



# Initiation of CMEs: the role of magnetic twist

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## Abstract

Recent multiwavelength observations, modelling results and theoretical developments indicate the importance of twisted magnetic configurations in solar active regions (ARs) in the initiation of coronal mass ejections (CMEs). Through multiwavelength analysis of a few representative events we make an attempt to provide constraints for CME models. The two events presented here in detail start with the expansion of sigmoids (S- or inverse S-shaped loops) observed in soft X-rays. Both events (on 25 October 1994 and 14 October 1995) occurred before the launch of the SOHO spacecraft, but indirect evidences (i.e. signatures of an outward propagation traced up to  $\approx 20$  solar radii and an associated magnetic cloud) suggest that both of them were related to CMEs. We show evidence that sigmoids are the coronal manifestations of twisted magnetic flux tubes, which start expanding presumably due to a loss of equilibrium. It is noteworthy that the analysed CMEs occurred in a complex (not simply bipolar) magnetic environment and in all cases we found evidences of the interaction (magnetic reconnection) with the surrounding fields. We propose a scenario for sigmoid expansion related CME events and suggest that twisted magnetic configurations are good candidates for being source regions of CMEs. © 2000 Elsevier Science Ltd. All rights reserved.

**Keywords:** Coronal mass ejections; Magnetic twist

## 1. Introduction

Twisted magnetic flux tubes have been observed in magnetic clouds propagating in the interplanetary space (see e.g. Burlaga et al., 1981). Their solar origin has been confirmed through MHD simulations of coronagraph observa-

tions of expanding toroidal flux ropes (see e.g. Wu and Guo, 1997; Gibson and Low, 1998). These simulations were motivated by modelling the very early stages of coronal mass ejections (CMEs). In particular, Gibson and Low (1998) based their model on the existence of three parts in the equatorial belt: the helmet streamer, the dark cavity and the prominence as a sheet of suspended material. An important question raised by these studies is whether a twisted flux rope is present in the solar corona in the pre-eruptive state before the CME occurs, or it is formed during the eruption.

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In the solar corona, the plasma  $\beta$  (defined as the ratio between the thermal and magnetic energy of the plasma) is of the order of 0.0001–0.1. This indicates that the nature of the driver of CMEs is very likely to be magnetic. Thus, magnetic energy is believed to be accumulated at first, and then released through the partial opening of the field, leading to a CME. In the solar corona, the increase of magnetic energy can only be caused by the creation of stresses in the magnetic field. Note that whether fields emerge through the photosphere in an already stressed state or the stresses are formed by photospheric footpoint motions of the coronal field is still under debate, but probably both mechanisms are at work. There are two main kinds of stressed magnetic configurations: sheared arcades and twisted flux ropes.

The opening of closed magnetic field lines cannot be reached from a force-free state by releasing energy, since the open field has the highest energy of all force-free configurations with the same boundary conditions (Aly, 1991; Sturrock, 1991). Theoretical MHD models have shown that magnetic shear exceeding a critical threshold, can lead to the destabilization of large-scale coronal arcades (Mikić and Linker, 1994, 1997), indicating that they can be considered to be candidates for the initiation of CMEs. The scenario proposed by Mikić and Linker (1994) allows a partial re-closing of the field during the process of opening the magnetic field. Then the field is only partially open during the eruption, which allows it to bypass the Aly-Sturrock limit for fully open fields. Antiochos et al. (1999) in their 2.5-D numerical simulations placed a sheared arcade in an overlying weak opposite polarity field. This configuration created a multipolar topology in which reconnection between the sheared arcade and neighboring flux systems could trigger an eruption. In this “magnetic breakout” model, reconnection “removes” the unsheared field above the low-lying, sheared core flux near the neutral line, thereby allowing this core flux to burst open. The opening is only partial. The eruption is driven by the magnetic free energy stored in the closed arcade. The shear could be produced by emergence of flux or motions in the photosphere. For this “magnetic breakout” model a large-scale complex magnetic topology is a necessary condition. In the cases discussed above, the opening of the initially sheared (and not twisted) field lines produces a vertical current sheet in between the anti-parallel fields (Aly, 1994). Reconnection occurring in the current sheet then produces not only newly closed arcades (as discussed above), but also a twisted flux rope which is expelled from the corona (see Mikić and Linker, 1994). This shows that the absence of a twisted flux rope in the low corona before the launch of a CME is not in contradiction with the observations of interplanetary twisted magnetic clouds.

Several models for CMEs propose that a twisted flux rope is in fact present in the pre-eruptive state. These models show that the eruption of a twisted structure can be caused by a slow photospheric evolution (e.g. converging motions or increasing flux rope twist, see e.g. Forbes and Priest, 1995; Lin et al., 1998, and references therein) or by a fast injection

of new magnetic flux (Chen, 1996, 1997) both processes leading to a loss of equilibrium of the structure. However, Forbes et al. (1994) showed that in a bipolar magnetic field the maximum energy released, due to the loss of equilibrium, is only a fraction of the free energy available: 9% in bipolar, 21% in quadrupolar configurations. These models thus suggest that the interplanetary magnetic clouds are due to the expansion of flux ropes initially present in the lower solar corona.

Translating the above simulation results to the observed complex magnetic configurations is not simple. In 3-D twisted magnetic configurations quasi separatrix layers (QSLs) replace the 2-D and 2.5-D separatrices, where reconnection is expected to occur (Démoulin et al., 1996, 1997). As the magnetic configuration evolves high current densities form along QSLs. Then, when the magnetic non-potentiality becomes too high, the twisted flux tube is likely to get unstable (like in the axisymmetric configurations modelled by Lin et al. (1998) and references therein) and start moving upward. This evolution of the magnetic configuration drives magnetic reconnection at the QSLs creating long twisted loops and an under-lying arcade (Titov and Démoulin, 1999). As the twisted flux tube expands it can encounter and push overlying weak magnetic loops outward. Such interaction with surrounding magnetic fields may lead to a partial opening of the field creating coronal dimmings or coronal holes.

Last but not least, the distinction between shear and twist is not always obvious for 3-D stressed magnetic fields. For example, applying a differential shear near the neutral line of an initially potential (i.e. unstressed) dipole, Antiochos et al. (1994) produced a slightly twisted flux tube, for which the wrapping number of the field lines (see Antiochos, 1987 for definition) is finite. Moreover, pursuing only shearing motions, DeVore and Antiochos (2000) show that reconnection with the unstressed fields produces more twist. Highly twisted fields can be present in equilibrium in the low corona (see e.g. Amari et al., 1999). Finally, Amari et al. (1996) highlight that regardless of the nature of the stress (twist or shear), what is important in 3-D for opening a magnetic field is the value of the current density along the field. Then, as more currents can be accumulated in a 3-D highly twisted flux tube than in weakly twisted or simply sheared fields, and even purely shearing motions will form twist anyway, the presence of 3-D twisted flux tubes in the corona before the launch of a CME is highly probable.

Twisted magnetic loops have actually been observed in the solar corona. Appearance of S- and inverse S-shaped soft X-ray (SXR) loops, which were named “sigmoids” by Rust and Kumar (1996) outline magnetic field lines and indicate the presence of important helicity in solar active regions (Pevtsov et al., 1997). Such loops, sometimes even after days of stability, can start expanding (Pevtsov et al., 1996). Sigmoidal coronal loops have been linked to the occurrences of CME events using coronal arcade, cusp, dimming(s) and coronal hole formation, all signatures of erup-

tive events, as proxies for CMEs (Sterling and Hudson, 1997; Canfield et al., 1999; Sterling, 2000, this issue). However, there are not many events of which the entire process of sigmoid formation, eruption and the related CME have been followed, thus the physical relationship among the different signatures need some clarification. In this paper we have a closer look at two CME events, which were related to the expansion of sigmoids and to long-duration X-ray events (LDEs). Sigmoids are frequently associated with filament eruption (Rust and Kumar, 1996). Both sigmoids and filaments were shown to be associated with twisted flux ropes (Rust, 1994; Titov and Démoulin, 1999; Aulanier and Démoulin, 1998; Aulanier et al., 1998a, 1999). Furthermore, long-duration events and filament eruptions have long been found to have the best association with CME events (e.g. Webb, 1992). Thus, these cases appear to be representative events to study CME source regions and the role of magnetic twist in the initiation of CMEs. Furthermore, through these well-observed events combined with magnetic modelling we make an attempt to provide a more complete scenario for sigmoid-related CME events.

## 2. The 25 October 1994 expanding sigmoid event

NOAA AR 7792 was close to the disc centre (S06 W11) when a long-duration event (LDE) started in the AR on 25 October 1994 at 09:49 UT (Manoharan et al., 1996). The GOES 1–8 Å, flux reached peak intensity at about 10:08 UT, and then returned to the background level 5–6 h later (Fig. 1). The SXT instrument (Tsuneta et al., 1991) on the Yohkoh spacecraft (Ogawara et al., 1991) observed the flare with full resolution ( $64 \times 64$  pixels,  $2.46''$  per pixel). Since flare mode was not triggered, full-disc images were also taken during the event, which enabled us to follow the large-scale consequences of the flare. Two sets of loops appear in the X-ray images (Fig. 2a): long, twisted loops connecting external parts of the AR and brighter shorter loops in the middle. The long twisted loops were observed to expand with a speed of  $200\text{--}300\text{ km s}^{-1}$ . Linear force-free magnetic field extrapolation using Stokes vector magnetograms from Mees Observatory (taken on 25 October 1994 starting at 16:51 UT, see Fig. 3) as boundary conditions show that such magnetic connectivity is only possible with a high level of non-potentiality (van Driel-Gesztelyi et al., 1997). The linear force-free coefficients (defined by  $\nabla \times \mathbf{B} = \alpha \mathbf{B}$  equation, with  $\alpha = \text{const.}$ ) which give the best fit to the observations are  $\alpha \approx -0.05\text{ M m}^{-1}$  for the long loops and even higher,  $\alpha \approx -0.09\text{ M m}^{-1}$  for the bright short loops. Linear force-free (lfff) extrapolations cannot recover the sigmoid shape exactly as it was observed in the corona, since the magnetic twist is likely to be more important and more concentrated in reality (Patty and Hagyard, 1986; Zhang 1995; Schmieder et al., 1996; Aulanier et al., 1998b) than in the lfff computations, where it is considered homogenous.

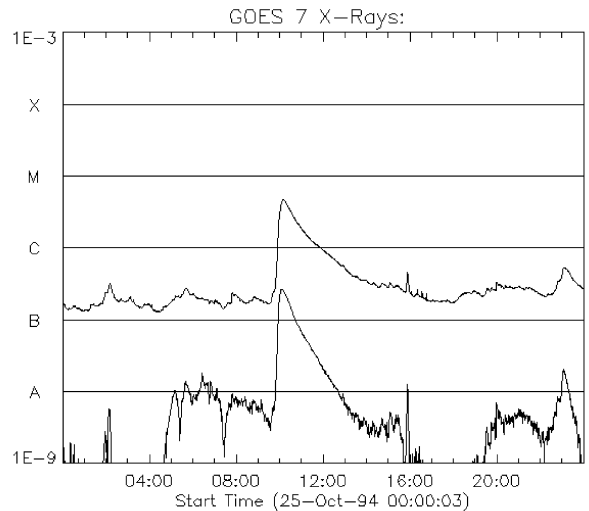


Fig. 1. Integrated solar soft X-ray (SXR) emission in the 1 – 8 Å range (GOES-7) on 25 October 1994. Note the long-duration event (LDE) between about 9:40 and 14 UT, which was related to the expansion of a sigmoid.

About 10–15 min after the flare onset, a series of different activity events were observed over about 1/3 of the solar disc. (i) Following a gradual increase in the non-thermal radio continuum emission of the AR, strong outburst activity was recorded at all the Nançay observing frequencies over the southern hemisphere. The outbursts, which lasted for about 15 min, followed the expanding X-ray loops in space and time (Manoharan et al., 1996). (ii) At about 10:06 UT, two remote X-ray brightenings (RXBs) appeared on opposite hemispheres of the Sun at 20 and 15 heliographic degrees distance from the AR, towards the NW and the SW, respectively (Fig. 4a). These brightenings were observed until the end of the SXT full-disc observations ( $\sim 10:20$  UT). The brightenings appeared over quiet solar regions of opposite magnetic polarity, the closest magnetic regions to AR 7792. In the vicinity of the two remote brightenings two coronal holes (CHs) started forming after the flare maximum (Fig. 4b). They were clearly visible during the next Yohkoh orbit (at about 11 UT) and could be followed for at least three days. Furthermore, new coronal loops appeared connecting the AR to remote quiet regions and to the boundaries of the new coronal holes (Fig. 4b).

Fig. 5 shows the SXR and radio time profiles of the long-duration C4.7 flare event. These profiles were obtained from GOES (1–8 Å), Nançay Radioheliograph (160–450 MHz), and Ulysses radio (50 kHz–1 MHz; URAP, Stone et al., 1992) measurements. According to the heliospheric density model (Bougeret et al., 1984), the 1-MHz plasma frequency corresponds to a distance of  $\sim 20$  solar radii ( $R_{\odot}$ ) above the photosphere, while Nançay measures coronal conditions at an altitude less than one solar radius. The URAP's interplanetary type-III emission seen in the high-frequency

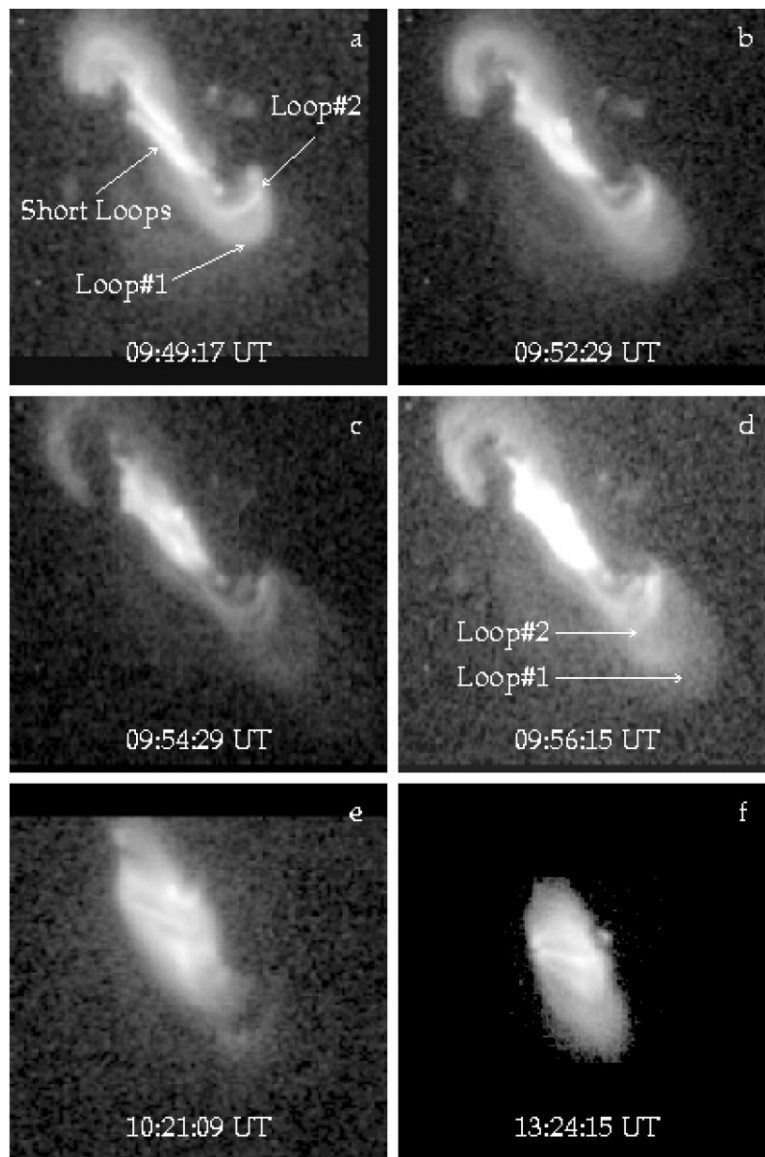


Fig. 2. Expanding flare loops observed with Yohkoh/SXT on 25 October 1994. Note that as their volume becomes bigger, the loops fade. After the sigmoid has been ejected, the orientation of the shorter bright loops became more perpendicular to the magnetic inversion line (cf. Fig. 3), indicating that the high magnetic non-potentiality in the region relaxed.

channel shows good correlation with the Nançay radio burst. Note that in Fig. 5 the heights above the photosphere from which the radiation comes increases from GOES measurements to Ulysses low-frequency channel data. The shifting maxima of the successive plots clearly indicate that the emitting source is propagating outward, which we regard as evidence for the occurrence of a CME related to this expanding sigmoid.

We propose that the series of radio bursts occurred when the expanding sigmoid encountered and reconnected with large-scale trans-equatorial loops connecting quiet-Sun re-

gions (Fig. 6). The two remote transient X-ray sources (RXBs, Fig. 4a) are interpreted as footpoint brightenings of the huge reconnected loops. The newly formed SXR loops between the AR and the quiet regions could only be created by such magnetic reconnection process (Fig. 4b). The reconnection was only partial, the external part of the overlying large-scale fields was pushed out in the solar wind by the expanding twisted loops, leading to the formation of the coronal holes (Figs. 4b and 6c). The interaction between the AR and the large-scale fields seemed to be in progress during the entire gradual phase of the flare. Recent MHD

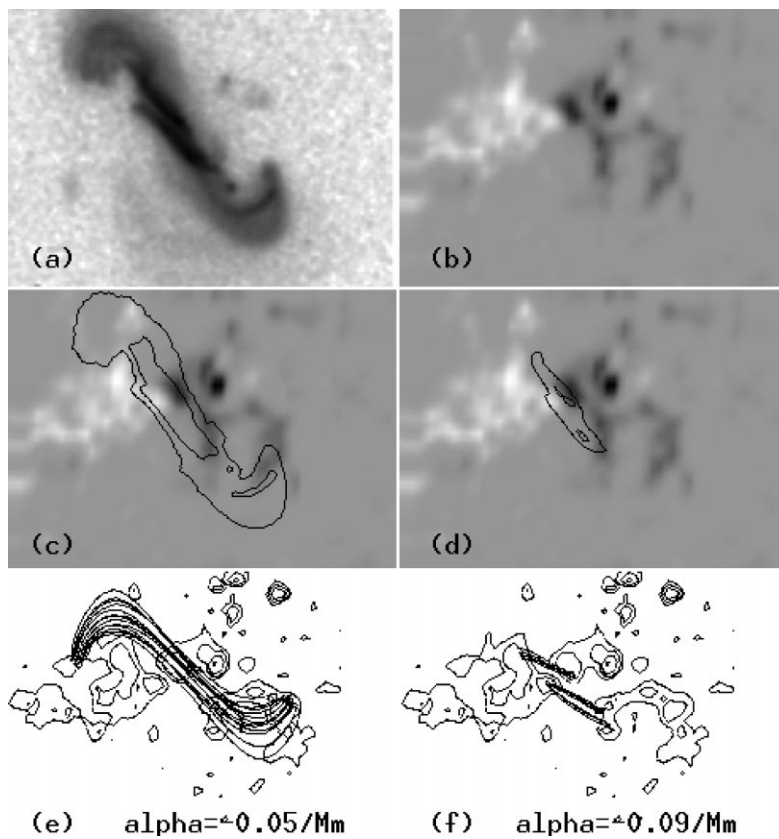


Fig. 3. Magnetic configuration and linear force-free magnetic field extrapolation related to the sigmoid on 25 October 1994 at 09:49 UT. (a) shows a Yohkoh/SXT image of the flare loops (b) is a Kitt Peak magnetogram (same field of view as the SXT image) (c) shows the magnetic fields overlaid with the contours of the big twisted X-ray loops; (d) is the same as c, but the contours show the brightest X-ray loops; (e) and (f) show linear force-free field extrapolations of a Mees Observatory magnetogram with different levels of non-potentiality corresponding to the observed X-ray loops.

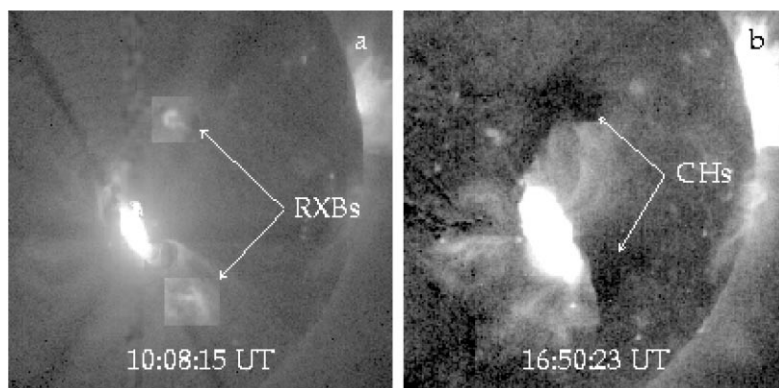


Fig. 4. (a) Yohkoh/SXT observations on 25 October 1994. Remote X-ray brightenings (RXBs) and (b) coronal hole formation (CH, dimming) over quiet solar regions of opposite magnetic polarity indicates that the expanding sigmoids encountered and reconnected with large-scale trans-equatorial loops.

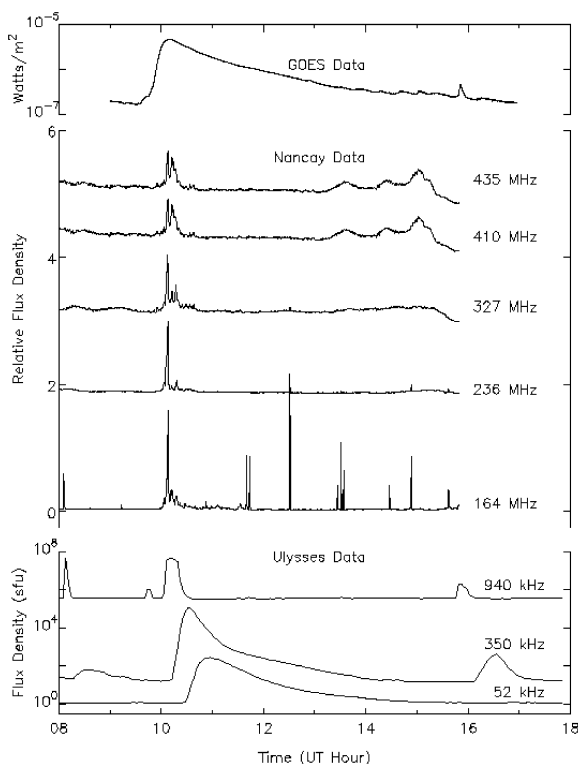


Fig. 5. Soft X-ray and radio time profiles of a C4.7 flare event that occurred at the location S06 W11 on 1994 October 25. These profiles were obtained from GOES (1–8 Å), Nançay Radioheliograph (160–450 MHz), and Ulysses radio (50 kHz–1 MHz) measurements. Note that the radiation heights above the photosphere increase from GOES measurements to Ulysses low-frequency channel data and correspondingly, there is a shift in the times of the LDE maxima as we go to greater distances from the Sun, giving a strong indication of the occurrence of a propagating (CME) event.

simulations by Amari and Luciani (1999) showed similar large-scale reconnection between an expanding twisted flux tube and overlying arcade. They find the formation of the new large-scale connectivities.

### 3. Sigmoid expansion: the launch of the 18–20 October 1995 interplanetary magnetic cloud

A magnetic cloud was observed with the Solar Wind Experiment and the Magnetic Field Instrument on board of the WIND spacecraft at 1 AU in the period of 18–20 October 1995. Magnetic modelling of the observations showed that the cloud could be well approximated with a flux rope of right-handed twist (positive helicity; Lepping et al., 1997). Smith et al. (1997) identified its solar source as a zone located between two interacting active regions (ARs 7912 & 7910, cf. Fig. 7b), where SXR dimmings and type IV metric radio bursts were observed. In this section, we take another look at the series of SXR events related to the ejection of the flux rope of the magnetic cloud and suggest that the cloud was actually launched from AR 7912. We propose that, due to the high non-potentiality, magnetic loops swelled up and then expanded into the interplanetary space. The expanding loops interacted with neighbouring magnetic systems of ARs 7910 & 7913, leading to radio bursts and sympathetic flaring.

AR 7912 consisted of a round leading and scattered smaller trailing spots with a few included polarities disturbing the bipolar structure (Fig. 7). The coronal (X-ray) loops had a sigmoidal shape with a positive helicity corresponding to the global south-hemispheric helicity. This South hemispheric AR, of which the magnetic orientation is the opposite to the general pattern formulated in Hale's law, at first glance seemed to be formed as the result of a kink-instability. Such instability (Linton et al., 1996) would create a "knot" in a submerged flux tube due to very strong twist, which would be observed as a reversed polarity group when reaching the photosphere. A characteristic of this

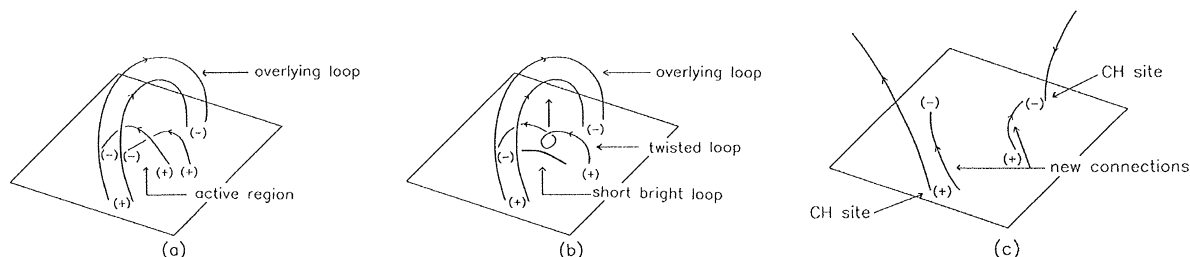


Fig. 6. Schematic representation of the series of events during the 25 October 1994 sigmoid expansion event. (a) Magnetic field configuration before the first reconnection at the active region. The overlying loops are transequatorial loops connecting opposite-polarity quiet-Sun regions (b) reconnection forms a twisted loop and a short, brighter loop. The twisted flare loop becomes unstable and starts expanding (c) Configuration after reconnection between the expanding twisted loop and the large overlying loop. New connections are created between the active region and the remote monopolar regions. The reconnection is partial, the external part of the overlying large-scale fields are pushed out in the solar wind by the expanding twisted loops, leading to formation of the coronal holes (Manoharan et al., 1996).

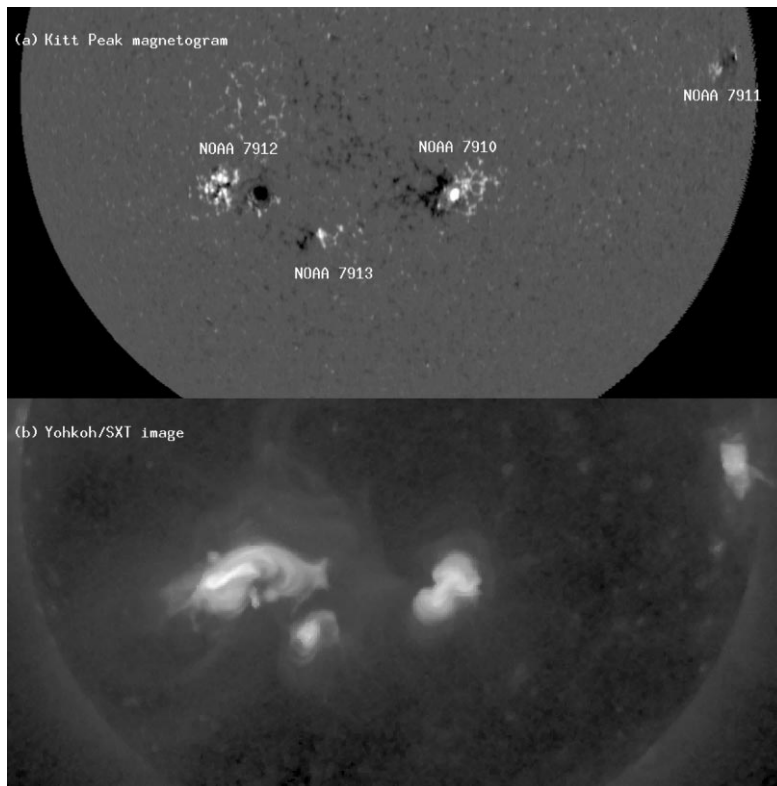


Fig. 7. (a) Magnetic map and (b) soft X-ray observation on 14 October, 1995. Note the S-shaped loops in the reversed polarity active region NOAA 7912. The twisted loops are in expansion in the X-ray image, which was taken before the peak of the LDE at 07:29 UT. Note the difference in brightness between the central shorter loops and the larger-scale expanding loops in the AR, which are essentially the same than the two different sets of loops in the 25 October 1994 event. At the western edge of the expanding loops an X-point-like structure appears to form, indicating that the swelling loops encounter with a neighbouring magnetic system.

instability is that the sign of the twist in the flux tube has to be the same as that of the writhe of the flux tube axis. Based on the long-term (four rotations) evolution of the AR, it was shown by López Fuentes et al. (2000) that this active region, having an opposite sign of twist and writhe, was formed by a helical flux tube which was deformed in the convection zone by external forces while ascending.

AR 7912 did not produce very important flares: there was no X-flare, but three M-flares and dozens of smaller flares originated from the region. On 14 October a C1.6 LDE started after 5:00 UT, reached maximum at 9:21 UT according to the Solar-Geophysical Data and lasted for at least 15 h longer. The GOES curve of the LDE is very spiky, several flares occurred in the same and neighbouring ARs during its duration (Fig. 8). Some of these flares seemed to be sympathetic events induced by the LDE. The LDE started by loop brightenings in the central part of the AR, and this was the time when some of the sigmoidal loops became visible (Fig. 9). Expansion of loops was already seen at 05:23 UT. By 07:29 UT the expanding loops encountered the magnetic fields of neighbouring regions and a coronal brightening, having an “X-point” shape, appeared presum-

ably indicating inter-AR reconnections. The expansion of the AR 7912 loops were seen at 08:22 UT and especially at 08:55 UT, when the span of the fading loops in projection became comparable to the solar radius. Flare activity started in AR 7910 after 11 UT, probably induced by the expanding loops of AR 7912.

We propose that the magnetic cloud, which passed the Earth between 18 and 20 October, was actually launched from AR 7912. The positive (right-handed) twist of the cloud, as deduced from the model developed by Lepping et al. (1997), agreed with the sign of the twist in the coronal loops indicated by their forward S-shape. The high non-potentiality of AR 7912 was further increased by the emergence of smaller-scale twisted flux-tubes, marked by the appearance of highly tilted bipoles in the following part of the AR (see van Driel-Gesztelyi et al. (2000) and Leka et al. (1996) for the relation between bipole tilt and twist). This increase in global twist forced the loops to swell up and expand into the interplanetary space. The related X-ray event was an LDE of class C1.6. The expanding loops interacted with neighbouring magnetic systems, leading to the observed radio bursts and sympathetic flaring. This

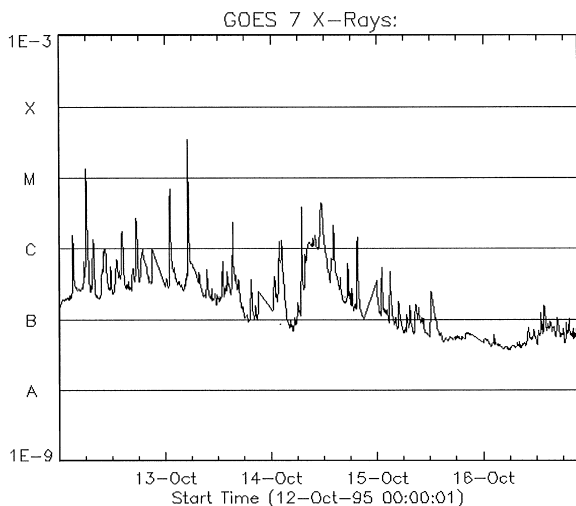


Fig. 8. Integrated solar soft X-ray emission in the 1–8 Å range (GOES-7) between 12 and 16 October 1995. Note the LDE between 5–24 UT on 14 October which was related to the launch of the 18–20 October 1995 magnetic cloud observed with WIND.

suggestion is supported by a recent non-linear force-free reconstruction of the magnetic field of AR 7912, before and after the LDE, by Bleybel et al. (1999). These authors found that both the total magnetic energy and the helicity decreased in the AR after this LDE. Such a decrease can only be achieved if helicity has been ejected from the AR. Thus, it is very likely that the expanding sigmoid carried helicity away.

#### 4. Scenario for sigmoid expansion related CMEs

A twisted flux tube can be formed in the corona either by magnetic reconnection in a sheared arcade or by emergence from the convective zone. Both processes are thought to be a long evolution which can progressively bring the magnetic configuration to an unstable state. Such eruption of a twisted flux tube has been proposed by several authors (e.g. Martens and Kuin, 1989; Moore and Roumeliotis, 1992; Forbes, 1992; Lin et al., 1998; Titov and Démoulin, 1999). Fig. 10 shows the main characteristics predicted in such model. The initial configuration consists of twisted flux-tubes embedded in a sheared magnetic arcade. When the configuration gets MHD unstable, the twisted flux-tubes start to move upward. It drives magnetic reconnection between field lines belonging to the arcade, mainly just below the magnetic flux tube. A pair of such field lines are represented before reconnection in Fig. 10a. They have the same kind of connectivity as any arcade field line located further away from the twisted flux tube (thin line). Fig. 10b shows the magnetic connectivities after reconnection. A long, S-shaped field line was formed at the border of the twisted flux tube between the “outer” ends of the two antiparallel J-shaped loop. Another,

short loops formed below it, connecting the “straight” internal parts of the two J’s. As reconnection proceeds, the flux tube becomes so extended (both in volume and height), that the newly formed S-shaped field lines have a density too low to radiate significantly. Then the expanding S-shaped loop, outlined by a thin line in Fig. 10c, progressively disappears from the images. Only the short reconnected loops remain visible below the flux tube. The fast outward motion of the twisted flux tube is likely to build a current layer below it (if the reconnection rate is slow enough during the onset of the loss of equilibrium, see Forbes and Lin, 2000). It implies the formation of a cusp shape for the new reconnected loops, which disappears as the magnetic field relaxes (see Forbes and Acton, 1996).

#### 5. Discussion and conclusions

The two events presented above started with spectacular expansion of sigmoids (S- and inverse S-shaped loops) observed in soft X-rays (Yohkoh/SXT) images. Both events occurred before the launch of the SOHO spacecraft, but indirect evidence suggest that both of them were lower-coronal manifestations of CMEs. For the 25 October 1994 event a series of plots of radio flux density of  $4 \times 10^8$ – $5 \times 10^4$  Hz versus time indicate an outward propagation of plasma which can be traced up to  $\approx 20$  solar radii (Fig. 5). For the 14 October 1995 event there is an associated magnetic cloud which was observed at 1 AU between 18 and 20 October (Lepping et al., 1997). Both sigmoid expansions were associated with long-duration flare events of C-class GOES level (Figs. 1 and 8), and in both cases we find two sets of loops, bright shorter central loops and dimmer longer S-shaped ones in the corona. The latter long loops are the expanding ones (Figs. 2 and 9). This loop morphology and their relative brightness bears close resemblance to the model of Moore and Roumeliotis (1992), Démoulin (1997) and Titov and Démoulin (1999) which imply that these two sets of loops are created by magnetic reconnection (Fig. 10).

The connection between sigmoidal flare loops and CMEs was proposed earlier by several authors (e.g. Rust and Kumar 1996, note how closely the erupting sigmoid in their Fig. 1 resembles the 25 October 1994 event). The observation that sigmoidal structures are more prominent in SXR than in EUV suggests that they are hot features (Sterling, 2000), which supports the suggestion that they are flare loops created by reconnection. Pevtsov et al. (1996) showed that a few tens of minutes before a great flare two antiparallel J-shaped coronal loops, which had been stable for days, started to form a sigmoidal structure. Their observation clearly supports the idea that the eruptive sigmoids are formed by magnetic reconnection. The J-shaped loop pair is interpreted as the pre-reconnection loops (Fig. 10a). It is noteworthy that if the loops at the external border of the expanding sigmoids are created and heated up by reconnection, it is not a necessary condition



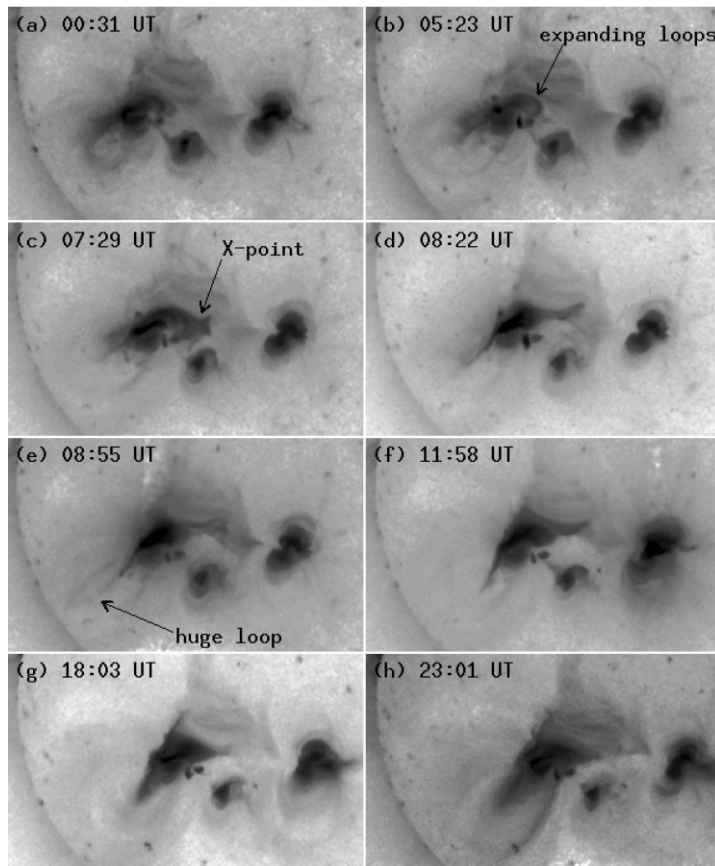


Fig. 9. Evolution of the soft X-ray structures on 14 October 1995 as observed with Yohkoh/SXT. The flare starts with loop brightenings of short loops in the center of the AR. Expansion of longer external loops start already after 05 UT. By 07:29 UT the expanding loops encounter with the magnetic fields of neighbouring regions and an X-point forms, indicating inter-AR reconnections. The continuing expansion of the AR 7912 loops are seen at 08:22 and especially at 08:55 UT. The dim “huge” loop at 08:55 UT corresponds to the expanding sigmoid in Fig. 10c, while the shorter bright loops in the centre of the AR at 07:29 UT correspond to the short reconnected loops in Fig. 10b. Flare activity starts in AR 7910 after 11 UT. This flare was likely to be induced by the expanding loops in AR 7912.

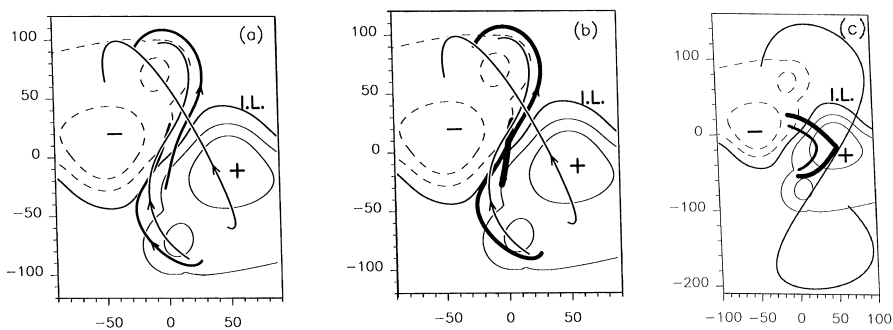


Fig. 10. Sigmoid formation by reconnection of two J-shaped loops and cusp formation after the sigmoid ejection. (a) Pre-reconnection configuration. Such two J-shaped loops are frequently observed in soft X-rays. (b) Reconnection forms a long sigmoid and short, bright loops around its middle part. (c) The sigmoid expands, building a current sheet below it, which creates a cusp above the short reconnected loops. In both (a) and (b) two characteristic field lines, not involved in the reconnection, have been added as a guide for the full magnetic configuration. They are representative of the large-scale arcade and of the twisted flux tube. “I.L.” indicates the magnetic inversion line.

that the pre-flare (pre-reconnection) active region coronal loop structure is visibly sigmoidal. The pre-reconnection loops may not be dense and/or hot enough to appear in SXR. Canfield et al. (1999), utilising the Yohkoh/SXT video movie during two medium-active years (1993 and 1997) classified all active regions according to morphology (sigmoidal- and non-sigmoidal) and activity (eruptive and non-eruptive). They found that a great majority of sigmoidal active regions were eruptive (51 out of 61), but also that 50% of non-sigmoidal active regions were eruptive (28 out of 56). We believe that the latter events were created by reconnection of previously invisible twisted loops.

The reconnection scenario displayed in Fig. 10 can clarify another point: the missing link between the sigmoid and the post-flare X-ray cusp structure. Sterling and Hudson (1997) and Sterling (2000) pointed out that the footpoints of the sigmoid and the post-flare cusp structures are far from being identical, and they offered no explanation how they are actually related. Fig. 10c clearly shows that the footpoints of these two structures are different indeed: the cusp appears above the short bright loops in the middle of the expanding sigmoid (Fig. 10c). According to the reconnection scenario the cusp is created there by the fast upward motion of the twisted flux tube which is likely to build a current sheet below it, due to the relatively slow reconnection rate (see e.g. Forbes and Lin, 2000).

However, not only a global instability followed by reconnection, but possibly slow photospheric evolution can also lead to a fast expansion of twisted flux without any reconnection. Amari et al. (1996) showed that flux tubes, which are being twisted, can enter a dynamical phase during which they suffer a very fast expansion, closely approaching after some finite time a semi-open configuration. In such extreme case, where there is no reconnection, we do not expect to see two sets of loops, i.e. short bright loops in the core and a dimmer expanding large sigmoid but just an expanding sigmoid (if the plasma density is enhanced enough in the sigmoid structure). Thus, expanding sigmoids, created by these two mechanisms, can easily be distinguished by the presence or lack of the short bright loops in the sigmoid centre. A further morphological investigation of a statistically significant sample of erupting sigmoids could decide which of the two is or whether both of these mechanism are in effect.

In both sigmoid-related CME cases we found evidence for interaction between the expanding sigmoids and other large-scale magnetic loops, suggesting the occurrence of magnetic reconnection. The expanding sigmoids encounter and reconnect with surrounding magnetic fields, which may play a role in liberating the swelling sigmoid being held down by overlying field lines (Antiochos et al., 1999). This reconnection is not expected to release much energy, thus radio wavelengths may provide the best chance for its detection. In the presented two sigmoid expansion events were associated with the onset of non-thermal radio continuum and metric radio bursts, which, in both cases, started after

the appearance of the two sets of loops when the sigmoids had been expanding for a few tens of minutes. During the 25 October 1994 event the LDE and the sigmoid expansion started at about 09:50 UT. The non-thermal radio continuum onset occurred at 09:58 UT (Aurass and Klein, 1997) and radio burst activity started at about 10 UT and lasted for about 15 min (Manoharan et al., 1996). During the 14 October 1995 event it is hard to define the beginning of the LDE (about 05 UT), but we know that the two sets of loops were created before 07:29 UT, and the expansion of sigmoidal loops speeded up after that. The first type IV bursts were observed between 08:06–08:19. The non-thermal radio continuum onset was at about 08:15 UT (Smith et al., 1997). Thus, in both cases metric radio storm and burst activity started at least 8 and 37 minutes, respectively, after the onset of the sigmoid expansion. We believe that these delays favour a reconnection above the expanding sigmoid which is triggered by the expanding sigmoidal field since they seem to occur too late in the process as a consequence of inevitable encounter of an expanding loop with others in the corona crammed with magnetic loops. Still, further studies are needed to fully clarify this point.

Though its role is far from being clear, magnetic helicity appears to play a crucial role in the initiation of CMEs. CME activity may serve as a valve through which the AR could get rid of excess helicity, in accordance to what Low (1996) proposed earlier. The recent result by Bleybel et al. (1999) provided evidence that CMEs do carry away helicity from the source region. Through non-linear force-free reconstruction of the coronal magnetic fields of AR 7912 before and after the 14 October 1995 LDE/CME event they found that the total helicity of the AR was significantly smaller after the event than before it. A high level of magnetic non-potentiality, which is normally associated with flaring young active regions, may persist or can even grow after the strong magnetic concentrations (sunspots) disappear (van Driel-Gesztelyi et al., 1998,1999; Mandrini et al., 2000). Thus, monitoring magnetic helicity of ARs with strong magnetic field concentrations but also later in their decay phase when they have more dispersed magnetic fields and contain long filaments will help us to understand the role of magnetic non-potentiality in the CME initiation process and may improve predictions of solar-caused geomagnetic activity.

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