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THE CORONAL-DIMMING FOOTPRINT OF A STREAMER-PUFF CORONAL MASS EJECTION: CONFIRMATION OF THE MAGNETIC-ARCH-BLOWOUT SCENARIO

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ABSTRACT

A streamer puff is a recently identified variety of coronal mass ejection (CME) of narrow to moderate width. It (1) travels out along a streamer, transiently inflating the streamer but leaving it largely intact, and (2) occurs in step with a compact ejective flare in an outer flank of the base of the streamer. These aspects suggest the following magnetic-arch-blowout scenario for the production of these CMEs: the magnetic explosion that produces the flare also produces a plasmoid that explodes up the leg of an outer loop of the arcade base of the streamer, blows out the top of this loop, and becomes the core of the CME. In this paper, we present a streamer-puff CME that produced a coronal dimming footprint. The coronal dimming, its magnetic setting, and the timing and magnetic setting of a strong compact ejective flare within the dimming footprint nicely confirm the magnetic-arch-blowout scenario. From these observations, together with several published cases of a transequatorial CME produced in tandem with an ejective flare or filament eruption that was far offset from directly under the CME, we propose the following. Streamer-puff CMEs are a subclass (one variety) of a broader class of "over-and-out" CMEs that are often much larger than streamer puffs but are similar to them in that they are produced by the blowout of a large quasi-potential magnetic arch by a magnetic explosion that erupts from one foot of the large arch, where it is marked by a filament eruption and/or an ejective flare.

Subject headings: Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: magnetic fields

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.

The streamer-puff CMEs reported by Bemporad et al. (2005) were produced together with the stronger members of a sequence of compact ejective flares observed near the limb in *SOHO* EIT He II movies. (An ejective flare is a flare in which the magnetic explosion that produces the flare heating also ejects plasma and/or plasma-carrying magnetic field far out of the flare site, as in a surge, filament eruption, or flare spray; Dodson-Prince & Bruzek 1977; Machado et al. 1988.) These flares were seated at an island of opposite-polarity magnetic flux at the edge of an old sunspot in the outskirts of a high-reaching magnetic arcade that was the base of a coronal streamer observed beyond 2 $R_{\odot}$ by the *SOHO* LASCO/C2 coronagraph. Each of the stronger of these explosions produced a streamer-puff CME. From these observations, Bemporad et al. proposed that these CMEs were over-and-out CMEs produced in

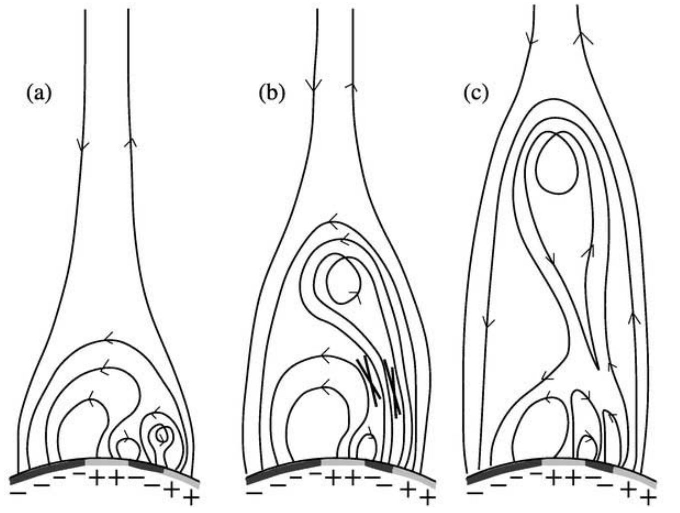

FIG. 1.— Schematic of the magnetic-arch-blowout model for the production of a streamer-puff over-and-out CME (from Bemporad et al. 2005). A compact sheared-core arcade explodes up the leg of an outer loop of a streamer arcade. Reconnection of the legs of the escaping field unleashes an expanding "plasmoid" that becomes the core of the CME. For the events of Bemporad et al. (2005), the rightmost light band at the base represents the positive-polarity sunspot and the adjacent short dark band represents the island of negative flux that was the seat of the compact ejective flares.

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. (Fig. 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 (Fig. 1*a*). 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 (Fig. 1*b*). 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 (Fig. 1*c*). 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 (Fig. 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 streamer-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 interior of a streamer-puff CME. On this basis, we expect that only the top of the plasmoid-guiding outer loop of the streamer arcade is blown out in the production of a streamer-puff CME, and that the rest of the arcade and streamer remains intact. As a result, as was observed in the streamer-puff CMEs of Bemporad et al., in the aftermath of the CME, the streamer [viewed in the direction along the arcade] should appear to be only somewhat altered rather than grossly destroyed.) Third, the blowing out of an outer loop of the streamer arcade could reasonably result in coronal dimming at the feet of the loop. This would demarcate the lateral extent of the opened section of the arcade. In this paper, we present observations of a strong compact ejective flare explosion and resulting streamer-puff CME that substantiate these expectations and thus confirm the magnetic-arch-blowout scenario.

2. OBSERVATIONS

The online *SOHO* LASCO CME Catalog (Yashiro et al. 2004) for 2002 May 20 shows that a southward CME occurred in tandem with a *GOES* X-class flare of unusually short duration (<1 hr). The CME Catalog gives the linear extrapolation of the CME trajectory back to the limb. This extrapolation crosses the limb at about 15:10 UT, which is a few minutes before the impulsive rise of the *GOES* X-ray burst. To this degree, the CME was observed to occur in conjunction with the flare explosion. That is, the observed timing and speed of the CME are consistent with the source of the CME explosion being the magnetic explosion that produced the short-duration X-call flare. EIT full-disk Fe XII λ195 images, together with *SOHO* MDI full-disk magnetograms, show that this flare was a very compact (base width ∼10,000 km) ejective flare at about S20°, E65° in an emerging active region near the limb.

Figure 2 (from the LASCO/C2 movie) shows that there was a radial streamer fan centered at about S60° in the southeast and that this streamer appeared to be transiently disrupted by the CME as it erupted out along the fan. So, the CME, being roughly centered on the fan, moved out along a radial that was far offset to the south from the compact X flare (by about 40° in latitude). Comparison of the before and after images in Figure 2 shows that the passage of the CME left the streamer largely intact (with only some change in substructure) even though the streamer appeared to be strongly disrupted during passage (Fig. 2, *middle*). In the LASCO/C2 movies, this CME is strikingly brighter and wider than any of the

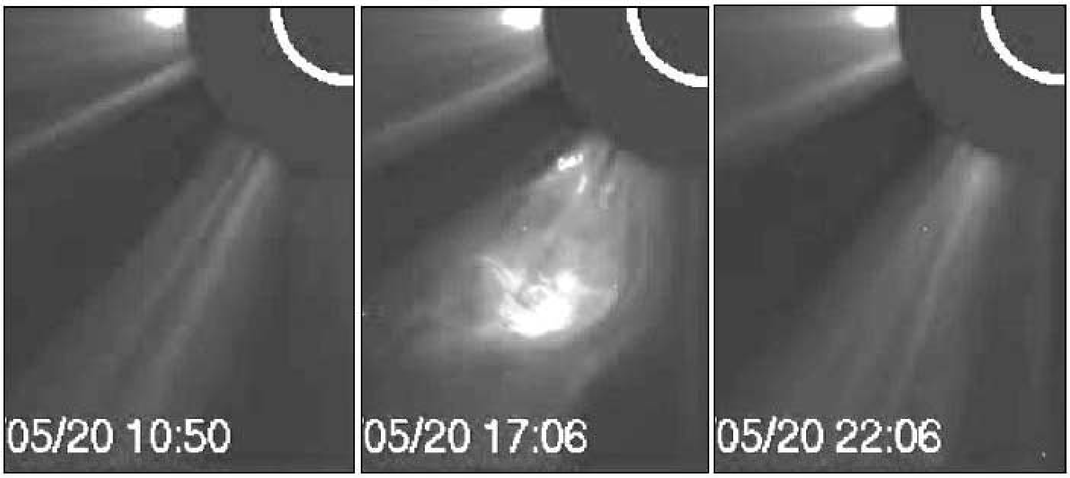

FIG. 2.— Steamer-puff CME of 2002 May 20. *Left*: Streamer fan hours before the eruption. *Middle*: CME exploding out along the streamer fan. *Right*: Slightly altered streamer fan after passage of the CME. Each image is from LASCO/C2 with north up, east left, and universal time at the bottom.

streamer-puff CMEs of Bemporad et al. (2005). For this CME, the measured angular width given in the *SOHO* LASCO CME Catalog is 69°, almost twice the 37° given for the widest of the streamer-puff CMEs of Bemporad et al. This is reasonable for our streamer-puff CME because the production of an X-class *GOES* X-ray burst in tandem with the CME is consistent with the driving magnetic explosion being much stronger than the explosions that produced the streamer-puff CMEs of Bemporad et al., which explosions produced only C-class or weaker *GOES* X-ray bursts. Thus, the LASCO/C2 movies show that the CME produced in tandem with the compact ejective X 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 (*top 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 (*top 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 (*bottom 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 cotemporal MDI intensitygram showed that this flux was in a small δ sunspot near the negative-polarity leading sunspot of the active region. In Figure 3, the arrow in the bottom left panel has the same placement in the Fe XII image as the arrow in the top right panel. This shows that the flare brightening seen at the tip of the arrow in the top right panel was at the southwest end of the neutral line in the δ 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 Fig. 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 λ10830 image from Kitt Peak. However, in the Fe XII images in Fig. 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 top two panels of Figure 3, each cavity is faintly discernible as a slightly dimmer arched vault enveloped in slightly brighter emission. In the bottom 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 (Fig. 2), it is plausible that both of the magnetic arcades were included in the base of the streamer. The bottom 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 λ284 negative image of the southeast quadrant of the corona on 2002 May 20 is shown in the top two panels of Figure 4. This image was taken a few hours after the flare and the coronal dimming had ended. The

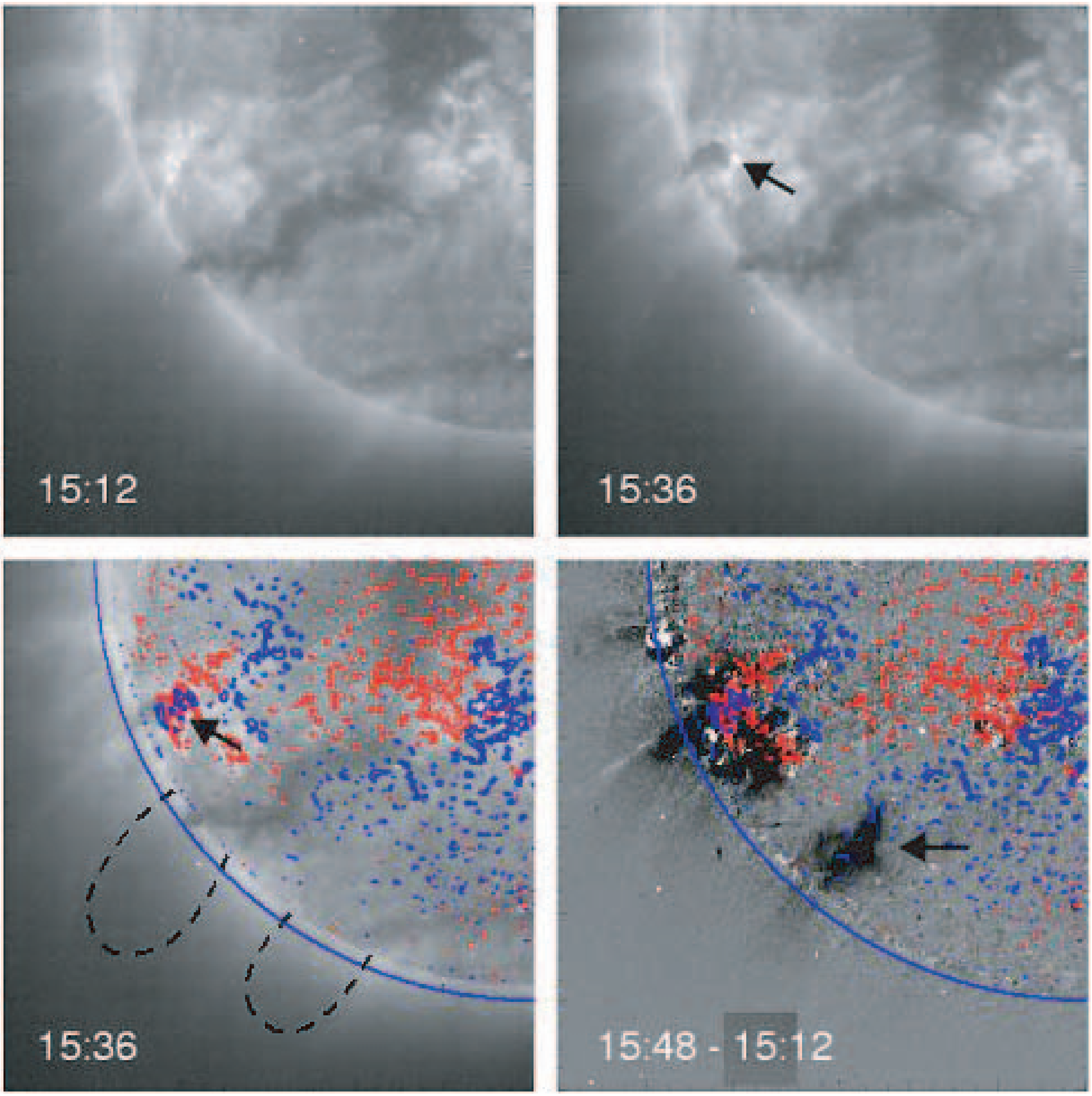

FIG. 3.—Compact ejective flare, the coronal dimming footprint of the streamer-puff CME, and their magnetic setting. *Top left*: EIT Fe XII λ195 image at 15:12 UT, minutes before the flare. *Top right*: EIT Fe XII image showing the ejective flare (*arrow*) in progress at 15:36 UT, and showing no change in either the filament south of the flare or in the polar-crown filament channel farther south. *Bottom left*: The 15:36 UT EIT image registered with an MDI magnetogram, showing that the flare was in an emerging active region. The dashed arches over the filament and over the filament channel outline faint coronal cavities. *Bottom right*: EIT Fe XII difference image (the image at 15:48 UT minus the image at 15:12 UT) registered with the magnetogram, showing the coronal-dimming footprint of the CME.

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 top 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 top 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 minimum span needed for the base of the streamer to cover both arcades. The two solid radial lines show the corresponding minimum needed heliocentric angular span.

An image of the southeast quadrant of the corona observed by the Mark IV Coronagraph of the Mauna Loa Solar Observatory is shown in the bottom two panels of Figure 4. This image is from 2002 May 19, the day before our event, when the middle of the east-west 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 IV did not observe on the day of our event.) The black quarter disk in this image is the occulting disk of the Mark IV, which extends 0.1 $R_\odot$ beyond the limb. The bottom left panel shows a helmet streamer centered at about S60°. This position is appropriate for the streamer fan observed above 2 $R_\odot$ by LASCO/C2 on the next day (Fig. 2) to have been the radial extension of this streamer. In the bottom 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 top right panel shows that the streamer base evidently included both arcades.

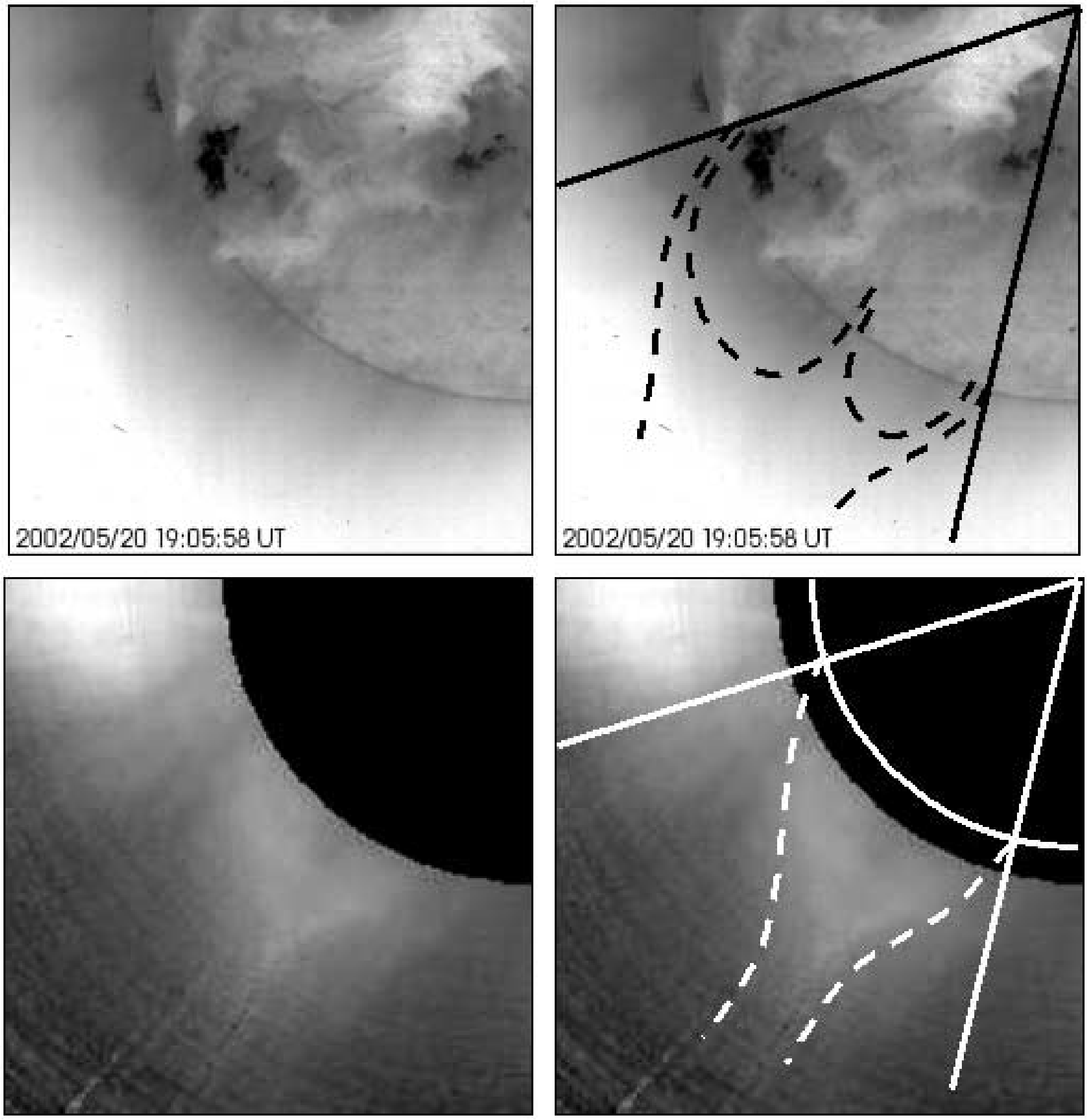

Fig. 4.— Evidence that the base of our streamer spanned both the magnetic arcade over the filament and the magnetic arcade over the filament channel, that the flare site was embedded in the northern flank of the magnetic arcade over the filament, and that the streamer was unipolar (had no extended current sheet; see text). *Top left*: EIT Fe xv λ284 negative image taken a few hours after the flare and the coronal dimming had faded out. *Top right*: Same image as on the left, with dashed arches outlining emission from the two arcades, dashed open curves indicating the span of the streamer base needed to cover both arcades, and solid radial lines showing the needed angular span. *Bottom left*: Visible-light image obtained by the Mauna Loa Solar Observatory Mark IV Coronagraph on the day before our event. *Bottom right*: Same image as on the left, with dashed curves tracing the northern and southern sides of the streamer, solid quarter circle marking the limb, and solid radial lines showing the approximate angular span of the streamer base at the limb.

Returning to Figure 3, in the bottom 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 (Fig. 2).

The LASCO/C2 movie shows that a somewhat narrower streamer-puff CME occurred in our streamer about 4 hr before our streamer-puff CME. In the CME Catalog, 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 hr. 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

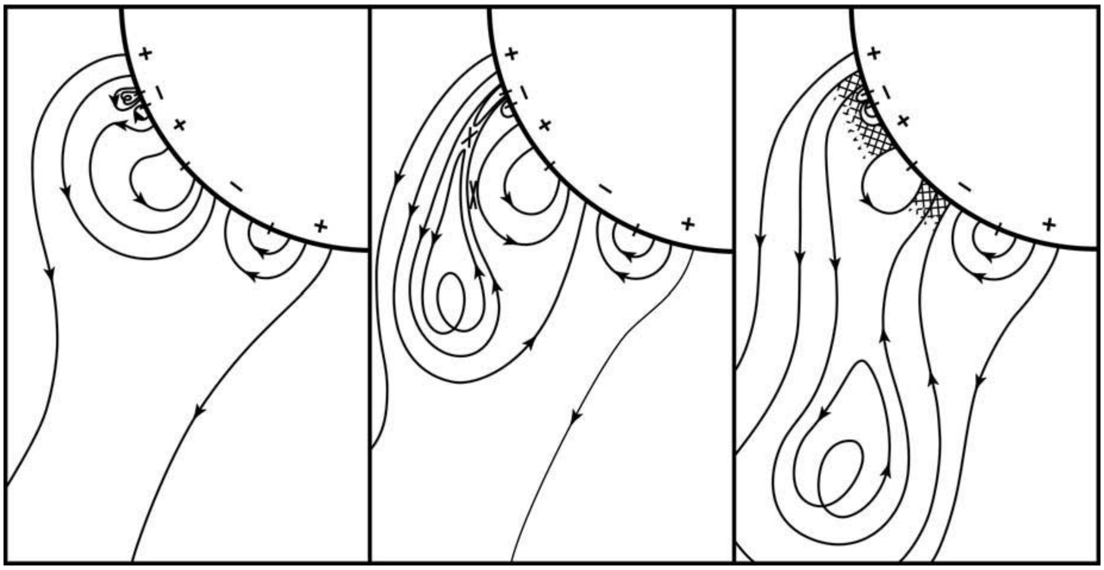

FIG. 5.—Schematic of the production of the streamer-puff CME of 2002 May 20. The polarity arrangement and the inferred topology of the field are shown in a cross section of the streamer through the seat of the compact ejective flare explosion. *Left*: Before the flare. *Middle*: Internal and external 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.

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.

3. MAGNETIC-ARCH-BLOWOUT SCENARIO

Our interpretation of the observations is sketched in Figure 5. The first panel shows the inferred topology of the magnetic field in and above the base of the streamer before the ejective flare began. The large-scale topology differs from that for the streamer of Bemporad et al. (2005) (Fig. 1) because we take the base of our streamer to include both of the two filament-cavity arcades, whereas the base of the streamer of Bemporad et al. was a single large arcade over a single main neutral line. Consequently, whereas in the Bemporad et al. case the streamer fan was bipolar, having its field pointing outward on one side and inward on the other (Fig. 1), in our case the pre-eruption streamer fan was plausibly unipolar, having all of its field outward, as we have drawn it in Figure 5. It is possible that there was some open field rooted between the two arcades. If there was, our streamer had two current sheets (one stemming from each arcade) instead of no current sheet. (We used the Potential Field Source Surface [PFSS] algorithm from SolarSoft to examine, in the southeast region of the Sun covered in Figs. 3 and 4, the topology of the PFSS model coronal field computed from a whole-Sun magnetic flux map derived from MDI magnetograms. The PFSS model field for 2002 May 20 has no open field lines rooted between the filament and the filament channel. However, this model field also has no open field rooted in the south polar cap of positive flux, and shows little evidence of the magnetic arcade over the filament channel. Because the EIT He II λ304 images on 2002 May 20 show a coronal hole in the south polar cap, we know that there was open field rooted there. From this contradiction, we conclude that the PFSS coronal field for 2002 May 20 cannot be trusted to show the true magnetic topology of our streamer, probably because most of the magnetic flux in the positive polar cap and in the negative domain between the filament and the filament channel was below the threshold of the MDI magnetograms.) Our conclusions in this paper are independent of whether our streamer had no current sheet (as we assume in Fig. 5) or actually had two current sheets. We believe that the evidence presented in Figs. 3 and 4 favors that there was no open field rooted between the two arcades. If there was not, a current sheet was not involved in the formation of the streamer-helmet cusp seen in Figure 4. According to S. T. Suess (2006, private communication), the streamer-boundary flow models of Suess & Nerney (2002) and Nerney & Suess (2005) indicate that unipolar streamer-helmet cusps are physically plausible.

In the vicinity of the flare site before eruption onset, the topology of the field in Figure 5 is the same as in the case of Bemporad et al. (Fig. 1*a*). In Figure 5, the small island of negative-polarity flux represents the negative domain of the δ sunspot that was the seat of the flare explosion. The northern edge of this island represents the neutral line through the δ spot. The small kinked loop straddling this edge of the island in the first panel of Figure 5 represents the sheared core field that is normally present along the neutral line in a δ sunspot (Zirin 1988). (The sheared field rooted along the neutral line of a magnetic arcade is commonly called the "sheared core field" of the arcade [e.g., Su et al. 2006; Wang 2006; Moore & Sterling 2006]. In large arcades, of size of order of that of either large arcade in the base of our streamer, in the chromosphere the sheared core field forms a channel of fibrils [called a filament channel] that traces the neutral line and that may or may not have a filament suspended above it. In the case of the compact magnetic arcade of our small δ 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 δ sunspot, was rooted in the δ 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 δ 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 (Fig. 5, *first two panels*).

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 ejective flare was produced by explosion of the sheared-core arcade anchored in the δ sunspot, and that this explosion was driven by the ejective eruption of the sheared core field as in the standard scenario for CME explosions from larger sheared-core arcades (e.g., as depicted in Moore et al. 2001 and in Moore & Sterling 2006). (In our version of the standard scenario for the CME-producing explosion of a sheared-core arcade, the explosion is driven by the magnetic pressure of the expanding flux rope that erupts from the core of the arcade [Moore & Sterling 2006]. As is expounded in Moore & Sterling [2006], the triggering and early growth of the eruption evidently result from either of two basically different mechanisms or from both acting in concert: [1] MHD instability or loss of equilibrium [without reconnection], and/or [2] reconnection that breaks the sheared-core arcade's pre-eruption global balance of magnetic pressure and magnetic tension.) In our scenario, for our case and for that of Bemporad et al., the compact arcade exploded up the leg of the encompassing large-arcade loop. As is sketched in Figures 1 and 5, as the explosion progressed, reconnection external and internal to the erupting arcade field built a partially detached escaping "flux-rope plasmoid" (*second panels*). This plasmoid was guided laterally away from the flare site by the field of the large arcade to near top of the arcade, then exploded the top of the guide loop (*second panels*), and went on to become the core of the streamer-puff CME (*third panels*) that traveled out along the streamer. The reconnection and escape of the core plasmoid "opened" an outer segment of the large arcade, allowing the coronal plasma in that segment to expand and escape upward. In our case, the opened segment was large enough that the resulting depletion of coronal plasma at its feet was enough to produce the observed coronal dimming, depicted by the shading in the third panel of Figure 5.

4. DISCUSSION

The streamer-puff CME presented here was similar to those found by Bemporad et al. (2005) in that (1) it occurred in concert with a compact ejective flare that was seated in an outer flank of the base of a streamer, and (2) the full-blown CME was laterally far offset from the flare, traveling radially outward along the streamer rather than radially outward from the flare site. Bemporad et al. inferred from their observations that as a consequence of the flare explosion an outer segment of the streamer arcade was blown out and became the streamer-puff CME. Because the passage of the CME left the streamer intact but changed in substructure, Bemporad et al. also inferred that only a short segment of outer arcade erupted in the CME. This interpretation is verified by the coronal dimming observed in our event. The observed dimming in the EIT Fe XII images (Fig. 3) indicates that an outer arcade loop having the flare in one foot did open with the CME. The observed absence of dimming between the two ends of the loop indicates that the inner arcade remained closed. In agreement with this, the filament in this arcade did not erupt and showed no change in the Fe XII movie. Thus, the coronal-dimming footprint of our streamer-puff CME in the Fe XII images confirms the basic causal sequence and magnetic structure inferred by Bemporad et al. (2005): the CME resulted from the offset flare explosion via expulsion of an outer arcade loop that had one end rooted around the flare.

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 magnetoplasma 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 quasipotential 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 eruption of the large arcade, not from the compact flare site. It would be clear from full-Sun coronal X-ray images, such as those from *Yohkoh* or *Hinode*, that such a

CME was not an over-and-out CME. The eruption of the large arcade would produce its own hot posteruption arcade along with the CME, and this large "flare" arcade would be discernible in coronal X-ray images even if it were too faint to be detected in plots of *GOES* X-ray flux (e.g., Moore et al. 2001; Sterling et al. 2001). The occurrence of a large posteruption arcade directly under the CME would show that the CME was not an over-and-out CME from the far offset compact flare site. For an over-and-out CME, there would be a laterally far offset ejective flare or filament eruption and no discernible flare arcade directly under the CME.

In the minimum phase of the solar magnetic activity cycle, the global coronal magnetic field is grossly dipolar, resulting in an equatorial streamer belt, much of the base of which is a transequatorial arcade that spans as much as $\sim\pm60^\circ$ in latitude and gives an equatorial streamer that has the magnetic topology sketched in Figure 1 (e.g., Crooker 2000). Remnants of old-cycle active regions within this transequatorial arcade can be present in some intervals of longitude as large embedded arcades centered at mid latitudes. In these intervals, the base of the streamer belt has a multiple-arcade topology of the character of that sketched in Figure 5 (e.g., Filippov et al. 2001). Early in a new cycle, active regions emerge at mid latitudes within the base of the streamer belt. In this epoch, most ejective flares and filament eruptions that occur together with CMEs are in the active latitudes, clustering around 30° north and south, whereas most of the corresponding CMEs, in the outer corona, move out along radial paths that cluster about the equator (Plunkett et al. 2001). Gopalswamy et al. (2000) and Gopalswamy & Thompson (2000) present observations of a filament eruption that happened in 1997 December (early in the cycle that is now ending) that occurred near the limb at S30°, had a nonradial equatorward trajectory, and resulted in a CME that in the outer corona was centered on the equatorial streamer. Plunkett et al. (2001) present an X9 flare that occurred in 1997 November near the limb at S20°, at the onset of a large, fast CME that in the outer corona was nearly centered over the equator. Khan & Hudson (2000) present a sequence of three disappearances of a large transequatorial loop in 1998 May. Each disappearance occurred in the launching of a transequatorial CME following an X- or M-class ejective flare at the south end of the transequatorial loop. These events, the global coronal magnetic configuration early in the cycle, and the 30° average offset in latitude between CMEs and the eruptive events at their onsets during this epoch all suggest that many of the large equatorial CMEs early in the solar cycle are over-and-out CMEs that are produced in basically the same way as streamer-puff CMEs but come from larger offset ejective-flare explosions or filament eruptions that blow out correspondingly large segments of the transequatorial streamer arcade.

A broader point is that our observations and those of Bemporad et al. (2005) of streamer-puff CMEs from offset flare explosions, together with the considerations of this section, encourage the view (e.g., Moore & Sterling 2006) that all large fast CMEs, including those that are over-and-out CMEs, are the same in that the driving magnetic explosion comes from the ejective eruption of a sheared-core arcade, basically as in the standard scenario for CME explosions.

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