FULL TITLE
*ASP Conference Series, Vol. **VOLUME**, **YEAR OF PUBLICATION***
NAMES OF EDITORS

Flare Energy and Magnetic Field Variations

H. S. Hudson,[1], G. H. Fisher,[1] B. T. Welsch[1]

Abstract. We describe ways in which the photospheric vector magnetic field might vary across the duration of a solar flare or CME. We also quantitatively assess the back reaction on the photosphere and solar interior by the coronal field evolution required to release flare energy. Our estimates suggest that the work done by Lorentz forces in this back reaction could supply enough energy to explain observations of flare-driven seismic waves.

1. Introduction

The dynamo that drives the solar cycle probably lies near the base of the convection zone. Magnetic field created in this region then ascends through the photosphere and emerges into the corona. The emerged flux contains embedded stresses that may accumulate for some period of time and then relax catastrophically, producing a flare and/or a CME (coronal mass ejection). Many problems exist in our understanding of these developments, especially during the disruption itself. However the solar corona normally is nearly force-free, and the flare/CME development has relatively clearly-defined states before and after the event. In recent years it has become increasingly clear that these two states have different photospheric magnetic signatures. Sudol & Harvey (2005) describe the line-of-sight field changes as observed by solar magnetographs during this process; this paper systematizes the discoveries of these stepwise changes by Wang (1992) and Cameron & Sammis (1999), and most directly by Kosovichev & Zharkova (1999). Figure 1 shows perhaps the first clear example of such an effect.

The coronal field changes reflect the energy stored there as a result of currents injected through the photosphere (Melrose 1995; Longcope & Welsch 2000; Green et al. 2002; Schrijver 2007). Currents produced *inductively* by photospheric motions, however, can also close above the photosphere; Longcope, 1996.

The behavior of the fields linking the interior and exterior of the sun, especially during flux emergence, is the subject of much current analysis and simulation (e.g., Fan 2004). In this paper we discuss two aspects of this linkage, for flares, that follow pioneering discussions by A. N. McClymont (McClymont & Fisher 1989; Anwar et al. 1993). These deal respectively with the sources of the stressed (non-potential) coronal fields (our Section 2) and the back-reaction of coronal magnetic reconfigurations on the solar interior (our Section 3). We also discuss predictions of the vector field changes analogous to the line-of-sight field

---

[1] SSL, UC Berkeley, 7 Gauss Way, Berkeley CA 04720-7450

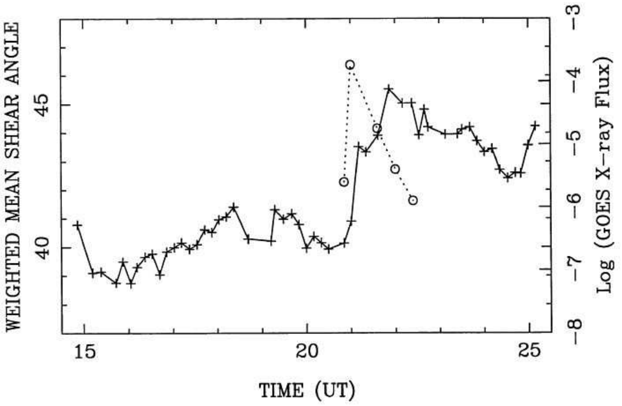

Figure 1. Perhaps the first clear illustration of a flare-associated magnetic field change (Wang 1992). Here the data represent an empirical measure of the shear in the photospheric field, and the dotted line shows the soft X-ray light curve of the flare. Note the stepwise change.

changes described by Sudol & Harvey (2005), which we feel may be observable in the vector magnetograms of *Hinode* or ground-based instruments.

The excitation of seismic waves by powerful impulsive flares (Kosovichev & Zharkova 1998) is a direct (and dramatic) linkage between coronal and sub-photospheric processes. Section 3 analyzes an alternative idea for the coupling of flare energy into a seismic wave, namely the magnetic "jerk" produced by the coronal restructuring; previous explanations center on the pressure pulse resulting from particle heating.

2. Origins of flare-related fields

The magnetic field permeating the corona arises in an poorly understood manner from the interior. Active regions represent intensifications of the coronal field via a process observationally known as "flux emergence"; see Harvey (1993) for an overview of the general observational state of solar photospheric magnetism. The stressed (current-carrying) magnetic fields appearing in the corona do not immediately relax into an unstressed state, but instead build up energy and wait to relax until a specific condition has been met. A flare and/or CME reduces the stress suddenly. We cannot yet identify the specific condition needed for this development, but Schrijver (2007) notes that the build-up phase may last for as much as a day in an active region. Observations suggest that it can be much longer in the quiet Sun and in decayed active regions, where filaments can exist for many days before erupting in a CME (e.g., Hudson et al. 1999).

3. Back reaction of coronal restructuring

The release of energy from the coronal magnetic field necessarily requires its restructuring. The observed stepwise changes in the photospheric field can be understood in this context, for example as tilts of the line-tied field. The line-tying of the pre-flare field implies an equilibrium force balance, which changes only slowly during the build-up phase of coronal magnetic energy storage. The release of coronal energy implies a sudden disruption of this force balance, which results in an acceleration of the photospheric material. In this section we describe this action with a simple model, which we use to estimate the energy deposited in the subphotospheric layers in this back-reaction. We dub this a "McClymont jerk" from the estimate by A. N. McClymont reported in Anwar et al. (1993). We compare the resulting motions with those necessary to launch a seismic wave, as first observed by Kosovichev & Zharkova (1998).

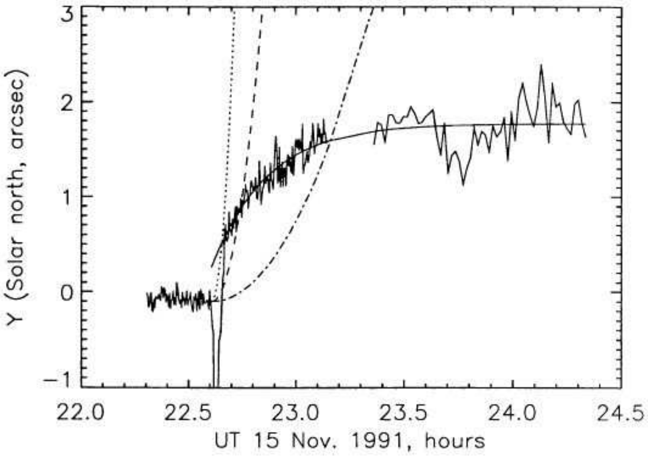

Figure 2. The observed displacement (jagged line) of a sunspot around the time of an X-class flare, based on *Yohkoh* white-light images (Anwar et al. 1993). The data suggest a northward step of about 0.7 arc sec during the 4 min of the flare impulsive phase. The solid curve shows the fit of an exponential decay toward the final position (with a decay time of 15 min), and the other curves show different *ad hoc* acceleration profiles.

As an MHD wave, a sudden change would be represented as either an Alfvén-mode or a fast-mode wave (see e.g. Roberts et al. (1984) for background information). Alfvén-mode energy will be reflected because of the sharp gradient in physical conditions separating the corona and the photosphere; Emslie & Sturrock (1982) estimate a transmitted energy fraction T_E given by $T_E = 4\Theta^{1/2}/(\Theta^{1/2}+1)^2$ for the transmitted energy fraction, where Θ is equivalent to the corona/photosphere temperature ratio across the boundary. For $\Theta \sim 200$, $T_E = 0.25$, so a considerable fraction of the wave energy penetrates to the photosphere and can perturb the magnetic field there. Observationally, it is clear from the Sudol & Harvey observations that the field distortion eventually penetrates to the photosphere.

The penetration of the wave into the interior depends in detail upon its spatial structure, about which we know almost nothing. The pattern of flare energy release (the UV emission kernels) points to small spatial and temporal scales (e.g. Fletcher et al. 2004; Hudson et al. 2006). Without knowing these scales, which apparently are unresolved at present, we cannot determine how much of the transmitted energy goes into organized motion (the seismic wave) and

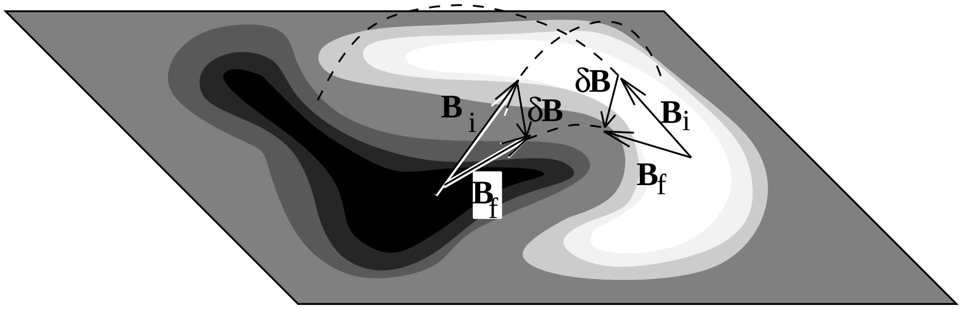

Figure 3. Sketch showing how the initial photospheric field vectors, denoted $\mathbf{B}_i$, tilt by $\delta\mathbf{B}$ as a result of coronal restructuring during a flare/CME — denoted here by changes in the connectivity of the coronal field (dashed lines) — to final states $\mathbf{B}_f$. Generally, we expect the photospheric field to become more horizontal, as depicted.

how much into broadband noise. However we can make an order-of-magnitude estimate, as McClymont did (Anwar et al. 1993), which gives an upper limit.

Given a change $\delta\mathbf{B}$ in the photospheric magnetic field, we can estimate the resulting Lorentz forces. Our analysis assumes that the photospheric plasma was in force balance before the field changes. The jth component of the Lorentz force density can be expressed as the contraction $\partial_i T_{ij}$, where T_{ij} is the Maxwell stress tensor, $T_{ij} = (2B_iB_j - \delta_{ij}B_i^2)/8\pi$. The force per unit area on the photosphere can be found by integrating the force density over the vertical coordinate z and assuming the magnetic field decays sufficiently fast as $z \to \infty$. Expanding the resulting expressions to first order in the perturbed magnetic field components δB_i gives the change in force per unit area (vertical component) as

$$\delta f_z = (B_z\delta B_z - \delta B_x B_x - B_y\delta B_y)/4\pi \ .$$

Integration over the area A over which the flare-driven field changes occur gives the total Lorentz forces on the uppermost layer of the solar envelope.

Sudol & Harvey quote median line-of-sight field changes of 90 G. They state that strong field changes typically occur in penumbrae, more often as decreases (about 2/3) rather than as increases, and their Figure 7 shows typical field strengths of 200-400 G. This suggests $|\delta B_z B_z| \sim 2 - 4 \times 10^4$ G^2. They do not quote a typical area for the region of field change, but their Figure 1 shows a matrix of magnetogram time series for 10 x 10 pixels, corresponding to an area $A \sim 3 \times 10^{18}$ cm^2 which we adopt as a first approximation.

Our estimated field perturbations correspond to a force per unit area of about 2.5×10^3 dyne cm^{-2} (∼1% of the nominal photospheric pressure). Multiplying by A gives a total force on the order of $\sim 10^{22}$ dyne. We note that the field changes reported by Sudol & Harvey (2006) exhibit spatial coherence, meaning that the integration over area required to derive this result is plausible. If the Lorentz force displaces the photosphere by ~ 3 km (Kosovichev & Zharkova 1998), then the work done would be $W \sim 3 \times 10^{27}$ erg. This is comparable to the wave energy estimated by Donea et al. (2006) for an M9.5 event or by Moradi et al. (2007) for an X1.2, so this mechanism provides an alternative to the excitation mechanism originally (pressure pulse induced by particle heating) proposed by Kosovichev & Zharkova (1998). Distinguishing these two mechanisms observationally may prove difficult.

We think that f_z must usually be negative. This is guaranteed if: (1) δB_z is antiparallel to B_z, and (2) $\delta \mathbf{B}_h \cdot \mathbf{B}_h > 0$. But $f_z > 0$ is also possible if one of these conditions is violated. As Hudson (2000) has noted, the decrease in coronal magnetic energy required to drive a flare should lead the coronal magnetic field to contract, in an "implosion." Loosely, we expect that field in the photosphere should become "more horizontal," as a result of this contraction. This suggests that conditions (1) and (2) could easily be satisfied.

4. Predictions for vector field changes

The stepwise line-of-sight field variations observed for essentially all X-class flares have a natural interpretation in terms of the horizontal component of the vector field, i.e. they represent tilts of the overall field structure. Such tilts would be expected from the need for the coronal field to undergo a drastic convulsion as energy is released; on simple energetic grounds this would imply an inward motion as described, for example, by Hudson (2000) or Liu et al. (2005). In most numerical simulations of flares and CMEs, the lower boundary condition assumes constant normal flux, i.e. rigorous line-tying. However a further condition would be required to preserve the vertical current, which Melrose (1995) argues must be constant across the flare energy-release time. The essential argument supporting this view is the low Alfvén speed in the photosphere, which prevents significant energy from crossing the photospheric boundary as a Poynting flux. Whether this argument is correct or not, and we note the interesting debate between Melrose and Parker on just this issue (Parker 1996; Melrose 1996), it makes a clear prediction that can easily be tested via an Ampere's law integral in an appropriate set of vector magnetograms.

We note that if $\mathbf{B} \rightarrow \mathbf{B} + \delta\mathbf{B}$ as a result of the flare, and if J_z at the photosphere remains unchanged as Melrose asserts, then $\hat{\mathbf{z}} \cdot \nabla \times \delta\mathbf{B}$ evaluated at $z = 0$ should vanish. This means $\delta\mathbf{B}$ must be potential at $z = 0$.

Another much less clear-cut prediction, of course, would be that the total coronal magnetic energy inferred from the photospheric field would diminish. This can be estimated, for example, via the magnetic virial theorem (e.g., Wheatland & Metcalf 2006). The reason for uncertainty is that the photospheric magnetic field is not force-free.

The physics of the "McClymont jerk" described in Section 3 also makes a clear qualitative prediction. The tilts of the photospheric footpoint fields must in some sense be equal and opposite if they are to agree with a post-flare field that is force-free.

5. Conclusions

The occurrence of a flare or CME provides a handle by which we can learn about the coupling of solar interior and exterior regions, at least on short time scales. We have described as best we can our understanding of the photospheric magnetic-field changes that must occur as the result of a coronal disturbance, with an eye towards predicting the forthcoming vector field observations from space-based observatories such as *Hinode* and ground-based observatories such as SOLIS, ATST, or FASR. A part of the released energy must propagate into the solar interior as a result of the large-scale forces of the large-scale coronal waves generated in the disturbance. This energy should partly go into seismic waves, as have now been observed in several flares extending down to the GOES M class. The details of this coupling are beyond the scope of this paper, but we find no problems in terms of the order of magnitude of the energy coupled, and suggest that this mechanism (the "McClymont jerk") needs to be considered as a possible source of such waves.

Many theories and numerical simulations of flares and CMEs have appeared (e.g., Forbes 2000). These should in general be consistent with the the observed photospheric field changes so clearly observable nowadays. We therefore suggest that theorists make predictions for the photospheric and coronal magnetic field changes implied by their ideas.

Acknowledgments. HSH acknowledges support from NASA under Grant NNG05GG17G for this work. GHF and BTW acknowledge the support of a NASA Heliophysics Theory Grant, NNG05G144G.

References

Anwar B., Acton L. W., Hudson H. S., Makita M., McClymont A. N., Tsuneta S., 1993, Solar Phys. 147, 287
Cameron R., Sammis I., 1999, ApJ 525, L61
Donea A.-C., Besliu-Ionescu D., Cally P. S., Lindsey C., Zharkova V. V., 2006, Solar Phys. 239, 113
Emslie A. G., Sturrock P. A., 1982, Solar Phys. 80, 99
Fan Y., 2004, Living Reviews in Solar Physics 1, 1
Fletcher L., Pollock J. A., Potts H. E., 2004, Solar Phys. 222, 279
Forbes T. G., 2000, JGR 105, 23153
Green L. M., López Fuentes M. C., Mandrini C. H., Démoulin P., Van Driel-Gesztelyi L., Culhane J. L., 2002, Solar Phys. 208, 43
Harvey K. L., 1993, Ph.D. thesis, Univ. Utrecht, (1993)
Hudson H. S., 2000, ApJ 531, L75
Hudson H. S., Acton L. W., Harvey K. L., McKenzie D. E., 1999, ApJ 513, L83
Hudson H. S., Wolfson C. J., Metcalf T. R., 2006, Solar Phys. 234, 79
Kosovichev A. G., Zharkova V. V., 1998, Nat 393, 317
Kosovichev A. G., Zharkova V. V., 1999, Solar Phys. 190, 459
Liu C., Deng N., Liu Y., Falconer D., Goode P. R., Denker C., Wang H., 2005, ApJ 622, 722
Longcope D. W., 1996, Solar Phys. 169, 91
Longcope D. W., Welsch B. T., 2000, ApJ 545, 1089
McClymont A. N., Fisher G. H., 1989, in Solar System Plasma Physics, p. 219
Melrose D. B., 1995, ApJ 451, 391
Melrose D. B., 1996, ApJ 471, 497
Moradi H., Donea A. C., Lindsey C., Besliu-Ionescu D., Cally P. S., 2007, ArXiv e-prints 704
Parker E. N., 1996, ApJ 471, 489
Roberts B., Edwin P. M., Benz A. O., 1984, ApJ 279, 857
Schrijver C. J., 2007, ApJ 655, L117
Sudol J. J., Harvey J. W., 2005, ApJ 635, 647
Wang H., 1992, Solar Phys. 140, 85
Wheatland M. S., Metcalf T. R., 2006, ApJ 636, 1151