particular examples where the observational data are well above the noise level are that analyzed and modeled by Hagyard (1989), and that analyzed by Canfield et al. (1990). The current distribution deduced by Hagyard (1989) is illustrated in Figure 4. Hagyard modeled this current in terms of a set of current loops centered on the neutral line. Each current loop is unneutralized, in that its upper half is in the corona and its lower half is below the photosphere. All the current loops have current flowing in the same sense around the loop. The fact that such a current pattern can account for the observed vector magnetic field reinforces the conclusion that coronal current are unneutralized. Canfield et al. (1990) found a current 3–4 × 10^{12} A, with the current flowing up in one region on one side of the neutral line and down in another region on the other side of the neutral line. The net current within the area of the magnetograph differed insignificantly from zero. This

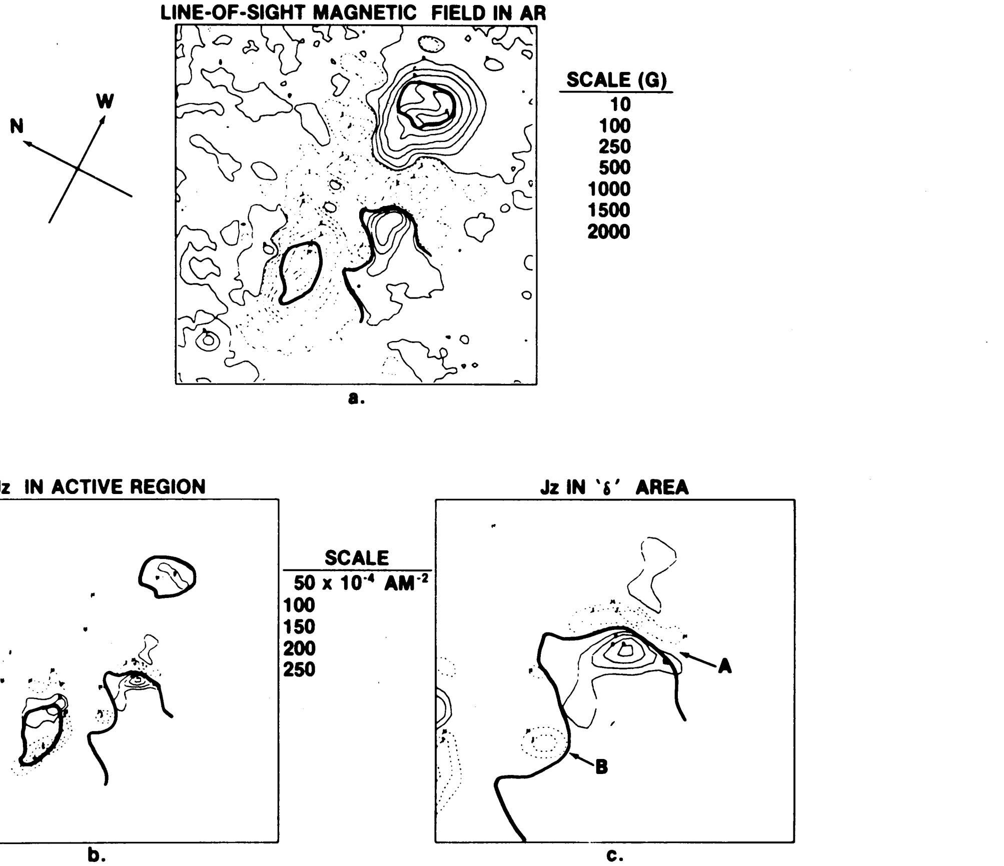

FIG. 4.—Current pattern deduced from observations for a particular active region by Hagyard (1989). Unclosed neutral line in (*a*) is redrawn on the same scale in (*b*) showing the current pattern, and (*c*) is a magnified portion of (*b*). In (*b*) and (*c*) solid and dashed contours correspond to opposite signs of J_z.

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suggests that the current flows from one of these regions to the other through the corona, and that there are no other regions of significant current in the region covered by the magnetograph.

In these two specific cases, and seemingly in all cases reported in the literature, the current apparently flows up on one side of the magnetic neutral line and down on the other.

There is no evidence for a return current through the corona. It might be remarked that an implicit assumption is made here concerning currents being confined to isolated current tubes. It may be that currents are not restricted to isolated tubes and that they do not close within the field of view of the magnetograph. However, this does not avoid the basic requirement for a return current. To each region carrying a large current into the corona there must be a region or group of regions carrying an equal current from the corona. The current may be regarded as neutralized only if the region where the current flows into the corona and the region where the current flows back from the corona are sufficiently close together, and only if they remain sufficiently close together along their path through the corona.

3.2. *Could a Return Current Have Escaped Detection?*

An important question that needs to be answered is whether it is possible that the return current is present in the corona and has hitherto escaped detection. There are two ways that such a return current could have escape detection. First, a weak return current over a large area might be below the threshold for detection. Second, a strong return current over a small area might be excluded by the algorithm used to determine the ambiguity in sign of the horizontal field.

3.3. *Thick Return Current Channel*

The first of these possibilities relies on the observational threshold for measurement of the current density J_z allowing weak currents to escape detection. It is conceivable that there is a large region of weak return current outside each region where currents are measured. For example, in Figures 1 and 2 the outer regions illustrating the return currents may be very much larger than the inner regions, so that the current density in the outer regions is below the threshold for detection, while the current density in the inner regions is above threshold.

To discuss this possibility quantitatively one would require a model for a neutralized coronal current that is also force free. However, no realistic model for a force-free flux tube carrying a return current is available. One might expect the current profile to be qualitatively similar to that in a reverse field pinch (e.g., Gross 1984) in which the total current $I = 2\pi \int dr\, rJ_z$ is equal to zero. The accepted model of a reverse field pinch, for which there is both theoretical and observational support (e.g., Taylor 1986; Bodin 1989), is a solution of the force-free condition curl $\boldsymbol{B} = \alpha \boldsymbol{B}$ with $\alpha = \text{const}$. However, in this case the magnetic flux $\Phi_M = 2\pi \int dr\, rB_z$ is proportional to the current, and current neutralization would imply zero magnetic flux. This is inconsistent with the concept of a coronal flux tube. Thus, the magnetic configuration cannot be similar to that in a reverse field pinch, and any acceptable model must have α change sign where the hypothesized change in sign of J_z occurs.

Even without a detailed mathematical model for a coronal flux tube carrying both a direct and a return current, one may identify the following qualitative implications of postulating the existence of an unobserved weak return current. First, one would expect the return current to be observed in the future as the resolution of vector magnetographs is improved. Indeed, one could expect there to be evidence for it in available data. Specifically, the assumption $I = 0$ implies that the current density times the area is equal for both the direct and return currents, and observational constraints on the ratio of the areas suggest that the ratio of the current densities cannot be extremely small. The assumption that the direct current is detected and the return current is not requires that when the former is above the threshold for detection the latter is always below threshold, and this is intrinsically implausible. Second, a current-carrying flux tube in the corona would have a characteristic structure of a core with a relatively high current density, and a thick outer sheath with a larger cross-sectional area carrying a current in the opposite direction. If this were the case, then two flux tubes would interact first through their current sheaths. The consequences of such an interaction are not obvious. Third, the assumed current pattern implies a stress pattern in the photosphere. Specifically, the stress must reverse sign where the direction of J_z reverses, with the stresses outside the line defined by $J_z = 0$ weaker and in the opposite sense to the stresses inside this line. For example, consider an idealized twisted flux tube in cylindrical geometry, in which the stress is due to the shear dv_ϕ/dr: the rotational motion v_ϕ of the flux tube (which, by implication, exists in the dynamo region) has $v_\phi = 0$ both on the axis and on the surface of the cylinder, and a maximum at some intermediate radius, which is where J_z changes sign. Any model for the generation of the coronal current pattern needs to take account of this change in sign of the stress, if indeed the current is neutralized. In principle such a model may be tested by comparison with the observed flows in the photosphere.

3.4. *Thin Return Current Channel*

The second possibility for an undetected return current arises from the way in which an ambiguity in the sign of the horizontal component of the magnetic field is resolved. In analyzing the data, an algorithm is required to determine this sign, and the algorithm used involves rejecting abrupt changes in the orientation of the field from one pixel to another (e.g., Canfield et al. 1990). It is conceivable that this algorithm excludes an alternative acceptable interpretation of the data in terms of a return current with a high current density. In this case the area of the outer regions in Figures 1 or 2 where the return current flows would be much smaller than the area of the inner regions. In practice the ambiguity in sign tends to arise near the neutral line (A. N. McClymont 1990, private communication). The return current might then be in a narrow current channel on the under (photospheric) side of the coronal magnetic loop.

A seemingly plausible related possibility is that a return current flows in many thin current channels throughout the current-carrying region. The estimated large current, $I \gtrsim 10^{12}$ A, corresponds to the net current inside a given contour (as implied by the integral form of Ampere's law). One cannot hide such a return current within this contour, in the form of thin current channels or in any other form. Thus, provided that the present techniques for analyzing the current are not seriously flawed, and it is not suggested here that they are, the only plausible location where one could hide a return current in thin current channels is on the edge of the current-carrying region, that is, essentially as a surface current on the current-carrying flux tube.

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This possibility could be tested by reanalyzing available data to see if they are compatible with such an alternative interpretation. If such a thin surface current sheet exists, then the highest current density should be in the surface and not in the body of the flux tube. An implication is that two current-carrying loops that are forced together would interact strongly through their surface currents. The consequences of this do not appear to have been considered.

More generally, it should be emphasized that models for twisted or sheared coronal loops are incomplete until the structure of the return current is specified, and the structure of the return current must be compatible with available vector magnetic field data. Although the foregoing two possibilities for hiding the return current in existing data have not yet been excluded on observational grounds, the simplest interpretation of the data is that there is no coronal return current and that the current is unneutralized in the sense defined above.

4. IMPLICATIONS OF AN UNNEUTRALIZED CURRENT PATTERN

As already stated, the data on the vector magnetic field suggest that the large currents that correlate with flares are unneutralized. Specifically, the observed regions of high current ($\gtrsim 10^{12}$ A) occur in pairs with opposite signs of J_z and with one region (with $J_z > 0$, say) on one side of the neutral line and the other region (with $J_z < 0$) on the other side of the neutral line. The discussion in § 2 implies that the expected signature for a neutralized current pattern is four associated regions, such that two neighboring regions with opposite signs of J_z occur on one side of the neutral line and two neighboring regions, also with opposite signs of J_z, occur on the other side of the neutral line. In over three decades of observational work there has been no report of such a pattern, let alone any suggestion that it is a characteristic pattern.

Let us assume, as seems likely, that the interpretation of the available data in terms of unneutralized current patterns is basically correct, and consider some of the implications of the data.

4.1. *Current Closure*

By hypothesis, the closure of an unneutralized coronal current occurs below the photosphere. Currents necessarily flow along field lines in a force-free region. Below the photosphere the magnetic field is not necessarily force free, and the force per unit volume $\boldsymbol{J} \times \boldsymbol{B}$ associated with a cross-field current flow may be balanced by a pressure force or by plasma inertia. Hence it is conceivable that current flows along a path of minimum electrical resistance rather than along magnetic field lines (e.g., Hudson 1987). The following arguments favor flow along the field lines and suggest that currents close across field lines only in specific dynamo regions.

One argument concerns force balance in a region of cross-field current flow. From a qualitative viewpoint the force $\boldsymbol{J} \times \boldsymbol{B}$ is weak for a diffuse current (weak $\boldsymbol{J}$) flowing across a weak field. Modest turbulent motions may then provide a balancing force. However, it is thought that the magnetic field below the photosphere is confined to the regions between supergranulation cells where the field is relatively strong, sometimes called the thin flux tube model (e.g., Spruit 1981; Parker 1979, p. 198). In this model it is much more difficult to identify pressure or other forces that can balance the $\boldsymbol{J} \times \boldsymbol{B}$ force. McClymont & Fisher (1989) explored the possibilities and concluded that in such a model current closure must occur deep in the atmosphere, near the base of the convection zone.

A second argument concerns the way in which a cross-field current flow may be set up. Imagine a situation where initially there are no forces and there is a current flowing along field lines. Any subsequently applied force can set up a steady cross-field current only on the time scale for magnetic field lines to diffuse across the region of cross-field current flow. The current can be deflected across field lines on the Alfvén propagation time, but a steady cross-field current requires that the magnetic field lines and the current lines diffuse relative to each other. In this context, it is sometimes helpful to use circuit language and to introduce three time scales (e.g., Sato & Holzer 1973; Holzer & Reid 1975; Sato 1985), the diffusive time, t_I, the Alfvén time, t_A, and the capacative time, t_C, with $t_A^2 = t_I t_C$. In regions with $t_I \gg t_C$, which applies to the flux tubes of interest, cross-field electric fields are set up (on the time scale t_C) and stresses propagate (on the time scale t_A) so that any stress imposed on the system tends to relax without setting up any steady cross-field current pattern. A steady cross-field current flow results only if the imposed stress is maintained for a time $\gtrsim t_I$ and if the boundary conditions do not allow the system to relax in any other way.

In summary, assuming that the thin flux tube model is a reasonable description of the magnetic field in the convection zone, one expects current to flow along field lines and that any cross-field current flow occurs near or below the base of the convection zone.

4.2. *Current Dissipation*

A large circuit implies a large inductive time scale. On estimating the coronal resistance during a flare from the power released (Melrose & McClymont 1987), one finds that the inductive time scale for the coronal portion of the circuit is longer than the time scale for the impulsive phase of a flare. The complete circuit is at least an order of magnitude larger than the coronal portion, and hence its inductive time scale is at least an order of magnitude longer. This long inductive time scale precludes a significant change in the current over the duration of a flare (e.g., Melrose 1987, 1991). Hence, at least to a first approximation, the coronal current remains constant during a flare. In a constant-current model the magnetic energy release must be attributed to a change in the inductance of the corona, reflecting a change in the current path or the current profile (Khan 1990; Melrose 1990). This implies that the energy release in a flare should not be attributed to current dissipation, but rather to a change in the current pattern that reduces the stored magnetic energy (Zuccarello et al. 1987). This change can be reversed, with the stored magnetic energy being resupplied on the inductive time scale.

4.3. *Isolated Flux Tubes*

It is widely believed that solar magnetic flux tubes, including coronal flux tubes, can be magnetically isolated from their surroundings. However, no current-carrying flux tubes can be magnetically isolated from their surroundings. In cylindrical geometry, for example, the axial current I produces an azimuthal field $B_\phi = \mu_0 I/2\pi r$ at radial distance r outside the current channel. In any realistic geometry in which the current is confined to a current channel, the current generates a magnetic field outside the current channel. This implies that current-carrying flux tubes interact with each other through their magnetic fields or, in circuit language, through the mutual inductance. The interaction between flux tubes is already present in some models that invoke current-current interactions, such as the flare model of Gold & Hoyle (1960), the filament model of Kuperus & Raadu (1974), and the model for loop transients of Anzer (1978). However, interaction between flux tubes is excluded in many models for solar magnetic structures, for example, in models involving flux ropes made up of braided thin flux tubes that are assumed magnetically isolated from each other. Two current-carrying (in the sense used here) flux tubes interact through the magnetic field of one and the current of the other causing a $\boldsymbol{J} \times \boldsymbol{B}$ force, which couples them dynamically, so that they cannot be isolated from each other.

A related implication concerns magnetically isolated flux tubes below the photosphere. There is a widely held belief that the magnetic field near and below the photosphere is confined to localized regions (e.g., Parker 1979) where the magnetic field strength is $B \gtrsim 0.1$ T, surrounded by unmagnetized plasma with $B \lesssim 10^{-4}$ T. A qualitative argument for this is that in the convection zone the field is pushed into boundary regions between convection cells to avoid the convective motions twisting up the field arbitrarily. However, a flux tube carrying an unneutralized current cannot be isolated because the magnetic field outside the current channel is nonzero. The concept of an isolated flux tube below the photosphere can be maintained only by postulating that the two legs of a coronal flux tube are tightly linked below the photosphere. One possibility is illustrated in Figure 5, where the two legs are shown twisted around each other. Such a twisted pair of flux tubes carrying opposite currents can be isolated.

4.4. *Magnetc Versus Plasma Stresses*

A further qualitative implication of the current being unneutralized is that the observed relative motions of flux tubes and photospheric plasma cannot be due primarily to the plasma pushing around the magnetic flux tubes. As already argued, stresses imposed on the magnetic field due to plasma motions produce neutralized current patterns. If the dominant current pattern is unneutralized, then the current is not due to local stresses, but must be generated in some remote dynamo region. The dominant motions of flux tubes then reflect the response to stresses transmitted along the magnetic field lines from deep in the atmosphere. By way of illustration, an observed rotation of the positive and negative polarities of a bipolar region should be attributed to an unwinding of the twist illustrated in Figure 5, rather than to a vortex motion of the plasma causing the rotation of the field pattern.

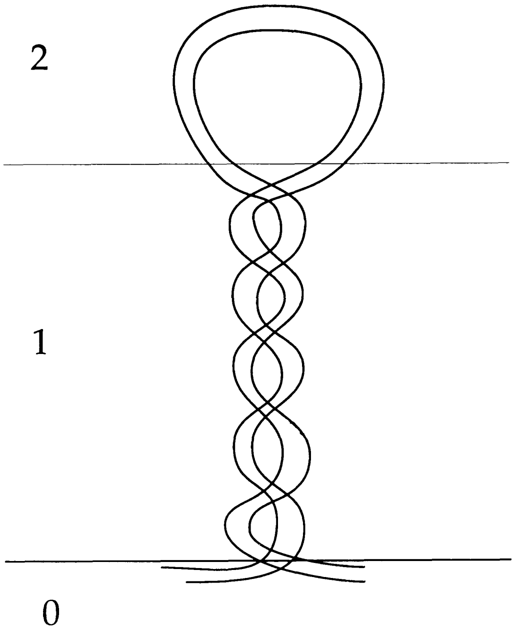

FIG. 5.—Coronal flux tube (region 2) is shown together with the legs in the convection zone (region 1) linking to the toroidal solar field below the base of the convection zone (region 0). If the flux tube carries an unneutralized current, the legs can form an isolated magnetic configuration by being wound around each other, as illustrated.

5. CONCLUSIONS

Current patterns implied by data on the solar vector magnetic field have been available for over three decades, and they have consistently shown that the current is unneutralized, in the sense that there is no return current through the corona. In contrast, favored models for solar flares invoke subphotospheric motions storing energy in the coronal field, and this implies a neutralized current. This inconsistency between observation and theory can be resolved in one of two ways: (1) further observations or reanalysis of the vector magnetic field may identify a return current through the corona, confirming that the current is neutralized, or (2) it will become accepted that the currents are unneutralized, and flare models that require a neutralized current will be abandoned in favor of models (yet to be formulated) that involve an unneutralized current.

Implications of the coronal current patterns being unneutralized include the following:

1.—There is no obvious way that an unneutralized coronal current pattern can develop after a flux tube has emerged, and hence the current must have been flowing before the flux tube emerged through the photosphere.

2.—An unneutralized current must close deep in the solar envelope, presumably in the solar dynamo region, and hence the coronal portion of the circuit is only a tiny fraction of a much larger current circuit.

3.—The idea that subphotospheric motions cause stresses that lead to energy storage in twisted or sheared coronal flux tubes should be abandoned as the basis for solar flare models.

4.—The current flowing through the solar corona cannot change significantly during a flare because the time scale for a flare is shorter than the inductive time scale for the full circuit in which the current flows.

5.—In circuit language, the energy release must be due to a change in the inductance of the corona, rather than to a change in the coronal current. A change in inductance corresponds to a change in the coronal current profile or of the current pattern.

6.—A flux tube carrying an unneutralized current cannot be isolated (in the sense that the magnetic field is confined to the flux tube which is surrounded by unmagnetized plasma). Current-carrying magnetic flux tubes below the photosphere may be isolated due to the two legs of the flux tube being wound around each other.

It is important that a flare model based on the assumption that the current is unneutralized be formulated and analyzed in as much detail as the coronal storage models that involve (usually implicitly) neutralized currents.

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The ideas underlying the discussion in this paper were developed in collaboration with Sandy McClymont; Ron Moore suggested that a paper should be written on this topic; and helpful comments on the presentation have been made by George Dulk, Jan Kuijpers, and Jack Thomas.

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