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ONSET OF THE MAGNETIC EXPLOSION IN SOLAR FLARES AND CORONAL MASS EJECTIONS

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ABSTRACT

We present observations of the magnetic field configuration and its transformation in six solar eruptive events that show good agreement with the standard bipolar model for eruptive flares. The observations are X-ray images from the *Yohkoh* soft X-ray telescope (SXT) and magnetograms from Kitt Peak National Solar Observatory, interpreted together with the 1–8 Å X-ray flux observed by *GOES*. The observations yield the following interpretation. (1) Each event is a magnetic explosion that occurs in an initially closed single bipole in which the core field is sheared and twisted in the shape of a sigmoid, having an oppositely curved elbow on each end. The arms of the opposite elbows are sheared past each other so that they overlap and are crossed low above the neutral line in the middle of the bipole. The elbows and arms seen in the SXT images are illuminated strands of the sigmoidal core field, which is a continuum of sheared/twisted field that fills these strands as well as the space between and around them. (2) Although four of the explosions are ejective (appearing to blow open the bipole) and two are confined (appearing to be arrested within the closed bipole), all six begin the same way. In the SXT images, the explosion begins with brightening and expansion of the two elbows together with the appearance of short bright sheared loops low over the neutral line under the crossed arms and, rising up from the crossed arms, long strands connecting the far ends of the elbows. (3) All six events are single-bipole events in that during the onset and early development of the explosion they show no evidence for reconnection between the exploding bipole and any surrounding magnetic fields. We conclude that in each of our events the magnetic explosion was unleashed by runaway tether-cutting via implosive/explosive reconnection in the middle of the sigmoid, as in the standard model. The similarity of the onsets of the two confined explosions to the onsets of the four ejective explosions and their agreement with the model indicate that runaway reconnection inside a sheared core field can begin whether or not a separate system of overlying fields, or the structure of the bipole itself, allows the explosion to be ejective. Because this internal reconnection apparently begins at the very start of the sigmoid eruption and grows in step with the explosion, we infer that this reconnection is essential for the onset and growth of the magnetic explosion in eruptive flares and coronal mass ejections.

Subject headings: Sun: coronal mass ejections (CMEs) — Sun: filaments — Sun: flares — Sun: magnetic fields — Sun: X-rays, gamma rays

1. INTRODUCTION

It is now well established that flares and coronal mass ejections (CMEs) are predominantly magnetic explosions. That is, they show rapid motion and heating that we infer to be driven by magnetic energy locally contained in the field (e.g., Svestka 1976; Sturrock 1980). All CMEs and many flares exhibit outward mass motion, even though it is likely that part of the magnetic field must shrink (implode) in order that there be an overall decrease in magnetic energy in the region of the explosion (Hudson 2000). Given that the magnetic field is the prime mover, the basic question posed by flares and CMEs is, what is the configuration of the magnetic field before the explosion, and how does the field change in the explosion? It is widely (but not universally) held that reconnection of the magnetic field is an essential aspect of the release process. Cast in terms of reconnection, the basic question becomes, is reconnection necessary for either the triggering or the growth of the explosion, or is reconnection only a consequence of the explosion, and, either way, where in the magnetic field does the reconnection take place, and how is it driven? In this paper we investigate these questions by examining the changing coronal X-ray structure in onsets of eruptive events observed by the *Yohkoh* soft X-ray telescope (SXT).

Flares and CMEs happen in mainly closed magnetic fields that encompass one or more neutral lines (polarity dividing lines) in the photospheric magnetic flux. That is, the magnetic field that yields a flare and/or CME is basically composed of one or more closed magnetic bipoles (Machado et al. 1988a; Moore et al. 1999). (In our usage, "closed" field lines return locally to the photosphere ["open" means that the field line has expanded into the solar wind], and "closed bipole" denotes the set of closed field lines linking two contiguous domains of opposite polarity.) Many flares and CMEs are multiple-bipole events, apparently involving interaction and reconnection between two or more bipoles (Machado et al. 1988a).

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Nevertheless, there are many single-bipole events, eruptions that straddle only one neutral line and show no apparent reconnection with other bipoles. In particular, many of the long-duration two-ribbon flares that are born in tandem with a CME appear to be single-bipole events (e.g., the four events studied by Sterling et al. 2000). The "standard model" for the magnetic explosion in eruptive flares and CMEs is for single-bipole events. This is the model first proposed by Hirayama (1974) and advanced by many later studies of eruptive flares (Heyvaerts, Priest, & Rust 1977; Moore & LaBonte 1980; Hagyard, Moore, & Emslie 1984; Sturrock et al. 1984; Moore & Roumeliotis 1992; Shibata et al. 1995; Tsuneta 1997; Shibata 1996, 1998). The approach of the present paper is to compare the explosion onset envisioned in this model with onsets of actual single-bipole eruptive events observed by the *Yohkoh* SXT.

For describing the configuration of the magnetic field of a bipole, it is useful to divide the bipole arbitrarily into two parts: an inner part, called the core field, and the outer remainder, called the envelope field (Moore & Roumeliotis 1992). The core field is rooted close to the neutral line through the middle of the bipole. The envelope is the rest of the bipole, the field rooted outside of the core. Before a bipole explodes in an eruptive flare and/or CME, its core field is usually strongly nonpotential, being so greatly sheared that it runs nearly along the neutral line rather than crossing right over the neutral line (Moore, Hagyard, & Davis 1987; Falconer 2000). Sheared core fields typically have suspended within them chromospheric temperature plasma forming an obvious dark filament in chromospheric images when the region is viewed on the disk. Before an explosion, the filament is a tracer of the core field, snaking along and above the neutral line. In chromospheric movies, a magnetic explosion in a bipole is often seen as a filament eruption. Because the plasma and the core field are frozen together as a result of the plasma's high electrical conductivity, the filament plasma rides with the field threading it.

In terms of its outcome, the explosion of a sheared-core bipole is one of two types: ejective or confined (Pallavicini, Serio, & Vaiana 1977; Machado et al. 1988a; Moore et al. 1999). Ejective explosions are the kind that frequently produces a CME and long-duration two-ribbon flare. In these, much of the sheared core field in and around the filament becomes an erupting twisted flux rope that escapes far out of the closed-field domain of the initial bipole, often rising through the corona to become part of a CME. The filament eruption presented by Moore (1987) is an example of an ejective eruption. The alternative to an ejective explosion, a confined explosion, produces a confined eruption of the sheared core field and filament in the impulsive phase of a short-duration flare: there is no CME and no long-decay X-ray event. The sheared core field and filament undergo an eruption that is soon arrested within the confines of the closed bipole, and the flare has a correspondingly short duration. The filament eruption presented by Moore (1988) is an example of a confined eruption. Viewed in chromospheric movies, the onset of the filament eruption in a confined explosion is similar to that in an ejective explosion. That is, in the onset phase, it is hard to tell from chromospheric images whether a filament eruption will be confined or ejective. This suggests that the initial internal field configuration and the onset of its explosion are essentially the same in either kind of single-bipole explosion, ejective or confined. A goal of the work reported here was to test this hypothesis against eruption onsets imaged in coronal X-rays by the *Yohkoh* SXT.

In the above paragraphs we have primarily summarized what was known about the magnetic explosion in flares in sheared-core bipoles before we had the coronal X-ray movies from *Yohkoh* SXT. For this reason the above descriptions are necessarily in terms of the filament and its eruption because that was the only tracer of erupting sheared core fields that we had before *Yohkoh*. Some bipoles with sheared core fields that show no filament have flares that are similar to those with filament eruptions in the way that the ribbons of chromospheric flare emission bracket the neutral line and spread away from it (Svestka 1976). We expect that the sheared core field erupts in the same way in most flares in sheared-core bipoles, regardless of whether it holds enough chromospheric temperature plasma to be seen as a filament. In any case, because sheared core fields are often visible in coronal X-ray emission, with the SXT we now have the capability of observing sheared core fields whether or not they are visible as filaments in chromospheric images.

Before *Yohkoh*, it had been inferred from the observed location and structure of chromospheric filaments and then confirmed by vector magnetographs that flare-productive bipoles have extensively sheared core fields along their neutral lines (e.g., Foukal 1971; Moore & Rabin 1985; Moore et al. 1987; Machado et al. 1988a). Chromospheric movies had long shown via filament eruptions that explosive eruption of the sheared core field was an integral part of flares in such bipoles (e.g., Smith & Ramsey 1964; Martin & Ramsey 1972; Hirayama 1974; Moore & LaBonte 1980; Moore 1987, 1988; Kahler et al. 1988). It was anticipated that, by virtue of plasma in the core field being heated to X-ray temperatures, the core field would become visible in *Yohkoh* X-ray images in the explosion onset, further revealing the exploding field configuration in sheared-core bipoles (e.g., Moore 1987; Moore et al. 1991). It is now known that the sheared core field is often quite visible in *Yohkoh* SXT images even when no explosion is underway (Canfield, Hudson, & McKenzie 1999; Falconer 2000). Because, for some reason, most sheared core fields harbor enhanced coronal heating, they steadfastly stand out as bright structures in SXT coronal X-ray images (Falconer et al. 1997, 2000). In bipoles that are prone to have ejective explosions, SXT images show that the sheared core field usually has an overall sigmoidal form, shaped like an S or inverse S. The middle of the sigmoid traces the neutral line through the bipole, and the two ends are oppositely curved magnetic elbows that loop out on opposite ends of the neutral line (e.g., see Sterling & Hudson 1997). During the explosion, the X-ray sigmoid is lost in the glare of the growing X-ray flare in the SXT images. Later, in the flare decay phase when the flare brightness no longer saturates the SXT images, an arcade of X-ray flare loops straddles the neutral-line corridor that was traced by the middle of the sigmoid before the explosion (and that may still be traced by a remnant of the preflare sigmoid; Rust & Kumar 1996; Sterling & Hudson 1997; Moore et al. 1997). This sigmoid-to-arcade transformation is compatible with the standard model for ejective two-ribbon flares (Sterling et al. 2000).

In this paper we present examples of single-bipole explosions for which there are SXT images with good coverage of the onset and that show good agreement with the standard model. These events were found by searching the sequential record (movie) of SXT full-disk desaturated coronal images. The cadence of these images is seldom faster than several per hour, and the sequence often has gaps of a few hours in its coverage. The events that we have selected are ones that started slowly enough, stayed dim enough, and happened when the movie cadence was fast enough that the brightening and motion could be followed well into the explosion without saturation. The set of events that we present was chosen partly for its sampling of different perspectives from near the limb to disk center. Primarily, though, each event was selected for clarity of sigmoidal core-field structure and evolution in the onset of the explosion. The SXT images of these events allow the initiation of the explosion to be examined in more detail than in SXT coverage of most eruptive events.

Before presenting our example observed events, we first give our version of the standard model for magnetic explosions in sheared-core bipoles. This is basically the model described by Hirayama (1974) with modern touches, including explicit accommodation of confined explosions in addition to ejective explosions. We then present four ejective events and two confined events that develop according to the model. From their agreement with the model, we infer that these explosions, ejective or confined, are unleashed by reconnection within the erupting sheared core field.

2. MAGNETIC EXPLOSION/IMPLOSION MODEL

Our version of the standard model for single-bipole magnetic explosions is sketched in Figure 1. Only a few representative field lines are drawn, intended to convey the essence of the three-dimensional field configuration in our idea of how the explosion is unleashed in a sheared-core bipole. The field configuration and reconnection/eruption scenario sketched here for the case of an ejective explosion is the same as that proposed by Moore & LaBonte (1980). Their model was based on *Skylab* coronal X-ray images of a large sheared-core bipole before and in the late phase of a large two-ribbon flare, together with a magnetogram of the region and an Hα movie of the filament eruption and flare onset. This was a modification of the original model of Hirayama (1974), which was based on chromospheric images of filaments, filament eruptions, and two-ribbon flares, together with magnetograms. The Moore & LaBonte (1980) picture fits the preflare sigmoid and the sigmoid-to-arcade switch seen in similar ejective events observed by SXT (Moore et al. 1997; Sterling et al. 2000). The only additional idea in our present version of the model is that the same basic model, originally deduced for ejective explosions, also accommodates confined explosions. (See Antiochos, Dahlburg, & Klimchuk 1994 for numerical modeling of a three-dimensional sheared bipolar field configuration.)

The four panels of Figure 1 show key stages of the explosion development in our version of the standard model. These sketches as drawn may suggest the presence of separate magnetic domains forming the sheared core and envelope fields mentioned above. This is an exaggeration done to emphasize the match with the observed configurations described in § 3. Because of the simplicity of the photospheric field morphology in the cases we discuss, we do not believe that separate domains actually exist; the field forms one continuous structure, and the separation between sheared core and envelope fields is completely arbitrary.

In Figure 1, the upper left panel shows the preflare state, emphasizing the strong shear at low altitudes along the neutral line; the upper right panel shows reconnection ("tether cutting") occurring in this region; the lower left panel shows the completion of the early reconnection; and the lower right panel shows the rising plasmoid distending the outer (envelope) field lines, which continue the process of reconnection to form the expanding flare ribbons. Eventually, the plasmoid escapes as part of the CME. We emphasize that the entire development proceeds smoothly and that the tether-cutting reconnection merges imperceptibly into the postflare arcade reconnection. In this model there is also no physical distinction between the rapid energy release in the impulsive phase and the gradual energy release during the postflare loops. The field configuration resulting from the plasmoid ejection contains a current sheet in the open field region, leading to a helmet-streamer configuration.

In a confined event, the explosion is not extensive enough to open the field. The reconnection ceases, and no CME results. The energy to drive either an ejective or a confined flare, in this model, comes from the simplification and shortening of field lines at low altitudes above the neutral line.

As will be substantiated in § 3, by virtue of its sigmoidal core field and the location and development of reconnection within this field, the model development fits the development of our events observed in SXT images. In the remainder of this section we describe in some detail the progression of the reconnection in the model and the signature of this progression to be expected in the SXT images.

Before the explosion, the sheared core field has two oppositely curved elbow regions, giving the core field its overall characteristic sigmoidal form. Low-lying parts of the elbow fields, the "arms" of the elbows, reach under the envelope field, which is less sheared than the core field and rooted farther from the neutral line. The envelope field presses down on the sheared core field, forcing the arms of the elbows to be nearly horizontal and putting dips in the sheared core field between the arms so that it can support a filament (Antiochos et al. 1994). The two elbow arms shear past each other along the middle stretch of the neutral line, where they are narrowly separated by the sheared field in which the filament is suspended. These opposite arms are poised to reconnect if and when they come into contact and push against each other, i.e., if and when the field between them develops a sharp interface (current sheet) across which there is an abrupt change in the direction of the field. We suppose that a sharp interface and ensuing reconnection arise spontaneously in the gradually evolving sheared core field, perhaps (as proposed by Moore & Roumeliotis 1992) as a result of tether-cutting flux cancellation at the neutral line in the photosphere.

In the upper right panel of Figure 1, the two crossed arms are beginning to reconnect. Two sets of newly connected field lines are exiting from the reconnection site, one set escaping upward and the other downward. The upward field lines form a rising twisted flux rope that connects the far ends of the two elbows. The downward field lines form short sheared new loops low over the neutral line. This process of reconnection and rearrangement of the sheared core field proceeds explosively: the two elbow arms implode sideways into the void left between them by the escaping upward and downward products of the reconnection. Following seamlessly after the reconnecting arms, progressively less sheared field lines from the outer core and inner envelope (rooted progressively farther from the neutral line)

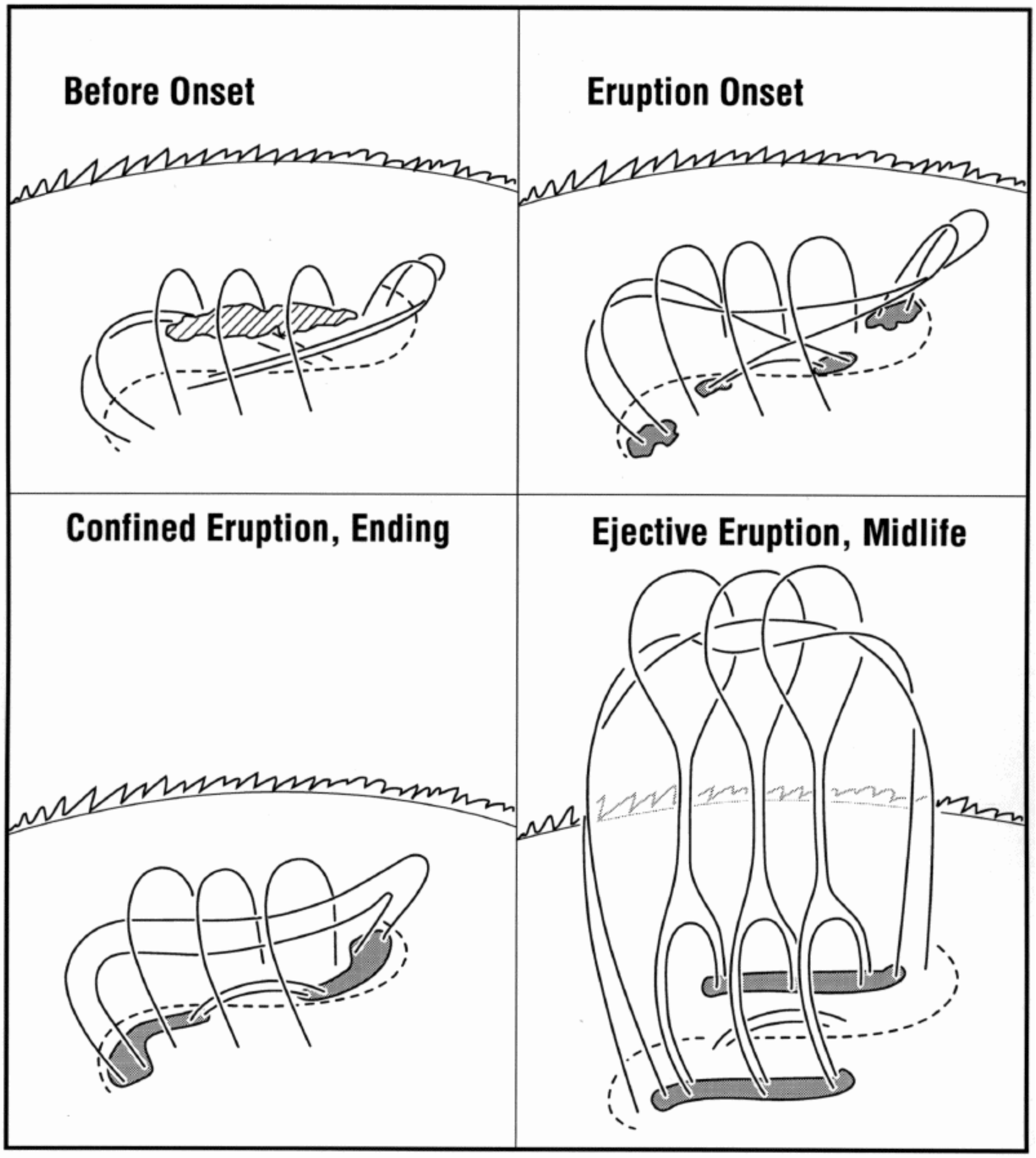

FIG. 1.—Our version of the standard model for the magnetic field explosion in single-bipole eruptive solar events (from Moore 2000). This version is tailored to bipoles having sigmoidally sheared and twisted core fields and accommodates confined explosions as well as ejective explosions. The rudiments of the field configuration are shown before, during, and after the onset of an explosion that is unleashed by internal tether-cutting reconnection. The dashed curve is the photospheric neutral line, the dividing line between the two opposite-polarity domains of the bipole's magnetic roots. The ragged arc in the background is the chromospheric limb. The gray areas are bright patches or ribbons of flare emission in the chromosphere at the feet of reconnected field lines, field lines that we would expect to see illuminated in SXT images. The diagonally lined feature above the neutral line in the top left panel is the filament of chromospheric temperature plasma that is often present in sheared core fields.

flow in to reconnect at the rising reconnection site. (For other depictions of this three-dimensional implosion/explosion process, in basically the same closed sheared configuration but from other perspectives, see Figs. 1, 2, and 3 of Moore, LaRosa, & Orwig 1995.) In this picture, the reconnection is expected to produce most of the particle acceleration and plasma heating that result in the flare burst of electromagnetic radiation across the spectrum from radio waves to hard X-rays or γ-rays (as Moore et al. 1995 have shown to be feasible in terms of the sheared core field, flare ribbon development, and number of energetic electrons required for the hard X-ray burst observed in a large ejective flare). The eruption onset panel in Figure 1 depicts this explosive release early on when the heating first becomes strong enough to initiate the brightening of the flare ribbons in the chromosphere and the rise of the soft X-ray burst. In this early stage of the explosion, if we are lucky enough to have SXT coverage, as the sigmoid brightens in the X-ray images we might also see the two products of the reconnection: the upward released flux rope and compact brightening under the middle of the sigmoid.

Once the runaway reconnection begins, there are two possibilities for how the explosion plays out. Either the explosion ejects the erupting flux rope out of the initially closed bipole, opening the envelope field (Fig. 1, *lower right panel*), or the explosion is arrested and confined within the closed bipole (Fig. 1, *lower left panel*). What determines which path the explosion takes is an unanswered question.

Two likely factors are the flux content of the sheared core field relative to the envelope field and the height at which the reconnection begins (the greater this height the smaller the fraction of the core field that can be released as the explosion proceeds; Moore et al. 1997, 1999).

In an ejective explosion, the envelope is blown out with the twisted flux rope inside it, and the reconnection is long lived. In progressing through the explosive phase and early late phase of the flare (in the interval between the onset panel and the ejective eruption panel in Fig. 1), the downward product of the reconnection grows continuously from an arcade of low sheared flare loops rooted next to the neutral line to a progressively higher and less sheared flare arcade rooted progressively farther from the neutral line. During this interval, the reconnection region is a rising and growing vertical current sheet, and the direction of the field lines flowing into the sides of the current sheet progresses from being nearly horizontal to nearly vertical. The late-phase arcade grows by gaining new hot outer loops formed by reconnection that closes the "opened" distended legs of the envelope in the wake of the ejected flux rope. This postejection arcade, bright in coronal X-ray emission, is the signature in SXT images for long-duration two-ribbon flares resulting from single-bipole explosions that produce CMEs (Sterling et al. 2000).

In a confined explosion, although there may be some inflation of the envelope field, the explosion is muffled within the envelope, there is no ejective opening of the bipole, and the reconnection, eruptive action, and flare heating end much sooner and more abruptly than in an ejective explosion. In our model, a confined explosion is unleashed by reconnection low in the sigmoidal sheared core field in the same way as in an ejective explosion. But instead of exploding out of the bipole and opening the envelope field, the expansion halts within the domain of the bipole, and there is no further reconnection or flare heating. Thus, in the SXT images, we expect to find some sigmoidal single-bipole explosions that start out the same way as the ejective explosions (with brightening of the core-field sigmoid, upward moving released core field, and compact brightening under the middle of the sigmoid) but then stop and fade away instead of going on to open the bipole and produce a CME and long-duration flare arcade.

3. OBSERVED ERUPTIONS THAT FIT THE MODEL

3.1. *Event Selection*

Table 1 lists six sigmoidal eruptive events that we have found in the first 4 yr (1992 October–1995 October) of the archive of SXT full-frame desaturated images and that we have chosen to show for their agreement with the model. (The SXT full-frame desaturated images are taken with either the thin aluminum filter or the aluminum/magnesium filter, have long enough exposures to show the quiet corona and coronal holes, and have any saturated areas restored from cotemporal, unsaturated, short-exposure images. Because these images have a spectral range of 3–45 Å, with a broad peak in sensitivity around 8 Å, they predominantly show coronal plasma that is hotter than 2×10^6 K; Tsuneta et al. 1991.) Each of our six events begins with brightening in sheared core field having elbows on both ends. The onset time given in Table 1 is the time of the SXT image in which the brightening can first be discerned. Because of their different heliographic locations and different orientations of the sigmoid, the six events together make a stronger case for the three-dimensional form, reconnection, and motion of the magnetic field in exploding sigmoidal bipoles than does any one event alone.

All but one of our events, although bright enough and large enough for their overall form and major structural components to be seen in the SXT images, were faint enough throughout that they did not trigger the SXT flare mode. In flare mode, the brightest point of the growing flare is centered in partial-frame images and followed at a higher cadence than for full-frame images. Large events that have onsets that are bright enough to trigger the flare mode usually quickly become so bright that image saturation and glare hide most of the coronal magnetic structure involved in the event, and the partial frames often cover only part of the exploding bipole. Moreover, whereas a partial-frame image sequence can cover no more than one large active region at a time, the full-frame movie has entire coverage of every sheared-core bipole on the face of the Sun. For these reasons, for showing the overall structure and development of the explosion onset in large events, the SXT coverage was often better when the event did not trigger the flare mode and the cadence of full-frame images was not interrupted. In addition, the eruption usually begins more slowly in large faint events than in large bright events. In particular, in our five faint events the explosion onset was gradual enough to be followed by the full-frame cadence. These selection effects result in five of our six events having only weak to moderate soft X-ray luminosity (*GOES* class B or C). The SXT coverage of our only M class event was exceptional in that, although flare mode was triggered early in the eruption, the flare brightness remained below saturation level well into the eruption, and the partial frames covered nearly the entire exploding sigmoid.

3.2. *Ejective Events*

For each of our four ejective events, the *GOES* 1–8 Å flux history through the time of the event is shown in Figure 2. Three of these events (1993 December 17, 1994 October 19, 1994 November 13) were either class C or M *GOES* X-ray bursts. Each of these dominated the Sun's 1–8 Å X-ray luminosity for several hours. The short-duration B9 burst a

TABLE 1

OBSERVED SIGMOIDAL ERUPTIVE EVENTS

Date	Onset Time (UT)	Heliographic Location	*GOES* X-Ray Class	Type	View of Sigmoid
1992 Feb 24	20:34	N15°, E30°	B3	Confined	Top
1992 Jul 12	21:01	S20°, E10°	C3	Confined	Side/Top
1993 Dec 17	19:19	N05°, E45°	C2	Ejective	Side
1994 Feb 28	14:43	N35°, W10°	B1	Ejective	Side
1994 Oct 19	20:35	N05°, W25°	M3	Ejective	Top/Side
1994 Nov 13......	10:41	N15°, E15°	C1.5	Ejective	Top/Side/End

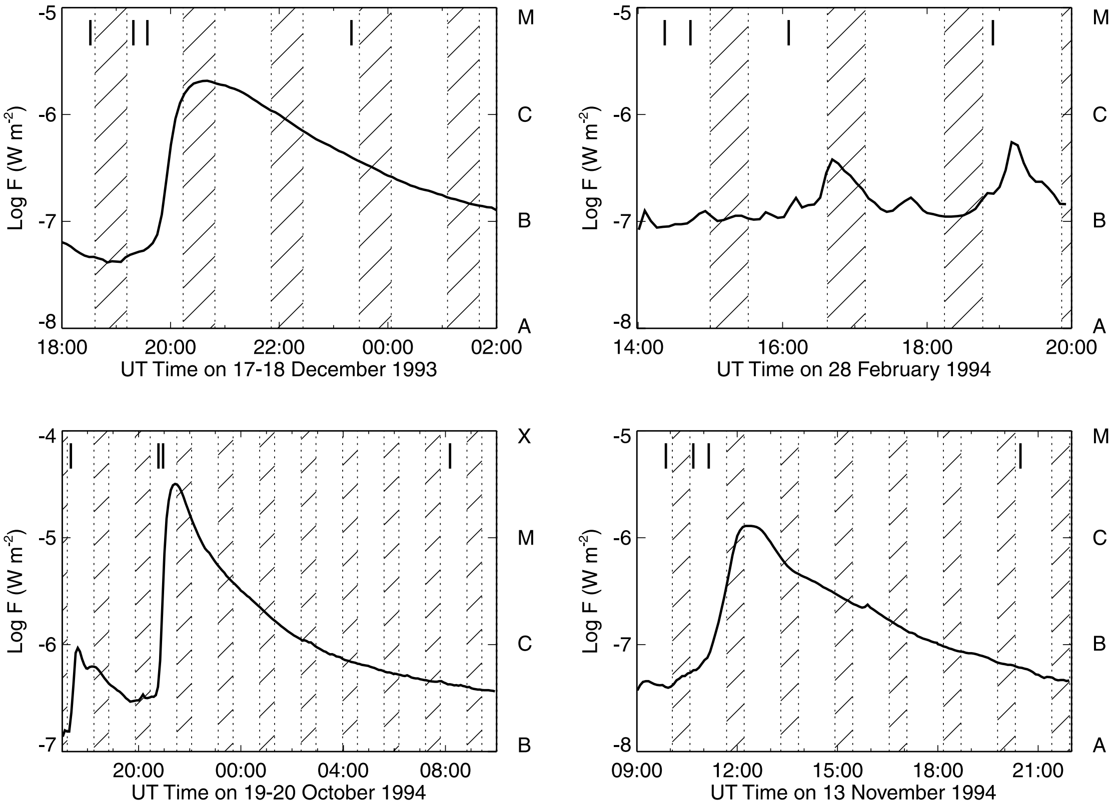

FIG. 2.—Solar 1–8 Å X-ray flux observed in space at Earth by *GOES* during each of our four ejective events. During each diagonally lined interval, *Yohkoh* was in the shadow of Earth. For each event, four times are marked by vertical bars above the X-ray flux time profile. These are the times of the four SXT images that we have chosen for display of the coronal magnetic structure and its development in the event (in Figs. 3–6).

few hours before the M class event on 1994 October 19 was a confined event within the sigmoid that erupted in the main event. During the confined event, the sigmoid and some loops of the envelope were brighter and more visible in the SXT images than they were closer to the time of the onset of the ejective eruption. The fourth ejective event (1994 February 28) was large but dim (only B level in *GOES* X-ray flux) and was the slowest of our events. It produced a gradual slight rise in background level from about 15:00 UT to about 19:00 UT. The shorter B class bursts superposed on this gradual rise came from an unrelated active region near the east limb.

The magnetic configuration and its transformation in each of the four events as observed by the SXT are shown in Figures 3–6. Each of these figures has the following layout. The upper four panels are SXT images of the region. The top left panel shows the sigmoidal bipole before eruption onset, and the middle right panel shows the long-duration late-phase arcade, which indicates that the eruption was ejective. The top right and middle left panels show the onset and liftoff of the eruption. The bottom left panel is part of a full-disk magnetogram, showing the distribution and polarity of the magnetic flux in the region and the location and direction of the neutral line through the bipole. Finally, the bottom right panel is a half-scale "road map" of the magnetic structures seen in the four SXT panels, delineating the loops and showing which ends are on which side of the neutral line. The limb, loops, and neutral line were traced from the other panels onto a transparent overlay. The bottom right panel is this four-panel tracing, scaled down to fit in a single panel.

In more detail, the neutral lines and loops drawn in the road map panels in Figures 3–6 (and in Figs. 8 and 9) were obtained as follows. The magnetogram in each figure was given the same spatial scale, same orientation (solar north up, west right), and same field of view (within a few pixels) as the X-ray panels. The neutral line was traced from the magnetogram onto a transparent overlay. In each X-ray panel the traced neutral line was superposed on the X-ray image and the X-ray loops were traced onto the transparency. The resulting four-panel transparency (one panel for each X-ray panel) was then scanned, reduced in size by a factor of 2, and inserted into the lower right panel of the figure. In each panel of the road map, the dotted curve is the tracing of the neutral line, and the solid curves are tracings of X-ray loops. That the position of the neutral line in each X-ray panel was basically correct is verified by the fact that all of the traced loops bridge the neutral line.

The arrows in Figures 3–6 point to X-ray features that we identify with magnetic components of the model. Each arrow is labeled with a letter according to the component. An arrow labeled A or C points to an elbow of the sigmoid. An arrow labeled B points to a loop of the envelope before or during the eruption onset. The label D is for the upper product of the reconnection, the released flux rope that erupts upward. The label E is for the lower product of the reconnection, the low-lying bright sheared loop or arcade that brightens under the middle of the sigmoid as the reconnection and eruption begin.

In Figure 3, the bipole of the event of 1993 December 17 is far to the east of disk center and the neutral line runs north-south, so that the sigmoid is viewed from the side.

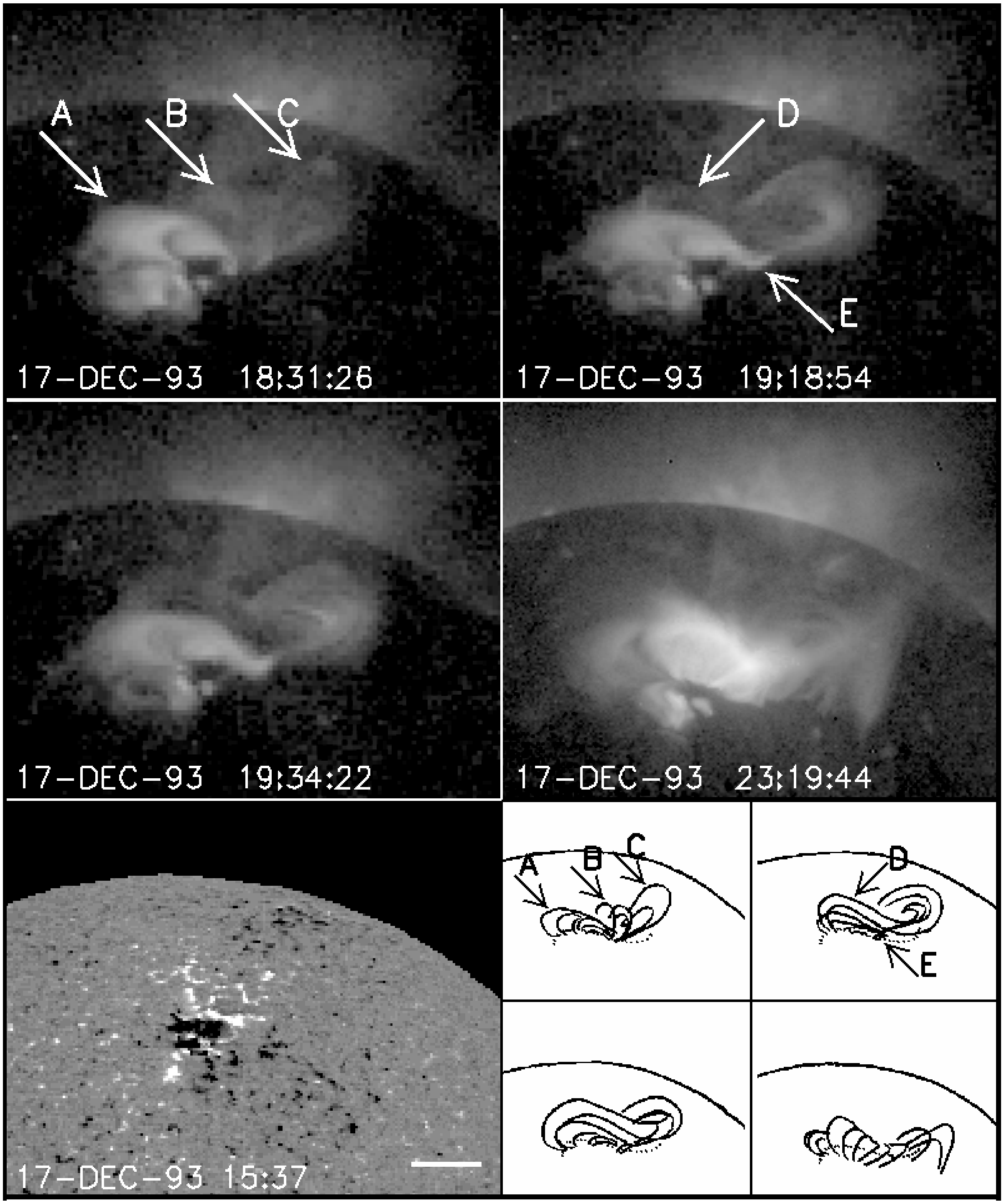

FIG. 3.—Ejective event of 1993 December 17. In these images, east is up and north is to the right. In the lower left panel, here and in the corresponding figures for our five other events, the magnetogram is from Kitt Peak National Solar Observatory, and the horizontal bar is 100,000 km long.

Both elbows (A and C) of the pre-eruption sigmoid can be seen in the top left panel, although the northern elbow (C) is faint. A couple of envelope loops (B) are also faintly visible. These are much less sheared with respect to the neutral line than is the sigmoid structure. In the top right panel, the envelope loops are no longer visible, but the northern elbow has brightened and become much more obvious. In addition, a low-lying bright sheared loop (E) has appeared under the middle of the sigmoid, and a new sigmoidal flux rope (D) runs above and between the two elbows. Fifteen minutes later (*middle left panel*), the flux rope is thicker and higher, and the underlying new bright feature is bigger and brighter than in the top right panel. All of these features and their development before the rapid rise of the *GOES* X-ray burst (Fig. 2) are in accord with the model. The SXT image in the middle right panel shows the postejection flare arcade about 3 hr into the decay of the *GOES* X-ray burst. This arcade is much less sheared than the pre-eruption sigmoid. It is seen that part of the southern elbow is still present with its arm reaching in under the arcade. This is compatible

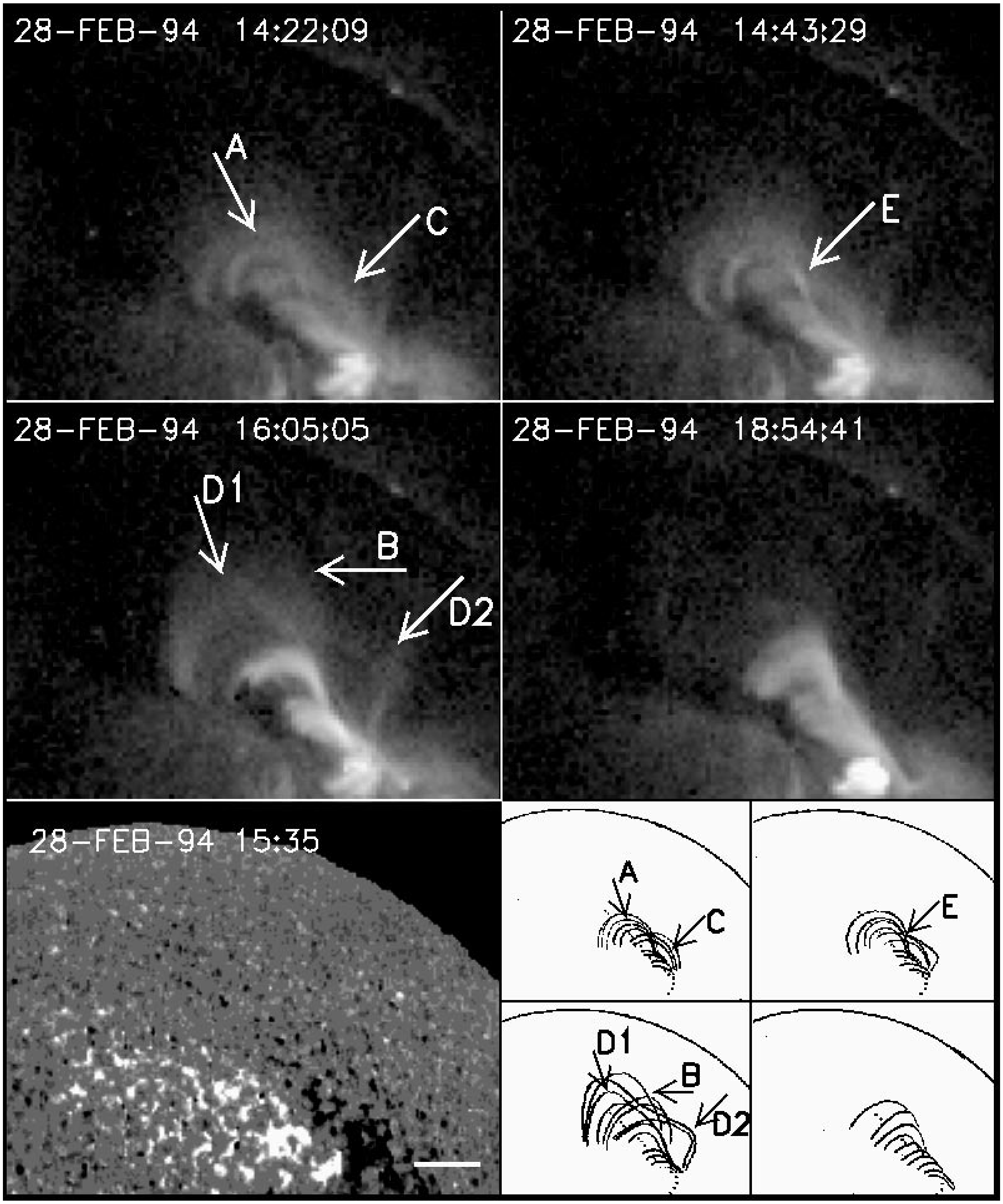

FIG. 4.—Ejective event of 1994 February 28. In these images and in all subsequent images, north is up and west is to the right.

with the model if only an inner or upper part of the arm of the southern elbow was accessed by the reconnection (Moore et al. 1997). Such partial reconnection and eruption of the southern elbow are consistent with the observed initiation of the flux rope in the top right and middle left panels.

In our slow dim event of 1994 February 28 (Fig. 4), we again have a side view of the erupting sigmoid. Before the eruption, the SXT image (*top left panel*), together with the magnetogram, shows that the core field of the bipole is sheared and has an elbow on each end and that the two elbow arms are crossed over the middle of the neutral line. In the top right panel, brightening (E) has started at the intersection of the two arms and the elbows have become more definite. These changes are appropriate signs of reconnection having just started at the interface between the two arms. In the middle left panel, it appears that this reconnection has progressed to produce a bright sheared loop below and to link the two elbows together to form a rising flux rope (D1, D2) rooted at the far ends of the elbows. It also appears that part of the envelope arcade (B) can be faintly seen in the middle left panel. Three hours later (*middle right panel*), the erupting elbows, flux rope, and envelope loop are all gone, and the flare arcade has grown larger and appears to be less sheared. The entire development follows our model scenario for single-bipole ejective events.

The strongest of our events in terms of brightness and luminosity in X-rays, the ejective event of 1994 October 19, is shown in Figure 5. The neutral line and sigmoid run north-south through the bipole and are viewed from above and from the east side at 25° from vertical. The SXT image in the top left panel shows the pre-eruption coronal structure of the bipole illuminated in the rise of the B9 confined event 3 hr before the onset of the ejective event. The two elbows (A and C) show that the core field of the bipole is sheared and twisted in the shape of an inverse S. A couple of envelope loops (B1 and B2), less sheared and arching over the sigmoid, are also faintly visible in the top left panel. The top right panel shows a partial-frame SXT image taken early in the rise of the *GOES* X-ray burst. No envelope loops are visible now, and the sigmoid is brighter and more obvious. The eruption is already underway, with the upward released flux rope (D) lifting off and the new bright low sheared loops (E) appearing below. The middle left panel is a larger partial-frame image taken 6 minutes later in the rise of the *GOES* burst. Now, the sigmoid has brightened still further; the low sheared flare arcade is bigger, brighter, and somewhat less sheared; and the flux rope has erupted farther out. The middle right panel shows the postejection flare arcade late in the decay of the *GOES* burst. These flare arcade loops are much less sheared with respect to the neutral line than those in the early flare arcade in the top right and middle left panels. A remnant of the sigmoid is faintly seen under the late-phase arcade. Again, all of the structure, brightening, and motion seen in the SXT images of this event, as well as their location and orientation with respect to the neutral line of the bipole, are in accord with the standard model for single-bipole ejective events.

The ejective event of 1994 November 13, shown in Figure 6, is viewed in yet another orientation. The bipole is northeast of disk center and the neutral line runs northeast-southwest, so that we look mainly down on the sigmoid but also view its southeast side and southwest end. In the top left panel, about an hour before eruption onset, the envelope field (B) arching over the middle of the sigmoid is more clearly visible than in our other events. The northern elbow (A) of the sigmoid is equally visible. The southern elbow (C) is less distinct, but it does appear that the arms of the two elbows shear past each other under the envelope arch. Low over the neutral line under the crossed arms, there is bright structure that appears to be a narrow arcade. Fifty minutes later (*top right panel*), in the gradual early rise phase of the *GOES* X-ray burst (Fig. 2), the arms of the elbows are more distinct, are slightly higher, and more clearly cross under the envelope arch, which is now fading. In addition, the inner arcade (E) under the crossed arms is now thicker and brighter. Forty minutes later (*middle left panel*), in the more rapid rise phase of the *GOES* X-ray burst, the envelope arch is gone, and the two elbows are erupting out, much of their arms now having connected to form the erupting flux rope (D). The flare arcade below has grown larger. It appears that some lower strands of the opposite elbow arms still cross each other over this arcade and have not yet reconnected. In the middle right panel, late in the decay phase, the erupting elbows and flux rope are gone, and a cusped arcade stands in place of the pre-eruption envelope arch. This event is perhaps the best of our four ejective events for display of all of the main magnetic components of the model and their transformation as the ejection is launched.

Hudson, Acton, & Freeland (1996) also presented and interpreted SXT images of the event of 1994 November 13. They concluded that this was an ejective event that probably launched a coronal mass ejection and that was generally consistent with the standard bipole eruption model, but they did not compare the observed coronal morphology and motion in detail with the version of this model that we are considering in this paper. Our comparison of the observed onset with the model is a new analysis of this event.

3.3. *Confined Events*

The *GOES* 1–8 Å flux history through the time of each of our two confined events is shown in Figure 7. The event of 1992 February 24 is barely detectable if at all in the *GOES* flux. It probably produced the gradual slight rise and fall between 20:00 UT and 22:00 UT. If so, at its maximum around 20:30 UT this confined event was somewhat more luminous in 1–8 Å flux than our ejective event of 1994 February 28, which in the SXT images was spatially larger and much longer in duration but slower and dimmer than this confined event. Our second confined event (1992 July 12) was strong enough to be obvious in the *GOES* flux plot. It produced a class C3 *GOES* burst, greater in peak flux than three of our four ejective events but much shorter lived than any of our ejective events.

In the same layout as for the ejective events shown in Figures 3–6, four SXT images, a magnetogram, and a road map are shown in Figures 8 and 9 for our two confined events. The correspondence of the letters labeling the arrows to the magnetic identity of the X-ray features pointed out is also carried over from Figures 3–6 to Figures 8 and 9.

The neutral line and sigmoid in the confined event of 1992 February 24 (Fig. 8) run roughly east-west. Although the bipole is situated 30° east and 15° north of disk center, the X-ray images in Figure 8 give the impression that we are looking down on the sigmoid from directly above. This indicates that the sigmoid in this event is pressed down flatter to the surface than are any of the initial sigmoids in our ejective events. In the top left panel of Figure 8, 3 hr before the eruption, the bright structure running along the neutral line does indicate that the core field of the bipole is strongly sheared. However, the overall form of the core field as illuminated by the X-ray emission looks only vaguely sigmoidal if at all. There are no clearly defined envelope loops over the middle of the bipole, but it does appear that the core field is inside an envelope of loops that bulges to the east, an appearance that may be partly from the 30° projection of a high envelope roughly centered on the bipole. In any case, this "halo" around and to the east of the sigmoid remains unchanged through the event. (Three hours after this confined event, this sheared-core bipole produced the long-duration flare that made the *GOES* M4 burst in Fig. 7. In SXT images, the M4 event had the usual signature of a large ejective two-ribbon flare, a late-phase arcade straddling the neutral line and centered on the bipole. This indicates that much of the envelope field over the center and western side of this bipole is not visible in the SXT images in Fig. 8.) In the top right panel, the overall inverse-S sigmoidal form of the core field is now obvious.

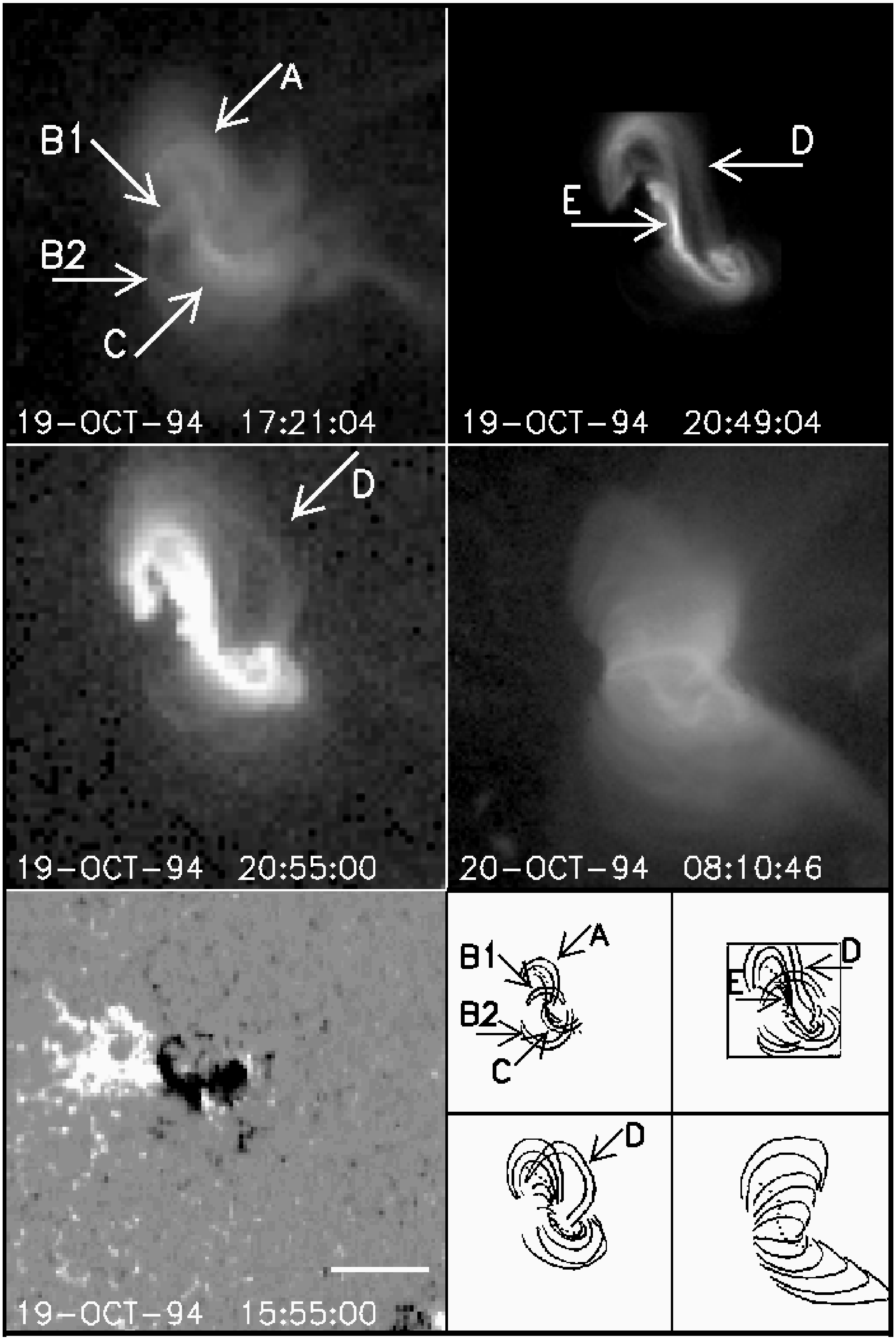

FIG. 5.—Ejective event of 1994 October 19

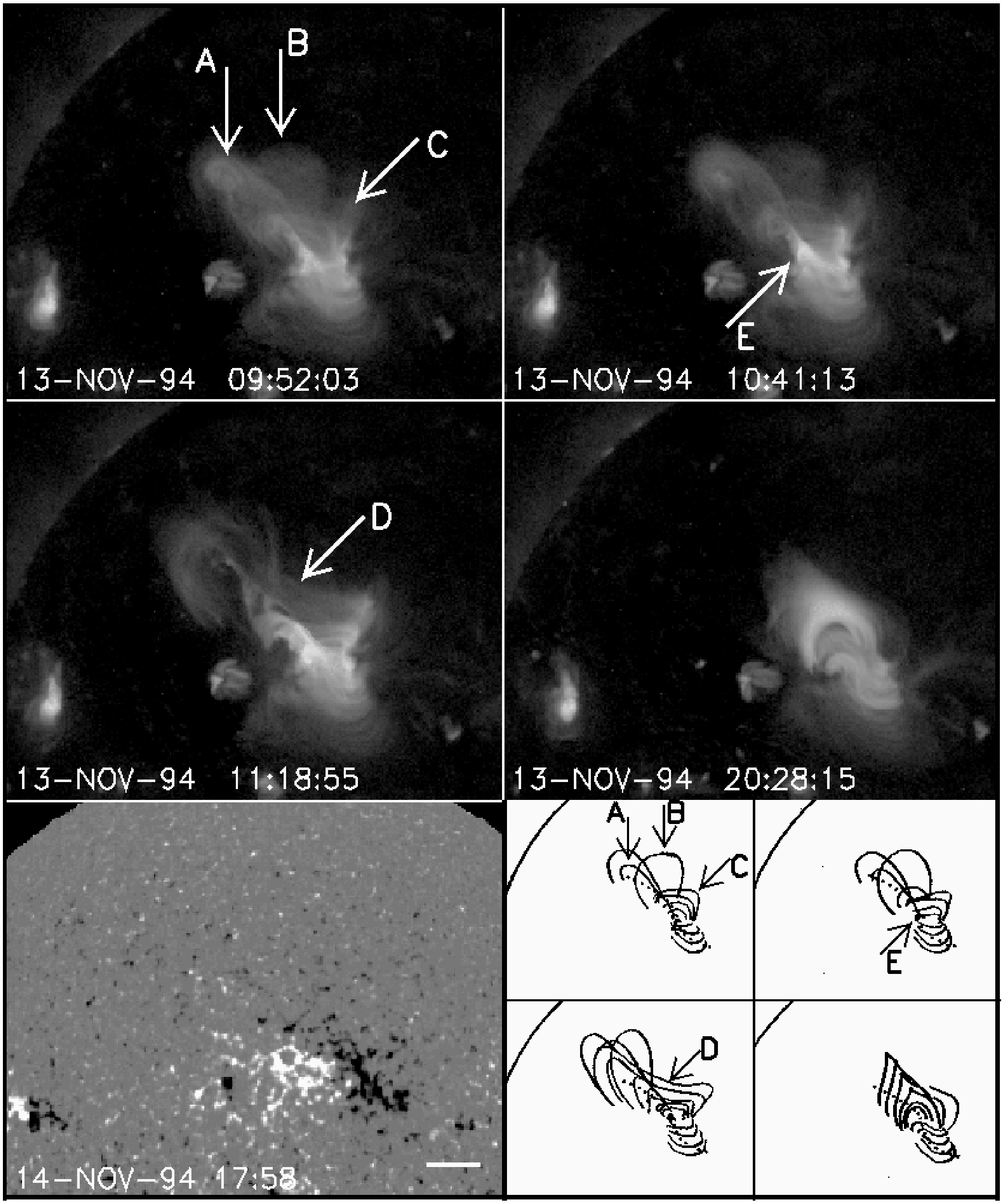

FIG. 6.—Ejective event of 1994 November 13

The two oppositely curved elbows (A and C) of the sigmoid have brightened along with a short sheared loop (E) between the two arms where they shear past each other along the neutral line in the middle of the bipole. The location, orientation, and length of this central bright loop are appropriate for it to be the downward product of reconnection of the crossed arms. Seventeen minutes later (*middle left panel*), the central sheared loop is still visible and both elbows have grown thicker and brighter. This is consistent with further reconnection of the arms that adds field and heat downward to the central loop and upward to a flux rope connecting the far ends of the elbows. The flux rope is not seen as a distinct feature but could be part of the observed thickening of the sigmoid. The middle right panel, an hour and a half later, shows that the brightening and eruption did not proceed much further. The bright features in the event have mostly faded away, and the core of the bipole again appears only vaguely sigmoidal. The short duration of flare brightness and the lack of formation of a long-duration arcade of little shear in place of the sigmoid

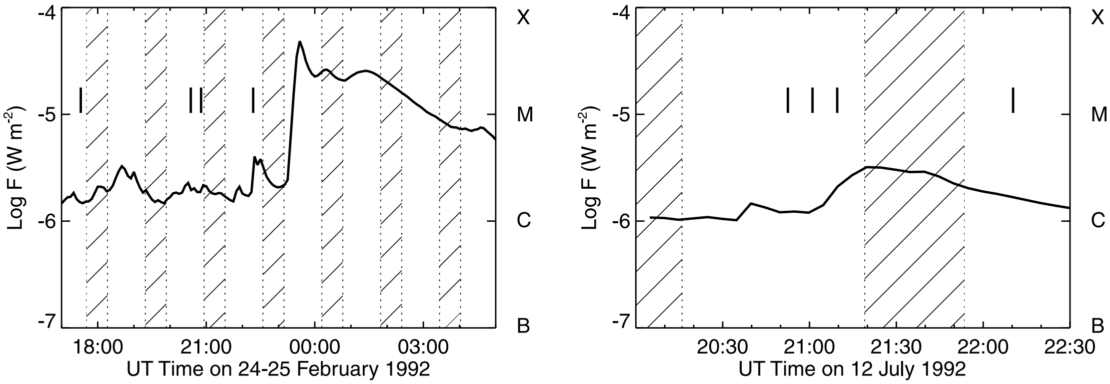

FIG. 7.—Solar 1–8 Å flux observed by *GOES* during each of our two confined events. The format is the same as in Fig. 2. The interval shown in 1992 February 24–25 extends well past the confined event to show an M4 long-duration burst, the signature of an ejective eruption that happened in the same bipole, starting about an hour after the confined event faded away.

show that this was a confined event. Thus, the magnetic location, form, and evolution of the observed coronal X-ray structure in this event are in good accord with our model for confined sigmoidal events.

The neutral line and "sigmoid" of our other confined event (1992 July 12, Fig. 9) run roughly east-west overall, even though the neutral line jogs southward at its eastern end. The region is only 20° south of disk center, but the SXT images give the impression that we have more nearly a side view of the event than a top view. This indicates that the mainly east-west loops in this event do not stand in vertical planes but lean over to the south. This is consistent with the magnetogram: there is more flux in the negative polarity domain on the north side of the neutral line than in the positive polarity domain on the south side. Among our six events, the view of this confined eruption is most similar to the view of the slow ejective eruption of 1994 February 28 (shown in Fig 4).

For the confined event of 1992 July 12, the pre-eruption SXT image (Fig. 9, *top left panel*) shows two elbows (A and C) that are rooted near the neutral line, are directed along the neutral line, and have their arms crossed over the middle of the neutral line. These features show that the core field rooted along this neutral line is sheared and has the two-elbow structure of a sigmoidal bipole, even though (as in the event of 1994 February 28) the S shape is not apparent because of the view direction. Eight and a half minutes later (*top right panel*), the two elbows have brightened and the arm of the eastern elbow (A) is now thicker and has two strands. In addition, a faint loop (D) now arches over the intersection of the two arms, which is appropriate for the upward product of reconnection between the arms. Along the neutral line below, three short loops (E1, E2, E3) have brightened. E3 is strongly sheared with respect to the neutral line. The location of E1 and E2 is plausible for them to be fed by the downward product of reconnection between the arm of the western elbow (C) and the eastern strand of the arm of the eastern elbow. The location of E3 is appropriate for it to be the downward product of reconnection between the arm of the western elbow and the western strand of the arm of the eastern elbow. Another 8.5 minutes later (*middle left panel*), the eruption and brightening have progressed further. Both elbows have risen, and the upward product of the arm reconnection (component D) has brightened and expanded upward even more so. The three underlying loops (E1, E2, E3) are brighter and E3 has grown thicker, as they should if they are being heated and built from the downward products of the reconnection. An hour later (*middle right panel*), the reconnection-released field bulge (D) and the two intertwined elbows have inflated some more, but the reconnection and expansion have stopped and the whole structure is now static and fading in place. Another SXT image (not shown in Fig. 9) taken 40 minutes later shows the same structure, only dimmer. The fading arch in the middle right panel is still strongly sheared with respect to the neutral line. The short duration of the X-ray flare brightness and the lack of formation of a long-duration, weakly sheared posteruption arcade show that this is a confined event. Thus, the magnetic location, form, and development of the observed coronal X-ray structure in this event, although somewhat more complicated than in our five other events, are consistent with the model for the magnetic topology and its change via internal reconnection in single-bipole confined explosions.

4. SUMMARY AND DISCUSSION

From searching the first 4 yr of the cumulative sequence of *Yohkoh* SXT desaturated full-disk coronal X-ray images, we found six sigmoidal single-bipole eruptive events in which the onset and early development of the eruption are well observed and show good agreement with the standard model for such events. The SXT images, together with a Kitt Peak magnetogram of each region, show the following:

1. Four of the eruptions were ejective explosions: the envelope of the bipole appeared to blow open and then gradually reclose to form and sustain a long-duration bright arcade.
2. The other two eruptions were confined explosions: the explosion was arrested within the bipole, the envelope stayed closed, and the field transformation and flare emission ended sooner than in the ejective eruptions.
3. The ejective eruptions and the confined eruptions all began in the same way: the two opposite elbow ends of the sigmoid, with crossed arms over the neutral line, brightened and expanded as a new bright sheared arcade appeared and grew below the crossed arms and a new bright strand connecting the far ends of the elbows appeared above the crossed arms and rose upward.

Thus, both in the ejective events and in the confined events,

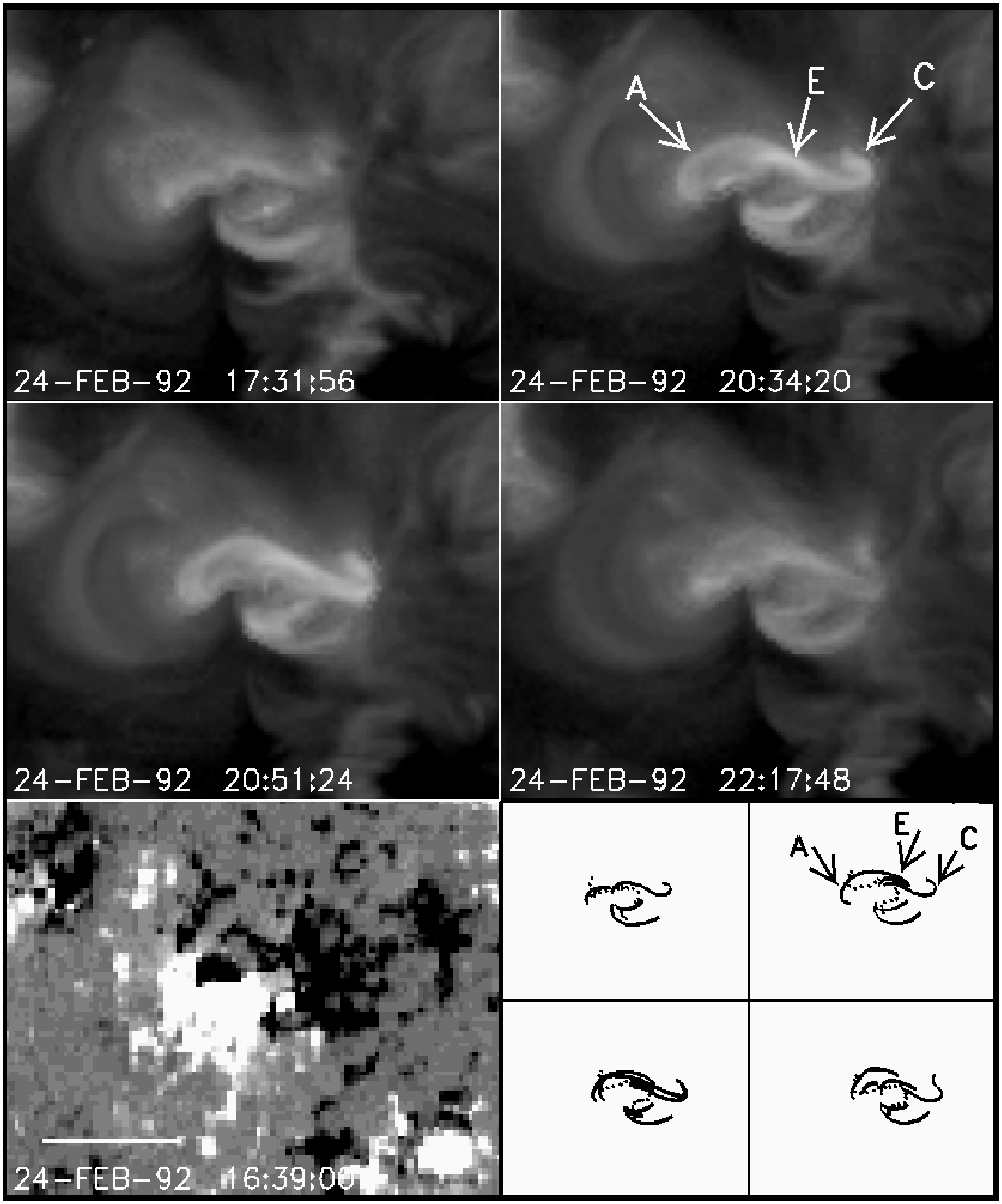

FIG. 8.—Confined event of 1992 February 24

the observed form and motion of the magnetic structure fit the model sketched in Figure 1. We conclude that implosive/explosive reconnection occurring within the twisted and sheared core field of a bipole (reconnection that begins in the field between the crossed elbow arms of a sigmoid) must be considered as a mechanism for both confined and ejective flares.

Our results from SXT images of ejective events at various locations on the face of the Sun complement the *Yohkoh* discovery that some ejective events observed at the limb also fit the bipole eruption model (e.g., Hiei, Hundhausen, & Sime 1993; Tsuneta 1996, 1997). For these limb events, soft X-ray images from the SXT are in accord with the eruption/reconnection picture under the assumption that the eruption is viewed end-on, along the direction of the neutral line and tunnel of the posteruption arcade. The magnetic explosion observed more or less from above in our ejective events meshes with this interpretation of these limb events. That is, if our ejective events were viewed end-on, they would display development and structure similar to that observed in these limb events: ejection of a plasmoid from above a growing bright loop that develops a cusp. In addition,

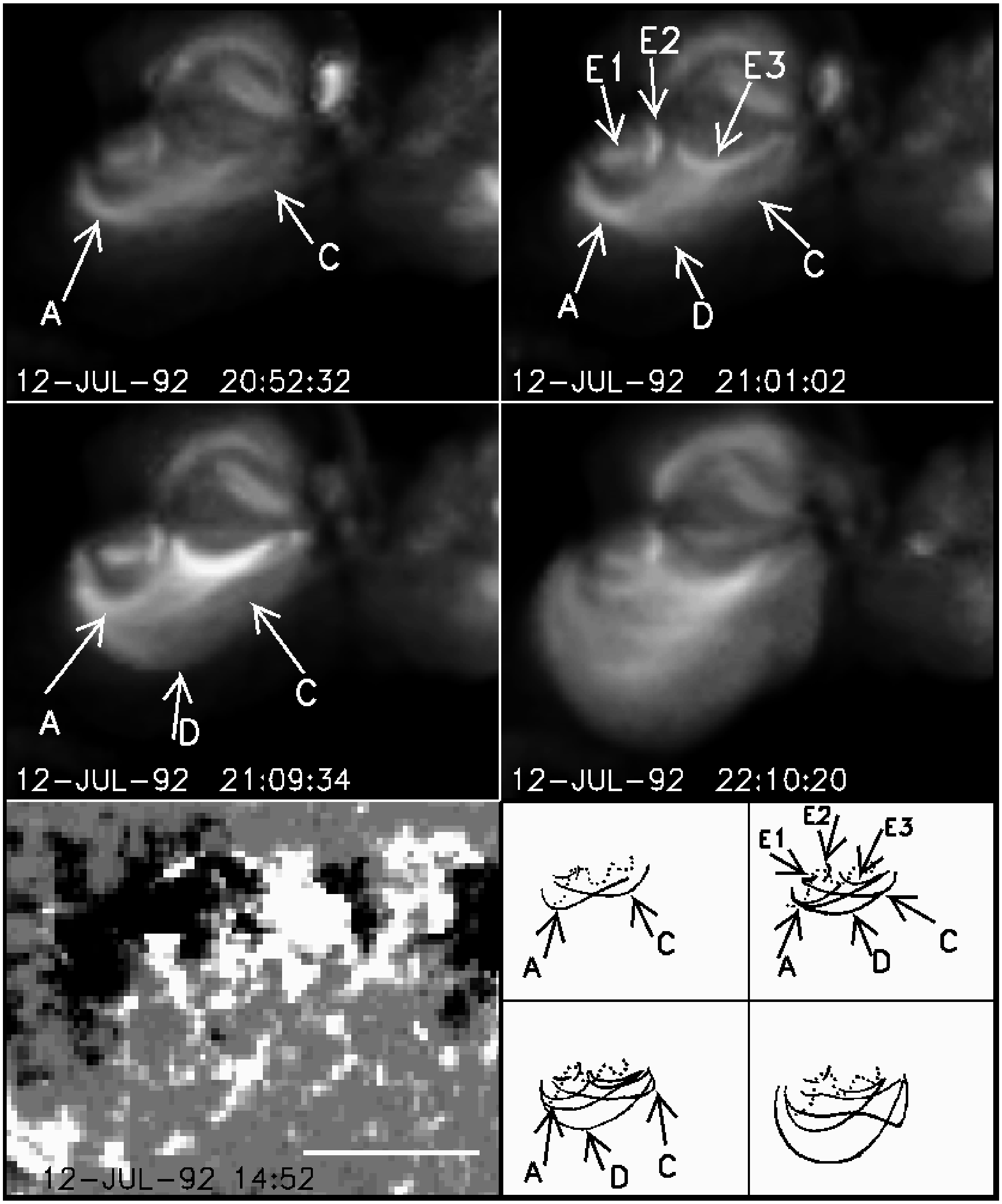

FIG. 9.—Confined event of 1992 July 12

recent observations of posteruption arcades at the limb (McKenzie & Hudson 1999; McKenzie 2000) have shown the common occurrence of downflow above the arcade that is consistent with the reconnection process in our bipolar eruption model.

In the model depicted in Figure 1, the essential idea is that the onset and growth of the explosion are the result of runaway tether-cutting reconnection (Moore & LaBonte 1980; Sturrock et al. 1984; Moore & Roumeliotis 1992). Before the explosion, the magnetic pressure (which tries to expand the field lines) is in balance with the magnetic tension (which tries to contract the field lines). The magnetic pressure keeps the bipole inflated, while the tension limits the inflation and keeps the field tied down (tethered) to its feet in the photosphere. During the explosion, the reconnection within the core of the sigmoid progressively cuts more and more of the tethers, allowing the unleashed part of the core field to expand upward, the new short loops to implode downward, and the crossed arms of the sigmoid and surrounding inner envelope field to flow into the reconnection site. From photospheric magnetograms and images of chromospheric structure in and around sheared core fields at and before explosion onset in observed filament-eruption flares, Moore & Roumeliotis (1992) proposed that the explosion is triggered when the field of the entire bipole (sheared core plus envelope) becomes globally unstable from evolution driven by flows in the photosphere. In particular, for single-bipole explosions, they proposed that this evolution usually involves slow tether-cutting reconnection in flux cancellation along the neutral line. In any case, in our version of the standard model, we suppose that the field evolves to a configuration that is globally unstable to the onset of fast reconnection. This runaway fast tether-cutting reconnection that then spontaneously begins in the sheared core field above the neutral line is an inherent part of the global instability. The reconnection region grows explosively along with the rest of the implosion/explosion of the core field.

In our example events, the observed development of the explosion onset agrees with the reconnection region growth expected from the model. The small initial size of the low bright arches (E) and their growth as the explosion proceeds are consistent with a reconnection interface region (current sheet) that starts small and grows with the explosion. Hence, our observations imply that no large current sheet builds up between the sigmoid arms before the explosion. This suggests that as soon as a current sheet begins to form, it is so rapidly diminished by reconnection that a sizeable current sheet (reconnection interface) can only be formed dynamically during the fast growth of the implosion/explosion, in the impulsive phase of the flare. Moore et al. (1995) empirically estimated the size of the reconnection region at the peak of the impulsive phase of a large ejective two-ribbon flare. The extent of the reconnection interface was found to be of the order of the size of the middle of the erupting sigmoid as inferred from the flare ribbons. Our observations of eruption onsets indicate that such a large reconnection interface in the impulsive phase is grown by the implosion/explosion itself from a reconnection region that is initially at least an order of magnitude smaller.

As was mentioned in § 1, eruptive events of the class sampled by our six examples, explosions of single sheared-core bipoles, may be a minority of all flares and CMEs. Two or more impacted bipoles appear to be interactively involved in many events. We now turn to implications that our observations of single-bipole eruptions have for multiple-bipole events.

A quite common configuration of two impacted bipoles is that formed when a relatively compact bipole emerges inside one polarity domain of an established larger bipole. If the new intruding bipole has a strongly sheared core field while the larger bipole has little shear, then the impacted configuration is of the active-passive type that has been identified for the heating of long bright coronal loops stemming from around islands of included polarity in active regions (Porter, Falconer, & Moore 1998; Moore et al. 1999; Falconer et al. 2000). This same basic field configuration is observed to produce X-ray jets (Shibata et al. 1992), surges (e.g., Hagyard, West, & Smith 1993), and flares (called flaring arches or double-loop flares) that have remote flare brightening and reverse-slope and U-shaped type III radio bursts (Tang & Moore 1982; Machado et al. 1988a, 1988b; Fontenla et al. 1991; Aschwanden et al. 1992; Hanaoka 1997). In all of these phenomena, the heating and/or flare brightening, surging, and jetting in the long magnetic loop are apparently driven by activity in the embedded bipole and its interaction with the long loop. Relative to the active embedded bipole, the long loop is passive in that it receives plasma, heat, and energetic particles by injection from the embedded bipole, presumably via reconnection driven by the embedded bipole at its interface with the long loop. The range of activity plausibly results from core-field explosions, ranging from micro-explosions of short substrands to full-blown explosions spanning the full length of the sheared core (Moore et al. 1999). If the embedded bipole is rooted in a sizeable (diameter greater than $\sim$20,000 km) sheared delta sunspot (consisting of two opposite-polarity sunspots crammed together, sandwiching a channel of strong magnetic shear between them), then the sheared core field is strong (greater than $\sim$1000 G) and has a large store of free magnetic energy (greater than $\sim 10^{31}$ ergs). It is therefore not surprising that full-span core-field explosions in such embedded sheared delta sunspots are often strongly ejective (blow open both the embedded bipole and the larger bipole). Two recent studies of strongly ejective flares from sheared delta sunspots in this active-passive configuration are those of Aulanier et al. (2000) and Sterling & Moore (2000).

In the context of the bipole eruption model (Fig. 1), the key new feature of the above impacted-bipole field configuration relative to the field configuration of a lone sheared-core bipole is that the embedded bipole has an X-type null above it on the interface between its envelope field and the envelope field of the larger bipole (e.g., see Fig. 4 of Moore et al. 1999 or Fig. 3 of Falconer et al. 2000). If the interface is in a relaxed state, the null will be potential-like with no appreciable current sheet. If, say, by further emergence the embedded bipole wells up against the interface, a current sheet will start to form at the null and any reconnection across the current sheet will cut some of the outer field lines of the envelope of the embedded bipole. This external tether cutting may help the overall configuration evolve toward explosive instability. In our picture for single-bipole explosions, both the slowly driven tether cutting leading to instability and the runaway tether-cutting reconnection in the explosion occur only at and low above the neutral line inside the sheared core field. Extending the tether-cutting idea to the embedded-bipole configuration, we expect that the slowly driven reconnection leading to the runaway instability can occur at the upper boundary of the envelope field in addition to low along the neutral line. That is, there can be both external and internal tether cutting leading to instability. Likewise, we expect that the runaway tether cutting that unleashes the explosion can begin first either at the upper interface or inside the core field, depending on the particulars of the overall configuration and its evolution to instability.

Antiochos (1998), Antiochos, DeVore, & Klimchuk (1999), and Aulanier et al. (2000) have argued that, in the above embedded-bipole configuration, for an ejective explosion of the sheared core field to be unleashed, the runaway reconnection must start first at the upper interface. To the contrary, our examples of single-bipole ejective eruptions suggest that in embedded sheared-core bipoles it should be possible for the runaway tether-cutting reconnection to start first inside the sheared core field in some cases. Our confined single-bipole eruptions appear to start by internal tether cutting in the same way as in our ejective single-bipole eruptions. This indicates that the core-field explosion can get started in more or less the same way whether or not the envelope of the bipole, together with any field outside the envelope, allows the explosion to become ejective. The presence of a null above the envelope may help the explosion break out and become ejective, but our single-bipole examples indicate that some ejective explosions happen with no external tether cutting. This suggests that in any configuration of two or more impacted bipoles, when one of the bipoles has a strong enough sheared core field, an explosion of this core field can be unleashed mainly by its own internal tether cutting, as in a single-bipole explosion.

Finally, we emphasize that our view of the observations poses specific problems for the theory of flares and CMEs. It is our view that the observations show that the explosion process can occur in a single sheared bipolar field. They further suggest that internal reconnection is an inherent part of the explosion that results in a catastrophic reconfiguration of the magnetic field, including, in ejective explosions, the opening of previously closed field lines. The observations are consistent with internal reconnection initiating the explosion and accelerating during its period of rapid development: the impulsive phase of the flare, the acceleration phase of the CME. Unfortunately, at present no comprehensive theory of such a process exists, and numerical simulations do not have enough fidelity to allow predictions yet. An alternate view of the process favored by some (e.g., Low 1996) would have an ideal MHD instability as the basis of the eruption and the reconnection as a by-product of the eruption. The distinction might be in the timing of the observed dissipation: an ideal MHD driving process might have a lag between the eruption and the reconnection. We see little evidence for such a lag and therefore predict that the eventual successful theory of the explosion process will have large-scale magnetic reconnection within the sheared core field of the exploding bipole being necessary from the very start of the explosion.

The work reported here was begun during an extended visit by R. L. M. to the *Yohkoh* Data Analysis Center at ISAS in Japan, as an ISAS Visiting Scientist. This visit was made possible and facilitated by many kind efforts by Tadashi Hirayama and Yoshiaki Ogawara. During this formative stage of the work, R. L. M. benefited from many stimulating discussions with Kazunari Shibata and his students. Completion of the work was funded by NASA's Office of Space Science through the Solar Physics Supporting Research and Technology Program and the Sun-Earth Connection Guest Investigator Program. The completion of the work was performed while A. C. S. held a National Research Council Resident Research Associateship with the Solar Physics Group at NASA/MSFC.

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