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Title: STUDY OF THE SOURCE REGIONS OF CORONAL MASS EJECTIONS USING YOHKOH SXT DATA

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1.0 INTRODUCTION

This document is the final report and summary of research for the Boston College grant NAGW-4578. This grant was for NASA's SR&T program under the Participating Scientist Program for the Yohkoh Mission. The overall Period of Performance was from 1 May 1995 to 30 April 1997. The original performance period was until 30 April 1996, but a one-year no-cost extension was granted. This extension was required because the PI was required to do work on other programs and also because he could not visit ISAS in Japan until early 1996 to acquire some of the Yohkoh soft X-ray data that was used in the analysis. The Co-I on the grant was Dr. Stephen Kahler of the AF Phillips Lab who had inter-governmental grant No. NACMGB88 for this work. This report also constitutes the final report for that grant.

The scientific objective of the program was to better understand how CMEs (Coronal Mass Ejections) are initiated at the sun by examining structures on the disk which are related to the origins of CMEs. CMEs represent important disruptions of large-scale structures of closed magnetic fields in the corona, and result in significant disturbances of the interplanetary medium and near-Earth space. The program pertained to NASA's objectives of understanding the physics of solar activity and the structure and evolution of the corona, and the results are being applied to understanding CMEs currently being observed by SOHO near the sun and by WIND and Ulysses in the heliosphere.

Three general areas of research were pursued in the program. One was to use Yohkoh soft X-ray telescope (SXT) images of eruptive events visible against the solar disk to examine the coronal structures and the boundaries of the large-scale magnetic fields considered to be involved in coronal mass ejections (CMEs). The second area involved a survey and study of SXT X-ray arcade events which exhibit dimming, or the possible depletion of coronal material above and possibly before onset of the bright long-duration event (LDE). Finally, we studied the SXT data during periods when white light CMEs were observed the HAO Mauna Loa K-coronameter and, conversely, we examined the white light data during periods when expanding X-ray loops were observed at the limb.

The results from each of these studies were presented to the scientific community primarily in three papers and in 7 presentations at scientific meetings. These publications and presentations are listed in Section 3 and copies of the papers are presented as Section 4. In the next section we briefly summarize the main results of the work on the grant.

2.0 SUMMARY OF RESEARCH RESULTS

2.1 Study of X-ray Eruptive Events as Disk Proxies of CMEs

To study the coronal structures and the boundaries of the global magnetic fields involved in CMEs, we selected large-scale Yohkoh eruptive events which we considered to be good solar

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4.2: Hudson, H.S. and D.F. Webb, "Soft X-ray signatures of coronal ejections", in Coronal Mass Ejections, N. Crooker et al., eds., Geophys. Monograph, Vol. 99, AGU, Washington, D.C., 1997.

4.3: Webb, D.F., S.W. Kahler, P.S. McIntosh, and J.A. Klimchuk, "Large-scale structures and multiple neutral lines associated with CMEs", J. Geophys. Res. (in press) 1997.

disk proxies of CMEs. This was necessary both because the coronal and magnetic field structures are best studied on the disk and, until SOHO began acquiring data in 1996, there were no spaceborne white light CME data available during the Yohkoh mission. These X-ray events were well onto the disk, were of long duration (≥ 4 hrs.), were associated with large disappearing filaments, and had bright bar- or cusplike features atop the arcades. Then we determined the locations of these events in the context of large-scale magnetic field patterns delineated by surface polarity patterns and inversion lines. Full-disk and 27-day synoptic neutral line maps of these patterns and their evolution were produced by our collaborator P. McIntosh. The daily full-disk maps were derived from the 27-day maps and scaled to match the disk size and time of the selected Yohkoh event.

We began with a list of about 100 events and studied 5 in detail. We found that the transient X-ray structures spanned distances across the solar surface ranging from 35 to >100° comparable to the spans of white light CMEs at the limb, and their durations ranged from 7 hours to 1.5 days. Filament disappearances were associated with 3 of the X-ray events, and transient coronal holes occurred during all five events. The widths of the coronal loop arcades spanned 2 or 3 neutral lines, or a single, highly convoluted neutral line. We concluded that multipolar magnetic systems are a common configuration of the source fields of many CMEs, contrary to the first-order approximation that CMEs involve the eruption of simple, bipolar structures. Another collaborator, J. Klimchuk, helped to analyze the Yohkoh data and compare the results with other models involving the origin of CMEs. These results are described in the paper by Webb et al. in Section 4.3.

2.2 Coronal Dimming Associated With X-ray Arcade Events

The identification of observational signatures of the opening of previously closed magnetic field lines involved in some models of CMEs has proven elusive. We performed two studies involving Yohkoh/SXT observations of X-ray transient structures of possible signatures of CME onset. The first was a survey and study of large-scale X-ray arcade events which exhibit dimming in association with bright long-duration events. The second was a survey and study examining SXT data during periods when CMEs were observed by the HAO K-coronameter and, conversely, we examined the white light data during periods when expanding X-ray loops were observed at the limb.

We found ~30 examples of arcade events displaying dimming of the corona above or around the bright LDE. We classified the dimming events four groups: 1) Dimming above a limb LDE; 2) Rapid disappearance on the disk of a large cloud adjacent to a flare/LDE; 3) Dimming surrounding or ahead of expanding helmet structures at the limb; and 4) Transient coronal holes seen on the disk. The dimmings can be rather amorphous and unstructured or structured material outflow. Class 2 and 3 events may represent different views of "streamer blowout" CMEs seen in white light.

In the second study we searched for what kind of transient X-ray features might be associated with the onsets of MLO CMEs. First, we examined the SXT data near the limb locations before and during periods when MLO CMEs were observed. Nearly 2/3 of those CMEs were associated with a transient X-ray structure, usually a loop, and most of these loops had a foot in a flaring active region. Second, we compared the list of expanding X-ray SXT loops observed at the limb during MLO observing periods compiled by *Klimchuk et al. [1994]* with MLO CMEs. We found that only 15% (4 of 27) of these loop events were assoc. with reported MLO CMEs.

Overall these results better elucidate the physical interpretation of CME onsets. Under the CME one often finds a brightening and expanding X-ray structure, typically looplike, with one end embedded in a flaring AR. However, there are many such expanding loops which are not associated with CMEs. X-ray dimmings, which we interpret as the expansion and opening of magnetic field lines during CME onset, often move out ahead of the LDE or appear before the main brightening. Thus, these depletions may be the first direct signature of the CME in soft X-rays. These results are described in the papers by Hudson et al. (1996) and Hudson and Webb (1997) in Sections 4.1 and 4.2, respectively.

3. PUBLICATIONS AND PRESENTATIONS

3.1 Publications

Hudson, H.S., J.R. Lemen and D.F. Webb, "Coronal dimming in two limb flares", in Magnetic Reconnection in the Solar Atmosphere, R.D. Bentley and J. T. Mariska, p. 379, eds., ASP Conf. Ser. 111, San Francisco, 1996.

Hudson, H.S. and D.F. Webb, "Soft X-ray signatures of coronal ejections", in Coronal Mass Ejections, N. Crooker et al., eds., Geophys. Monograph, Vol. 99, AGU, Washington, D.C., 1997.

Webb, D.F., S.W. Kahler, P.S. McIntosh, and J.A. Klimchuk, "Large-scale structures and multiple neutral lines associated with CMEs", J. Geophys. Res. (in press) 1997.

3.2 Presentations

Hudson, H.S., J.R. Lemen and D.F. Webb, "Coronal dimming in soft X-rays". Presented by Hudson at the Yohkoh Conference on Observations of Magnetic Reconnection in the Solar Atmosphere, Bath, UK, 20-22 March 1996.

Hudson, H.S. and D.F. Webb, "Yohkoh soft X-ray observations and the solar wind". EOS, 77, S209 (Abstract). Presented by Hudson at the Spring AGU Meeting, Baltimore, MD, 20-24 May 1996.

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Lemen, J.R., H. Hudson and D. Webb, "Observations of coronal depletion and ejection". BAAS, 28, 939 (Abstract). Presented by Lemen at the 188th AAS Meeting, Madison, WI, 9-13 June 1996.

Webb, D. and H. Hudson, "A signature of CME onsets in soft X-rays". BAAS, 28, 939 (Abstract). Presented by Webb at the 188th AAS Meeting, Madison, WI, 9-13 June 1996.

Webb, D.F. and H.S. Hudson, "Signatures of CME onsets in soft X-rays and white light". Conference Guide, p. 17 (Abstract). Presented by Webb at the Chapman Conference on Coronal Mass Ejections: Causes and Consequences, Bozeman, MT, 11-15 Aug. 1996.

Webb, D.F., H.S. Hudson, and R.A. Howard, "X-ray Signatures of CMEs Observed in White Light". EOS, 77, F563 (Abstract). Presented by Webb at the Fall AGU Meeting, San Francisco, 15-19 December 1996.

4.0 COPIES OF PUBLICATIONS

4.1 Hudson, H.S., J.R. Lemen and D.F. Webb, "Coronal dimming in two limb flares", in Magnetic Reconnection in the Solar Atmosphere, R.D. Bentley and J. T. Mariska, p. 379, eds., ASP Conf. Ser. 111, San Francisco, 1996.

4.2 Hudson, H.S. and D.F. Webb, "Soft X-ray signatures of coronal ejections", in Coronal Mass Ejections, N. Crooker et al., eds., Geophys. Monograph, Vol. 99, AGU, Washington, D.C., 1997.

4.3 Webb, D.F., S.W. Kahler, P.S. McIntosh, and J.A. Klimchuk, "Large-scale structures and multiple neutral lines associated with CMEs", J. Geophys. Res. (in press) 1997.

Coronal X-ray Dimming in Two Limb Flares

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Abstract. The *Yohkoh* SXT observations of flares and large-scale arcade events frequently show *coronal dimming* accompanying X-ray brightening in long-duration events. We tentatively identify this with the process of field-line opening in the initial phase of a coronal mass ejection (CME), although few simultaneous coronagraph and soft X-ray observations have yet been described. The dimming signature may reduce the coronal soft X-ray intensity by as much as a factor of 2-3, and thus has a higher contrast than the cavity often seen in white-light CME observations. In the cases examined thus far, we find a close match between the onsets of X-ray brightening and coronal dimming, suggesting a close physical relationship. The dimming appears (in movie representations) to result from outward expansion; highly structured features (multiple loops) are recognizable in the dimming regions of some events, suggesting that the soft X-ray data may be used to characterize the velocity field of the expansion.

1. Introduction

A coronal mass ejection should result in a "dimming" of the hot (X-ray) corona as a result of the expansion of coronal material. Such an effect would match the depletions observed in white light (e.g. Hansen et al. 1974), as well as the formation of a "transient coronal hole" as detected in Skylab X-ray (Rust 1983) and ground-based He 10830Å (Harvey et al. 1996)) observations. The *Yohkoh* SXT has observed coronal dimmings related to flares and to the formation of large arcades (Hudson 1996; Hudson et al. 1996). We briefly describe

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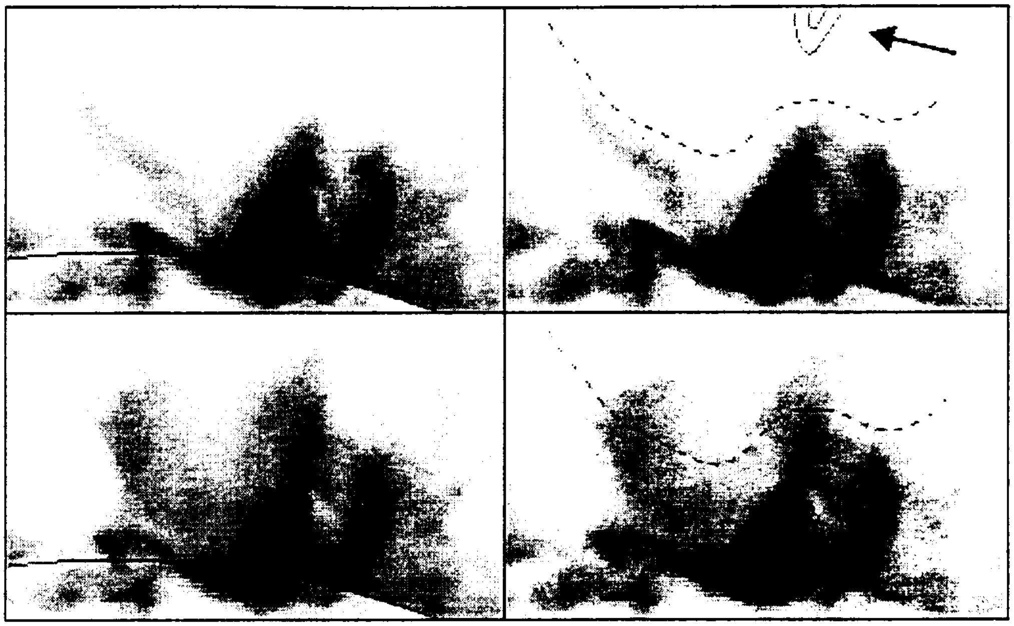

Figure 1. Dimming associated with the M3.2 flare of 21 February 1992. Upper images, 02:59 UT; lower images, 02:33 UT. The images on the right have a contour to show the location of the dimming. Note also the compact ejection indicated by the arrow. The images have been rotated so that the E limb is up, north to the right.

two of the flare-related events here. Unfortunately we have no coronagraph observations at these times.

Both of these events occurred near the limb, where the geometry favors an SXT detection of dimming in the corona above the flare. Other flare or arcade events may show dimming at different locations (e.g. the 24 January 1992 event described by Hiei et al, 1993; see Hudson, 1996, for a description of the dimming). Some events may not show significant dimming in spite of the probable occurrence of a coronal mass ejection (e.g. the 14 April 1994 event; Hudson et al. 1995; Alexander et al. 1996; McAllister et al. 1996). Generally speaking, we have no real knowledge of the relationship of the dimming signature to the structures seen by coronagraphs, but that situation may change rapidly with the exploitation of the Mauna Loa (e.g. Sime et al., 1994) and SOHO observations.

2. Flare-Associated Dimmings

The two dimming events we discuss here appear to have been similar. Figure 1 shows the well-studied 21 February 1992 flare, a limb arcade seen roughly perpendicular to its axis (see Tsuneta et al. 1992 for an introduction, Tsuneta 1996 for a mention of the dimming, and Lemen et al. 1996 for an estimation of the

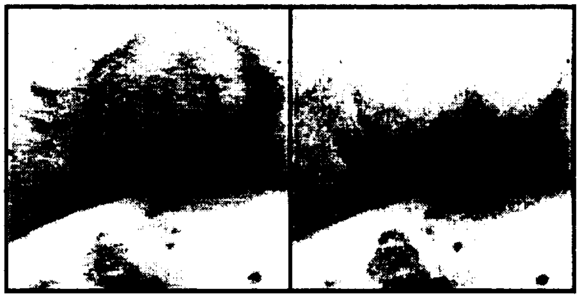

Figure 2. Images of the 28 August 1992 flare at 21:34 UT (left) and 22:16 UT (right), showing the dimming above the bright flare structure. Note the filamentary structure in the dimming region, which appeared to enclose an erupting prominence (Watanabe et al., personal communication). This structure moved outwards systematically during the dimming. The images have been rotated so that the E limb is up, north to the right.

mass loss). Figure 2 shows an approximately side-on arcade event of 28 August 1992, also described by Hudson and Khan in these proceedings.

The general pattern of dimming in these two events was the same: a large volume of the corona above the flare began to disappear as the brightening developed. The flare loops subsequently grew into the regions of the dimming. In both events the dimming motion could be recognized as an outward flow in a movie representation, and in the 28 August 1992 event this outward motion contained a sparse filamentary structure that indicated a general outward flow (Hudson and Khan, these proceedings). The dimming occurred at the onset of each brightening, consistent with the a CME launch prior to the peak soft X-ray brightness of the flare (e.g. Hundhausen, 1996).

Lemen et al. (1996) have estimated the X-ray-emitting mass ejected in the 21 February 1992 flare at about 3×10^{14} g, comparable to the mass of a small coronal mass ejection, and consistent with that reported by Hudson et al. (1996) for a different event. The close similarity of the two limb flares reported here implies a comparable mass for the 28 August 1992 event.

3. Conclusions

We have described two flare-related coronal dimmings detected by the *Yohkoh* SXT, both associated with long-duration flares and therefore probably with coronal mass ejections. The dimming phenomenon thus represents one of the ways in which a CME launch may be studied via the use of soft X-ray imaging. The mass estimates suggest that these dimmings did correspond to coronal mass ejections, although no coronagraph data were available in either case to confirm this. What does the dimming volume correspond to in terms of the familiar CME structure of front, cavity, and filament? We suggest the cavity as the most likely identification, but note that the dimmed region in these events is *bright* prior to the dimming in soft X-rays, rather than *faint* as in optical wavelengths.

In both of these cases all detected motions were outwards, roughly radially away from the flare brightening. We do not know at present if this is also the pattern of other types of dimming events.

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SOFT X-RAY SIGNATURES OF CORONAL EJECTIONS

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Abstract

We have a new view of the time behavior of the inner solar corona via the extensive soft X-ray observations of *Yohkoh*. These show many forms of expansion of coronal material, ranging from highly collimated structures (jets) to large-scale evacuations ("dimmings") of the diffuse corona. We review these effects, emphasizing those probably related to CMEs, and present a preliminary classification scheme of the large-scale ejections seen in soft X-rays. The new observations bring clarity and focus to the well-established scenario of filament channel → CME → X-ray arcade. The associated X-ray brightening typically occurs in a close temporal relationship with the ejection as inferred from the dimming, but the location of the ejected mass may be displaced from the region of strongest brightening. The soft X-ray observations thus far have shown no clear example of the familiar three-part structure of CMEs as seen in white-light coronal images.

1. INTRODUCTION

The solar wind and disturbances within it originate in the solar corona. This paper reviews the recent increases in our knowledge of this region of space, emphasizing the new views of coronal transient phenomena made possible by the Soft X-ray Telescope (SXT) on *Yohkoh*. The coronal mass ejections (CMEs) constitute the largest and most energetic of these transient events. In our usage "coronal mass ejection" refers to the phenomena seen with a white-light coronal imaging instrument [*e.g.*, ***Hundhausen***, 1996].

The soft X-ray view of the solar corona differs substantially from the familiar view provided by white-light imagers. We therefore begin this review by discussing the differences. We then list various kinds of soft X-ray disturbances interpreted as ejecta, and conclude by describing the X-ray phenomena we believe to be most directly associated with the CME phenomenon. The original soft X-ray imaging observations from *Skylab* (see *Sturrock* [1980]) showed some of the same phenomena seen by *Yohkoh*, but not in such detail: see for example *Kahler* [1992] or *Webb* [1992] for reviews of the earlier data on CMEs.

The work of identifying X-ray coronal features with coronal mass ejections remains in its early stages. An initial survey of the *Yohkoh* data [*Klimchuk et al.*, 1994] showed that many X-ray eruptive events could be observed above the limb, like the *Skylab* event of *Rust and Hildner* [1978]. *Hiei et al.* [1993] described an X-ray "streamer re-formation" event that almost certainly involved a CME, and *Sime et al.* [1994] gave preliminary comparisons of two events observed by the HAO Mauna Loa K-coronameter with *Yohkoh* observations. Beyond this, the current literature presents few examples of approximately simultaneous white-light and X-ray observations. There are several reports of associations between coronal X-ray events and either interplanetary observations or non-simultaneous coronagraph observations [*Lemen et al.*, 1996; *McAllister et al.*, 1996a; *Weiss et al.* 1996]. Data from the K-coronameter at Mauna Loa Solar Observatory and from the coronal instruments on board SOHO are already changing this situation. Because of the rapid pace of observational work, we have tried to include some literature published after 1996 (the Chapman Conference on CMEs), and to incorporate ideas from these observations in the discussion.

Finally, we note that CMEs play an important role in stimulating geomagnetic activity [*Gosling*, 1991; *Webb*, 1995]. *Hudson* [1997] has recently reviewed some of the same material presented here but with an emphasis on the application of the solar observations to geomagnetic storms. That paper presents some additional data, including a list of dimming events (see below) observed prior to 1996.

2. THE X-RAY VIEW OF THE CORONA

We normally image the solar corona in white light or in the coronal emission lines in the visible range. This can be done during eclipses or via coronagraphs, but the brightness of the solar disk restricts the observations to the region above the solar limb. To see the corona against the disk requires going to long (radio) or short (X-ray) wavelengths to reduce the photospheric competition. The lower temperature of the visible photosphere makes it appear dark in X-rays; at radio wavelengths the height of optical depth unity rises far up into the corona, so again the photosphere becomes invisible. Because most of the corona is hot, it has the highest contrast in EUV and soft X-radiation. For general information please refer to standard monographs, *e.g.*, *Kundu* [1964] or *Zirin* [1988]. In this section we briefly summarize coronal morphology as seen in soft X-rays, then make some comments about the specific limitations of the X-ray observations, with emphasis upon the *Yohkoh* soft X-ray telescope.

The X-ray spectrum of hot plasma consists of the emission lines and continua of highly ionized atoms and, at typical coronal temperatures (*i.e.*, 1-3 $\times$ 10^6 K, or below the temperatures achieved by flares), the emission lines dominate energetically. The complicated structure we see in the lower solar atmosphere in an X-ray image is defined by small-scale magnetic fields. These simplify with height and eventually map into the solar-wind flow, which has a predominantly bidirectional magnetic structure (with inward-pointing and outward-pointing sectors) dominated by the flow itself. Most of the magnetic field lines extending into the heliosphere originate in coronal holes, which thus provide the sources of the high-speed solar wind. Other areas of "open" magnetic fields (defined as field lines that extend beyond the Alfvénic critical point of the outward flow) exist elsewhere, for example in the hearts of active regions as evidenced by the occurrence of Type III radio bursts with high starting frequencies. The larger open-field regions are dark as viewed with a soft X-ray telescope. The slow component of the solar wind is less well understood, but probably originates in or near large closed-field regions of the solar atmosphere at lower latitudes [*e.g.*, *Withbroe et al.*, 1991].

In addition to the quasi-steady structure of the X-ray corona, there are transient events of many kinds. These usually take the form of injections of mass into apparently stable magnetic loop structures (microflares, flares, arcade events). Ejective events, well-observed in the sense that successive images actually show the motion of the structure, frequently occur, most often in association with flare-like brightenings. The ejected mass, along with its frozen-in magnetic fields, may become a part of the outward flow into the solar wind [*Uchida et al.*, 1992]. The soft X-ray emission rapidly drops with height, however, so that identifying soft X-ray ejecta with solar-wind features requires some interpolation.

Because in soft X-rays we see the general corona and transient features such as ejections, we have the possibility of observing CMEs directly in emission as they actually start. The *Yohkoh* observations represent the first soft X-ray imaging data suitable for these purposes since the *Skylab* obervations. *Yohkoh* began observations in September, 1991. A comparison of these improved X-ray data with those in white light (or other wavelengths), at the times of CME launches, should have high priority.

There are several substantial differences between soft X-ray observations of the *Yohkoh* type, and white-light observations. Most of our knowledge of CMEs comes from the white-light data, so it is important to understand the differences in the data reported here. The X-ray images show the entire Earth-facing hemisphere, offer a better view near the surface of the Sun, and provide some information on temperatures and densities. The fields of view are typically different, with a coronagraph viewing structures higher up in the corona ($\geq 1.2 R_S$ projected height) compared to those viewed near the surface ($\leq 1.5 R_S$) in X-rays. Another difference between the white light and X-ray observations is that of their line-of-sight dependences. The white light emission arises from Thomson scattering of photospheric radiation, but the X-ray emission arises directly from the emission of the hot coronal gas; X-radiation is isotropic and not concentrated in the plane of the sky. X-rays thus let us see the source of the emission against the disk and so determine the heliographic coordinates of any discrete source.

The white-light brightness (K-corona) varies in proportion to the electron density, and does not depend on the temperature. In contrast, the X-ray emission is a complicated function of density (approximately the square) and the temperature. For the thinnest *Skylab* X-ray filter, for example, *Kahler* [1976] found the signal to depend on the square of the electron pressure. The SXT signal S has a stronger dependence on temperature T ($d(\ln S)/d(\ln T) \sim 2\text{-}6$) than did *Skylab* and is biased towards shorter wavelengths. These different instrumental dependences mean that similar coronal features may look quite different when viewed in X-ray or white-light emissions.

Tsuneta et al. [1991] give a full description of the *Yohkoh* SXT instrument, which uses a grazing-incidence mirror, a set of broad-band filters sensitive in the range 0.3 - 3 keV (4 - 40 Å), and a CCD sensor with 1024×1024 pixels $2.45''$ square (see *Acton et al.* [1992] for an survey of the data). The telemetry capacity of *Yohkoh* allows the transmission of about 21 whole-Sun images, with 2×2-pixel summations ($\sim 5''$) per 97-minute orbital period of the spacecraft. The *Yohkoh* SXT provides a global view of the corona within its total field of view, which is a square 0.70° across. A flare mode is normally triggered at about the GOES C2 level, some 2×10^{-3} ergs(cm^{2}sec)$^{-1}$ in the 2–8 Å (1.5-4 keV) band. This results in the loss of full-Sun imaging for an extended interval, in exchange for more telemetry devoted to high-resolution observations of the flare itself, with a maximum field of view $10'$ square. The optical axis of the telescope is almost always pointed so that the entire disk is visible, except during special operations.

3. SXT OBSERVATIONS OF SOLAR MASS LOSS

The *Skylab*, Solwind *P78-1*, and *Solar Maximum Mission* observations generally showed a complicated relationship between the white-light CMEs they observed and the soft X-ray corona as inferred from the GOES photometry [*e.g.*, *Kahler et al.*, 1992]. This situation could be attributable to poor temporal data coverage in the coronagraphs, to poor GOES X-ray sensitivity to the main bulk of the ejected coronal material, or of course to a weak physical relationship. With the improved data cadence and sensitivity of the *Yohkoh* X-ray images we hoped to find consistent signatures of CMEs in the low corona [*e.g.*, *Klimchuk et al.*, 1994]. This turned out not to be so simple: some of the CME motions may be observed directly in X-rays, but the morphology can also be different. *Yohkoh* detects some kinds of coronal mass ejection not resembling CMEs at all. We summarize the ejection events in different categories below. While the categories may overlap, there are clearly different physical effects at work, as distinguished by the direction (parallel or perpendicular to the field) and speed of the motion. Parallel flows much slower than the Alfvén speed are common, suggesting hydrodynamic driving, while perpendicular flows provide good evidence for magnetic driving. Following this list we discuss "dimming", which we think of as one of the best soft X-ray signatures of the onset of a CME, in a separate section.

3.1 Expanding active-region loops

One of the first discoveries in the new X-ray data was the tendency for some active-region loops to expand at intermediate speeds (10-50 km s^{-1}), rather than remain static [*Uchida et al.*, 1992]. This observation suggests that magnetically-driven outward flows from active regions may contribute to the global coronal structure or even to the slow, dense component of the solar wind [e.g., *Hick et al.*, 1995]. Such a mechanism may also be of general interest for stellar mass loss.

3.2 Soft X-ray jets

Highly collimated jets, of various types, occur frequently in the *Yohkoh* soft X-ray observations [*Shibata et al.*, 1992; *Strong et al.*, 1992]. These appear to be essentially hydrodynamically driven flows along the large-scale magnetic field, and are strongly linked to flare-like effects near their feet. *Yokoyama and Shibata* [1995] suggest magnetic reconnection in an emerging-flux scenario as the key physical mechanism.

We believe that at least some of the magnetic fields involved are unipolar and open to the heliosphere because of the identification of the jets with meter-wave Type III bursts [*Aurass et al.*, 1994; *Kundu et al.*, 1995; *Raulin et al.*, 1996]. Closed-field structures also support similar behavior, including meter-wave U-bursts [*Pick et al.*, 1994], "two-sided loop jets" [*Shimojo et al.*, 1996], and jets that re-enter the chromosphere at large (0.5 solar radii) distances from their point of origin [*Strong et al.*, 1992].

3.3 Flare ejecta

Direct *Yohkoh* soft X-ray imaging of flares may show motion, mostly outwards. These motions are distinguishable (as image displacements) from the presumably field-aligned flows associated with "evaporation" detected mainly in soft X-ray emission-line blue shifts [*e.g.*, *Acton et al.*, 1982]. Compact flare ejecta range from the relatively slow (<500 km s^{-1}) outward motion of compact blobs, to faster outward motions during some flares (>500 km s^{-1}). The flare-related flows [*Shibata et al.*, 1995] in the soft X-ray observations may take various forms, as do those at lower temperatures (surges and sprays). We distinguish these from jets (above) but do not really know yet whether this distinction is physically justified. Certainly, many flare ejecta are not jet-like from the point of view of collimation and velocity.

3.4 CME-like ejecta at the limb

Klimchuk et al. [1994], in an early study of the *Yohkoh* data based upon the standard movie images, found expanding features at the limb which had similar parameters (widths, speeds and occurrence rates) as those of CMEs observed in coronagraphs (see also *Sime et al.* [1994]; *Hundhausen* [1996]). Recently *Gopalswamy et al.* [1996] have described *Yohkoh* observations of a slow ejection at the limb on 10-11 July 1993 that appeared to incorporate the three elements of a "classic" CME – front, cavity and embedded filament. In this case the filament was well-observed with the Nobeyama 17 GHz radioheliograph, and the front clearly was a slowly-rising magnetic structure. The mass of this event was estimated as 1.2 $\times 10^{14}$ g. at the low end of the range of masses of white-light CMEs [*Hundhausen et al.*, 1994], but not very different from the mass found by *Hudson et al.* [1996b] for a different *Yohkoh* SXT mass-ejection event. It has not yet been possible to do a thorough calibration of the *Yohkoh* data set against coronagraph data, but there are many common event periods with the Mauna Loa K-coronameter observations (*A. Hundhausen*, personal communication 1995; also see below).

3.5 Filament eruptions

The behavior of Hα filaments has always provided one of the best guides to the occurrence of a solar eruptive event (the *disparition brusque*). *Skylab* data showed the X-ray coronal structure of the channel in which the filament forms and the bright, long-duration loop arcade which appears late in the event. The new X-ray data show many beautiful examples of arcades of this type [*Alexander et al.*, 1994; *Hanaoka et al.*, 1994; *Khan et al.*, 1994; *Lemen et al.*, 1996; *McAllister et al.*, 1992; 1996a; *Tsuneta et al.*, 1992; *Watanabe et al.*, 1992; 1994; *Watari et al.*, 1996]; these observations are bringing the puzzling relationship between the filament and the CME into sharper focus. The sense of chirality of the filament, in such cases, appears to be related to that of the magnetic cloud resulting from the eruption [*Bothmer and Schwenn*, 1994; *Rust*, 1994; *Bothmer and Rust*, this volume]. An important new link in this chain is presented by *Martin and McAllister* [this volume]: the chirality of an erupting filament bears a fixed relationship to the skew of the resulting X-ray arcade. These insights offer encouragement that the pre-event coronal configuration can eventually be linked to the geoeffectiveness of the event, since this depends upon the field orientation and flow properties.

4. THE "DIMMING SIGNATURE"

At times and locations expected for CME launches, *i.e.* near an LDE flare or large arcade event, a large volume of the soft X-ray corona may rapidly become significantly dimmer. Coronal depletions were first described using HAO K-coronameter data by *Hansen et al.* [1974], and corresponding X-ray effects (in the *Skylab* data) by *Rust and Hildner* [1978]. *Rust* [1983] describes the dimming effect as viewed against the disk as a "transient coronal hole". The *Skylab* observations, however, were limited in sampling and photometry and not well optimized for detecting such effects. The *Yohkoh* SXT data also have sampling limitations; with more frequent images and better image dynamic range the velocity field could have been measured more easily. The new results are nevertheless extensive, and will be described in more detail below.

In some of the cases studied thus far, the dimming appears to be amorphous and unstructured. It results in a decrease of the coronal surface brightness directly above the accompanying brightening. In other cases a structured mass flows outward from the region that dims. The dimming or outward mass flow can occur either above or near the brightening, or can be widespread in the vicinity of the brightening. *Hudson et al.* [1996b] point out that the radiative cooling time for such temperatures and spatial scales greatly exceeds the characteristic time scale of the dimming, consistent with the interpretation in terms of material ejection, assuming unity filling factor in the estimate of source volume or density. The strong temperature dependence of the soft X-ray signal noted above suggests that adiabatic cooling upon expansion will result in a rapid brightness decrease with height, as is observed during the outward motion.

Large-scale clouds adjacent to the sites of solar flares have been directly observed to move outwards and disappear during the flare brightening. Large-scale X-ray clouds were also observed during Skylab, but not to disappear rapidly [*Rust and Webb*, 1978]. In the best-studied SXT event, on 13 November 1994, the coronal cloud moved outward in a direction consistent with radial and a projected (constant) velocity consistent with the range expected from a CME [*Hudson et al.*, 1996b]. Other excellent examples of disappearing clouds are the events on 27 February 1994 and 6 February 1995. Some large-scale flare ejecta [*e.g.*, *Manoharan et al.*, 1996; R. L. Moore *et al.* (poster paper, Chapman Conference on CMEs, 1996)] show two-lobed structures in the pattern described by *Moore and LaBonte* [1979], strongly suggesting non-vertical motions. In many of these cases the outward motion takes the form of a succession of large-scale loops, each physically moving outwards as established by the image continuity from frame to frame.

The first *Yohkoh* SXT event directly associated with white light observations, on 23-24 January 1992, consisted of a streamer disruption followed by a re-formation observed by the Mauna Loa K-coronameter [*Hiei et al.*, 1993]. This event also provides an excellent example of coronal dimming [*Hudson*, 1996], allowing a determination of the probable time of the CME launch (the bulk of the dimming occurred between 08:00 and 11:00 UT, consistent with the non-observation of a CME at Mauna Loa because of local night). The event occurred just at the limb, and the coronal dimming occurred both above the location of the arcade formation and to either side. The dimming region thus appeared to envelop the region that brightened. In some other large arcade events, the standard *Yohkoh* movie clearly shows the dimming to occur on a large scale. The event of 24 February 1993, for example, appears to unmask a large region of the south polar coronal hole and also to be in the "enveloping" category (see below) [*Harvey et al.* 1996]. However, dimming is not obvious in all large X-ray events.

We can measure the mass of such a dimming region, especially if it has the form of a discrete cloud. For the ejected cloud of 13 November 1994, we derive a lower limit of 4×10^{14}g. Only a lower limit is possible because of confusion with the brighter parts of the flare, the lack of complete knowledge of the differential emission-measure distribution, and the theoretical problem of estimating any replenishing mass coming from the deeper atmosphere. This latter difficulty results from the continuous nature of the outward flow during the interval of flare brightening, and from the contrast problem (the difficulty of detecting faint features near bright ones). For the 24 January 1992 large-scale event, a rough mass estimate is about 10^{15}g. These estimates are consistent with the range of white light CME masses, which are 10^{14} to 10^{16} g [*Hundhausen et al.*, 1994].

For events in which we can see the ejected cloud of material actually departing from the low corona (*e.g.*, on 21 February 1992, 28 August 1992, 27 February 1994 and 13 November 1994) we can in principle determine the flow field of the ejected material. Difference images show that the flow tends to be everywhere outwards, with no obvious trace of the inward flow that might be expected if large-scale magnetic reconnection were the source of the flare energy [*Hudson et al.*, 1996c]. T. Watanabe *et al.* (poster paper, Chapman Conference on CMEs, 1996) presented an Hα image of the 28 August 1992 event locating an erupting filament within the X-ray cloud whose outward motion constitutes the dimming. This suggests an identification of the X-ray dimming volume with the void component of the classical 3-part visible CME.

5. CLASSIFICATION OF X-RAY DIMMING SIGNATURES

The X-ray dimming phenomena most probably associated with CME launching have a variety of morphological properties. We discuss here a preliminary classification scheme for such events, with main emphasis on the description of the dimming signature. The formation of a long-enduring arcade of hot loops occurs in each case; statistically such long-duration X-ray events are well associated with white-light CME occurrence [*e.g.*, *Sheeley et al.*, 1983]. The dimming signature is of fundamental importance because it probably represents at least some of the expelled mass of the CME itself. Not all arcade events with filament eruptions or other good CME proxy signatures show clear dimming signatures. We do not know at present if this is due to the detection biases intrinsic to the X-ray observations, but we suspect so and suggest that appropriate coronal observations will always show a depletion or dimming of the corona at the time of a CME. Figures 1-4 shows representative examples of each of the four types of dimming event.

Dimming above an LDE flare (Figure 1). There are several examples of events in which the dimming signature appears over a well-defined volume *above* the arcade that is forming: 21 February 1992 [*Tsuneta*, 1996] and 28 August 1992 are the prototype events *Hudson et al.* [1996c]. Such events must be observed at the limb.

Cloud ejections (Figure 2). In other flare-associated events, a well-defined X-ray coronal cloud adjacent to the flare moves away from the flare region and disappears. Events in this category include 27 February 1994 [*Hudson et al.*, 1996a] and 13 November 1994 [*Hudson et al.*, 1996b]. The observations suggest a large-scale twist (approximately one turn) in each cloud. The double-lobed ejecta of the 25 October 1994 event [*Manohoran et al.*, 1996] may also fit in this category.

Enveloping dimmings (Figure 3). We identify these as "streamer blowout" CME events seen in white light [*Howard et al.* 1985; *Hundhausen*, 1993]. The classic example of this in the *Yohkoh* data is the event of 24 January 1992 [*Hiei et al.*, 1993; *Hudson*, 1996].

Transient coronal holes (Figure 4). The diffuse corona near an arcade development on the disk occasionally dims at or near the time of the X-ray brightening, strongly suggesting the formation of a new area of open field lines. These areas are not permanent, gradually filling in after several hours or a day or so. The term "coronal hole" is used because in X-rays the brightness of these areas can decrease to approximately the level of the larger and more permanent coronal holes.

6. ASSOCIATION OF X-RAY AND WHITE-LIGHT SIGNATURES

The comparison of the new X-ray signatures of coronal ejections must be understood in the context of white-light coronagraph data. Since the demise of SMM in late 1989 there have been no spaceborne coronagraph instruments, until the current era of SOHO. Thus, during most of the lifetime (to date) of *Yohkoh*, white light CME observations were only available from the ground-based Mauna Loa K-coronameter with the usual problems of day/night cycles (a typical observing day of ~5 hr.) and weather (including the airborne dust effects of Mt. Pinatubo).

D. Webb and H. Hudson (poster paper, Chapman Conference on CMEs, 1996) reported on a preliminary examination of the SXT data for transient X-ray features (involving brightenings and outward motion) near the appropriate limb location occurring before and during periods when white light CMEs were observed at Mauna Loa. We found that nearly 2/3 of the CMEs were associated with a transient X-ray structure, usually a loop, and a majority of these loops had at least one foot in a flaring active region. Consistent with previous results, the X-ray feature typically did not lie symmetrically underneath the CME.

The other major new source of white-light data is the LASCO suite of instruments on SOHO. These data represent a significant advancement over previous white-light coronal observations [see *Howard et al.*, this volume]. Although LASCO observes transients resembling the classical events observed by the *Skylab*, SOLWIND and SMM coronagraphs, it has better sensitivity and a larger field of view than these instruments, enabling it to observe other kinds of outward flows that may also be identifiable in the soft X-ray observations. At this time, no study comparing flows or ejections observed by SOHO at visual wavelengths and by *Yohkoh* in soft X-rays has been carried out. However we have made preliminary surveys which show that there have been many events observed in common, both with LASCO (*C. St. Cyr*, private communication 1996) and also with other SOHO instruments.

7. TIMING AND CAUSALITY

The physical processes involved in launching a CME remain poorly understood, so the X-ray view of the behavior of the lower corona during well-defined CMEs is of great interest. In cases where a large-scale flow can actually be observed in soft X-rays, we can learn about the geometry of the ejection process and the origin of the ejected mass. Even in the more common cases where only a dimming of diffuse coronal material can be detected, the relative timing of the X-ray dimming signature and the X-ray brightening might point towards the direction of causality. Standard models of large-scale magnetic reconnection suggest that post-flare loop arcades might occur after some delay relative to the CME onset. This indeed appeared to be the case from earlier soft X-ray observations with less sensitivity than the *Yohkoh* observations, *e.g.*, *Hundhausen* [1996], but the *Yohkoh* observations indicate that the flare-related arcade brightening may occur with little or no delay [*Hudson*, 1997].

The filament eruption is well-known to begin, by activation including turbulent motion and a slow rise, well before the main part of the X-ray arcade development. Recent data confirm this pattern well (*Hanaoka et al.*, 1994; *Khan et al.*, 1994; *McAllister et al.*, 1996b]) and suggest that the main arcade development takes place when the filament has risen to about 10 times the width of the arcade.

The *Yohkoh* observations show a wide variety of soft X-ray loop arcades, extending this type of observation beyond that found with *Skylab* and *Solar Maximum Mission.* They confirm the *SMM* observation of "giant arches", which may be morphologically distinct from the post-flare loops [*Švestka et al.*, 1996]. Either kind of loop system - or perhaps both or neither - may be identifiable with the large-scale reconnection scenario (see *Tsuneta* [1996], for a positive view of such a picture, or *Hudson and Khan* [1997], for a skeptical view). *Klimchuk* [1996] comments on the absence of reconnection signatures in CME development, but *Kahler and Hundhausen* [1992] point out that the "legs" of CMEs may in fact consist of multiple cusp (bipolar) structures.

8. CONCLUSIONS

Soft X-ray imaging of the solar corona reveals several forms of mass ejecta, some of which are new with the *Yohkoh* SXT observations. Compared with the traditional coronagraph or K-coronameter observations, the *Yohkoh* data have better sensitivity and sampling, and view the entire visible hemisphere. Events probably associated with CMEs often show clearly measurable dimmings of the X-ray corona near the site of a flare or arcade brightening. We interpret the X-ray dimmings as the expansion and opening of magnetic field lines during the early phase of a CME. Transient coronal holes, dimmings seen against the disk, usually appear at the same time or later than the first arcade brightening and are skewed relative to its center, suggesting that they mark the evacuated feet of the flux ropes of the rising CME. In general the main arcade brightening follows the mass ejection and the impulsive phase of any associated flare ("impulsive" here means non-thermal energy release as detected in hard X-ray bremsstrahlung; *Hudson et al.* [1994] show that this occurs even in slowly-rising arcade events).

In some of the cases that have been studied, the *Yohkoh* SXT observations show details of the origin of the ejected material. For example, the 13 November 1994 cloud event has the appearance of a large structure with approximately one full twist ($\sim 2\pi$); the structure appears to be anchored at one end in a flaring active region [*Hudson et al.*, 1996b]. The 21 February 1992 event and others, on the contrary, appear to dim only above the developing arcade, even when viewed from apparently different perspectives relative to the arcade axis. Finally some of the large-scale arcade events appear to show large-scale dimming both at and remote from the arcade location. These different dimming signatures suggest that there may be a variety of physical processes involved.

The relationship between CMEs and flares or flare-like brightenings also does not seem now so simple as previously thought: it now appears in many cases that there is no appreciable delay between the launching of mass and the associated flare brightening [*e.g.*, *Hudson* 1997]. This is consistent with recent discussions of this relationship by *Feynman and Hundhausen* [1994] and *Harrison* [1995]. Our comparison of SXT and Mauna Loa data better elucidates the physical interpretation of CME onsets [Webb and Hudson, poster paper, Chapman Conference on CMEs, 1996]. Under the CME one can usually find a brightening and expanding X-ray structure, which is typically looplike with one end embedded in a flaring active region. On the other hand, such expanding loops are not usually associated with the Mauna Loa CMEs, despite having speeds, widths and occurrence rates similar to those of CMEs [*Klimchuk et al.*, 1994]. Thus, we conclude that the dimming effect seems a more consistent X-ray signature of CME *onset*, if not occurrence.

Do flares and CMEs divide naturally into two classes of events? We note that no single parameter of a solar flare or arcade disturbance has been reported to exhibit actual bimodality, *i.e.* a distribution function with two resolved maxima. All parameters seem to have broad or unimodal distributions, suggesting that flares and CMEs form a continuum with the same underlying physics. On the other hand several properties of the interplanetary counterparts of CMEs clearly have bimodality (see *Reames* [1994] and references therein).

Phenomena observable in the low corona, on the solar disk, in principle give us our earliest possible hint that a CME has been launched and might strike the Earth. We can hope that further understanding of these phenomena may even help us to predict the terrestrial consequences ("space weather"). Unfortunately we currently have no firm theoretical basis for such predictions, but we can hope that further empirical understanding will also help us to understand the basic physics.

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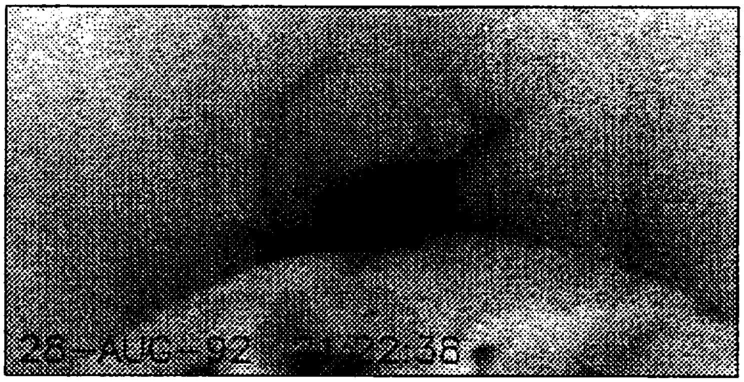
Figure 1. An "LDE flare dimming" in a limb event of 28 August 1992. This and the subsequent figures have reversed colors and have north at the top, west to the right. The top frames show the filamentary structure that had formed above the flare loops prior to the flare. This filamentary structure rises as the diffuse corona in the same region dims, almost simultaneously with the flare brightening. *Hudson and Khan* [1996] show difference images, demonstrating the outward motion of the filamentary structure. As mentioned in the text, these hot filaments appeared to wrap around a cool filament seen in Hα (*Ta. Watanabe*, personal communication)

Figure 2. A "cloud dimming" associated with the long-duration flare of 13 November 1994 [*Hudson et al.*, 1996b]. The flare proper is outside the field of view of the two images to the SW (lower right). Prior to the left image, the structure seen had been rising steadily as the flare brightened, and in the interval shown (about an hour) it disappeared almost completely except for the dimly-seen legs.

Figure 3. An "enveloping" dimming event, that of 24 January 1992 [*Hiei et al.*, 1993; *Hudson*, 1996]. The plot at the bottom shows light curves from two regions of the corona, one (*) to the S of the developing arcade, and one (+) at its brightest point at about 12:00 UT. The image at the top shows the difference of two images (14:33 minus 06:01), with the zero contour overlaid; the boxes show the locations integrated to generate the light curves. Note that the light curve from the cusp region shows an initial dimming, followed by an increase as the tip of the bright cusp enters the integration box. The voids left by the blowout are the regions S and N of the arcade, plus the areas at the top of the image on the disk.

Figure 4. Example of transient coronal holes. The image at left (16 January 1993, 12:46:23 UT) shows two regions (enclosed within dashed lines) that dimmed suddenly. These regions fit within the S-shaped bright structure that evolves with time to become the bright arcade seen at right (14:58:23 UT). The dimmed region does not quite reach the darkness level of the south polar hole.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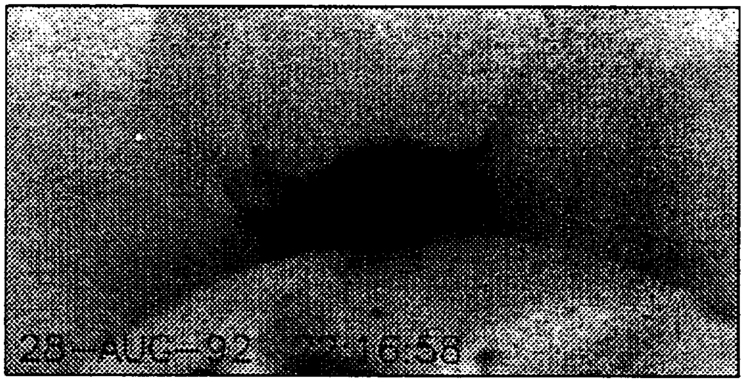
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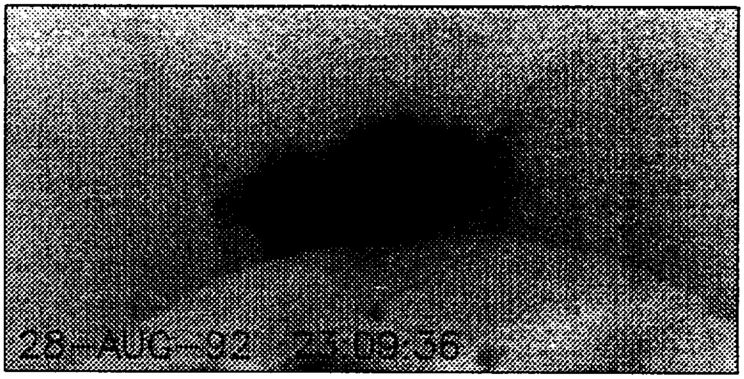
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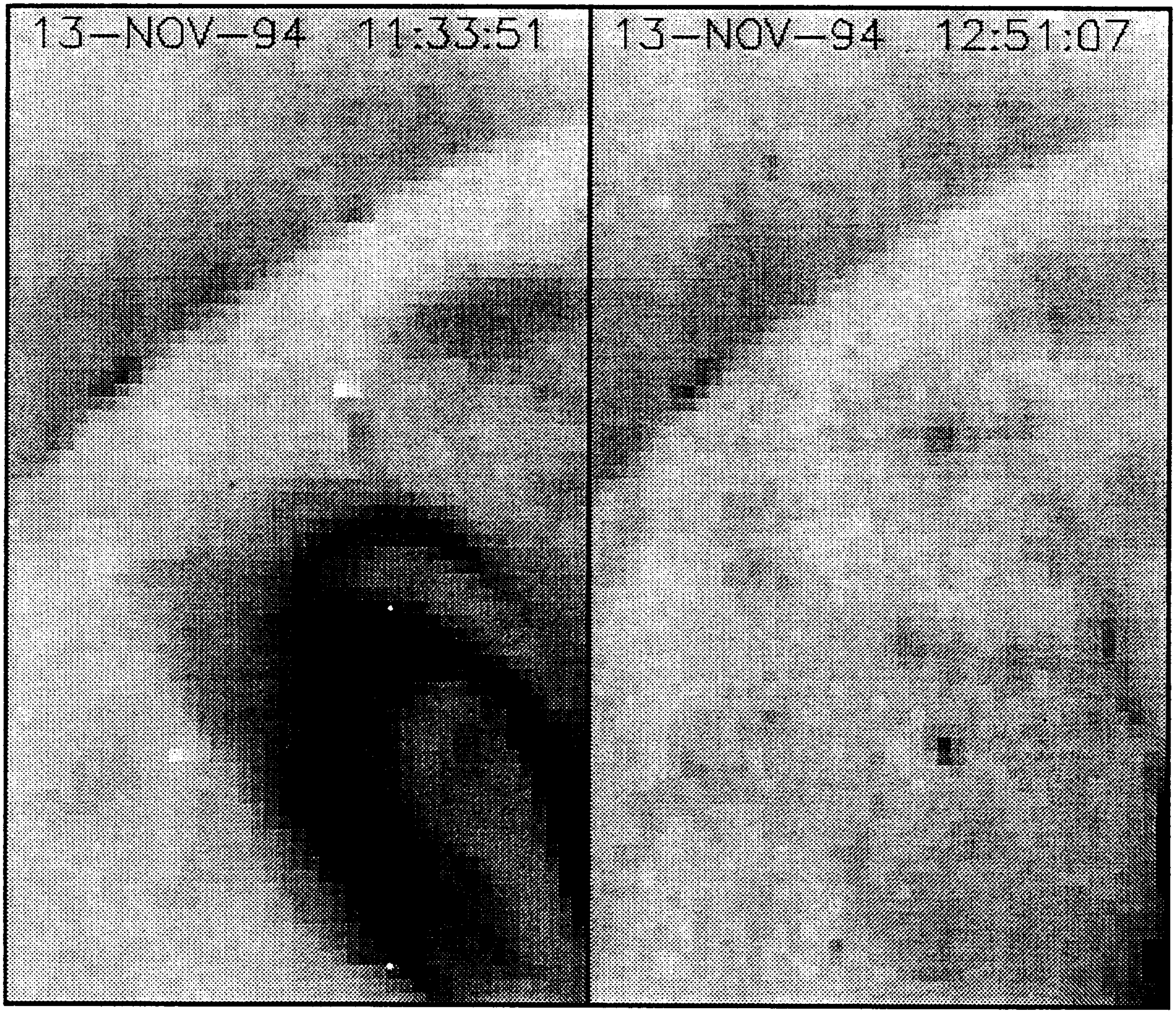
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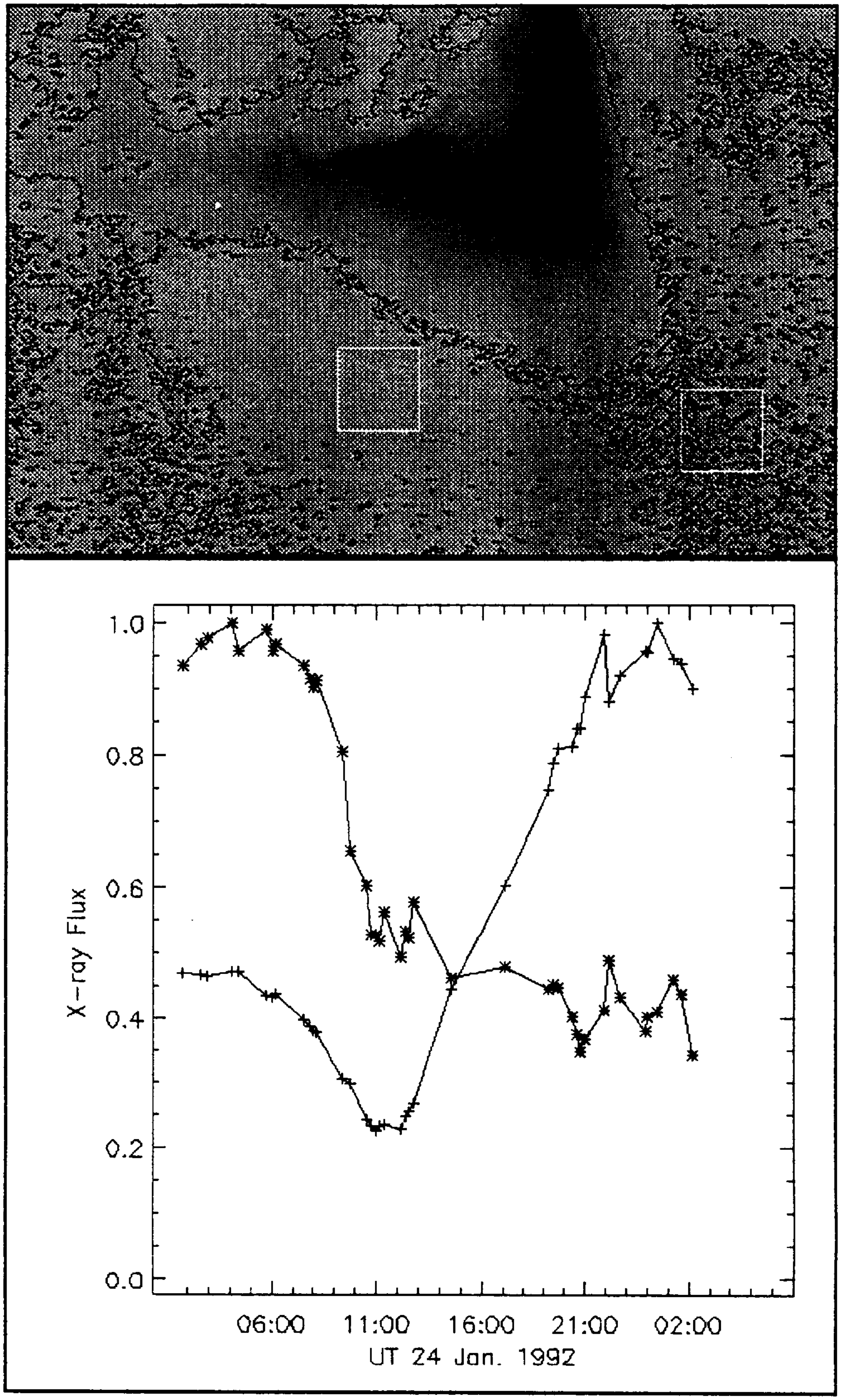
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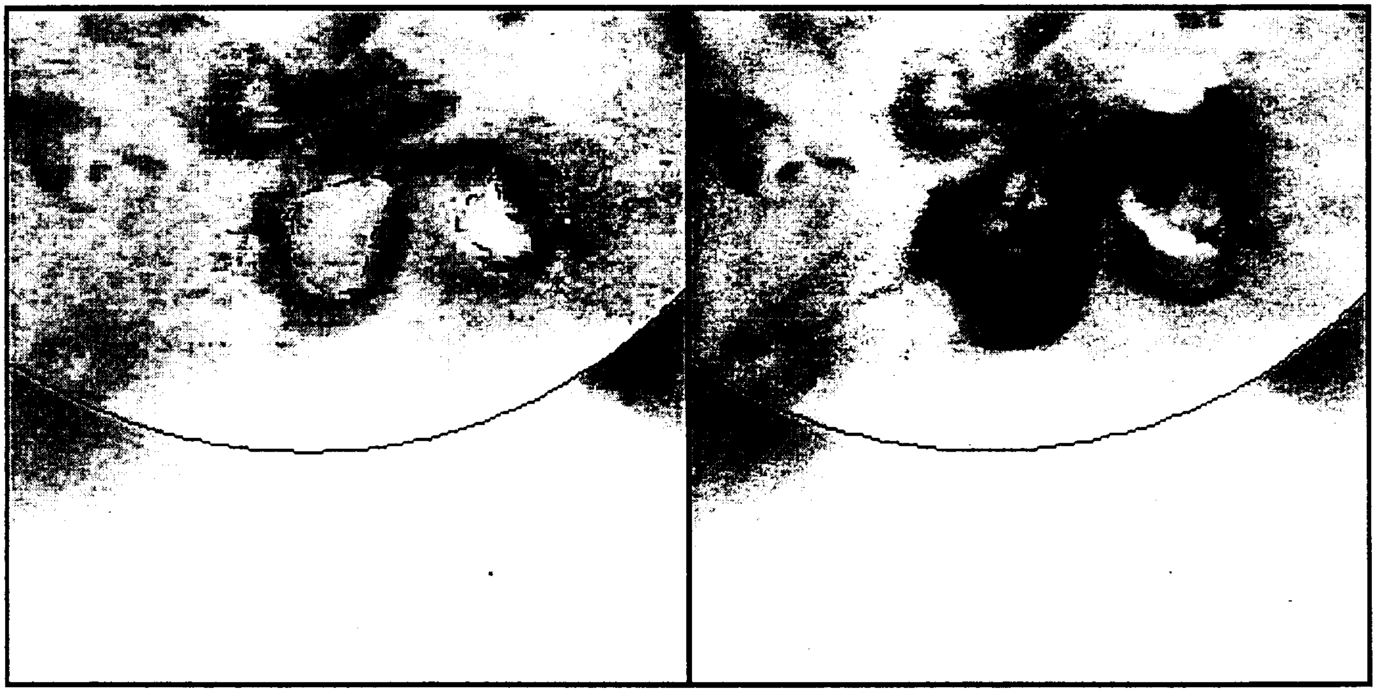

Large-scale structures and multiple neutral lines associated with coronal mass ejections

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Abstract

We use Yohkoh soft X-ray telescope (SXT) images of eruptive events visible against the solar disk to examine the coronal structures and the boundaries of the large-scale magnetic fields considered to be involved in coronal mass ejections (CMEs). From an initial list of about 100 large-scale events we selected five for detailed study. The transient X-ray structures in these events spanned distances across the solar surface ranging from 35 to >100 heliographic degrees, comparable to the spans of white light CMEs observed at the limb. The widths of the coronal loop arcades spanned two or three neutral lines, or a single, highly convoluted neutral line. Our interpretation of these results is that multipolar magnetic systems are a common configuration of the source fields of many CMEs, contrary to the first-order approximation that CMEs involve the eruption of simple, bipolar structures.

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1. Introduction

Coronal mass ejections (CMEs) are an important aspect of the evolution of the corona, involving the disruption of large structures of plasma and magnetic fields and their expulsion into the heliosphere. CMEs are also now considered the key causal link between solar activity and major transient interplanetary and geomagnetic disturbances [e.g., *Kahler*, 1992; *Gosling*, 1993; *Webb*, 1993]. The most energetic CMEs drive interplanetary shocks [*Cane et al.*, 1987] and the solar energetic particle events [*Kahler*, 1992] associated with major interplanetary disturbances and hazardous effects at Earth.

The activity near the solar surface with which CMEs are most commonly associated is erupting prominences [cf. *Webb*, 1992]. In X-ray images, erupting prominences are often associated with large-scale, long-duration events, originally called LDEs during the Skylab era [*Webb et al.*, 1976; *Kahler*, 1977]. Morphologically, these events consist of bright elongated arcades of coronal loops often topped by bar- or cusp-like features [e.g., *Watanabe et al.*, 1992; *Hiei et al.*, 1993; *Shibata*, 1996]. As viewed in white light by coronagraphs, the observed shapes of CMEs tend to be symmetrical and loop-like leading to the following concept. The "classic" CME is a three-part event consisting of a bright leading edge or shell, followed by a dark, low-density cavity and a bright core of denser material [*Illing and Hundhausen*, 1985]. In this picture the CME represents the symmetrical eruption of the coronal arcade and cavity and a prominence, respectively, overlying a single magnetic polarity inversion, or neutral, line. A prime example is the April 14, 1980, north polar CME, in which an erupting polar crown prominence lay symmetrically within the outer CME "loop" [see *Hundhausen*, 1988, Figure 1]. Most eruptive flare or CME models also assume a single, straight neutral line geometry as an initial condition for the eruption, which thus evolves from a simple bipolar field system. These include the reconnection-type models based on the *Kopp and Pneuman* [1976] erupting prominence model [e.g., *Forbes et al.*, 1989; *Svestka and Cliver*, 1992] and recent MHD simulations involving the dynamical evolution of 2.5-dimensional arcades [*Mikic and Linker*, 1994; *Wu et al.*, 1995].

As a first-order approximation to the real coronal topology the concept of a CME arising from the symmetrical eruption of coronal structures overlying a bipolar field system with a single, straight neutral line has been a useful tool. However, it is unlikely that this simple picture is correct in detail, at least for many CMEs. The following are some reasons that support this view. The average widths of white-light CMEs are ~45°, but some CME widths exceed 100° [*Howard et al.*, 1985; *Hundhausen*, 1993], much wider than active regions, flares or even prominences [cf. *Webb*, 1992]. Neutral lines associated with the CMEs can be found on photospheric magnetograms and, more clearly, on 27-day Hα synoptic maps [*McIntosh*, 1972, 1979; *McIntosh et al.*, 1991]. The synoptic maps are constructed by using daily Hα photographs of the sun to map filaments and chromospheric patterns that delineate lines of polarity inversion of the magnetic field and using daily He I 10830 Å spectroheliograms to map coronal holes. Each map exhibits the solar surface in cylindrical, heliographic coordinates and reveals patterns of polarity inversion lines mapped from filaments and filament channels, active region fibril patterns, plage corridors, and arch-filament systems. These features form continuous neutral lines of various lengths dividing opposite magnetic polarity regions, and these lines correspond closely to X-ray coronal structures such as arcades, filament cavities, and coronal hole boundaries [*McIntosh et al.*, 1976].

The separation between adjacent neutral lines on these synoptic maps is indicative of the size scale of the magnetic polarity patterns. Such maps clearly show that this separation is typically of the order of only 10° to a few tens of degrees, especially around sunspot maximum, when the global field is more complex. Since long neutral lines tend to wrap around the sun in an east-west direction, this implies that they are separated in latitude by only 10° ~30°. Therefore, it seems likely that a typical CME, which spans ~50° in position angle (approximately latitude) at the limb, might overlie two or three neutral lines, rather than a single one, suggesting that its source region is magnetically complex. One might argue that CMEs are like bubbles, with their legs emerging from much narrower regions at the base of the corona. However, this argument is not supported by white light observations, which show that the angular widths of many CMEs remain nearly constant as a function of radial height (e.g., A. Hundhausen, private communication, 1996).

Such differences between the near-surface and outer coronal field patterns involved in CMEs suggest to us that the topology of the magnetic fields involved in CMEs can be complex. We believe that this complexity has not yet been adequately explored; observational results bearing on this complexity will certainly be important in modifying the theoretical approaches for modeling the origins and development of CMEs. As part of a general study of the source locations of CMEs, in this paper we explore this question, using features observed with the Yohkoh soft X-ray telescope (SXT) as signatures for the source structures involved in CMEs. We note that a limitation of our study was that we chose very large–scale X-ray events that could not be directly associated with white–light CMEs. Although these observations are not conclusive, we conclude that they are at least consistent with the idea that many CMEs arise from complex magnetic systems. In the next section we discuss our approach and the methodology of the study. Then we describe the results, with illustrations of each event, and in the last section we review other pertinent results and address important implications of the study.

2. Methodology

In this study we used Yohkoh SXT full–sun images [*Tsuneta et al.*, 1991] of eruptive events visible against the disk to study the source regions of the large–scale fields involved in CMEs. The SXT images are ideal for such a study because they provide coverage of the low corona with high spatial resolution (2.5 arc sec pixel size) and good time cadence (usually several full-disk images per 97 min orbit) over a long time period that now spans $4\frac{1}{2}$ years. We employed the same types of observations used to produce the video movies of desaturated, full-frame images. These data include full- disk observations made with the "thin" X-ray analysis filters (0.1 μ Al and Al-Mg-Mn), which are sensitive to plasmas of several million degrees K, and in either the half (5 x 5 arc sec^2) or quarter (10 x 10 arc sec^2) resolution modes.

There were no spaceborne coronagraph observations with which to study white light CMEs available during the period of our study. We examined large–scale transient X-ray events occurring near disk center to minimize the positional uncertainties of features near the limb. However, it is understood that the X-ray events are only proxies for the occurrence of CMEs and may not reveal the exact boundaries of the CMEs themselves. Although X-ray LDEs are well associated with white light CMEs [*Sheeley et al*, 1983], the size, brightness and other physical parameters of any given event observed in X-rays and in white light are not necessarily well correlated [*Hundhausen*, 1997a]. Our working assumption was that any large, long–enduring X-ray arcade event will be associated with a CME and that the spatial extent of the surface fields involved in the CME will encompass and be at least as large as the spatial extent of the observed X-ray event. We were particularly interested in the pattern of the neutral lines underlying the X-ray events.

The SXT arcade events considered to be good candidates for CMEs were selected on the basis of the following criteria. First, we selected events from SXT images from the start of the mission in late 1991 through early 1994. We compiled an initial event list composed of: (1) GOES whole–sun events having long–decay X-ray profiles with durations of ≥4 hours [*Sheeley et al.*, 1983] and relatively free from contamination by other briefer events, (2) large disappearing disk filaments [*Wright and Webb*, 1990; *Feynman and Martin*, 1995], and (3) events consisting of the brightening of large–scale coronal arcades often topped by bar- or cusp-like features [*Kahler*, 1977; *Hiei et al.*, 1993; *Shibata*, 1996]. Then, from this list we selected only those events that had full-frame images obtained with at least one of the two "thin" X-ray filters once per orbit during the event and for several hours before and after the event. This approach resulted in a list of about 100 events. We then examined these candidate events on a video of full–disk SXT images, permitting identification of the GOES LDE events and the locations of the arcade events.

Finally, we chose five of these events for detailed study. These events involved larger structures outside active regions where the large scale and relatively simple topology of such structures enhances our ability to understand their relationship to the evolving magnetic field patterns. We are aware that the comparison of such large events with the surface field can suffer from the confusion of overlapping but unrelated structures and projection effects. However, we believe that the careful analysis of the evolution of the arcades combined with the use of accurately drawn neutral line maps minimized these problems. In addition, we felt that our selection of large events with long time durations was necessary to assure that they were coronal signatures of CMEs. Except for this bias we considered the selected events to be typical of the class of X-ray arcades. Each of the selected events was spatially extended (tens of degrees), had a long timescale (hours), and had other characteristics typical of eruptive events. Three of the five events were associated with filament disappearances.

We examined each of the events in detail, studying their morphological structures and temporal evolution in the X-ray images and measuring the shapes and widths of any coronal structures considered associated with the event. These structures included transient brightenings *and darkenings* of ambient coronal features and changes in the boundaries of preexisting coronal holes.

We then compared the areas and locations of the X-ray events with the polarity patterns and coronal hole boundaries from full–disk and 27–day synoptic maps produced by one of us (PSM). The daily disk maps were produced for this study by translating data from global synoptic charts, where polarity boundaries are averaged positions of structures over 10 days of a disk passage, and then adjusting the patterns as needed to the day of the event by using solar images for that date. The resulting disk map was scaled to match the disk size and approximate time of maximum of each of the selected SXT events. We note that such maps show only the average locations of the magnetic patterns; for example, coronal hole boundaries are obtained from daily He I images and do not necessarily reflect their evolution during an event. Full–disk maps like these were first used to deduce the magnetic field polarity patterns associated with stable Skylab X-ray coronal structures [*McIntosh et al.*, 1976]. We have found such maps to be very useful, because in most cases they permit us to immediately determine which neutral lines and polarities underlie the X-ray events and where possibly associated filaments and coronal holes lie.

3. Results

An example of our technique is illustrated by describing the large–scale event on November 12, 1991. Figure 1 displays four SXT thin Al filter images showing the development of an arcade event that evolved over the entire day in a longitudinal direction from east to west [see also *Tsuneta et al.*, 1992]. At first it appears to be a typical, though very large scale, example of an event involving a relatively simple polar crown neutral line. Tsuneta et al. noted that although there was no obvious long filament present over most of the neutral line before the X-ray event, it was associated with a He I double–ribbon event visible on the daily 10830 Å image at 1709 UT in the northwest part of the disk (K. Harvey, private communication, 1994). A small filament segment at 41°N47°W (Figure 1d) lay between the He I ribbons, which appeared later. The filament disappeared between the time of the He I image on November 11, 1807 UT, and the Boulder Hα image at November 12, 1640 UT (*Solar Geophysical Data*, 1991). Such He I events are also considered disk proxies of CMEs [cf. *Webb*, 1992].

A more detailed study of the global field structure around this event indicates that it was not so simple. Figure 1a shows the pre-event X-ray image of the northern solar hemisphere early on the day, and Figures 1b, 1c, and 1e show the evolution of the event. Figure 1d is the northern half of the full–disk neutral line map constructed for November 12. The images show that there were two preexisting coronal holes of opposite polarity, which changed in area during the event. The negative–polarity hole in the northwest decreased dramatically in area as the coronal arcade evolved westward and widened, and the positive hole in the northeast increased somewhat in area during the same period.

The neutral line involved in the overall coronal restructuring on this day was hairpin–shaped (arrows). The main event occurred over the long northern polar crown segment at latitude 40°–50°N. At the eastern end of this feature the neutral line bends sharply backwards toward the southwest, where it is adjacent to the eastern positive–polarity hole. We call this a switchback neutral line. This second segment lay under a second X-ray arcade, which brightened late in the evolution of the first arcade event, starting about November 12, 1900 UT. The second arcade extended into active region 6908 at 20°N15°W (Figure 1e).

We conclude that there was probably a general restructuring of the solar magnetic field in the northern hemisphere on this day, likely involving large–scale reconnection of field lines and also likely associated with one or more CMEs, that encompassed an area conservatively estimated to extend over 90° in longitude and 40° in latitude at the surface. This restructuring would have involved X-ray arcade events over two adjacent neutral line segments and changes in two preexisting, opposite–polarity coronal holes ~70° apart. The coronal hole on the east side of the arcade was a narrow extension from the positive–polarity north polar hole. The interaction between this narrow lane of open field and the closed arcade field of the polar crown may have led to the assumed coronal eruptions.

Four other large–scale Yohkoh events were selected for detailed study. All five events, including the one on November 12, 1991, are summarized in Table 1. The table lists the date, time and duration of each event, its location on the disk, its approximate surface dimensions, the span (separation) between associated neutral lines in heliographic degrees, the number of neutral line segments spanned by the width of the X-ray loop arcade, the numbers of transient and preexisting coronal holes that appeared or changed area during the event, whether a filament disappeared (DF?) over one of the associated neutral lines, whether there was an associated GOES X-ray event, and other references to the event. We note in column 8 that "neutral line segments" can be either segments of a single neutral line folded back on itself in a switchback (S) configuration, or completely separate, individual (I) neutral lines. The event duration was a rough estimate of the arcade lifetime based on viewing of the video. A more quantitative estimate of duration would require light curves integrated over the event with the background level removed. Such work was beyond the scope of our study since our requirements were simply that the events be of sufficiently long duration and large scale to assure their being good X-ray proxies for CMEs.

The most recent event, on April 14, 1994, was very similar in its X-ray appearance to the November 12, 1991, event. Because of its association with a heliospheric CME–proxy event observed at Ulysses near 60°S latitude and a geomagnetic storm at Earth, the April 14 event has been discussed in detail by others [e.g., *McAllister et al.*, 1994a, 1996a; *Alexander et al.*, 1994; *Hudson et al.*, 1995], so we do not include illustrations of the event in this paper. The interested reader can examine the figures in the above papers. The X-ray arcade resembled that on November 12, 1991 in the following ways: (1) It was very large-scale, encompassing a significant fraction of the entire southern solar hemisphere; (2) it involved a polar crown filament channel with few visible filament segments; (3) it lay between two preexisting, opposite-polarity coronal holes that changed area during the event; and (4) it propagated in a longitudinal direction from east to west across the disk. It differed in that the neutral line was generally straight along the path of the arcade but contained a Z–shaped convolution severe enough that the X-ray arcade loops crossing this region spanned three segments of the neutral line. The brightest parts of the arcade developed over this region, suggesting a significant coronal response to this complex portion of the neutral line. *McAllister et al.* [1996a] surmise that the convolution was related to the rapid growth and rotation of the coronal hole (an extension from the north polar hole) that lay equatorward of the southern polar crown. This region developed rapidly between February and May 1994.

The April 27 and June 1, 1992, SXT events were of similar size, and each involved apparently related activity crossing two neutral lines, as well as a transient darkening or hole. The June 1 event is illustrated in Figure 2 and was briefly described by *McAllister et al.* [1994b]. Figure 2a shows the pre-event image, and Figures 2b and 2c show the development of the event. The neutral line map for ~1800 UT is shown in Figure 2d. The event appeared at first to be a classic disappearing filament and X-ray arcade involving a single, curving neutral line in the south central part of the disk. A transient dark "hole" appeared astride the northeast side of the arcade. A second long filament (bottom arrow on the map) lay between the first filament and the south polar hole and appeared unaffected. However, simultaneous with the first event a subtle brightening occurred poleward of the second filament, filling in a portion of the south polar hole (bottom arrow in Figure 2b). By 1530 UT (Figure 2c) this brightening had dimmed considerably. Both the area on the northern side of the disappearing filament and the polar hole area were of negative polarity. Since they were separated by two parallel neutral lines, this suggests that the affected magnetic system was quadrupolar, with a positive band dividing two negative regions.

The April 27 event is shown in Figure 3. It occurred in the northwest and could be interpreted as a two–phase X-ray event, which developed over a neutral line to the north of active region 7145 and migrated southwestward to form a very bright tunnel-like system overlying possibly parallel neutral lines (arrows in Figure 3d) near active region 7138. The X-ray event first developed north of active region 7145, where a preexisting loop system spanned the long east–west neutral line (top arrow in Figure 3d). The event involved a transient extension of the preexisting circular, positive–polarity coronal hole east of active region 7145 (Figure 3d) and later evolution of the arcade southwestward to include the second neutral line (bottom arrow in Figure 3d). The eastern feet of this later arcade sharply defined the western boundary of the transient hole (Figure 3c), which shrank as the arcade widened.

The last event in Table 1 occurred on November 4–5, 1992, and is shown in Figure 4. There were actually several transients, which indicate that a complex, interconnected series of eruptive events occurred, encompassing a significant fraction of the entire solar disk. The events proceeded in a general northeast to southwest direction over a period of less than 12 hours and could have been associated with one very large transequatorial CME or two or three smaller CMEs. The first two X-ray events, starting late on November 4, occurred in the northeast in an area of rapid restructuring east of an elongated negative–polarity coronal hole (Figure 4a and 4c). The first arcade appeared over a disappearing filament at 15°N10°E forming the eastern boundary of the hole. Later, long thread-like loops appeared crossing a second neutral line, or a sharp bend of the same line, with their northern feet ending at the boundary of the north, positive–polarity polar hole. During this time the western feet of the first arcade were decreasing the area of the central (negative–polarity) hole. However, concurrently, a large area of negative–polarity emission in the center of the disk adjacent to the hole darkened, as if the total amount of open field were being conserved. Then, to the south of this region at about 0100 UT November 5, a narrow dark lane appeared in X-rays in the channel where a short filament at 15°S10°W later disappeared. A long, bright scorpion–shaped arcade then brightened over this neutral line (Figures 4a and 4d). (See *McAllister et al.* [1996b] for a detailed description of this latter event). A total of at least three neutral line systems appeared to be involved in the overall series of events. *Watari et al.* [1995] also noted this series of events, associating them with a flux rope structure in the solar wind and geomagnetic storm at Earth on November 8–9.

4. Discussion

Our study of these Yohkoh data indicates that two or more neutral lines, often parallel to each other, or a single but highly convoluted neutral line, are likely involved in many large–scale coronal eruptions and CMEs. The transient X-ray structures involved in these events spanned distances across the solar surface ranging from 35° to >100°, comparable to the spans of CMEs observed in white light at the limb, and their durations ranged from ~7 hours to $1\frac{1}{2}$ days. For each event, two or three neutral line segments were spanned by the widths of the X-ray arcades; the separations between these neutral line segments ranged over several tens of degrees. Filament disappearances were associated with three of the X-ray events. Transient depletions or holes appeared during three of the events, and at least one preexisting coronal hole changed area during all five events.

In summary this study provides evidence that large–scale multiple magnetic systems may be a common configuration of the source fields of many CMEs. Thus the first–order approximation of a CME as the simple eruption of a structure overlying a single, straight neutral line is not likely to be correct or typical, at least for many CMEs. One limitation of our study was that we chose very large–scale X-ray events that could not be directly associated with white–light CMEs. However, although these observations are not conclusive, we conclude that they are consistent with the multiple field concept.

We believe that this view is supported by other extant observations, which raise questions about the simple "bipolar CME" idea. Prominences, whether erupting or not, do not always underlie CMEs, and even when they do, their original position often is not centered under the subsequent CME. Recent results reveal systematic latitude offsets between CMEs and their associated prominences. For example, on the basis of comparisons of white light CME and Hα images, D. G. Sime [private communication, 1992] found that prominence eruptions tended to be systematically offset from their associated CMEs. During the rise of cycle 22 in 1987–1989 the prominences tended to lie poleward of the CMEs, in agreement with similar results comparing active regions and CMEs [*Kahler*, 1991] and He I double–ribbon events, associated with filament eruptions on the disk, and CMEs [*Webb et al.*, 1991]. In the context of this study, such an offset would be expected if the CME overlay multipolar fields with two or more neutral lines.

Researchers familiar with full–sun X-ray images recognize that very long, stable loops often interconnect distant active regions, even across the equator [e.g., *Chase et al.*, 1976; *Harrison and Simnett*, 1984]. In many cases, such long loops might cross three neutral lines to end in sites of opposite polarity. The Yohkoh images likewise clearly reveal such large–scale structures. The occasional eruption of such loops as CMEs, as suggested by *Simnett and Harrison* [1985], implies a complex magnetic source region for the CME.

Above $\sim 2R_S$ the bright white light corona is confined to streamers, which are arcades of large–scale closed loops in the low corona topped by narrow ray-like structures (i.e., helmets). Recent studies suggest that many CMEs may be physically related to the evolution of coronal streamers [e.g., *Sime*, 1989]. A. J. Hundhausen and S. W. Kahler (private communication, 1993) have compared the locations of

SMM CMEs and streamers, concluding that ~75% of all CMEs can be associated with preexisting streamers. Some of the largest CMEs are so-called streamer blowouts, in which a preexisting streamer increases in size and brightness for about one to several days before erupting as a CME [*Hundhausen*, 1993]. Following the CME, the streamer is gone, often replaced by a thin ray.

Other white light observations support the idea that such helmet streamers can overlie, at least in projection against the limb, two coronal enhancements (arcades) and parallel neutral lines as outlined by filaments. The best examples are from total solar eclipse observations, during which the corona can be viewed down to the limb. A fine example of a single helmet streamer apparently overlying twin coronal arcades and parallel filament segments was observed at the 1966 eclipse and is illustrated in Figure 5a. This observation was discussed by *Saito and Tandberg-Hanssen* [1973], who also listed many double–arch systems seen at other eclipses [see also *Eddy*, 1973]. Recently, this picture has been nicely corroborated by the SOHO/LASCO suite of coronagraphs. During most of 1996 the lower corona had a quadrupolar appearance wherein a single equatorial helmet streamer seen in the LASCO C2 and C3 coronagraphs overlay smaller loop arcades at high north and south latitudes [e.g., *Howard et al.*, 1997]. *Crooker et al.* [1993] have developed a model in which the coronal streamer belt, which forms the base of the heliospheric current sheet, consists of multiple helmet streamers. Thus the streamer belt can contain multiple current sheets that, in turn, explain the frequent observations of multiple directional discontinuities at heliospheric sector boundary crossings.

The complete or partial eruption of such a hybrid helmet streamer would suggest that the source region of the resulting CME(s) consisted of a complex magnetic system of preexisting multiple arcades and neutral lines. We know of at least two examples of combined HAO SMM and Mauna Loa Solar Observatory (MLSO) coronagraph observations showing the eruption of coronal arcade systems bridging twin neutral line/filament segments. The first event occurred on October 15, 1986, and is illustrated by color Figures 7–11 of *Hundhausen* [1988]. Those figures combine MLSO and SMM images, showing a loop-like CME over the northwest limb rising over two coronal arcades seen in the MLSO data. The northern arcade contained a large erupting prominence, but the Hα synoptic maps showed that another filament, which did not erupt, lay on a separate parallel neutral line under the southern arcade.

A similar eruption occurred on the northwest limb on October 5–6, 1989, and is presented in Figure 5b. A spectacular erupting prominence at the limb (EPL) was superposed near the base of the CME's northern leg. This leg was bounded by the negative polarity field of the north pole, especially by an elongated midlatitude hole, which had separated from the north polar hole during the previous three rotations (region denoted by diagonal hatches in Figure 5c). The southern leg of the CME appeared to end over a brightening arcade. This southern arcade then erupted shortly after the northern CME, blowing out the preexisting streamer, with the event continuing into October 6. The Hα synoptic map for this rotation (Carrington 1820) reveals that the latitudinal span at the limb of the first CME may have crossed two filament segments that were part of a long U– or hairpin–shaped neutral line (Figure 5c). If so, then this CME would represent the eruption of a preexisting structure that spanned a quadrupolar system, like that shown in Figure 5a.

Together these observations suggest that multiple or convoluted neutral lines may be involved in many large–scale eruptions and CMEs. However, not all CMEs appear to arise over complex neutral line systems. For example, many "three–part" CMEs are associated with concentric prominence eruptions that appear to be centered over a single, straight neutral line segment (for example, the aforementioned April 14, 1980, CME and CMEs on August 18, 1980, and June 1, 1988, shown in Figures 2–11 of *Hundhausen* [1997b]). (But we recognize that because of problems with viewing geometry and how an event evolves with height in the corona, the presence or absence of apparent symmetry may be misleading.) Also, in the Yohkoh data we do not observe simultaneous, parallel large–scale events such as might be expected if twin arcades erupt. On the other hand, events such as the one on June 1, 1992, provide evidence that the second X-ray arcade can brighten, in analogy with the above white light CME observations. In addition, several distinct phases or separate eruptions may be involved during 1–2 days of the large–scale restructuring of the field (e.g, the November 12, 1991, event). We noted that in the two polar crown events we studied, the arcade loops brightened and widened successively from east to west longitude, giving the impression of the unzipping of a coat (i.e., the *zipper effect*). In these two cases the arcades widened into areas previously occupied by opposite–polarity pairs of large bounding coronal holes, implying the closing down of previously open fields. These aspects emphasize the temporal as well as spatial complexity in such arcade events. We speculate that such separate phases or eruptions might reveal themselves as two or more consecutive CMEs at different positions along one or more complex neutral lines.

Empirical models of the formation of multiple neutral line systems were discussed by *Hansen and Hansen* [1975; 1977] 20 years ago. We believe that these ideas are pertinent to the generation of CMEs over multipolar magnetic systems. Their models were based on extensive observations made with the MLSO MKII K–coronameter. One of their concepts involved polar crown filaments and is illustrated in Figure 6. Differential rotation would eventually bring a lower–latitude active center or filament into close proximity with a preexisting polar crown filament, resulting in restructuring of the field lines. For the ascending phase of a cycle the leading polarity field of an active region ("A" in the figure) would reconnect with the opposite–polarity, poleward field of a polar crown filament segment ("P"), resulting in a new, third arcade between the two older systems ("M"). An extended coronal structure ("E") would also connect the most distant opposite–polarity regions and might develop into a streamer (the cusp-shaped structure in the figure), which would then overlie a quadrupolar magnetic system with three neutral lines. Further differential rotation or newly emerging flux might build stress in the system, leading to its eruption as a CME. Figure 6c is a view of such a system as it might appear at the limb; compare with the observations in Figure 5. *Hansen and Hansen* [1975] also proposed that similar restructuring could occur during the descending phase of the cycle, such as during the Yohkoh period. In this case, however, the polarities would be reversed, and the following polarity of the lower–latitude region would reconnect with the polar crown filament to form the quadrupolar system.

Further study is needed to determine how well this picture fits the formation and eruption of the magnetic systems associated with the Yohkoh events. However, we note that all of the events we studied had mid– to high–latitude boundaries involving a polar crown neutral line or, at least, the highest–latitude neutral line in the vicinity of the event. The "polar crown" designation usually refers to the most poleward ring of filaments that rushes to the poles just before the polarity reversal of each cycle. At lower latitudes is a second neutral line ring, which forms the "polar crown" during the descending phase of the cycle pertinent to this study. The poleward movement of the main polar crown is an integral part of the magnetic reversal phenomenon [*Webb et al.*, 1984; *McIntosh*, 1992] and has recently been linked to the occurrence rate of CMEs [*Cliver et al.*, 1994]. Unstable magnetic structures conducive to the occurrence of CMEs may develop in response to the long–term differential motions of large–scale magnetic field structures, including anomalies in the general circulation patterns (i.e., divergence, convergence and shear). Eruption of flux from below the surface, especially in the form of a new active region, is a common precursor to filament eruption [*Feynman and Martin*, 1995] and is also associated with enhanced flare activity. This new flux, in turn, may be related to the evolution of the large–scale structures surrounding it.

Most models assume a single, straight neutral line geometry for CMEs, which thus evolve from a simple bipolar field system. This assumption follows from the observational concept of a CME consisting of a bright leading loop or shell, followed by a dark, low-density cavity and a bright core of denser material, assumed to be a prominence or flux rope over a single neutral line. However, our conclusion that many large–scale eruptive events involve multiple magnetic flux systems, including quadrupolar and hexapolar fields, presents a challenge to theoreticians to produce models that incorporate this newfound complexity. We note that Uchida has recently adapted an older model based on the collapse and reconnection of a quadrupolar field system to explain Yohkoh filament eruption/X-ray arcade–type flares [*Uchida et al.*, 1994; *Uchida*, 1996].

On the other hand, that CMEs might involve complex magnetic systems is perhaps not surprising theoretically. *Sturrock* [1991] and *Aly* [1991] have offered proofs of Aly's [1984] original conjecture that the maximum energy state of a force–free field is the open state for which all of the field lines extend to infinity. It is therefore not energetically favorable for an erupting magnetic field to fully open. A more likely scenario is that the field opens partially, in one of two ways. For a single isolated arcade, as in the models of *Forbes* [1991], *Wolfson and Low* [1992], and *Mikic and Linker* [1994], only the outer portion of the field erupts, leaving the inner core of the arcade magnetically closed. A vertical current sheet is formed extending from the top of the core, at a finite height in the corona, out into space. We question whether this scenario is consistent with observations, however, since coronagraph images suggest that the field opens down to a height below the coronagraph occulting disk ($\approx 0.1 R_S$ at MLSO), and the presence of an erupting prominence implies an opening down to very low altitudes. (We note that the recent erupting streamer model of *Linker and Mikic* [1995] may be consistent with these observations.)

A fundamentally different scenario is possible in the presence of multiple arcades. Although it has not yet been demonstrated, it may be energetically favorable for one of the arcades to open fully, forming a current sheet that extends all the way to the photosphere, while the other arcade(s) remains essentially intact. Since only part of the complete system opens, the total energy remains below the Aly-Sturrock limit. (A small amount of the total energy might be released in the remaining arcade, in agreement with events such as June 1, 1992.) For this reason we believe that the interplay between different magnetic flux regions is fundamental to the eruption process, as was noted earlier by *Biskamp and Welter* [1989]. That the force-free approximation is probably unrealistic for real coronal structures also needs to be accounted for [e.g., *Hundhausen*, 1997b].

We conclude that our observational results are entirely consistent with the theoretical ideas presented above. The results also suggest that to understand the initiation of CMEs, we need to compare the locations of CMEs with data showing the evolution of the global field over long time periods.

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Figure 1. Yohkoh SXT thin Al filter negative images of the northern hemisphere of the sun on November 12, 1991, showing the evolution of a large-scale polar crown arcade event at four times: (a) Pre-event image at 0010 UT, (b) 0757 UT, (c) 1128 UT, and (e) 2300 UT. (d) A full-disk map showing the positions of neutral lines, Hα filaments and He I coronal holes (short hatches) at ~0900 UT on November 12. The map was constructed by using daily Hα and He I photographs and the Hα synoptic map for Carrington rotation 1848. The arrows point to the two neutral line segments discussed in the text. Solar north is up and west to the right in this figure and all subsequent ones.

Figure 2. (a) SXT thin Al negative images of the full sun on June 1, 1992, showing a pre-event image at 1140 UT, (b, c) two images showing the development of the event at 1400 and 1530 UT, respectively, and (d) neutral line map constructed for ~1800 UT. The topmost arrows in Figures 2b and 2d indicate the neutral line and filament (Figure 2d) involved in the main X-ray arcade (Figure 2b). The bottom arrow (Figure 2d) shows the second neutral line and filament which did not erupt, and the bottom arrow (Figure 2b) shows the area of restructuring between this filament and the border of the south polar hole (hatches).

Figure 3. (a) SXT thin Al negative images of the northwest portion of the sun on April 27, 1992, showing a pre-event image on April 26 at 2317 UT, (b, c) two images showing the development of the event at 1215 and 1652 UT, respectively, and (d) neutral line map constructed for ~1600 UT. The X-ray event first developed north of the bright central active region (7145) from a loop system which likely spanned the long east–west neutral line (top arrow in Figure 3d). The event involved a transient-hole darkening of the positive–polarity region encircling active region 7145, as well as later evolution of the arcade southwestward to include a second neutral line (bottom arrow).

Figure 4. SXT thin Al negative images of the full sun on November 4–5, 1992, showing an interconnnected series of X-ray events across the disk: (a) neutral line map constructed for ~1600 UT, November 4, (b) a pre-event X-ray image at 1737 UT, November 4, and (c, d) two images showing the development of events at 0058 UT, November 5 and 0411 UT, November 5, respectively. The transient activity first involved two arcade events in the northeast (arrows in Figure 4c), then a large-scale dimming of the negative–polarity region surrounding the hole (hatches) at disk center, and finally the eruption of a filament and resulting bright X-ray arcade in the southwest (arrow in Figure 4d).

Figure 5. (a) Example of a helmet streamer/double arcade system seen in white light. Sketch of twin coronal arcades overlying two prominences at the northwest limb (Position Angles 305° and 327°) seen at the November 12, 1966, total eclipse. A single helmet streamer appears to overlay the double arcades. The data points connected by lines are intensity isophotes. Note that the prominences overlay two parallel neutral lines extending onto the disk, separating polarities as shown. A third prominence/neutral line lay at P.A. 295°, suggesting that the streamer may have spanned a quadrupolar magnetic system. From *Saito and Tandberg-Hanssen* [1973]. (b) The possible eruption of such a system as a CME over the northwest limb on October 5–6, 1989. Above the limb are superposed images from MLSO of the inner corona in white light and in Hα and from the SMM coronagraph of the outer corona. A spectacular EPL lies near the base of the northern leg of the CME loop. An earlier view of the EPL in Hα emission is shown on the limb under the MLSO EPL. The southern leg of the CME is superimposed over a brightening arcade, which erupted late on October 5 and into October 6. (Courtesy A. Hundhausen and J. Burkepile, High Altitude Observatory, Boulder, Colo..) A neutral line disk map for ~1800 UT on October 5 is overlaid on the solar disk. (c) A portion of the Hα synoptic map for the October 1989 rotation (Carrington 1820) centered on the west limb meridian, L=130°, for October 5. This reveals that the projected latitudinal span at the limb of the first CME (thick bracket) may have crossed two filament segments (small hatches) that were part of a long U–shaped neutral line. The thinner bracket shows the span of the second CME, which erupted from the southern bright arcade.

Figure 6. Empirical concept of the formation of a multiple neutral line system involving a polar crown filament. (a) Differential rotation brings a lower–latitude active center close to a preexisting polar crown filament, resulting in (b) the leading polarity field of the active region ("A") reconnecting with the opposite–polarity, poleward field of the polar crown filament ("P"); this yields a new third arcade ("M"). An extended coronal structure ("E") might also connect the most distant opposite–polarity regions and might develop into a streamer (the cusp-shaped structure in Figure 6b), which would then overlie a quadrupolar magnetic system. (c) A view of the new system rotated to the limb; compare this view with the observations in Figure 3. After ***Hansen and Hansen*** [1975].

Table 1. Large-Scale Eruptive Events Observed by Yohkoh SXT

	Onset		Disk		Span	NLs	Tran.	P-E		GOES	
Date	UT	Duration^a	Quadrant	Size^b	NLs^b	Crossed^c	CHs^d	CHs	DF?	Event?	References
Nov. 12-13, 1991	12, 0010	~28	NNW	90 x 40	27	2/S	none	2	yes	no	*Tsuneta et al.* [1992]
Apr. 27-28, 1992	<27, 1000	≥32	NW	65 x 45	(?)	2(?)/?	1?	1?	no?	B8 LDE; >27,06-21	
June 1-2, 1992	1, 1200	18	S20CM	35 x 55	12-20	2/I	1	1	yes	B4 LDE? 1,1214-1430	*McAllister et al.* [1994b]; *Kano* [1994]
Nov. 4-5, 1992	<4, 2230	≥7	NE; SW	35 x 55; 50 x 50	37- (85)	~3/I	1	2	yes yes	no? C1?; 5,0415	*McAllister et al.* [1994b, 1996b]; *Watari et al.*[1995]
Apr. 14, 1994	14, 0240	≥18	SE-SW	150 x 40	22	3/S	none	2	no	B1 LDE?; 0230->0830	*McAllister et al.* [1994a, 1996a];Alexander et al. [1994];*Hudson et al.* [1995]

[a] Estimated duration of X-ray event in hours.

[b] Heliographic degrees. "NL Span" means the separation between associated neutral lines.

[c] The number of neutral lines crossed by the width of the X-ray event. The letter indicates whether these were separate, individual (I) NLs or a switchback (S) of the same NL.

[d] CH = coronal hole.

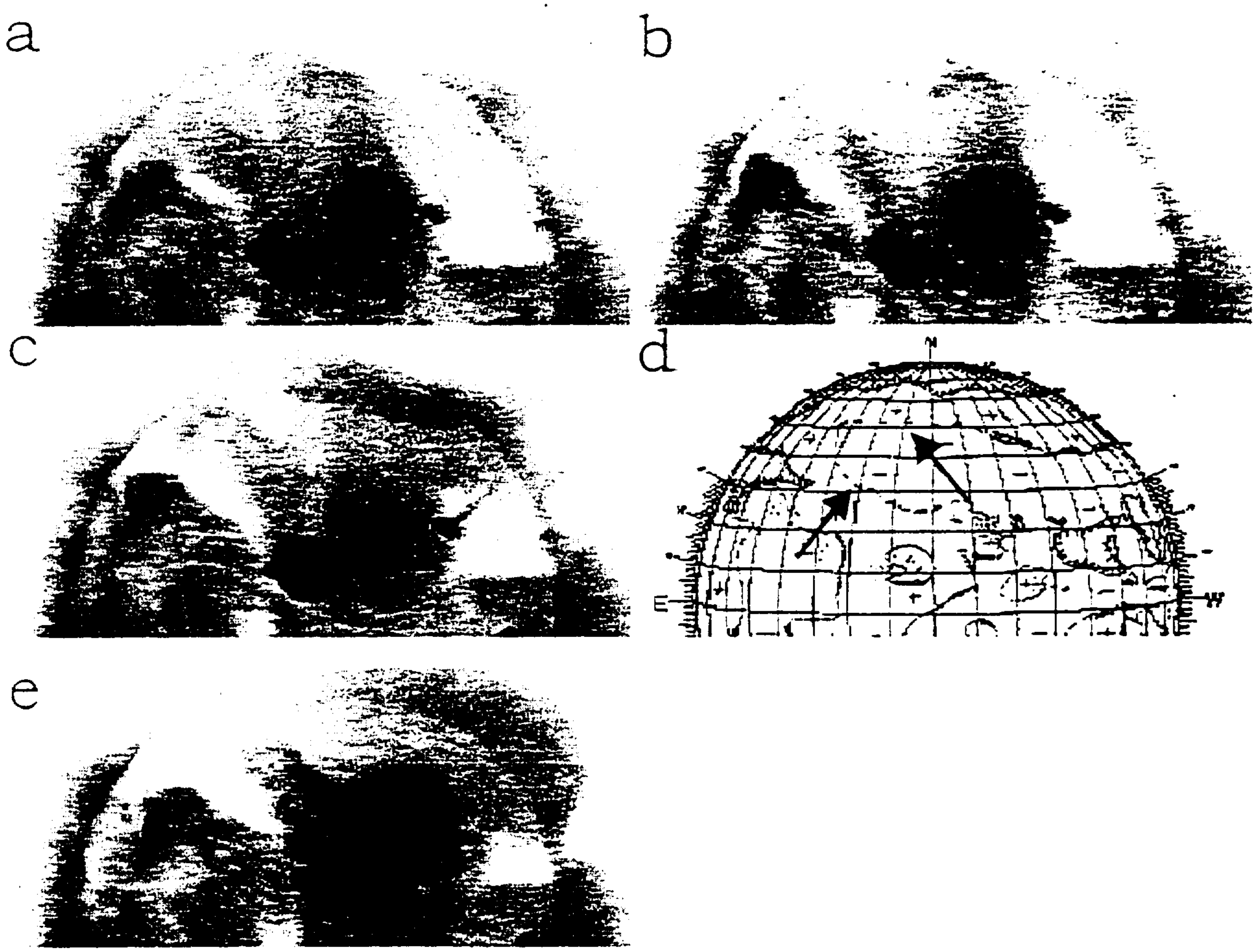

FIG-1

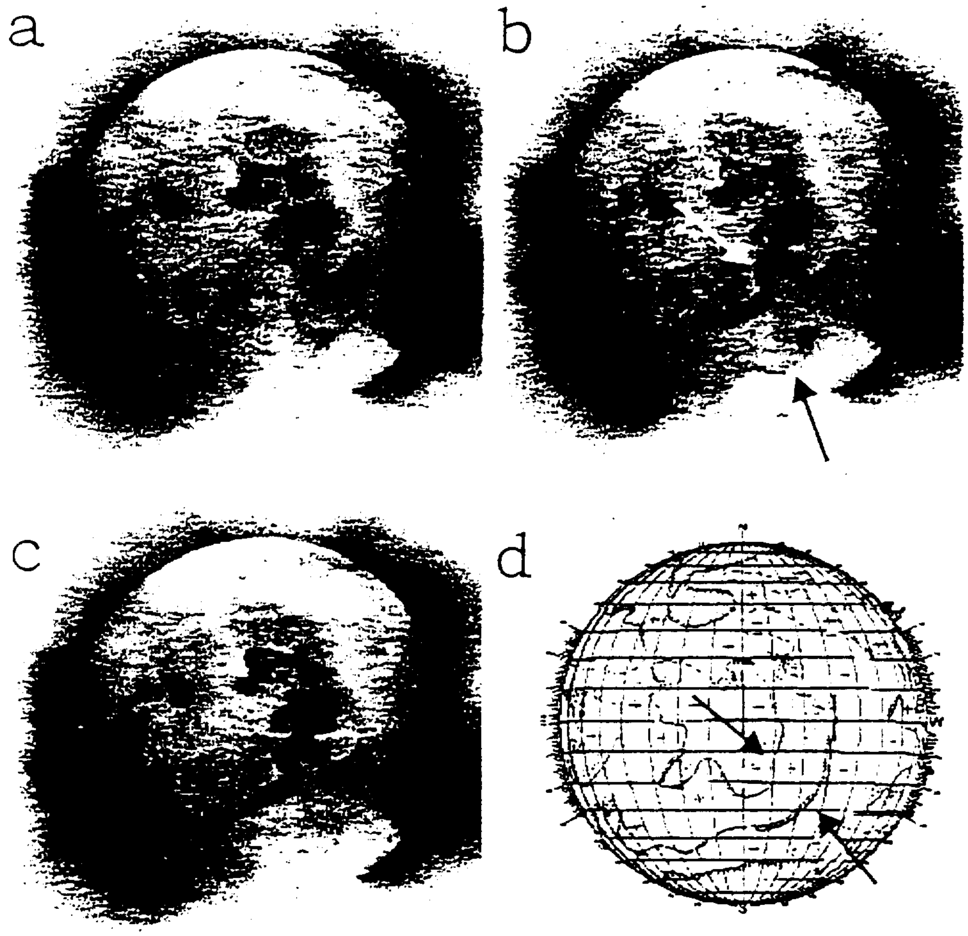

FIG. 2

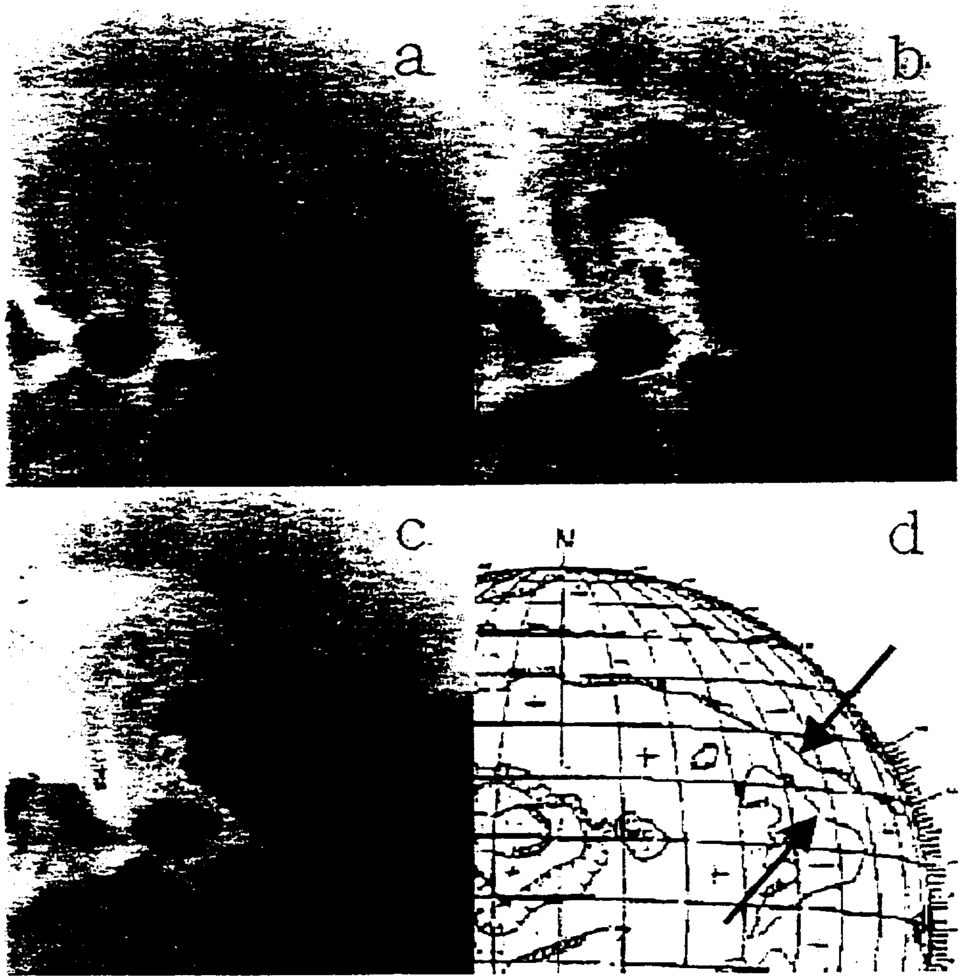

FIG 3

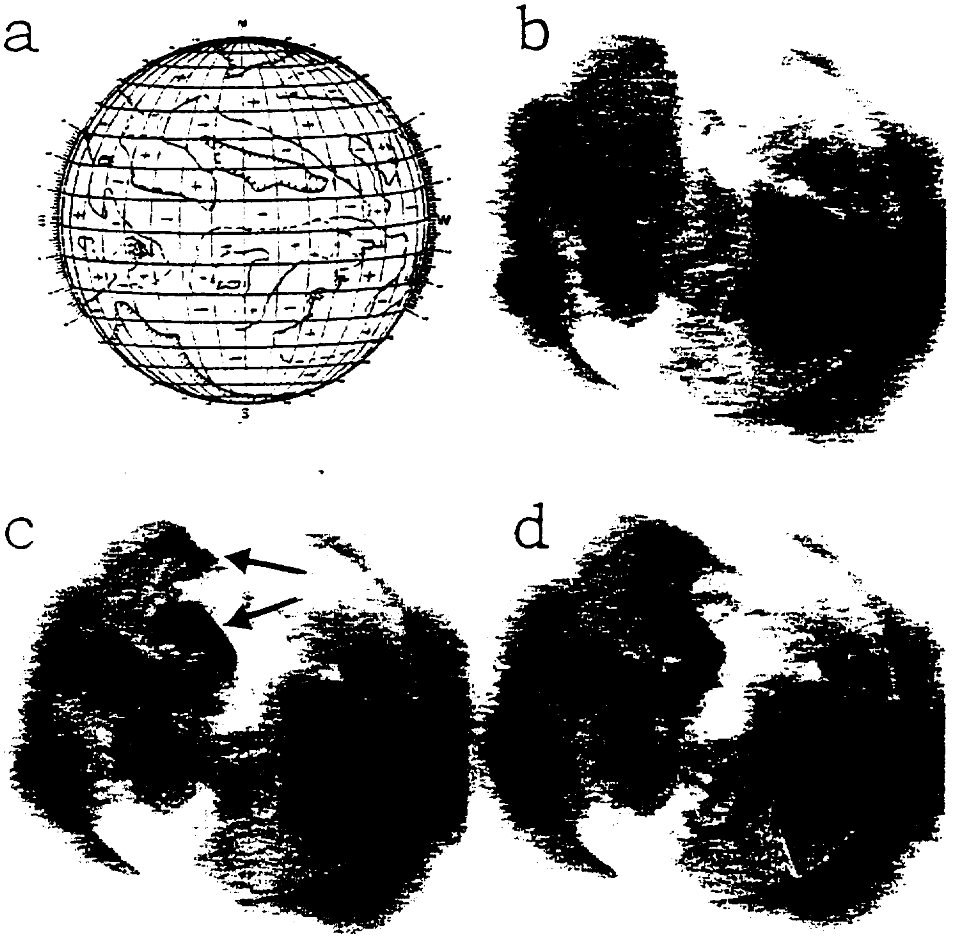

FIG 4

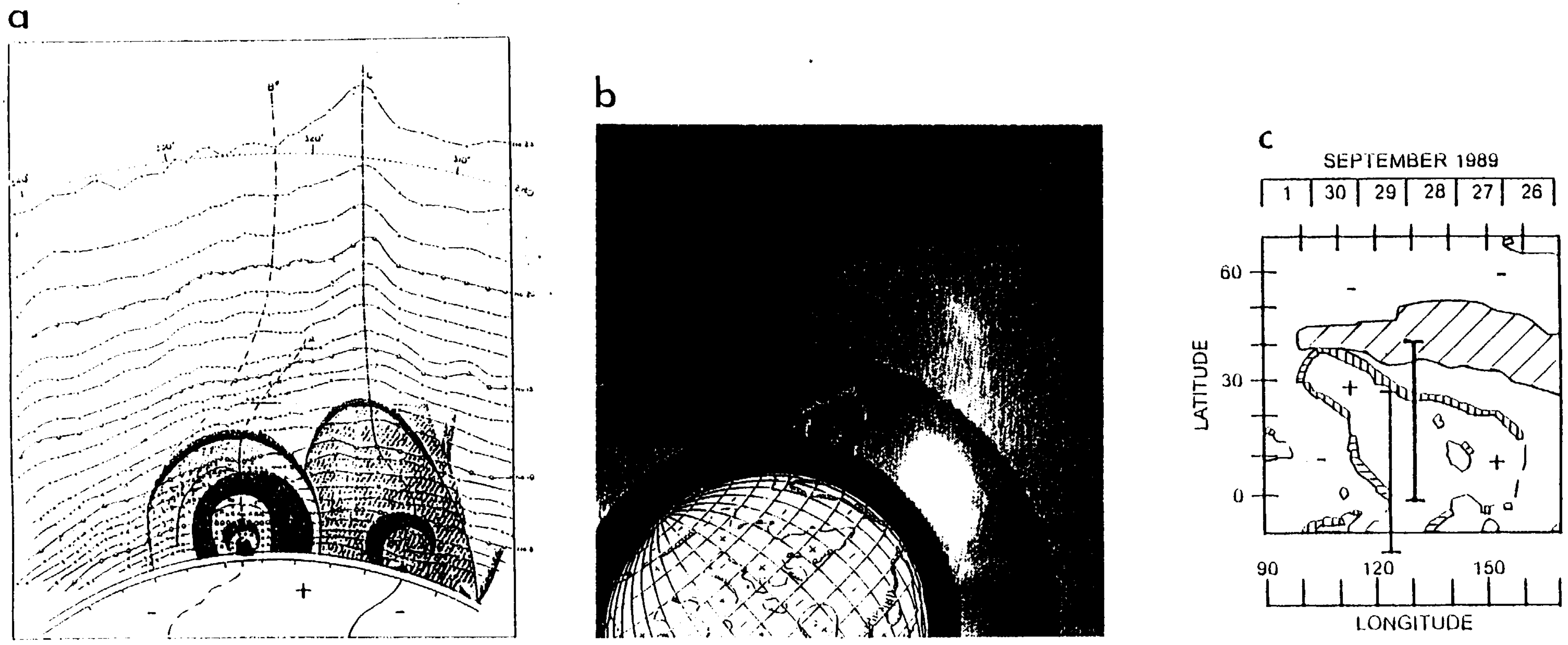
a
b
c
SEPTEMBER 1989
1
30
29
28
27
26
LATITUDE
60
30
0
90
120
150
LONGITUDE
+
-

FIG 5

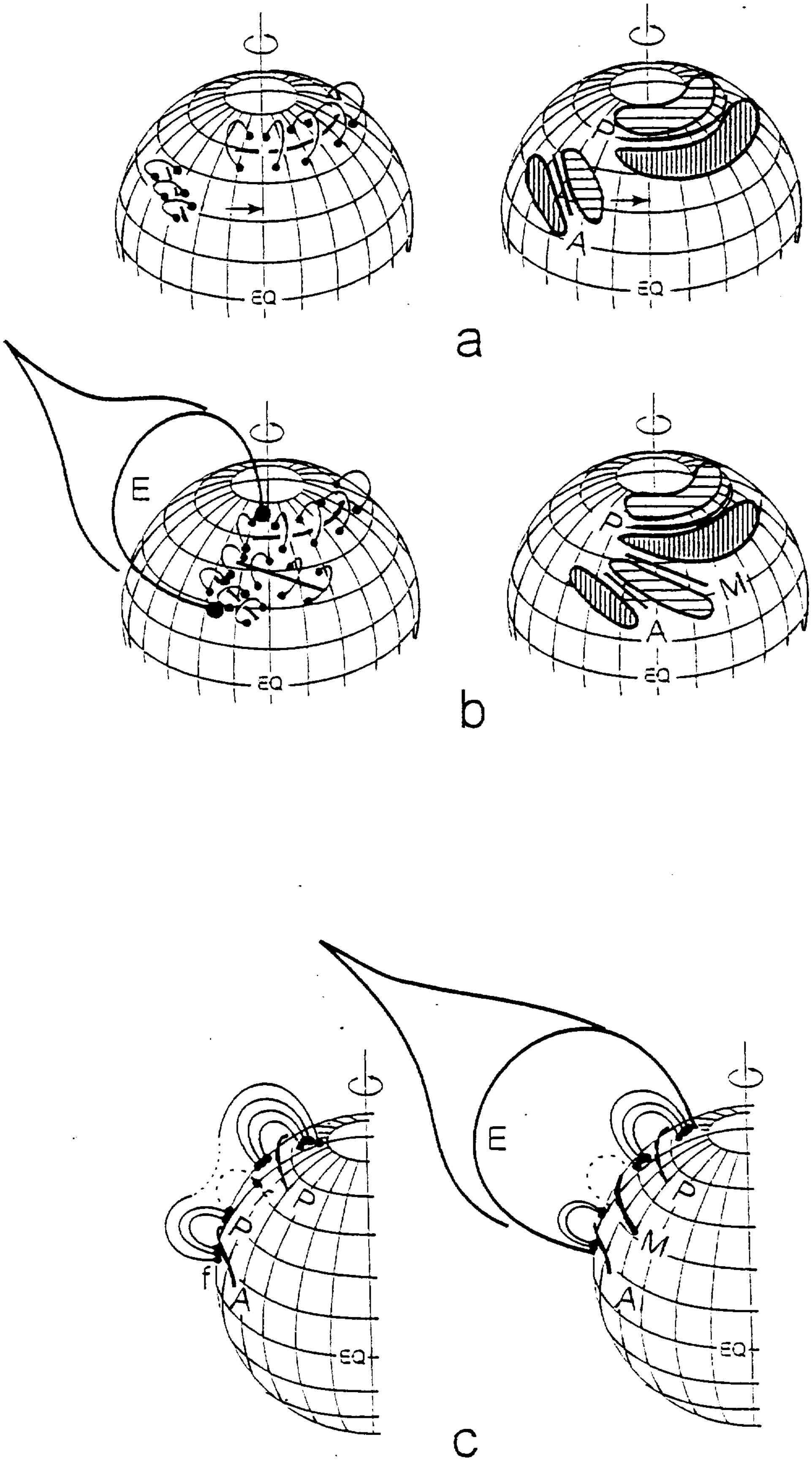

FIG 6