

SIGNATURES OF RECONNECTION IN ERUPTIVE FLARES

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ABSTRACT

Solar flares are defined by magnetism. The energy that is stored up, transferred, and released is done so in and by the magnetic fields of the Sun; the structures in which the flares occur are wholly dependent on the configuration of magnetic connections; and it is the rearrangement of these connections that we believe plays such a large and important role in many of the processes observed in flares. Many of our theoretical pictures of flare mechanisms rely in some part on magnetic reconnection, and one by one the observable signatures of these models are being uncovered in chromospheric and coronal data. These data, in turn, introduce observational constraints that help to drive the models. I will summarize some key observations that have helped to support the case for reconnection, and that have helped us to peer more deeply into the behavior of coronal plasmas and magnetic fields.

INTRODUCTION

This article is a review of observations, in particular observations that resemble our expectations of reconnection. By the term “magnetic reconnection”, I am referring to the process by which magnetic flux is swept into a small area, where oppositely directed components annihilate each other, and the residual magnetic tension in the newly-reconnected field causes it to be expelled from the reconnection region. The resulting conversion of magnetic energy into kinetic energy is responsible for the observables in a flare — the particle acceleration, plasma heating, motions, etc. The cartoon shown in Figure 1 is one representation of this fundamental idea; the arguments in this article will be built upon the geometry shown in the commonly invoked picture due to Carmichael (1964), Sturrock (1968), Hirayama (1974), and Kopp & Pneuman (1976) — hereinafter called CSHKP, a good summary is in Shibata (1999) — but it should be made clear that this is only one orientation. Many other orientations are possible, variations on a common theme, but this article will not attempt to consider them all.

Roughly speaking, reconnection is what happens after the creation of a current sheet. I will not attempt to discuss how the current sheet is arrived at, nor how energy is stored in the magnetic field. I will not discuss the “breakout model” or “tether cutting” as flare initiation scenarios — although both of these scenarios may be supported by observational evidence, they are beyond the scope of this article.

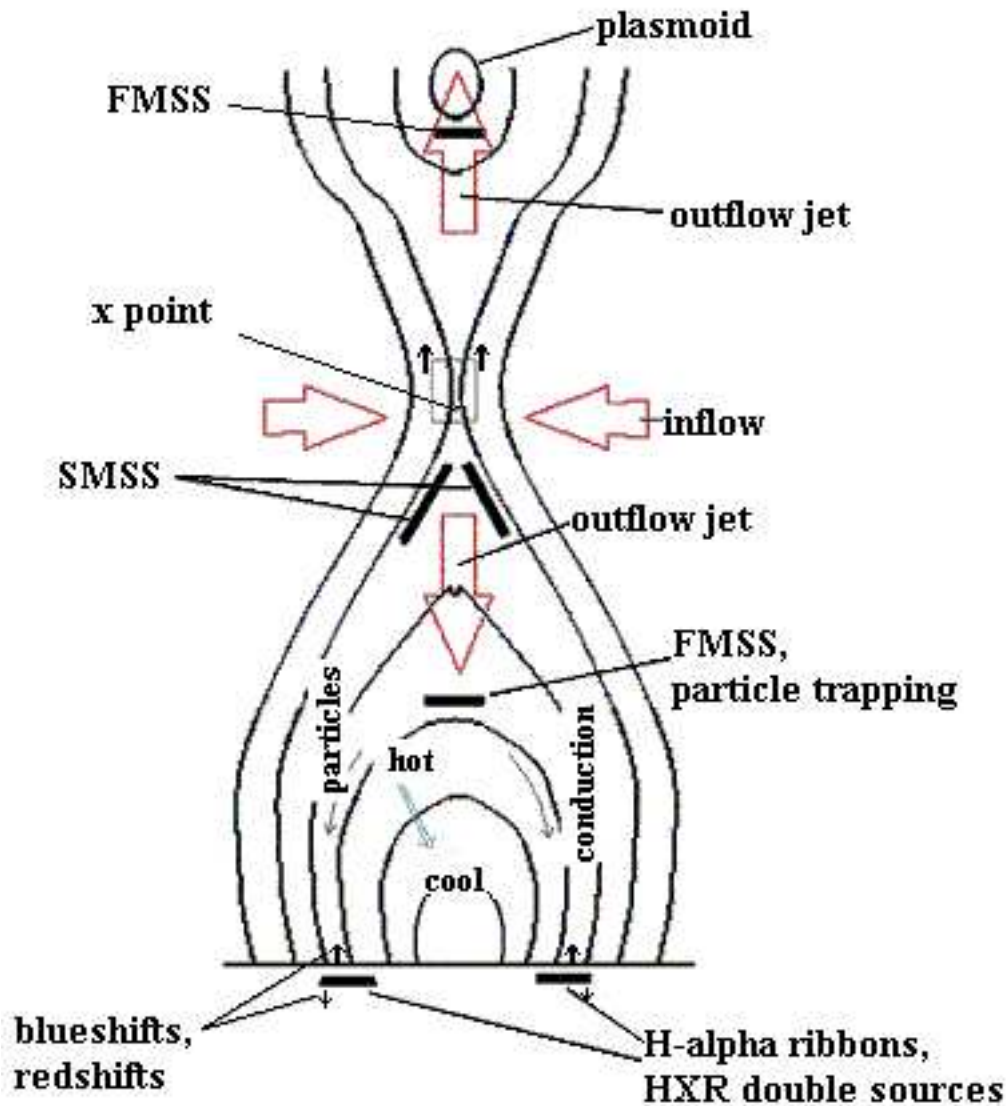


Fig. 1. Two-dimensional cartoon of the CSHKP model, wherein post-eruption coronal arcades result from magnetic reconnection. Some possibly observable features are annotated and discussed in the text.

In what follows, I will briefly review the major components of the standard reconnection model as it is represented in Figure 1; a lengthy explanation of each is not necessary, since the references offered in this article provide much more complete treatments than I can offer, as do many of the other articles in these proceedings. Afterwards, observations which seem to show examples of each of these signatures will be summarized.

Some of the observed signatures are not precisely as were anticipated by theoretical predictions. I will try to make the case that these data provide constraints for the theoretical models.

Finally, many of our cartoons of the reconnection model have perforce been drawn in two dimensions, and have nonetheless been extremely successful. Some aspects of the observations, though, require three-dimensional treatment. I will give some examples of this situation.

REVIEW OF THE CSHKP PICTURE

The fundamental parts of the model are annotated in Figure 1. Magnetic field is shown moving into the middle region with some inflow velocity. In this diffusion region, characterized as an X-point, magnetic field of opposing directions cancel out, and the tension that exists in the external field causes the expulsion — upwards and downwards — of outflow jets. A detached plasmoid of closed magnetic field is shown moving upwards, away from the Sun, while the downward expelled field piles up to form the post-eruption arcade. There may be slow-mode standing shocks (SMSS) at the upper and lower edges of the diffusion region, but only the lower are shown; fast-mode standing shocks (FMSS) may exist where the outflow jets collide with previously closed field — a termination shock. As successive field is introduced from the sides, the location of the X-point moves steadily higher and higher. The released energy may go in accelerated particles, which stream down along the magnetic field into the chromosphere below, or thermal energy which is conducted downward along the magnetic field. The introduction of this energy to the chromosphere yields the H α ribbons, hard X-ray double sources, and chromospheric evaporation. The latter means that a pressure imbalance is generated which results in chromospheric material being heated and piped up into the coronal portions of the closed magnetic fields; it is that heated material which appears as the long-lasting soft X-ray arcade.

Not all of these elements will necessarily be clearly observable in each and every flare, and in some instances the importance of each may be different, depending on the particulars of magnetic field strength, amount of helicity and interconnectedness, amount of stored energy, and plasma density. This makes the observational task more challenging, but piece by piece over the years many of the elements of the standard picture have revealed themselves. In Figure 2, a bibliographical representation of the same CSHKP picture is introduced, highlighting key observational papers which describe these signatures.

OBSERVED SIGNATURES

From Figure 2 one can judge that many of the elements of the standard picture appear to have been observed, though a few of the identifications are still tentative. Brief commentary about some of these is in order.

Yohkoh/SXT observations reported by Ohyama & Shibata (1996) describe dense collections of X-ray emitting material ejected from flares: these ejecta may well represent the closed-field plasmoid downstream of the reconnection (top of Figures 1 and 2). Further out, the plasmoid may have been observed by Sheeley *et al.* in 1997, though their first paper does not explicitly make that identification. The subsequent analyses by Wang *et al.* (1998) and van Aalst *et al.* (1999) interpret the “streamer blobs” in terms of reconnection artifacts. More directly, Tsuneta (1997) describes a set of *Yohkoh* observations that seem to have several of the elements of Figure 1. In addition to an apparent closed-field plasmoid, Tsuneta (1997) shows images which seem to include a region of hot plasma above the X-point and below the plasmoid. This feature (Figure 3) moves slowly upwards in subsequent images, and may be evidence of a fast-mode shock in the region downstream of the reconnection.

All three of the papers referenced in regards to the rising of the X-point (Moore *et al.* 1980; Seely & Feldman 1984; Tsuneta 1996) report the well-known fact that X-ray loops get taller and taller during the flare. This is a proxy for the upward motion of the X-point, since the X-point itself is not directly observable. The growth rate is on the order of 20 – 50 km s⁻¹, but the rise speed of the X-point is probably greater than that (and in three-dimensional reconnection, difficult to define).

The velocity field surrounding the X-point has been a long-sought observational signature, since the speeds and plasma parameters in the inflow and outflow regions (upstream and downstream of the reconnection, respectively) can reveal information about conditions inside the diffusion region. The first tentative observations of outflows are those of Hiei & Hundhausen and Forbes & Acton, both in 1996, and both indicating rather slow outflow speeds — Hiei & Hundhausen on the order of less than 5 km s⁻¹. This flow, in retrospect,

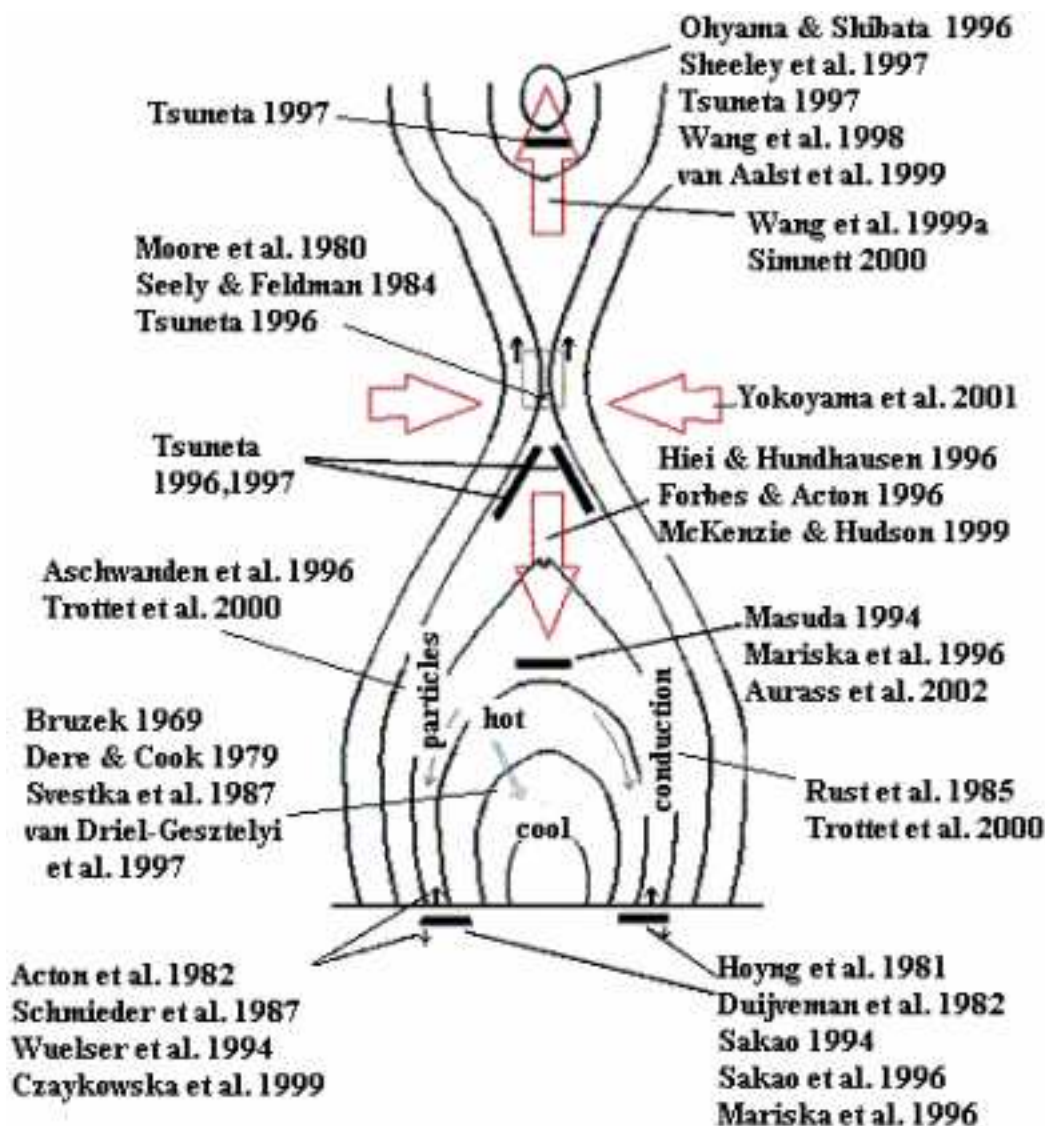


Fig. 2. Bibliographical rendition of Figure 1. The references indicate possible observations related to the annotated features of Figure 1.

seems more like the thermal shrinkage described by Švestka *et al.* (1987, see below) than a shrinkage due to the relaxation of magnetic tension (i.e., “thermal shrinkage” rather than “magnetic shrinkage”). A report by Sterling *et al.* (1996) described *Yohkoh*/BCS data with simultaneous red- and blue-shifts in the upper reaches of a far-beyond-the-limb flare. Sterling *et al.* argued that the observed line shifts are probably not due to reconnection outflows, but the uncertainties attending their assumptions cause this observation to remain contentious.

The observations described by McKenzie & Hudson (1999) and McKenzie (2000) show many features moving downward into the tops of flare arcades at speeds between $40 - 500 \text{ km s}^{-1}$. These flow fields have been interpreted as signatures of reconnection outflows, but the speeds are slower than typically expected. There are some other characteristics of the “supra-arcade downflows” which will be discussed below. Wang *et al.* (1999a, 1999b) and Simnett (2000) have demonstrated many examples of features both up-flowing and down-flowing in LASCO image sequences, with speeds of a few hundred km s^{-1} . These also have been interpreted as signatures of reconnection outflows; some are found at sector boundaries in times of quiescence, but some seem to be part of the post-CME rearrangement.

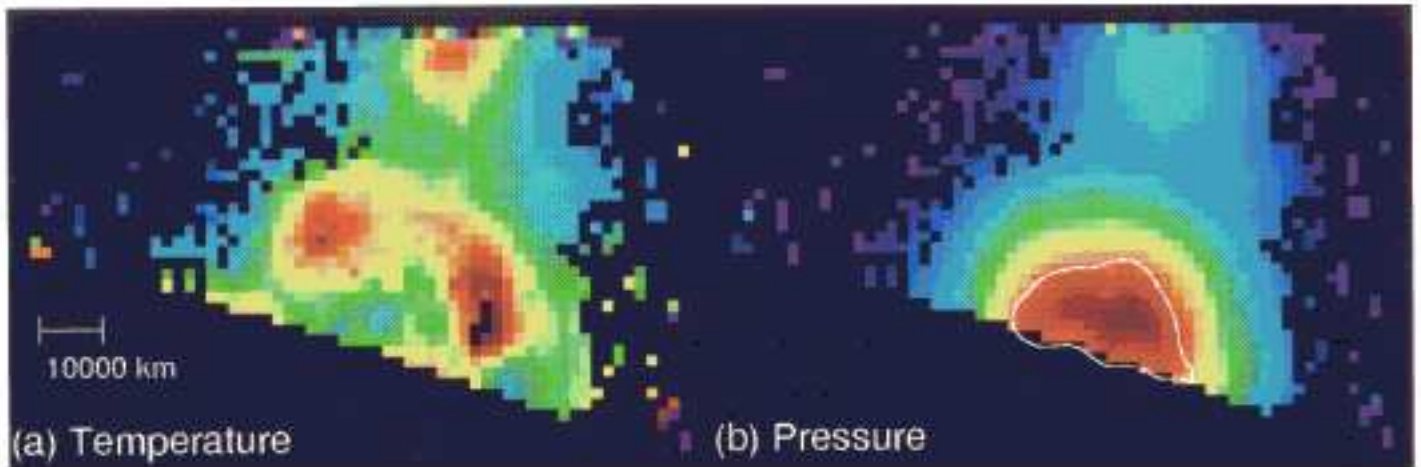


Fig. 3. Adapted from Tsuneta (1997), displaying a hot source above the X-point and below the closed-field plasmoid. The possible fast-mode shock feature is at the top of the frame; the plasmoid has left the field of view.

Just as important, Yokoyama *et al.* (2001) have described an observation by SOHO/EIT that closely resembles the expected appearance of reconnection inflow. The inflow speed is $1 - 5 \text{ km s}^{-1}$, and the resemblance to the two-dimensional reconnection picture is remarkable.

The hot plasmas observed by Tsuneta (1996, 1997) (Figure 4) can be interpreted as due to heating in the slow-mode standing shocks. The long extension of the two hot lobes along the vertical direction, separated by a cool “tower”, is consistent with conduction of heat energy along the magnetic field lines. The cool, dense “tower” has been interpreted as the result of catastrophic cooling — thermal instability leading to plasma condensation (e.g., Tsuneta 1996, Forbes & Acton 1996).

The Masuda-type sources are very well known (Masuda 1994, Mariska *et al.* 1996), and depicted in Figure 5 (reprinted from Masuda 1994). Though initially described in terms of thermal radiation from superhot plasma, the consensus now seems to favor a non-thermal population of particles, trapped in the looptop for some time before escaping to the footpoints. A very good treatment of the data, and review of analyses, is found in Alexander & Metcalf (1997).

The paper by Aurass *et al.* (2002) argues that if a Type II radio burst indicates a fast-mode shock, then a standing Type II suggests a fast-mode standing shock (FMSS). The authors report an observation which suggests such a standing shock, at a plasma density of a few times 10^9 cm^{-3} ; this is tentatively identifiable as evidence for a termination shock.

Hot plasmas cool. As they do so, they may contract a little. Additionally, as new field gets swept into the reconnection region, the newly reconnected loops are generally higher than the previously reconnected loops. So one might expect to see hotter loops above the cooler loops, and loops shrinking (slightly) as they cool. Observations of this nature are not unknown (Bruzek 1969; Dere & Cook 1979; van Driel-Gesztelyi *et al.* 1997); see especially the paper by Švestka *et al.* (1987).

At the chromosphere, a variety of signatures are observed. Little discussion of these signatures is offered in this article, primarily because more complete descriptions appear elsewhere in these proceedings. Hard X-ray double sources are common, demonstrating the connectivity of the footpoints. An especially good example is shown in Masuda *et al.* (2001), whose analysis reveals two hard X-ray ribbons; most observations show HXR sources of considerably smaller extent. The co-location of these sources with the $H\alpha$ ribbons is further support for the standard picture, particularly in light of the observation by Wuelser *et al.* (1994)

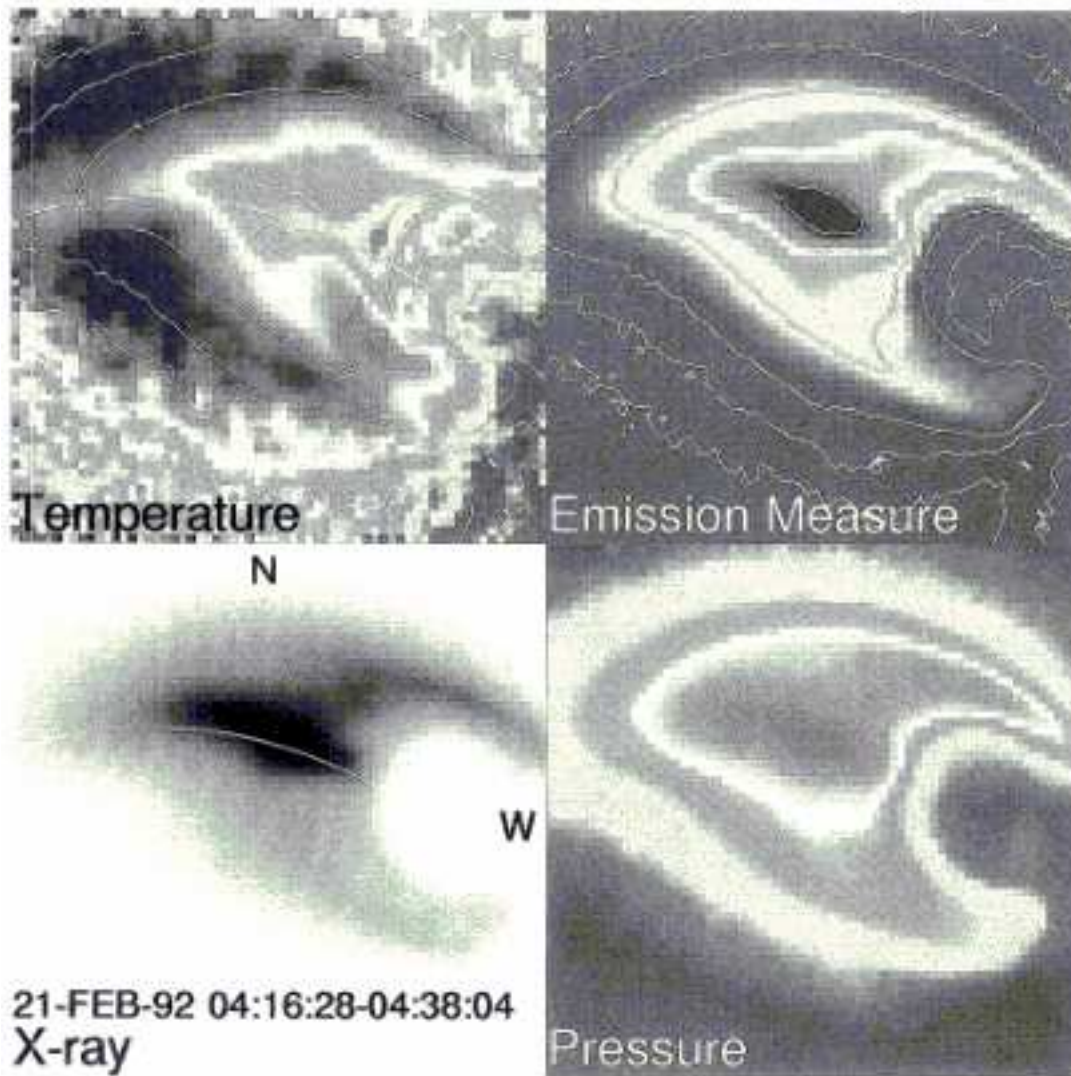


Fig. 4. Adapted from Tsuneta (1996); the results are consistent with plasma heating due to slow-mode standing shocks, coupled to heat conduction along (but not across) the magnetic field lines. “The contours in the temperature and emission measure maps indicate the locations of 83%, 20%, 5%, 2%, and 1% levels of the peak X-ray intensity of the map” (Tsuneta 1996).

indicating blueshifted soft X-rays coincident with redshifted $H\alpha$. That observation, as well as Czakowska *et al.*'s extended system (1999) of red- and blueshifts, are strongly suggestive of chromospheric evaporation. The analysis of Acton *et al.* (1982) concluded that evaporation may be driven by either electrons and conduction.

OBSERVATIONS TO QUESTIONS

Despite the argument that these observations appear to support the standard reconnection picture, it must be understood that the match is in some cases not perfect. Perhaps these “imperfect matches” offer a chance to refine either some details of the standard picture, or our understanding of the physical parameters of the plasmas in and around the flares.

The downward flows observed by McKenzie & Hudson (1999) and Wang *et al.* (1999) are slower than

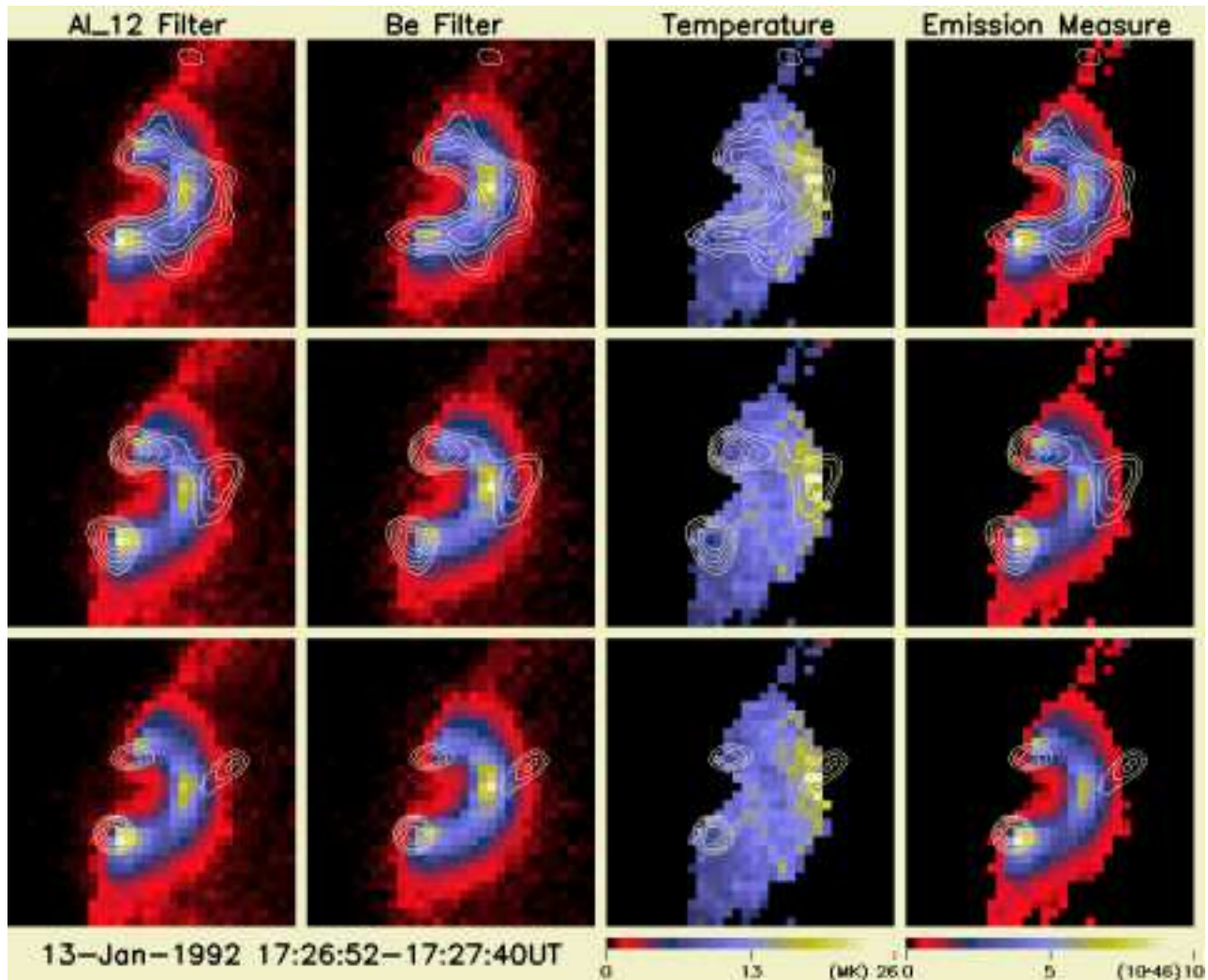


Fig. 5. Adapted from Masuda (1994), revealing a hard X-ray source at the top of the flaring loop, in addition to the more common footpoint sources. The grey scale images are from *Yohkoh/SXT*, and the contours from *Yohkoh/HXT*, energy passbands 13.9-22.7 keV (top row), 22.7-32.7 keV (middle row), and 32.7 – 52.7 keV (bottom row).

nominally expected: $50 - 500 \text{ km s}^{-1}$, not thousands of km s^{-1} . If these flows are to be interpreted as reconnection outflows, then either the reconnection outflow is not necessarily Alfvénic, or the Alfvén speed is not what we thought it was. The former solution may be a result of plasma parameters in the downstream region — Priest & Forbes (2000) demonstrated that the outflow speed and the may be affected by the plasma conditions downstream of the reconnection — or possibly of interaction with a return current at the downstream edge of the diffusion region (Biskamp 1984). On the other hand, lower-than-expected Alfvén speeds may result from our incomplete knowledge of the plasma parameters and magnetic field in a region where the magnetic field is un-measurable and partly annihilated, the temperature and density of the plasma is unknown, and the velocity is poorly known, changing, and possibly turbulent. Additionally, the LASCO outflows which move upwards away from the Sun have speeds between $150 - 300 \text{ km s}^{-1}$; these characteristics must tell us something about the physical conditions at these high altitudes.

Similarly, what about the possible FMSS observed by Tsuneta (1997) and Aurass *et al.* (2002)? If the standard model is correct, then why is this signature not observed more often? The visibility must place some limits on the outflow speed, the density of the downstream plasma, and the velocity of the X-point. Aurass

et al. suggest that the rarity of the observation indicates that “for a majority of flares the plasma parameter β is comparatively high.” Alternatively, the FMSS is simply not a common feature in reconnections.

The sole, tentative observation of reconnection inflow, by Yokoyama *et al.*, points to a reconnection rate on the order of $M_A \approx 0.001 - 0.03$. According to Yokoyama *et al.*, the implication is Petschek-type reconnection, rather than Sweet-Parker, though the precision of the measurements is pretty coarse. If more of these observations can be acquired, then perhaps they will provide a useful test of the reconnection rate, as well as constraints on the modeling of the atmosphere and conditions up- and downstream of the diffusion region.

DIMENSIONALITY

Finally, a word on dimensionality. Many of the diagrams and models in the literature have been strictly two-dimensional, and have been extremely successful. Surprisingly, several of the analyses which have made the greatest impact have dealt with flare structures that closely resemble the 2D cartoons (e.g., Tsuneta; Forbes & Acton; Aschwanden *et al.*; Yokoyama *et al.*). At least one of the observations mentioned herein bears a striking resemblance to a 2.5D representation: Czakowska *et al.* But some flare observations can only be described in 3D (e.g., Švestka *et al.*; McKenzie (2000); Fletcher *et al.* (2001)), and so the models must reproduce the “strictly-3D” features.

For example, in the region above some post-eruption coronal arcades, there are “spikey” structures extending high up into the corona. These tall features, first analyzed by Švestka *et al.* (1998), are extremely hot, may persist for many hours, and evolve on fairly short time scales (see also McKenzie & Hudson 1999, McKenzie 2000). The mechanism which produces such a hot fan above an arcade is still to be determined.

A model that may be worth considering builds upon the results of Forbes & Malherbe (1986), as emphasized in Forbes & Acton (1996). In particular, these studies indicated that arcades with strong magnetic fields may be distinguishable from those with weaker fields by the presence of supermagnetosonic downflow jets. In events with weaker fields, Forbes & Acton (1996) suggest that most of the reconnection outflow may be directed upwards (i.e., away from the Sun and the arcade), and that thermal condensation at the location of the termination shock is less likely to occur. Figures 1 and 2 of Forbes & Acton (1996) demonstrate the possible distinction, including high-temperature signatures above the cusped loops in the high-B case but not in the low-B configuration. A possible 3D model might interleave these two essentially 2D constructions — by allowing the field strength to vary along the length of the arcade, such a model might recover the spikey appearance of the supra-arcade region.

Moreover, the supra-arcade downflows (McKenzie & Hudson 1999, McKenzie 2000) are traced by discrete X-ray features with a characteristic size. If the downflows are reconnection outflows, then these tracers strongly suggest that the reconnection takes place between discretized collections of magnetic flux, e.g., flux tubes. Such a conclusion would indicate a piecewise, or “patchy” reconnection, recalling Arons (1984): “rather rarely does one see the theorists’ idealization of steady reconnection flow on a scale large compared to the local dissipation region.”

A cartoon to depict the patchy reconnection and subsequent supra-arcade downflow is shown in Figure 6. This cartoon is created in the spirit of reconnection *à la* Klimchuk (1997, his Figure 5) leading into McKenzie & Hudson (1999, their Figure 3): reconnection occurs in small patches, creating discrete flux tubes, which then individually shrink to relax the magnetic tension. The shrinking flux tubes dipolarize to form the post-eruption arcade. If models can be developed which have features like the supra-arcade spikes and downflows, then comparison with the observations should tell us how the patchiness and characteristic size (and even the presence or absence of supra-arcade structures) depend on parameters like field strength, helicity, etc.

Apart from predictive modeling, observational analyses that attempt to recover the three-dimensional con-

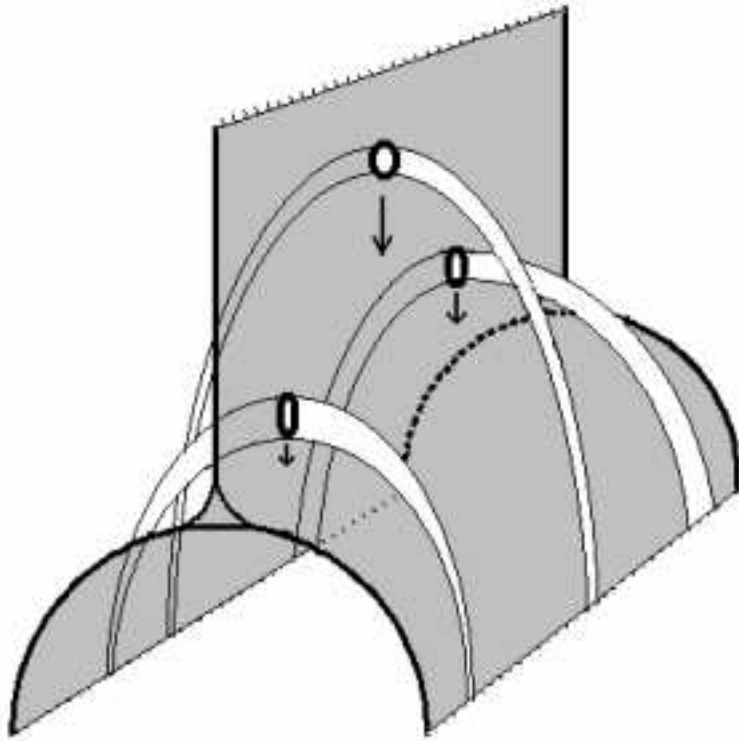


Fig. 6. Cartoon to depict supra-arcade downflows resulting from patchy reconnection (see text).

figurations of coronal structures are making considerable advances. In analysis like that by Mandrini *et al.* (1997), separators and/or quasi-separatrix layers indicate where flare brightenings should occur, with reasonable accuracy. In Fletcher *et al.* (2001), observed changes in magnetic topology (changes in separatrix position or configuration) seem consistent with the timing and morphology of the observed flare brightenings. These studies indicate significant advances in the quantitative treatment of flare morphologies since the initial diagrams of the CSHKP model.

CONCLUSION

Many observations seem to support the validity of the magnetic reconnection model of solar (and stellar) flares. They are, at the very least, consistent with the expectations of that model. But the appropriate use of observational data includes not only the confirmation (or refutation) of theoretical models, but also the obligation to push the models to ever-higher levels of sophistication. In the present case flare observations certainly exist which are difficult to describe in terms of the current “standard picture”. It behooves us, then, to study these “outlying” observations and learn what they are telling us about the physics of magnetic plasmas.

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