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ScienceDirect
Advances in Space Research 42 (2008) 858–865
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
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Multi-scale reconnections in a complex CME

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Received 16 January 2007; received in revised form 6 April 2007; accepted 18 April 2007

Abstract

A series of three flares of GOES class M, M and C, and a CME were observed on 20 January 2004 occurring in close succession in NOAA 10540. Types II, III, and N radio bursts were associated. We use the combined observations from TRACE, EIT, Hα images from Kwasan Observatory, MDI magnetograms, GOES, and radio observations from Culgoora and Wind/ WAVES to understand the complex development of this event. We reach three main conclusions. First, we link the first two impulsive flares to tether-cutting reconnections and the launch of the CME. This complex observation shows that impulsive quadrupolar flares can be eruptive. Second, we relate the last of the flares, an LDE, to the relaxation phase following forced reconnections between the erupting flux rope and neighbouring magnetic field lines, when reconnection reverses and restores some of the pre-eruption magnetic connectivities. Finally, we show that reconnection with the magnetic structure of a previous CME launched about 8 h earlier injects electrons into open field lines having a local dip and apex (located at about six solar radii height). This is observed as an N-burst at decametre radio wavelengths. The dipped shape of these field lines is due to large-scale magnetic reconnection between expanding magnetic loops and open field lines of a neighbouring streamer. This particular situation explains why this is the first N-burst ever observed at long radio wavelengths.
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Keywords: Magnetic reconnection; Sun: magnetic fields; Sun: EUV; Sun: flares; Sun: coronal mass ejection; Sun: radio; Radio burst

1. Introduction

CMEs are believed to occur when a loss of equilibrium or instability takes place in a magnetic system due to the presence of excess shear or twist. Above some threshold, magnetic systems react to the injection of free energy by a rapid expansion. Since magnetic fields on the Sun are ubiquitous, when a magnetic loop expands it is likely to encounter and push against another loop. With the presence of an anti-parallel magnetic field component, a current sheet will form, where magnetic reconnection may take place. Such forced reconnection may play different roles, e.g. it may:

(i) Remove overlying stabilizing field lines, facilitating the eruption.
(ii) Increase the complexity of flares (several energy release sites).
(iii) Make coronal mass ejections truly large-scale, and/or
(iv) Lead to "sympathetic" events by destabilization of other magnetic structures or simply reconnection with distant magnetic structures.

Case (i) is called the magnetic break-out proposed by Antiochos et al. (1999). Observational evidence for the break-out have been found by e.g. Aulanier et al. (2000), Gary and Moore (2004), and Harra et al. (2005).

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doi:10.1016/j.asr.2007.04.065

Cases (ii)–(iv) have been widely investigated, but there are relatively few papers suggesting explicitly the role of magnetic reconnection in these processes (e.g. Delannée and Aulanier, 1999; Attrill et al., 2006, 2007).

We analyse a complex, three-phase flare event, observed on 20 January 2004 in NOAA AR 10540, which was related to a CME. We show that multiple reconnection processes between expanding magnetic structures gradually shifted the flaring site along the main magnetic inversion line. The ensuing CME interacted with a neighbouring streamer and another CME, which erupted from the same AR about 8 h earlier. We provide broad multi-wavelength evidence that magnetic reconnection was indeed at work from small AR-scales up to scales of a few solar radii making this event truly complex.

2. The three-part flare and CME launch – magnetic interaction within the AR

The GOES light-curve of the 20 January 2004 event in Fig. 1 clearly shows the three phases, which started at about 07:32 UT and peaked successively at 07:37, 07:43 and at about 08:05 UT. The first two (GOES M-class) flares appeared to be fast rising and decaying impulsive flares, while the third (GOES C-class) flare had a very gradual decay phase, consistent with signatures of a long-duration event (LDE). The flares were followed by the observation of a CME (Fig. 2), which was first seen with LASCO C2 at 08:06 UT.

At first, we considered the LDE to be the signature of an energy release in the wake of the CME, since LDEs are more commonly associated with CMEs than impulsive flares. However, as we will show below, conventional thinking may be misleading in this case!

The source region of the complex flare/CME event was NOAA AR 10540 (Fig. 3). SOHO/MDI (Scherrer et al., 1995) magnetograms between 18 January 00:00 to 20 January 6:56 UT, prior to the event show the emergence of new flux in the previously bipolar AR. New bipoles emerged in at least three episodes at the south periphery of the dispersed positive (following) polarity increasing the magnetic complexity, while the strong shearing motions observed during the emergence built up non-potentiality in the AR (Goff et al., 2007). The complex flare involved both the new and the pre-existing bipoles: all the three flares of this event were observed along the magnetic inversion line of the new flux, also involving the magnetic fields of the large pre-existing bipole.

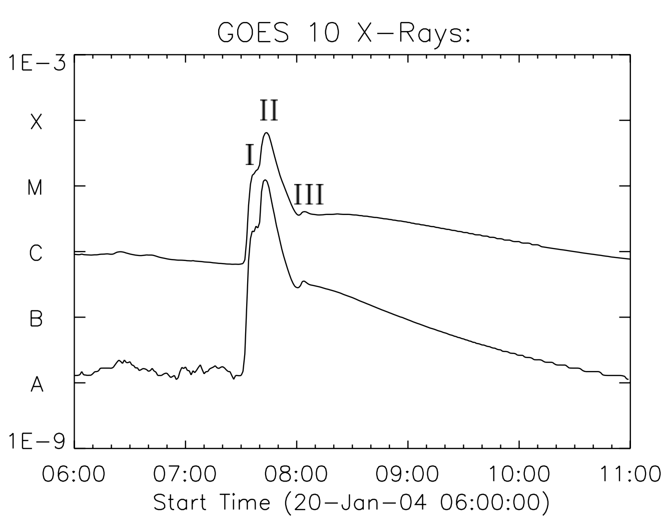

Fig. 1. GOES integrated soft X-ray light-curve on 20 January 2004 showing the complex flare event analysed in this paper. The three phases (I–III) are indicated. Phases I and II are impulsive flares, while phase III is a long-duration event (LDE).

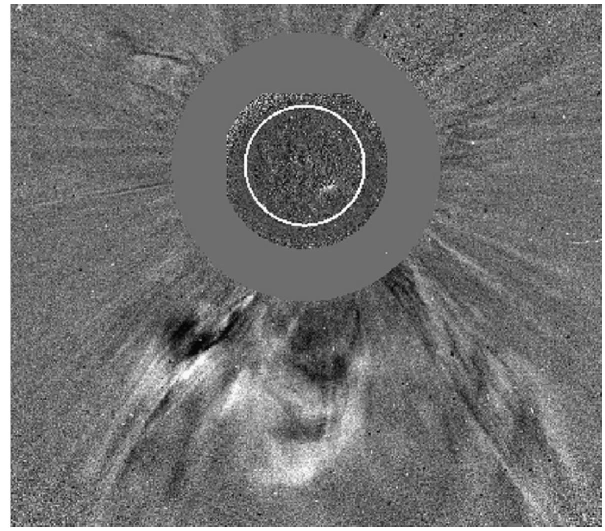

Fig. 2. LASCO C2 running difference image of the coronal mass ejection on 20 January 2004 at 09:54 UT related to the complex flare. The CME consists of loop-like structures expanding towards south, which apparently interact with (wiggle) a streamer located to the east, see the movie at http://cdaw.gsfc.nasa.gov/CMElist/dailymovies/2004/01/20/c2 eit.html.

We ask the questions: (i) how these flare phases were connected, (ii) what was their role in launching the CME (tether cutting, break-out) and (iii) which phase can be linked to the actual CME launch?

Characteristics of the three-part event can be summarised as follows:

(i) Flare ribbons of consecutive phases represent E–W progression along the magnetic inversion line and there is a spatial (and temporal) overlap between the consecutive flare phases, implying that magnetic reconnection is progressing, in a stepwise manner, along the magnetic inversion line (Figs. 4 and 5). Step-wise propagation of reconnection along magnetic inversion line has been earlier reported by Grigis and Benz (2005), Bogachev et al. (2005), Tripathi et al. (2006).

(ii) The flare ribbons appear curved (hook shaped; Figs. 4 and 5) which is considered an indicator of the presence of a twisted core magnetic field having positive helicity (Démoulin et al., 1996).

(iii) All three flares were quadrupolar, even the LDE (Fig. 4).

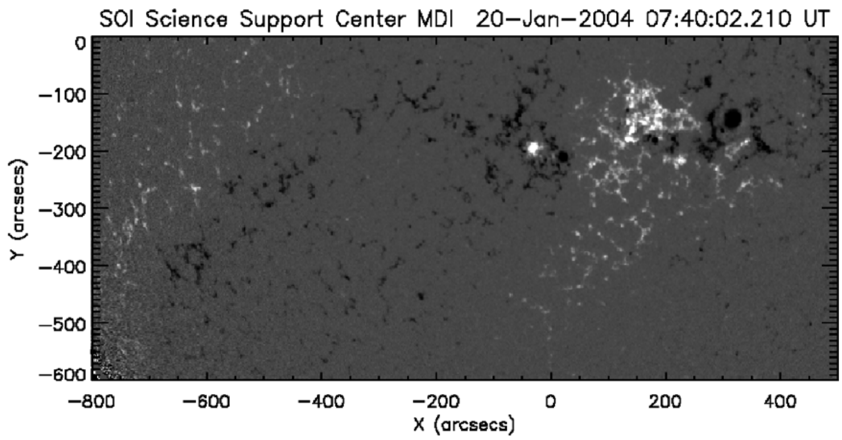

Fig. 3. Magnetic configuration and large-scale magnetic environment of the CME source region AR 10540 (in the upper right corner). The ARs dominantly bipolar structure was made more complex by flux emergence in the southern part of its dispersed positive (following) polarity. To the east/south-east there is a large dispersed bipolar region, which is the footpoint of a streamer seen in the LASCO images. Note that the positive polarity fields of the AR are interfaced with the negative polarity footpoint of the streamer – a configuration which is favourable for magnetic reconnection. The streamer was seen in the LASCO movies to wiggle during the CME event (Fig. 2) suggesting interaction.

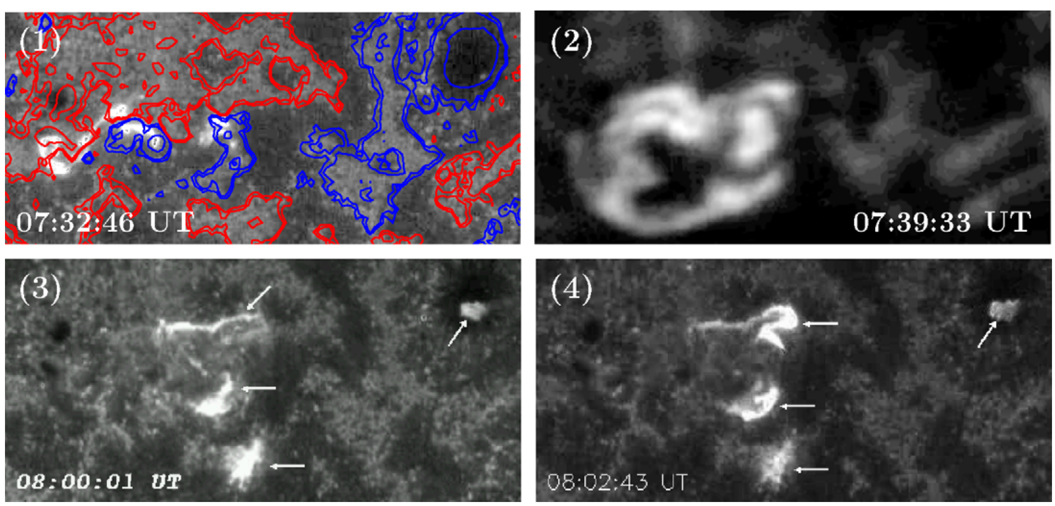

Fig. 4. TRACE (Handy et al., 1999) and Kwasan Observatory Hα images showing the three phases of the complex event (1): phase I, TRACE 1600 Å observations with MDI magnetic field contours (±50, 100, 500 G) overlaid, red/blue correspond to positive/negative values; (2) transition (overlap) between phases I and II (Hα image); (3) phase II; (4) phase III. Note the spatial overlap between the flare ribbons of consecutive phases. The four flare ribbons, which are sketched in Fig. 7, are indicated by arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

From multi-wavelength observations we are able to obtain the following information on the flare-CME relationship:

(i) Backward extrapolation of the CME distance–time plot (LASCO C2 and C3 data; Brueckner et al., 1995; Goff et al., 2007) indicates that the CME started before the first flare phase; considering that CMEs start with a slow rising phase followed by acceleration puts the starting time even earlier.
(ii) EIT base difference images (see Goff et al., 2007) indicated the start of coronal dimming south of the AR at about 08:00 UT, before the peak of the LDE. Since coronal dimming is considered a consequence of CMEs, this timing also suggests that the CME was launched before phase III.
(iii) Radio observations of type III and II bursts are generally linked to CME launches. Culgoora and Wind/WAVES (Bougeret et al., 1995) observations show type III bursts between 07:34 and 07:39 UT and type II bursts starting at 07:39 UT at about 160 MHz all before the LDE.
(iv) In phase II, flare ribbons showed considerable expansion, moving away from the magnetic inversion line – a characteristic sign of an eruption.

Based on the above evidence, we propose the scenario depicted in Fig. 6 for the launch of the CME. Tether cutting reconnections gradually, in a step-wise manner, transform the sheared arcade into a twisted flux tube, which becomes unstable and erupts. The eruption took place in phase II, but the magnetic configuration had started

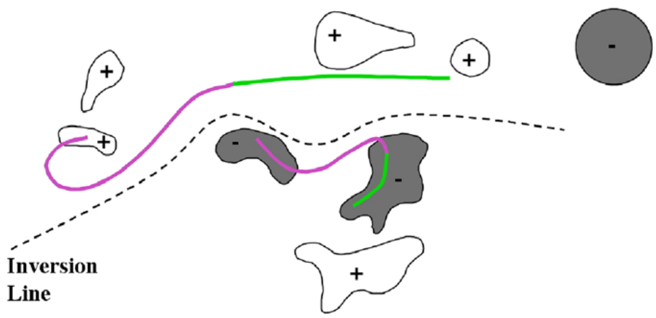

Fig. 5. Cartoon showing the main magnetic polarities in AR 10540 (dark, negative; white, positive), the magnetic inversion line (dashed) and the flare ribbons in phase I (dark, grey/pink) and phase II (light, grey/green). Note (i) the E–W progression of the ribbons (i.e. the reconnection site) along the magnetic inversion line and (ii) the curved, hook-like end-shape of the ribbons, which indicate the eruption of a (positive) twisted flux tube (Démoulin et al., 1996). (For interpretation of the references to pink and green colours in this figure legend, the reader is referred to the web version of this paper.)

expanding (due to increased non-potentiality) even before the start of phase I, i.e. the CME expansion started prior to the start of the complex flare.

Therefore, we conclude that the LDE occurred after the CME had been launched. Flux rope eruption is generally linked to two-ribbon flares. However, phase II is, like all the flares in this event, quadrupolar. An investigation of the magnetic configuration suggests that the erupting (and therefore expanding) flux rope met and reconnected with field lines connecting magnetic concentrations of the old pre-existing bipole: its leading (negative polarity) spot and a (positive) facular region to its south-east. This reconnection, forced by the expanding CME, slightly extends the two-ribbon flare westward and adds two more flare kernels (Fig. 7).

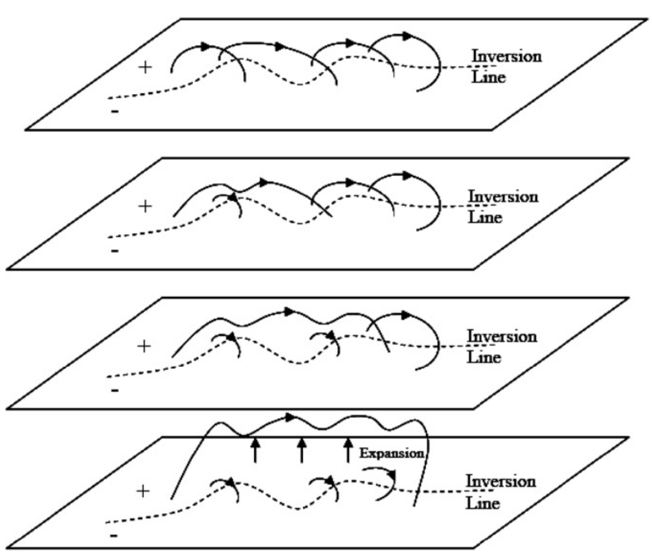

Fig. 6. Cartoon of the scenario of flare phases I and II, during which the CME was launched: tether cutting reconnections gradually, in a step-wise manner, transform the sheared arcade into a twisted flux tube, which becomes unstable and erupts. The eruption took place in phase II, but the magnetic configuration had started expanding (due to increased non-potentiality) even before the start of phase I, i.e. the CME expansion began prior to the start of the complex flare.

Since LDEs have long been considered eruptive flares, i.e. having strong link to CMEs (Sheeley et al., 1983; Tripathi et al., 2004), the physics behind this LDE merits further investigation. LDEs are two-ribbon flares in most of the cases, however, this LDE was quadrupolar. How can we explain this? We suggest that the LDE of phase III was a direct consequence of the reconnection forced by the erupting CME in phase II. As soon as the forcing has stopped (the CME left the lower corona) reconnection began to proceed backwards, gradually restoring some of the pre-CME connectivities (Fig. 7, right panel). This scenario can explain why the kernels of the LDE are situated in between the flare ribbons of phase II. Therefore this LDE was not related to the closing-down of the field lines in the wake of an erupted filament, but to the relaxation of a forced magnetic field restoring pre-CME connectivities.

3. Interaction between the CME and its magnetic environment

Since magnetic structures are ubiquitous in the solar corona, the expanding magnetic structure of CME inevitably meets (pushes against) other fields. This generally induces a current sheet formation and reconnection can result. In this present situation we find that the CME related to the complex three-part flare went through two important interactions with large-scale magnetic structures: (i) a neighbouring streamer and (ii) a "*leg*" of another CME, which erupted from the north part of the same active region about 8 h earlier.

We have the following evidence for reconnection between the CME and the neighbouring streamer:

(i) MDI magnetic maps show that the interfacing polarities were opposite, presenting a favourable configuration for reconnection (Fig. 3). This reconnection could take place when magnetic loops from the AR swell up sufficiently to push against open field lines of the streamer.
(ii) LASCO C2 observations show a wiggling streamer during the CME eruption (c.f. the black-and-white pattern along the streamer in Fig. 2 and the associated movie).
(iii) EIT observations of shrinking loops formed at the beginning of the three-part flare/CME event between the AR and the streamer base (Fig. 8).
(iv) Type III bursts observed at the start of the event, which indicate that open field lines participated in reconnection processes (Fig. 9).

Decametre radio observations provide evidence for reconnection between the CME and the magnetic structure of a previous CME, launched about 8 h earlier from the same source region, as follows. At about 07:34 UT, type

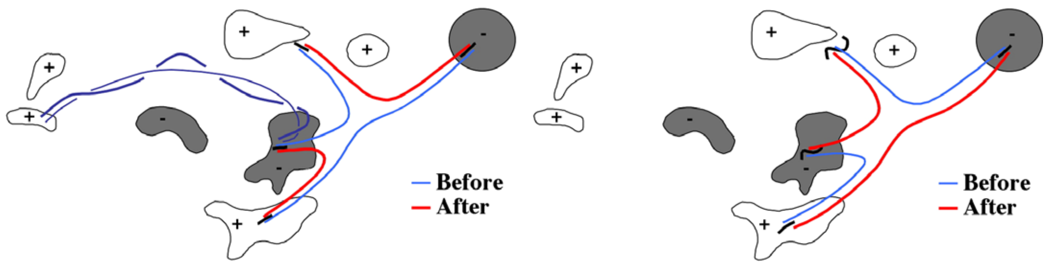

Fig. 7. (Left panel) Phase II: reconnection forced by the expanding magnetic flux rope/CME structure makes the two-ribbon flare quadrupolar. (Right panel) Phase III (LDE): after the CME had left the low corona, i.e. the forcing was gone, relaxation set in, and reconnection starts to restore some of the pre-CME connectivities.

III bursts are seen in Culgoora (see Démoulin et al., 2007) and Wind/WAVES data (Fig. 9). Type III bursts are related to beams of accelerated electrons travelling along field lines "open" towards the interplanetary space. In the Wind/WAVES decametre dynamic spectrum (Fig. 9) we see some of the type III radio emission shifting slower towards lower frequencies and at about 07:42 UT around 3 MHz turning back towards the higher frequencies (point 2 in Fig. 9), in a loop-like manner. Such a burst is called a "type U" burst, due to its shape in the dynamic spectrum. Type U-bursts have been shown to originate from electron beams travelling along magnetic loops and are rarely seen at metre and decametre wavelengths (Leblanc et al., 1983, 1999). The latter is not surprising, since it would imply loops as high as a few solar radii! In the present case the apex of the loop is observed at 3 MHz, corresponding to a height of $\geqslant 5R_{\odot}$.

The decametre dynamic spectrum in Fig. 9 shows an even more complicated feature than a U-burst: at around 07:48 UT ($\approx 3R_{\odot}$) the electrons appear to turn over again towards lower frequencies, transforming the U-burst into an N-burst. N-bursts are very rare and have been interpreted as the reflection of the electron beam by converging magnetic fields in the coronal loop where they propagate; having started as a U-burst (Caroubalos et al., 1987; Aurass et al., 1994). However, at the large height implied at decametre wavelengths, where no N-burst has ever been reported before, magnetic fields are not sufficiently strong and convergent (for more details see discussion in Démoulin et al., 2007). A shock front may be able to perform such a reflection of electrons.

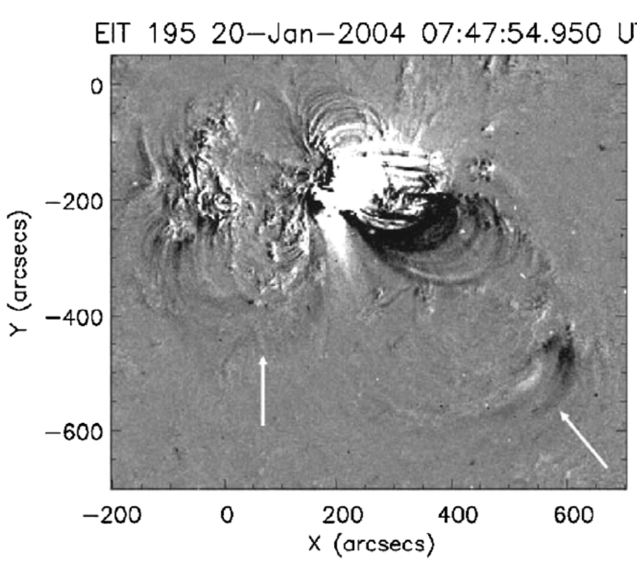

Fig. 8. Running-difference EIT image shows the formation of new loops (indicated by the left arrow) between the CME source region and the streamer base shortly after the start of the three-part flare/CME event. The loops appear to be shrinking, as expected from an interchange reconnection between the (closed) expanding CME structure and the "open" field lines of the streamer. This reconnection is also expected to form large dipped field lines rooted in the western part of the AR.

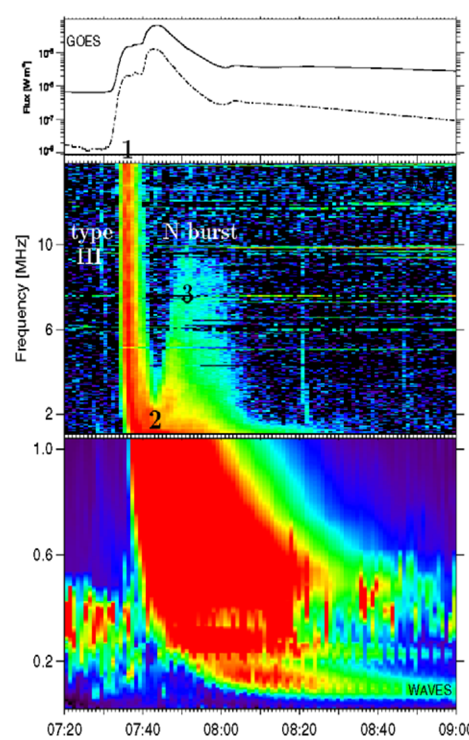

Fig. 9. Dynamic spectrum showing a decametre N-burst observed with Wind/WAVES. The upper panel shows the GOES integrated X-ray light curve on the same time-axis. The radio emission starts with a type III burst (branch 1), part of which turns back towards the higher frequencies at about 3 MHz (point 2, U-burst). The drift of type III electrons is reversed again at point 3. The dynamic spectrum of this twice reversed electron drift resembles the (reversed) letter N, hence its name.

Could the type II bursts observed at Culgoora, which are thought to be signatures of shock waves, have caused this second turn-over in the radio emission frequencies? This is impossible, since at 07:48 UT the type II burst was at much higher frequencies.

The frequency drift between positions 2 and 3 may appear relatively slow. Can this branch be caused by non-thermal type III-like electrons? An estimate of the exciter speed can be obtained from the frequency drift rate, i.e. 6 min to go from 3 MHz (position 2) to 7 MHz (position 3). Using the relative drift rate at the centre frequency between the turnovers, i.e. 5 MHz, and an exponential density model (Koutchmy, 1994), the speed of the exciter of the radio burst is $\upsilon = \frac{2H}{\nu}\frac{\Delta\nu}{\Delta t} = 440(\frac{r}{R_\odot})^2$ km s^{-1}, where H is the density scale height. The electron density at the summit of the flux tube, which from the turnover frequency is 10^5 cm^{-3} for fundamental emission and 3×10^4 cm^{-3} for harmonic emission, is typical for equatorial regions at heliocentric distances of about $5R_\odot$ and for streamers at heliocentric distances exceeding $10R_\odot$ (Koutchmy, 1994). This range implies an exciter speed in the descending branch of the type N-burst of between 11,000 and 44,000 km s^{-1} (0.04–0.15 c), which is about the range of exciter speeds of type III bursts in the solar corona and interplanetary space (e.g. Buttighoffer, 1998). This confirms our interpretation of the spectral feature as the signature of an electron beam that propagates along a sunward curved magnetic flux tube. However, how can such a large loop exist?

Investigation of data in a broader wavelength and time window suggests a plausible solution to the above problem. Eight hours earlier, at 00:06 UT on 20 January 2004, a partial halo CME erupted from the northern part of same AR (NOAA 10540). This CME showed clear signs of interaction with the neigbouring streamer on the east (wiggling motion and a U-shaped feature of increased brightness at the meeting point of the CME and the streamer – see the middle panel of Fig. 10 and the movie at http://cdaw.gsfc.nasa.gov/CMElist/dailymovies/2004/01/20/c2eit.html). Fazakerley et al. (2005) proposed that the two magnetic structures magnetically reconnected, creating large-scale dipped field-lines as shown in the rightmost panel in Fig. 10, supporting their suggestion that their in-situ measurements indicated unidirectional electron flow in the related magnetic cloud. Interaction with the streamer, which was seen to last for several hours, creates large-scale dipped field lines (see upper panel in Fig. 11), rooted around the leading negative spot in the AR. Though the magnetic tension force will straighten out such dipped field lines within an hour (taking 500 km s^{-1} for the Alfvén speed), dipped field lines were still present at the time of the N-burst, since the last expanding loops of the midnight CME were seen in LASCO C2 images (at 7:48 UT) to be about $6R_\odot$ and interaction with the streamer was still going on (as suggested by wave-like structures along the streamer in running difference images). Magnetic interaction with the later CME (as depicted in the lower panel in Fig. 11) sends accelerated electrons (in a type III burst manner) along these dipped field lines, leading to the N-burst shown in Fig. 9. Since field lines reconnected earlier were less dipped, the type III electrons traveling along all these field lines created a continuum of frequency drifts in radio emission seen after position 3 in Fig. 9.

Magnetic reconnection between the two CMEs was made possible by the fact that though they both came from AR 10540 and involved the magnetic field of the big leading negative spot, they were launched from different parts of the AR, which had opposite signs of magnetic helicity. More precisely, the midnight CME originated from the northern pre-existing bipole having negative helicity (Fazakerley et al., 2005), while the erupting flux rope of the second CME launched from the emerging flux region carried positive helicity (as indicated by the flare ribbons shown in Fig. 5). Thus in spite of the seemingly similar magnetic field line orientation there was a finite angle between the magnetic vectors of the two CMEs. Therefore, we conclude that the N-burst appeared as the result of magnetic interactions between two consecutive CMEs erupting from different parts of the same source region which both interacted with open magnetic field lines of a neighbouring streamer.

We would like to emphasize that the magnetic interaction we describe above is different from the interaction of CMEs described earlier by Gopalswamy et al. (2001), i.e. a slow CME launched earlier was overtaken and "cannibalised" by a fast CME. In the case we analyse, the first CME was the faster one ($\upsilon_{1st} = 965$ km s^{-1}, while υ_{2nd}=590 km s^{-1}, see http://cdaw.gsfc.nasa.gov/CMElist/UNIVERSAL/200401/univ200401.html), therefore no overtaking was possible. Magnetic reconnection between the two CMEs happened close to their western footpoints, i.e. *low in the solar atmosphere* (lower than $1R_\odot$), not between their frontal parts.

4. Summary of the results and conclusion

Two impulsive M-flares followed by a C-class LDE and a CME were observed on 20 January 2004. We suggest the following scenario:

- The two impulsive flares were signatures of tether-cutting reconnections, which formed a flux rope and through its eruption launched the CME.
- The expanding flux rope (CME) forced reconnection with another bipole in the AR, making the two-ribbon flare of the flux rope eruption quadrupolar.
- After the forcing CME was gone, the magnetic fields relaxed and reconnection started restoring some pre-CME connectivities (LDE).
- Interaction with a neighbouring streamer (open field lines) led to a type III burst and created large-scale dipped field lines.

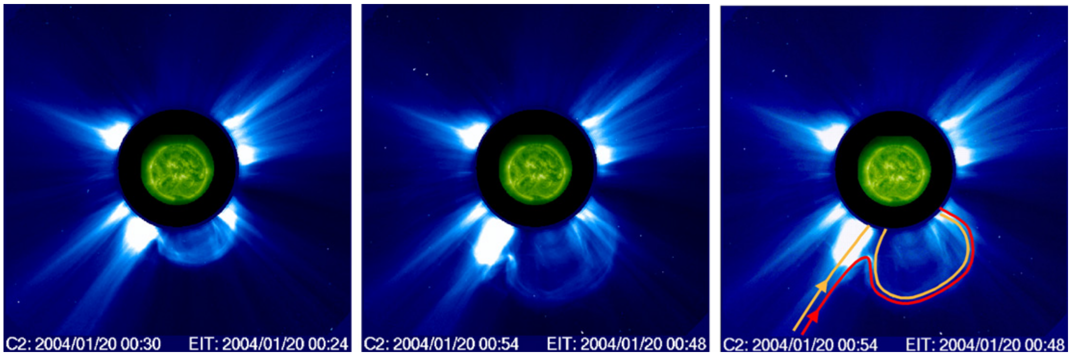

Fig. 10. Eight hours earlier than the event shown in Fig. 9, at 00:06 UT on 20 January 2004, a partial halo CME erupted from the northern part of same AR (NOAA 10540). This CME showed clear signs of interaction with the neigbouring streamer on the east (wiggling motion and a U-shaped feature of increased brightness at the meeting point of the CME and the streamer). Fazakerley et al., 2005 proposed that the two magnetic structures magnetically reconnected, creating large-scale dipped field-lines as shown in the rightmost panel (light grey/yellow shows pre-reconnection, dark grey/red post-reconnection field lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

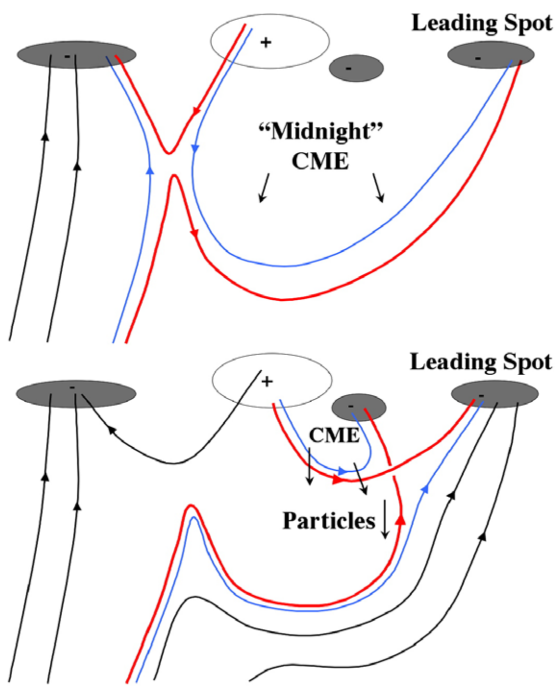

Fig. 11. Cartoon depicting the interaction between the "midnight" CME and the streamer (upper panel) and the ensuing interaction between the midnight CME and the one analysed in this paper, which erupted about 8 h later (lower panel). Interaction with the streamer, shown in Fig. 10 in LASCO images, which is seen to last for several hours, creates large-scale dipped field lines, rooted around the leading negative spot in the AR. Magnetic interaction with the later CME sends accelerated electrons (in a type III burst manner) along these dipped field lines, leading to the N-burst shown in Fig. 9.

- Interaction with another CME launched 8 h earlier from the same AR, which also interacted with the same streamer, injected type-III electrons (among others) along the large-scale dipped field lines leading to the observed decametre N-burst.

Our main conclusion is that CMEs are expanding magnetic structures which interact/reconnect with other favourably oriented magnetic structures along their path, making CMEs *more complex* truly large-scale events even in the lower corona.

Acknowledgements

The authors thank the anonymous referees for their helpful comments, as well as the SOHO/MDI, LASCO, EIT and TRACE consortia for their data. SOHO is a joint project of ESA and NASA. The CME movies used are from the CME catalog generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval research Laboratory. L.v.D.G. acknowledges the Hungarian government Grant OTKA T048961 and a Royal Society travel grant. J.L.C. thanks the Leverhulme Trust for the award of a Leverhulme Emeritus Fellowship. C.H.M. is grateful for a PPARC funded visitor's grant. C.H.M. and P.D. acknowledge financial support from CNRS (France) and CONICET (Argentina) through their cooperative science program (05ARG0011 No. 20326). C.H.M. thanks the Argentinean Grants: UBACyT X329 (UBA), PICT 12187 (ANPCyT) and PIP 6220 (CONICET). C.H.M is a member of the Carrera del Investigator Científico (CONICET).

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