LOSS OF MAGNETIC TENSION IN PRE-FLARE MAGNETIC CONFIGURATIONS

P. VENKATAKRISHNAN

Indian Institute of Astrophysics, Bangalore 560034, India

(Received 1 January 1989; in revised form 2 March, 1990)

Abstract. We demonstrate that magnetic tension vanishes at regions of large magnetic 'shear' on the polarity inversion line. The characteristics of these tension-free fields depend on the density of the medium and, therefore, change as a consequence of instabilities which modify the density. These instabilities may possibly evolve into solar flares. We suggest this as a possible explanation for the observed occurrence of flares at locations of large magnetic shear along the polarity inversion line.

1. Introduction

Flares are believed to be fuelled by the free energy stored in non-potential magnetic fields. In the case of the great flare of August 7, 1972 (Zirin and Tanaka, 1973), the Hα structures appear to be aligned along the polarity inversion line before the flare. Later on, the new loops, formed at greater heights, made larger angles to the inversion line. This was interpreted as either the relaxation of the shear in the field or the existence of a vertical gradient in this shear (Švestka, 1981).

With the availability of vector magnetograms, the magnetic 'shear' of the field can be evaluated in terms of the angular deviation of the observed transverse field vector from a 'potential' transverse field (Hagyard *et al.*, 1984). This 'potential' field is calculated solving Laplace's equation for the scalar potential and using the measured values of the line-of-sight component of the magnetic field as the boundary conditions. For four major flares, it turned out that the sites of flare onset coincided with positions of strong transverse field on the polarity inversion line, where magnetic shear was a maximum (Hagyard *et al.*, 1984; Hagyard and Rabin, 1986; Hagyard, Venkatakrishnan, and Smith, 1989).

In this paper, we demonstrate that the downward magnetic tension vanishes at these sites of large magnetic shear. We also show that such a configuration can easily be modified by instabilities that alter the plasma density. These instabilities may eventually develop into flares thereby explaining why flares tend to occur at positions of large magnetic shear and strong transverse field on the polarity inversion line.

2. Magnetic Tension in Sheared Fields

The equation for magneto-hydrostatic equilibrium is

$$(\nabla \times \mathbf{B}) \times \mathbf{B}/4\pi - \nabla p + \rho \mathbf{g} = 0\,, \tag{1}$$

where $\mathbf{B}$ is the magnetic field, p is the gas pressure, ρ is the plasma density, and $\mathbf{g}$ is

Solar Physics **128:** 371–376, 1990.

the acceleration due to gravity. The vertical component of Equation (1) is

$$\mathbf{B}_T \cdot \nabla_T B_z / 4\pi - \partial(B_T^2/8\pi + p)/\partial z - \rho g = 0 \,, \tag{2}$$

where $\mathbf{B}_T$ is the transverse component of the field and $\nabla_T = (\hat{\mathbf{x}}\, \partial/\partial x,\, \hat{\mathbf{y}}\, \partial/\partial y)$ represents the transverse or lateral gradient operator, while B_z is the vertical component of the magnetic field. The first term in Equation (2) is the force due to magnetic tension. Near the polarity inversion line, the transverse field generally points from the positive to the negative polarity regions of vertical flux. Furthermore, the pattern of the isocontours of the longitudinal magnetic field in any magnetogram shows that the lateral gradient of the longitudinal field B_z is orthogonal to the polarity inversion line. Generally, the gradient of B_z in the direction of B_T is negative and the tension term in Equation (2) thus provides, along with the weight of the material ρg, a downward directed force. This is true for all 'closed' field configurations where both the foot points of the field lines are anchored in the photosphere.

The lateral gradient of the longitudinal field is generally large near flare sites. In a magnetogram of AR 4474 taken 80 min prior to the white light flare of 24 April, 1984 (Venkatakrishnan, Hagyard, and Hathaway, 1988) this gradient attains values as high as ≈ 1200 G pixel^{-1} at the flare site which translates to ≈ 0.66 G km^{-1}. The transverse field in this region is ≈ 3000 G. Had this field not been 'sheared', i.e., had this field been normal to the polarity inversion line, then the downward acceleration due to magnetic tension – obtained by dividing the product of the lateral gradient of B_z and B_T by the density – attains a value $\approx 10^4$ cm s^{-2}, for $\rho \approx 10^{-7}$ g cm^{-3}, which is comparable to the acceleration due to gravity. Assuming that such large gradients of B_z can indeed exist even for non-sheared fields, we note that the magnetic tension term is an important ingredient in the balance of forces even at the photosphere. Since we expect the magnetic field to vary with height at a smaller rate than that of the plasma density (Spruit, 1981), the tension term for non-sheared fields would be much larger than ρg at greater heights.

If the transverse component of the magnetic field lies along the polarity inversion line, it will not have a component in the direction of the lateral gradient of the longitudinal field. The tension term is Equation (2) thus vanishes for such highly 'sheared' fields. The observation that flares tend to occur at highly sheared regions can thus be translated into the observation that flares tend to occur in regions of low magnetic tension along the polarity inversion line. In the next section we will examine the physical consequences of the loss of magnetic tension and thus arrive at an explanation for the association of flares with tension-free fields.

3. Tension-Free Fields and Solar Flare Onset

In a force-free field the tension force would cancel the magnetic pressure gradient term, reducing Equation (2) to that of hydrostatic equilibrium. In this case the plasma pressure scale height would be independent of the scale height of the magnetic field. For tension-free fields, Equation (2) reduces to

$$\partial/\partial z(B_T^2/8\pi + p) = \rho g . \qquad (3)$$

The field of Equation (3), however, cannot be force-free. In a non-force-free field the transition from a situation where the tension term is non-zero to the equilibrium governed by Equation (3) depends on the ratio between the magnetic and the plasma pressure scale height. If originally the magnetic scale height was smaller than the pressure scale height, then the magnetic scale height has to increase to compensate for the vanishing of the tension force. On the other hand, if the magnetic scale height was larger than the pressure scale height, then the loss of tension would not change the magnetic scale height. In either case, the final tension free equilibrium would have a large magnetic scale height which depends on the density of the plasma. A corollary of the above arguments is that tension cannot completely vanish in a very low beta plasma, because the scale height of the total magnetic + plasma pressure variation is then likely to be much larger than the plasma pressure scale height (as given, for instance, by its isothermal value $kT/\mu g$).

Consider now the onset of an instability, like the thermal instability initiated by enhanced heating, which decreases the plasma density. As a consequence, the density term will decrease, and this will require a similar decrease of the left-hand term of Equation (3), possibly to be reached via vertical stretching of atmosphere and magnetic field. A field line 'extension' may trigger a further density decrease, as plasma flows along the stretched field lines. It could thus happen that the change in density at lower heights creates, at higher levels, a magnetic pressure gradient larger than that which can be balanced by the total magnetic tension available there. A possible scenario for this non-equilibrium situation implies a rapid re-arrangement of the magnetic field which in turn will promote the centrifugal acceleration of plasma along the field lines (cf. Hasan and Venkatakrishnan, 1980; Venkatakrishnan, 1984a, b) eventually leading to the formation of shocks. These shocks can cause heating and particle acceleration, manifesting as a solar flare. Alternatively the changing magnetic field can induce electric fields that can be tapped for particle acceleration (Colgate, 1978).

The above scenario suggests a dynamical means of converting the non-potential energy of the magnetic field into kinetic and thermal energy of the plasma.

The observation that flares are initiated at the positions of maximum shear will then imply that the above scenario will be effective only at regions of extremely low tension. A further question then arises as to why some regions with a shear as large as that in the flare producing regions, do not flare (cf. Hagyard and Rabin, 1986). A possible criterion for discriminating between these two types of sheared regions could be the vertical gradient of shear. Configurations with a steeper decrease of shear with height would become completely force-free at lower heights than those with a more gradual vertical decrease of shear. The undisturbed transverse field component at the level where tension becomes once again dominant would thus be larger than in the case where the shear extends to great heights. In order to reach this conclusion, we made the assumption that the transverse component of the field decreases with height. We deem this a not unreasonable assumption for typical magnetic arcades spanning the polarity inversion line. Thus, when expanding in response to a decrease in the plasma density, configurations with a steeper vertical decrease of the shear will have, at the higher unsheared levels, a larger magnetic tension and, therefore, will be capable of balancing the pressure of the lower sheared regions. These more compact structures will hence have a better chance of maintaining their equilibrium and thus will be less likely to flare.

Even if two configurations had the same gradient of shear, an evolving magnetic region has more chance of being affected by thermal instabilities than a quiescent region because of the increased probability of enhanced heating produced by reconnection between the evolving magnetic field and the pre-existing magnetic arcade. The activation of filaments before flares, apparently initiated by the local emergence of new flux (Rust, 1976), seems to be a manifestation of this process.

4. Discussion and Conclusions

We showed that magnetic tension vanishes at regions of large magnetic 'shear' on the polarity inversion line and that the resulting tension-free equilibrium, being non force-free, will depend on the plasma density. This in turn makes such configurations more likely to be affected by instabilities that change the density. We also suggested how such instabilities might possibly lead to a solar flare.

The present interpretation of magnetic 'shear' in terms of tension reduces the importance of comparing the transverse field with a 'potential' field for predicting local effects. This should come as a relief to observers since calculating a consistent potential field has many theoretical (Sakurai, 1982) as well as practical (Venkatakrishnan and Gary, 1989) difficulties. In fact, local non-potentiality has no rigorous basis since the quantities like free energy are meaningful only in the global sense (Molodensky, 1974; Low, 1982). A comparison with potential configurations would, in principle, allow one to estimate only the amount of free energy available for flaring and not the probability or exact location of the flare. In practice, the errors in the energy estimates resulting from the errors of measurement become comparable to the value of the energy released in single flares (Gary *et al.*, 1987), thus making predictions for individual flares very uncertain.

In contrast, empirical parameters like magnetic 'shear' have been more successfully related to individual flares. This paper attempts to provide a physical interpretation for such empirical correlations on the basis of tension-free magnetic fields. It is hoped that direct evaluation of the vertical tension force from vector magnetograms will afford a clearer picture of the pre-flare state. In particular, one can look at maps of magnetic tension for possible differences in the pattern of shear between flaring and non-flaring sheared fields. Modelling of the 3-D field could perhaps yield estimates of the vertical gradient of tension based on the observed lateral gradient of tension.

We have neither presented quantitative models for the tension-free equilibria nor demonstrated their instability. Solutions to these problems are beyond the scope of the present work. In this paper our main result was the identification of the tension-free state of the field as the one that most probably resembles the observed field at flare sites. We concede that the force-free approximation is indeed the correct one on global or active region scales on account of the low plasma β in chromospheric and coronal plasmas. However, in the crucial sites where flare onset is seen, the vector magnetograms reveal a state that can be affected by instabilities that change the plasma density. In the global force-free field these tension-free states could well provide the 'weak spots' that trigger eruption of this field. Explicit demonstration of the mechanism that causes eruption of, or non-equilibrium in, a force-free field has eluded researchers so far. In fact, Zwingmann (1987) has shown that merely increasing the shear by footpoint evolution does not lead to bifurcations or catastrophes. Likewise, Finn and Chen (1988) have shown that specifying the entropy does not lead to non-equilibrium, while specifying the pressure might not be a realistic procedure to search for field eruptions. A 'hybrid' model, which is tension free at lower heights and force-free at larger heights, might hold better promise in this context.

Future theoretical work clearly lies in trying to construct such hybrid models, using vector magnetograms as a constraint.

Finally, a word about active region prominences or filaments. The conventional models for prominences, in general, rely on the upward directed tension-force as the support mechanism. This upward directed force results from a curvature of field lines that is convex towards the photosphere. In the Kippenhahn and Schlüter (1957) model this curvature is produced by a local dip in the global field configuration, while in the Kuperus and Raadu (1974) model, it is produced by reconnection in a current sheet at a magnetic singularity of the field. The tension-free field discussed in this paper provides yet another support mechanism due to the upward magnetic pressure gradient (see also Low, 1984, for several relevant references). At large heights, the low plasma β prevents the tension from completely vanishing. Here, a small predominance of the magnetic pressure gradient over the tension could perhaps support the prominence. The fact that filaments form by alignment of fibrils along the polarity inversion line (Zirin, 1979) could be invoked as evidence for this mechanism. At the same time, since highly sheared fibrils cannot exist under conditions of low plasma beta, these structures must be either low lying or dense structures. Filaments and flares seem to be intimately related (Švestka, 1976; Kahler *et al.*, 1988) and thus modelling 'hybrid' magnetostatic equilibria may lead to a unified interpretation of filament support as well as its disruption.

Acknowledgements

This paper was possible because of the author's exposure to solar vector magnetic data during his tenure as a NAS–NRC Resident Research Associate at NASA/MSFC. The author appreciates the criticisms of the referee on the first version of the paper as well as his/her substantial help in rewriting the second version.

References

Colgate, S. R.: 1978, *Astrophys. J.* **221**, 1068.
Finn, J. M. and Chen, J.: 1988, NRL Memorandum Report 6402.
Gary, G. A., Moore, R. L., Hagyard, M. J., and Haisch, B. M.: 1987, *Astrophys. J.* **314**, 782.
Hagyard, M. J. and Rabin, D. M.: 1986, *Adv. Space. Res.* **6**, 7.
Hagyard, M. J., Venkatakrishnan, P., and Smith, J. B., Jr.: 1989, *Astrophys. J. Suppl. Ser.* (in press).
Hagyard, M. J., Smith, J. B., Jr., Teuber, D., and West, E. A.: 1984, *Solar Phys.* **91**, 115.
Hasan, S. S. and Venkatakrishnan, P.: 1980, *Kodaikanal Obs. Bull. Ser.* **A3**, 6.
Kahler, S. W., Moore, R. L., Kane, S. R., and Zirin, H.: 1988, *Astrophys. J.* **328**, 824.
Kippenhahn, R. and Schlüter, A.: 1957, *Z. Astrophys.* **43**, 36.
Kuperus, M. and Raadu, M. A.: 1974, *Astron. Astrophys.* **31**, 189.
Low, B. C.: 1982, *Solar Phys.* **77**, 43.
Low, B. C.: 1984, in M. J. Hagyard (ed.), *Measurements of Solar Vector Magnetic Fields,* NASA CP-2374, p. 49.
Molodensky, M. M.: 1974, *Solar Phys.* **39**, 393.
Rust, D. M.: 1976, *Phil. Trans. Roy. Soc. London* **A281**, 427.
Sakurai, T.: 1982, *Solar Phys.* **76**, 310.
Spruit, H. C.: 1981, in S. Jordan (ed.), *The Sun as a Star*, NASA SP-450, p. 385.
Švestka, Z.: 1976, in *Solar Flares*, D. Reidel Publ. Co., Dordrecht, Holland, p. 220.
Švestka, Z.: 1981, in E. R. Priest (ed.), *Solar Flare Magnetohydrodynamics*, Gordon and Breach, New York, p. 47.
Venkatakrishnan, P.: 1984a, Ph.D. Thesis, Bangalore University.
Venkatakrishnan, P.: 1984b, *Kodaikanal Obs. Bull.* **4**, 19.
Venkatakrishnan, P. and Gary, G. A.: 1989, *Solar Phys.* **120**, 235.
Venkatakrishnan, P., Hagyard, M. J., and Hathaway, D. H.: 1988, *Solar Phys.* **115**, 88.
Zirin, H.: 1979, in E. Jensen, P. Maltby, and E. Q. Orall (eds.), 'Physics of Solar Prominences', *IAU Colloq.* **44**, 193.
Zirin, H. and Tanaka, K.: 1973, *Solar Phys.* **32**, 173.
Zwingmann, W.: 1987, *Solar Phys.* **111**, 309.