

Solar Cycle Variation of Real CME Latitudes (Postprint)

Authors: Song, Wenbin, Feng, Xueshang, Hu, Yanqi

Date: 2016-12-22T00:00:00+00:00

Abstract

With the assumption of radial motion and uniform longitudinal distribution of coronal mass ejections (CMEs), we propose a method to eliminate projection effects from the apparent observed CME latitude distribution. This method has been applied to SOHO LASCO data from 1996 January to 2006 December. As a result, we find that the real CME latitude distribution had the following characteristics: (1) High-latitude CMEs ($\theta > 60$ degrees, where θ is the latitude) constituted 3% of all CMEs and mainly occurred during the time when the polar magnetic fields reversed sign. The latitudinal drift of the high-latitude CMEs was correlated with that of the heliospheric current sheet. (2) Four percent of all CMEs occurred in the range $45 \text{ degrees} \leq \theta \leq 60 \text{ degrees}$. These midlatitude CMEs occurred primarily in 2000, near the middle of 2002, and in 2005, forming a prominent three-peak structure. (3) The highest occurrence probability of low-latitude ($\theta < 45$ degrees) CMEs was at the minimum and during the declining phase of the solar cycle. However, the highest occurrence rate of low-latitude CMEs was at the maximum and during the declining phase of the solar cycle. The latitudinal evolution of low-latitude CMEs did not follow the Sporer sunspot law, which suggests that many CMEs originated outside of active regions.

Full Text

Preamble

Solar Cycle Variation of Real CME Latitudes

Wenbin Song, Xueshang Feng, and Yanqi Hu

State Key Laboratory for Space Weather, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100080, China

wbsong@spaceweather.ac.cn

Abstract

Assuming radial motion and uniform longitudinal distribution of coronal mass ejections (CMEs), we propose a method to eliminate projection effects from the apparent observed CME latitude distribution. Applying this method to SOHO/LASCO data from January 1996 to December 2006 reveals the following characteristics of the real CME latitude distribution: (1) High-latitude CMEs ($> 60^\circ$, where θ represents latitude) constituted 3% of all CMEs and occurred primarily during periods when the polar magnetic fields reversed polarity. The latitudinal drift of these high-latitude CMEs correlated with that of the heliospheric current sheet. (2) Four percent of all CMEs occurred in the range 45° – 60° . These mid-latitude CMEs appeared mainly in 2000, around mid-2002, and in 2005, forming a prominent three-peak structure. (3) The highest occurrence probability for low-latitude ($< 45^\circ$) CMEs occurred at solar minimum and during the declining phase of the solar cycle. However, the highest occurrence rate of low-latitude CMEs was at solar maximum and during the declining phase. The latitudinal evolution of low-latitude CMEs did not follow the Spörer sunspot law, suggesting that many CMEs originated outside active regions.

Subject headings: Sun: coronal mass ejections (CMEs)

Introduction

Coronal mass ejections (CMEs) are observed with white-light coronagraphs as significant changes in coronal structure moving outward (Skirgiello, 2003). They are believed to be the primary driver of most space weather events, including interplanetary shocks, high-energy particles, and geomagnetic storms (Gosling, 1993). Recently, many studies have investigated the properties of CME source regions to gain insight into the initiation mechanisms of this phenomenon. Subramanian and Dere (2001) found that 41% of CME-related transients are associated with active regions but show no filament eruptions, 44% are associated with eruptions of filaments embedded in active regions, and 15% are associated with eruptions of filaments outside active regions. Zhou et al. (2003) found that 88% of Earth-directed halo CMEs are associated with flares and 94% with eruptive filaments. Regarding the locations of CME source regions, they determined that 79% of CMEs originate from active regions while 21% originate outside active regions. In this letter, we focus on the latitudinal variations of CME source regions to provide clues about CME triggering processes. Skirgiello (2003) proposed a mathematical tool to deduce the real latitude distribution from the apparent latitude distribution. Building upon this idea, we have developed a much simpler and more straightforward method with the same capability to obtain the evolution of real CME latitudes during solar cycle 23.

2. Data

We selected CMEs from the catalog at <http://cdaw.gsfc.nasa.gov/CME> list for the interval January 1996 to December 2006, as observed by SOHO/LASCO.

The SOHO/LASCO coronagraph has continuously imaged the solar corona since 1996, covering a field of view from approximately $1.5 R$ to $32 R$ (Gopalswamy et al. 2003, where R is the Sun's radius). Through preliminary estimation, St. Cyr et al. (2000) found that its CME detection efficiency was no less than 95%. Since CMEs are observed on the plane of the sky, all apparent spatial parameters represent projections of real values onto that plane. The apparent latitude δ derives from the central position angle (CPA), which is defined and listed in the CME catalog by Yashiro et al. When $0^\circ \leq \text{CPA} < 180^\circ$, $\delta = 90^\circ - \text{CPA}$, and when $180^\circ \leq \text{CPA} < 360^\circ$, $\delta = \text{CPA} - 270^\circ$. We excluded complete halo events with an angular width of 360° from our statistics due to difficulty in determining δ .

Considering both CME number and temporal resolution, we divided the entire interval into 22 parts, as shown in Figure 1 [Figure 1: see original paper]. If the time interval for a part is set too short, the CME number becomes too small to represent the real distribution of δ ; if too long, the temporal resolution becomes too poor to clearly reveal solar cycle variations. For each time interval, we computed the occurrence percentages of CMEs corresponding to $\delta = 0^\circ$, $\delta = 1^\circ$, ..., and $\delta = 90^\circ$, respectively. The bin width of δ is 1° , following that of the CPA. We thus define a vector $S = [s_0, s_1, \dots, s_{90}]$ to represent the distribution of δ , where s_i denotes the percentage at $\delta = i^\circ$. In this study, S is smoothed with a 10° window, shown as thin solid lines in Figure 1. Furthermore, we summed the distributions for the northern ($\delta > 0$) and southern ($\delta < 0$) hemispheres without considering the north-south asymmetry of solar activities, such as sunspots (Oliver & Ballester, 1994), filaments (Hansen & Hansen, 1975), X-ray flares (Li et al. 1998), and high-latitude CMEs (Gopalswamy et al. 2003).

3. Method

Our method is based on the assumption of radial motion and uniform longitudinal distribution of CMEs. As shown in Figure 2 [Figure 2: see original paper], point E indicates the CME source region, OE represents the direction of CME motion, and OH is the projection of OE onto the plane of the sky. Consequently, HOY, LOY, and ACE correspond to the apparent latitude δ , the real latitude ϕ , and the longitude θ , respectively. Through simple deduction ($|\text{CH}| = |\text{CE}| \sin \theta = |\text{OC}|/\tan \phi$, $|\text{CE}| = R \cos \phi$, $|\text{OC}| = R \sin \phi$), we obtain:

$$\tan \theta = \sin \phi \tan \delta$$

We define the discrete variable $\delta = [0^\circ, 1^\circ, 2^\circ, \dots, 90^\circ]$. For each fixed δ , we can obtain 91 values using Equation 2 when $\theta = 0^\circ$, $\theta = 1^\circ$, ..., $\theta = 90^\circ$. We convert all θ values to integer type after adding 0.5° and then define a vector $A = [a_0, a_1, \dots, a_{90}]$, where a_i represents the percentage at $\theta = i^\circ$ among the 91 values.

Special cases are handled as follows: When $\delta = 0^\circ$, $A = [1, 0, \dots, 0]$; when $\delta =$

90° , $A = [0, \dots, 0, 1]$; when $\theta = 0^\circ$ and $\theta = 90^\circ$.

Combining 91 vectors A yields a 91×91 matrix $M = [A_1, A_2, \dots, A_91]$, where subscript j corresponds to the case $\theta = j^\circ$. Figure 3 [Figure 3: see original paper] shows the contour of matrix M . If we use vector $R = [r_1, r_2, \dots, r_{91}]$ to represent the real distribution of θ , we have:

$$M \times R = S$$

$$R = M^{-1} \times S$$

4. Results and Discussion

The final results for R , also smoothed with a 10° window, are plotted as 22 thick solid lines in Figure 1. Compared with S , most high-latitude CMEs are replaced by events originating from low latitudes. This occurs because, through projection, CMEs far from the solar limb can be observed at any $\theta > 0$. To directly demonstrate the solar cycle variation of θ , we combined all vectors R in chronological order and present a filled contour plot in Figure 4a [Figure 4: see original paper]. Figure 4b then shows the variation of the actual (not percentage) CME occurrence rate $\theta = R \times n/t$, where n is the CME number and t is the time interval length (in years), both given in Figure 1.

From Figure 4, we find that most high-latitude CMEs occurred during the period from 1999 to mid-2001. Gopalswamy et al. (2003) found a general spreading of CME latitudes reaching 60° by 1999, with northern high-latitude CMEs becoming nonexistent after October 2000, while southern ones continued until the first quarter of 2002. Our time interval for most high-latitude CME occurrences is approximately consistent with Gopalswamy et al. As indicated by white dotted lines, we identify a poleward motion with a speed of 12.5 deg/year and an equatorward motion with a speed of 25.4 deg/year occurring during 1999–2001 and from 2000 to mid-2001, respectively.

For the poleward motion, years 1999 and 2001 correspond to the polarity reversal time at $\theta = 60^\circ$ and the epoch when the polar region area is at minimum (Song & Wang, 2006). We therefore suggest this motion results from collisions between unipolar poleward meridional flows (Song & Wang, 2006) and polar regions of opposite polarity. Such collisions hasten the formation of polar crown filaments, whose eruptions closely correspond to CMEs (Gopalswamy et al. 2003). The much lower speed compared to that of meridional flows (> 20 deg/year) can be explained by polar regions blocking the flow. The equatorward motion may share the same mechanism, as during its interval the tilt angle—defined as the maximum extent of the heliospheric current sheet (HCS)—also declines sharply with a similar speed (see Figure 8 [Figure 8: see original paper] in Gopalswamy et al. 2003). High-latitude CMEs constitute 5–10% during periods when polar magnetic fields reverse polarity and 3% of all CMEs during the entire solar cycle.

In the range $[45^\circ, 60^\circ]$, we find only three prominent peaks located in 2000, around mid-2002, and in 2005, respectively, which appear to have a period of 2.5 years. Comparing these peak positions with sunspot number variation (see pink solid lines in Figure 4) reveals no close correlation, making this phenomenon quite puzzling. Wang et al. (1989) found many poleward surges of alternating polarities in the active belts—could these initiate mid-latitude CMEs? We have no definite answer at present. Such CMEs constitute 6-12% during their main phases and 4% of all CMEs.

Ninety-three percent of CMEs occur in the range $< 45^\circ$. From Figure 4, we find that the highest occurrence probability (R) for these low-latitude CMEs occurs at solar minimum and during the rising phase of the solar cycle. However, the highest occurrence rate (λ) occurs at solar maximum and during the declining phase. As shown by green solid lines, at solar minimum and during the rising phase, the average CME latitude increases linearly. Then at solar maximum and during the declining phase, the average CME latitude remains in a nearly steady state around 15° - 25° . This obviously does not follow the Spörer sunspot law, indicating that a large number of CMEs originate outside active regions. Zhou et al. (2006) classified CME-associated large-scale structures into four categories: extended bipolar regions (EBRs), transequatorial magnetic loops, transequatorial filaments, and long filaments along the boundaries of EBRs (possibly corresponding to high-latitude CMEs). The latitudes of the first three categories are higher or lower than those of active regions, resulting in a much wider distribution of CME latitudes.

5. Conclusions

Using our proposed method, we have studied the solar cycle variation of real CME latitudes during cycle 23 and identified three main features: (1) The latitudinal drift of high-latitude CMEs ($> 60^\circ$) correlated with that of the HCS. (2) Mid-latitude CMEs ($[45^\circ, 60^\circ]$) occurred primarily in 2000, around mid-2002, and in 2005, forming a prominent three-peak structure. (3) The latitudinal evolution of low-latitude CMEs ($< 45^\circ$) did not follow the Spörer sunspot law, suggesting that many CMEs originated outside active regions. We believe these features can provide insights for understanding CME origins. Currently, the Solar Terrestrial Relations Observatory (STEREO)—a NASA mission successfully launched last October—is observing the solar corona in 3-D rather than on the plane of the sky. With STEREO, locating CME source regions is no longer difficult, enabling better determination of the real CME latitude distribution.

This CME catalog is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA. This work is jointly supported by the National Natural Science Foundation of China (40621003, 40536029, and 40604019), the 973 project under grant 2006CB806304, and the CAS International Partnership Program for Creative Research Teams.

References

- Gopalswamy, N., Lara, A., Yashiro, S., et al. 2003, International Solar Cycle Studies (ISCS) Symposium, 'Solar Variability as an Input to the Earth's Environment', 403
- Gosling, J.T. 1993, JGR, 98, 18937
- Hansen, R., & Hansen, S. 1975, Sol. Phys., 44, 225
- Li, K.J., Schmieder, B., & Li, Q.S. 1998, A&AS, 131, 99
- Oliver, R., & Ballester, J.L. 1994, Sol. Phys., 152, 481
- Skirgiello, M. 2003, GRL, 30, SSC1
- Song, W.B., & Wang, J.X. 2006, ApJ, 643, L69
- St. Cyr, O.C., Howard, R.A., Sheeley, N.R., et al. 2000, JGR, 105, 8169
- Subramanian, P. & Dere, K.P. 2001, ApJ, 561, 372
- Wang, Y.-M., Nash, A.G., & Sheeley, N.R. 1989, Science, 245, 712
- Zhou, G.P., Wang, J.X., & Cao, Z.L. 2003, A&A, 397, 1057
- Zhou, G.P., Wang, J.X., & Zhang, J. 2006, A&A, 445, 1133

This preprint was prepared with the AAS LATEX macros v5.2.

Fig. 1.—The distributions of the apparent (S, thin solid line) and real (R, thick solid line) CME latitudes during 22 time intervals which are smoothed with a window of 10° . The dashed lines around them indicate the unsmoothed variations. In the top right corner of each plot, the time range and the CMEs number have been shown.

Fig. 2.—The spatial sketch of the apparent latitude (θ , HOY), the real latitude (θ_r , LOY) and the longitude (ϕ , ACE) of a CME event initiating from the point E. OX is the direction of the observer, OE is the direction of CME motion, CA OX, CL OY, and EH CL.

Fig. 3.—The contour of the transition matrix M defined in section 3. The distributions of the apparent (S) and real (R) CME latitudes are related by the equation $S = M \times R$. Bright white in the upper left and down right corners indicates the value of zero only for being pleasing to the eye. The bin widths of θ and θ_r are both 1° .

Fig. 4.—The solar cycle variations of the real CME latitude (a) and the CME occurrence rate (b). The white dotted lines show the poleward and equatorward motions of the high-latitude CMEs. The pink solid line indicates the monthly averaged sunspot number during each period of time. The green solid line indicates the average latitude of CMEs in the range $\theta < 45^\circ$. Bright white in the upper regions indicates the value of zero.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.