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THE PHOTOSPHERIC SOURCES OF JETS

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ABSTRACT

Most jets observed in the solar atmosphere are thought to be driven either by waves (magnetic or acoustic) or by the interaction between magnetic fields, i.e. magnetic reconnection. The morphology and dynamics of fields in the upper atmosphere, where the jets are seen, are in many cases driven by the motion of their footpoints in the solar photosphere. It is in this layer that the solar magnetic features are ordered, moved and mixed by the convection (granulation and supergranulation) and at which they are most easily observed. Similarly, it is the granulation and the p-modes in the solar photosphere which excite the waves propagating into the chromosphere and the hotter parts of the solar atmosphere.

Here four kinds of jets are considered, chromospheric jets seen in the EUV, spicules, explosive events and X-ray jets. For each of these the observed properties and basic model are briefly summarized before a description of their probable photospheric source is given.

1. INTRODUCTION

A variety of solar phenomena have been given the label "jets", often on the basis of morphological or spectroscopic signatures, usually well before the physical nature of the process was identified. This class of phenomena is consequently fairly broad and encompasses members as diverse as chromospheric jets and X-ray jets which are entirely unrelated to each other. These two examples have little in common in their appearance, physical parameters, method of observation, physical cause, or (of particular interest in the context of the present paper) the photospheric driver. This makes the task of coherently reviewing the photospheric sources of jets a difficult one. I have therefore restricted myself to just 4 basic types of jets. These are:

- Chromospheric jets: probably produced by acoustic waves (see Sect. 2)
- Spicules: probably driven by flux-tube waves (see Sect. 3)
- Explosive events: probably the signature of small-scale magnetic reconnection (see Sect. 4)
- X-ray jets and Hα surges: probably accelerated by larger scale magnetic reconnection (see Sect. 5)

X-ray jets and Hα surges are discussed together inspite of a factor of roughly 100 difference in temperature, since observations reveal that they are associated in a number of cases and numerical simulations suggest that they have similar causes.

Polar plumes are not reviewed, since they are far less dynamic than the above 4 phenomena. Their connection with the photospheric magnetic field is dealt with by De Forest (1998).

For the production of all except chromospheric EUV jets the magnetic field plays a central role, although different scales and features of the field are of relevance for the different types of jets. For spicules it is the waves within individual magnetic elements (best described by flux tubes) which are important, so that flux-tube physics, in particular the excitation and propagation of the wave modes supported by flux tubes is particularly relevant.

The other types of jets are thought to be associated with magnetic reconnection. In this case it is the motions and dynamics of magnetic flux tubes as a whole which is of interest. In the case of X-ray jets and Hα surges, which are often associated with flares, a substantial amount of magnetic flux is involved in the reconnection and the motion of whole groups of flux tubes is most relevant. Further details are given in the sections in which the individual types of jets are discussed.

2. CHROMOSPHERIC JETS

The observational signature of chromospheric jets is the presence of localized (a few arc s wide) blue or redshifts of C I lines located around 1560 Å corresponding to velocities of 10–20 km s^{-1}. Such jets were discovered in spectra obtained with HRTS (High Resolution Telescope and Spectrograph) and are described by Dere et al. (1983, 1986). Approximately twice as many blue- as redshifts are observed. Although lines other than those of C I also exhibit associated blue- and redshifts, lines formed above 2×10^4 K appear to remain completely unaffected. Hence these jets are a purely chromospheric phenomenon.

Of particular interest for determining the mechanism driving them is that they are generally located in the

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intranetwork (i.e. where the C I and other chromospheric lines are rather weak). This speaks for a non-magnetic source (although a connection with the weak intranetwork fields cannot be ruled out).

The other localized chromospheric phenomenon found mainly in the interiors of supergranules (i.e. in the intranetwork) are K_{2V} bright-points or grains (i.e. transient brightenings of the blue, and only the blue, emission peak in the core of the Ca II K absorption line) and 1600 Å continuum bright points. It therefore appeared natural to look for a relationship between these phenomena. No adequate K_{2V} data are available simultaneously with HRTS observations. Even between 1600 Å bright points and chromospheric jets no one-to-one relationship was found (Cook et al. 1996), even after allowing for a time delay of as much as 3 min between the brightening and the C I velocity shift. Due to their different heights of formation such a time delay is possible if a vertically propagating wave is the common source of both 1600 Å bright points and EUV jets. Later, Hoekzema et al. (1997) did find a small, but significant statistical correlation.

This suggests that there is inded a connection between the two. Hence, if the correlation is robust and can be extended to the K_{2V} grains then chromospheric jets would be driven, just like the K_{2V} grains, by 3 minute shock waves propagating through the chromosphere (Carlsson & Stein 1992, 1995, 1997). The velocities observed in the jets (which are on the order of Mach 1–2) speak for this interpretation, but in the absence of a direct correlation with the K_{2V} grains it cannot as yet be considered to be secure.

A variant of this interpretation of K_{2V} grains was proposed by Rutten & Uitenbroek (1991), who suggested that it is positive wave interference which leads to enhanced emission at the K_{2V} bright locations. Note that the Carlsson & Stein simulations, which reproduce the K_{2V} signature almost perfectly, are 1-D, so that such interference effects can indeed also occur and augment their results, although the success of the Carlsson & Stein simulations does not appear to leave a strong need for wave interference.

One great advantage of chromospheric jets is that the EUV emission lines in which they are observed are far less saturated than the Ca II K line core and may thus provide better constraints on the properties of the non-linear waves proposed to underly them.

The photospheric driver of the non-linear 3-minute propagating chromospheric waves is the high-frequency tail of the p-modes with possible contribution from the high-frequency part of the convective power spectrum. Recall that the cutoff frequency of the photosphere lies close to 3 minutes and the power of p-modes decreases rapidly as the period drops below 4 min. The dominant time scale of convection is the granule lifetime of 6–8 minutes. Hence a large part of the power of propagating chromospheric waves is expected to be located close to the 3 minute cutoff. This is confirmed by the simulations of Carlsson & Stein (1997), who used measured time series of photospheric velocities (filtered to keep only periods below the cutoff) to calculate the chromospheric waves, and obtained mainly 3 min waves in the chromosphere.

3. SPICULES AND FLUX TUBES

3.1. Spicules

Spicules are elongated, narrow structures (1–3″ wide) seen in emission at the solar limb. They are usually observed in Hα and are seen to propagate outwards at approximately 25 km s^{-1}. On average they are vertical, although individual spicules can be considerably inclined. Usually they are only seen in lines formed below roughly 15000 K. A detailed description of their properties is given by Beckers (1972) and recent observations are reviewed by Suematsu (1998). Their most likely counterparts on the disc are dark mottles seen in Hα (Tsiropoula et al. 1993, 1994, Tsiropoula & Schmieder 1997), which generally coincide approximately with the chromospheric network. Grossmann-Doerth & Schmidt (1992), on the other hand, see problems with this identification due to the absence of sufficient Doppler shift in the dark mottles (in contrast to Tsiropoula et al. 1993).

The most generally accepted models of spicules involve waves propagating along magnetic field lines, as first proposed by Parker (1964) and later developed by Hollweg (1982), Hollweg et al. (1982), Suematsu et al. (1982), Sterling & Hollweg (1984, 1988), Sterling & Mariska (1990), Cheng (1992a, b), De Pontieu (1998) and Kudoh & Shibata (1998), among others. See Sterling (1998) for a more complete list of references to the models, as well as a detailed discussion.

At the heights at which spicules are normally seen the magnetic field is relatively homogeneous in strength, although it may be considerably inhomogeneous in orientation (both in inclination and azimuth). If we follow it down into the photosphere the field becomes increasingly filamented with increasing depth, forming structures having a horizontal scale of approximately 100 km or less. Starting from a strength of only a few G in the quiet upper chromosphere the field strength reaches 1500 G in the lower photosphere, but the field only fills 1% or less of the solar surface in this layer (i.e. the magnetic filling factor is small). In more active regions the filling factor is larger (reaching 100% in sunspots). These filaments of strong field are often referred to as magnetic flux tubes. The properties of flux tubes have been reviewed by Spruit et al. (1992), Schüssler (1992), Solanki (1993) and Stenflo (1994).

3.2. Waves in flux tubes: theory

According to linear theory, axially symmetric thin flux tubes can support the following basic wave modes, all of which propagate along the field lines. Waves in flux tubes have been reviewed recently by, e.g., Roberts & Ulmschneider (1997).

- Magnetoacoustic waves, i.e. acoustic waves modified by the magnetic field. This is a longitudinal wave mode with a propagation velocity given by the tube speed,

$$c_T = \frac{c_s v_A}{\sqrt{c_s^2 + v_A^2}} ,$$

where c_s is the sound speed and v_A is the Alfvén speed,

$$v_A = \frac{B}{\sqrt{4\pi\rho_m}} .$$

Here ρ_m is the gas density within the flux tube. Note that $c_T < c_s$ and $c_T < v_A$. The cutoff frequency above which these waves propagate is relatively short, approximately 160 s. Thus only rather short-period waves propagate, and there is relatively little power in the granulation or the *p*-modes to excite such waves.

Thicker flux tubes also support a fast magnetosonic mode with a propagation speed above the sound and Alfvén speeds. It is, however, not well studied in the context of gravitationally stratified flux tubes.

- Torsional Alfvén waves (which are present if the flux tube is sufficiently thick to possess significant radial structure) are incompressible, have no cutoff frequency and propagate with the Alfvén speed. Even very slowly excited torsional waves propagate, unless the flux tube is part of a small loop, in which case the twist of the loop is affected.

- Transverse kink waves are incompressible and are thus Alfvén-like, but propagate at the kink speed which is slower than pure Alfvén waves:

$$c_k = v_A \sqrt{\frac{\rho_m}{\rho_m + \rho_s}} ,$$

where ρ_s is the gas density in the field-free surroundings of the flux tube. The kink wave has a cutoff frequency that is approximately 480 s or 8 min for typical photospheric flux-tube parameters. This is on the same order as the typical lifetime of granules. In the linear case kink waves are therefore expected to be easily excited by the constant buffetting which magnetic flux tubes endure from the granulation (see below).

The excitation of at least the longitudinal tube waves by turbulence in the external medium has been investigated by Musielak et al. (1989, 1990) in an analytical manner (in the linear regime; cf. Musielak 1992). The comparison of the wave fluxes with the outer atmospheric emission from stars across the cool part of the HR diagram looks encouraging.

In the non-linear regime (which is of particular importance in connection with spicules) the possible spectrum of waves is enriched by shock waves and non-periodic motions such as wave pulses or pulses of material transported up into the upper atmosphere.

The 2-D simulations of Steiner et al. (1993, 1995, 1996) show a number of examples of shock-wave pulses of a variety of strengths travelling up along the field lines of a flux tube. The stronger shocks locally heat the gas by considerable amounts. These simulations are fully compressible solutions of the complete set of MHD equations in slab geometry and include a 2-D grey radiative transfer. Unfortunately, these simulations only cover the photosphere. Following the further propagation and development of such a wave pulse right up to the transition region would be of great interest for the physics of spicules, but has so far not been attempted.

The studies of Steiner et al. are complementary to the simulations reviewed by Sterling (1998). The latter deal with the formation of spicules given the presence of a photospheric or chromospheric disturbance, whereas the work of Steiner et al. illustrates how such shock waves may be excited in the first place, and what their properties may be in the photospheric layers. For example, in the simulations of Steiner et al. the shock wave can be very inhomogeneous across the flux tube, with the velocities being rather different along different field lines.

The simulations of Steiner et al. show that the flux tube is buffeted quite strongly by the convective cells. As granules form and decay they hit the flux tube on the side. The antisymmetric part of the lateral force produced by the granular dynamics cause the flux tube to tilt, while the symmetric part squeezes it. Due to the supersonic velocities reached by the horizontal flow in the granulation (Cattaneo et al. 1990, Solanki et al. 1996) these lateral forces can be considerable. This squeezing can cause material to shoot out at near the sound speed. Although this appears to be the likely cause of the propagating shocks seen in the Steiner et al. simulations other mechanisms for their production cannot as yet be ruled out (e.g. overstability). In principle, the bending of the flux tube due to the granules hitting it on the side can also cause propagating kink waves (Choudhuri et al. 1993).

The excitation of torsional waves cannot be modelled by simulations in a 2-D slab geometry, but it is interesting to note that flux tubes are observed to be located at the boundaries of granules, in the intergranular lanes (Title et al. 1987, Solanki 1989). Due to the conservation of angular momentum the material flowing into the intergranular lanes should easily form vortices as it begins to flow down. Such vortices, if really present, would be ideal to excite torsional wave modes. Theoretically, a strong case for such vortices exists since there is a problem of keeping flux tubes above a certain size stable to the fluting instability if they are not located within a vortice of sufficient strength (Schüssler 1984, 1986, Bünte 1993, Bünte et al. 1993a, b).

3.3. Waves in flux tubes: observations

Observations of waves in magnetic elements or the network are not very common and partly give rather surprising results. Most photospheric observations relating directly to flux tubes (i.e. those based on polarimetric observations) exhibit significant oscillations only at periods close to 5 minutes (Giovanelli et al. 1978, Fleck 1991). Volkmer et al. (1995), however, find 100 s periods in Stokes V, with a 280 m s^{-1} amplitude. According to linear theory this period corresponds to propagating longitudinal tube waves. Unfortunately, only a single magnetic feature was found to exhibit such oscillations and confirmation is important. Also, it is unclear to what extent waves of this amplitude are of interest for spicules, particularly since they are expected to be radiatively and acoustically damped on the way to the upper chromosphere. They may nevertheless be important for chromospheric heating. Volkmer et al. (1995) estimate an energy flux of 1.6–2.3 × 10^7 erg cm^{-2} s^{-1}, sufficient to heat the associated chromospheric network, in the absence of damping and if such waves are common.

Observations of a more indirect nature, such as those of line broadening or of the spatial rms of Stokes V wavelength shifts indicate larger amplitudes. The rms shifts have values of 300–400 m s^{-1} (Kneer & Stolpe 1996, Martínez Pillet et al. 1997). The association of such seemingly random wavelength shifts with waves is unclear.

Observations of Stokes V asymmetry and width show values that suggest the presence of even stronger (2 km s^{-1}) non-stationary motions within magnetic elements. But again, which fraction of these is due to propagating waves (i.e. those that can carry energy into the upper atmosphere) is at present open.

Finally, observations of oscillations in chromospheric layers of the network show that the power is lower and shifted to lower frequencies in the network relative to the intranetwork (Deubner & Fleck 1990, Bocchialini et al. 1994). However, both Deubner & Fleck (1990), from phase relations, and Bocchialini & Baudin (1995), from comparison of wavelet transforms of time series of different lines, conclude that the chromospheric waves travel downwards in the network. These observations are certainly not supportive of wave models of spicules, which all have in common that they require upward propagating waves. A misinterpretation of the observations cannot be completely ruled out, however. For example, Bocchialini & Baudin (1995) point out that if the relative heights of formation of the 2 lines they use (He I 10830Å and Ca II K) were contrary to what they assumed (i.e. if Ca II were formed higher) then their data would be consistent with upward propagation.

4. EXPLOSIVE EVENTS

These are localized, short-lived intense broadenings of spectral lines formed in the temperature range 2×10^4–2×10^5 K (such as C IV 1548 Å, 1550 Å, or Si IV 1393 Å, 1402 Å, e.g. Brueckner & Bartoe 1983, Dere et al. 1984, Cook et al. 1987, Dere 1989, Curdt et al. 1998). They typically possess broadening velocities of around 100 km s^{-1}, but broadenings as large as 400 km s^{-1} have been observed. In addition, the line profile may, but need not, be shifted by a significant fraction of the broadening (both red- and blueshifts are observed). Explosive events are a common quiet-sun phenomenon and are found all over the solar disc. See the review given by Wilhelm (1998) for the most recent, SUMER-based results on explosive events.

Dere et al. (1991) and Innes et al. (1996) have proposed that the line broadenings are due to the (symmetric) outflow jets located on both sides of a reconnection site and Innes et al. (1996) have presented strong evidence supporting this proposal. Explosive events are highly localized structures (generally only a few arc s in length). Because of this and since they are observed mainly in the quiet sun the underlying reconnection must involve small amounts of magnetic flux.

Magnetic reconnection generally occurs following earlier changes in the amount or distribution of magnetic flux. These changes can be caused by any one, or a combination of the following processes:

- flux emergence
- foot point motions
- flux cancellation

In the quiet sun these processes often run in parallel. If we consider a sufficiently large portion of the solar surface fresh flux is continuously emerging. At very small scales this is in the form of intranetwork features, which appear on the surface inside supergranule cells (they carry a flux of 10^{16}–10^{17} Mx per feature); at larger scales ephemeral active regions emerge in the quiet sun (approximately 10^{19} Mx per region) and on the largest scales active regions transport 10^{21}–10^{22} to the surface per region, but only within 30° of the equator (Harvey & Martin 1973, Harvey et al. 1975, Howard 1991). The total rate of flux emergence averaged over the whole sun increases rapidly towards smaller fluxes per feature, being 10^{20} Mx/day in active regions, 10^{22} Mx/day in ephemeral regions and an estimated 10^{24} Mx/day in intranetwork fields, implying that the magnetic field in the network is replenished on a time scale of a couple of days (Zirin 1987, Stenflo 1991, Schrijver et al. 1997). Such a high rate of flux emergence requires an equally high rate of flux removal. Since the two polarities of an emerging dipole generally separate rapidly from each other and don't usually come back together again, the removal of flux often must be preceded by magnetic reconnection. But let us first briefly consider the emergence.

When fresh flux emerges into an atmosphere already containing a significant amount of field, reconnection is almost inevitable, unless the axis and polarity of the emerging loop happens to be aligned with that of the overlying field. The reconnection probably does not take place in the photosphere, since the field only covers a small part of the solar surface in these layers. However, in the chromosphere the field of the individual flux tubes spreads out and fills the atmosphere so that the emerging and the ambient fields collide. Depending on the speed of emergence, the relative orientation of the old and new field and the resistivity of the plasma the reconnection will take place in the chromosphere, or in a higher layer.

Magnetic reconnection can also be triggered by the movement of individual flux tubes, which can force the field to move away from the equilibrium it had previously occupied. Such translations along the surface, which in the coronal community are generally referred to as foot-point motions, may be caused either by the influence of differential rotation, the dragging along of field lines by convective motions, or the motions of the flux rope underlying the active region in the solar interior (e.g., as part of a relaxation or unwinding process). It is thought that the many small flux tubes forming an active region are produced by the fragmentation of a large flux rope that rises from the base of the convection zone to the solar surface (Zwaan 1978, Moreno-Insertis et al. 1992, D'Silva & Choudhuri 1993, D'Silva & Howard 1993a, b, Schüssler et al. 1994). For the quiet-sun fields involved in producing explosive events convection is probably the most important source of foot-point motions (see Spruit et al. 1990 for a review of solar near-surface convection).

We must also keep in mind that the magnetic structure of the quiet sun is basically 3-dimensional. The features seen in a magnetogram have complex interconnections, with the field lines emanating from a given photospheric magnetic feature being connected to a number of other such features. These could in turn be connected to each other, as well as to others and so on (Van Ballegooijen, private communication). Such an environment, in which field lines criss-cross the atmosphere, is highly condusive to reconnection.

Footpoint motions can be deduced from high-resolution magnetograms (or more indirectly from filtergrams) with the help of a cross-correlation analysis. It reveals motions on the mesogranular (approximately 7 Mm, November et al. 1981) as well as the supergranular scale (20 Mm, Simon & Leighton 1964, Simon et al. 1988). The time-scales of these motions are an hour and 20–30 hours, respectively.

In general, observations do not possess the resolution to show clearly motions at the granular and in particular the subgranular scale. Exceptions are filtergram movies with very high spatial resolution (Muller et al. 1994, Berger & Title 1996). Also, simulations of granular convection allow motions on these scales to be revealed. As expected, foot-point motions on a time-scale of minutes turn out to be common, if we assume that magnetic foot points correspond to local brightenings (in the case of the observations), or are located in and moving with the intergranular lanes (in the simulations). These assumptions are supported by both observations and theory.

Returning now to explosive events, the main observational finding related to the photosphere is that they are generally located close to the magnetic network, but not in or even very close to the strongest parts of the network (Porter and Dere 1991, Moses et al. 1994, Wilhelm 1998).

The location of explosive events at the edge of the network suggests that the reconnection may involve intranetwork fields, although it by no means constitutes a proof. Intranetwork fields emerge in supergranular cell interiors and are advected outward until they merge with the network (if both have the same polarity) or cancel with it (if they possess opposite polarities; Martin 1988). Since the intranetwork elements seem to emerge as bipolar pairs, they probably are not initially connected with the network. Hence the cancellation with network fields must be accompanied by magnetic reconnection.

Inspite of this tentative identification of explosive events with cancelling magnetic features it is worth noting that broad profiles typical of those identifying explosive events have been seen in an emerging flux region (a young active region) by Brueckner et al. (1988), implying that the reconnection taking place there produced similar outflows as in the explosive events seen around the network.

5. X-RAY JETS AND Hα SURGES: EMERGING OR CANCELLING FLUX?

X-ray jets and Hα surges are in a geometrical sense larger than the other phenomena discussed so far in this paper and are usually found in active regions (also in contrast to the rest). X-ray jets have an average length of 1.5×10^5 km and an average velocity of 200 km s^{-1}. For more details on their observed properties see Shibata et al. (1992), Shimojo et al. (1996) and Shibata (1998). They differ strongly in temperature from the Hα surges, as is already evident from the respective wavelength ranges in which they are seen. In some cases both hot and cool jets occur together (Canfield et al. 1996), in other cases individually (e.g. Schmieder et al. 1995).

X-ray jets are often associated with loop brightenings (Shimizu et al. 1992) and sometimes with flares. According to Shibata (1998) many if not all X-ray bright points (XBPs) also show X-ray jets at some point in their evolution.

Both X-ray jets and Hα surges are thought to be produced by magnetic reconnection involving substantial amounts of flux. The most detailed model is that of Yokoyama & Shibata (1995, 1996). They carry out two-dimensional simulations of the emergence of a magnetic loop into the solar atmosphere, which is already filled with a homogeneous field (cf. Hanaoka 1998, Yokoyama 1998). Their model successfully reproduces a number of observations, although, e.g., the twist observed in the Hα surges studied by Canfield et al. (1996) can, of course, not be reproduced by a 2-D slab simulation. Nevertheless, the success of the Yokoyama & Shibata model has shed much light onto the physical nature of X-ray jets, including the association of hot and cool jets. Also see Shibata & Uchida (1986) for a model incorporating twist.

The photospheric part of the story is related to the magnetic evolution of active regions (Zwaan 1987, Howard 1991, 1992), where again the magnetic field is distorted by the same basic processes as in the quiet sun (flux emergence, foot point motions and flux cancellation), but on a larger scale, in the sense that larger amounts of flux are involved. Also, the relative importance of the various possible drivers of footpoint motions is different from the quiet sun, since the amount of flux in active regions is sufficiently large to significantly influence the underlying convection (at least near the surface layers). Convection still plays an important role: e.g., moving magnetic features around sunspots are propelled by the moat flow, flux tubes in active region plage seem to be ordered around convection cells, and the dispersal of active regions is at least partly driven by the changing pattern of convection cells. However, the contribution of movements of the flux rope that underlies the active region as a whole (e.g. if the emerging flux rope is twisted) and solar differential rotation to the build up of shear is probably quite substantial (Hagyard et al. 1984, Zappala & Zuccarello 1989, Zuccarello 1992).

The relation of X-ray jets to the underlying magnetic field has been specifically studied by Shimojo et al. (1998). They considered the distribution of magnetic flux in the near vicinity of the jet foot-points and found that in at least 85% of all cases both polarities are present there. Only in 10–15% of these mixed-polarity cases is the field ordered in the form of a dipole, for the rest the distribution of the polarities is more complex.

For 3 active regions Shimojo et al. (1998) have also followed the time-evolution of the magnetic field in fixed areas which repeatedly produced jets. They employed daily magnetograms recorded at Kitt Peak for this purpose. Their results show that a total of 7 jets were produced at a time when total flux was increasing in the considered areas, whereas 9 jets were produced while flux was decreasing.

Unfortunately, this observation alone is not sufficient to tell us the true source of the apparent change in flux, as the following discussion illustrates. An apparent increase in flux, as deduced from the strength of the magnetogram signal, on a selected part of the solar surface (e.g., a rectangular box) can be produced either by the emergence of fresh flux inside the box or by the lateral movement of flux into the box. Furthermore, since only the longitudinal component of the magnetic field is measured a change in the average inclination of the field can also appear like a seeming change of flux. Finally, thermodynamic changes may also influence the results (e.g. Grossmann-Doerth et al. 1987). Similarly, the movement of flux out of a box, flux cancellation or retraction, effects of the magnetic inclination or of the thermodynamic parameters can produce the observed apparent flux decrease.

If, however, we neglect the horizontal transport of flux and other effects related to the interpretation of a magnetogram for the moment then the observations of Shimojo et al. (1998) suggest that approximately half the X-ray jets in the 3 considered active regions are connected with flux emergence as modelled by Yokoyama & Shibata (1995, 1996), whereas the other half appears to be associated with flux cancellation. The evolution of the magnetic field in these latter cases may be closer to the scenario proposed by Priest et al. (1994) and Parnell et al. (1994a, b) to explain XBPs, namely the transport of two previously unconnected flux tubes of opposite polarity towards each other in the presence of a more or less homogeneous overlying coronal field. This model was inspired by the observations of Harvey (1984, 1985) and Webb et al. (1993) that XBPs are generally associated with cencelling magnetic features: 72% of XBPs are associated with cancelling magnetic features (i.e. opposite polarity magnetic features that have converged and are now merging with an associated decrease in flux) and 88% with converging magnetic features (which also encompass the cancelling features).

In the Priest et al. model the reconnection between the fields of the two flux tubes is expected to lead to the production of a jet-like feature. In the exact geometry they consider it is a a two-sided jet, but this may be changed if, like Yokoyama & Shibata (1995), they allow the coronal field to be inclined. Interestingly, Shibata (1998) pointed out the intimate connection between XBPs and jets in his excellent review of the subject. This lends further support to the need to also consider cancelling magnetic fields in future jet models. A simulation similar to that of Yokoyama & Shibata (1996), but for cancelling magnetic features should provide new insight into the production of the X-ray-jet phenomenon.

From an observational point of view it would be very useful to extend the Shimojo et al. (1998) study in different ways, e.g. by studying the evolution of the field with the higher temporal (and partly also spatial) resolution provided by MDI, and by improving the methodology in order to be able to distinguish between emergence of flux at the jet footpoints or transport of flux towards it. A collaborative effort is planned to settle this question.

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