The Coronal-Dimming Footprint of a Streamer-Puff Coronal Mass Ejection: Confirmation of the Magnetic-Arch-Blowout Scenario

Ronald L. Moore and Alphonse C. Sterling

Space Science Office, VP62, Marshall Space Flight Center, Huntsville, AL 35812

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1. INTRODUCTION

Solar flares and coronal mass ejections (CMEs) are produced by explosion of stressed (nonpotential) initially closed magnetic fields (e.g., Svestka 1976; Sturrock 1980; Moore et al 1987, 2001; Moore 1988, 2001; Zhang & Low 2005; Moore & Sterling 2006). Many substantial flares occur with no CME, and some CMEs occur with no obvious flare (e.g., Kahler 1992; Webb et al 1998). When a CME occurs in tandem with an obvious flare, the lateral span of the CME is nearly always several times that of the flare, and the CME is often not centered on the flare (e.g., Harrison et al 1990; Kahler 1992; Harrison 1995). Especially when the flare is in the outskirts of the CME, it is often inferred that the CME does not explode from the flare site (e.g., Kahler 1992; Gosling 1993; Harrison 1995). To the contrary, recent observations (those of Bemporad et al (2005) and those presented and cited in this paper) indicate that some CMEs are indeed driven by the magnetic explosion from an offset flare site.

In this paper, for a CME of the particular variety recently identified by Bemporad et al (2005), we present new evidence that strengthens the conclusion of Bemporad et al that for these CMEs the pre-eruption magnetic field that explodes to drive the CME is laterally far offset from the radial path of the full-blown CME in the outer corona. In CMEs of the particular variety of those found by Bemporad et al, the flare-site field that explodes is much more compact than the flare-site fields that explode in most major flares and large CMEs, and is located in a flank of the base of a streamer. After presenting our new evidence for how CMEs of this variety are produced, we cite and discuss examples of larger flare-producing magnetic explosions that are not necessarily in a flank of a streamer but occur together with a large CME that in the outer corona is laterally far offset from the flare. We conclude that there is a broad class of CMEs that come from flare-producing magnetic explosions of various sizes and that are laterally far offset from the flare. We propose that all CMEs of this broad class are produced in basically the same way as those of the particular variety of the one that we present in this paper. In this paper, it is therefore convenient and useful to refer to this broad class of CMEs (regardless of the pre-eruption size of the offset field that explodes and whether or not this field is in the flank of a streamer), as "over-and-out" CMEs. Because the lack of recognition of this class of CMEs has contributed to the confusion and controversy regarding the relation between flares and CMEs (e.g., Kahler 1992; Gosling 1993; Hudson et al 1995), it is important that this class of CME have an explicit name. We adopt the name over-and-out CME because it is a needed descriptive term, especially for the purpose of this paper.

In this paper, following Bemporad et al (2005), CMEs of the particular subclass of over-and-out CME identified by Bemporad et al (2005) are called streamer-puff CMEs. This name evokes the observed morphology and slight lasting consequences of these CMEs in the outer corona. It also connotes that these CMEs are distinctly different from the more common streamer-blowout CMEs (Howard et al 1985). Like a streamer-blowout CME, a streamer-puff CME erupts from the base of a streamer and travels out along the streamer in the outer corona, but in contrast to a streamer-blowout CME, a streamer-puff CME only transiently inflates the streamer: after the CME, the streamer is nearly the same as before rather than obliterated.

were over-and-out CMEs produced in the manner depicted in Figure 1. Figure 1 features all of the elements of what we call the magnetic-arch-blowout scenario for over-and-out CMEs, tailored to the case of the streamer-puff CMEs of Bemporad et al. [To be clear, we note the distinction between our three terms: (1) streamer-puff CME, (2) over-and-out CME, and (3) magnetic-arch-blowout scenario. The first two terms are descriptive names of certain observed types of CMEs, the first type being one variety of the second type. These names are appropriate independent of the physics of the production of the CMEs. The third term is our name for our proposed physical picture for the production of over-and-out CMEs.] In the version of the magnetic-arch-blowout scenario for the streamer-puff CMEs of Bemporad et al (Figure 1), there was a low, compact, sheared-core magnetic arcade over the polarity dividing line (neutral line) between the negative magnetic island and the positive sunspot in the foot of an outer magnetic loop of the streamer arcade (Figure 1a). Each ejective flare was produced by an ejective eruption of the sheared core field, and the escaping "flux-rope plasmoid" was guided up the leg of the encompassing arcade loop (Figure 1b). If the exploding plasmoid was strong enough, when it reached the top of the loop, it blew out the top, producing a streamer-puff CME laterally offset from the loop-foot flare and source of the CME-driving explosion (Figure 1c). [If the exploding plasmoid was not strong enough to overcome the loop-top magnetic field, the loop top was not blown out and no CME was produced. (Bemporad et al observed that for the weaker of the compact ejective flare explosions in the foot of the streamer-arcade loop there was no CME.)]

Relative to the span of the streamer base along the limb, the flaring magnetic-island source of the streamer-puff CME explosions studied by Bemporad et al (2005) was more compact than depicted in Figure 1. The base of each ejective flare spanned only ~10,000 km, whereas the streamer arcade spanned about 300,000 km. Each flare was short-lived, lasting <~1 hr, and produced only a C-class or weaker GOES X-ray burst.

From the magnetic-arch-blowout scenario for streamer-puff CMEs (Figure 1), we have the following three expectations. First, we expect that a compact magnetic explosion that is similarly located in a streamer arcade but produces a compact flare that is much stronger than those produced together with the steamer-puff CMEs of Bemporad et al will generate an escaping plasmoid that explodes more strongly than those that produced the streamer-puff CMEs of Bemporad et al. Consequently, because a stronger exploding plasmoid should produce a streamer-puff CME that is wider and contains more mass, we expect that in LASCO/C2 images the CME will be wider and brighter than those of Bemporad et al. Second, so long as the source of the explosion is compact relative to the streamer arcade, the explosion should blow out only a short section of the streamer arcade. [From the observation that streamer-puff CMEs escape from the top of the a streamer arcade laterally offset from the source of the driving plasmoid, we reason that the magnetic field in the guiding leg of the streamer arcade is strong enough to laterally deflect the erupting plasmoid from erupting radially outward until the plasmoid is near the top of the arcade (resulting in the over-and-out progression of the driving plasmoid), and hence that the field in the guiding leg is strong enough to rather tightly limit the lateral expansion of the plasmoid. In the magnetic-arch-blowout scenario, the erupting plasmoid overpowers the arcade field only near the top of the guiding loop, where the arcade's field is weaker than in its legs, and the plasmoid is only then able to explode radially outward and become the

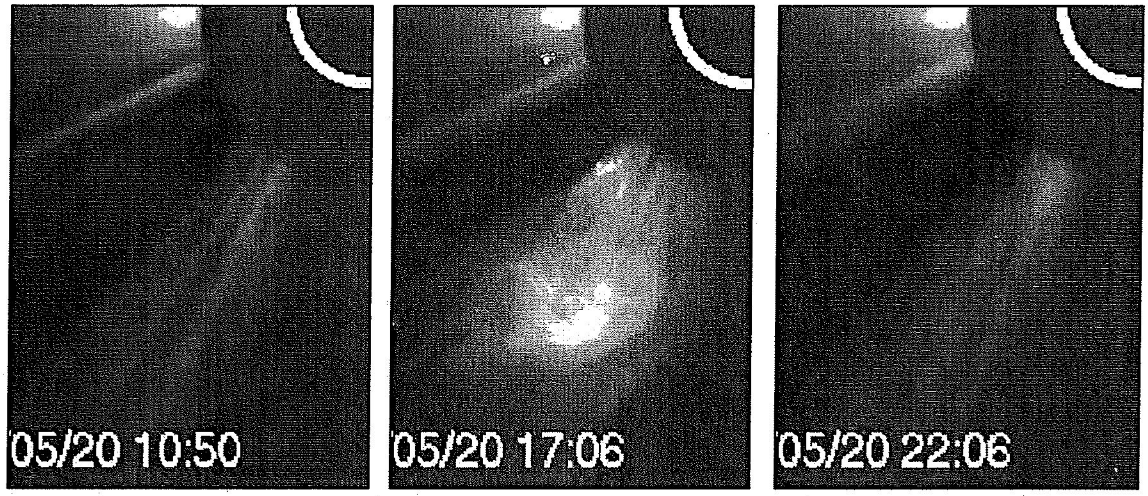

Figure 2. The steamer-puff CME of 2002 May 20. Left: The streamer fan hours before the eruption. Middle: The CME exploding out along the streamer fan. Right: The slightly altered streamer fan after passage of the CME. Each image is from LASCO/C2 with north up, east left, and universal time at the bottom.

flare of 2002 May 20 was a streamer-puff CME, and that the CME explosion was decidedly stronger than those that produced the Bemporad et al streamer puffs.

The flare explosion and consequent coronal dimming observed in EIT Fe XII images, along with their setting in a registered MDI magnetogram, are shown in Figure 3. The Fe XII image at 15:12 UT (upper left) shows the southeast quadrant of the corona minutes before the impulsive rise of the X flare. The Fe XII image at 15:36 UT (upper right) shows the ejective flare in progress during the GOES X-ray burst; the arrow points to the bright base of the eruption. The superposed magnetogram (lower left) shows that the flare was seated on the south side of the emerging active region, in strong mixed-polarity magnetic flux. Registration of the magnetogram with a co-temporal MDI intensitygram showed that this flux was in a small delta sunspot near the negative-polarity leading sunspot of the active region. In Figure 3, the arrow in the lower-left panel has the same placement in the Fe XII image as the arrow in the upper-right panel. This shows that the flare brightening seen at the tip of the arrow in the upper-right panel was at the southwest end of the neutral line in the delta sunspot. Thus, it appears that the flare erupted from along this neutral line.

The Fe XII images in Figure 3 show an obvious large dark filament running roughly east-west at about S40° (about 20° south of the flare site), and a fainter polar-crown filament channel farther south at about S65°. The superposed magnetogram shows that the dark filament traced a neutral line having positive flux on its north side and negative flux on its south side. The negative domain south of this filament extends to the filament-channel neutral line along the edge of the south polar cap of positive flux. [On 2002 May 20, full-disk Hα images from Big Bear Solar Observatory show a faint fragmentary filament along the neutral line that in Figure 3 is traced by the faint dark channel at S65°. This filament is also faintly discernible in the 2002 May 20 full-disk He I 10830 Å image from Kitt Peak. However, in the Fe XII images in Figure 3, it is not clear to us whether the darkness of the faint channel is mostly from absorption of background Fe XII emission by cool filament material, or instead is mostly from lack of Fe XII emission from the low corona above the neutral line (that is, perhaps the plasma at low coronal heights in this filament channel was too cold to emit in Fe XII and too tenuous to show itself in absorption in Fe XII). In any case, for conciseness and clarity, we simply refer to the dark filament at S40° as "the filament" and to the fainter and narrower dark channel at S65° as "the filament channel."] In the Fe XII corona above the southeast limb, there was a faint coronal cavity (e.g., Koutchmy 1977) over the filament, and a neighboring smaller faint cavity over the filament channel. In the upper two panels of Figure 3, each cavity is faintly discernible as a slightly dimmer arched vault enveloped in slightly brighter emission. In the lower-left panel of Figure 3, we have outlined each cavity with a dashed curve that follows the sweep of the enveloping coronal arch. The larger cavity marks the magnetic arcade that held the filament in its core, and the smaller cavity marks a separate magnetic arcade that straddled the filament channel. The proximity of the two cavities suggests that the negative-polarity sides of the two arcades abutted each other, together covering the negative domain between the filament and the filament channel. Because the streamer fan was centered at about S60° (i.e., between the filament and the filament channel) and spanned about 20° of latitude (Figure 2), it is plausible that both of the magnetic arcades were included in the base of the streamer. The lower-left panel of Figure 3 shows that the active region hosting the flare emerged within a positive-polarity flux domain that was bounded on its south side by the filament. So, it is also plausible that the active region and flare were seated in an outer loop of the magnetic arcade that held the filament.

The above inferences from Figure 3 that the base of the streamer spanned both the arcade over the filament and the arcade over the filament channel, that together the two arcades included all of the flux in the negative domain between the filament and the filament channel, and that the flare site was in the positive foot of an outer loop of the arcade over the filament, are also supported by the coronal images in Figure 4. An EIT Fe XV 284 Å negative image of the southeast quadrant of the corona on 2002 May 20 is shown in the upper two panels of Figure 4. This image was taken a few hours after the flare and the coronal dimming had ended. The active region in which the flare occurred is the darkest feature in this negative image. The filament seen in the Fe XII images in Figure 3 is also obvious in this Fe XV image, but the polar crown filament channel is hardly discernible. In the upper-left panel, the Fe XV emission pattern near and above the southeast limb is consistent with the arcade over the filament being wide enough to have the active region embedded in its northern flank and with the arcade over the filament channel being somewhat smaller than the arcade over the filament. In the upper-right panel, for each arcade a dashed arch roughly traces the faintly discernible sweep and extent of the arcade's Fe XV emission near and above the limb. These outlines of the two arcades indicate that the negative sides of the two arcades abutted, and hence that there was no appreciable open field between them. The two dashed open curves indicate roughly the extent of the filament, the filament channel, and their enveloping arcades (and presumably the east-west middle of the streamer that arose from these arcades) was a day's rotation closer to the limb and to the plane of the sky than on the day of our event. (The Mark-4 did not observe on the day of our event.) The black quarter disk in this image is the occulting disk of the Mark-4, which extends 0.1 R_{Sun} beyond the limb. The lower-left panel shows a helmet streamer centered at about S60°. This position is appropriate for the streamer fan observed above 2 R_{Sun} by LASCO/C2 on the next day (Figure 2) to have been the radial extension of this streamer. In the lower-right panel, the white quarter circle locates the solar limb, the two open dashed curves roughly trace the two sides of the streamer and their extrapolation down to the limb, and the two radial solid lines show the angular span of the base of the streamer. Comparison of this angular span with that in the upper-right panel shows that the streamer base evidently included both arcades.

Returning to Figure 3, in the lower-right panel, the magnetogram is superposed on an Fe XII difference image that shows the coronal dimming that had occurred by 15:48 UT, when the X flare was ending. Strong dimming is seen at two places: around the active region that flared and in a remote area (arrow) about 30° south of the flare site. The remote dimming covers a limited part of the negative-polarity domain south of the filament's neutral line. The extent of this dark area in the direction along the neutral line is somewhat greater than its extent in the orthogonal direction, and is comparable to that of the dimming around the active region. Thus, the magnetic location and extent of the remote dimming were appropriate for this dimming to have been in the negative-polarity end of a large magnetic loop that was part of the arcade over the filament and that had the active region embedded in its positive-polarity end.

The remote coronal dimming seen in Figure 3 is centered midway along the east-west extent of the filament. This is good evidence that our CME did not originate from in front of or behind the streamer along the line of sight, was not merely projected against a background or foreground streamer, and hence was a bona fide streamer-puff CME. This evidence is in addition to the changed substructure of the streamer fan after passage of the CME (Figure 2).

The LASCO/C2 movie shows that a somewhat narrower streamer-puff CME occurred in our streamer about 4 hours before our streamer-puff CME. In the CME Catalogue, the linear extrapolation of the trajectory of this earlier CME back to the limb indicates that the CME started to erupt at the onset of a GOES M-class X-ray flare. The EIT Fe XII movie shows that this M flare occurred in the same active region as our short-duration X flare. In the GOES X-ray flux-time plot, the M flare lasts about 3 hours. In the Fe XII movie, this flare covers more of the active region than does our X flare, but is still rather compact. We suppose that the consequent streamer-puff CME was narrower than ours because the M-flare magnetic explosion ejected a plasmoid that was weaker than the one ejected by our X-flare magnetic explosion. In any case, because the remote coronal-dimming footprint of this earlier streamer-puff CME was much fainter than in our X-flare-producing event, in this paper we present no observations of this earlier event.

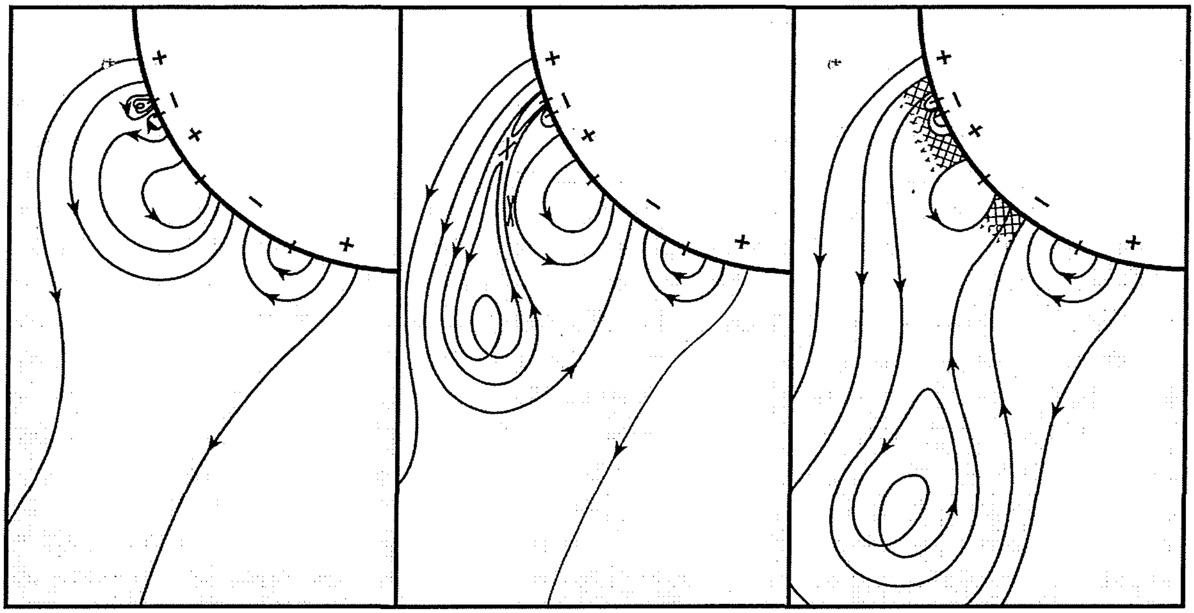

Figure 5. Schematic of the production of the streamer-puff CME of 2002 May 20. The polarity arrangement and the inferred topology of the field are shown in a cross section of the streamer through the seat of the compact ejective flare explosion. Left: Before the flare. Middle: Internal and external reconnection of the ejected plasmoid as it explodes up an outer loop of the arcade over the filament. Right: Coronal dimming in the feet of the magnetic arch as the escaping plasmoid blows the top of the arch out along the streamer.

small delta sunspot, its filament channel and any pre-eruption filament were too small to be seen in the Fe XII images.] In the first panel of Figure 5, the small loop over the kinked loop represents the enveloping magnetic arcade that was formed by the emergence of the magnetic field of the delta sunspot, was rooted in the delta sunspot, and had the sheared field in its core along the neutral line. The location of the flare in Figure 3 indicates that this compact arcade was situated on the south side of the active region. Consistent with this, the flare surge or spray (i.e., the erupting dark material, perhaps a small erupting filament) seen in Figure 3, because of its large vertical extent relative to the width of the active region, suggests that on its south side, before it erupted, this arcade was in direct or nearly direct contact with high-reaching field lines rooted nearby outside the active region. In the first panel of Figure 5, we have taken these field lines to be in an outer loop of the large arcade over the filament. The polarity orientation of the delta sunspot with respect to the large arcade implies that there was a magnetic null between the compact arcade and the field of the large arcade, and hence that reconnection would be driven there by eruption of the compact arcade (first two panels of Figure 5).

Because the inferred pre-eruption field configuration of our compact flare is similar to that of the compact flares of Bemporad et al (2005), we suppose that the flare explosion occurred in basically the same way in both cases. Namely, we suppose that our compact

In the scenario for streamer-puff CMEs proposed here and in Bemporad et al (2005), the outer arcade loop that erupts in the production of the CME does not explode itself. It is not triggered to explode by the flare at its foot. Instead, the eruption of the arcade loop is directly driven by the plasmoid that explodes up the leg of the arcade loop from the flare. That is, in this scenario, the pre-eruption magnetic field in the outer arcade is nearly potential and hence not capable of driving its own eruption. In our case, the core of the arcade, the inner part traced by the filament, was evidently strongly sheared and had a large store of nonpotential magnetic energy. Hence, in principle, the core of the arcade could have erupted. However, the observed absence of change in the filament shows that this sheared core field was not involved in the eruption, and the observed direction in which the remote dimming was offset from the active region shows that the outer loop that did erupt was not strongly sheared but nearly orthogonal to the neutral line of the arcade. Thus, the coronal dimming footprint of our streamer-puff CME supports the basic idea of the magnetic-arch-blowout scenario that the arcade loop is potential and passive, guiding the magneto-plasma ejection from the flare explosion up its leg, and being blown out by this plasmoid rather than exploding itself.

From the observation that our full-blown CME traveled out along the streamer 40° south of the flare explosion, we infer that the field in and around the leg of the arcade loop was strong enough to direct the plasmoid to near the top of the loop, but at the top the field was not strong enough to contain the explosion and was blown out in front of the plasmoid. It is only reasonable to expect that, among ejective plasmoid explosions that produce streamer-puff CMEs, the stronger the plasmoid explosion, the wider and brighter should be the CME. Our event meets this expectation in that the compact ejective flare (and presumably the ejected plasmoid produced together with the flare) was stronger than the compact ejective flares of Bemporad et al and the consequent CME was wider and brighter than those of Bemporad et al.

We expect that our streamer-puff CME and those of Bemporad et al (2005) belong to a broader class of similar over-and-out CMEs in which the ejective-flare-producing source explosion of the CME and the resulting CME can be much larger than in our event. An over-and-out CME should be produced whenever: (1) an ejective-flare explosion of any size is embedded in the foot of a quasi-potential much larger magnetic arch, (2) this surrounding field is strong enough to channel the flare-explosion plasmoid to near the top of the arch, and (3) the explosion of the plasmoid is strong enough to explode the top of the guide arch and become a CME. If the arch field is too weak, there will be little lateral deflection of the CME. If the arch field is too strong, the ejective flare explosion will produce a confined flaring arch rather than a CME (Martin & Svestka 1988; Hanaoka 1997; Moore et al 1999). We expect that many large ejective flares and filament eruptions happen to be situated in the foot of a still much larger magnetic arch of the appropriate strength for the production of an over-and-out CME.

It is well known that if a relatively compact flare occurs next to a larger sheared-core arcade, the compact flare explosion may trigger the arcade to erupt (e.g., Machado et al 1988). The eruption of the large arcade could produce a CME that is laterally far offset from the site of the compact flare, but in that case the CME explosion comes from the

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