THE EVOLUTION OF A RAPIDLY-EXPANDING ACTIVE REGION LOOP INTO A TRANS-EQUATORIAL CORONAL MASS EJECTION

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ABSTRACT

On 23 February 1997 a coronal mass ejection erupted off the NE limb of the Sun from a coronal loop system which had earlier been visible in soft X-rays and Fe XIV. The ejection coincided with the onset of a small soft X-ray event, and it left the corona at a position angle of around 60 degrees at around 880 km s⁻¹. This ejection then merged with a much larger event which spanned the equator and became indistinguishable, in projection, with the primary event. The soft X-ray images indicate that the highest temperature plasma was associated with the loop system near the original erupting loop. A large loop system became visible south of the equator as the CME developed. It appears that there are high closed coronal magnetic loops linking the northern region to that in the south.

Key words: coronal mass ejections; soft-X-rays.

1. INTRODUCTION

Since the beginning of SOHO scientific observations in early 1996 it has been possible to study coronal mass ejections (CME) from the low corona out to 30 R☉. However, whereas the passage of a CME through the majority of this range is not particularly sensitive to the cadence of the observations, observing the moment of launch is more critical. It is clearly of interest to be able to study the physical conditions in the plasma at the base of the CME, but full-disk observations of high temperature plasma are available at a relatively low cadence compared to what would be desired. In this paper we report observations of a CME from a loop prominence system which had been well observed as it crossed the north-east limb of the Sun. The event quickly spread in latitude until had an angular extent of around 70°, spanning the solar equatorial plane. The loop prominence system is observed at soft X-ray wavelengths and in the lines of Fe XIV and Fe X. The X-ray emission persisted for several hours after the launch of the CME, whereas the Fe X emission underwent a rapid decline. This indicates that the X-ray-emitting plasma is in a physically-separate magnetic system, and that it did not erupt into the corona at the time of the CME. The rapid spread of the event to south of the equator suggests that there is a good physical connection between the two hemispheres, which we suggest is via high, closed coronal loops.

2. OBSERVATIONS

The coronal mass ejection which erupted off the north-east limb of the Sun on February 23, 1997 was well observed by the LASCO coronagraphs on SOHO (Brueckner et al 1995) and the soft X-ray telescope (SXT) on Yohkoh (Tsuneta et al 1991). LASCO is a set of three nested coronagraphs covering the corona.
The onset of the CME in Fe XIV running difference images. The occulting disc is at 1.1 Rs. The CME onset was studied in detail by the C1 coronagraph in the Fe XIV and Fe X lines, which are temperature-sensitive. Its evolution through the outer corona was monitored by C2 and C3 in white light, which is photospheric light Thomson-scattered off free electrons and therefore is strictly mass-sensitive.

The magnetic structures contained plasma at a variety of temperatures. The origin of the high temperature emission was in a relatively stable active region loop system from a spotless region about to come across the NE limb. The Yohkoh SXT image is shown in Figure 1, which represents a difference image from the frames taken at 01:40:35 UT and 01:32:03 UT. Thus the white loops off the northeast limb in Figure 1 represent a growth in the X-ray emission at that altitude. In the soft X-ray image the loopops extended to around 1.16 Rs. Inset in Figure 1 is the GOES full-Sun X-ray intensity-time profile with the Yohkoh orbit-night periods shown hatched; SXT images were taken almost continuously over the period covering the soft X-ray rise.

The loops extended to a projected altitude of 1.33 Rs as seen in the Fe XIV line and spread in latitude from around 30 - 40 degrees north. As this event appears predominantly to be a limb event, all our observed altitudes and velocities are projected onto the plane of the sky. The altitude of the loopops slowly rose throughout February 22, part of which would be explained by solar rotation. At 02:23 UT on February 23 the loops suddenly erupted. The evolution of the Fe XIV activity is shown in Figure 2, which represent running difference images at line centre. Figure 2 frame (a), at 00:55 UT, clearly shows that the loop system is quite active. This may be deduced from the strong black and white features, which are indicative of changes in the frame from the previous frame. There is a faint impression of a loop visible in this frame. The loops with Fe XIV emission are much higher in the corona than the X-ray loops. Forty five minutes later (frame b) the loop has expanded slightly, and the central region is quite dark, indicating that hot plasma that was there has disappeared; this could either be due to a temperature change or to mass motion. Frames (c) and (d) now show rapid evolution and an expansion of the highest part of the structure. The GOES X-ray intensity shown inset in Figure 1 indicates that the rapid rise in X-ray emission was a few minutes after 02:10 UT, the time of image 2c.

Image 2d shows two significant developments. The first is the dark streak extending eastwards from the southern end of the structure and the second is the bright region to the north. The dark streak indicates that Fe XIV-emitting material has disappeared from this location. Examination of the X-ray image shown in Figure 1 reveals what could be interpreted as two large loops, one in the foreground appearing to be orientated approximately along a solar meridian, and the other (behind) orientated approximately east-west. Figure 2d suggests that the base of the meridional loop has brightened, together with the loopop, as well as expanding in altitude.

The full-frame Fe XIV running difference images show a large loop structure becoming visible off the southeast limb. A representative sample of these is shown in Figure 3. In Figure 3a there is a bright feature at the southern edge of the large loop off the southeast limb, at a position angle of 125°, which suggests that there has been either the addition of mass or heating of the ambient plasma. This large structure is still apparent in the later images. The

Figure 3. The development of the large southerly loop as seen in Fe XIV running difference images. (a) 03:50 UT; (b) 04:10 UT; (c) 04:59 UT; (d) 05:40 UT. The occulting disc is at 1.1 Rs.
The evolution of the main CME as seen in the C2 coronograph. The occulting disc is at 2 R_\odot.

position

angle is measured antclockwise from the north solar pole. In this frame there is also a suggestion of some continuous structure going from the bright southerly region to the system off the northeast limb.

When the event was first seen at 02:55 UT in the C2 coronograph it was consistent in position angle with the top of the Fe XIV loop. However, the next C2 image showed a remarkable development. The top of the original expanding loop appeared to have continued outwards at the same position angle, but the bulk of the coronal mass was now in what appears to be an overlaid series of discrete loops which span the equator. Two images of this structure are shown in Figure 4 which represent C2 images with a pre-event base frame subtracted. The left panel was taken at 03:25 UT and it is clear that the southern portion of the ejection is now part of a huge structure extending south of the equator. The outer edge is sharply defined, and the most distant portion of the CME is at a position angle around 55°, consistent with a radial outward motion of the original disturbance. The right panel is taken thirty minutes later, at 03:55 UT, and the southern leg is apparently rooted in the streamer coming off the limb from 15-35 degrees south. Events such as this are not unique in the LASCO data, and a very similar event erupted off the northwest limb on 9 September 1997.

After the ejection had left the C2 field-of-view the event continued to be observed by the C3 coronograph, and Figure 5 shows two difference images at 05:45 UT (a) and 06:45 UT (b). Note that the bright leading edge of the event, at position angle 90° is still visible. The angular extent of image 5a is ~60°. Thus this ejection as seen in the outer corona is a typical large event. The brightest part of the image is still on the southern edge, and in Figure 6b there is a bright ray extending back towards the Sun at this position. At around 14:30 UT a small bright blob was ejected at a position angle of 94° just south of the dark streamer visible in Figure 5b. Note that this region appears dark because of the bright streamer present in this position in the subtracted image at 00:37 UT.

The observations of the February 23, 1997 ejection enable us to confirm and expand a number of features of CMEs, which may eventually lead to a more complete understanding of the their origin and their relationship to the flare phenomenon.

The region from which the bulk of the X-ray emission originated was a spotless region around the edge of the streamer belt in the northern hemisphere. The GOES soft X-ray intensity-time profile shows a precursor to the eruption at 02:23 UT, which started around 01:30 UT. There was nothing in the coronagraph images which showed a noticeable change at this time, so we conclude that the energy responsible for the X-ray enhancement was dissipated in the low lying coronal loops and did not result in an expulsion of mass into the high corona.

We have been able to track the outward radial expansion of the initial expanding loop from the inner corona out to 29 R_\odot. The datapoints from the three LASCO coronagraphs are shown in Figure 6. The looptop was moving outwards with a velocity of 880 ± 15 km s^{-1}. The errors on the points are less than or comparable to the size of the symbols. There is no evidence for any significant acceleration or deceleration as the leading edge of this event left the Sun. It is possible to measure the height-time history of other feature of the CME which are following behind; however, these do not add anything to the present study.

It seems that the erupting loop was connected somehow to a much larger magnetic structure which probably overlaid both it and the loops which developed off the SE limb. However, the initial main mass ejection seems to have continued out into the interplanetary medium, while at the same time a more massive eruption within neighbouring loops produced the bulk of the signal seen in the coronograph. Thus the initial fast event could be equivalent to the fast forerunners identified in the Skylab data by Jackson and Hildner (1978). In the February 23 event this was followed by the dominant mass ejection from a trans-equatorial structure. This CME had a very complex
structure which is perhaps best seen in the left panel of Figure 4. From this image it is possible to get a sense of the structure in the third dimension. Thus attempts to model CMEs from an MHD standpoint should take this complexity into account if they are to be realistic.

Simnett & Harrison 1985 showed for the CME-associated X-ray events they studied with the Hard X-ray Imaging Spectrometer on the Solar Maximum Mission that the site of the X-ray activity was often from, or near, one leg of the CME. Thus the CME may not be the result of a blast wave spreading out from a flaresite and this conclusion is consistent with the 23 February event.

The activity we have discussed, as seen in the Fe XIV line, is from plasma at a temperature around $1.5 \times 10^6$ K, while the SXT images are from plasma at temperatures around $3 \times 10^6$ K. LASCO also takes images in the line of Fe X, at around $1.0 \times 10^6$ K. Figure 7 shows the evolution of the Fe X line minus continuum image of the region as it came over the northeast limb. The continuum image subtraction is designed to remove the background coronal signal, leaving primarily the high temperature emission. These images show the complicated pre-event loop system very well. The first image, at 22:15 UT, shows a foreground set of loops in front of some higher loops in the background. There is an angled loop at the southern end, which is similar to the east-west X-ray structure discussed above. There is a general halo of emission encompassing all this activity, extending to about $1.5 \ R_\odot$. In the next image, at 00:10 UT, just prior to the onset of the precursor X-ray activity, the most noticeable change is in the bright, apparently radial, extension just north of the angled loop. The final image was taken at 04:15 UT, by which time the leading edge of the CME is already at $\sim 10 \ R_\odot$. The bulk of the Fe X emission has now disappeared, leaving behind a dark region at a position angle of $59^\circ$. This image leaves us in no doubt as the source of at least some of the mass in the CME. We believe it is most unlikely that the dark region in this image is the result of a change in temperature, and therefore the decrease in emission measure is likely to be the result of a loss of material at this location.

While the CME was in progress off the east side of the Sun, there was a weaker, slower event in progress off the southeast limb, at a position angle of around $225^\circ$. This event was just detectable in the Fe X running difference images at a height of $1.6 \ R_\odot$ at 22:15 UT on February 22. It subsequently accelerated but by the time it had reached $20 \ R_\odot$ it only had a velocity of $\sim 300 \ km \ s^{-1}$. The leading edge of this feature is indicated by the arrows in Figure 5. The LASCO team is in the process of completing a statistical study of the occurrence of large, loop-like CMEs to establish if they are truly random events, or if there is any evidence that some time-overlapping CMEs, such as those on 22/23 February 1997, are causally-related.
One of the main objectives of a study such as we have made is to try to understand better the energetics of CMEs. In the February 23 event there was clearly energy being fed into the extensive loop system coming over the northeast limb. However, this was not accompanied by any radio activity, as Solar Geophysical Data contained no entries at metric or microwave wavelengths from 21:00 UT February 22 to after 08:30 UT on February 23. The SXT images show that the only X-ray activity was off the northeast limb; therefore it is safe to assume that the intensity reported by GOES is all coming from this region.

From the observations we have discussed above the following points emerge:

1. The CME starts in the low corona from a diffuse loop system off the NE limb.

2. It quickly destabilises a sequence of much larger structures to the south, while continuing out radially at around 880 km s$^{-1}$.

3. The mass ejection from the more southerly structures dominates the overall event, as may be seen from the images in Figure 4.

4. The projected angular extent of the main CME is 65$^\circ$.

5. The strongest coronagraph signal is from the southernmost leg of the main event, as may be seen from Figures 4a and 5a.

6. The X-ray emission is from a lower-lying structure than that involved in the primary ejection. This conclusion is based on the remarkable decay of the Fe X line emission shown in Figure 7, and the relatively slow decline of the X-ray intensity shown in Figure 1. This is almost certainly an example of dimming in the corona which follows some events.

7. It is not clear what role the large structure visible off the south west limb in Figure 3 plays in the evolution of the CME. However, the bright arc of emission in Figure 3a appears to project towards the base of the structure seen in the C2 image in Figure 4.

REFERENCES


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