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Distributions of Energy and Mass of Coronal Mass Ejections

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Abstract The present study investigates the energy and mass distributions of all (11 322) coronal mass ejections (CMEs), 1406 CMEs associated solely with flares (FL CMEs), and 325 CMEs associated solely with filament eruptions (FE CMEs), all of which were observed by the Large Angle and Spectrometric Coronagraph on board the *Solar and Heliospheric Observatory* (SOHO/LASCO) from January 1996 to December 2009. The results show the following. *i*) The mean energy of FL CMEs is significantly lower than that of all CMEs. The mean energy of FE CMEs is significantly higher than those of FL CMEs and all CMEs. *ii*) The mean mass of FL CMEs is slightly larger than that of all CMEs. The mean mass of FE CMEs is significantly larger than those of FL CMEs and all CMEs. Our results suggest that CMEs should shed excess helicity stored in the corona and that the magnetic complexity determines the likelihood of CMEs.

Keywords Methods: data analysis · Sun: coronal mass ejections · Sun: filaments · Sun: flares

1. Introduction

The relationship between coronal mass ejections (CMEs) and the associated solar surface activities is of great importance in understanding the origin of CMEs. Lin (2004) pointed out that the correlation between CMEs and solar flares depends on the energy that is stored

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in the relevant magnetic structure, which is available to drive the eruption. The more energy is stored, the better the correlation; otherwise, the correlation is poor. From a statistical point of view, this indicates that the energy released in CMEs (or the sum of the potential, kinetic, and magnetic energies of CMEs) associated with flares should be larger than the energy in CMEs not associated with flares. The correlation between CMEs and eruptive prominences, on the other hand, depends on whether the relevant magnetic configuration prior to the eruption includes enough material or plasma (Lin, 2004). If the configuration includes enough plasma so that the filament or prominence is recognized, then a CME starts with an eruptive prominence; otherwise a CME develops without apparent association with an eruptive prominence because there is not enough mass to load the filament (or prominence) (Lin, 2004). From a statistical point of view, this implies that the mass of CMEs associated with eruptive prominences should be larger than the mass of CMEs not associated with eruptive prominences.

Zhang and Low (2005), alternatively, suggested that flares and CMEs play different roles in the magnetohydrodynamic (MHD) processes driving eruptions. They noticed that although flares can dissipate magnetic free energy, it is CMEs that shed the excess helicity stored in the corona. Due to the probable existence of an upper bound to the total magnetic helicity stored in the corona (Zhang, Flyer, and Low, 2006), CMEs could be the consequence of accumulating helicity which is generated by the dynamo and transported through the photosphere into the corona. The observation of Liu *et al.* (2010) showed some characteristics in support of Zhang and Low (2005). They pointed out that the pre-CME quasi-static structure has little direct connection with flares. The pre-CME state is, on the other hand, temporally identified with a phase of significant helicity injection from the photosphere and followed by the frequently observed three-phase paradigm, including an initial phase, an acceleration phase, and a gradual phase, as the arcade suddenly erupts as a CME. In observations twisted CME structures are frequently seen, and there is ample evidence that a considerable amount of twist is being carried away from the Sun by CMEs.

Rust (2000) argued that the accumulation of magnetic helicity in filaments and their coronal surroundings leads to filament eruptions and CMEs. According to a new paradigm, subsurface motions generate toroidal magnetic flux ropes, and after these flux ropes emerge to form active regions, the most twisted parts migrate into the corona to form filaments (Rust, 2001). Filaments become unstable and are ejected after a sufficient accumulation of twist (*i.e.*, magnetic helicity). Schmieder (2006) argued that CME activity can also originate from the so-called quiet solar regions which contain filaments. Estimations showed that the filament-arcade system has enough magnetic helicity to account for the helicity carried by the related CMEs (Wang *et al.*, 2006). From a statistical point of view, this implies that the CMEs associated with filament eruptions should have larger energies than those not associated.

Vourlidas *et al.* (2010) presented an extensive analysis of the first full solar-cycle database of CMEs from the viewpoint of their mass and energy properties. Their measurements are incorporated in the online database of the Large Angle and Spectrometric Coronagraph (LASCO) Principal Investigator (PI) team at Naval Research Laboratory (NRL). This work provided us with a good source to investigate the CME energy. For each CME event, they compiled the evolution of the mass, potential energy, height, and other quantities as the CME progressed through the LASCO C2 and C3 fields of view. Here, we focus on the properties of the full CME sample rather than the evolution of particular events. Thus, we want to treat each event as an individual data point and therefore need to extract, for each event, a representative set of parameters at a single time frame. Vourlidas *et al.* (2010) pointed out that it is natural to assume that a representative point for each event is the time when the CME achieves its maximum mass and they extracted parameters at that time frame. Thus, we also extract mass and potential energy at that time frame. The kinetic energy is obtained from the mass and linear speed (see Vourlidas *et al.* (2000) for details). The linear speed is obtained by linearly fitting the height-time measurements.

The calculations of the potential and kinetic energies of CMEs are made directly from the LASCO images. However, the values Vourlidas *et al.* (2000) used for the magnetic energy of those CMEs are only estimates, because the magnetic field strengths in CMEs are unknown. Their estimates of the magnetic energy of CMEs are made on the basis of *in situ* measurements of magnetic clouds (MCs) near the Earth. Huttunen *et al.* (2005) have identified 73 MCs from the *Advanced Composition Explorer* (ACE) and *Wind* solar wind data during the seven-year period 1997 – 2003, or 0.90% of all the 8101 CMEs observed by LASCO on board the *Solar and Heliospheric Observatory* (SOHO). From Figures 3 through 6 of Vourlidas *et al.* (2000), we find that the sum of the potential and kinetic energies of a CME is one order of magnitude higher than the magnetic energy of the CME for almost all CMEs they studied. Thus, we adopt the sum of the potential and kinetic energies of a CME as the total CME energy without consideration of the magnetic energy of the CME.

In this paper, we will investigate the energy and mass distributions in *i*) all CMEs, *ii*) CMEs associated solely with flares (FL CMEs), and *iii*) CMEs associated solely with filament eruptions (FE CMEs), all observed by SOHO/LASCO from 1996 to 2009. The study will help us to understand the relationship between CMEs and associated solar surface activity, which is of great importance in understanding the origin of CMEs.

2. Data Selection and Analysis

After the launch of the SOHO satellite in December 1995, the LASCO telescope (Brueckner *et al.*, 1995) observed tens of thousands of CMEs. The CME mass is made available in a database of SOHO/LASCO produced by a consortium of NRL (USA), Max-Planck-Institut für Aeronomie (Germany), Laboratoire d'Astronomie (France), and the University of Birmingham (UK).[1] The CME energy can be derived from this database. Solar flares are routinely recorded in the *Solar-Geophysical Data* (SGD) reports.[2] Filament eruption events are collected by SGD and the National Geophysical Data Center (NGDC).[3]

In this paper, we consider those CMEs that are associated solely with flares (FL CMEs) or filament eruptions (FE CMEs). The LASCO instrument consists of a set of three nested coronagraphs with overlapping and concentric fields of view: C1 ($1.1 - 3R_\odot$), C2 ($2 - 6R_\odot$), and C3 ($4 - 30R_\odot$). The C1 images of the low corona (Plunkett *et al.*, 1997; Schwenn *et al.*, 1997) provide key information on the early evolution of CMEs. C2 and C3 are traditional externally occulted white-light coronagraphs that observe Thomson-scattered visible light through a broadband filter. Zhang *et al.* (2001) investigated the temporal relationship between CMEs and X-ray flares by making use of observations with the LASCO, which covers the corona from 1.1 to $30R_\odot$, and found that the impulsive acceleration phase of a CME coincides very well with the rise phase of the accompanying soft X-ray flare. However, the C1 telescope was disabled in June 1998, and thereafter the acceleration phase has not been observed by LASCO for most CME events. Thus, we followed the conventional

[1] http://lasco-www.nrl.navy.mil/.

[2] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES.

[3] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FILAMENTS.

way of assuming that the acceleration phase of each CME is within a time window that is generally set to $\pm$ 1 h, relative to the estimated CME onset time (Yeh, Ding, and Chen, 2005; Chen, Chen, and Fang, 2006; Gao, Li, and Li, 2009). The X-ray flare events stronger than B1.0 in the SGD reports are searched during the time window. The flare that occurred during this window and was located within the angular span of the CME is considered to be associated with the CME (see Gao, Li, and Li (2009) for details).

Filament eruptions and CMEs have been found to start roughly at the same time (Gopalswamy *et al.*, 2003). Since there is uncertainty in estimating the CME onset time, a time window of $\pm$1.5 h relative to the estimated CME onset time was set to judge the association with a filament eruption (Chen, Chen, and Fang, 2006).

Note that, for FE CMEs, we mean by "associated solely with filament eruptions" those CMEs that have no associated soft X-ray flares above B1.0 class recorded in the SGD reports; for FL CMEs, we mean by "associated solely with flares" those CMEs that have no associated filament eruption events collected by SGD and NGDC. We exclude some CMEs with negative mass which may indicate overlapping events (Vourlidas *et al.*, 2010). The kinetic energy is obtained from the mass and linear speed (see Vourlidas *et al.*, 2000 for details). A minimum of two height-time measurements is needed for an estimate of the speed, but the accuracy increases when there are more measurements. Thus, we also exclude some CMEs with too few (≤ 3) measurements. The remaining sample contains 11 322 CMEs during the interval from 1996 to 2009. We select the CMEs that are associated solely with flares or filament eruptions in both space and time, as described above. There are 1406 FL CMEs and 325 FE CMEs.

3. The Energy and Mass Distributions of CMEs

We plot the probability distributions of all CMEs, FL CMEs, and FE CMEs versus their energies in Figure 1. The probabilities in terms of a bin size of 3×10^{30} erg are obtained by dividing the number of CMEs in each bin by the total number of CMEs. As to the energies higher than 18×10^{30} erg in our sample, there are 750 CMEs, or 6.62% of all the 11 322 CMEs, 85 FL CMEs, or 6.04% of all the 1406 FL CMEs, and 37 FE CMEs, or 11.3% of all the 325 FE CMEs. These events are put into the bin of $18 \times 10^{30} - 21 \times 10^{30}$ erg. We find that the probability of FL CME events with higher energies is lower than that of all CMEs and the probability of FE CME events with higher energies is higher than those of all CMEs and FL CMEs. We then calculate the mean energies of all CMEs, FL CMEs, and FE CMEs. Their mean energies are $7.73 \times 10^{30} \pm 6.69 \times 10^{29}$ erg, $5.75 \times 10^{30} \pm 5.87 \times 10^{29}$ erg, and $1.28 \times 10^{31} \pm 2.93 \times 10^{30}$ erg, respectively. The error represents the uncertainty in the mean ($\sigma/\sqrt{n}$, where σ is the standard deviation and n is the number of data points). The mean energy of FL CMEs is 75% that of all CMEs. The mean energy of FE CMEs is 1.7 times that of all CMEs and 2.2 times that of FL CMEs.

We also plot the probability distributions of all CMEs, FL CMEs, and FE CMEs versus their masses in Figure 2. The probabilities in terms of a bin size of 6×10^{15} g are obtained by dividing the number of CMEs in each bin by the total number of CMEs. As to the masses higher than 36×10^{14} g in our sample, there are 1083 CMEs, or 9.56% of all the 11 322 CMEs, 141 FL CMEs, or 10.0% of all the 1406 FL CMEs, and 56 FE CMEs, or 17.2% of all the 325 FE CMEs. These events are put into the bin of $36 \times 10^{14} - 42 \times 10^{14}$ g. We find that the probability of FL CME events with higher masses is slightly higher than that of all CMEs and the probability of FE CME events with higher masses is higher than those of all CMEs and FL CMEs. We have also calculated the mean masses of all CMEs, FL CMEs, and

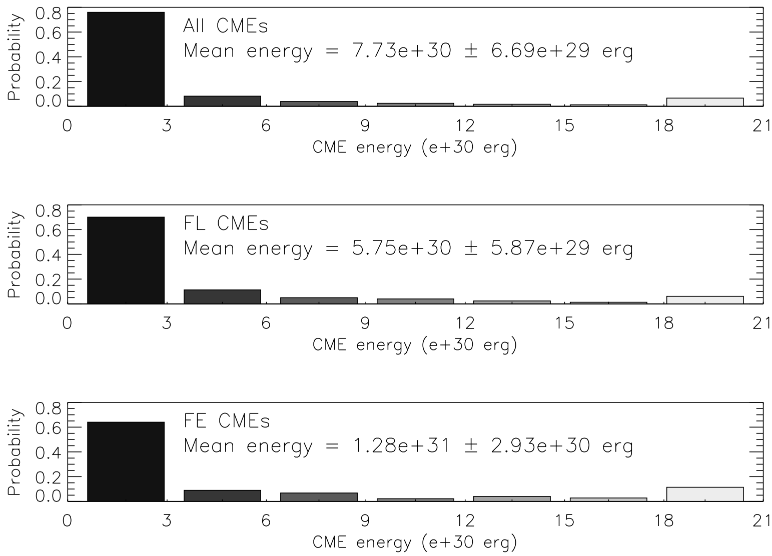

Figure 1 The energy distributions for all CMEs (top panel, vertical bars), FL CMEs (middle panel, vertical bars), and FE CMEs (bottom panel, vertical bars). All 750 CMEs, 85 FL CMEs, and 37 FE CMEs with energies higher than 18×10^{30} erg are put into the bin of $18 \times 10^{30} - 21 \times 10^{30}$ erg. The mean energy and the uncertainty in the mean in each case are given.

FE CMEs. Their mean masses are $1.42 \times 10^{15} \pm 5.35 \times 10^{13}$, $1.52 \times 10^{15} \pm 1.32 \times 10^{14}$, and $3.03 \times 10^{15} \pm 7.68 \times 10^{14}$ g, respectively. The mean mass of FL CMEs is slightly (6.5%) higher than that of all CMEs. The mean mass of FE CMEs is 2.2 times that of all CMEs and 2.0 times that of FL CMEs.

4. Conclusions and Discussion

In this paper, we have investigated the energy and mass distributions of all (11 322) CMEs, 1406 FL CMEs, and 325 FE CMEs, all of which were observed by SOHO/LASCO from 1996 January to 2009 December. The results show the following. *i*) The mean energy of FL CMEs is significantly lower than that of all CMEs. The mean energy of FE CMEs is significantly higher than those of FL CMEs and all CMEs. *ii*) The mean mass of FL CMEs is slightly larger than that of all CMEs. The mean mass of FE CMEs is significantly larger than those of FL CMEs and all CMEs.

Lin (2004) treated the flare and CME as integral constituents of a single process within the framework of the catastrophe model and pointed out that the flare-CME correlation depends on the free energy stored in the relevant magnetic structure: the more free energy, the better the correlation. From a statistical point of view, this indicates that the energy released in CMEs associated with flares should be larger than the energy released in CMEs not associated with flares. Zhang and Low (2005) suggested that flares and CMEs play different roles in the MHD processes driving eruptions: Flares can dissipate excess magnetic energy while CMEs can shed excess helicity stored in the corona. From a statistical point of view, this indicates that the energy released in CMEs associated with filament eruptions should be larger than the energy released in CMEs not associated with filament eruptions.

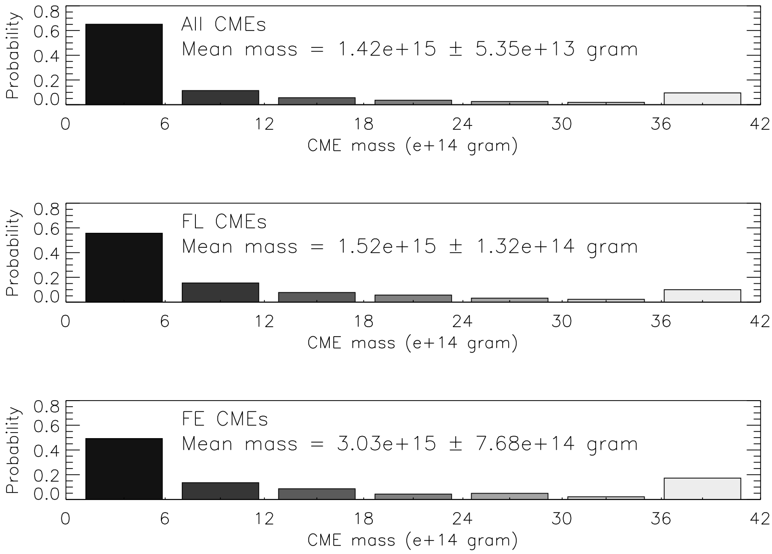

Figure 2 The mass distributions for all CMEs (top panel, vertical bars), FL CMEs (middle panel, vertical bars), and FE CMEs (bottom panel, vertical bars). All 1083 CMEs, 141 FL CMEs, and 56 FE CMEs with masses higher than 36×10^{14} g are put into the bin of $36 \times 10^{14} - 42 \times 10^{14}$ g. The mean mass and the uncertainty in the mean in each case are given.

Our results, namely, that the mean energy of FL CMEs is significantly lower than that of all CMEs and the mean energy of FE CMEs is significantly higher than those of FL CMEs and all CMEs, show some characteristics in support of Zhang and Low (2005): CMEs should shed the excess helicity accumulated in the corona. The magnetic helicity quantifies how the magnetic field is sheared or twisted compared to its lowest energy state (the potential field). Strong shear and twist are necessary conditions for a CME to occur; *i.e.,* the highly CME-active source regions are magnetically complex (Schmieder, 2006). Our results also suggest that the magnetic complexity determines the likelihood of CMEs.

Lin (2004) pointed out that the correlation between CMEs and eruptive prominences depends on whether the relevant magnetic configuration prior to the eruption includes enough material or plasma. Kilper, Gilbert, and Alexander (2009) found that there is a combined trend of an apparent increase in the homogenization of the filament mass composition starting at least one day prior to eruption. From a statistical point of view, this implies that the mass of CMEs associated with filament eruptions should be larger than the mass of CMEs not associated with filament eruptions. Our results, namely that the mean mass of FE CMEs is significantly larger than those of FL CMEs and all CMEs, support these conclusions.

We must also point out the following. *i*) CMEs are closely related to filament eruptions as well as flares. It is widely accepted that filament eruptions, flares, and CMEs are different aspects of the same physical process (Shibata *et al.*, 1995; Forbes, 2000; Priest and Forbes, 2002). *ii*) In the typical theoretical model for CMEs, FL CMEs and FE CMEs are all associated with the ejection of flux ropes (Forbes and Priest, 1995; Antiochos, DeVore, and Klimchuk, 1999; Lin, 2004; Jacobs and Poedts, 2011). *iii*) SGD and NGDC only provide an overall view of solar activity. For example, if SGD and NGDC do not report a filament eruption, it does not mean that no filament is associated with the ejected CME; if the SGD report does not report a soft X-ray flare above B1.0 class, it does not mean that no flare is associated with the ejected CME. However, in this paper, we have focused on the statistical properties of CMEs associated with observed filament eruptions and CMEs associated with observed flares. Thus, we have selected FL CMEs and FE CMEs following the conventional method and have investigated the statistical properties of FL CMEs and FE CMEs. A great many events (1406 FL CMEs and 325 FE CMEs) have been analyzed, which should have reduced the uncertainties. This will give us clues in understanding the CME trigger mechanism.

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