

YOHKOH-SXT OBSERVATIONS OF RECONNECTION

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ABSTRACT

In this paper I review the different strong indications for the occurrence of reconnection in the solar corona observed with *Yohkoh*-SXT. I make a distinction between the unique indicator of reconnection, i.e. the change in connectivity in the magnetic field, and non-unique *signatures* of reconnection, that also can originate from other processes. I review five different types of *Yohkoh*-SXT observations that indicate reconnection in the solar corona: erupting plasmoids, X-ray jets, formation of sigmoids through “linkage”, the existence of interconnecting loops, and the rigid rotation of coronal holes. I conclude that the presence of reconnection in the solar corona has been established with near certainty, but that higher resolution soft X-ray and EUV observations are needed to firmly establish the full physical picture for each of the phenomena described.

INTRODUCTION

Yohkoh has left a splendid legacy of nearly a full solar activity cycle of soft and hard X-ray imaging combined with spectroscopic observations. The *Yohkoh* satellite was launched on August 30, 1991 by the Institute of Space and Astronautical Science (ISAS) from its Kagoshima Space Center, and operated until December 14, 2001, despite having a design goal of a lifetime of only three years. In its ten years of operations since, *Yohkoh* has acquired about 6 million soft X-ray snapshot images and detected more than 2800 high energy X-ray solar flares. More than a thousand papers by authors worldwide have been published from *Yohkoh* in journals and proceedings, and a new generation of solar physicists has begun thesis research using *Yohkoh* data.

In this paper I will attempt the difficult task of reviewing the progress made with observations from the Soft X-ray Telescope (SXT, Tsuneta et al. 1991) in establishing the presence of reconnection in the solar corona. This presence is expected on theoretical grounds because soft X-ray images of the corona reveal a very complex topology with discontinuities in the magnetic connectivity, and a ceaseless activity, including very powerful eruptions, that is hard to understand without there being reconnection. Yet undisputable proof of reconnection in specific instances is still hard to come by, because the resolution of current X-ray imagers is still limited (the X-ray Telescope (XRT) on Solar-B will be a great step forward, see Golub 1999), and because the full 3D structure of magnetic regions is obscured since we observe from only one vantage point. The latter situation will be remedied by the upcoming STEREO mission.

In the following I will describe the only observation that, in my view, can provide indisputable proof of reconnection, and distinguish it from non-unique signatures of reconnection. Then I will review five types of phenomena for which *Yohkoh*-SXT has amply observed reconnection: erupting plasmoids, X-ray jets, formation of sigmoids through “linkage”, the existence of interconnecting loops, and the rigid rotation of coronal holes.

Yohkoh-SXT observations of signatures of reconnection by other instruments, the Hard X-ray Telescope (HXT) and the Bent Crystal Spectrometer (BCS) have recently been reviewed by respectively Masuda (2002) and Harra (2002).

HOW DOES YOHKOH OBSERVE RECONNECTION?

There are many signatures of reconnection, e.g. sudden plasma heating, the many manifestations of the presence of high energy particles, such as radio emission and hard X-rays, fast (i.e. $v \approx v_A$) plasma flows, and changes in field line connectivity. Most of these signatures are not unique: for example high energy particles can be accelerated by shocks (and we know this happens in interplanetary space, see Reames, 1999), plasma flows, can be generated by “buffeting”, as may be the case for spicules (Roberts 1979), and plasma can be suddenly heated by compression or conduction (Priest et al. 2002).

A unique indicator of magnetic reconnection is a change in connectivity of the magnetic field; in fact this can be the definition of reconnection (see Priest and Forbes 2000, Chap. 8.1 for an extensive discussion). To establish reconnection in the solar corona in this manner one has to observe for example that one or both foot points of a magnetic loop connect to different end points after an ‘event’, such as an eruption. A great decrease in the shear of magnetic loops after an eruption may be a case in point. Of course one has to rule out that photospheric footpoint motions can lead to the same change in connectivity; in most cases the velocities required during the ‘event’ would be larger than any ever observed in the photosphere.

Note that this topological indicator of reconnection does not require detailed observations of the reconnection site (usually a current sheet or a “null”) itself. This is a great advantage, because estimates of sheet thickness vary from 10 cm to 10 km in the solar corona, still by a long way out of reach of our highest resolution coronal imagers. Indeed the rearrangement of topology through reconnection can manifest itself from very short to the very large scales of the overall coronal structure. *Yohkoh* is ideally designed to observe reconnection on a large scale in the solar corona, because its field of view is the whole Sun, while its resolution is sufficient to identify individual soft X-ray loops.

In closing this section I note that while the non-unique signatures of reconnection (flows, heating, high energy particles) discussed above do not unambiguously establish reconnection, once reconnection has been demonstrated from a change in connectivity observed in a time series of *Yohkoh*-SXT mages, then these signatures become important quantitative diagnostics of the reconnection process. They will yield clues to the field strength, energy conversion rate, and the collisionality of the reconnection regime in operation.

FIVE TYPES OF RECONNECTION OBSERVED BY YOHKOH-SXT

Cusps in the Aftermath of Erupting Plasmoids

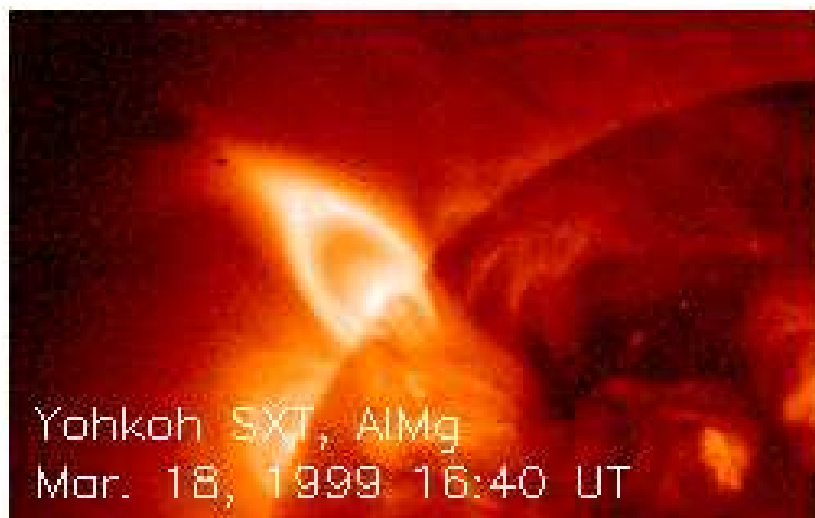


Fig. 1. A “cusp” on the solar limb observed by *Yohkoh*-SXT through the Aluminum-Magnesium combination of filters.

The “cusp”, a bright loop in soft X-rays with a pointy top (see Figure 1), has become sort of an emblem for SXT. Cusps occur in the aftermath of plasma eruptions and are part of two-ribbon flares. Their discovery seems to confirm the “standard” picture for two-ribbon flares, known as the Carmichael (1964) - Sturrock (1968) - Hirayama (1974) - Kopp and Pneuman (1976) model (CSHKP), extensively described in the literature; see the recent review by McKenzie (2002). However, as I will describe below, in 3D the picture is far from clear yet. This CSHKP interpretation is summarized by Figure 2, taken from McKenzie’s review, which identifies the major physical processes and the papers in which they are described. The *Yohkoh*-SXT observations have to a large degree confirmed and refined this “standard” model, but its origin predates *Yohkoh*, as the cartoons by Cliver (1983), and Martens and Kuin (1989) demonstrate.

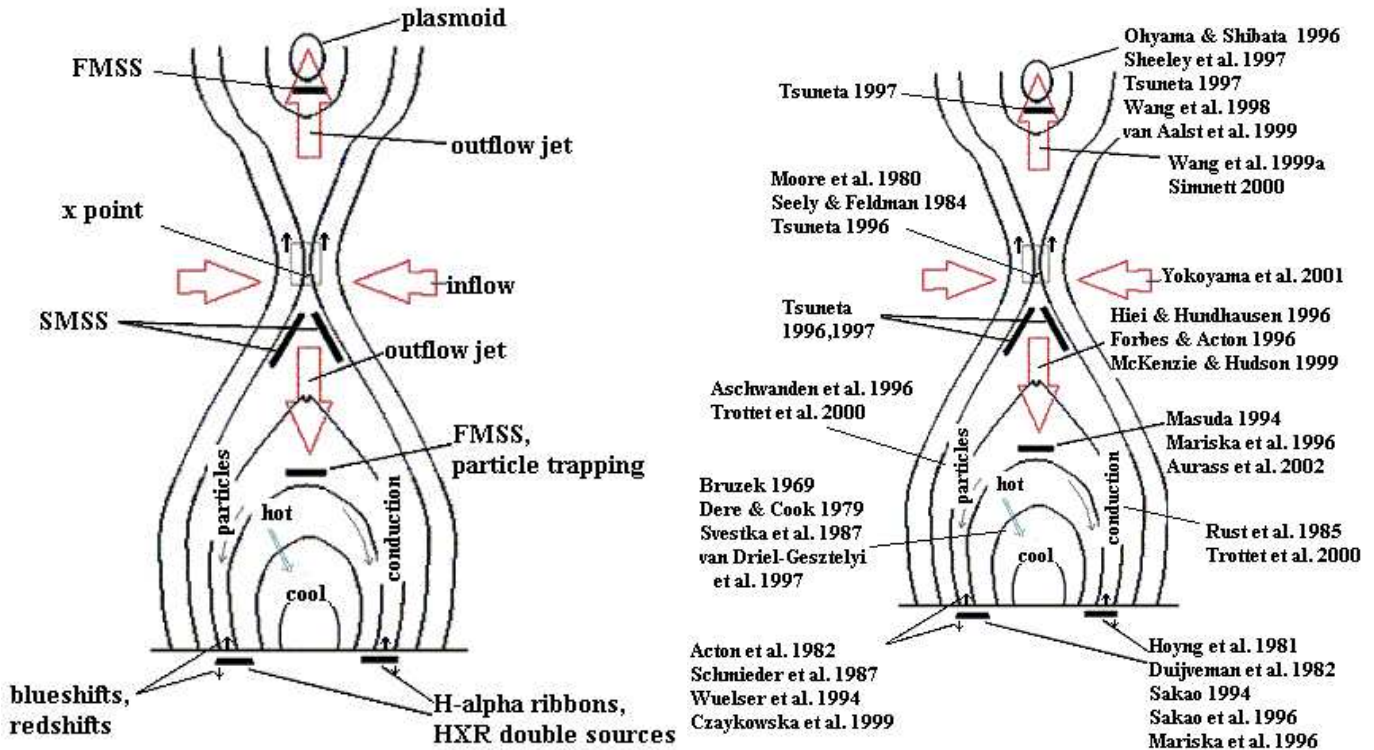


Fig. 2. The “standard” CSHKP model for filament eruptions and two-ribbon flares, with the main physical processes identified on the left and pertinent papers listed on the right. From McKenzie (2002).

The CSHKP scenario implies reconnection and the formation of a current sheet in the wake of the erupting plasmoid. The presence of a cusp in the magnetic field configuration is exactly what one expects from MHD models below such a current sheet, and the brightness of the cusp loop indicates that the bulk of the energy release takes place in the current sheet on top of the sheet. Time-of-flight analysis of high energy particles implied by hard X-ray emission from the footpoints of the flare loops (see the review by Aschwanden, 2002) confirms that scenario.

Reconnection is a necessity in the 2D or 2.5D versions of this scenario, since fieldlines that start from the same photospheric footpoints originally connect over the erupting plasmoid and later close below it as part of the postflare loop system. The observed decrease in the shear of magnetic loops after the eruption appears to clinch the case. Yet, the full 3D situation might be more complicated than the CSHKP picture, and it is here that future higher resolution observations, for example from XRT on Solar-B could shed more light. One problem with the “standard” model is that cusps observed on the disk usually do not form arcades, as the 2D or 2.5D model implies, but single loops (see Figure 3), with the other parts of the arcade much less bright and with loop tops at lower height. Theoretically, in full 3D, the erupting plasmoid could wiggle itself through the overlying field without the need for reconnection (e.g. the cartoon by Sturrock 1989, his Figure 2), very much like a hernia. I expect that progress in the remainder of this decade will come from observing and analyzing this full 3D picture, and that reconnection will be confirmed to play

a major role but in a more complicated geometry – it is difficult to understand the enormous energy release within the short duration of the flare otherwise.

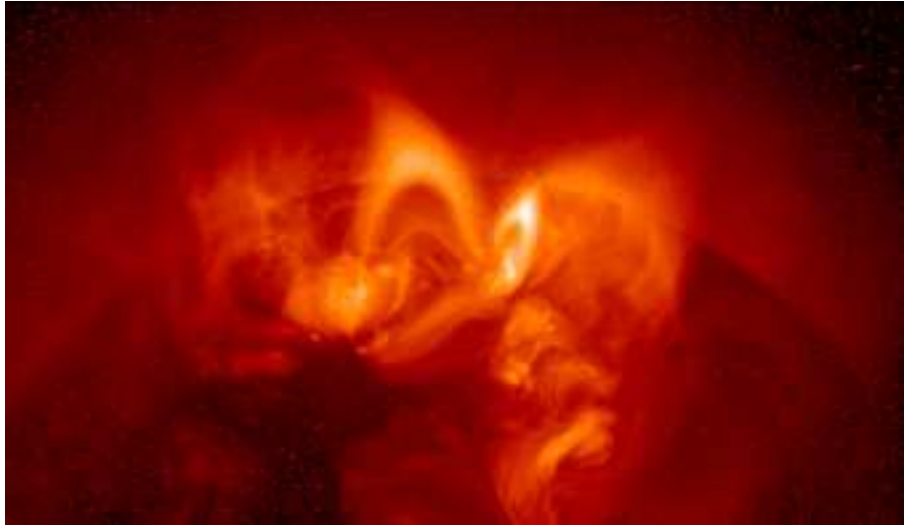


Fig. 3. A pair of cusps on the disk, observed by *Yohkoh*-SXT. The cusp on the right demonstrates that cusps are not part of a simple translationally symmetric arcade of postflare loops as in the standard model, while the cusp on the right appears to have its point linked to a remote footpoint rather than interplanetary space. Figure courtesy of Alex Pevtsov.

X-ray Jets

The discovery of X-ray jets is, to my knowledge, also a *Yohkoh* first. In particular Shibata and co-workers (e.g. the review by Shibata 1999) have studied and modeled these features extensively. The length of jets ranges from 1000 to 400,000 km and the apparent velocity is 100 - 1000 km/s. The interpretation, summarized in Figure 4, is that reconnection opens up new pathways for energy released by the same process to escape along the field to remote footpoints or into interplanetary space. Simultaneous radio observations of type III bursts (Aurass et al. 1994, Kundu et al. 1995) demonstrate the presence of high energy electrons in such events, reinforcing the reconnection interpretation.

Figure 4(c), from Yokoyama and Shibata (1995), shows that for single jets reconnection is envisaged to take place in a geometry similar to that for cusps, but in this case what is the postflare loop in the cusp case is the one being reconnected with an overlying field line, and the reconnected field line containing the jet that carries the liberated energy is what is the preflare overlying fieldline in the cusp case. Hence the reconnection goes in the opposite direction. The driver for the reconnection is assumed to be the emergence of new flux, in the central arcade, which is the postflare arcade for the CSHKP geometry.

There is, as far as I know, no direct evidence of a change of connectivity of field lines at the onset of a jet. Such evidence would indeed be hard to come by, since the preflare loop is small and would be tenuous. However, despite this lack of direct proof, reconnection as in Shibata's models is a very plausible explanation. Other mechanisms of generating jets, such as granular buffeting, are not likely to produce the observed high energy electrons and high temperature (4-6 MK) jet plasma. Future high resolution, high cadence observations might be capable of detecting the "slingshot" effect of the newly reconnected fieldline in the jet.

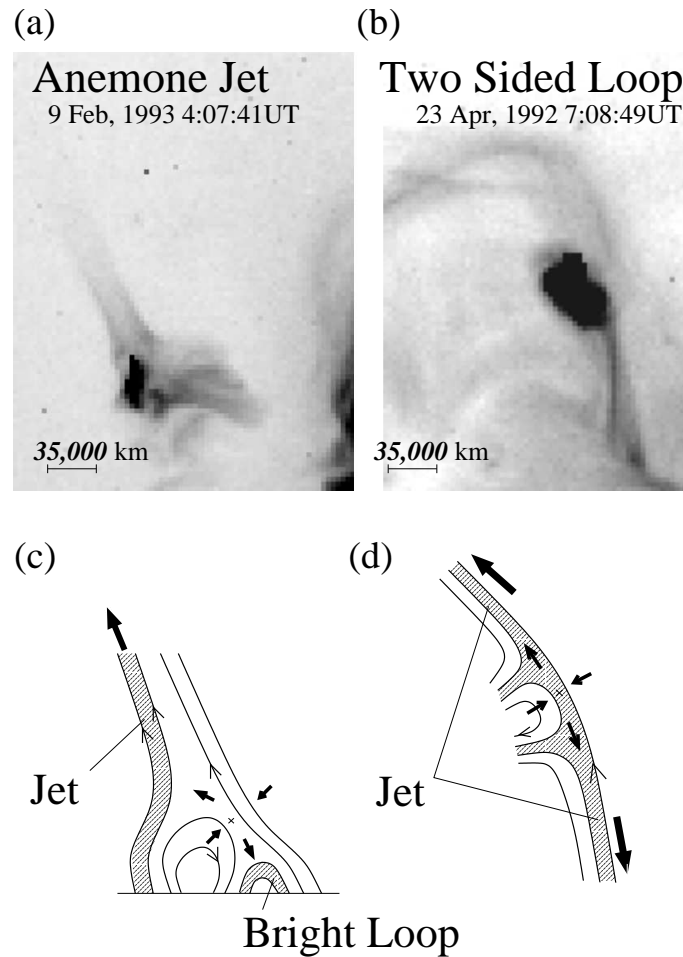


Fig. 4. Two types of reconnection between emerging and overlying flux. The left pair shows reconnection with open field, and the right pair with closed field. On top are *Yohkoh*-SXT images, and on the bottom cartoon interpretations. From Yokoyama and Shibata (1995).

The Formation of Sigmoids and Filaments

It is well known that the formation of a coronal filament or sigmoid often is the precursor to a plasmoid eruption and two-ribbon flare. Recent detailed observations of the formation of sigmoids (e.g. Pevtsov et al. 1996) and of filaments (e.g. the review by Martin 1998) have revealed that reconnection may also be an important feature not only in the eruption of these features, but also in their formation. Martens and Zwaan (2001) have coined the term “linkage” to describe such events, and presented a model in which flux cancellation in a mixed polarity magnetic field (at least a quadrupole) causes such linkage. Figure 5 (left), from Pevtsov et al. (1996), shows an example of linkage in the formation of a sigmoid observed by SXT. Two loops, each in the shape of a fish-hook link up at their end points to form fully developed sigmoid. The interpretation of Martens and Zwaan (2001) is shown in Figure 5 (right): two simply connected magnetic dipoles converge and reconnect at their sides to form more complicated field lines that follow the polarity inversion line all along. This scenario was developed for prominence formation, but may apply to sigmoids as well, as Figure 5 (left) suggests. Note that in this case the reconnection, which shows up as “cancellation” in magnetograms (Martin 1998) occurs beneath the corona, probably in the temperature minimum region (Litvinenko and Martin 1999). The resulting sigmoids or filaments however, show up in the corona, and are observed by *Yohkoh*-SXT, the latter as a void.

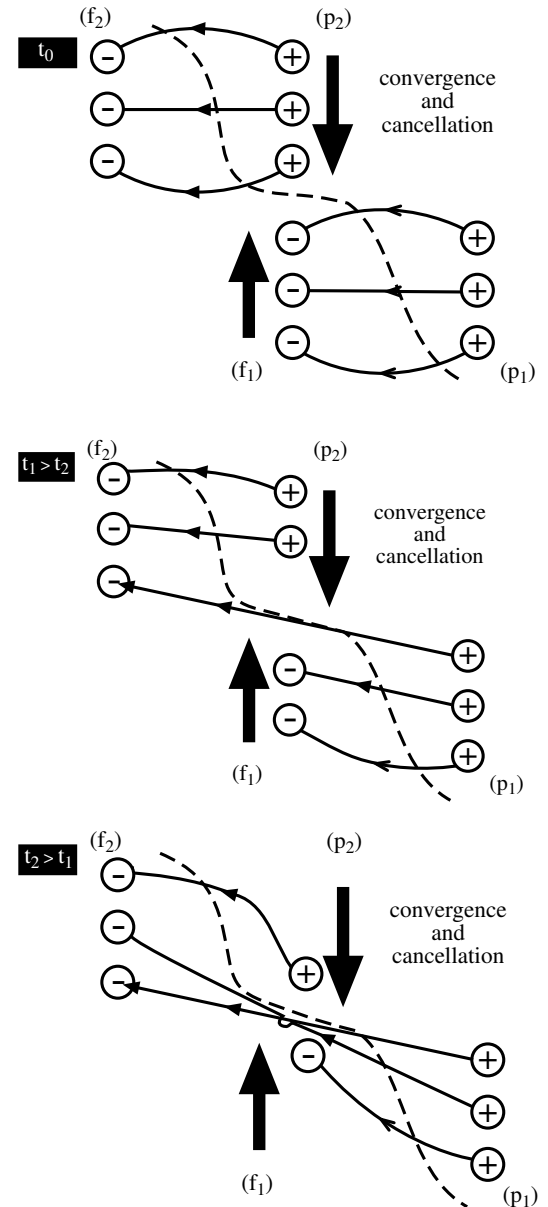
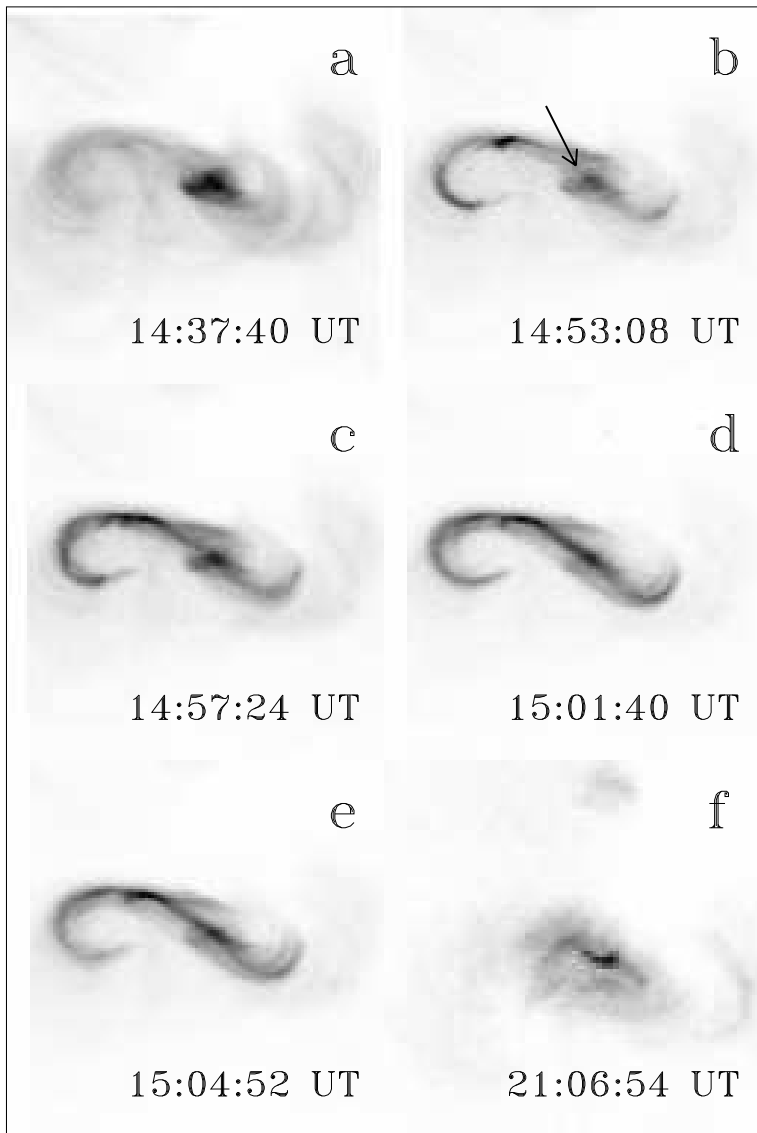


Fig. 5. Left: *Yohkoh*-SXT observations of two soft X-ray loops (a) linking (b-e) into a single sigmoid, followed by the sigmoid's eruption (f). From Pevtsov et al. 1996. Right: A model for "linkage" through convergence and cancellation of the magnetic field of two previously unconnected dipoles, leading to the formation of a prominence or sigmoid at the cancellation region. From Martens and Zwaan (2001).

It is important to inform the reader at this point that there exists an alternative interpretation of these events, advocated by Rust (2001) and others. The "linkage" can be the final phase of the emergence of a preexisting flux tube: the emergence a U-type loop segment that connects the two sigmoid or filament segments beneath the photosphere. This model is particularly plausible in newly emerging active regions with a fairly uncomplicated magnetic structure. However, it is wholly implausible for filament formation in the polar crown or the switchback, or in decaying active regions, where flux emergence on such a scale is simply never observed. Moreover, the segments that link up in these regions originate from different bipoles or active regions, and thus are unlikely to have connections below the photosphere. Hence observations of "linkage" by SXT and ground based telescopes (particularly $H\alpha$) outside of newly emerging active regions are a good direct indicator of reconnection below the corona.

Interconnecting Loops

The existence of loops that connect distinct active regions, often over very large distances and sometimes across the equator, is nearly indisputable evidence of the occurrence of reconnection in the corona. The full disk SXT soft X-ray image in Figure 6 illustrates the case. The interconnecting loops often bridge large regions of very small field strength in which no emergence other than that of tiny dipoles is observed. Moreover, of the two active regions that these loops connect one is usually demonstrably older than the other, so that a loop connecting them could not have emerged with the older one, because it would have had nowhere to connect to. EUV observations by *TRACE*, taken at a very high cadence, have indeed shown rapid coronal restructuring and the formation of interconnecting loops during the emergence of active regions.

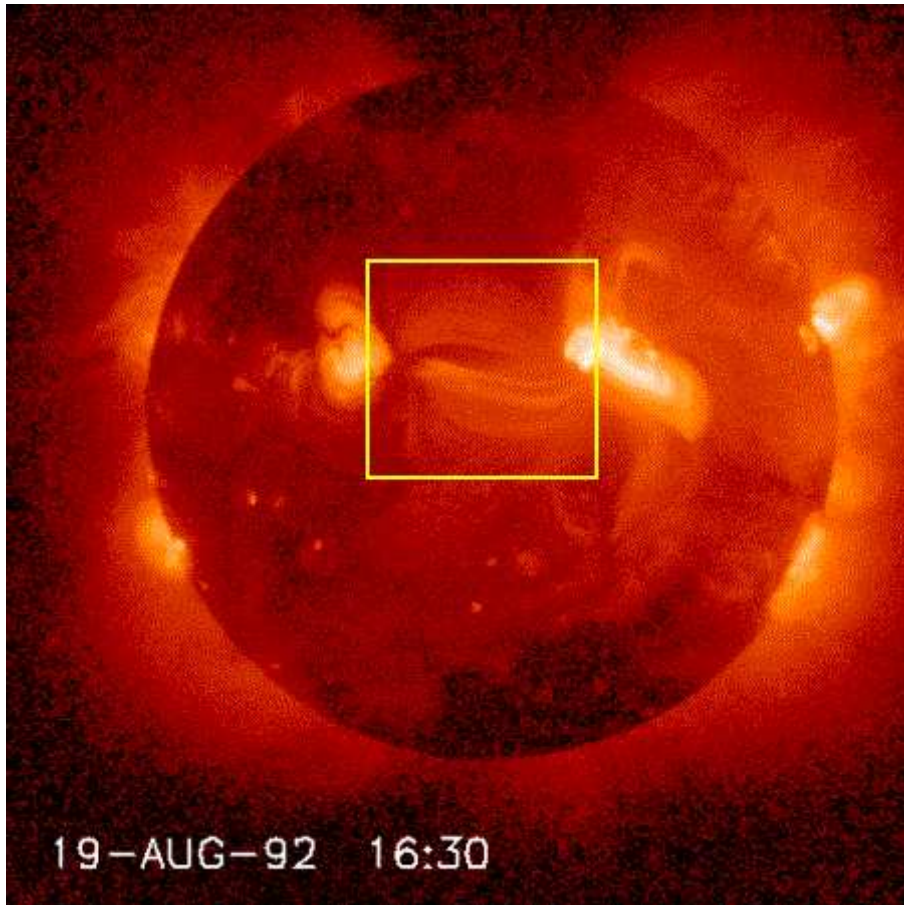


Fig. 6. *Yohkoh*-SXT full disk image clearly showing the presence of interconnecting loops across the meridian between two Active Regions in the northern hemisphere.

Transequatorial loops are a strong case in point: it is very unlikely on theoretical grounds, and has never been observed, that such loops emerge as pre-existing flux tubes from below the chromosphere. Figure 7, from Pevtsov (2000), captures the formation of such a loop in a time span of two days between a mature and an emerging active region.

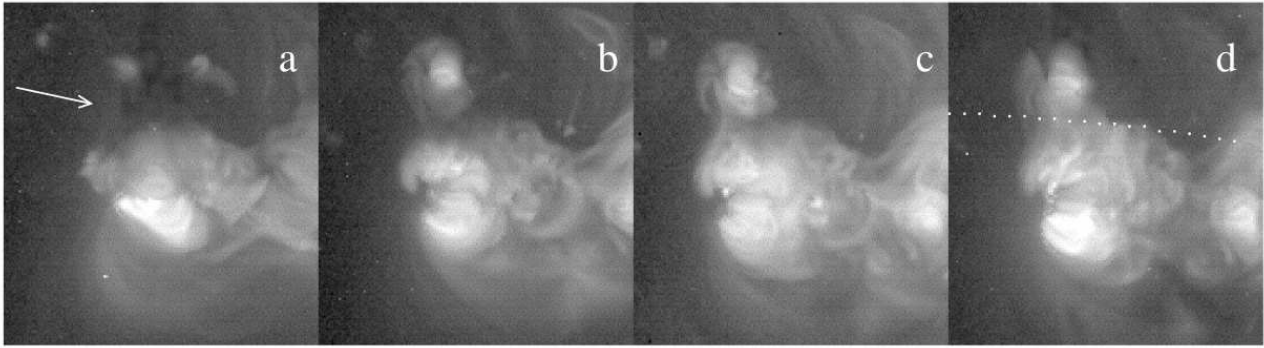


Fig. 7. Formation of transequatorial loops between mature and emerging flux from 1993 April 7 to 9. The dotted line indicates the solar equator. From Pevtsov (2000).

Reconnection at the Boundaries of Coronal Holes?

I put a question mark in the title of this subsection, because the evidence presented in the literature is much less firm than that for the four cases described above. The observations are very much worth while describing though because they clearly indicate that future observations, with a higher resolution and a higher cadence, will very likely verify or reject the reconnection hypothesis.

The issue here is that coronal holes observed in (the lack of) soft X-rays appear to rotate rigidly, while the underlying photosphere, in which the open field lines permeating the hole are rooted, rotates differentially. Clearly, if the footpoints of the fieldlines rotate differentially, one expects their extension into the corona to do the same, or at least something similar. They do not, holes rotate rigidly, and why this is so remains one of the solar enigmas.

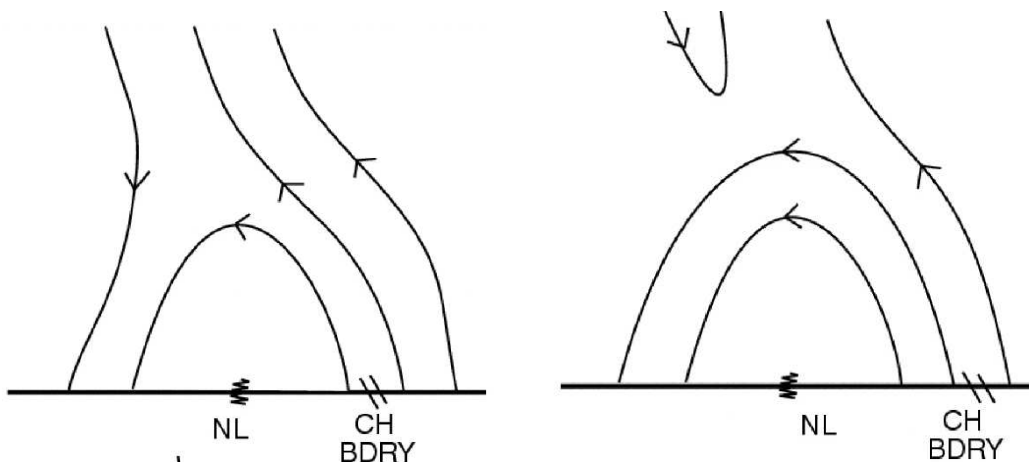


Fig. 8. A possible magnetic reconnection scenario at a coronal hole boundary. The open fieldline at the Eastern (left) coronal hole boundary (left figure), closes down after reconnection (right figure), whereby the Eastern coronal hole boundary shifts to the West (right). From Kahler and Hudson 2002.

Several cartoon-type solutions involving reconnection have been proposed. Figure 8, from a recent paper by Kahler and Hudson (2002) represents one of these models. An open coronal field line at the eastern boundary of the coronal hole on the right, reconnects and forms a closed loop, while a U-type loop escapes into interplanetary space.

This causes the coronal hole boundary to shift westward in a co-rotating frame, and thus allows the boundary at high latitude to keep up with that at lower latitudes. Note that in order to preserve the shape of the coronal hole the reverse process must occur at the western boundary of the hole, and proceed at the same speed. Moreover, to preserve the shape of a coronal hole extending from the polar crown deep into lower latitudes, as is occasionally observed (e.g. the Elephant's Trunk; for more detail see Kahler and Hudson 2002), the westward migration of the hole boundaries must occur at a predetermined speed for each latitude! Such a coincidence seems highly unlikely.

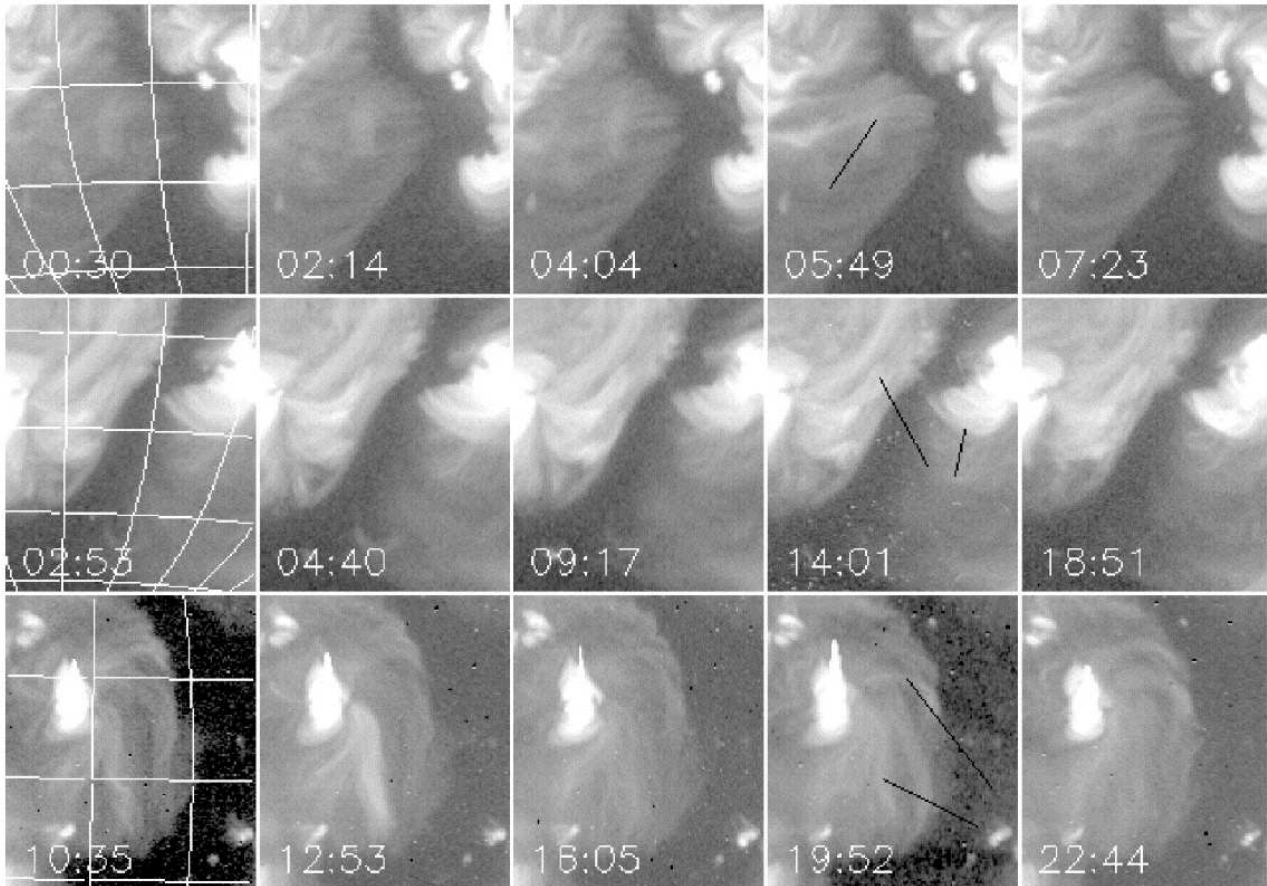


Fig. 9. Three examples of loop variations at coronal hole boundaries, indicated by the black lines. All are *Yohkoh*-SXT images, the top two in the Al.1 filter combination, and the bottom one in AIMg. The top row shows a coronal hole on 1992 January 27, the middle row shows brightness changes in loops connecting the western boundary of a coronal hole with NOAA AR 7130 on 1992 April 19, and the bottom row activity in loops connecting AR 9254 with the eastern boundary of a coronal hole on 2000 December 8. From Kahler and Hudson 2002.

Yet, reconnection at the boundaries is one of the more plausible scenarios offered at this time, so it is worth while looking for evidence of reconnection at the coronal hole boundaries. Using SXT Kahler and Hudson repeated an earlier study from *Skylab* data (Kahler and Moses 1990). Kahler and Hudson's main result, as stated in the paper, is "*Our basic observational result is that, except at ARs, the processes that retain the rigid boundaries proceed with no clear signatures in the X-ray images*". However, in few cases, some of which are illustrated in Figure 9 by black lines, the authors did find brightening of faint loops accompanied by a small shift in the loop position. This could be interpreted as reconnection. So the problem is worth looking at with future instruments for further indications of reconnection, although a completely unanticipated solution, perhaps related to dynamo action in the subphotospheric layers seems more likely to this author.

CONCLUSION

I can be brief here: reconnection in the solar corona is an established fact, as it is in laboratory plasmas and in the Earth's magnetosphere. This is important because the ability of reconnection to release energy impulsively and accelerate particles to high energies is a common characteristic of magnetized cosmic plasmas throughout the Universe, from magnetospheres to active galaxies. The proximity of the Sun provides us with one of the few opportunities to study this process in spatial detail on a cosmic scale, and thus acquire information that applies throughout all of astrophysics. Current (*RHESSI*) and future (XRT on Solar-B and AIA on SDO) soft X-ray and EUV telescopes, as well as fast and imaging spectrometers (EIS on Solar-B and MOSES), with a considerably higher resolution and cadence than SXT, will provide a much more detailed knowledge of the physical processes at work in reconnection, but *Yohkoh* will forever retain the credit of having laid the groundwork.

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