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Distribution of Latitudes and Speeds of Coronal Mass Ejections in the Northern and Southern Hemispheres in Cycle 23

P. X. Gao[1,2,*], Q. X. Li[1,2] & S. H. Zhong[1]
[1]*National Astronomical Observatories/Yunnan Observatory, CAS, Yunnan, China.*
[2]*School of Graduate, CAS, Beijing, China.*
[*]*e-mail: gpx@ynao.ac.cn*

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Abstract. Distribution of latitudes and speeds of Coronal Mass Ejections (CMEs) in the northern and southern hemispheres in cycle 23, from September 1996 to December 2006, have been analyzed. By calculating the actual probability of the hemispheric distribution of the activity of the CME, we find that a southern dominance of the activity of the CME is shown to occur in cycle 23 from September 1996 to December 2006. The CME activity occurs at all latitudes and is most common at low latitudes. This should furnish evidence to support that CMEs are associated with source magnetic structures on a large spatial scale, even with transequatorial source magnetic structures on a large spatial scale. The latitudinal distribution of CMEs in the northern and southern hemispheres are no different from a statistical point of view. The speed distribution in the northern and southern hemispheres are nearly identical and to a good approximation they can be fitted with a single lognormal distribution. This finding implies that, statistically, there is no physical distinction between the CME events in the southern and northern hemispheres and the same mechanism of a nonlinear nature acting in both the CME events in the northern and southern hemispheres. Our conclusions seem to suggest that the northern–southern asymmetry of the CME events is related to the northern–southern asymmetry in solar dynamo theory (Jiang *et al.* 2007).

Key words. Sun: activity—Sun: Coronal Mass Ejections (CMEs).

1. Introduction

Coronal Mass Ejections (CMEs), known as the most energetic form of solar magnetic activity, are now believed to be the main sources of the strong interplanetary disturbances that cause moderate-to-intense geomagnetic storms. So, a study on CMEs is an important topic that relates directly to near-Earth space environments. 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) onboard the Solar and Heliospheric Observatory (SOHO) mission has observed the most CMEs, providing us with a great opportunity to examine the statistical properties of CMEs, such as their 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).

Howard *et al.* (1985) examined the Solwind coronagraph images obtained during the interval period March 28, 1979 to December 31, 1981 and found that the CME activity occurs at all latitudes and is most common at low latitudes. A similar result was reported from the SMM coronagraph/polarimeter obtained images of the solar corona in 1980 and from 1984 to 1989 by Hundhausen (1993). Yashiro *et al.* (2004) found a N–S asymmetry in 1996–2002 from the latitudinal distribution, especially in 2001–2002. By analyzing the data of CMEs observed by SOHO/LASCO in the interval from October 19, 1996 to December 26, 2001, Aoki *et al.* (2003) found that the distribution of the speeds of CMEs is very similar to lognormal distribution. More recently, Yurchyshyn *et al.* (2005) found that the speed distribution for accelerating and decelerating CME events can be modeled by a single lognormal distribution with the use of CMEs in the interval of the years 1998 to 2001 (ascending period of cycle 23). The accelerating CMEs, as a group, are slower than the decelerating ones (Yurchyshyn *et al.* 2005). In this paper, based on the data of CMEs observed by SOHO/LASCO, we will consider the distribution of latitudes and speeds of CMEs in northern and southern hemispheres, and further, the dates used are extended almost to a cycle, in cycle 23.

2. Asymmetry of the activity of CMEs

The data of CME used here come from a catalog of observations of the SOHO/LASCO, which are 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 co-operation with the Naval Research Laboratory, covers the period from 1996 January to the present. For each CME event, the catalog contains central position angle (CPA), plane-of-sky speeds, and so on. CME latitude is obtained from the CPA of the CME, assuming that CMEs propagate radially away from the solar source region (Gopalswamy *et al.* 2003; Yashiro *et al.* 2004). 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, which are 3.4% of all the 11584 CMEs. The minimum between cycles 22 and 23 occurred in September 1996 (Harvey & White 1999), so we study the activity of CMEs from September 1996 to December 2006.

From September 1996 to December 2006, there are 5256 CME events in the northern hemisphere and 5705 CME events in the southern hemisphere. We can find that a southern dominance of the activity of CMEs is shown to occur in solar cycle 23. To be sure that this result cannot be obtained purely by chance we check by calculating the actual probability of obtaining a result. Let us consider a distribution of n objects (CMEs) in 2 classes. The probability that one CME (one object) occurs in one hemisphere (class one) by chance is $p = 1/2$. We use the following binomial formula to derive the probability $P(k)$ of getting k objects in class 1 and $(n - k)$ objects in class 2 (Li *et al.* 1998).

$$P(k) = \binom{n}{k} p^k (1 - p)^{n-k}. \tag{1}$$

In our case for a total number $n = N_N + N_S = 10961$, we have for example:

$$P(k) = \frac{10961!}{(10961 - k)!k!} \frac{1}{2^{10961}}.$$

The probability to get more than d objects in one class is:

$$P(\geq d) = \sum_{k=d}^{n} P(k). \quad (2)$$

In general, when $P(\geq d) < 5\%$ we have a statistically significant result, and when $P(\geq d) < 1\%$ the result is highly significant. From September 1996 to December 2006, we have 5705 CME events occurring in the southern hemisphere within the total 10961 CME events, $P(\geq 5705) = 9.4 \times 10^{-6}$, which means that a southern dominance of the activity of the CME is highly significant, that is to say, this result cannot be obtained purely by chance. This conclusion was predicted by Ataç and Özgüc in 1996 and confirms that the hypothesis about a 12-cycle periodicity is valid (Li *et al.* 2002).

It must be pointed out that, in this paper, in order to study the latitudes of CMEs, we convert CPAs to projected heliographic latitudes. It is likely that some CME events in the northern (southern) hemisphere may be misidentified as in the southern (northern) hemisphere because of projection effects. To minimize this, we group CMEs with projected heliographic latitudes $\geq 10°$ as the CME events in the northern hemisphere and those with projected heliographic latitudes $\leq -10°$ as CME events in the southern hemisphere. Based on the above grouping, we calculate the actual probability of the hemispheric distribution of the activity of the CME again. From September 1996 to December 2006, we have 4538 CME events occurring in the southern hemisphere within the total 8677 CME events, $P(\geq 4538) = 9.6 \times 10^{-6}$. We also find that a southern dominance of the activity of the CME is shown to occur in cycle 23 from September 1996 to December 2006.

3. The latitudinal distribution of CMEs

We divide CMEs into 18 unsigned latitudinal bands (one band per 5°, from 0° to 90°) and count the number of CMEs within each band. The result of this binning is shown in Fig. 1. In the figure, the number of CMEs for each band is divided by the total number of CMEs from September 1996 to December 2006, so that the histograms show ratios that define the probability percentage of CMEs for each latitudinal band. We can also find that the CME activity occurs at all latitudes and is most common at low latitudes, augmenting the results obtained by Hundhausen (1993). However, the statistical characteristics of such latitudinal distribution of CMEs are different from those of sunspot groups. The latitudinal distribution of sunspot groups can be represented by a probability density function of the Γ distribution having maximum probability at about 15.5° (Li *et al.* 2003). Sunspots seem to be specified on active regions (AR), but CMEs are a kind of large-scale solar activity. So, our conclusion — the statistical characteristics of such latitudinal distribution of CMEs are different from those of sunspot groups — should furnish evidence to support that CMEs are intrinsically associated with source magnetic structures on a large spatial scale, even with transequatorial source magnetic structures on a large spatial scale (Zhou *et al.* 2006).

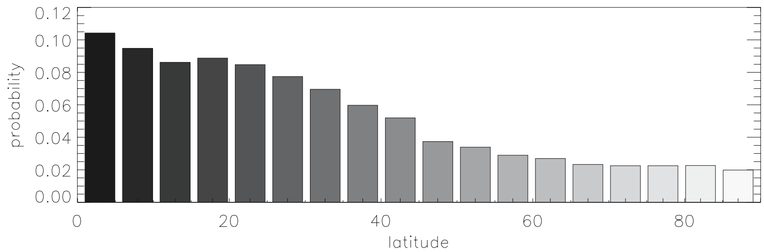

Figure 1. Percentages of CMEs to occur at the 18 latitude bands in 23 cycles.

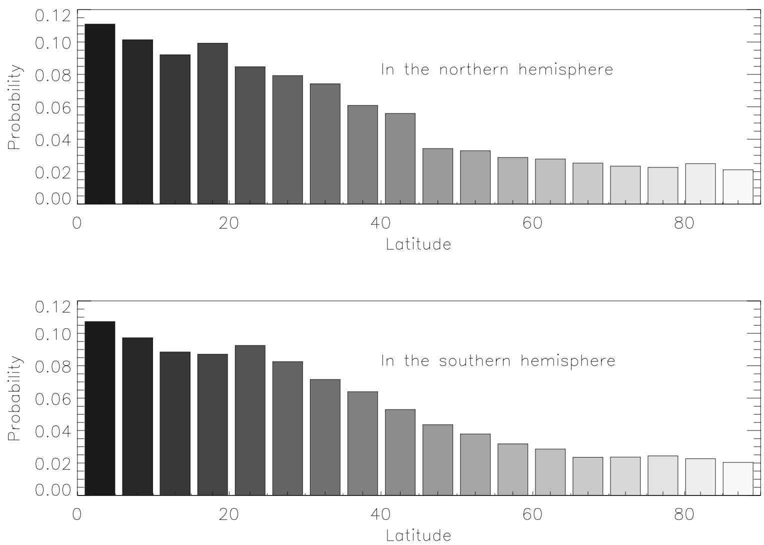

Figure 2. Percentages of CMEs to occur at the 18 latitude bands in the northern and southern hemispheres in 23 cycles.

We divide CMEs into 18 latitudinal bands (one band per 5°, from 0° to 90°) in the northern and southern hemispheres respectively and count the probability percentages of CMEs within each band. The result of this binning is shown in Fig. 2. Then we inspect whether the latitudinal distributions in the northern and southern hemispheres have a statistically significant difference or not. The method used here is the so-called rank sum test (Liu 1996). Firstly, we take the number difference between the corresponding latitudinal bands in the northern and southern hemispheres. The rank sum test has been made by first arranging the 18 points in decreasing order after taking their absolute values to assign a serial number from 1, 2, 3, 4, ... to ≤ 18. If number n and number $n+1$ points have the same value, then both share the same serial number $n+0.5$, the average of their serial numbers. If three points have the same value, then the three points share the same serial number, the average of their serial numbers, and so on. It is found that the sum of the serial numbers of the points with a positive sign is $T_+ = 25$ and the number of the points with a positive sign is $n_+ = 2$, while the sum of the serial numbers of the points with a minus sign is $T_- = 146$ and the number of the points with a minus sign is $n_- = 16$. Accordingly, we have

$$U_+ = n_+ n_- + \frac{n_+(n_+ + 1)}{2} - T_+ = 10,$$

$$U_- = n_+ n_- + \frac{n_-(n_- + 1)}{2} - T_- = 22.$$

$U_+ = 10 > U_\alpha = 6$, where U_α is the critical value of the rank sum test at the level 0.05 (Liu 1996). Therefore, it is concluded that there is no difference between the two distributions from the statistical point of view.

Then we grouped CMEs with projected heliographic latitudes $\geq 10^\circ$ as the CME events in the northern hemisphere and those with projected heliographic latitudes $\leq -10^\circ$ as CME events in the southern hemisphere. We can obtain $n_+ = 2, T_+ = 22, n_- = 14, T_- = 114, U_+ = 9, U_- = 19$, and $U_+ = 9 > U_\alpha = 5$. That is to say, it is concluded that there is no difference between the two distributions from the statistical point of view.

4. Speed distribution of CMEs in the northern and southern hemispheres

In that catalog, the CME plane-of-sky speeds are determined from both linear and quadratic fits to the height-time measurements. Yurchyshyn *et al.* (2005), through analyzing the linear (constant speed) fit, found that constant speed is preferable for 90% of all analyzed CMEs. In addition, Zhang & Dere (2006) found that the acceleration of CME in the outer coronal region (larger than $2\,R_\odot$) can be almost neglected in contrast to that in the inner coronal (less than $2\,R_\odot$). LASCO has three telescopes C1, C2, and C3, but the catalog contains all the CMEs detected by C2 and C3, which cover a combined field of view of $2.1\,R_\odot$–$32\,R_\odot$, because C1 was disabled in June 1998. That is, the speed observed is almost constant in the field of view of $2.1\,R_\odot$–$32\,R_\odot$. So, when we analyze the distribution of CME speeds, constant speeds are adopted.

Firstly, we divide all CMEs into those in the northern and southern hemispheres according to their latitudes. Then, we plot the 5-point smoothed distributions of $\ln(v)$ in the northern and southern hemispheres respectively in Fig. 3. We find that the statistical distributions of $\ln(v)$ in the northern and southern hemispheres are all very similar to Gaussian distribution, that is, the statistical distribution of speeds of CMEs should be very 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):

$$P = A_0 \exp - \frac{1}{2}\left(\frac{\ln(v) - \mu}{\sigma}\right)^2, \quad (3)$$

where P is the probability density function and σ^2 and μ are the variance and the mean of $\ln(v)$. The distributions of $\ln(v)$ are then approximated with a normal fit by the equation (3). The solid line and the dashed line in Fig. 3 are the normal fit to the distributions of $\ln(v)$ for the CMEs in the northern and southern hemispheres respectively. The fitting parameters for two normal distributions are collected in Table 1, where the last four columns show the goodness of the fit, χ^2, probability, p, reduced χ^2, and degree of freedom, dof.

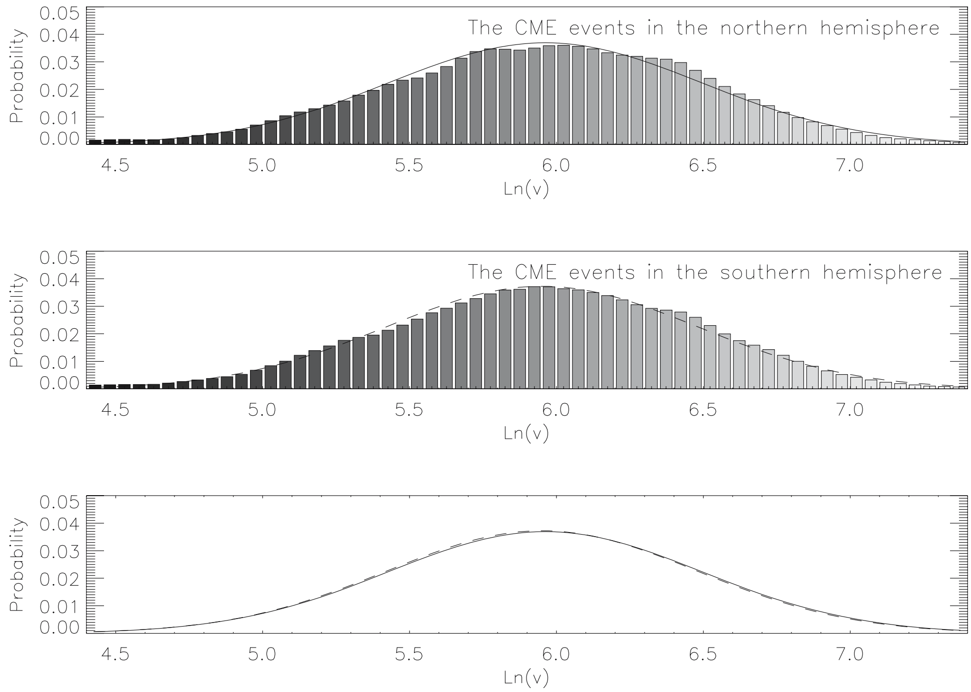

Figure 3. The 5-point smoothed distribution of $\ln(v)$ in the northern (top panel, vertical bars) and southern hemispheres (second panel,vertical bars) observed by SOHO/LASCO in cycle 23 from September 1996 to December 2006. The solid line in the top panel and the dashed line in the second panel show the corresponding Gaussian fits. The bottom panel shows the same Gaussian fits as in the top (solid line) and the second panels (dashed line).

Table 1. Fitting parameters.

	A_0	$\ln(v)$	μ(km s^{-1})	σ	χ^2	P	Reduced χ^2	dof
Northern hemisphere	0.0369	5.9619	388.3	0.5328	36.9	0.98	0.65	57
Southern hemisphere	0.0373	5.9510	384.1	0.5285	31.2	0.99	0.55	57

From Fig. 3 and Table 1, we find that the normal approximations for the $\ln(v)$ distribution of CMEs in the northern and southern hemispheres are nearly identical ($\chi^2 = 34.6400$, with degrees of freedom = 57 and probability $p = 0.99$). And the speed distribution in the northern and southern can be fitted with a single lognormal distribution. This finding implies that, statistically, there is no physical distinction between the CME events in the northern and southern hemispheres. The lognormal distribution of the CME speeds suggests that the same driving mechanism of a nonlinear nature is acting in the two groups of CME events (Abramenko *et al.* 2003; Kaufmann *et al.* 2003).

Then we grouped CMEs with projected heliographic latitudes $\geq 10^\circ$ as the CME events in the northern hemisphere and those with projected heliographic latitudes $\leq -10^\circ$ as CME events in the southern hemisphere. We also find that the speed

Table 2. Fitting parameters.

	A_0	$\ln(v)$	$\mu(\mathrm{kms}^{-1})$	σ	χ^2	P	Reduced χ^2	dof
Northern hemisphere	0.0369	5.9713	392.0	0.5317	41.2	0.94	0.72	57
Southern hemisphere	0.0371	5.9577	386.7	0.5299	31.4	0.99	0.55	57

distribution in the northern and southern hemispheres are nearly identical ($\chi^2 = 35.9366$, with degrees of freedom $= 57$ and probability $p = 0.99$) and to a good approximation they can be fitted with a single lognormal distribution. The fitting parameters are collected in Table 2. When the CMEs at the band $-10°$–$10°$ are excluded, the fitting parameters have a slight change, such as, that the parameter μ that descries the position of the maximum in a distribution is slightly greater than that when all the CMEs are considered.

5. Conclusions and discussions

In the present work, the distribution of latitudes and speeds of Coronal Mass Ejections (CMEs) in the northern and southern hemispheres in cycle 23, from September 1996 to December 2006, has been analyzed. The following conclusions are obtained:

- Through calculating the actual probability of the hemispheric distribution of the activity of the CME, we find that a southern dominance of the activity of the CME is shown to occur in cycle 23 from September 1996 to December 2006.
- In a solar cycle, the CME activity occurs at all latitudes and is most common at low latitudes.
- The latitudinal distribution of CMEs in the northern and southern hemispheres are no different from the statistical point of view.
- The speed distribution in the northern and southern hemispheres are nearly identical and to a good approximation they can be fitted with a single lognormal distribution.

By calculating the actual probability of the hemispheric distribution of the activity of CMEs, we find that a southern dominance of the activity of CMEs is shown to occur in cycle 23 from September 1996 to December 2006. This conclusion was predicted by Ataç and Özgüc in 1996 and confirms that the hypothesis about a 12-cycle periodicity is valid (Li *et al.* 2002). The physical interpretation of the asymmetry in the solar activity has not been clearly given so far. Waldmeier (1971) found that the N–S asymmetries might be caused by phase differences between the magnetic activity in both hemispheres. Haber *et al.* (2002) found that the meridional flows in the northern and southern hemispheres exhibit a striking asymmetry during the years 1998–2001 (ascending period of cycle 23). Zhao & Kosovichev (2004) have recently concluded that the extremely rich and complicated dynamics of the upper convection zone reveals remarkable organization on the large scale, which can be correlated with the magnetic activity zones. They found that the zonal flows in the southern and northern hemispheres are not symmetrical.

The CME activity occurs at all latitudes and is most common at low latitudes. The statistical characteristics of such latitudinal distribution of CMEs are different from those of sunspot groups. The latitudinal distribution of sunspot groups can be represented by a probability density function of the Γ distribution having maximum probability at about 15.5° (Li *et al.* 2003). We know that sunspots seem to be specified on active regions (AR), but CMEs are a kind of large-scale solar activity. So, our conclusion – the statistical characteristics of the latitudinal distribution of CMEs are different from those of sunspot groups – should furnish evidence to support that CMEs are intrinsically associated with source magnetic structures on a large spatial scale, even with transequatorial source magnetic structures on a large spatial scale (Zhou *et al.* 2006). The latitudinal distribution of CMEs in the northern and southern hemispheres are no different from the statistical point of view.

We find that the speed distributions in the northern and southern hemispheres are nearly identical and to a good approximation they can be fitted with a single lognormal distribution. This finding implies that the presence of nonlinear interactions and multiplicative processes in a system of many flux loops (Yurchyshyn *et al.* 2005), and statistically, there is no physical distinction between the CME events in the northern and southern hemispheres. The lognormal distribution of the CME speeds suggests that the same driving mechanism of a nonlinear nature is acting in the two groups of CME events.

Although we find that a southern dominance of the activity of CMEs is shown to occur in cycle 23 from September 1996 to December 2006, the latitudinal distribution of CMEs in the northern and southern hemispheres are no different from the statistical point of view and the speed distribution in the northern and southern hemispheres are nearly identical. The result should furnish evidence to support that the N–S asymmetry of the CME events is related to the N–S asymmetry of dynamo theory.

It must be pointed out that, in this paper, we adopt the plane-of-sky speeds when we analyze the speed distribution of CMEs in the northern and southern hemispheres. Recently, for non-halo CMEs, Hundhausen *et al.* (1994), Leblanc (2001) and Yeh *et al.* (2005) developed a method to correct the projection effect and obtain the real CME speeds. Further efforts are being undertaken to inspect whether the real speed distributions in the northern and southern hemispheres are nearly identical and to a good approximation whether they can be fitted with a single lognormal distribution or not.

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