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OBSERVATIONAL EVIDENCE FOR MAGNETIC RECONNECTION IN SOLAR FLARES

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ABSTRACT From studies of the magnetic topology of flaring active regions, the separator - a region were magnetic reconnection can take place - appears to be magnetically connected to places of intense chromospheric flare brightening. This suggests that magnetic reconnection occurs in the separator region in solar flares. Observational support for magnetic reconnection releasing the energy stored in field align currents systems is presented.

INTRODUCTION

Since a potential magnetic field is a state of minimum energy, it is widely accepted that the energy released in solar flares is stored in the non-potential component of the field; this component is generated by electric currents flowing in the solar atmosphere. However, the mechanism by which the free magnetic energy is released is not yet completely understood. The presence of DC electric fields has been advocated in order to explain some features of the X-ray spectrum. Nevertheless, the origin of these fields is not surely known. Following Alfvèn and Carlqvist (1967), models based on current interruption have been proposed (Khan 1989, Zaitsev and Stepanov 1992). On the other hand, Lin and Schwartz (1987) and Wingley *et al.* (1991a,b) suggested that the electric fields are due to magnetic reconnection and that they finally lead to field aligned particle acceleration.

Considering that the model of Wingley *et al.* is basically a two dimensional model and is not based on a known topology of the magnetic field, the main observational support for magnetic reconnection still comes from the observed motions of chromospheric ribbons in large two-ribbons flares. Various flare observations suggest qualitatively that flares result from the interaction of magnetic structures (Machado *et al.* 1985, 1988, Kundu 1986, Pallavicini 1991 and references herein). In this review we present more quantitative evidences for 3D magnetic reconnection in flares with more complex magnetic topologies. Here, support for magnetic reconnection acting in solar flares is derived from the observed magnetic link between chromospheric flares and the singular line

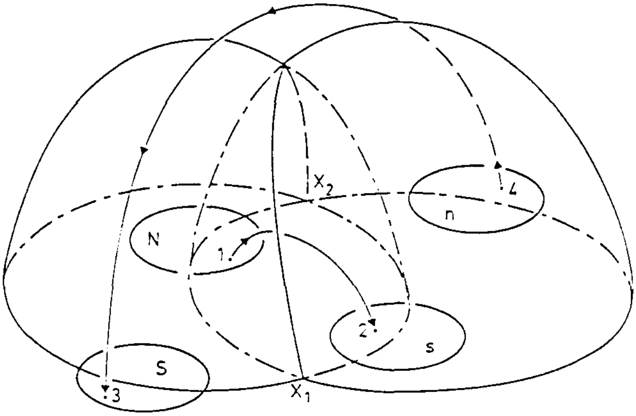

FIGURE I Schematic three-dimensional representation of magnetic field separatrices and separator for an ensemble of four magnetic sources (circles) derived from Hénoux and Somov (1987). The separator intersects the plane representing the photosphere in X_1 and X_2.

called separator where reconnection can take place.

It is doutful that magnetic reconnection in a current sheet can satisfy the flare energy release rate requirements; its rôle may be limited to the release of the energy stored in DC currents. The still incomplete set of measurements of the electric current density available suggests that the energy released in the flares under study comes from the energy stored in current systems and that magnetic reconnection converts this energy.

IMPORTANT MAGNETIC FIELD TOPOLOGY FEATURES

Sweet (1958, 1969) first pointed out the importance of topological features of the magnetic field called separatrices and separator. The geometry of the separatrices and of the separator for the simple case of two bipolar regions is shown in Fig. I. Separatrices are surfaces that separate regions of different magnetic connectivities, they delimit flux systems. Separatrices intersect on a singular line called separator. The separator has two properties (Priest 1991 and references therein, Lau and Finn 1990): i) an electric field parallel to the magnetic field can be present ($\underline{E}+\underline{v}\wedge\underline{B}\neq 0$), ii) it is a singular line of type X (Syrovatskii 1981) with field lines in a plane perpendicular being hyperbolic. The separator region is therefore a possible location for magnetic reconnection.

In systems having sufficient symmetry the separatrices and the separator can be derived analytically. Using numerical methods, Baum and Brathenal (1980) derived their locations for the potential field of four magnetic charges in pairs of opposite polarity. The conditions for the generation of the separator as a function of the relative magnitudes and positions of four charges have been studied by Gorbachev *et al.* (1988). Since the efficiency of the magnetic reconnection process may depend on the strength of the magnetic field, the ap-

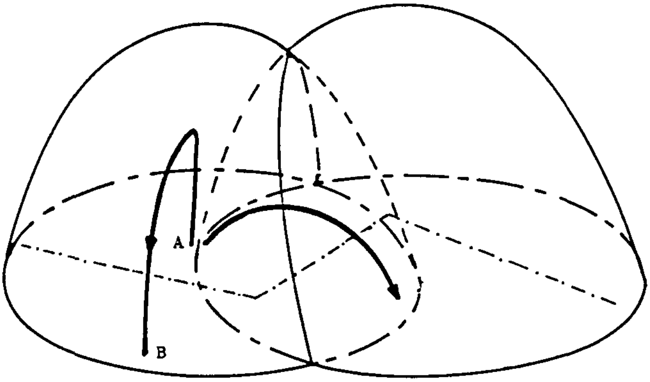

FIGURE II Schematic representation of the discontinuous change of connectivity expected when a field line foot is crossing a separatrix in a magnetic topology where the separator has emerged from the photosphere.

pearance and shift of neutral points along the separator were studied by these authors (see also Molodenskii and Syrovatskii, 1977).

LOCATION OF THE SEPARATRICES IN ACTIVE REGIONS

Methods to find the separator in active regions

There are three known main methods to find the separator location in the observed magnetic field topology of an active region.

1 - The first method is based on the discontinuous change of connectivity of magnetic field lines from one side of a separatrix to the other. Then, when crossing a separatrix a continuous change in the position of one end A of a field line leads to a discontinuous jump of the location of the other end B, where A and B are the intersections of the field line with the photospheric plane (see Fig. II). One of us (P.D.) is building a numerical computer code based on this property which would allow a direct use of any measured photospheric magnetic field. The discontinuous jump arises both from the presence of a separator above the photosphere and from the existence of field lines tangent to it.

2 - There may be situations were the magnetic field topology is such that some field lines are just tangent to the photospheric plane. Then, in the region of contact, the field lines do not rise from the positive polarity to the negative one, and the transverse field is directed from negative to positive polarity (Seehafer 1985a,b, 1986). Seehafer used this property to find the location of the separatrices associated with a δ configuration. The magnetic field of the active region was represented by a linear force-free field ($\nabla \times \underline{B} = \alpha \underline{B}$). A continuous change of the parameter α was observed to lead to a discontinuous change of the field lines connectivity. It is worth noting that this method is a particuliar case of method 1.

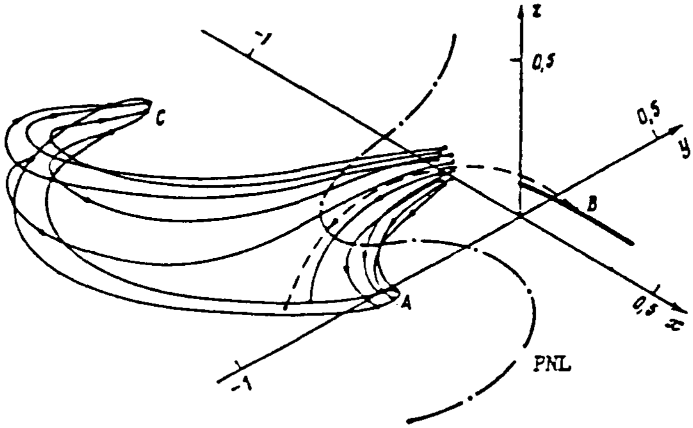

FIGURE III Field lines originating from a small region near the separator are found to end into the flare ribbons of November 5, 1980 flare (only field lines ending on one ribbon (over four) are shown). Figure taken from Gorbachev and Somov (19898)

3 - An easier method is based on the observed field line convergence to subphotospheric layers. The geometrical properties of field lines can be described by the location of the well confined subphotospheric sources where they converge. These sources can be represented as well by magnetic charges or by dipoles with vertical axis (the two representations give the same answer when a great number of sources are used). The definition of the field lines connectivity is straigthforward when the number of sources equal the number of observed polarities. However a good representation of the observed field requires usually a higher number of localised subphotospheric sources, and the connectivities are then defined by groups of sources. This method is well suited to begin a topological study of the observed complex regions (because the separatrices are closed surfaces, the topological cells are well defined). At the limit of infinitly concentrated photospheric fields, this method gives the same answer as method 1.

In the dipole representation the total field is given by:

$$\underline{B}(\underline{R}) = \sum_{i=1}^{N} \Phi_i \underline{B}_i(\underline{R}),$$

where N is the number of dipoles $\underline{B}_i(\underline{R})$ is the magnetic field created at the location $\underline{R}$ by the dipole i with unit flux ($\Phi_i = 1.$) located at X_i, Y_i, Z_i. In the charge representation

$$\underline{B}(\underline{R}) = \sum_{i=1}^{N} q_i \underline{R}/R^3,$$

where N is then the number of charges. The depth Z_i is estimated by the size of the field concentration.

A numerical code was developed by P. Démoulin where the intensity of the dipoles (Φ_i) or charges (q_i) are computed by using a least square method

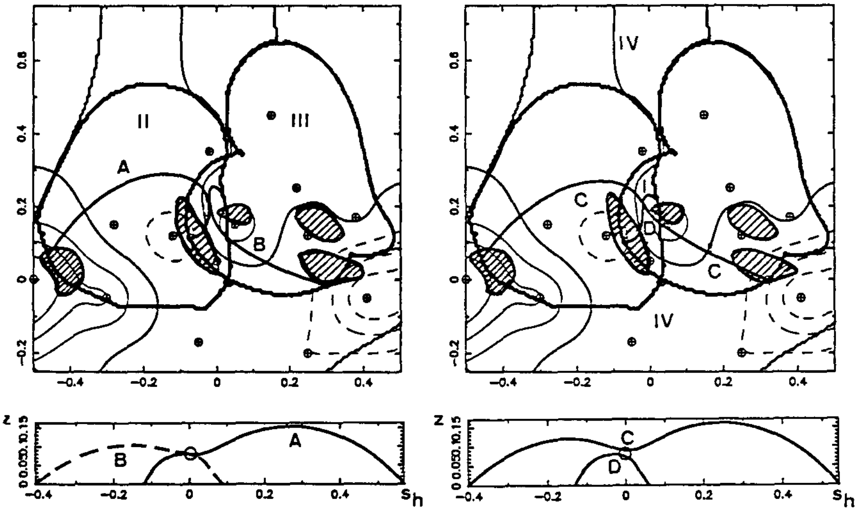

FIGURE IV In some part of the separator region, field lines in each of the four connectivity cells end in the off-band Hα kernels. Two pairs of field lines in two opposite connectivity cells have been selected and are shown here. The bottom curves show the height versus the projection on the horizontal plane of the distance along the field line from the starting point near the separator (taken from Mandrini *et al.* 1991).

minimizing the difference between the observed longitudinal field and the vertical component $\underline{B}_Z(\underline{R})$. At various heights and at any pixel in the horizontal plane, the computer code integrates numerically the differential equation defining a field line towards both ends. The connectivity of the running pixel, and therefore its affiliation to a circumscribed connectivity cell, is defined by the magnetic sources found at its ends. The size of the mesh is first chosen in order to identify all possible connectivities with a small number of pixels; then the mesh size is made smaller between pixels of different connectivity. The process is repeated until an adequate spatial resolution is obtained. More details on the 3D representation of the magnetic topology by potential or force-free fields using charges or dipoles are given in Démoulin *et al.* (1992).

Chromospheric flare location relatively to separatrices and separator

Gorbachev and Somov (1988, 1989) modelled the magnetic field of active region NOAA 2776 by the potential field of four point charges located below the photosphere. The magnitude and location of each charge were chosen in order to represent the main features of the magnetogram. As illustrated in Fig. III the field lines originating from a small region near the separator were found to end in the Hα ribbons of the November 5, 1980 flare.

Using vector-magnetograms taken at the Marshall Space Flight Center, Mandrini *et al.* (1991, 1993) studied active region NOAA 2372 during a fraction of its disk transit, from April 6 to April 8, 1980. The observed magnetic field was modelled by the potential field of dipoles with vertical axis, and the

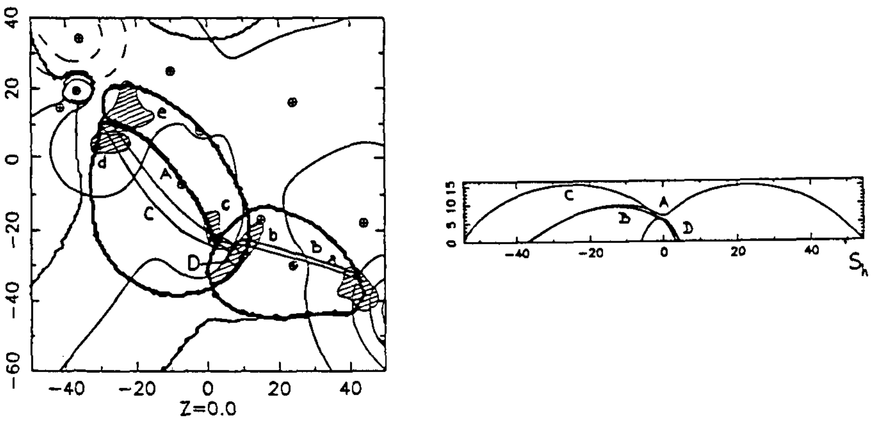

FIGURE V Location of the Hα kernels of a flare observed on April 7, 1980 relatively to the separatrices and their magnetic link. Field line A joins kernels **a** to **e**, B joins **a** to **b**, C joins **c** to **d**, and D joins **b** to **c** (taken from Mandrini *et al.* 1993).

intersections of the separatrices with various horizontal planes were derived following the method described in the preceeding subsection. Then the location of the separator was found by its intersections with selected horizontal planes. On April 6, four of the five off-band Hα kernels of a flare that occured less than twenty minutes before obtaining the magnetogram were found to be localised on the separatrices. Moreover, as shown in Fig. IV, these kernels are linked by magnetic field lines that all pass in a same small region near the separator.

The extension of the analysis of the magnetic topology of the active region to the 7 and 8 April, 1980 confirms these results. Two flares were observed before the corresponding magnetograms were taken. A second parasitic bipole in a δ configuration was present creating new separatrices. The five Hα kernels of the flares are all found on the separatrices. As on April 6, a region around a fraction of the separator is magnetically connected to the kernels (see Fig. V). The main features of the magnetic topology are due to the presence of a bipole 3,4 in a δ configuration inside a bipole 1,2. From the 6 to the 8 of April, the magnetic flux in regions 3 and 4 decreased and the distance between magnetic regions 1 and 2 increased. This topological evolution corresponds to line-dipoles being pulled apart from each other and is therefore favourable to the reconnection of the field lines inside cell 3-4 with the field lines inside cell 1-2. Since the Hα kernels are expected to be located at the feet of reconnected field lines and since the magnetograms used were obtained after flare occurence, they must be found inside cells 1-4 and 2-3 (see Fig. VI). That is the case, the Hα kernels are observed to extend from the separatrices to the inside of cells 1-4 and 2-3 supporting the hypothesis of magnetic reconnection taking place on the separator region.

Recently Démoulin *et al.* (1993) studied the more complex magnetic topology of active regions NOAA 2511 and 2512 where flares were observed from June

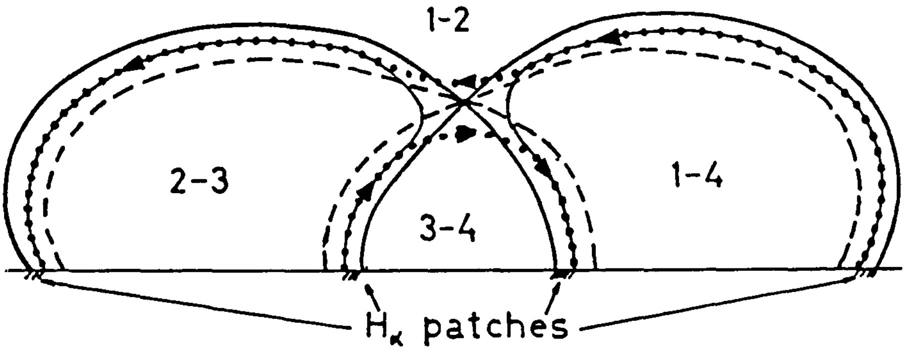

FIGURE VI Scheme of the reconnection process taking place in 6,7 and 8 April flares as suggested in Mandrini *et al.* (1993). The field lines from cells 1-2 and 3-4 (dotted lines with arrows) reconnect, and become part (full lines with arrows) of cells 1-4 and 2-3. Accordingly, the separatrices move from a position indicated by dashed lines to a one indicated by a full line. The Hα kernels are then expected to be located on the border of the separatrices inside the cells 1-4 and 2-3 (because the magnetogram was taken after the flare).

13 to June 15. The magnetic field was modelled by an ensemble of charges and the locations of the separatrices were computed. Despite the complexity of the magnetic topology, in all the flares reported in AR 2511, the flare kernels were found to be close to or on the separatrices (Fig. VII). Flares occured although the emerging bipole was almost parallel to the main bipole. The authors pointed out that a separator was present. On the other hand there were cases where the emergence of a parasitic bipole of opposite polarity to the main bipole did not produce any flaring. The separatrix surrounding the parasitic polarity did not intersect with another separatrix; this leads to the interpretation that the inactivity of the parasitic polarity was due to the absence of a separator.

Rôle of the DC currents

Hagyard (1987) calculated the line of sight component of the current densities in AR on April 6. Lin and Gaizauskas (1987) then find a close correspondence between chromospheric flare kernels and the site of strong currents. The current densities on April 7 and 8 were computed by Wilkinson (see Wilkinson *et al.* 1992, Mandrini *et al.* 1993). In bipole 3,4 the currents persist from April 6 to April 8 (Fig. VIII). They are located near separatrices and overlap partially with Hα intense kernels. The other current system changed dramatically from April 6 to 8 and was not located near a separatrix (this current system may be due to the effect of Faraday rotation, Wilkinson *et al.* 1992). Therefore currents in cell 3-4 are natural candidates to store magnetic energy. As seen precedently, both the time evolution of the active region magnetic topology and the location of the Hα kernels relatively to the separatrices sustains the hypothesis that field lines in cell 3-4 reconnect with field lines in cell 1-2. This also suggests that some

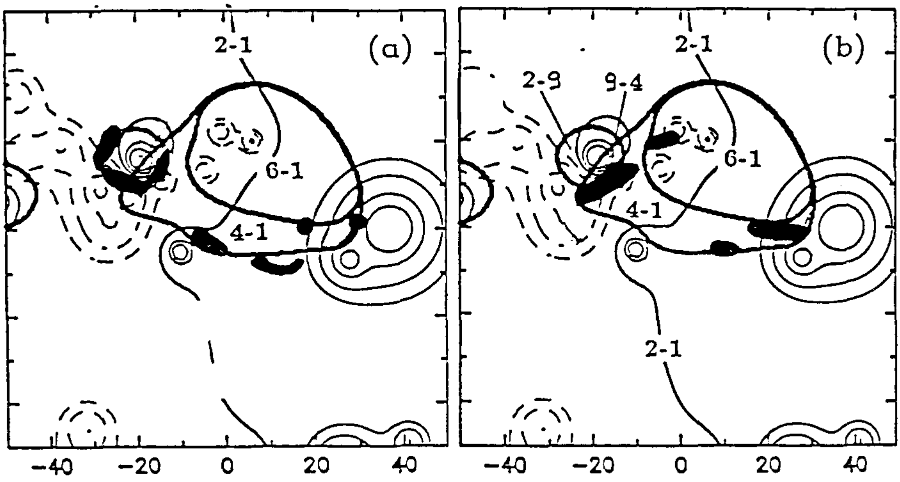

FIGURE VII Chromospheric flares on 13 June 1980 in AR 2511 are located on the separatrices. a : 14:14 UT flare; b : 6:23, 7:31 and 12:23 UT flares. Note the disymmetry of the nergy release in these eruptions. (from Démoulin *et al.* 1993).

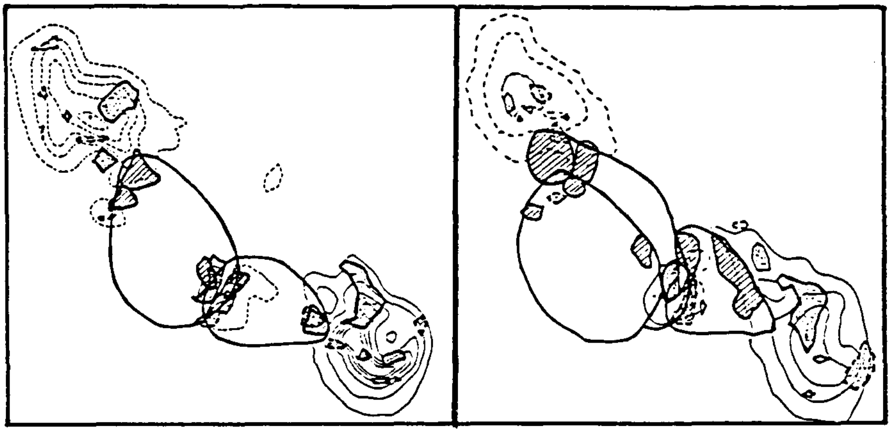

FIGURE VIII Maps of the line of sight component of the current density on April 7 and 8. Strong current densities are principally present on the main parasitic bipole in the connectivity cell 3-4 (Mandrini *et al.* 1993) fraction of the currents flowing in cell 3-4 is interrupted by the reconnection process and feed energetically the flares.

DISCUSSION AND CONCLUSION

An increasing number of investigations clearly relates the location of chromospheric flares with the topological features of the overall magnetic field of the active region. Chromospheric Hα kernels are found on the separatrices and, in the few cases where their link with a separator were searched for, this link was found: Hα kernels are magnetically connected to a common region near the separator. Moreover, the presence of a separator seems to be a necessary condition for flare occurence. Since reconnection is expected to take place in the separator region, this strongly suggests that reconnection takes place in solar flares. This hypothesis is also supported by both the evolution of the magnetic topology in AR NOAA 2372 from April 6 to April 8 and the location of observed flare Hα kernels.

Hénoux and Somov (1987) suggested that the energy stored in DC currents is released by magnetic reconnection. The few observations of the longitudinal current density in AR 2372 qualitatively agree with this hypothesis. Only a fraction of the separator is magnetically linked to the flare kernels. This can be interpreted in two ways: either reconnection is limited to some regions of the separator depending on the magnitude of the field along the separator (null points or weaker field ?) or reconnection takes place in a more extended part of the separator and the dominant energy release process is then limited to regions where currents flow along field lines. This question can be partially solved by a study of the variation of the magnetic field along the separator.

The results presented in this paper are based on a potential representation of the magnetic field. The main features of the separatrices are reproduced since the differences with a linear force-free field model with a reasonable α value are small (Démoulin *et al.* 1992). However, the currents appear localized and the modelling will be improved by taking into account the current localization. More work, both theoritical and observational, has still to be done. To confirm that a necessary condition for flare occurence is the appearence of a separator, the time evolution of the magnetic topology of active regions has to be studied in detail. The increasing number of vector-magnetographs in use and the improvement of the data acquisition and data handling systems will presumably lead to a systematic research of separators in active regions for flare prediction. Still more theoritical work is needed to understand how reconnection could release the energy stored in current systems in the complex observed geometry.

REFERENCES

Alfvèn, H. and Carlqvist, P., 1967, *Solar Phys.*, **1**, 220

Baum, P.J. and Brathenal,A., 1980,*Solar Phys.*, **67**, 245

Démoulin, P., Hénoux, J.C. and Mandrini, C.H., 1992, *Solar Phys.*, **139**, 105

Démoulin, P., van Driel-Gesztelyi,L., Schmieder, B., Hénoux, J.C., Csepura, G. and Hagyard, M.J., 1993, *A&A*, in press

Gorbachev, V.S., Kel'ner, S.R., Somov, B.V. and Shvarts, A.S., 1988, *Sov. Astron*, **32**,3, 308

Gorbachev, V.S. and Somov, B.V., 1988, *Solar Phys.*, **117**, 77

Gorbachev, V.S. and Somov, B.V., 1989, *Sov. Astron*, **33**, 57

Hagyard, M.J., 1987, *Solar Phys.*, **107**, 239

Hénoux, J.C. and Somov, B.V., 1987, *A&A*, **185**, 306

Khan, J.I., 1989, *Proc. Astron. Soc. Australia*, **8**, 29

Kundu, M., 1986, *Adv. Space Res.*, **6**, 53

Lau, Y.T. and Finn, J.M., 1990, *Ap.J.*, **350**, 672

Lin, R.P. and Schwartz, R.A., 1987, *Ap.J.*, **312**, 462

Lin, Y. and Gaizauskas, V., 1987, *Solar Phys.*, **109**, 81

Machado, M.E., Somov, B.V., Rovira, M.G. and de Jager, C., 1985, *Solar Phys.*, **85**, 157

Machado, M.E., Moore, R.L., Hernandez, A.M., Rovira, M.G., Hagyard, M.J. and Smith, J.B.Jr., 1988, *Ap.J.*, **326**, 425

Molodenskii, M.M. and Syrovatskii, S.I., 1977, *Sov. Astron*, 21, 734

Mandrini, C.H., Démoulin, P., Hénoux, J.C. and Machado, M.E., 1991, *A&A*, **250**, 541

Mandrini, C.H., Rovira, M.G., Démoulin, P., Hénoux, J.C., Machado, M.E. and Wilkinson, L.K., 1993, *A&A*, submitted

Pallavicini, R., 1991, *Phil. Trans. Roy. Soc. Lond.*, **A**, **336**, 389

Priest, E.R., 1991, *Phil. Trans. Roy. Soc. Lond.*, A, **336**, 363

Seehafer, N., 1985a, *Solar Phys.*, **96**, 307

Seehafer, N., 1985b, *Astron. Nachr.*, **306**, 193

Seehafer, N., 1986, *Solar Phys.*, **105**, 223

Sweet, P.A., 1958, *Nuovo Cimento Suppl.*, **8**, Ser. X, 188

Sweet, P.A., 1969, *An. Rev. Astron. Ap.*, **7**, 149

Syrovatskii, S.I., 1981, *An. Rev. Astron. Ap.*, **19**, 163

Wilkinson, L.K., Emslie, A.G. and Gary, G.A., 1992, *Ap.J. Lett.*, **392**, L39

Wingley, R.M., Kiplinger, A.L., Zarro, D.M., Dulk, G.A. and Lemen, J.R., 1991a, *Ap.J.*, **375**, 366

Wingley, R.M., Dulk, G.A., Bornmann, P.L. and Brown, J.C., 1991b, *Ap.J.*, **375**, 382

Zaitsev, V.V. and Stepanov, A.V., 1992, *Solar Phys.*, **139**, 343