Solar flares in the recent sunspot maximum

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Abstract

At the time of writing (October, 2005) we have almost completed the fourth solar maximum of the space age, during which we have had nearly continuous study of solar activity from above the Earth's atmosphere. During the most recent part of this era the progress of technology has enabled new observations with unprecedented scope. As a result we have learned many new and important things about solar flares and coronal mass ejections (CMEs), the two main forms of violent magnetic activity in the solar corona. In this paper I briefly discuss these observations, which have come from a remarkable flotilla of spacecraft led by *Yohkoh* and continuing through RHESSI.

1 Introduction

The remarkable new series of observations really started with *Yohkoh*, which with a launch in 1991 began to produce data just after the solar maximum of 1990. Then came SoHO[1], TRACE[2], and RHESSI[3] among other spacecraft capable of observations relevant to flaring; for a recent comprehensive view, with full literature citation, please see Aschwanden (2004).

We understand that a solar flare (and/or CME) results from the sudden transition of the coronal magnetic field from one equilibrium state to another lower-energy equilibrium state. This transition takes place in a medium with low plasma beta (Gary 2001), thus with magnetic forces dominant, and it happens suddenly enough (the "impulsive phase") to preclude simultaneous energy input through the photosphere. Coronal mass ejections (CMEs), although strongly associated with solar flares, may involve somewhat different physics because they involve the higher-beta structure of the solar wind. In the low-beta limit, the structures visible in coronal images only mark tracers of the field structure and have no independent significance. Because the corona involves such a large range of temperatures, a feature prominent in one wavelength may not show up at all in another. The corona also involves extremely large dynamic ranges of brightness. Soft X-ray images such as those of *Yohkoh*/SXT[4] require

[1]Solar Heliospheric Observatory
[2]Transition Region And Coronal Explorer
[3]Reuven Ramaty High Energy Solar Spectroscopic Imager
[4]Soft X-ray Telescope

elaborate control of this dynamic range, which can exceed five decades. No single printable image can successfully display structural details across such a huge range.

In this paper I discuss new observational results from these data and assess how our thinking about the underlying theory has changed as a result. We have only quite incomplete observations, and so we rely upon cartoon[5] representations of the theory to help bridge the gaps. In the field of flare/CME physics the "standard reconnection model" remains the preferred framework. This framework dates from the work of Sweet (1958), who followed Giovanelli (1946) and others in recognizing the importance of magnetic reconnection. A complete understanding of the physics of reconnection remains obscure, though, since in this context the processes involve ranges of scales too great to simulate with complete-enough physics.

2 Observations

2.1 Coronal dynamics

The "two-ribbon flare" and inferences from its behavior (e.g., Švestka 1976) provided the underpinning for the development of the orthodox model of solar flares, well-accepted even prior to the recent epoch. The cartoon describing the this orthodox "eruption-reconnection model" attained its modern form in the works of Hirayama (1974), Anzer & Pneuman (1982), and Forbes & Malherbe (1986). Several novel observations relating to the dynamics of the solar corona during the eruption have emerged. These all relate in different ways to the coronal restructuring and do not disagree with the standard model, even though (see Section 3) it does not readily predict the details of what we now observe.

X-ray dimming; The *Yohkoh* soft X-ray data showed many examples of "X-ray dimming" as originally seen in Skylab soft X-ray images. This dimming has a natural interpretation as the outward flow of the CME (Hudson & Webb 1997), a flow perpendicular to **B** associated with its opening into the solar wind. The entire corona surrounding a large arcade event appears to participate in this flow, and the time profile of dimming looks like a mirror image of the flare time profile. Identifying the dimming with the source of CME mass, this timing agrees with that found via coronagraph observations, namely that the *acceleration phase* of the CME matches the *impulsive phase* of the associated flare (Zhang et al. 2001).

Supra-arcade downflows: The soft X-ray movies[6] of arcade flares also revealed a downward flow field usually in the form of voids descending through a fan-like rayed structure extending above the arcade (McKenzie & Hudson 1999). TRACE observations give a much better view of the downflows, which we illustrate in Figure 1 (movies show these phenomena more clearly). Identifying the supra-arcade downflows with exhaust from the coronal reconnection, in the standard model, seems attractive, and yet the observed flows have speeds of at most 100-250 km/s as observed by TRACE (Asai et al. 2004) even in the impulsive phase. The standard

[5] http://solarmuri.ssl.berkeley.edu/∼hhudson/cartoons
[6] Search for example in http://solar.physics.montana.edu/nuggets/

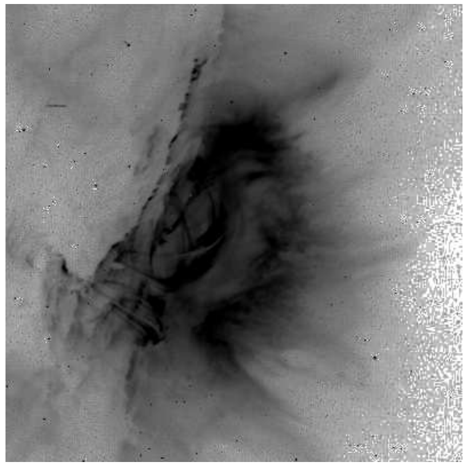

Figure 1: *TRACE 195Å image of the limb flare of 2002 April 21, 01:34:32 UT (negative image). Above the limb a spiky cloud (temperature >10 MK) occupies the region that had previously dimmed. The supra-arcade downflows occur within this cloud, and appear as void inclusions (bright regions in this image). Movie views of these phenomena make these features clearer.*

model would predict Alfvénic speeds in a simple exhaust flow geometry (on the order of Mach 2, according to Forbes & Acton (1996)).

Footpoint behavior: In the standard model the footpoint motions reflect the reconnection of coronal magnetic flux. Thus rapid apparent footpoint motions should coincide with strong energy release, as indeed the RHESSI observations (e.g., Krucker et al. 2003) tend to show. Because the nonthermal electrons carry a large fraction of the impulsive-phase energy, the footpoint locations also in principle would map out the geometry of the locus of reconnection, if we could trace the coronal field sufficiently accurately. Bogachev et al. (2005) have recently shown that the hard X-ray footpont motions in most cases do not follow the expected pattern of outward motion. Thus a successful magnetic mapping could provide important new information about the physical nature of the coronal restructuring.

Shrinkage: In another recent RHESSI observation, Sui et al. (2004) found evidence for Masuda-like "above-the-loop-top" sources, but seen in (thermal) soft X-rays rather than (non-thermal) hard X-rays (Masuda et al. 1994). Strikingly these sources show a downward motion prior to the impulsive phase of the flare. When the impulsive phase begins, the soft X-ray sources begin to ascend, as commonly observed and directly explained by the standard model. Unfortunately the standard model failed to predict the downward motions, which therefore require new theoretical work to explain.

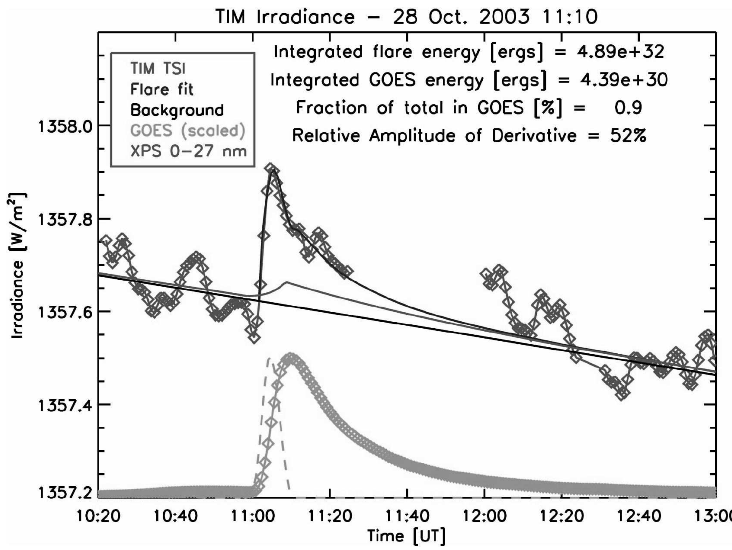

Figure 2: *Illustration of the SORCE total irradiance observation of the solar flare of 2003 October 28. The lower plot shows the GOES soft X-ray light curve; note the correlation with the GOES derivative (the impulsive phase). (Illustration courtesy of T. Woods and G. Kopp).*

2.2 Energetics

Only the invention of the telescope made it possible to discover solar flares, or at least to observed them at visual wavelengths. Although the brightest "white-light flare" may locally double the photospheric intensity, until recently even a flare as bright as Carrington's original one in 1859 would go undetected in integrated sunlight. Howver recent observations in TSI[7] have now detected energetic solar flares in the same way that we detect stellar flares: by changes in the brightness of the Sun as a star. The TSI observations show the total radiated power bolometrically, as seen in Figure 2 (cf. Woods et al. 2004).

The TSI background level shown in Figure 2 fluctuates not just because of detector noise, but also solar p-modes and broadband noise associated with convective motions in the photosphere. As a comparison with the GOES soft X-ray photometry shows, the TSI signal appears to have an impulsive-phase component, ie. one that correlates well with the GOES rise phase. This points to powerful and heretofore unknown UV emission in the impulsive phase, as discussed by Emslie et al. (2005). Direct imaging observations by TRACE in its UV passbands probably show the spatial and temporal distribution of this dominant radiant energy (Hudson et al. 2005). We illustrate some of these observations in Figure 3.

[7]Total Solar Irradiance

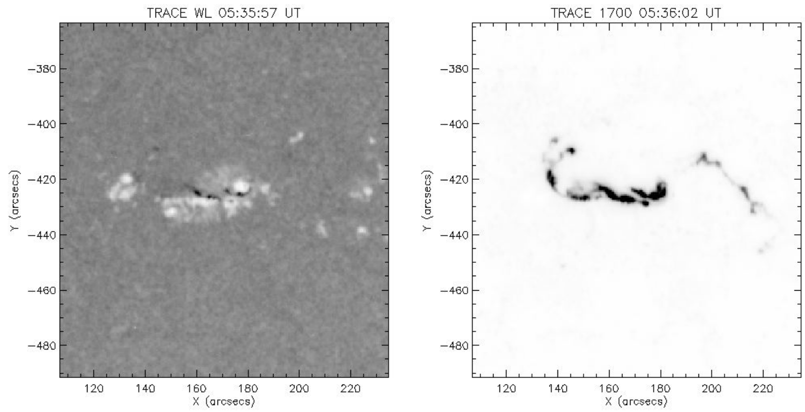

Figure 3: *TRACE observations of a white-light flare (left; GOES M4.0, 2002 October 4) compared with UV (right). The reversed color table means that sunspots appear white, flare emissions dark. Note the vastly larger contrast in the UV.*

2.3 Photospheric magnetic field

We had long expected to see photospheric magnetic field changes associated with flares, since the coronal images imply drastic changes. Finally Wang et al. (2002) found clear evidence for permanent changes in the line-of-sight field, in localized regions. We show a good example of this in Figure 4, from Sudol & Harvey (2004). Note that the field changes tend to occur only during the impulsive phase, a clear feature of 10 of the 15 events presented by Sudol & Harvey. The standard cartoon does not predict this feature, since energy release (and field change) should continue as long as the reconnection does. We do not know much about these observations quantitatively, since they come from longitudinal magnetograms and (as of the time of writing) no extrapolation or modeling analyses had appeared in the literature. In principle before-and-after comparisons of 3D coronal field maps derived from vector magnetograms should allow us to observe the drop in coronal energy storage accompanying an event.

3 Implications for theory

How do we learn from these observations about a more correct theory of solar flares and CMEs? Most of the new observational material fits into the standard reconnection model, and yet surprises repeatedly appear (we have mentioned some of them above). In particular the downward motions of the pre-impulsive coronal soft X-ray sources, the non-simple hard X-ray footpoint motions in the impulsive phase, and the sub-Alfvénic supra-arcade motions – none of these features appear in the standard reconnection model, The explanation for the downward motions could lie somewhere in a more complicated version of the model, or it could reflect an initial stage of contraction necessary for energy accumulation

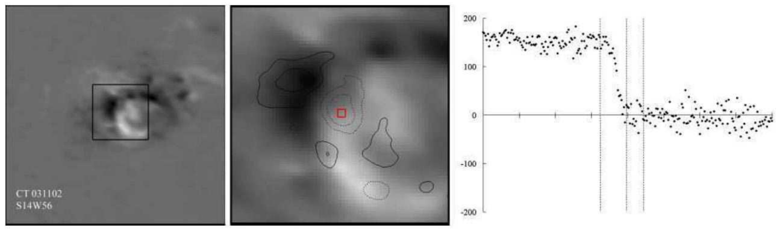

Figure 4: *GONG magnetographic observations of a GOES X8.3 flare, 2 November 2003, at S14W56 (Sudol & Harvey 2004). The small square on the enlarged panel (center) shows the region for the flux measurement shown on the right; the vertical lines show the GOES start, peak, and end times for the flare.*

to support the eruption, as suggested by Hudson (2000). In any case we have a clear message: our understanding of flare and CME theories, both analytical and numerical, has not reached the point where we can predict the detailed behavior of these processes.

I believe that to get to a predictive theory we will need to go beyond MHD approximations to flare/CME theory and make use of the full plasma physics of particles and waves. Indeed, the basic morphology of flare loops as observed in soft X-rays by *Yohkoh* immediately presented another unpredicted feature: the ubiquitous soft X-ray brightenings in flare loop tops (Acton et al. 1992). An explanation for this feature goes beyond geometry (Alexander & Katsev 1996) and probably involves complex structures in the plasma (e.g., Jakimiec et al. 1998).

As a footnote to the discussion of flares and CMEs, evidence continues to link these two manifestations of solar activity closely. Especially for GOES X-class flares, a CME almost always occurs in association, and the timing of the eruption closely matches the impulsive phase of the flare. Lesser flares may not have CMEs, presumably because the magnetic restructuring does not involve the opening of coronal magnetic fields into the solar wind. No longer do we need to think of flares and CMEs as having independence of action.

4 Conclusions

The new data from *Yohkoh*, SoHO, TRACE, and RHESSI (among other spacecraft and also not forgetting ground-based observations, such as GONG) have shown us new things about flares and CMEs. The standard picture of large-scale magnetic reconnection has found a great deal of support, but it repeatedly has failed to predict the new findings and in some cases we simply don't understand how to put it back together. Much of the difficulty, in my view, lies in our ignorance of the three-dimensional structure of the coronal magnetic field. We cannot confindently model this even during an equilibrium state, much less during a loss of equilibrium. We also do not have a clear idea why some structures (the loops) appear at a given temperature (really, pressure) in a given equilibrium state. Because flares (and I believe, CMEs as well) involve sudden heating and massive particle acceleration, we really need future observations with improved hard X-ray and γ-ray imaging as well as soft X-ray imaging spectroscopy, something not included in Solar-B, STEREO, or SDO among the future missions for solar observation.

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