

Large-scale source regions of earth-directed coronal mass ejections[★]

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ABSTRACT

Based on SOHO/MDI, EIT, Yohkoh/SXT, $H\alpha$, and other relevant observations, we analyzed all the earth-directed halo coronal mass ejections (CMEs) in the interval from Mar. 1997 to Dec. 2003. A total of 288 earth-directed CMEs were studied and their associated surface activity events identified. Unlike the previous studies that often attributed a surface activity event or a given active region to a CME source region, this statistical analysis puts emphasis on the large-scale magnetic structures of CMEs, in which the CME-associated surface activity takes place. All the CMEs are found to be associated with large-scale source structures. The identified large-scale structures can be grouped into four different categories: extended bipolar regions (EBRs), transequatorial magnetic loops, transequatorial filaments and their associated magnetic structures, and long filaments along the boundaries of EBRs. The relative percentages of their associated CMEs are 36%, 40%, 13%, and 11%, respectively. The analysis indicates that CMEs are intrinsically associated with source magnetic structures on a large spatial scale.

Key words. Sun: coronal mass ejections (CMEs) – Sun: activity – Sun: magnetic fields

1. Introduction

Coronal mass ejections (CMEs) often consist of very large structures that contain plasma and magnetic fields that are expelled from the Sun into the heliosphere (Webb 2000). They are believed to be the main source of strong interplanetary disturbances that may cause intense geomagnetic storms (Gosling 1997). Since CMEs were first detected in the 1970s, many of their properties have been learned, such as their morphology, geometry, mass, and dynamics (e.g. Hundhausen 1997; Forbes 2000). However, some key problems about CME origins are still far from being solved, such as where they initiate or what the characteristics of their source structures are.

Thanks to the joint observations from SOHO (Solar & Heliospheric Observatory, 1996-present; Domingo et al. 1995), MDI (the Michelson Doppler Imager, Scherrer et al. 1995), EIT (the Extreme Ultraviolet Imaging Telescope, Delaboudinière et al. 1995), LASCO (Large Angle and Spectrometric Coronagraph Experiment, Brueckner et al. 1995), Yohkoh SXT (Soft X-ray Telescope, Tsuneta et al. 1991), and the $H\alpha$ and radio observations, more and more scientists have revealed that CMEs are associated with the commonest near-surface activity events like flares (Shibata et al. 1995; Nitta & Akiyama 1999; Zhang et al. 2001a), eruptive filaments (Webb & Hundhausen 1987; Delannée et al. 2000; Zhang et al. 2001b; Subramanian & Dere 2001), moving magnetic features (e.g. Vrabec 1971;

Lee 1992; Zhang & Wang 2002), magnetic flux emergence (e.g. Feynman & Martin 1995; Wang & Sheeley 1999; Chen et al. 2000), and magnetic flux cancellations (e.g. Martin 1986; Wang & Shi 1993; Zhang et al. 2001c).

More recently, Zhou et al. (2003) identified closer correlations between CMEs and surface magnetic activity with a sample of 197 earth-directed CMEs. These studies provided clues about the CME triggering processes. However, as a kind of large-scale solar activity, CMEs are very disproportional to these surface activity events being observed on such a small scale. As an example, when a CME was associated with a flare, it seemed that the related flare only appeared in an active region (AR). However, most of the time, larger volume changes around the AR were observed in the corona. This indicates, therefore, that each CME may have a corresponding source magnetic structure that has an intrinsically large spatial scale.

Statistics and case studies also provide hints about CME-associated large-scale magnetic structures. X-ray or EUV dimmings (brightness depletions) are expected to be the very first signature of CMEs, often originating from ARs and extending to large areas most of the time (Rust & Hildner 1976; Sterling & Hudson 1997; Gopalswamy & Hanaoka 1998; Thompson et al. 2000). CMEs are sometimes observed arising from a coronal streamer, a preexisting large-scale structure (e.g. Hundhausen 1993; Subramanian 1999). AR-interconnecting or transequatorial loops observed in SXR or EUV that link the primary flaring site and other magnetic regions are related to CMEs (Klimchuk et al. 1994; Khan & Hudson 2000;

[★] Figures 3 to 8 and Appendix are only available in electronic form at <http://www.edpsciences.org>

Chertok 2001; Harra et al. 2003; Cheng et al. 2005). A transequatorial filament and its related large-scale magnetic field is also recognized as being closely linked to CMEs (Wang 2002; Wang et al. 2005a,b). They suggest that a long eruptive prominence and its overlying coronal cavity, as well as the ambient corona, are the pre-event structures that erupt to become a three-component CME (Webb 2000). Thus, CMEs seem to involve both the smaller scale activity and this destabilization of large-scale coronal structures. Since the most commonly associated activity on a small scale are very likely not the main driving force for CMEs (e.g. Hundhausen 1999; Lin 2004), it becomes important to understand the CME origins from the configuration and evolution of rather large-scale magnetic structures.

As suggested by Zirin (1985), there might be a hierarchy of solar activity. From mini-filament eruptions (Wang et al. 2000) on the quiet Sun to flares in ARs, to global CMEs, activity takes place on a small-scale, on AR scale, and on a large or global scale, respectively. Each level of activity is proposed as the manifestation of magnetic structures destabilizing on the corresponding scale (Wang 2002). For example, flares or AR filaments seem to be specified by the sunspot fields on AR scale. So it is suggested that each CME may have a corresponding source magnetic structure with an obviously large spatial scale. Moreover, those large-scale magnetic structures that host CMEs may appear to be an intrinsic component of solar magnetism. Their destabilization, expansion, and eruption into interplanetary space are the basic processes that lead to CMEs.

To understand CME initiation and onset mechanisms, the characteristic magnetic evolution of large-scale magnetic structures should be studied or else meaningful results can never be obtained in the studies of the CME mechanism (Wang et al. 2002b). However, there have so far been no systematic efforts to investigate the large-scale source structures of CMEs.

The current study attempts to determine whether or not we can identify either some typical large-scale magnetic structures or patterns that may be considered as the pre-eruption magnetic topology or parent magnetic structures of CMEs. To make the study useful for CME prediction, we chose the primary data base as the commonly-accessible MDI synoptic charts, in which large-scale magnetic structures can be adequately revealed, and selected the full disc EIT and the soft X-ray and $H\alpha$ intensity structures as necessary supplements. Our purpose was to identify a few types of large-scale structures in photospheric magnetic fields that are closely correlated with the initiation and development of CMEs. The basic logic is to first allocate the CME-associated activity events, say filament eruptions, flares, and/or relevant ARs, in the MDI magnetic synoptic charts, then to extract the common features of these CME-prolific large-scale magnetic structures, and finally to develop the necessary statistics on the different levels of CME productivity for each type of large-scale magnetic structures.

The data analysis is presented in the next section, while Sect. 3 describes the categories of the large-scale source magnetic structures of CMEs. Section 4 presents the statistics, and the conclusion and discussion are given in the last section.

2. Data analysis

The successful missions of SOHO and Yohkoh made disc observations possible, particularly for earth-directed CME initiations. To avoid ambiguity in locating CME-associated surface activity, as discussed by Feynman & Martin (1995), only earth-directed halo CMEs were selected in our statistics. A CME with span angle greater than 130° is referred to as a halo CME in our approach.

CMEs were selected from the catalog on the website of http://cdaw.gsfc.nasa.gov/CME_list/ in the interval from Mar. 1997 to Dec. 2003, as observed by LASCO aboard SOHO. To clearly identify the earth-directed halo CMEs and to study their large-scale source regions, many other spaceborne and ground-based observations were analyzed. We explored the observations from the instruments EIT, LASCO, and MDI on SOHO. In addition, Yohkoh SXT images were necessary, as well as $H\alpha$ filtergrams, which come from Big Bear Solar Observatory (BBSO), Huairou Solar Observing Station (HSOS), Hiraio Solar Terrestrial Research Center (HSTRC), and Holloman Air Force Base (HAFB).

Two criteria for identifying these earth-directed halo CMEs are discussed in the paper by Zhou et al. (2003). One is that the associated surface activity appeared in the time interval (*CME initiation time* ± 30 min). Here the *CME initiation time* means the approximate time of CME initiation from the solar surface. It was obtained by inverse extrapolation of the CME front from $2.2 \sim 30 R_\odot$ to $1 R_\odot$ according to a linear fitting of height-time curves based on LASCO C2/C3 observations. Most CME initiation times were taken from SOHO LASCO CME Category (see http://cdaw.gsfc.nasa.gov/CME_list/), and a small number of them were extrapolated by the authors. The other criterion is that the surface activity's position identified in the EIT images was under the span of the associated CME or just near the span edge. If both criteria were satisfied, the CME was considered to be Earth-directed. A total of 288 earth-directed halo CMEs from Mar. 1997 to Dec. 2003 were identified well.

This database provided nearly complete temporal coverage of the observations. The MDI synoptic charts in particular provide a good opportunity for studying large-scale source regions of CMEs. Most CMEs, whatever their associated surface activity, are initiated within some type of large-scale, well-organized, magnetic field regions (Hundhausen 1988). To explore the properties of large-scale magnetic structures, the positions of CME-associated surface activity in EIT observations were allocated to the corresponding MDI synoptic charts. As shown in Fig. 1, a CME-associated flare on April 26, 2001 was identified from an EIT image (see the black arrow), with its central location (N23W05) considered as the CME initiation site. This initiation site was further allocated on the corresponding MDI synoptic chart (asterisk in the left panel). Then, we investigated the large-scale source structures of all the 288 earth-directed CMEs by combining the MDI synoptic charts with the other SXR, EUV, and $H\alpha$ observations.

From the MDI synoptic charts, it was found that the CME initiation sites are often located in some large-scale magnetic structures that present regular magnetic morphologies in the

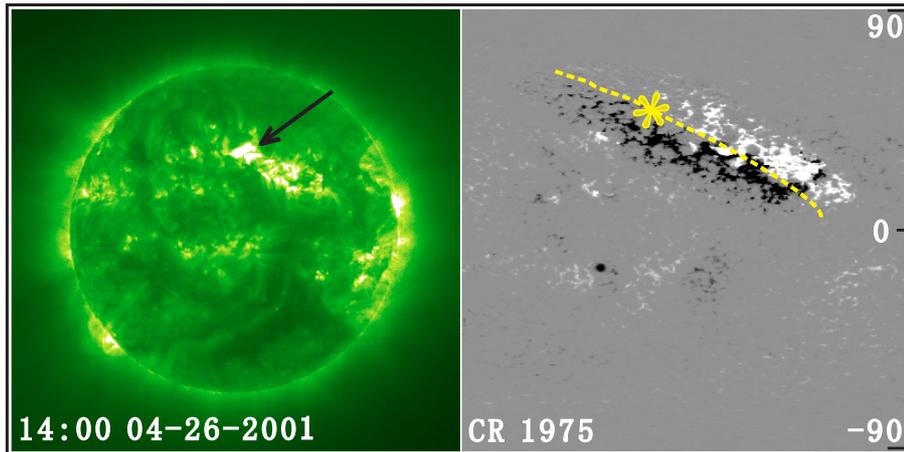


Fig. 1. Allocating a CME associated surface activity in the corresponding MDI synoptic chart according to its position in EIT images. The surface activity is indicated by a black arrow in the left EIT image, and its position is shown by a asterisk on the right MDI synoptic chart. The right panel also indicates the definition of an extended magnetic bipole in the MDI synoptic chart; the dashed line denotes the magnetic neutral line of the EBR.

photosphere. One of them is of particular interest: a coherent large-scale bipolar flux region. By coherent we mean that the large-scale magnetic bipoles follow the Hale polarity law for ARs in each solar cycle and also change their magnetic orientations from one cycle to another cycle. It is natural to call these large-scale magnetic structures *extended bipolar regions* (EBRs) (see the right panel of Fig. 1). In the 23rd Solar Cycle, the leading polarity of an EBR in the northern hemisphere is positive, while negative in the southern hemisphere.

The size of an EBR in this study falls in the range of $34^\circ \sim 197^\circ$ in longitude and of $33^\circ \sim 83^\circ$ in latitude. As an entity, an EBR region involves flares, ARs and quiescent filaments, magnetic flux eruption, and magnetic shearing (Feynman & Hundhausen 1994; Feynman 1997). All these surface activity events are observed to be possibly associated with CMEs. Although it is not known exactly whether EBRs are the parent magnetic structures of CMEs, many CMEs have been found to close correlate with EBRs. Therefore, they are considered as a form of large-scale magnetic field structure that is associated with CME initiation. In order to show the large-scale background magnetic structures more clearly, we sometimes smoothed the MDI synoptic data over $10 \sim 20$ pixels.

3. Categories of CME large-scale source structures

Based on the combined analysis of MDI magnetic field data and other multiple-wavelength observations, the large-scale source structures of CMEs were classified into four different categories (see Fig. 2): Category One (C1), EBRs (top row); Category Two (C2), transequatorial magnetic loops (the second row); Category Three (C3), transequatorial filaments and their associated magnetic fields (the third row); and Category Four (C4), long filaments along the boundary of EBRs (bottom row). The asterisks in the figure indicate the CME initiation sites in MDI synoptic charts.

3.1. Category One, EBRs

After allocating the CME initiation sites in the corresponding MDI synoptic charts, we found that a large fraction of them are situated in EBRs. There are two kinds of association between CMEs and magnetic activity that appear inside EBRs as indicated in the top two panels of Fig. 2. One is that CMEs are associated with long filament eruptions above the magnetic neutral lines (polarity inversion lines) of the EBR, which we will call as C1(a). The eruptive filaments can be identified from both EIT images and $H\alpha$ filtergrams. They often have same lengths as the EBR neutral lines (see the black line in the top left panel of Fig. 2). The other C1(b) is that CMEs are related to AR activity in EBRs (top right panel of Fig. 2). The AR activity events include flares, AR filament eruptions, magnetic surges, and possible magnetic flux changes. There are 104 CMEs whose source structures were identified as EBRs. Two examples are demonstrated to explain the two kinds of associations in this category.

The first example is a CME that occurred on Oct. 25, 1999 associated with a filament eruption in an EBR. The leading edge of the halo CME first appeared southward at 14:06 UT in the field of view of LASCO C2 (see Fig. 3A). The associated filament eruption began at 13:36 UT. The post-flare loops that formed after its eruption are shown in EIT images (arrow in Fig. 3B). The filament in its pre-eruption stage can be observed clearly in an $H\alpha$ filtergram (Fig. 3C). By allocating the CME associated surface activity in the corresponding MDI synoptic chart in Carrington Rotation (CR) 1955 (Fig. 3D), it can be seen that the $H\alpha$ filament is at the site of an EBR neutral line in the southern hemisphere. The quadrangles in Figs. 3C and 3D outline the same filament in the $H\alpha$ image and the MDI synoptic chart, respectively. With the same identifying method, 41 CMEs are found to relate to long eruptive filaments above the magnetic neutral lines of EBRs.

The remaining 63 CMEs in this category were recognized to be associated with AR activity in EBRs. The associated ARs were in the close vicinity of the EBR neutral lines. Figure 4 shows the second example that belongs to this kind of CME.

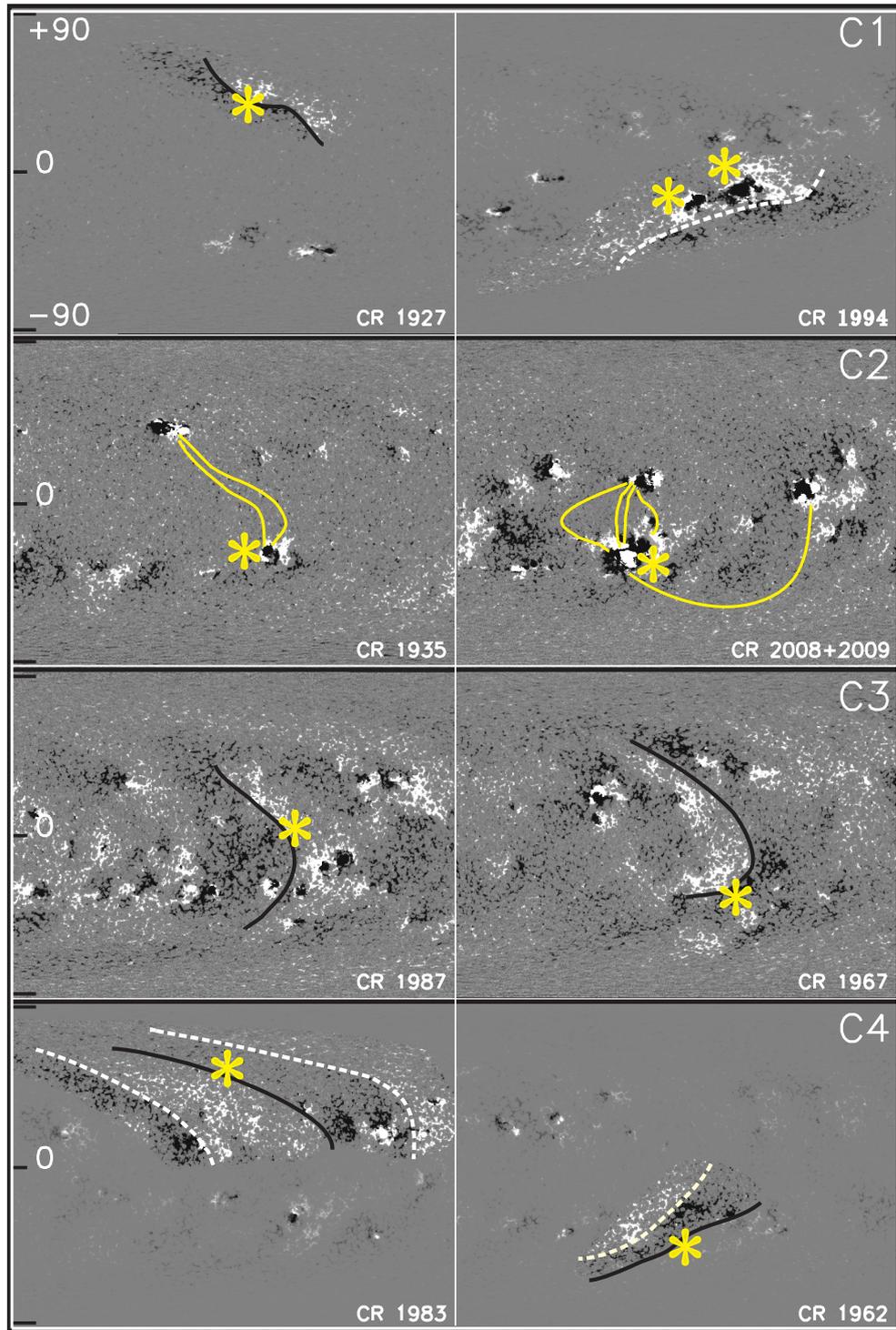


Fig. 2. The four categories identified for CME large-scale source structures shown on MDI synoptic charts; from top to bottom row: Category One (C1), extended bipolar regions (EBRs); Category Two (C2), transequatorial magnetic loops; Category Three (C3), transequatorial filaments and their background magnetic fields; and Category four (C4), long filaments along the boundary of EBRs. In this figure, the asterisks indicate the positions of CME-associated surface activity; the black solid lines in the graph denote filaments; the white dash lines show the magnetic neutral lines of EBRs; the light solid lines indicate transequatorial loops. The scale of each panel in this figure in latitude and longitude is $180^\circ \times 180^\circ$.

A CME on July 26, 2002 first appeared at 22:06 UT in the field of view of LASCO C2 and continuously spread southeastward (see Fig. 4A). Its associated flare started at about 21:00 UT in the position of S22E22 according to EIT observations (e.g.,

Fig. 4B). There were AR filaments (see Fig. 4C) erupting in the AR that accompanied the flare activity. After locating the CME-associated AR activity in the MDI synoptic chart in CR 1992, we found that the relevant AR was located in an EBR,

a coherent large-scale magnetic structure as shown in Fig. 4D. The EBR is illustrated even more clearly by artificially weakening its surrounding magnetic features. A dash in Fig. 4D indicates the EBR neutral line, near which the associated AR lies.

In total, there are 104 CMEs initiated in EBRs, which themselves constitute 36% of all the 288 earth-directed halo CMEs.

3.2. Category Two: transequatorial magnetic loops

The second category discerned for CME-associated large-scale structures is comprised of transequatorial magnetic loops, evidence of which was first observed in Skylab X-ray data (e.g., Chase et al. 1976; Svestka et al. 1977; Pevtsov 2000). They may develop between existing ARs or between a mature region and new magnetic flux shortly after flux emergence. Approximately one-third of all ARs on the Sun exhibit transequatorial loops (Pevtsov 2000). Harra et al. (2003) discovered flare behavior of transequatorial magnetic loops. As shown in the second row of Fig. 2, the CME-associated transequatorial loops observed in EIT or SXT images are overlaid in the corresponding MDI synoptic charts. They are represented by solid lines, and they stride the opposite solar hemispheres. During the erupting process of CME-associated surface activity, the plasma within the loop forms part of the CME material.

Figure 5 presents a CME on Nov. 5, 1998 where its large-scale source structure is recognized as a transequatorial loop. From the LASCO C2 observations (see Fig. 5A), we find that the CME propagated northwest from its first appearance at 20:44 UT. Its associated surface activity, a GOES M8.4 flare, began at 19:00 UT in the position of N22W18 identified from the EIT image (black arrow in Fig. 5B). The flare is spatially and temporally associated with the transequatorial loop in Fig. 5B. The X-ray analog of the transequatorial loop is also seen in the SXT image (arrow in Fig. 5C). Figure 5D shows the flare and the transequatorial loop in the corresponding MDI synoptic chart in CR 1942. The transequatorial loop connects a complex AR in the northern hemisphere with a plage region in the southern hemisphere. All together, they constitute a large-scale source structure of the CME.

In order to get some idea of the height of the identified transequatorial loops observed from EIT or SXT images, we selected an associated transequatorial loop on Nov. 6, 1997, where the distance between the two footpoints is very long, as an example. It was assumed that the distance between two footpoints of a transequatorial loop was directly proportional to its height. We calculated the loop's height following Loughhead et al. (1983). This method is based on the assumptions that (1) the loop's central axis lies in a plane, (2) its footpoints can be located, and (3) it is symmetrical in its own plane about an axis at right angles to the line joining the footpoints. As a result, we get the loop's height of 4.2×10^5 km. For this example, the distance between two footpoints of the observed X-ray loop is 6.4×10^5 km in heliographic coordinates, and its height is $2/3$ of its footpoint distance. It would be quite safe to assume that the height of a transequatorial loop is 0.5–1.0 times of its footpoint distance by considering the different shapes of the loops. Since the distance between the footpoints of this transequatorial loop

was almost the longest one in our sample, we estimated that the height range of the transequatorial loops identified in our work, which can be observed from EIT or SXT images, may not be more than 5.0×10^5 km. However, using the extrapolation method of a potential magnetic field (Wang et al. 2002a), it is found that part of the associated transequatorial magnetic lines was higher than $1.0 R_{\odot}$, i.e., 7×10^5 km. Therefore, it cannot be excluded that some associated transequatorial loops might be even higher than 5×10^5 km in the corona, outside of the field of view of observations. In addition, some transequatorial loops may lack necessary SXR data. Under these conditions, they may not be easily identified from EIT or SXT observations.

Alternatively, dimmings are sometimes associated with large transequatorial loops (Maia et al. 1999; Wills-Davey & Thompson 1999). The observed dimmings are due to a decrease in plasma density during the opening of the transequatorial loops (Delannée & Aulanier 1999; Harra & Sterling 2003), so the transequatorial dimmings can be considered as the proxies of transequatorial loop-like structures. Dimmings can be observed well in EUV (Dere et al. 1997; Bumba et al. 1998; Gopalswamy et al. 1998; Thompson et al. 1998; Delannée et al. 2000). Thus by using those EIT data that have full coverage for all the 288 earth-directed CMEs, transequatorial dimmings are identified as the manifestation of associated transequatorial loops from EIT base-difference or running-difference images for some events. As indicated in Fig. 6, the associated surface activity of a CME on Nov. 24, 2000 is an X-ray flare of X2.3 class (see the arrow in Fig. 6A). Since we could not find an SXT image before 05:12 UT on Nov. 24, a SXT image at 09:18 UT on Nov. 23 was presented. From the EIT or SXT images (see Figs. 6A, 6B), we could not easily observe the associated transequatorial loop connecting AR 9236 with a region in the southern hemisphere. However, there was transequatorial dimming across the two solar hemispheres (Panel C). In this case, we consider that the CME is related to transequatorial loops. Moreover, using the extrapolation method of potential magnetic field (Wang et al. 2002a), a bundle of transequatorial magnetic lines were found to exist above the transequatorial dimming (arrow in Panel D). These magnetic lines may be considered as the associated transequatorial loops.

As a result, 116 CMEs, whose source structures were associated with transequatorial magnetic loops in SXT or EIT observations, were identified in Category C2. They constitute up to 40% of all the 288 earth-directed CMEs. In most cases, the individual flux systems tend to have the same helicity sign or chirality (Wang et al. 2004). As suggested by Canfield et al. (1996) and Pevtsov (2000), only the interconnected regions with the same helicity sign can form transequatorial loops. That is to say, the transequatorial loops, together with the interconnected regions, have the same helicity sign in their magnetic field and represent at least a part or all of a large-scale intercoupled magnetic flux system.

However, as a rule for hemispheres (Seehafer 1990; Pevtsov et al. 1995, 2001; Abramenko 1996; Bao & Zhang 1998), magnetic flux regions on the two solar hemispheres generally have opposite signs of helicity. A transequatorial loop has the same helicity sign, but connects magnetic flux regions

that are located on the opposite hemispheres, which implies that one foot of the transequatorial loop should be surrounded by magnetic flux with opposite sign helicity. Wang et al. (2004) suggested that the interaction and reconnection of flux systems with opposite sign helicity are key elements in the magnetism of CME initiation. This might be the reason so many CMEs are associated with transequatorial loops, which appear to be the favorite pre-CME large-scale source structures. This revelation may be useful for CME predictions.

3.3. Category Three: transequatorial filaments and their associated magnetic fields

Filament eruptions, one of the earliest known forms of mass ejections from the Sun, are the near-surface activities that are most frequently associated with CMEs, and they have received considerable attention since the late 1900s (Webb et al. 1976; Munro et al. 1979; Webb & Hundhausen 1987; St Cyr & Webb 1991; Tandberg-Hanssen 1995; Zhang & Wang 2000; Gopalswamy 2003). They can erupt on different scales, from mini-filaments to AR filaments to long eruptive filaments. Since sometimes long filament eruptions themselves can reach the scale of a CME, we consider these filaments and their associated magnetic fields as probable large-scale source structures of CMEs. The length of the long eruptive filaments considered are at least greater than 300 arcsec, and the longest of them can reach 1900 arcsec. Except for some long eruptive filaments located in EBRs, the associated long filaments are further grouped into transequatorial filaments (C3) and long filaments along the boundaries of EBRs (C4), which are thought of as two forms of CME large-scale source structures. Wang (2002) used the term of giant filament and filament channel to describe this type of CME parent magnetic structure.

One example that illustrates the CMEs correlated with eruptive transequatorial filaments is presented. Wang and his co-authors first recognized the role of transequatorial filaments in the initiations of CMEs (Wang 2002; Wang et al. 2005a,b). As indicated in Fig. 8, a CME-associated eruptive transequatorial filament began to elongate and twist from 11:00 UT on Sep. 12, 2000, accompanied by an M1.0 flare in X-ray importance. At 11:54 UT, the corresponding CME first appeared in the field of view of LASCO C2 and expanded southwest (see Fig. 7A). After the filament eruption, post-flare loops formed in EIT observations (see the arrow in Fig. 7B). Since there were no clear $H\alpha$ observations to show the morphology of the pre-erupting filament, an $H\alpha$ image after the filament eruption is given as Fig. 7C. The eruptive transequatorial filament is identified in the MDI synoptic chart in CR 1967 of Fig. 7D. The filament lies along the boundary of a transequatorial background magnetic flux with the same polarity. In fact, for the large-scale magnetic structures of the CMEs in C3, we could always see that the enhanced magnetic flux of the same polarity concentrated in the lower latitudes in MDI synoptic charts, which go through the opposite hemispheres on the Sun. This is the common property of the background magnetic morphology for transequatorial filaments.

Just like transequatorial loops, since transequatorial filaments go through the opposite hemispheres with different vorticity and helicity properties, it is speculated that transequatorial filaments and their magnetic arcades would also be unstable. But unlike the transequatorial loops, a transequatorial filament and its magnetic arcades seem to present a large-scale magnetic shear in the solar atmosphere. Their associated CMEs are suspected having some distinct properties, which will be studied in our next work.

A total of 37 CMEs were identified as being associated with transequatorial filament eruptions in this category that includes 13% of all the CMEs.

3.4. Category Four: filaments along the boundaries of EBRs

In addition to the related eruptive transequatorial filaments, long eruptive filaments along the boundaries of EBRs and their related magnetic fields are classified as the fourth category of CME large-scale source structures. This group can exist along the boundary between two/three EBRs or can separate the polar coronal holes from the medium to high latitude EBRs. In the latter case, the filaments act as polar crown filaments (McIntosh 1980). CMEs associated with these filaments were studied by Zhou et al. (2005).

An example is given to show this category. A CME on Jun. 5, 1998 was related to the eruption of a filament along the boundary of three EBRs. The CME first appeared at 7:02 UT during LASCO C2 observations. The associated eruptive filament began to erupt at 04:39 UT in EIT observations. Figure 8B presents post-flare loops after the filament eruption. An $H\alpha$ image on June 4, 1998 shows the filament before its eruption (in Fig. 8C). The eruptive $H\alpha$ filament is further mapped in the corresponding MDI synoptic charts in CR 1936 and 1937 (black line in Fig. 8D). It was located along the boundary of three EBRs. In order to show the associated EBRs more clearly, a procedure was used to make the other magnetic features weak, smoothing the MDI synoptic data over 10 pixels and displaying it in a restricted range. There are 31 CMEs (11%) whose related large-scale source structures were grouped into C4.

4. Statistics

Using the observations from the SOHO LASCO, EIT, MDI synoptic & daily magnetograms, Yohkoh SXR, GOES X-ray, and $H\alpha$ observations, we extended the CME sample used in Zhou et al. (2003) to 288 earth-directed halo CMEs from Mar. 1997 to Dec. 2003, including the rising and the declining phases of Solar Cycle 23. We present the first systematic study of large-scale source magnetic structures of earth-directed halo CMEs. Detailed information for each CME is appended in Table A1, where we list the CME category according to the large-scale source structure, date, first time seen in LASCO C2 observations (TM), central position angle (CPA), span angle (Width), linear fit speed (Speed), position of associated surface activity on the solar surface (Position), and the NOAA number of related ARs. If a CME is correlated with more than one AR,

Table 1. Categories of CME large-scale source structures

Associa. large-scale source structures	CME number	percent
C1, EBRs	104	36%
C2, transequatorial magnetic loops	116	40%
C3, transequatorial filaments	37	13%
C4, filaments along the boundaries of EBRs	31	11%
Total earth-directed CMEs	288	100%

Table 2. Associations of CMEs with ARs and long eruptive filaments

Associations	CME number	percent
related to ARs	231	80%
related to long eruptive filaments	109	38%
Total earth-directed CMEs	288	100%

we only give one of the NOAA numbers of the CME-associated ARs.

As a result, the identified large-scale source structures of all the 288 CMEs are classified into four groups: (C1) EBRs, (C2) transequatorial magnetic loops, (C3) transequatorial filaments and their associated background magnetic structures, (C4) long filaments along the boundaries of EBRs. Among them, the EBRs and the transequatorial magnetic loops are significantly CME-prolific. The associated CMEs constitute 36% and 40% of all the earth-directed CMEs. Though the other two identified large-scale source structures are only related to a small fraction of CMEs, they present some distinguished characteristics that are favorable to the occurrence of CMEs. The different levels of CME productivity for each class of large-scale magnetic structures is summarized in Table 1.

Another statistic about the associations between CMEs and ARs and long eruptive filaments is listed in Table 2. Regardless of the background magnetic fields of associated surface activity, about 38% CMEs are related to long filament eruptions. This means that the instabilities of long filaments correlate closely with CMEs. For the relationship between ARs and CMEs, about 80% CMEs are related to ARs, which is similar to results in Zhou et al. (2003).

The statistics presented in this paper follow a rule that when a CME was related to more than one type of large-scale magnetic structure, we always chose the structure which appeared more specific or characteristic as the CME source structure. For example, if a CME-associated surface activity happened in an EBR and, at the same time, took place in association with transequatorial magnetic loops, we selected the transequatorial magnetic loops as the large-scale source structure of the given CME. The reason is that transequatorial loops are more specific, and they represent a larger magnetic flux system, which an EBR cannot fully cover.

Although the identity of the large-scale source magnetic structures of CMEs is based on detailed analysis of a combined data set, several key factors still exist that may bring uncertainties into the statistics. First, for some CMEs, especially those initiated close to the solar limb, their associated surface activity may be misidentified. They may even be Earth-away CMEs. The lack of coronal observations in the range of $1.0 \sim 2.2 R_{\odot}$

severely constrained us from directly imaging the early development of CMEs, while the low cadence of LASCO and EIT observations would not allow us to accurately determine the time of CME initiation or the associated surface activity (Zhou et al. 2003). We estimated that all the above inaccuracy may be less than 5% of the total 288 CMEs. Secondly, the identity of transequatorial loops may not be accurate in the following situations: (1) when the related transequatorial loops are located at the limb of the Sun, they suffer from heavy projection effects; (2) if heated to higher temperatures or situated in the higher corona, they may be put out of the range ($\leq 5 \times 10^5$ km) of EIT or SXT observations; and (3) on the other hand, some resemblant or fuzzy structures in EIT or SXT observations may be mistaken for transequatorial loops. Since we confirm the associated transequatorial loops by direct observations of EIT and SXT images where possible, together with the observable transequatorial dimming and potential extrapolation of 3-dimension magnetic lines of force, the ambiguity could be minimized. The fact that the data base covers almost 7 years and a large sample makes the statistics meaningful.

5. Discussion and conclusion

The large-scale source structures are identified and classified into four groups (C1)–(C4) for the 288 earth-directed halo CMEs: (C1) extended bipole regions (EBRs), (C2) transequatorial magnetic loops, (C3) transequatorial filaments and their associated background magnetic structures, and (C4) long filaments along the boundaries of EBRs. The associated CMEs in each category constitute 36%, 40%, 13%, and 11% of all the 288 earth-directed CMEs, respectively. These four categories present the large-scale characteristics of CME source magnetic structures. In addition, if only considering the long eruptive filaments from the four categories, 38% of the CMEs are related to long filament eruptions. It presents a close relationship between CMEs and long eruptive filaments (Wang 2002). We also look at the relation between CMEs and ARs. AR fields have a smaller scale than the large-scale source regions described in this paper, but they show great magnetic complexity with strong magnetic intensity. They may interact with larger scale structures and possibly lead to the instabilities of large-scale magnetic structures through magnetic emergence and/or cancellation. Similar to the result of Zhou et al. (2003), approximately 80% of the CMEs are related to ARs in the enlarged sample. The identity of favorable large-scale magnetic structures supplemented with detailed vector field observations in relevant ARs may make the CME predictions possible in the future.

In Zhou et al. (2003), we illustrated the close correlations between CMEs and solar surface activity. All the CMEs are accompanied by some solar surface activity in the form of either flares, or filament eruptions, or both. However, the associated magnetic evolution, say in an AR, normally presented no difference among flares with and without CMEs. All of the eruptive activity events, e.g., flares and filament eruptions, are driven by the rather similar process observed in the photosphere, which was interpreted by Song et al. (2002) as the transport of magnetic energy and complexity into the higher solar atmosphere.

We speculated that the associated surface activity may act as either triggers of the instability of the globally-coupled magnetic flux systems with different spacial scales, or the local manifestation of the instability, while the real basis for deciding CME properties should be the pre-CME large-scale source structures. Though some studies about the large-scale magnetic activity associated with CMEs have already been carried out, the analysis in this paper is the first attempt to investigate the large-scale source structures of CMEs based on the MDI magnetic synoptic charts.

This is only the first step in our series of studies to identify and classify the large-scale magnetic structures that favor CMEs. Work needs to be done to evaluate the reliability and feasibility of the categories. Further, for example, we need to know the topological connectivity of the 3-D magnetic lines of force for each kind of large-scale source structure, and whether we can use their properties to distinguish between the CMEs that correspond to different groups of source structures. In this work, CME-associated long eruptive filaments distributed in three of the four categories according to their background magnetic fields: C1(a), long filaments above the neutral lines of EBRs; C3, transequatorial filaments; and C4, long eruptive filaments along the boundaries of EBRs. The average CME velocities related to long filament eruptions in the 3 categories are 690, 894, and 827 km s⁻¹, respectively. Large errors exist in the CME speed estimations because of projection effects, but it is feasible that the CMEs associated with C1(a) are slower than the ones related to the other two categories. Therefore, identifying the possible large-scale source magnetic structure for each CME is only the first step in CME studies. In addition to evaluating the validity of this classification, further efforts need to be made to explore the physical properties of each large-scale source structure and to understand whether or not the structural characteristics on the solar surface can affect the properties and geo-effectiveness of associated CMEs.

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