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Speed Distributions of CMEs in Cycle 23 at Low and High Latitudes *

Peng-Xin Gao[1,2] and Ke-Jun Li[1]

[1] National Astronomical Observatories / Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011; *gpx@ynao.ac.cn*
[2] Graduate School of Chinese Academy of Sciences, Beijing 100049

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Abstract We analyzed the speed (v) distributions of 11584 coronal mass ejections (CMEs) observed by the Large Angle and Spectrometric Coronagraph Experiment on board the Solar and Heliospheric Observatory (SOHO/LASCO) in cycle 23 from 1996 to 2006. We find that the speed distributions for high-latitude (HL) and low-latitude (LL) CME events are nearly identical and to a good approximation they can be fitted with a lognormal distribution. This finding implies that statistically the same driving mechanism of a nonlinear nature is acting in both HL and LL CME events, and CMEs are intrinsically associated with the source's magnetic structure on large spatial scales. Statistically, the HL CMEs are slightly slower than the LL CMEs. For HL and LL CME events respectively, the speed distributions for accelerating and decelerating events are nearly identical and also to a good approximation they can be both fitted with a lognormal distribution, thus supplementing the results obtained by Yurchyshyn et al.

Key words: Sun: activity — Sun: coronal mass ejections (CMEs)

1 INTRODUCTION

Coronal Mass Ejections (CMEs) are large-scale eruptions of plasma and magnetic fields from the Sun (Webb et al. 2000; Gopalswamy et al. 2000), which are believed to be the main source of strong interplanetary disturbances that cause many moderate to intense geomagnetic storms (Wang et al. 2003). Thus, studies on CMEs are important topic because of their direct connection to 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. The Large Angle and Spectrometric Coronagraph (LASCO) on board the Solar and Heliospheric Observatory (SOHO) mission has observed most number of CMEs, providing us with a good source to examine the statistics of their properties such as speed, acceleration, travel time (Sun to 1 AU), width, latitude, and initial location (Gopalswamy et al. 2000, 2001; Wang et al. 2002; Cane & Richardson 2003; Yashiro et al. 2004; Yurchyshyn et al. 2005).

Aoki et al. (2003) found a lognormal distribution between the CME speeds and the peak fluxes of their related X-ray flares. The lognormal distribution is defined as follows: a random variable μ is lognormally distributed when $\ln(\mu)$ is normally distributed. From the central-limit theorem, we know, when $\ln(\mu)$ is normally distributed, it is the sum of a large number of independent random variables (Yurchyshyn et al. 2005). Therefore, the random variable μ is the product of a large number of independent random variables. In other words, the lognormal distribution of an observed variable implies the presence of a multiplicative process

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in a system of many independent random variables (Yurchyshyn et al. 2005). Early measurements of the speeds of CMEs suggested that there are two distinct types of the speed profile: slow CMEs, which are associated with eruptive prominences, and fast CMEs, which originate in solar active regions (Gosling et al. 1976). Through analyzing some CMEs, some authors (Sheeley et al. 1999; Gopalswamy et al. 2000; Andrews & Howard 2001) found that slow CMEs are accelerating and fast CMEs are decelerating. However, Yurchyshyn et al. (2005) found that the speed distributions for accelerating and decelerating CME events can be modeled by a single lognormal distribution for the CMEs in the years 1998 to 2001 (ascending period of cycle 23). The lognormal distribution of the CME speeds suggests that the same driving mechanism of a nonlinear nature acts in both slow and fast dynamical types of CMEs (Yurchyshyn et al. 2005).

It is well known that the characteristics of the magnetic field at high and low latitudes of the Sun are distinctly different, for example, the magnetic field is much weaker at high than low latitudes. The relation between the activities of a given type of solar events at high and low latitudes is an interesting topic. In this paper, we will consider in detail the speed distributions of high-latitude (HL) and low-latitude (LL) CMEs, and our data are extended to the cycle 23.

2 SPEED DISTRIBUTIONS OF HL AND LL CMES

The CME data used here come from SOHO/LASCO, available at *http://cdaw.gsfc.nasa.gov/CME_list/ index.html.* This CME catalog, generated and maintained at the CDAW Data Center by NASA and the Catholic University of America in cooperation with the Naval Research Laboratory, covers the period from 1996 January to the present. LASCO has three telescopes, C1, C2, and C3, the catalog contains all the CMEs detected by C2 and C3, in a combined field of view of $2.1 - 32R_\odot$, the telescope C1 was disabled in June 1998.

For each CME event, the catalog gives height-time plots, plane-of-sky speeds, central position angles (CPA), and so on. The CME speeds are obtained by linearly fitting the height-time measurements. By analyzing the linear (constant speed) fit, Yurchyshyn et al. (2005) found that a constant speed was preferable for 90% of all the selected CMEs. In addition, Zhang & Dere (2006) suggested that the acceleration of a CME in the outer coronal region (larger than $2R_\odot$) can almost be neglected compared to that in the inner coronal region (less than $2R_\odot$). So it is reasonable to assume constant CME speeds in the field of view of $2.1 - 32R_\odot$. In order to determine whether the CME is accelerating or decelerating, quadratic fitting to the CME height-time plot was also made.

To study the latitude distribution of CMEs, we convert the CPAs to projected heliographic latitudes (Yashiro et al. 2004). For example, CPA 0°, 90°, 180° and 270° correspond to apparent latitudes 90°, 0°, -90° and 0°, respectively. Halo CMEs are excluded for which the CPAs cannot be determined. The LASCO/SOHO has observed 393 halo CMEs from January 1996 to December 2006, or 3.4% of all the 11584 CMEs recorded. The CMEs observed in the latitude band $0^\circ - 40^\circ$ are regarded as LL CMEs, and those in the latitude band $60^\circ - 90^\circ$, HL CMEs (Gopalswamy et al. 2003b).

Because HL CMEs are likely to mixed with fakes (projected LL disk CMEs), we examine the relationship between HL CMEs (width $>$ 30 degree) and the associated LL flares. If an LL disk CME appears in a high latitude, its apparent width would be high (Hundhausen 1993). The data of solar flares used here are available at *ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/HALPHA_FLARES.* The CME onset times obtained by extrapolating the linear fit to the solar surface (height = 1 solar radius) are adopted. All solar flares within $\pm$ 1 hour time window are selected, while only those flares that are located within the angular span of the CMEs are chosen for the flares associated with the CMEs (Yeh et al. 2005). We found that only 86 HL CMEs (5.33% of 1613 HL CMEs) are associated with LL flares. These HL CMEs are excluded.

We divide all CMEs into HL and LL CMEs according to their projected heliographic latitudes and then, similarly as did Yurchyshyn et al.(2005), plotted the probability distributions of both HL and LL CMEs versus the natural logarithm of their speeds, v. See Figure 1. The vertical bars of Figure 1 are the five point smoothed distribution of natural logarithm of speeds for HL and LL CMEs. The distributions of natural logarithm of the CME speeds are very near to a Gaussian distribution, i.e., the statistical distribution of speeds of CMEs should be similar to a lognormal distribution. When a random variable, in our case the speed of a CME, v, is lognormally distributed, its natural logarithm $\ln(v)$ is normally distributed (Yurchyshyn et al. 2005):

$$P = A_0 \exp -\frac{1}{2}\left(\frac{\ln(v) - \mu}{\sigma}\right)^2, \quad (1)$$

where P is the probability density function, σ^2 and μ are the variance and mean of $\ln(v)$, respectively. The distributions of natural logarithm of the CME speeds are then approximated with a normal fit by Equation (1). The solid line and the dashed line in Figure 1 are the normal fit to the distributions of natural logarithm of speeds determined separately for HL and LL CMEs. The fitting parameters for the normal distributions are collected in Table 1, in which the last four columns show the goodness of the fit, χ^2, the probability, P, the reduced χ^2, and the degrees of freedom, dof, respectively.

From Figure 1 and Table 1 we can find that the normal approximations for the distributions of natural logarithm of speeds for both HL and LL CMEs are nearly identical (χ^2=26.0447, with degrees of freedom =

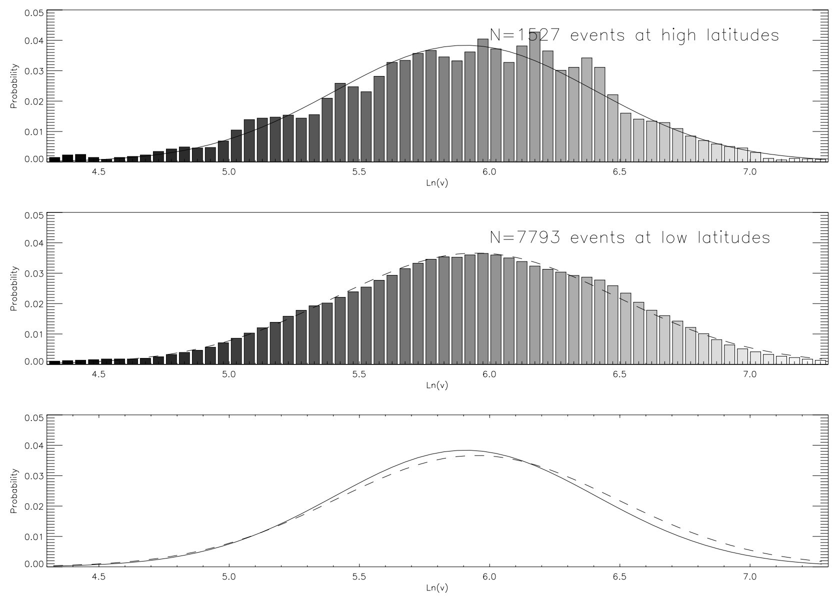

Fig. 1 Five point smoothed distribution of natural logarithm of speeds determined for 1527 HL CMEs (top panel, vertical bars) and 7793 LL CMEs (second panel, vertical bars) observed by SOHO/LASCO in cycle 23 from 1996 to 2006. The solid line in the top panel and the dashed line in the second panel show the respective Gaussian fits. These two Gaussian fits are repeated in the bottom panel.

Table 1 Fitting Parameters

	A_0	$\mu(\ln(v))$	μ(km s^{-1})	σ	χ^2	P	Reduced χ^2	Dof
At low latitudes	0.0366	5.9491	383.4	0.5387	43.0	0.92	0.75	57
At high latitudes	0.0384	5.9068	367.5	0.5017	42.9	0.91	0.75	57
With positive acceleration at low latitudes	0.0380	5.9072	367.7	0.5187	26.6	0.99	0.47	57
With negative acceleration at low latitudes	0.0384	6.0832	438.4	0.5131	31.5	0.99	0.55	57
With positive acceleration at high latitudes	0.0387	5.8350	342.1	0.5024	24.0	0.99	0.43	57
With negative acceleration at high latitudes	0.0413	6.0314	416.3	0.4720	28.8	0.99	0.50	57

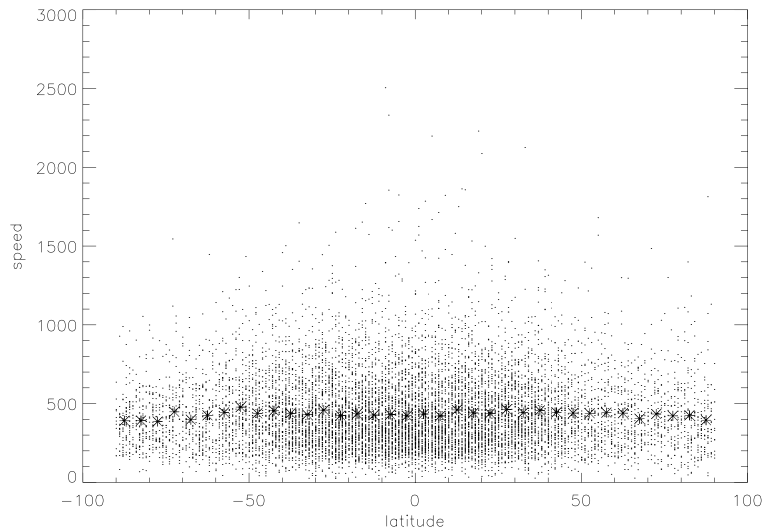

Fig. 2 Scatter diagam of CME speed and latitude for all CMEs. The asterisks indicate the average speeds in 5° latitude intervals.

57 and probability $P = 0.99$), implying that the same driving mechanism of a nonlinear nature is acting in both HL and LL CME events. As we know, the characteristics of the magnetic field at high and low latitudes of the Sun are intrinsically different, for example, the magnetic field at high latitudes is much weaker than that at low latitudes. This result seems to support the idea that CMEs are intrinsically associated with the source magnetic structure on a large spatial scale (Zhou et al. 2006;Wang et al. 2006). The largest difference between the two fits is in the parameter μ, describing the position of the maximum of the distribution, which implies that HL CMEs, as a group, are slower than LL ones.

Then we analysis the relationship between the CME speed and the latitude. Figure 2 shows the scatter diagram of the speeds and latitudes for all CMEs. We again find that, at high latitude, the average speed is slightly slower. This result is consistent with the relationship between the CME speed and latitude found for the CMEs from 1980 and 1984–1989 by the SMM (Hundhausen et al. 1994).

It is well known that the constant speeds used here are subject to the projection effect. That is, the apparent speeds we measure are the real speeds projected on the plane of the sky. Now, the magnetic field is radially directed in the outer coronal region (larger than $2.6R_\odot$) away from the Sun's source surface (Altschuler et al. 1977), thus it is acceptable to assume that CMEs propagate radially in the outer coronal region. The latitude of a CME is obtained from the CPA of the CME, again assuming that the CME propagates radially away from the solar region (Gopalswamy 2004). Here, we assume that CMEs radially propagate, then, the projection effect in the longitude direction should be corrected approximately by Equation (2):

$$v_{\rm cor} = v/|\sin\phi|, \tag{2}$$

where ϕ is the apparent latitude of a CME event. Thus, according to this equation, a lower latitude of CMEs implies larger projection effect, and, statistically, HL CMEs are apparently slower than LL CMEs after correcting the projection effect.

We divide all LL CMEs into accelerating and decelerating events according to their acceleration sign determined from the quadratic fit and then plot the five point smoothed distributions of natural logarithm of the CME speeds separately for the two groups. See Figure 3. As the distributions are nearly Gaussian, they are approximated with a normal fit. The fitting parameters are collected in Table 1. From Figure 3 and Table 1, we can find that the normal approximations for the accelerating and decelerating LL CME events are nearly identical (χ^2=34.7254, for 55 degrees of freedom, with probability $P = 0.99$), implying that, at low latitudes, the same driving mechanism of a nonlinear nature is acting in both the accelerating and decelerating events. The difference in the parameter μ of the two fits means that at low latitudes the accelerating CMEs are 1.9% slower than the decelerating ones. Our conclusion partially agrees with Yurchyshyn et al. (2005), who found that, for the whole solar disk, the accelerating CMEs are 2.2% slower than the decelerating ones (Yurchyshyn et al. 2005 gave $\mu = 392$ and $477\ \mathrm{km\,s^{-1}}$, respectively, for the accelerating and decelerating CMEs).

Similarly, we divide all HL CME events into accelerating and decelerating events, and then plot in Figure 4 the five point smoothed distributions. The distributions are also nearly Gaussian, and are again approximated with normal fits. The fitting parameters are also collected in Table 1. From Figure 4 and Table 1, we find that the two distributions for accelerating and decelerating HL CME events are nearly identical (χ^2=29.5274, for 56 degrees of freedom, probability $P = 0.99$), implying that at high latitudes the same driving mechanism of a nonlinear nature is acting in both the accelerating and decelerating CME events. Again, two fits differ in the parameter μ, implying that the accelerating CMEs are 2.1% slower than the decelerating ones. Note that the accelerating and decelerating HL CMEs are statistically slower than the corresponding LL CMEs.

Here, we note that our parameter μ (km s^{-1}) is smaller than that of Yurchyshyn et al. (2005). For the positive acceleration events, our value is 367.7 at low latitudes and 342.1 at high latitudes, smaller than their value of 392, and for negative acceleration events, our value is 438.4 at low latitudes and 416.3 at high latitudes, again smaller than their value of 477. The discrepancy should be due to the different time intervals considered: they analyzed the distribution of CMEs' speeds in the interval from 1998 to 2001, i.e., the ascending time of cycle 23, while we analyzed the interval from 1996 to 2006, almost a complete solar cycle, and the result suggests that the CME speeds vary with time in the cycle (Yashiro et al. 2004; Gopalswamy 2004).

3 DISCUSSION AND CONCLUSIONS

In the present work, we have found: (1) That the speed distributions of HL and LL CMEs are nearly identical and to a good approximation that can be fitted with a lognormal distribution. This suggests that a same driving mechanism is acting in the two types of CME events. We have known that the characteristics of the magnetic field on AR scale are different at low and high latitudes, so this finding suggests that CMEs are intrinsically associated with source magnetic structures on a large spatial scale (Zhou et al. 2006; Wang et al. 2006). (2) That for HL and LL CMEs respectively, the speed distributions for accelerating and decelerating CME events are nearly identical and also to a good approximation that can be both fitted with a lognormal distribution. It implies that the same driving mechanism of a nonlinear nature is acting in both accelerating and decelerating CME events, even if CMEs are divided into HL and LL CMEs, thus strengthening the results obtained by Yurchyshyn et al. (2005).

Previous reports (Gosling et al. 1976; Sheeley et al. 1999; Andrews & Howard 2001; Moon et al. 2002) showed that flare-related CMEs tend to be faster than those CMEs associated with eruptive prominences. Now, at high latitudes flares infrequently occur while filaments are sometimes seen. Thus, our finding that HL CMEs statistically are slower than LL CMEs are in agreement with the previous results. Zhou et al. (2006) speculated that the associated solar surface activity of a CME may act as either triggers of 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. In general, the dynamics of solar ejecta is believed to be determined by the Lorentz and pressure forces (Vrsnak 1990; Chen 1996; Yurchyshyn et al. 2005). The Lorentz force is related to the amount of magnetic flux confined in the erupted field, and the magnetic field at high latitudes is much weaker than that at low latitudes, this is why HL CMEs, statistically, are slower than LL CMEs. That is to say, for the CMEs with high speeds, they often appear in the low latitudes, which would be related to the strong magnetic evolutions.

In order to study the latitudinal distribution of CMEs, generally, one converts CPAs to projected heliographic latitudes (Hundhausen 1993; Gopalswamy et al. 2003a, b; Yashiro et al. 2004). However, there is some uncertainty, when apparent latitudes are used, for example, the CME at 13:27 UT on 2002 April 10, apparently appeared at high latitude, but the CME originated from low latitude since it was associated with an M8.2 flare at AR9893 (N19W02). The so-called low latitudes of solar activity generally denote the latitudes of $0^\circ - 50^\circ$(Sakurai 1998). To minimize the uncertainty, here, we have grouped CMEs with

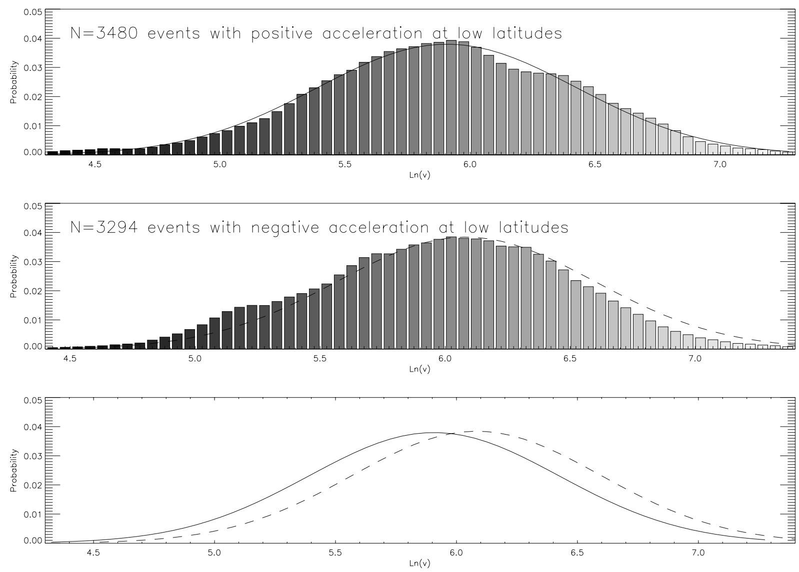

Fig. 3 Five point smoothed distribution of the natural logarithm of speeds of 3480 LL CMEs with positive acceleration (top panel, vertical bars) and 3294 LL CMEs with negative acceleration (middle panel, vertical bars) observed by SOHO/LASCO in cycle 23 from 1996 to 2006. The solid line in the top panel and the dashed line in the middle panel show the Gaussian fits, which are repeated in the bottom panel.

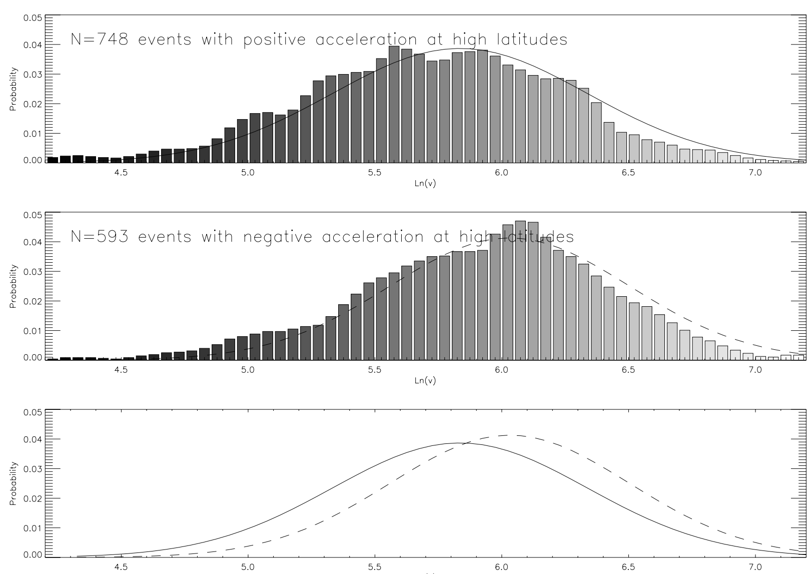

Fig. 4 Five point smoothed distribution of the natural logarithm of speeds determined of 748 HL CMEs with positive acceleration (top panel, vertical bars) and 593 HL CMEs with negative acceleration (second panel, vertical bars) observed by SOHO/LASCO in cycle 23 from 1996 to 2006. The solid line in the top panel and the dashed line in the second panel show the corresponding Gaussian fits, and these are repeated in the bottom panel.

projected heliographic latitudes less or equal 40° as LL CMEs and those with latitudes great or equal 60° as HL CMEs, as did Gopalswamy et al. (2003b). Because HL CMEs are likely to mixed with fakes (projected LL disk CMEs), we examine the relationship between HL CMEs (width > 30 degree) and the associated LL flares. If an LL disk CME appears in high latitude, its apparent width would be high (Hundhausen 1993). Those HL CMEs associated with LL flares are excluded. It is well known that we could not consider the probability of backside HL CMEs that are related to LL flares, i.e., the HL CMEs include about 86 backside HL CMEs related to LL flares. Moreover, a great many events (11584 CMEs) are analyzed, which should also reduce the uncertainties.

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