Variations of CMEs Properties during the Different Phases of the Solar Cycle 23

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Abstract. As coronal mass ejections introduce large-scale changes in the corona, which have fundamental implication for the evolution of the magnetic flux of the Sun, the long-term behavior of CMEs is of great interest to be investigated. In this work the main properties of 13985 coronal mass ejections (CMEs) observed by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO) from January 1996 until December 2008 covering the last solar cycle 23 are studied. Specifically, the detected CMEs taking into account the gaps of SOHO during this solar cycle, seem to present fluctuations from the expected behavior of the sunspot number during the declining phase of this solar cycle. Separating the CMEs according to their linear speed, their width and their kinetic energy a detailed study during the rising and the declining phase of the solar cycle 23 has been performed. Moreover, a correlative analysis of all these properties of CMEs and all registered solar proton enhancements (SPEs) with proton flux >0.1pfu at energy>10MeV measured at the Earth's orbit during this time period, is also presented.

Keywords: Coronal Mass Ejections, Solar Energetic Particles, Proton Events, Solar Flares
PACS: 96.60.ph

INTRODUCTION

Coronal mass ejections (CMEs), as we know them today, were first detected in the coronagraph images obtained on December 14, 1971 by NASA's OSO-7 spacecraft [1]. Typical coronagraphs have an occulting disk to artificially eclipse the bright photosphere, so the faint coronal structures outside the periphery of the occulting disk can be viewed in the photospheric light scattered off these structures. CMEs are now understood as large-scale magnetized plasma structures originating from closed magnetic field regions on the Sun: active regions, filament regions, active region complexes and trans-equatorial interconnecting regions. In this work, we highlight our research on CMEs spurred by the extensive and uniform data from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO). Since coronal mass ejections bring large-scale changes in the corona, which have fundamental implication for the evolution of the magnetic-flux of the Sun, it is interesting to examine the long-term behavior of the CME. As it is known, the sunspot number R_z in annual values shows a steady increase (rising phase) in about 4-5 years to a maximum value R_z (max), followed by a steady decline (declining phase) in about 6-7 years (for a total span of about 11 years). With finer time scale data (3-month averages), the maximum seems to show a multiple peak structure.

CP1203, 7th *International Conference of the Balkan Physical Union,* edited by A. Angelopoulos and T. Fildisis

The peaks are called Gnevyshev peaks and the spaces in between are called Gnevyshev gaps [2, 3]. The declining phase is not always smooth and, often, fluctuations are observed.

On the other hand, large solar energetic particle (SEP) events are known to be closely related to coronal mass ejections [4]. Fast CMEs drive MHD shocks, which in turn accelerate the SEPs (protons and minor ions). SEP acceleration may also occur during flares, but these events are typically short-lived (hours). For space weather purposes, the large gradual SEPs from CME-driven shocks are more important [5] mentioned that most of large SEP events are associated with wide CMEs having velocities above 400 km/sec. A detail study of various properties of coronal mass ejection (CMEs) during the time period 1996-2002 showed that the fast (average speed >1500 km s^{-1}) and wide (mostly full or partial halos) CMEs are associated with SEP [6]. In addition, SEP events with ground level enhancements (GLEs) in the ground based detectors are connected with the fastest known population of CMEs (average speed ~ 1798 km s^{-1} (sky-plane)) [7]. Up to 15% of the CME kinetic energy goes into the accelerated particles suggesting that the CME-driven shocks are efficient particle accelerators [8].

In this work, using an update extend database of solar proton enhancements in different energy channels >10 MeV and >100 MeV as well as >500MeV (ground level enhancements-GLEs) [9] and the complete catalogue of CMEs (http://cdaw.gsfc.nasa.gov/CME_list), we try to study the behaviour of CMEs during the ascending , maximum and descending phases of the last solar cycle (1996-2008) as well as the possible connection of the SPEs and the coronal mass ejection for the entire above time period. Specifically the characteristics of CMEs associated with SPEs are considered.

DATA SELECTION

Coronal mass ejections data were taken from the Large Angle and Spectrometric Coronagraph (LASCO) having three telescopes C1, C2 and C3 on board the Solar and Heliospheric Observatory (SOHO) mission (http://cdaw.gsfc.nasa.gov/CME_list). However, in our analysis only C2 and C3 data were used for uniformity, as C1 was disable from June 1998. The database includes except its exact date and time many basic attributes of a CME such as its speed, width, acceleration, and central position angle (CPA), all with reference to the sky plane. These are obtained from a time sequence of coronographic images, in which the CME can be recognized as a moving feature occupying a well-defined region. The angular extent of the moving feature defines the width. The central angle of this extent with reference to the solar north is the CPA. The speed is normally determined from a linear fit to the height–time (h–t) plots. But CMEs often have finite acceleration, so the linear-fit speed should be understood as the average value within the coronagraphic field of view. Quadratic fit to the h–t plots gives the constant acceleration, which again is an approximation because the acceleration may also change with time. It is important to note that the existed data gaps are calculated in scale of hours and were taken into account in our calculations.

The database of solar proton enhancements updated and expanded database from the previous work (Belov et al., 2005[9, 10]; Gerondidou et al., 2008) is used. In order to obtain this database, we use the integral proton fluxes measured onboard IMP-8 and GOES 5-12 satellites. In the earlier period 1975-1986 only data from IMP-8 have been available. At times during the time period 1987-2001 when data from the IMP-8 and GOES satellites were available only one spacecraft's data were used, because of gaps existing in the conjugate set. During the period 2002-2008 only GOES data are available. GOES corrected integral fluxes were extracted for proton energies >10, >30, >60 and >100 MeV (see http://spidr.ngdc.noaa.gov/spidr/) as well as IMP-8 >10, >30 and >60 MeV data (see http://nssdc.gsfc.nasa.gov/omniweb/ow.html). Additionally, the IMP-8 >106 MeV/n proton and nuclear channel were also incorporated (see http://ulysses.sr.unh.edu/WWW/Simpson/imp8.html).

In addition an extend database of soft X-Ray measurements as listed in NOAA website (http:// www.ngdc.noaa.gov/stp/SOLAR/ftpsolarflares.htl#Xray) covering the time period from 1996 to 2008, is used.

It is important to note that, most previous works [11, 6, 12] dedicated to the study of energetic proton events and their relationship to CMEs has relied upon the widely used NOAA standard for solar particle events that are defined as events with fluxes >10 pfu at energy >10 MeV. In a recent work [9] we the term solar particle enhancement (SPE) has been applied, including flux intensities well below that of the NOAA standard (>0.1 pfu), in order to emphasize the point that a broad range of near-Earth proton flux intensities is being investigated. A complete database of 1275 solar proton enhancements has been created almost for all the extended period 1976-2008. During the years 1996-2008 a number of 368 solar proton enhancements (SPEs) in the energy range of >10 MeV, 178 SPEs having energy >100 MeV and finally only 15 of these events were recorded by Neutron Monitors having cut of energy ≈500 MeV. The time distribution of all above datasets is presented in Fig. 1. More specific the time distributions of the yearly corrected CMEs together with the time variation of sunspot number (upper panel of Fig. 1) , the time variation of soft X-ray flares (middle panel) and with the variation of SPEs with fluxes >0.1pfu and energy > 10 MeV (bottom panel) are presented in Fig. 1.

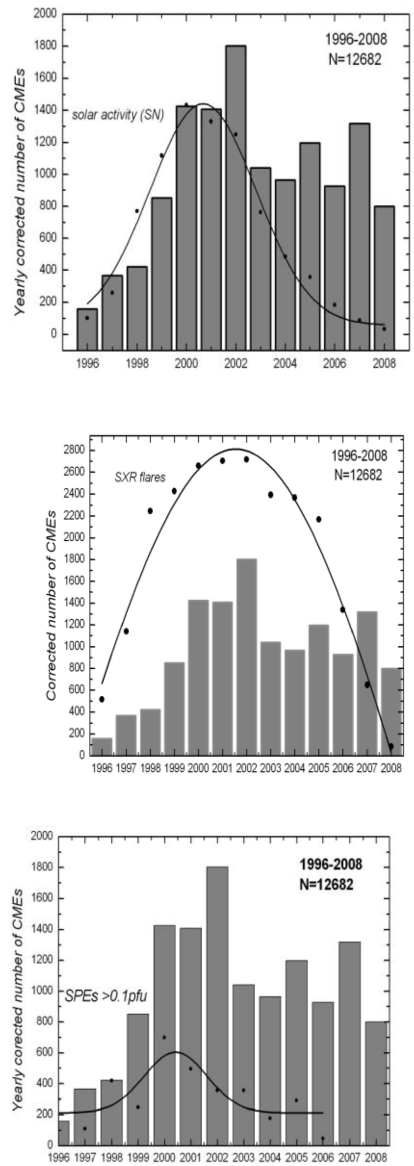

FIGURE 1. Time distribution of the yearly corrected number of CMEs

As it can be seen, the corrected number of CMEs seems to be well correlated with the sunspot number. At this point we can note that pre-SOHO CME rate was found to have a good correlation with the sunspot number (SSN), which indicated a solar maximum rate of ~3 [12], confirmed by data from the SMM and Solwind coronagraphs [13]. The SOHO CME rate, although initially is consistent with pre-SOHO results [14], this is in accordance with the obtained results of our analysis. In general, the corrected number of CMEs follows a trend with similar behavior to that one of sunspot number during the rising phase of solar cycle 23, while there are large fluctuations on the maximum and declining phase.

CORRELATION ANALYSIS

Separating the monthly corrected number of CMEs according to their linear speed in every range of 300 km/sec we calculated the correlation coefficient between them and the monthly sunspot number during the ascending, descending and maximum phase of solar cycle 23. The results presented in Table 1. As it can be concluded only in ascending phase of solar cycle the correlation coefficient have a positive value in all linear speed ranges and growing up with the speed of CMEs except in the very fast ones having linear speed in the range 900-1200km/s, which are very rare. There is also an anti correlation for slow CMEs having speed 0-300km/s during the maximum and descending phase of the solar cycle 23. It is notable there is a jump in the value of correlation coefficient for the CMEs having linear speed in the range 600-900km/s during the descending phase of solar cycle. This result is connected with the fast CMEs which are associated with solar proton enhancements [10].

TABLE 1. Correlations coefficient for CMES with different linear speed and solar activity

					Standard Deviation			
	0-300km/s	300-600km/s	600-900km/s	900-1200km/s				
Ascending phase	0.21	0.62	0.65	0.55		14	5.6	1.9
Maximum	-0.19	0.28	0.39	0.15				
	-0.56	0.53	0.73	0.59	21.25	12.22	5.85	2.26

A correlation plot together with the confidence bars of calculated mean kinetic energy of CMEs with the sunspot number in monthly time scale during the solar cycle 23 is presented in Fig. 2.

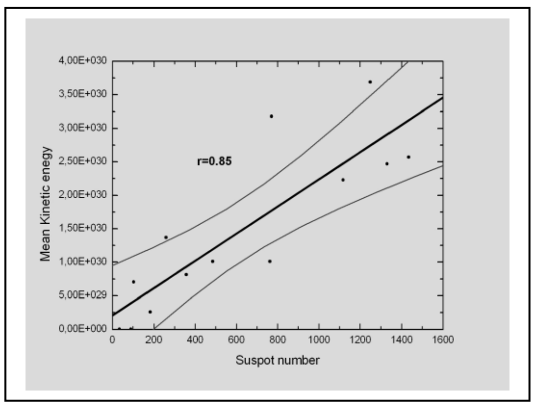

FIGURE 2. Scatter plot of monthly calculated mean kinetic energy of CME versus sunspot number during the solar cycle 23.

As we can conclude there are well associated appearing a correlation coefficient r=0.85 with standard deviation SD=6.6.

In order to investigate in more detail the behavior of CMEs during the different phases of solar cycle 23, a scatter plot of monthly corrected number of CMEs and monthly number of sunspot number for the ascending, maximum and descending phase of solar cycle 23 is performed and presented in Fig 3. As we can remark the monthly corrected number of CMEs seems to be well connected with monthly number of sunspot number during the ascending phase of solar cycle 23, while large fluctuations appear in the maximum and descending phase.

For our correlative analysis in the time period 1996 to 2008, only 317 from 13985 detected CMEs seems to have a close temporal association with the proton enhancements, taking into account the gaps on SOHO. The term temporal association means that within a window of four hours before or/and after the SPE appearance, one at least CME detection occurs. The distribution of time delay between CME detection and SPE is presented in Figure 4. As we can see the great majority of CMEs are detected within the time interval from -1 to +1.5 hours after SPEs detection.

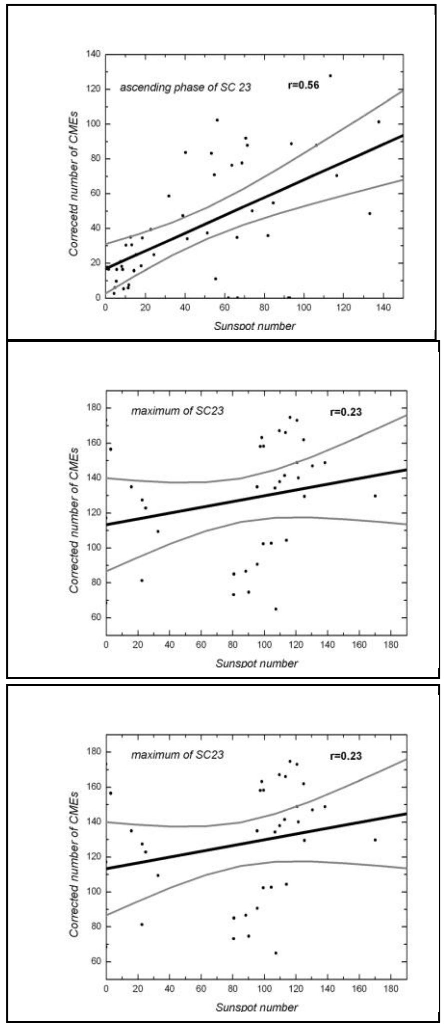

FIGURE 3. Scatter plot of monthly corrected number of CMEs versus sunspot number for the ascending (left panel), maximum (center panel) and descending phase of solar cycle 23.

As it is obtained from this figure, the SEPs and CMEs are appeared in the time interval 0-30 min. It is interest to note that the fraction of these events to the rest event is 1.26. Minor sub peaks in the distribution that are observed may attribute to different source longitude. However, the general trend is monotonic decrease to the greater time delays.

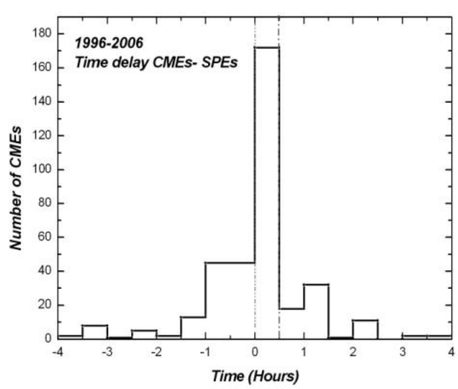

FIGURE 4. Distribution of time delay between time detection of CME and SEP

Finally, based on the result that a high correlation exists between the number incidence of SPEs and major (>M4) flares on a scale of months and years [9], the relation between corrected number of CMEs and SXF with importance >M4 is studied. The calculated correlation coefficient is r=0.7. This result is important since the occurrence rate of SPEs and SXR flares >M4 in relation with other manifestations of solar activity such as coronal mass ejections seems to have an ability to emit protons sufficient to be registered near Earth vicinity.

CONCLUSIONS

In this work a first attempt to accomplish an extended study of the behavior of coronal mass ejections and its properties during the different phases of the solar cycle 23 is performed. For this purpose a comparative analysis of 13985 CMEs and 368 proton enhancements is presented.

Summing up the main results of this study we note that, together with appropriate results published since today, our findings provide new important information about the interplanetary and solar –terrestrial relationships.

- Coronal mass ejections escaping from the Sun vary in the same way as the sunspot number only during the rising phase of the solar cycle 23. On the contrary, CMEs have large fluctuations in the maximum and the declining phase of this solar cycle.
- CMEs with linear speed up to 300km/s (slow CMEs) present an anticorrelation with the sunspot number in the max and descending phase of solar cycle .For linear speed >300km/s the correlation coefficient became smaller as the linear speed increase specially in the declining phase of solar cycle..
- CMEs seems to be well connected with SXR flares with importance >M4 (correlation coefficient r=0.7).This result is important since solar proton events are well related with SXR flares >M4.

Finally, additionally the present work provides strong evidence of the relation between the two solar phenomena, solar proton enhancements and CMEs, that are important from the Space weather point of view.

ACKNOWLEDGMENTS

This work is supported by the State Scholarships Foundation of the “European Regional Development Fund” and the Greek Public.

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