AN ERUPTIVE FLARE OBSERVED BY TRACE
AS A TEST FOR THE MAGNETIC BREAKOUT MODEL

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ABSTRACT

The aim of this work is to investigate the possibility of the magnetic breakout scenario (Antiochos et al., 1999) for the July 14, 1998 flare. Mees vector magnetograms show that the flare occurred right above the sheared portion of the neutral line surrounding a δ-spot. A potential magnetic field extrapolation from a Kitt Peak line-of-sight magnetogram reveals the presence of a 3-D null point above the δ-spot. The flare was observed by TRACE in the 171Å line, with a 1 minute time resolution and 0.5" spatial resolution. These observations show in particular the opening of some loops prior to the flare, indicating it was an eruptive flare which probably led to a CME. We show that the evolution of the observed features during the whole event, combined with the location of the null point and of its separatrix in the corona, can be interpreted in terms of the magnetic breakout.

Key words: X-rays; eruptive flares; MHD; magnetic fields.

1. THE MAGNETIC BREAKOUT MODEL

Recently Antiochos et al. (1999) proposed a 2.5-D model for solar eruptions and CMEs, the “magnetic breakout” (MB) model. The hypotheses of the model are: a quadrupolar photospheric magnetic field, leading to a complex topology, where one null point is present in the corona. The driver of the eruption is a local magnetic shear concentrated around the central neutral line.

In this context, the configuration evolves as follows: the central sheared arcades slowly expand outward, as the rate of reconnection is slow compared to the rate of shearing. Then the magnetic energy of the configuration can eventually reach a value which is above the one of the partially open state. After the collapse of the current layer at the null point, fast reconnection starts. It removes the unsheared overlying flux to the side. Then, as the sheared field lines now have a lot of energy and as there is much less flux above them to prevent their expansion, they suffer a very fast opening. These sheared field lines also push upward some of the large-scale remaining overlying arcades. Finally, reconnection of the open field lines creates new closed arcades above the central inversion line.

In this work, we propose now that the MB can occur if one of the inverse line is sheared instead of the central one as in Antiochos et al (1999). We believe that the step to 3-D will reveal that these two cases are indeed the same. The MB scenario in this context is summarized in see Fig. 1.

The “magnetic breakout” model for CMEs mainly differs from the classic “tether cutting” (TC) one (see Sturrock 1989, Moore & Roumeliotis 1992, Mikić & Linker 1994 and Amari et al. 1996) for 3 reasons: (i) in TC the field is bipolar whereas it is quadrupolar in MB. (ii) in TC, the sheared field lines slowly expand, and only the formation of a disconnected plasmoid, by reconnection below them, allows a fast opening of the field. In the MB however, the sheared field lines almost do not expand, because the compressing overlying flux. This remains true until fast reconnection occurs above them, suddenly removing this overlying flux. Then the sheared field lines relax and suddenly open. (iii) The late reconnection leading to the formation of a plasmoid and post-flare loops is only a sub-product of the fast opening in MB, and not its cause as in TC.

2. THE “BASTILLE DAY” FLARE


2.1. TRACE observations

The TRACE telescope observed AR 8270 from 12:05 UT to 14:00 UT, giving UV data in 195Å (FeXII), 171Å (FeIX) and 1600Å (UV continuum). Observations in 195Å /171Å (resp. 1600Å) were recorder on images of 768 × 768 (resp. 256 × 256) pixels, with a mean time step of 40 seconds between two images, and with a spatial resolution of 0.5". More details


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about the TRACE instrument can be found in Handy et al. (1999), and first have been shown by Golub et al. (1999).

The images were corrected from the cosmic rays, and derotated so that they are all co-aligned with each other. A 171Å image of AR 8270 before the flare is shown on Fig. 2, left. It shows a large-scale set of loops connecting the main bipole of the AR.

2.2. Magnetograms

A Kitt Peak full-disc line-of-sight magnetogram is available for the day of the event. It was observed at 17:00 UT with a spatial resolution of 2.3". It shows that there is a δ-spot AR 8270, where two sunspots of opposite magnetic polarities share a same penumbra. In AR 8270, the negative spot of the δ-spot is completely surrounded by facules of positive polarity, so that there is a close inversion line around it (see Fig. 3, left). Moreover, a Mees IVM vector magnetogram shows that there is a large amount of magnetic shear around the northern part of the inversion line of the δ-spot.

The origin of δ-spots is still under debate. However, observations show that the magnetic field can emerge with a pre-existing shear (Leka et al. 1996), and numerical simulations have been able to reproduce such behaviour (Mok et al. 1997). A global view of the formation of δ-spots have been proposed by Linton et al. (1999) in terms of kinked twisted flux tubes emerging from underneath the photosphere. Finally, the magnetic field in AR 8270 is typical of what can be expected of a 3-D version of the magnetic breakout model, as previously pointed out by Antiochos (1998).

2.3. Co-alignment

The key of the understanding of the quiet and dynamic structures in the solar corona is knowing the magnetic field, unfortunately no clean measurements are available in this layer of the Sun. However the photospheric magnetograms can give some hints about it, combined with theoretical magnetic field extrapolations. The calculated field can then be compared to observed UV features, providing that a correct co-alignment was done between the magnetogram and the UV observations. This becomes crucial when dealing with small scale events or resolved features, such as the connectivity of thin loops or local inversion lines around parasitic polarities.

In our case we proceeded in three steps to get a co-alignment: (i) overlay one 1600Å image with the magnetogram, using the network brightenings and the weak fields in the facets, in the 256×256 TRACE pixels field of view. (ii) overlay the 1600Å image with one of the 195Å /171Å image, using the darkenings of sunspots and some brightenings of the facets. (iii) the 195Å /171Å images are then naturally co-aligned with the magnetogram. We estimate that the errors on the co-alignment should not exceed two Kitt Peak pixels (i.e. 4.6")

The connectivity of the thin loops is consistent with the δ-spot (see Fig. 3, left). Moreover, the large-scale (768×768 TRACE pixels) field of view shows that the UV brightenings in a northern decaying AR look to be in agreement with the weak fields of the co-aligned magnetogram, giving an independent check on the validity of the method.

3. THE MAGNETIC TOPOLOGY

3.1. The extrapolation method

The magnetic field was extrapolated in the corona from a 515" × 515" portion of the Kitt Peak line-of-sight magnetogram, centered on the sheared inversion line of the δ-spot, and including a large-scale weak field region around AR 8270. The extrapolation was done in the potential approximation (i.e. $\nabla \times B = 0$), with a 201×201×101 non-uniform grid. The photospheric boundary conditions are periodic, and the field amplitude is assumed to drop to zero at infinite altitudes, so that the magnetic field is expressed in the form of Fourier harmonics (see Alissandrakis 1981). The method takes into account the transformation of coordinates from the AR location to the disc center (see Démoulin et al. 1996).

3.2. A 3-D null point above the δ-spot

The potential extrapolation reveals the presence of a magnetic null in the corona, right above the δ-spot. Its associated separatix forms a so-called “fan” surface enclosing the negative parasitic polarity of the spot, and a singular “spine” field line, connecting the negative spot to the negative leading polarity of AR 8270 (see Fig. 3, right). More details about the structure of 3-D null-points and the possible 3-D reconnection at their locations can be found in Lau & Finn (1990).

We assume that the potential approximation is valid at the zeroth order, and that it can give an initial configuration which can be sheared (by stirring or by emergence) to get the free energy to allow the breakout.

In this context, Antiochos (1998) have pointed out that this too simple topology cannot allow the eruption of a sheared field all around the closed inversion line of the parasitic polarity. This is because reconnection at the null cannot decrease the total amount of flux under the fan. But in AR 8270, the shear is concentrated only around one part of the inversion line (see Sec. 2.2.2). So we can conjecture that magnetic reconnection at the null can shift the overlying unsheared flux above the sheared part of the inversion line, to its unsheared part. In the context of the breakout, this allows the eruption of the field located around the sheared portion of the inversion line only.
4. RELATING THE OBSERVED EVENTS WITH THE BREAKOUT SCENARIO

TRACE observations show that some small-scale loops, located above the sheared part of the inversion line surrounding the δ-spot, suddenly start to expand and begin to be pushed sideward at 12:27 UT (Fig. 4). The flare itself starts at 12:35 UT (Fig. 4). Then, while postflare loop formation is in progress (Fig. 4), a large-scale dimming wave propagates to the NW and SW of the AR, which is hardly detectable before 13:01 UT (Fig. 5). Several dynamic features also appear during the event, such as a very thin loop brightening, the compression of the large loops of the AR, and some loop oscillations triggered by the flare (studied by Nakariakov et al. 1999). A summary of the evolution of the observed features is shown in the first column of Table 1.

As the breakout model predicts the opening of some field lines leading to a CME, we first need to check that this indeed occurred for the July 14, 1998 flare in AR 8270. Unfortunately no coronagraph observation is available for this event, so we cannot directly prove that an eruption or CME occurred. However recent SOHO/EIT and LASCO observations show that ~85% of coronal dimming waves observed in 195Å /171Å (such as the one observed in AR 8270) are associated with a CME (Delannée et al. 1999). This suggests that the July 14 flare was probably an eruptive flare accompanied with a CME.

It is interesting to know if the flare occurred before or after the expansion of the field lines: the high temporal/spatial resolutions of TRACE permit to show that the large scale dimming is accompanied by rapidly expanding large loops (see Fig. 5). We propose that (i) the large-scale loop expansion (13:01 UT) is in fact following the small-scale expansion (12:27 UT), and that (ii) it can be interpreted in terms of opening of some field lines. If these hypotheses are correct, then the flare occurs after the opening of the field lines. Moreover, the presence of the null point implies that the field must open "through" the fan surface, showing that reconnection at the null is very likely to occur during the opening.

The interpretation of the observed features is reported in Table 1. Some of them are not directly addressed by this model, or were not initially expected. However Table 1 shows that there is a good agreement between the breakout scenario and the TRACE observations.

5. DISCUSSION

We have shown that the July 14, 1998 flare occurred in a complex topology, where a 3-D null point is present above a δ-spot. We have then explained how this topology, combined with a magnetic shear localized around a fraction of the closed inversion line of the parasitic polarity, can lead to a 3-D version of the 2.5-D magnetic breakout (Antiochos et al. 1999). We have related the evolution of loops, brightenings and dimmings observed in 171Å by TRACE, to the breakout scenario. We have also raised some questions not directly addressed by this model.

These comparisons have shown that the July 14 event may be caused by the opening of the field lines due the magnetic breakout (MB), but three-dimensional MHD numerical simulations are required to test this conjecture. In particular what needs to be shown is if the reconnection at the null is essential for the opening (as the MB suggests) or is it only a sub-product of an independant opening, because the flux of the overlapping archedes would be too low to confine the sheared field lines (this would explain for example why does the spine brightens 1.5 min after the impulsive phase).

6. WHAT HAVE WE LEARNT FOR FUTURE SOHO OBSERVATIONS?

We propose that the understanding of similar events observed by SOHO/EIT would mainly require high cadence observations, with the maximum time resolution, which for the concern of this study has been revealed to be the greatest advantage of TRACE. In this scope, we finally highlight the necessity of well co-aligned magnetograms.

ACKNOWLEDGMENTS

This work is supported, at SAO by a NASA contract to Lockheed-Martin, and at NRL by NASA and ONR.

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Figure 1. Expected scenario for the "magnetic breakout": In an initial complex topology, where (a) there is a local magnetic shear and a null point, (b) the flux overlying the sheared field lines is transferred to the side through reconnection at the null point, allowing (c) a local fast opening of the system. Reconnection finally produces an energetic flare as (d) some open field lines close down. In this context, the opening occurs before the flare.

Figure 2. (Left) AR 8270, observed by TRACE in 171Å, on 07/14/98 at 12:05:40 UT. The field of view is 384 x 384 arcsec. The boxes show the regions selected in the next figures. (Right) potential magnetic field extrapolation from a Kitt Peak line-of-sight magnetogram obtained at 17:30 UT.
Figure 3. (Left) zoom on “Box 3” from Fig. 2, with isocontours of the magnetic field from the co-aligned magnetogram. White (resp. black) refers to positive (resp. negative) value, and the thick black lines are the inversion lines. There is a large “parasitic” negative sunspot entirely surrounded by positive magnetic fields. This forms a δ-spot. (Right) field lines computed from the potential extrapolation. These form the separatrix associated to a 3-D null point present in the corona above the δ-spot. The separatrix is made by a “fan” surface surrounding the δ-spot, which intersects a singular “spine” field line originating from the δ-spot. The elongated 171Å “round shaped brightening” can be interpreted as the intersection of the fan with the chromosphere.

Figure 4. Zoom on the “Box 1” from Fig. 2, showing a time-sequence of TRACE 171Å observations for the July 14 flare. (First row) some loops rooted in the “round shaped brightening” are pushed sideways as they expand just above the inversion line of the δ-spot. (Second row) impulsive phase, where a second “elongated brightening” appears to the right of the “round shaped” one. (Third row) decay phase, where post-flare loops are continuously formed, and are rooted in the “elongated brightening”.

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Figure 5. Zoom on the “Box 2” from Fig. 2, showing the rapid expansion of two 171Å loops, followed by a coronal dimming wave. This naturally leads to think that a CME was associated to the July 14 flare. We believe that this opening is initiated before the flare (see first row of Fig. 4).

<table>
<thead>
<tr>
<th>Hour (UT)</th>
<th>171Å TRACE observations &amp; potential field extrapolation</th>
<th>Breakout scenario</th>
<th>Possible interpretation for the “?”</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:05:40</td>
<td>elongated faint brightening along the intersection of the fan with the photosphere</td>
<td>weak reconnection at the null point, allowing flux transfer on the side of the sheared loops</td>
<td>-</td>
</tr>
<tr>
<td>12:27:44</td>
<td>expanding loops suddenly pushed aside, and small dimming</td>
<td>beginning of fast reconnection at the null, and local opening of underlying sheared field lines</td>
<td>-</td>
</tr>
<tr>
<td>12:55:16</td>
<td>start impulsive phase: elongated brightening above IL</td>
<td>reconnection in the expanding sheared field lines</td>
<td>-</td>
</tr>
<tr>
<td>12:56:32</td>
<td>start shrinkage of large scale loops of the AR start of propagation of a brightening along the spine</td>
<td>expanding fields create a downward magnetic pressure as they expand in the high corona</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>energy release causing particle acceleration</td>
</tr>
<tr>
<td>12:57:38</td>
<td>round-shape brightening appears at the footpoint of the spine</td>
<td>?</td>
<td>accelerated particles hit the chromosphere</td>
</tr>
<tr>
<td>12:58:50</td>
<td>the spine becomes dark</td>
<td>?</td>
<td>end of particle beam</td>
</tr>
<tr>
<td>12:59:57</td>
<td>end of impulsive phase: beginning of post-flare loops</td>
<td>steady reconnection in the open loops</td>
<td>-</td>
</tr>
<tr>
<td>13:01:09</td>
<td>large scale loop expansion propagation of a large dimming wave with these loops</td>
<td>on-going opening of field lines</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>the density decreases as the loop length increases</td>
</tr>
<tr>
<td>13:02:26</td>
<td>end shrinkage of large scale loops of the AR</td>
<td>the field is now open near the center of the AR</td>
<td>-</td>
</tr>
<tr>
<td>13:06:15</td>
<td>transverse oscillations in the southern loops of the AR</td>
<td>?</td>
<td>direct response to the very fast opening</td>
</tr>
<tr>
<td>13:22:35</td>
<td>end of oscillations</td>
<td>?</td>
<td>the loops have reached a new equilibrium</td>
</tr>
<tr>
<td>13:49:01</td>
<td>formation of post flare loops continues</td>
<td>the open field keeps reconnecting to get to a low energy state</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1. Summary of the events observed by TRACE for the July 14 flare, and their interpretation in the context of the 2.5-D magnetic breakout model. Some observed features cannot be directly explained by the model (see the “?”), but are not inconsistent with what could really happen on the Sun.