

STATISTICAL DISTRIBUTIONS OF SPEEDS OF CORONAL MASS EJECTIONS

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ABSTRACT

We studied the distribution of plane of sky speeds determined for 4315 coronal mass ejections (CMEs) detected by Large Angle and Spectrometric Coronagraph Experiment on board Solar and Heliospheric Observatory (SOHO/LASCO). We found that the speed distributions for accelerating and decelerating events are nearly identical and to a good approximation they can be fitted with a single log-normal distribution. This finding implies that, statistically, there is no physical distinction between the accelerating and the decelerating events. The log-normal distribution of the CME speeds suggests that the same driving mechanism of a non-linear nature is acting in both slow and fast dynamical types of CMEs.

1. Introduction

Early measurements of the speeds of coronal mass ejections (CMEs) suggested that there are two distinct types of the speed profiles. Slow CMEs, which are associated with eruptive prominences and fast CMEs, which originate in solar active regions (Gosling et al. 1976). Analyzing 12 CMEs, MacQueen & Fisher (1983) found that fast CMEs propagate at a constant speed, while slow CMEs are accelerating. Later, Sheeley et al. (1999) separated CMEs into two classes: i) gradual CMEs, which have speeds in the range 400-600 km/s, are associated with erupting prominences; ii) impulsive CMEs, which are associated with solar flares and have speeds ≥ 750 km/s. They also concluded that the impulsive CMEs are decelerating. This classification was further supported by reports that median speed of CMEs increases as time nears a solar maximum (St. Cyr et al. 2000) and that flare associated CMEs have higher median speeds than those associated with eruptive filaments (Moon et al. 2002). A study by Andrews & Howard (2001) provides further evidence for the bi-modal distribution of CMEs: events showing constant speed are usually associated with X-ray flares and they are also brighter, larger, and faster than accelerating events (see Fig. 1.2 in Gopalswamy 2004). However, it is worth noting here that the speed-height profiles of all CMEs taken together do not form two discrete populations but rather represent a continuous spectrum (Low & Zhang 2002), which implies that the classification of CMEs into two distinctive groups is not distinct.

The origin of the two dynamical types of CMEs is not clear so far. MacQueen & Fisher (1983) suggested that there could be a qualitative difference between the driver mechanism, which causes CMEs:

flare-associated events arise from an impulsive input in the low corona, while eruptive-associated CMEs are subject to a significant net propelling force over extended periods. Thus, Low & Zhang (2002) presented a qualitative theory where the two kinds of CMEs are represented by different initial states of the erupted magnetic configuration, while Chan & Krall (2003) concluded that one mechanism is sufficient to explain the bi-modal speed distribution.

It is accepted that magnetic reconnection plays a major role in the origin of a coronal ejecta, which are driven through the ambient solar wind by magnetic and pressure forces (Vršnak 1990, Chen 1996). After the driving forces cease to act and the maximum acceleration is reached within several solar radii, fast ejecta have a tendency to decelerate while the slow ones get an additional acceleration due to the interaction with ambient magnetic fields (Gopalswamy et al. 2000; Andrews & Howard 2001). CMEs propagating in the interplanetary space, asymptotically approach the wind velocity due to the viscous drag high in the corona (Gopalswamy et al. 2001; Wu, Wang, & Gopalswamy 2002; Vršnak & Gopalswamy 2002; Vršnak 2003). We would like to note here that the origin of CMEs and their propagation in the solar corona and interplanetary space are complex non-linear phenomena, where dissipative processes associated with the electric resistivity and viscosity should not be neglected.

One possible way to address the problem of the existence of two types of CMEs is to analyze their statistical properties. Recently, Aoki, Yashiro & Shibata (2003) used the log-normal distribution to fit X-ray peak fluxes of 254 solar flares and speeds of the associated CMEs. The log-normal distribution is defined as follows: a random variable u is log-normally distributed when its logarithm $\ln(u)$ is normally distributed. In other words, when $\ln(u)$, is distributed normally then it is a sum of large number of independent random variables. Therefore, the random variable u , is a *product* of a large number of independent random variables (for the central-limit theorem). Thus, the log-normal distribution of a observed variable implies the presence of multiplicative processes in a system of many independent random variables. In this paper, we analyze the statistical properties of 4315 events by utilizing data from the catalog of SOHO/LASCO CMEs. We compare statistical distributions against observed speed distributions. It is important to know which of the methods can model the data best, since it gives us a hint whether fast and slow CMEs are caused by two distinct physical mechanisms.

2. Speed distributions of slow and fast CMEs

The CME Catalog, generated and maintained at the CDAW data center, NASA/ Goddard Space Flight Center, covers the period from January 1996 to present. For each event, the catalog contains height-time plots, plane of the sky speeds and the corresponding accelerations. The CME speeds are determined from both linear and quadratic fit to the height-time measurements. In our study we analyzed the linear (constant speed) fit which is preferable for 90% of the CMEs. However, in order to separate all CMEs into two groups according to their dynamical behavior (accelerating and decelerating) we used the sign of their acceleration obtained from the quadratic fit. More details on the CME catalog can be found at <http://cdaw.gsfc.nasa.gov/>; Gopalswamy et al. 2003; Yashiro et al. 2004.

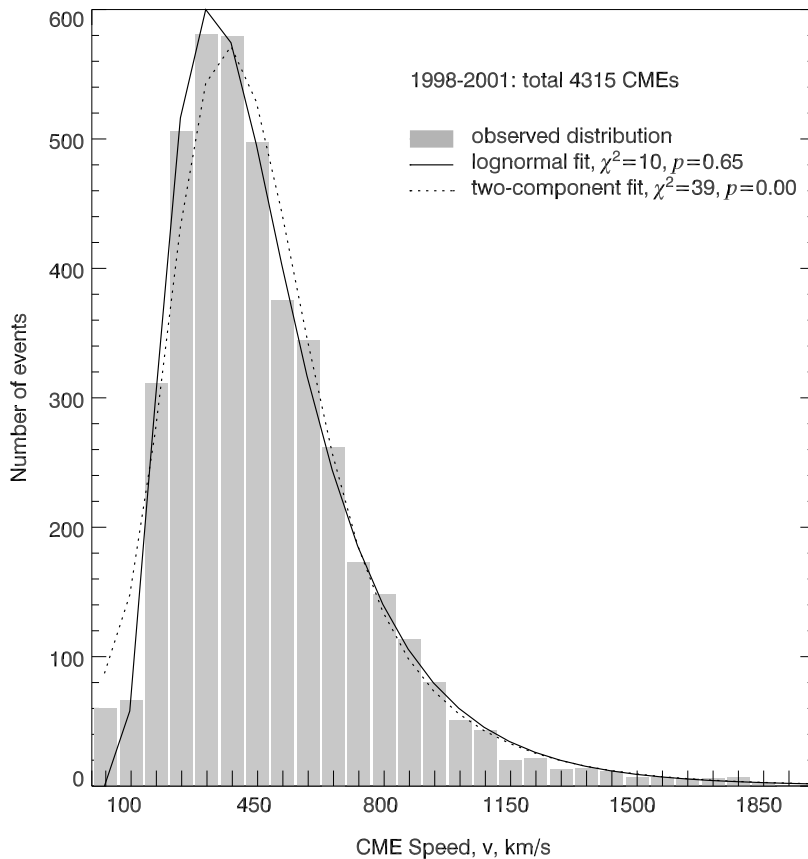


Fig. 1.— Distribution of the observed speeds of 4315 CMEs (vertical bars). The width of the bar is 70 km s^{-1} . The solid line represents a single log-normal fit to the observed data, while the dashed line is a sum of a Gaussian and a log-normal fits.

Figure 1 shows distribution of the number of CMEs, N , versus their projected speeds, v . The distribution is not symmetrical and two prominent components can be distinguished: a strong peak at $v = 350 \text{ km s}^{-1}$ and a long tail. The skewed form of the distribution precludes its fit with a single Gaussian and suggests that it may be modeled either with a sum of several Gaussian, a log-normal distribution or a sum of a log-normal and a Gaussian distributions. At least three Gaussian curves are needed to reasonably fit the main part of the distribution. However, because this three component fit fails to account for the long tail ($>1200 \text{ km s}^{-1}$) and because there are 9 free parameters involved in the procedure, we are reluctant to consider it as a possible statistical model for the observed speed distribution.

The log-normal distribution has several properties which favor its use to model the observed speed distribution: i) it provides a reasonable shape in cases when the random variable may assume values over

one or more orders of magnitude and ii) it is strongly peaked and positively skewed and thus it is well suited to model distributions with a sharp maximum and a pronounced tail.

When a random variable, in our case the speed of a CME, v , is log-normally distributed then its natural logarithm $\ln(v)$ is normally distributed:

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

where P is the probability density function and σ and μ are the mean and variance of $\ln(v)$. The log-normal fit can then be calculated as

$$N = N_0 \frac{\exp -\frac{1}{2} \left[\frac{\ln(v) - \mu}{\sigma} \right]^2}{v \sigma \sqrt{2\pi}}, \quad (2)$$

where the parameters μ and σ are determined from equation (1).

The solid line in Figure 1 shows the log-normal fit from eq. (2) to the observed speed distribution, while the solid line in Figure 2 is the normal fit (eq. (1)) to the distribution of $\ln(v)$. The log-normal approximation shown in Figures 1 and 2 seems to capture the intensity of the observed distribution in all speed ranges and it accurately represents the long tail as well. The χ^2 goodness-of-fit test produced small test statistics, which indicates that the hypothesis on the lognormal distribution of CME speeds can be accepted at significance levels of $p = 0.65$ ($\chi^2 = 10$, degrees of freedom $d.f. = 13$, reduced $\chi^2 = 0.77$).

The dashed line in Figure 1 is a sum of a log-normal and a Gaussian distributions (hereinafter, two-component distribution). At first sight, the two-component distribution seems to be a reasonable approximation over the main part of the observed distribution, however χ^2 statistics is larger ($\chi^2 = 39$, $d.f. = 13$, $p = 0.0002$, reduced $\chi^2 = 3.0$) and therefore the hypothesis on two-component distribution can be rejected with 100% confidence. This failure is unlikely to be attributed to the under-representation of slow and faint CMEs in the data set as a result of limited sensitivity of the LASCO instrument. The comparison of earlier CME data from Solwind instrument, Solar Maximum Mission coronagraph and from the Mauna Loa Solar Observatory MK3 k-chronometer to the more sensitive SOHO LASCO data has shown that there is no significant undetected population of fainter CMEs (St. Cyr et al. 2000).

Further, we separated all CMEs into accelerating and decelerating events according to the sign of acceleration determined from the quadratic fit. We plot distributions of $\ln(v)$ determined separately for the two groups in Fig. 3. The distributions of $\ln(v)$ were then approximated with a normal fit (see eq. (1)). The fitting parameters for all three normal distributions are collected in Table I, where the last two columns show the goodness of the fit, χ^2 , the probability, p , reduced χ^2 and degree of freedom, $d.f.$

From Figures 2, 3 and Table I we conclude the following. The normal approximations for $\ln(v)$ determined for accelerating and decelerating events are substantially the same ($\chi^2 = 0.0033$ with $d.f. = 3$ and the probability $p = 0.99$). The largest difference between the two fits is the parameter μ which describes the position of the maximum in a distribution and it implies that accelerating CMEs, as a group, are slightly slower than the decelerating ones. We would like to note that the distribution of speeds of 4315 CME events,

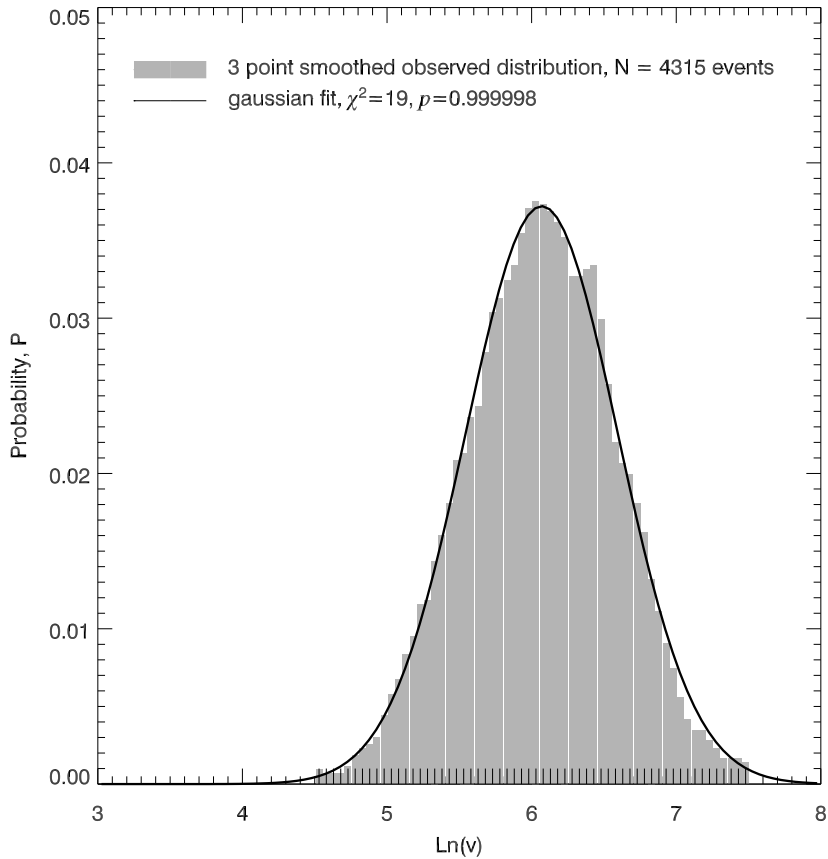


Fig. 2.— Distribution of $\ln(v)$ determined for all 4315 CMEs (vertical bars). The solid line represents normal fit to the observed data.

reported here, peaks at about 430 km s^{-1} (Figure 2 and Table I), which is smaller than the value of 605 km s^{-1} for 254 flare-related CMEs reported by Aoki, Yashiro & Shibata (2003).

3. Discussion

We analyzed the distribution of CME speeds observed by LASCO instrument from 1996 till 2001. We found that the speed distributions determined for all observed events and separately for accelerating and decelerating events are nearly identical and they can be, to a good approximation, fitted with the log-normal distribution. We thus conclude that this statistical study furnishes no evidence to support the claim on two distinguished types of CMEs. The results show that, statistically, there is no physical distinction between the accelerating and the decelerating events. The two-component model, while being a relatively good

approximation, may not represent the nature of the CME speed distribution. We would also like to note that in the case there do exist two types of CMEs, the physical distinction between them can not be easily revealed.

The fact that the two groups of CMEs (accelerating and decelerating events) can be modeled by a single distribution may suggest that the same driving mechanism is acting in both slow and fast dynamical types of CMEs. What then can we learn from the fact that CME speeds are distributed log-normally?

Very often, a phenomenon displays a well determined behavior where observables fluctuate around the average value. In particular, an observed random variable may be represented as a *sum* of the large number of independent random variables. Such a variable can be described by the normal (or Gaussian) distribution with a fast-diminishing tail. Large fluctuations do occur, however, they are extremely rare and they do not contribute to the mean value.

For other phenomena, however, fluctuations themselves dictate the mean values, while the average value becomes irrelevant. Large fluctuations can not be neglected any more since they significantly contribute to the mean value. In this case a broad distribution with the long tail, e.g. log-normal distribution is needed to describe a random variable. The property of the log-normal distribution is that logarithm of a random variable, $\ln(u)$, is distributed normally and it may be represented as a sum of large number of independent random variables. Therefore, the random variable u , is a *product* of a large number of independent random variables. This kind of random variables arises, for example, through the fragmentation process or multiplicative random cascade, when a quantity is subjected to a large number of random, independent subdivisions. In this case the structure acquires an intermittent character, when the bulk of the quantity is concentrated into small-scale features of high intensity surrounded by extended areas of much lower fluctuations. Intermittent structures arise invariably in the evolution of dynamical systems where dissipative processes are not negligible. Such systems are described by non-linear equations and they possess a non-linear interaction between substructures of different spatial scales.

It is accepted that magnetic reconnection between independent magnetic systems plays a major role in the origin of a coronal ejecta. The log-normal distribution of the speeds of CMEs implies then the presence of nonlinear interactions and multiplicative processes in a system of many magnetic flux loops. When complexity of an evolving magnetic field reaches its peak so the magnetic configuration is no longer stable,

Table 1. Fitting Parameters

	A_0	$\mu, (\ln(v))$	$\mu, (\text{km/s})$	σ	χ^2	p	reduced χ^2	$d.f.$
All events	0.0374	6.0697	433	0.5267	19.0	0.99	0.34	56
accelerating	0.0386	5.9708	392	0.5125	16.0	0.99	0.28	51
decelerating	0.0389	6.1681	477	0.5086	35.0	0.91	0.73	48

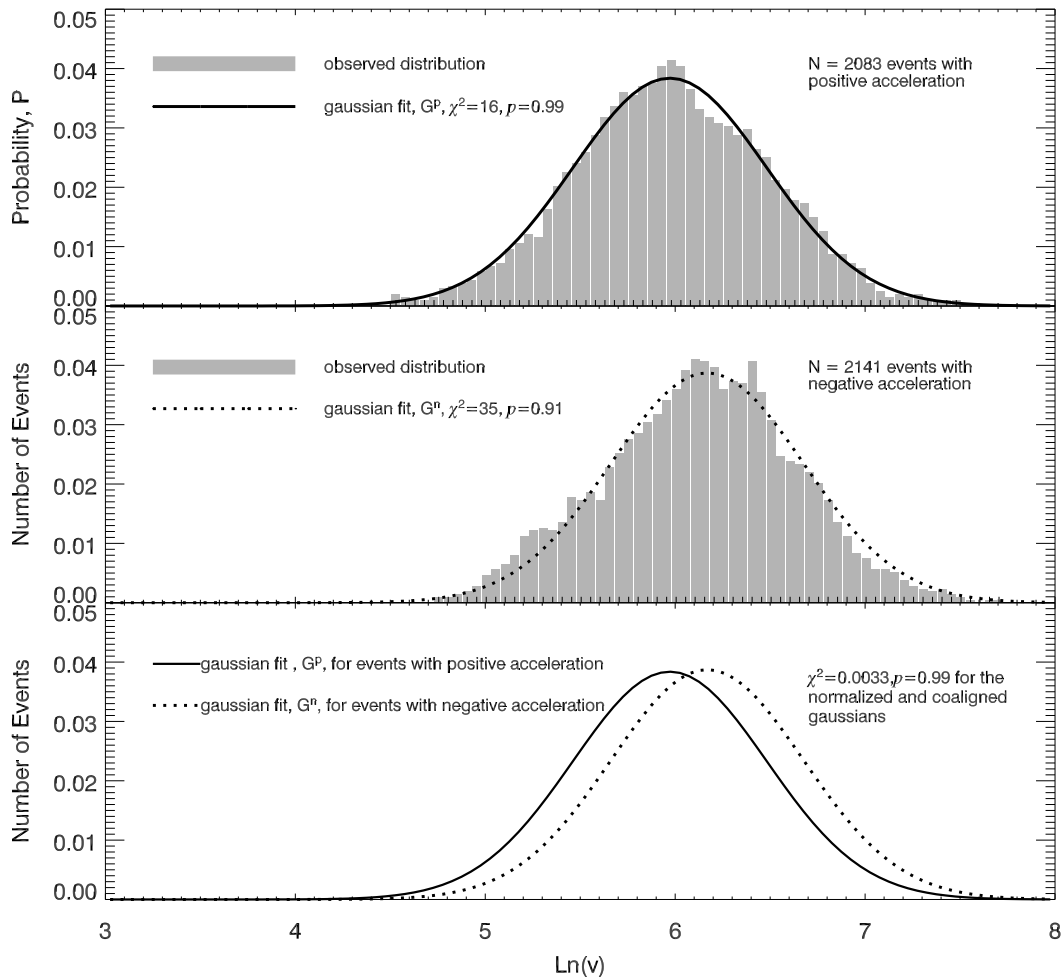


Fig. 3.— Distribution of $\ln(v)$ determined separately for accelerating (top panel, vertical bars) and decelerating (middle panel, vertical bars) events. The thick lines in the top and middle panels show the corresponding Gaussian fits. The bottom panel shows the same Gaussian fits as in the top and middle panels.

a major instability as well as a entire spectrum of smaller scale instabilities may develop in the system of many loops and fluxes, regardless of the assumed initial configuration (Maia et al., 2003). Thus, Kaufmann et al. (2003) interpreted sub-millimeter pulse bursts at the CME onset as signatures of energy release due to small-scale instabilities in the magnetic field. In this sense, the reconnection process in a CME model can be viewed as a multiple reconnection process or as an avalanche of multiple reconnection sites (Lu

& Hamilton 1991; Vlahos et al. 1998; Wang et al. 2000; Charbonneau et al. 2001; Abramenko et al. 2003; Kaufmann et al. 2003; Ji et al. 2003) in a fragmented magnetic field (Kuklin 1980; Bogdan 1988; Ograpishvili 1994; Petrovay, Martínez Pillet, & van Driel-Gesztelyi 1999, Abramenko & Longcope 2004). However, to what extent the multiple reconnection process of fragmented solar magnetic fields is responsible for the log-normal distribution of the CME speeds is yet to be determined.

Finally, data in Figure 2 along with previous reports (e.g. Moon et al. 2002) show that flare-related CMEs tend to be faster than eruptive events. At the same time, CMEs associated with weak flares tend to be slower than those associated with strong flares. In general, dynamics of solar ejecta is believed to be determined by the Lorentz and pressure forces (Vršnak 1990, Chen 1996). Lorentz force is related to the amount of the magnetic flux confined in the erupted field. Is, then, the higher speed of flare associated CMEs related to the fact that the intensity of active region magnetic fields tends to be higher as opposed to the intensity of magnetic fields in chromospheric filaments? In order to address all these questions, extensive studies of a multi-wavelength data set complemented with simulations of the evolution of coronal ejecta in the interplanetary space needs to be carried out.

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