

# Waiting Time Distribution of Coronal Mass Ejections

Chin-Teh Yeh, Ming-De Ding and Peng-Fei Chen

Department of Astronomy, Nanjing University, Nanjing 210093; [jdye@nju.edu.cn](mailto:jdye@nju.edu.cn)

Received 2004 August 31; accepted 2004 October 22

**Abstract** Inspired by the finding that the large waiting time of solar flares presents a power-law distribution, we investigate the waiting time distribution (WTD) of coronal mass ejections (CMEs). SOHO/LASCO CME observations from 1996 to 2003 are used in this study. It is shown that the observed CMEs have a similar power-law behavior to the flares, with an almost identical power-law index. This strongly supports the viewpoint that solar flares and CMEs are different manifestations of the same physical process. We have also investigated separately the WTDs of fast-type and slow-type CMEs and found that their indices are identical, which imply that both types of CME may originate from the same physical mechanism.

**Key words:** solar flares – coronal mass ejections

## 1 INTRODUCTION

Coronal mass ejections (CMEs) are eruptions of magnetized plasma carrying huge quantities of plasma material out of the Sun. Observations show that CMEs are often accompanied by solar flares, while the causal relation between them has been widely debated for many years. For example, Dryer (1982) and Wu (1983) proposed that CMEs are propelled by pressure forces from associated flares. However, Harrison (1995) arrived at a different picture from the finding that CMEs often precede the flares by tens of minutes using data from the Coronagraph/Polarimeter and the Hard X-ray Imaging Spectrometer on board the Solar Maximum Mission. Now, many authors have realized that CMEs and flares may be different manifestations of the same eruptions process (Harrison 1995; Priest 2002), and some researchers emphasized that the differences are due to the fact that flares are localized phenomenon, whereas CMEs correspond to global magnetic disturbances. It is essential to study the connections between the two major solar eruptions from various aspects.

The distribution of the time interval between two successive eruptive events, i.e., the so-called waiting time, has been extensively studied for solar flares (Rosner et al. 1978; Pearce et al. 1993; Wheatland et al. 1998; Boffetta et al. 1999; Giuliani et al. 2000; Wheatland 2001; Norman et al. 2001; Moon et al. 2001; and Lepreti et al. 2001). For example, Boffetta et al. (1999) calculated the probability distribution function of the waiting time using flare data of 20 years from the National Geophysical Data Center of USA, and found the distribution to follow

clearly a power law form:  $P(\tau_L) = A\tau_L^{-\alpha}$  with  $\alpha = 2.38 \pm 0.1$  (in the range  $6 \leq \tau_L \leq 67$  hr) for the same active region, and  $\alpha = 2.4 \pm 0.1$ , regardless of the positions of the flares on the solar surface. Wheatland (2000) examined the waiting time distribution (WTD) of Geosynchronous Operational Environmental Satellites (GOES) soft X-ray flares in 25 years, and obtained again a power law distribution, which they proposed to explain as a time-dependent Poisson process. The index of the power law distribution they obtained is about  $-2.16$ , in contrast to Boffetta et al.'s estimate of  $-2.4$ . The difference in the index is owing to the different selection criteria: Wheatland (2000) used flares greater than class C1, while Boffetta et al. (1999) included all flares in their statistics.

Yeh et al. (2002) made a statistical study of the WTD of CMEs, and compared it with the WTD of solar flares in the same period. It is found that both exhibit the power-law form, with index  $-2.3$  for the CMEs and  $-2.4$  for the solar flares. In the same time and independently, Wheatland (2003) investigated the WTDs of the same solar flares and CMEs, obtained a similar CME index of  $-2.36$ , and found that the power-law index varied with the solar cycle: it is  $-1.86$  for the years 1996–1998, and  $-2.98$  for the years 1999–2001. The observed WTD of CME and its variation with the cycle, may be understood in terms of CMEs occurring as a time-dependent Poisson process. In this paper, we extend our earlier statistical study of the WTDs of solar flares and CMEs and further investigate the WTDs of fast-type and slow-type CMEs from 1996 to 2003. Section 2 describes the data analysis and the results. Their implications for the flare-CME relation are discussed in Section 3.

## 2 DATA ANALYSIS AND RESULTS

The data examined here include flares and CMEs observed during the period 1996–2003. The soft X-ray flare data come from the GOES satellite which is supported by National Geophysical Data Center (NGDC). X-ray flares including classes A, B, C, M and X are used for the calculation of the index of WTD, where the waiting time is defined as the time interval between the “start times” of two successive flares. CMEs are routinely observed by the LASCO telescope on board the SOHO satellite (Brueckner et al. 1995). Their properties are collected from the CME CATALOG, which is maintained by the Center for Solar Physics and Space Weather (CSPSW)<sup>1</sup>. The catalog contains a list of all visible CMEs and the following information: date and time of the first appearance in the field of view of C2 coronagraph, central position angle, angular width, speed, acceleration obtained from quadratic fitting, etc. In the present paper we use the “first C2 appearance time” to calculate the WTD of the CMEs. There is a time delay between the first C2 appearance and the realistic CME onset; the difference between these two times depends on the location of the source region and the motion of individual CME. In order to minimize the ambiguity of the real onset time full halo CMEs are skipped.

During the period from 1996 to 2003, a total of about 16774 flares were identified. The waiting time of all these flares is sampled in intervals of 10 min. The WTD of flares is shown in Fig. 1. It is seen that a large part of the curve fits a power law distribution. For the index calculation, the sample points over 15 hours are skipped because of the large fluctuation that results from the small size of the data, and the sample points less than 10 hrs are ignored because of the finite resolution of the flare detection. With 15724 sample points less than 10 hrs and 454 sample points larger than 15 hrs subtracted, 596 sample points remain between 10 to 15 hrs. These 596 sample points are fitted by a power-law distribution, with an index of about  $-2.52$ , in which  $\chi^2$  does not exceed 0.32. With full halo CMEs and extremely slow CMEs

---

<sup>1</sup> <http://cdaw.gsfc.nasa.gov/>

ignored, 7551 out of 7880 CMEs are collected in the same period from 1996 to 2003. The waiting time is sampled in intervals of 40 min. The WTD of the CMEs is shown in Fig. 2. Among the total 7551 sample points, there are about 5537 points below 10 hrs, 414 points above 24 hrs, and 1600 points between 10 to 26 hrs. The sample points below 10 hrs and those above 26 hrs are skipped in the power-law fitting for the same reason mentioned above. The remaining sample points are well fitted by a power-law distribution, with a power index of about  $-2.41$  (the corresponding  $\chi^2$  is below 0.06). Note that including also the halo CMEs makes only a tiny change to the power-law index. For example, in an independent study, Wheatland (2003) obtained an index of  $-2.36$ .

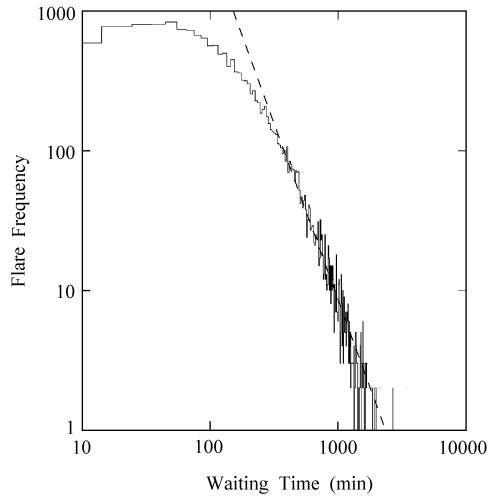


Fig. 1 WTD of GOES soft X-ray flares during the years 1996–2003 (solid line), which is fitted by a power law with an index of  $-2.52$  (dashed line).

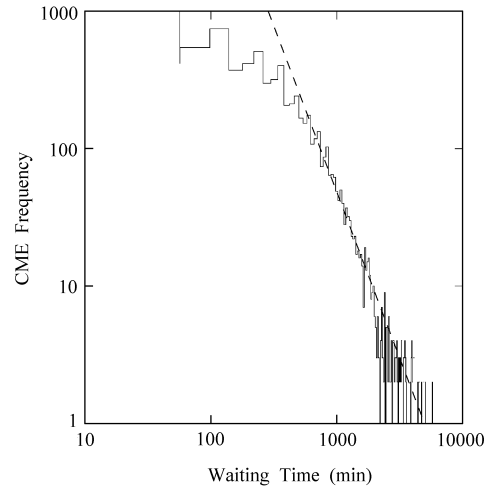


Fig. 2 WTD of CMEs observed by SOHO/LASCO during the years 1996–2003 (solid line), fitted by a power law with an index of  $-2.41$  (dashed line).

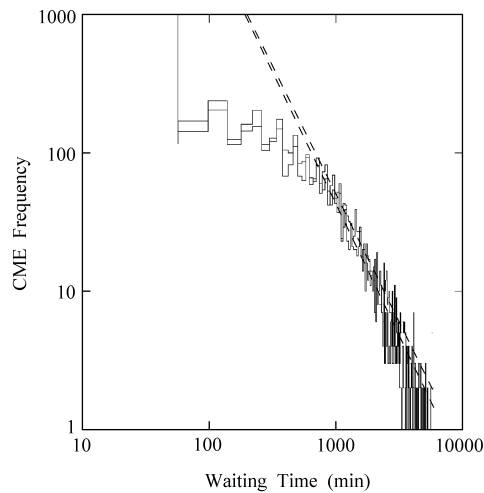


Fig. 3 WTD of CMEs grouped according to their speeds. The thick line for those with speeds exceeding  $410 \text{ km s}^{-1}$ , and the thin line for those with speeds lower than  $410 \text{ km s}^{-1}$ . The former has an index of  $-1.9$ , the latter one of  $-1.85$ .

To study whether the CMEs with different velocity profiles show different WTD behaviors, we divided the CMEs into two groups according to speed, a fast group for speeds greater than  $410 \text{ km s}^{-1}$ , and a slow group for speeds less than  $410 \text{ km s}^{-1}$ . Each group has about 3700 sample points. The results are shown in Fig. 3. It is found that the fast group shows an index of about  $-1.90$  (the corresponding  $\chi^2$  is 0.16), and the slow group shows an index of about  $-1.85$  (the corresponding  $\chi^2$  is 0.13), which indicates that there is no significant difference between the high-speed and low-speed CMEs in the waiting time distribution.

### 3 DISCUSSION

Observations show that solar flares and CMEs are highly associated with each other (e.g., Harrison 1995). However, their causal relation has long been controversial. One reason is that flares are localized phenomena, whereas CMEs correspond to a kind of global magnetic rearrangement. Another reason is due to the fact that CMEs are observed by coronagraphs which occult the solar disk well above the solar limb. Therefore, it is very difficult to determine the onset time of the CMEs precisely. Zhang et al. (2001) analyzed four CME events observed by the LASCO C1 coronagraph and found them to be all associated with solar flares, and that the rise phase of the flares coincides with the acceleration phase of the CME. A similar association was obtained by Chen & Shibata (2000) from numerical simulation. A statistical survey by Zhou, Wang & Cao (2003) further indicated that almost all Earth-directed halo CMEs are associated with EUV brightening on the solar disk. There is mounting evidence up to the present day that CMEs and solar flares are different manifestations of the same process (e. g., Priest & Forbes 2002). Research on the WTDs of the two populations may provide hints for any underlying mechanism. Therefore, we have checked the WTD of CMEs in 1996–2001 (Yeh et al. 2002) and found that, similar to solar flares, the CMEs also present a power law behavior in their WTD, with a power index identical to that for solar flares. This result is agreement with Wheatland (2003), who independently investigated the WTDs of CMEs and solar flares and their solar cycle variations from 1996 to 2001. Here, we perform a further study, with the data sample extended to the year 2003. It is found that the CMEs and solar flares in this period again show power law WTDs, with power index  $-2.52$  for the CMEs and  $-2.41$  for the solar flares. Both these indices are slightly larger than those obtained by Yeh et al. (2002). It may result from the the power index varying with the solar cycle, as illustrated by Wheatland (2003).

Observations show that there may be two types of CMEs, i.e., impulsive and gradual CMEs: the former has very large velocities with little acceleration, while the latter has significantly small velocities with large acceleration in the outer corona (Dryer 1996; Sheeley et al. 1999; Andrew et al. 2001). This has prompted many researchers to consider whether different mechanisms are involved (Low & Zhang 2002; Zhang & Golub 2003). Therefore, it is of interest to study the WTD separately for these two types. We divided all the CMEs into two groups, one corresponding to the fast type, one to the slow type. It is found that despite of their different height-time profiles, they show almost the same WTD. Such a result reminds us of the suggestion that the different height-time profiles of the two types of CMEs are only a matter of different Alfvén time-scales for the MHD process involved in the eruptions (Cliver & Hudson 2002; Feynmmen & Ruzmaikin 2004). It also supports the conjecture that the impulsiveness of CMEs can decrease continuously and eventually leads to gradual CMEs, with the physical nature unchanged (Zhang et al. 2001).

To summarize, in this paper, we study the WTDs of CMEs and flares that occurred during the period from 1996 to 2003, and find that similar to the flares, the CMEs have a power-law behavior in their waiting time distribution. The corresponding power indices are  $-2.41$  for the

former and  $-2.52$  for the latter, respectively. These two values are almost identical within the statistical uncertainty. This result is strongly in favor of the viewpoint that flares and CMEs are different manifestations of one and the same eruptive process. Moreover, it is found that both the slow and fast CMEs present almost the same behavior in their WTDs.

## References

- Anderew M. D., Howard R. A., 2001, *Space Science Reviews*, 95, 147  
Boffetta G., Carbone V., Giuliani P. et al., 1999, *Physical Review Letters*, 83, 4662  
Brueckner G. E., Howard R. A., Koomen M. J. et al., 1995, *Solar Phys.*, 162, 357  
Chen P. F., Shibata K., 2000, *ApJ*, 545, 524  
Cliver E. W., Hudson H. S., 2002, *Journal of Atmospheric and Solar-Terrestrial Physics*, 64, 231  
Dryer M., 1982, *Space Science Reviews.*, 33, 233  
Dryer M., 1996, *Solar Phys.*, 169, 421  
Feynman Joan., Ruzmaikin Alexander., 2004, *Solar Phys.*, 219, 301  
Giuliani P., Carbone V., Veltri P. et al., 2000, *Physica A*, 280, 75  
Harrison R. A., 1995, *A&A*, 304, 585  
Lepreti F., Carbone V., Veltri P., 2001, *ApJ*, 555, L133  
Low B. C., Zhang M., 2002, *ApJ*, 564, L53  
Moon Y. -J., Choe G. S., Yun H. S. et al., 2001, *J. Geophys. Res.*, 106, 29951  
Norman J. P., Charbonneau P., McIntosh S. W. et al., 2001, *ApJ*, 557, 891  
Pearce G., Row A. K., Yeung J., 1993, *Ap&SS*, 208, 99  
Priest E. R., Forbes T. G., 2002, *Astronomy and Astrophysics Review*, 10, 313  
Rosner R., Vaiana G. S., 1978, *ApJ*, 222, 1104  
Rosner R., Vaiana G. S., 1978, *ApJ*, 222, 1104  
Sheeley N. J., Watter J. H., Wang Y. -M. et al., 1999, *J. Geophys. Res.*, 104, 12493  
Wheatland M. S., Sturrok P. A., McTiernan J. M., 1998, *ApJ*, 509 448  
Wheatland M. S., 2000, *ApJ*, 536, L109  
Wheatland M. S., 2001, *Solar Phys.*, 203, 87  
Wheatland M. S., 2003, *Solar Phys.*, 214, 361  
Wu S. T., Wang S., Dryer M. et al., 1983, *Solar Phys.*, 85, 351  
Yeh C.-T., Ding M. D., Chen P. F., 2002, *ASP Conference Series*, 289, 471  
Zhou G., Wang J., Cao Z., 2003, *A&A*, 559, 452  
Zhang J., Dere K. P., Howard R. A. et al., 2001, *ApJ*, 559, 452  
Zhang J., Dere K. P., Howard R. A. et al., 2004, *ApJ*, 604, 420  
Zhang M., Golub L., 2003, *ApJ*, 595, 1251