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Flares and the Chromosphere

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The chromosphere (the link between the photosphere and the corona) plays a crucial role in flare and CME development. In analogies between flares and magnetic substorms, it is normally identified with the ionosphere, but we argue that the correspondence is not exact. Much of the important physics of this interesting region remains to be explored. We discuss chromospheric flares in the context of recent observations of white-light flares and hard X-rays as observed by TRACE and RHESSI, respectively. We interpret key features of these observations as results of the stepwise changes a flare produces in the photospheric magnetic field.

Key words: Solar flares, Solar chromosphere, Solar corona, Alfvén waves

1. Introduction

The chromosphere historically has been the origin of much of what we understand about solar flares. The reason for this was the recognition, in the 19th and early 20th centuries, of the extreme sensitivity of Hα, a strong Fraunhofer absorption line formed in the chromosphere, to solar magnetic activity. Spectroscopic observations of this line and its imaging led to exciting discoveries regarding active prominences, ejecta, flare brightenings etc. (Hale, 1930). Eventually it was realized that the original flare observation of 1859 (Carrington, 1859) was simply the tip of the iceberg, and that the entire solar atmosphere was participating in events that have now come to be defined more by their coronal X-ray emission (the GOES classification) rather than their Hα importance levels (Thomas & Teske, 1971). Research attention, indeed, has largely left the chromosphere layers in favor of coronal and even interplanetary effects (CMEs and ICMEs; see Schwenn 2007 for a recent review).

Our understanding of the chromosphere, until recently, has been limited to the "semi-empirical" models, based on 1D radiative-transfer physics. Such an approach omits dynamics except for the "microturbulence" factor and much of the interesting plasma physics; for example these models assume T$_e$ = T$_i$ everywhere. See Berlicki (2007) and Hudson (2007) for recent reviews about the flaring chromosphere, and for references to the abundant literature on this subject.

In the often-discussed but imperfect analogy between solar flares and auroral substorms, the chromosphere plays the role of the ionosphere, but these regions have substantially different properties and the detailed physics may not produce analogous effects (e.g., Haerendel 2007). On the larger scale there is also no analog of the solar wind flowing around an active-region field concentration in the solar corona, so that the convective ($\mathbf{v}\times\mathbf{B}$) electric field across the geotail does not have an appropriate analog. The presence of a highly conductive solar atmosphere *below* the chromosphere also distinguishes it from the ionosphere. Thus, although striking observational parallels between flares and aurorae have been noted by many authors (e.g., Obayashi 1975), the basic physics may be quite different in regard to causation or the dynamical development of the phenomena. In this paper we touch on flare energetics (Section 2), energy build-up (Section 3), and energy release (Section 4), attempting to use magnetospheric concepts as a guide to understanding.

2. Chromospheric flare energetics

The radiative energy of a solar flare appears mainly in the optical and UV continuum, which form in the lower solar atmosphere, most probably the chromosphere (e.g. Allred et al., 2006; Fletcher et al., 2007). This is in spite of the fact that the chromosphere itself (for this purpose, all regions of the solar atmosphere between photospheric and coronal temperatures) cannot contain sufficient energy to power a flare (see Hudson 2007 for discussion). For example, the gravitational energy contained in coronal filaments does not play a strong role in flare energization. The radiated flare energy appears in compact emission patches that our current observations do not resolve either in space or in time (Hudson et al., 2006), and Fletcher et al. (2007) have confirmed that the immediate source of the radiated energy lies in the electrons accelerated in the impulsive phase of the flare. Of this energy the chromospheric Hα component and the coronal soft X-ray component each comprise less than about 10% of the total (Thomas & Teske, 1971).

Zeeman-splitting observations (Wang 1993; Sudol & Harvey 2005) have shown convincingly that flares result in large-scale perturbations of the photospheric magnetic field (see Figure 1). This would generally be expected from any model of energy release from the coronal magnetic field, which will require restructuring in order to reduce the stored magnetic energy $\int (B^2/8\pi)dV$ (e.g., Hudson 2000), as for example with large-scale magnetic reconnection. The main contribution to the coronal magnetic energy and its stress are concentrated strongly in the lower solar atmosphere (e.g., Régnier

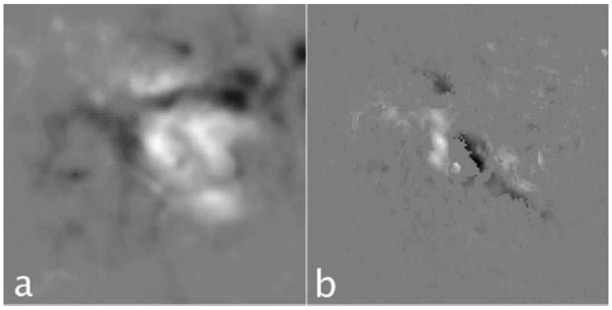

Fig. 1. GONG observations of the line-of-sight solar magnetic field prior to the X-class flare of 2003 October 29 (*Panel a*); a difference map showing flare-related changes in the field (*Panel b*); after Sudol & Harvey (2005). The field changes are of order 10% of the line-of-sight field and can be detected in essentially all X-class flares, according to Sudol & Harvey.

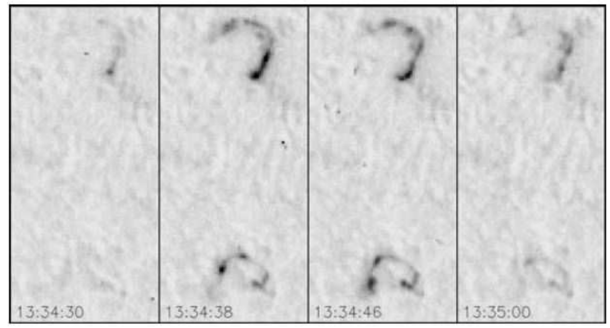

Fig. 2. Snapshots of TRACE observations (white light filter) of the C4.8 flare of 24 July 2004, showing the intermittency of the continuum emissions in both space and time. Spatial scale for each frame is $32'' \times 68''$; the times shown on the figure span 30 s (from Hudson et al. 2006).

& Priest, 2007). Thus we need a theoretical understanding of how the coronal stored energy can flow to and focus itself into the chromospheric emission regions. Heretofore this coupling has been understood as the result of beams of electrons coming from an unknown coronal acceleration site, for which there are several possibilities (e.g., Miller et al. 1997). These ideas underlie the "thick target" model for the impulsive phase of a flare, which envisions electron beams capable of transporting energy from the coronal storage site into the dissipation regions (Brown, 1971; Hudson, 1972). We do not know yet how the particle acceleration relates to the magnetic restructuring needed to release coronal energy.

3. Cross-field currents

Another aspect of flare energetics and the chromosphere is the mapping of subphotospheric magnetic twist into coronal currents (Longcope & Welsch, 2000). This in principle involves the use of the full conductivity tensor, though there is little discussion of this yet in the solar literature (e.g., Kazeminezhad & Goodman, 2006; Arber et al. 2007) at least as regards flares. Haerendel (2007) points out that the large ion-neutral coupling in the chromosphere makes the perpendicular conductivity is smaller than the parallel conductivity, at least for slowly-varying currents, and yet cross-field current systems must develop slowly in such a way as to match the conflicting boundary conditions at the two independent footpoints of a coronal flux tube. Auroral models make use of ionospheric currents to close coronal current systems, but in the case of the Sun we believe that the significant currents are injected *through* the photosphere in a slowly-evolving manner, and that these currents serve to energize the non-potential fields in the corona. In this sense the chromosphere must play the roles of both the ionosphere and the magnetopause.

We can write the perpendicular conductivity as

$$\sigma_{\perp,x} = \frac{Ne^2}{m_e} \frac{\nu_{xn}}{\nu_{xn}^2 + \omega_{cx}^2} \tag{1}$$

with x representing either ions or electrons (Banks, 1966), where ω_{cx}^2 represents the Larmor frequency for particle species x and n denotes neutrals. The neutral collision frequencies ν_{xn} largely determine the perpendicular conductivity, and so the perpendicular current system the predominantly neutral chromosphere dominates the steady-state perpendicular current system. In any case for "normal" chromospheric and coronal conditions, as inferred from standard semi-empirical models, the Larmor frequencies greatly exceed the neutral collision frequencies so that the perpendicular conductivity is small relative to the parallel term. So far as we are aware, the questions posed by the requirement to establish slowly varying cross-field currents in the chromosphere have not been discusssed in the literature, and we do not know the role that they play in energy storage or dissipation.

4. Field restructuring, waves, and energy transport

Changes of the coronal magnetic structure imply the transport of energy via Poynting fluxes (Melrose, 1992). The observations indicate that coronal energy dissipates in the chromosphere, and the hard X-ray signature directly implicates weakly relativistic electrons. Thus the magnetic restructuring, and the energy transport it implies, must somehow result in the acceleration of electrons to non-thermal energies. We sketch how this may happen in Figure 3 (Fletcher & Hudson, 2008). The sudden reconfiguration of the field, in the ideal MHD approximation, would launch Alfvén waves. Emslie & Sturrock (1982) argue that the suddenness of flare energy release requires that the Alfvén mode and the fast mode predominate in the partition of this energy. The Alfvén mode is particularly interesting in this context, because as a transverse wave its Poynting flux $\mathbf{E} \times \mathbf{B}$ must be strictly parallel to **B** and thus be strongly ducted into the footpoint regions.

The mechanism for electron acceleration remains ill-understood. Because it is energetically so important (Kane & Donnelly, 1971; Lin & Hudson, 1971), its identification is fundamental to understanding the physics of solar flares. In the view of Figure 3, the acceleration must happen as a result of the Alfvén-wave energy flux ducted along the arcade loops that result from the restructuring. This suggests several possible acceleration mechanisms, some of which have been recently reviewed by Miller et al. (1997).

Our scenario suggests additional acceleration mechanisms. Alfvén waves in the lower corona may propagate dispersively (e.g., Stasiewicz et al., 1991), inducing parallel electric fields directly. If the plasma beta, β = 2nkT/($B^2/8\pi$),

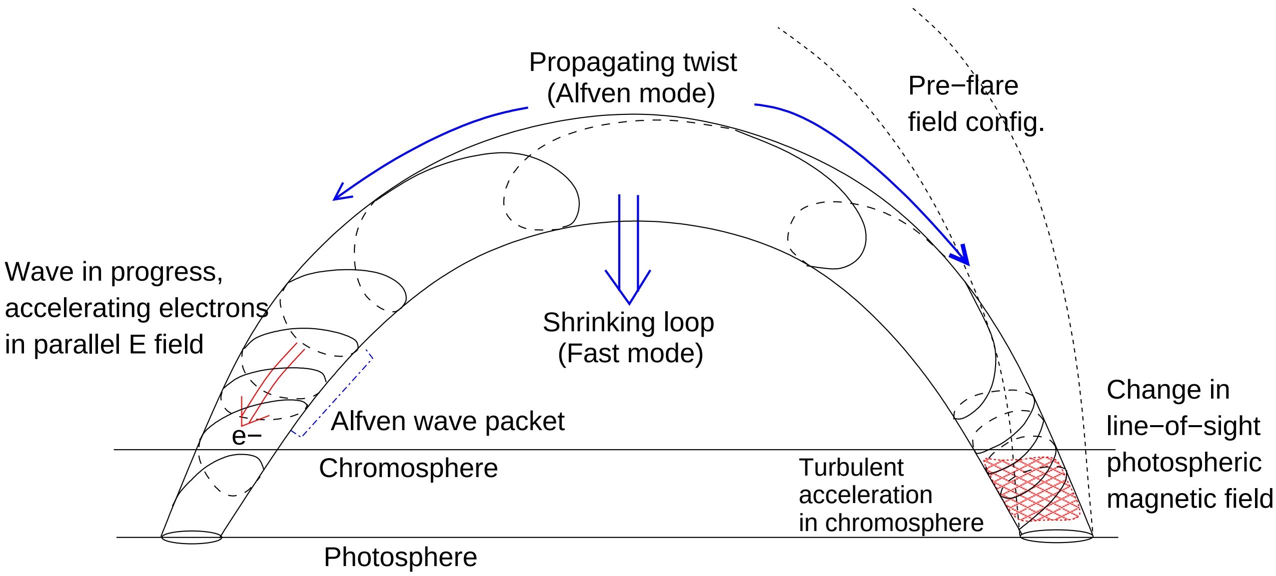

Fig. 3. Sketch of flare mechanisms as discussed in the text. Deformation of a flux tube results in Alfvén waves that transport energy into the footpoint regions via the Poynting flux. The wave deformation also perturbs the global structure to produce effects such as those seen in Figure 1. Particle acceleration results either directly from parallel electric fields produced by the waves, or in tubulent cascades developing from their interactions.

ratio, then the Alfvén mode can become dispersive in the form of a kinetic Alfvén wave and develop a parallel field directly. Fletcher & Hudson (2008) review how this happens. The waves may also cascade into forms of turbulence suitable for stochastic particle acceleration, and this cascade may develop promptly under some conditions. First-order Fermi acceleration and the betatron effect may also play roles in the "collapsing trap" (e.g., Veronig et al. 2006), and finally the disruption may create shock waves that may also accelerate particles.

Our preferred scenario (Figure 3) has the virtue of linking the observed magnetic-field variations with the powerful energy release seen in the visible and UV continua. The sketch by Haerendel (2006), reproduced in Figure 4, illustrates the generation of Alfvén waves from the reconnection process. Particle acceleration, in this picture, could readily occur in the lower solar atmosphere, where the ambient electrons are numerous enough to overcome the "number problem" and concerns about electron beam dynamics. One weakness may be the apparent time-of-flight signature noted by Aschwanden (2002), which – though somewhat ambiguous – provides the main observational evidence for the existence of the intense coronal electron beams the thick-target model requires. Type III radio bursts also require beams, but of significantly lesser intensity.

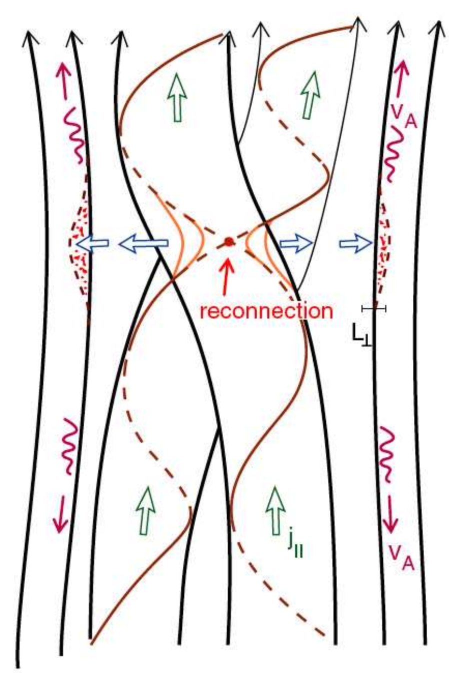

Fig. 4. Sketch showing how magnetic reconnection may excite Alfvén waves. From Haerendel (2006).

5. Conclusions

Research in solar flares and terrestrial aurorae has long been stimulated by the observational analogies one can draw between the phenomena (e.g., Obayashi 1975). The analogous elements include ribbon-like optical emissions, electron acceleration to keV energies, and similar magnetic geometries. There are observational differences though, and theoretically there also are good reasons not to have a strict analogy. Nevertheless we feel it important to discuss the and release stages, in ways that exploit some of ideas auroral physics offers to the understanding of solar problems. We interpret the observed photospheric magnetic field changes as the result of large-scale Alfvén waves created during coronal magnetic restructuring (Fletcher & Hudson, 2008). Particle acceleration, a key observable in solar flares because of hard X-ray and γ-ray emission, then becomes secondary to the transport of energy via the Poynting fluxes of the waves. There are different ways in which the necessary particle acdispersive in nature, but the identification of the acceleration mechanism remains an open problem.

Consideration of wave transport of energy in solar flares and CMEs seems like a logical and necessary development for the advancement of theoretical ideas. Some large-scale manifestations of waves are readily observable, originally as type II bursts and Moreton waves (e.g., Uchida et al., 1973), but now also at higher resolution in the EUV as the EIT waves (Thompson et al., 1999). The EIT waves introduce new kinds of behavior not seen before and it has become clear that not all of the motions can be identified with the Moreton-wave phenomenon (Biesecker et al., 2002). Small-scale waves such as those that could be directly responsible for particle acceleration are difficult to observe remotely, but their presence may be just as fundamental to solar-flare physics as comparable structures are in auroral physics. We therefore urge theoretical work involving the ideas discussed here.

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References

Allred, J. C., Hawley, S. L., Abbett, W. P., and Carlsson, M., Radiative Hydrodynamic Models of the Optical and Ultraviolet Emission from Solar Flares, *ApJ*, **630**, 573-586 (2005).

Arber, T. D., Haynes, M., and Leake, J. E., Emergence of a Flux Tube through a Partially Ionized Solar Atmosphere, *ApJ*, **666**, 541 (2007).

Aschwanden, M. J., Particle Acceleration and Kinematics in Solar Flares, *Space Science Revs.*, **101**, 1-227 (2002).

Banks, P., Collision Frequencies and Energy Transfer. Ions, *Planet. Space Sci.*, **14**, 1105-1122 (1966).

Berlicki, A, Observations and Modeling of Line Asymmeteries in Chromospheric Flares, in *The Physics of Chromospheric Plasmas*, Edited by P. Heinzel, I. Dorotovič, and R. J. Rutten, 387-406 (2007).

Biesecker, D. A., Myers, D. C., Thompson, B. J., Hammer, D. M., and Vourlidas, A., Solar Phenomena Associated with "EIT Waves", *ApJ*, **569**, 1009-1015 (2002).

Brown, J. C., The Deduction of Energy Spectra of Non-Thermal Electrons in Flares from the Observed Dynamic Spectra of Hard X-Ray Bursts, *Solar Phys.*, **18**, 489-502 (1971).

Carrington, R. C., Description of a Singular Appearance seen in the Sun on September 1, 1859, *Mon. Not. R. astr. Soc.*, **20**, 13-16 (1859).

De Pontieu, B., Martens, P. C. H., and Hudson, H. S., Chromospheric Damping of Alfvén Waves, *ApJ*, **558**, 859-871 (2001).

Emslie, A. G., and Sturrock, P. A., Temperature Minimum Heating in Solar Flares by Resistive Dissipation of Alfvén Waves, *Solar Phys.*, **80**, 99-102 (1982).

Fletcher, L., Hannah, I. G., Hudson, H. S., and Metcalf, T. A., A TRACE White Light and RHESSI hard X-ray study of Flare Energetics, *ApJ*, **656**, 1187-1196 (2007).

Fletcher, L., and Hudson, H. S., Flare Energy Transport by Alfvén Waves in the Impulsive Phase, *ApJ*, to be published (2008).

Hale, G. E., The Spectrohelioscope and its Work, *ApJ*, , 73-101 (1930).

Haerendel, G., Commonalities between Ionosphere and Chromosphere, *Space Sci. Revs.*, **124**, 317-331, (2007).

Hudson, H. S., Thick-target Processes and White-light Flares, *Solar Phys.*, **24**, 414-428 (1972).

Hudson, H. S., Implosions in Coronal Transients, *Ap. J.*, **531**, L75-L77 (2000).

Hudson, H. S., Wolfson, C.J., and Metcalf, T. R., White-light Flares: a TRACE/RHESSI Overview, *Solar Phys.*, **234**, 79-93 (2006).

mas, Edited by P. Heinzel, I. Dorotovič, and R. J. Rutten, 365-386 (2007).

Kane, S. R., and Donnelly, R. F., Impulsive hard X-ray and ultraviolet emission during solar flares, *Ap. J.*, **164**, 151-163 (1971).

Kazeminezhad, F., and Goodman, M., Magnetohydrodynamic Simulations of Solar Chromospheric Dynamics using a Complete Electrical Conductivity Tensor, *Ap. J. (Suppl.)*, **166**, 613-633 (2006).

Lin, R. P., and Hudson, H. S., *Solar Phys.*, 10-100 keV Electron Acceleration and Emission from Solar Flares, **17**, 412-435 (1971).

Longcope, D., and Welsch, B. T., A Model for the Emergence of a Twisted Magnetic Flux Tube, *ApJ*, **545**, 1089-1100 (2000).

Melrose, D. B., Energy propagation into a flare kernel during a solar flare, *ApJ*, **387**, 403-413 (1992).

Miller, J. A., Cargill, P. J., Emslie, A. G., Holman, G. D., Dennis, B. R., LaRosa, T. N., Winglee, R. M,, Benka, S. G., and Tsuneta, S., *JGR*, **102**, 14,631-14,659 (1997).

Obayashi, T., Energy Build-up and Release Mechanisms in Solar and Auroral Flares, *Solar Phys.*, **40**, 217-226 (1975.

Régnier, S., and Priest, E. R., Nonlinear Force-free Models for the Solar Corona. I. Two Active Regions with very different Structure, *A&A*, **468**, 701-709 (2007).

Stasiewicz, K., et al., *Space Sci. Revs.*, **92** 423-533 (2001).

Schwenn, R., Space Weather: The Solar Perspective, *Living Reviews in Solar Physics*, **3**, no. 2 (2007).

Sudol, J. J. & Harvey, J. W., Longitudinal Magnetic Field Changes Accompanying Solar Flares, *Ap. J.*,. **635**, 647-658 (2006).

Thomas, R. J., and Teske, R. G., Solar Soft X-Rays and Solar Activity. II: Soft X-Ray Emission during Solar Flares, *Solar Phys.*, **16**, 431-453 (1971).

Thompson, B. J., Gurman, J. B., Neupert, W. M., Newmark, J. S., Delaboudinière, J.-P., St. Cyr, O. C., Dere, Stezelberger, S., Dere, K. P., Howard, R. A., and Michels, D. J., SOHO/EIT Observations of the 1997 April 7 Coronal Transient: Possible Evidence of Coronal Moreton Waves, *ApJ*, **517**, L151-L154 (1999).

Uchida, Y., Altschuler, M. D., and Newkirk, G., Jr., Flare-Produced Coronal MHD-Fast-Mode Wavefronts and Moreton's Wave Phenomenon, *Solar Phys.*, **28**, 495-516 (1973).

Veronig, A. M, Karlický, M., Vršnak, B., Temmer, M., Magdalenić, Dennis, B. R., Otruba, W., and Pötzi, W., X-ray Sources and Magnetic Reconnection in the X3.9 Flare of 2003 November 3, *Astron. Astrophys.*, **446**, 675-690 (2006).

Wang, H., Evolution of Vector Magnetic Fields and the August 27 1990 X-3 Flare, *Solar Phys.*, **140**, 85-98 (1993).

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