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Cyclical Behavior of Coronal Mass Ejections

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Abstract With the use of coronal mass ejections (CMEs) observed by the Large Angle and Spectrometric Coronagraph (LASCO) onboard the *Solar and Heliospheric Observatory* (SOHO) from January 1996 through December 2005, it is found that, for the cyclical activity of CMEs, there is surprisingly no equatorward drift at low latitudes (thus, no "butterfly diagram") and no poleward drift at high latitudes, and no antiphase relationship between CME activity at low and high latitudes. The cyclical behaviors of CMEs differ in a significant way from that of the small-scale solar photospherical and chromospherical phenomena. Thus, our analysis leads to results that are inconsistent with a close, physical relationship with small-scale aspects of solar activity, and it is suggested that there is possibly a single so-called large-scale activity cycle in CMEs.

Keywords Coronal mass ejections · Solar cycle, observations

1. Introduction

Coronal Mass Ejections (CMEs), the large-scale eruptions of plasma and magnetic fields from the Sun (Gopalswamy *et al.*, 2000; Webb *et al.*, 2000), are believed to be the main sources of strong interplanetary disturbances, which cause many moderate to intense geomagnetic storms (Wang, Ye, and Wang, 2001; Wang *et al.*, 2004). So, a study of CMEs is an important topic that relates directly to the space environment. Since CMEs were first discovered in 1971 using the seventh *Orbiting Solar Observatory* (OSO-7) coronagraph (Tousey, 1973), they have been observed by several space-borne coronagraphs and ground-based instruments. In this solar cycle, the Large Angle and Spectrometric Coronagraph (LASCO) onboard the *Solar and Heliospheric Observatory* (SOHO) (Brueckner

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et al., 1995) mission observed the most CMEs, providing us with a great opportunity to examine the statistical properties of CMEs, such as their speed, acceleration, travel time (from the Sun to 1 AU), width, latitude, and initial location (Cane and Richardson, 2003; Cremades and Bothmer, 2004; Gopalswamy, 2004; Gopalswamy *et al.*, 2001; Wang, 2002; Yashiro *et al.*, 2004; Yurchyshyn *et al.*, 2005; Zhou, Wang, and Cao, 2003; Zhou, Wang, and Zhang, 2006). Some statistical characteristics of the activity of CMEs have been found, such as the occurrence rate of CMEs tending to track the activity cycle in both amplitude and phase, the distribution of the speeds of CMEs showing a log-normal distribution, and so on (Gopalswamy *et al.*, 2003; Howard *et al.*, 1985; Hundhausen, 1993; Munro *et al.*, 1979; St. Cyr, Howard, and Sheeley, 2000; Webb, 1991; Webb and Howard, 1994; Yurchyshyn *et al.*, 2005).

As we know, one of the best-known aspects of a normal solar-activity cycle is the equatorward drift of sunspot latitudes over the approximate 11 years between successive minima in activity. This effect is often displayed as a scatterplot of individual sunspot latitudes *versus* time for one or more activity cycles; the resulting pattern is commonly referred to as a "butterfly diagram" (Hundhausen, 1993). At the same time, a low-latitude branch moves poleward from latitudes of about 50° – 60° and reaches the two poles around sunspot maximum, namely the "rush to the pole" phenomenon (Stenflo, 1988; Makarov and Sivaraman, 1989). The other important aspect of a normal solar-activity cycle is that solar activity at low latitudes is in antiphase with solar activity at high latitudes (Sheeley, 1991; Li *et al.*, 2002). In this paper, we will report cyclical behavior of CMEs for the aforementioned aspects, which usually appear in solar photospheric and chromospheric phenomena and surprisingly do not appear in the activity of CMEs.

2. Cyclical Behavior of the Coronal Mass Ejections

Sunspots, active regions (ARs), and solar flares are called "small-scale solar activity"; they are much smaller than CMEs, which are called "large-scale solar activity" (Hundhausen, 1993). The primary CME data needed for this study are obtained by the SOHO mission's LASCO experiment (Brueckner *et al.*, 1995) for cycle 23, which come from a catalog of observations of SOHO/LASCO and are available at the Web site http://cdaw.gsfc.nasa.gov/CME_list/. For each CME event, the catalog contains height – time plots, plane-of-sky speeds, central position angles (CPAs), and so on. We convert CPAs to projected heliographic latitudes (Yashiro *et al.*, 2004). For example, CPAs of 0°, 90°, 180°, and 270° correspond to the apparent latitudes of 90°, 0°, −90°, and 0°, respectively. A total of 378 halo CMEs are excluded from the total of 10 513 CMEs for which the CPAs cannot be determined. Figure 1 shows the apparent central latitudes of CMEs varying with time, observed with the LASCO from January 1996 through December 2005, covering about a solar cycle. The monthly mean latitudes of CMEs at low latitudes (0° – 50°) in the northern and southern hemispheres are calculated and plotted in the figure, as well as the mean latitudes of CMEs over half a year at high latitudes (60° – 90°), respectively, in the northern and southern hemispheres. The figure clearly indicates that the mean latitudes of CMEs at high latitudes hardly change with time in a solar cycle, having no poleward drift and thus no "rush to the pole" phenomenon. The monthly mean latitude of CMEs at low latitudes shifts from the Equator to about 20° within about two years starting from 1996, the minimum of cycle 23, then it hardly changes with time in the following ≈ eight years of the cycle, having no "equatorward drift" and thus no "butterfly diagram."

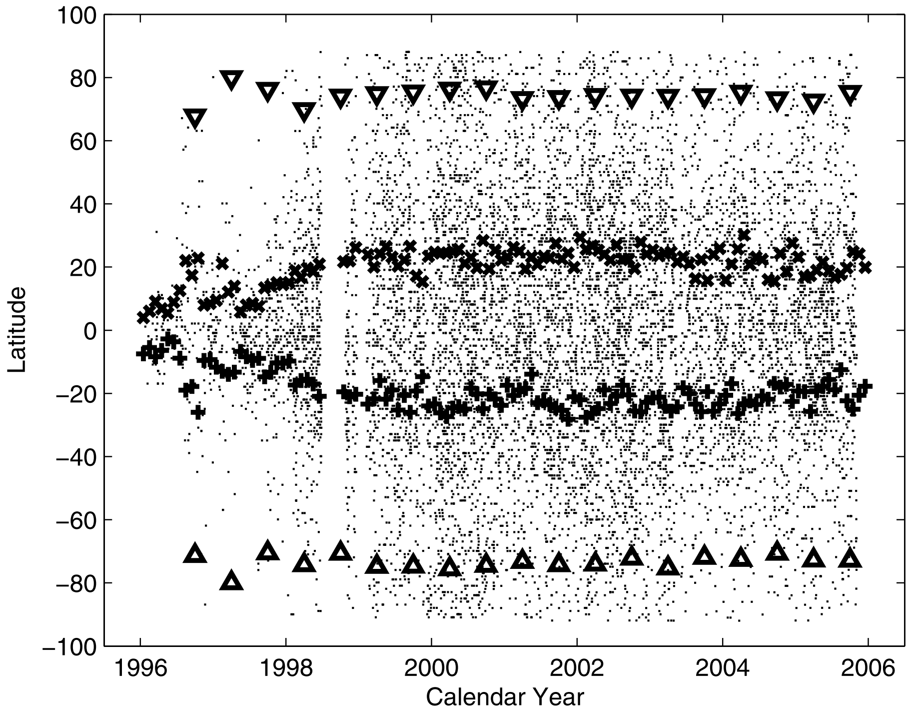

Figure 1 The apparent central latitudes of CMEs changing with time, observed with LASCO from January 1996 through December 2005. The monthly mean latitudes of CMEs at low latitudes (0° – 50°) in the northern and southern hemispheres are marked by the symbols + and ×, respectively. The mean latitudes of CMEs over half a year at high latitudes (60° – 90°) in the northern and southern hemispheres are marked by the symbols △ and ▽, respectively.

For small-scale solar active events, such as sunspots and polar faculae, latitudes of 0° – 50° are usually regarded as low latitudes and 60° – 90° as high latitudes, and solar activity at low latitudes is in antiphase with solar activity at high latitudes (Sheeley, 1991; Sakurai, 1998; Li *et al.*, 2002). Thus, here we regard CMEs observed in the band 0° – 50° as the activity at low latitudes and in the band 60° – 90° as the activity at high latitudes, as is small-scale solar active events for. We count the monthly occurrence numbers of CMEs, respectively, at low (≤50°) and high (≥60°) latitudes, which are shown in Figure 2. The figure indicates that the activity of CME events at low latitudes seems to have the same phase as that at high latitudes. In the figure are also plotted the monthly mean sunspot numbers, which are from the Web site ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS. It is found that the activity of CME events, respectively, at low and high latitudes seems to have the same phase as the sunspot activity.

To study the phase relationship between the monthly occurrence numbers of CMEs at low and high latitudes, respectively, we performed a cross-correlation analysis of both. Figure 3 shows the result of the cross-correlation analysis, in which the abscissa is the shift of the numbers of CMEs at low (high) latitudes *versus* the monthly mean sunspot numbers, with backward shifts given negative values. The figure indicates that the best (positive) correlation occurs with a correlation coefficient of 0.6913 (or 0.7286) when the numbers of CMEs at low (or high) latitudes is shifted backward by about zero (or three) months. Therefore, the

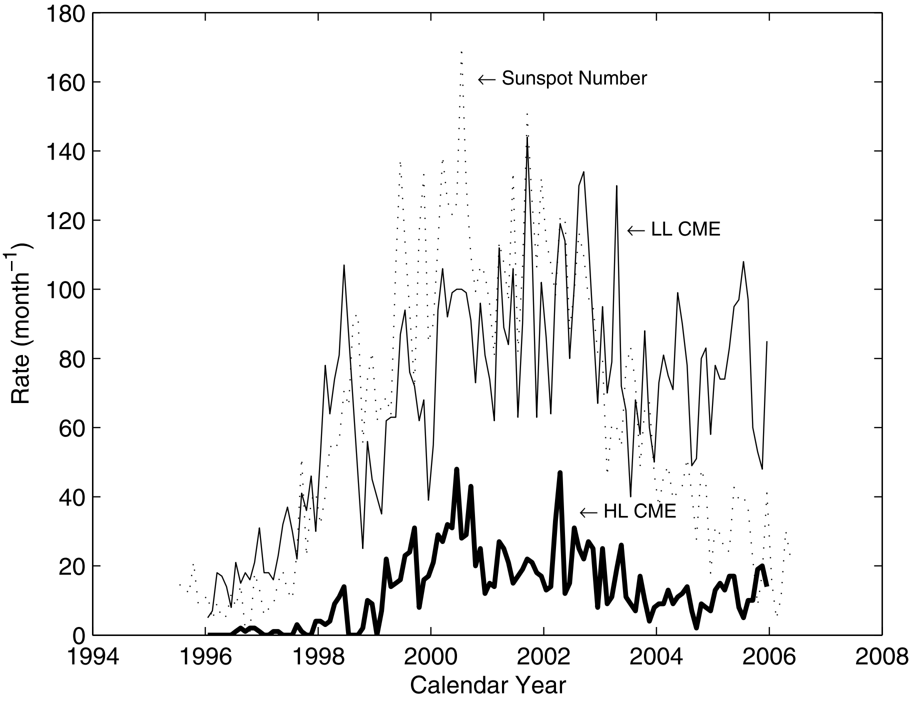

Figure 2 Occurrence rate of CMEs obtained by the SOHO/LASCO coronagraphs compared with the monthly mean sunspot numbers (the dotted line). CME rates corresponding to low (≤50°) and high latitudes (≥60°) are shown by the solid thin line and the solid thick line, respectively, and also marked as LL CME and HL CME, respectively.

activity cycle of CMEs at low latitudes is inferred to be almost in phase with the activity cycle of CMEs at high latitudes, and surprisingly, the antiphase relationship between small-scale solar activity of photospheric phenomena, respectively, at low and high latitudes does not appear in the large-scale activity of CMEs.

3. Results and Conclusions

There is no expectation that sunspots (small-scale activity) have a direct, physical connection to CMEs; they have been introduced as a familiar form of solar small-scale activity that illustrates the behavior of solar magnetic-field structures on the spatial scales directly related to many well-known types of activity (Hundhausen, 1993). The interpretation of CMEs as disruptions of evolving closed magnetic structures in the corona suggests the origin of CMEs (large-scale activity) in magnetic fields with much larger spatial scales than the fields in active regions or flares or even in prominences (Hundhausen, 1993). It is found in the present study that for the activity of CMEs there are no equatorward and poleward drifts and no antiphase relationship between activity at low and high latitudes. The cyclical behavior of CMEs differs in a significant way from that of the small-scale solar photospheric and chromospheric phenomena. Thus, our analysis leads to results that are inconsistent with a close, physical relationship with small-scale aspects of solar activity, and it is suggested that there should possibly be a large-scale activity cycle in CMEs.

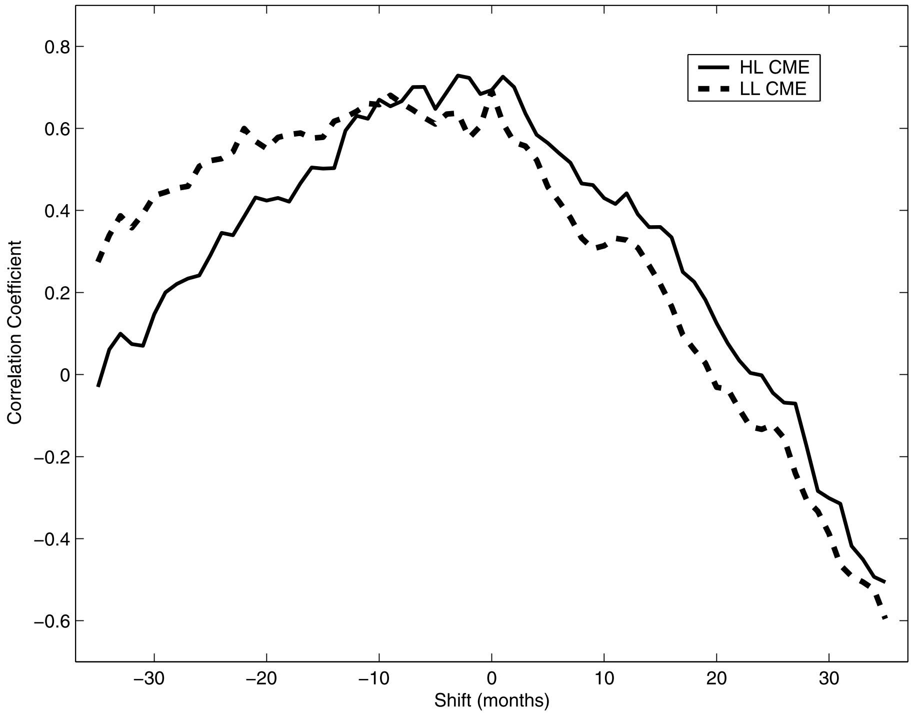

Figure 3 Cross-correlation coefficient between the monthly occurrence numbers of CMEs at low (dashed) and high (solid) latitudes and the monthly mean sunspot numbers.

Thompson *et al.* (2000) studied seven CME events and found that the dimming regions correspond to the white-light extent of the CME better than the flare location. CMEs are sometimes observed arising from a coronal streamer, a pre-existing large-scale structure (Hundhausen, 1993). Active-region interconnecting loops observed in SXR or EUV that link the magnetic regions are related to CMEs (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). Zhou, Wang, and Zhang (2006), through the study of 288 Earth-directed CMEs, found that all of the CMEs were associated with large-scale source structures. As studies of individual CME events suggested, from mini-filament eruptions on the quiet Sun to flares in ARs to global CMEs, activity takes place on a small scale, on the scale of active regions, and on a large or global scale, respectively (Wang *et al.*, 2000). Each level of activity is proposed as the manifestation of magnetic structures destabilizing on the corresponding scale (Wang, 2002).

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