Unneutralised Currents in Solar Flares

D. B. Melrose, *School of Physics, University of Sydney, NSW 2006*

Abstract: Observations of the vector magnetic field imply that there is a net current flowing through the corona, and there is also evidence that this current is directly related to flares. It is argued that if the currents are unneutralised, then this requires a radical rethinking of several widely accepted ideas on solar magnetic fields and their role in solar flares.

1. Introduction

Magnetograph observations of the solar magnetic field provide direct information on the component of the magnetic field along the line of sight, which is approximately the vertical component of the field in the photosphere. In active regions, the areas of opposite magnetic polarity are separated by neutral lines where the vertical component of the field is zero. The inferred three-dimensional structure of the magnetic field near and above the neutral line is an arcade of flux loops. Vector magnetic field observations provide information on the component of the magnetic field perpendicular to the line of sight. A potential model would imply that this component should cross a neutral line approximately perpendicular to it, corresponding to low-lying flux loops connecting the areas of opposite polarity. However, observations show that in strongly sheared regions this third component is often closer to parallel than to perpendicular to the neutral line, implying that the field is non-potential, and hence that electric currents are flowing. The vertical component of the electric current flowing through the photosphere into the corona may be inferred from the vector magnetic field data (e.g., Moreton and Severny 1968; Krall *et al.* 1982; Gary *et al.* 1987; Ding *et al.* 1987).

The observed currents can be up to about $I \approx 10^{12}$ A in an active region. This is near the maximum possible current, corresponding to the self-field due to the current being approximately equal to the idealised potential field. The inferred currents appear to flow up on one side of the neutral line and down on the other. The simplest and seemingly only plausible interpretation is that the current in the corona flows along the flux loops from one footpoint to the other. It is this interpretation of the current pattern that is the central point in the following discussion.

Solar flares tend to occur in the vicinity of neutral lines, with the classic two-ribbon flares showing brightening along two parallel ribbons on either side of the neutral line, with the ribbons delineating the footpoints of the flaring loops. There is a correlation between regions of high inferred current and the location of flare kernels (e.g., Ding *et al.* 1987; Lin and Gaizauskas 1987), suggesting a possible causal relation (e.g., Severny 1971; Machado *et al.* 1988).

In this paper it is argued that the currents inferred from observations of the vector magnetic field are inconsistent with such coronal storage models and with some other widely accepted models of solar magnetic fields. The possibility that the interpretation of current pattern implied by the vector magnetic field data is incorrect also is discussed briefly.

2. Current Closure

It is useful to distinguish between a coronal current that is *neutralised* and one that is *unneutralised*. A neutralised current is one has that has direct and a return current flowing along neighbouring sets of magnetic field lines in the corona. Such a current must close across field lines in two 'dynamo' regions below the photosphere, one below each footpoint. An unneutralised current flows around a circuit with one section in the corona so that there is a direct current but no return current in the corona. Such a current must close along some path that completes the circuit from one footpoint to the other below the photosphere.

An important point is that all currents that are generated after a magnetic flux tube emerges from below the photosphere are neutralised. Consider two idealised models for the generation of currents by sub-photospheric motions. First, for a cylindrical flux tube (an idealised isolated flux tube) that is twisted due to opposite ends being rotated at different angular speeds. The increasing twist of the field implies a uniform current density along the body of the cylinder with the return current flowing along the surface of the cylinder (e.g., Takakura 1971), with these currents increasing with time. Second, consider a slab (an idealised arcade of flux tubes) that is sheared due to relative motion of the fluid on opposite faces of the slab. The increasing shearing of the field implies equal oppositely directed surface currents on the opposite faces, with these currents increasing with time. These currents must close by flowing across the field line in two 'dynamo' regions, one below each footpoint, where the $\boldsymbol{J} \times \boldsymbol{B}$ force is balanced by the postulated twisting or shearing motion.

The vector magnetic field data are not consistent with what one expects for neutralised currents. If all currents were neutralised then one would expect the vector magnetic field data to show pairs of oppositely directed currents on each side of the neutral line. On the contrary, the data on vector magnetic fields seem to show no indication of such nearby return current paths, e.g., Hagyard (1989). Thus the data seem to imply that unneutralised currents flow through the corona. This leads to the question as to where such currents might close. According to present ideas, a coronal loop has two footpoints in the photosphere and has two flux tubes continuing below the photosphere from each footpoint, extending down to the base of the convection zone in the thin flux tube model (Parker 1979; Spruit 1981). If the coronal current is unneutralised then it would appear that the current must flow up from the base of the convection zone along one flux tube and back down the other, closing in the solar dynamo region, whose actual location is not relevant here. Note that such a current flows in a circuit whose length is at least an order of magnitude larger than the length of the coronal portion of the flux tube.

3. Some Implications of the Inferred Current Patterns

Let us accept for the case of discussion that the currents do flow up on one side of a flux tube and down on the other, closing deep inside the solar atmosphere, as the observations suggest. The following are some implications.

(a) Such currents are unneutralised, thereby excluding all 'coronal storage models' for solar flares (e.g., Sturrock 1980), where the energy is stored in twists or shears after the flux tube has emerged from below the photosphere. This is because all processes that involve storing energy in the corona set up neutralised current patterns in the corona.

(b) The current that flows into the corona in the active region either (i) is flowing in the flux tubes as they emerge from below the photosphere (the 'emerging flux tube model'), or (ii) builds up on the inductive time-scale of the global circuit in which it flows after the flux tubes have emerged. There seems no reason to favor the more complicated assumption (ii) over the simpler assumption (i).

(c) The current-carrying flux tubes cannot be isolated in the corona, because any isolated flux tube must have a surface current that neutralises the internal current. This implies strong inductive coupling between current-carrying flux tubes in the corona.

(d) For flux tubes below the photosphere the non-existence of neutralising currents precludes the localisation of the magnetic field to the boundaries between the large-scale convection cells unless the flux tubes are coupled into pairs with equal and opposite currents, much like in the wiring of a radio-quiet warship or submarine.

(e) The line-tying boundary condition, often used to model twisted or sheared coronal magnetic fields (e.g., Priest 1982), is unacceptable for an unneutralised current because it implies that all currents are short-circuited at the photospheric boundary. A realistic model must include current closure below the photosphere, as in the multiple current-loop model of Hagyard (1988).

(f) The current closes deep in the solar atmosphere at the base of the convection zone or in the solar dynamo region (McClymont and Fisher 1989). This implies a relatively large inductance for the global circuit, $L \gtrsim 40\,\mathrm{H}$ (Melrose 1990).

(g) An impulsive flare can have only a small effect on the magnitude of the net current flowing through the corona, i.e., there can be no 'interruption' of the current (e.g., Alfvén and Carlqvist 1987), because the inductive time-scale of the global circuit is long compared to the time-scale of the energy release in the impulsive phase of a flare, and *a fortiori* in elementary flare bursts.

Thus if one accepts that the vector magnetic field data imply that an unneutralised current flows through the corona and that this current plays central role in solar flares, then a radical rethinking is required for several of the widely accepted interpretations of the structure of solar magnetic fields and of their role in solar flares. In particular, (a) the energy released in solar flares cannot be due to the storage of mechanical stresses in the coronal magnetic field, (b) line-tying and related assumptions are unacceptable boundary conditions for current-carrying coronal flux tubes, (c) the concept of isolated flux tubes is invalid for coronal magnetic loops, and (d) the structure of the sub-photospheric magnetic field needs to be revised to include pairing of flux tubes carrying oppositely directed currents so that the pair can act as an isolated magnetic entity.

4. Are there Unobserved Neutralising Currents in the Corona?

Why have these radical implications of the vector magnetic field data been ignored in the past? The answer to this question appears to be that little weight has been given to the interpretations of the data because the observations are close to the limit of resolution of existing vector magnetographs. The view seems to be that if the data are ignored, eventually they will go away. However, as an increasing number of groups have reported vector magnetic field data, a consistent picture has developed in accord with the original work of Severny (e.g., Moreton and Severny 1968), as outlined above. It would seem that for those who wish to maintain the existing interpretations threatened by these data, the only hope is that future observations with higher resolution will uncover a return current that has hitherto been undetected. It is likely that an increase in resolution, by perhaps a factor of ten, will occur within the next year or so (R. C. Canfield, private communication). It seems that a return current could be missed in the existing data only if it filled a large area at low current density outside where the measured currents are located. It seems unlikely that such return currents will be found and, if not, then the radical implications of the non-existence of return currents in the corona will be inescapable.

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