Solar proton enhancements in different energy channels and coronal mass ejections during the last solar cycle

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***Abstract* – The main properties of 11622 coronal mass ejections (CMEs) observed by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO-C2) from January 1996 through December 2006 are considered. Moreover the extended database of solar proton enhancements (SPEs) with proton flux >0.1 pfu at energy >10 MeV measured at the Earth's orbit is also studied. A comparison of these databases give new results concerning the sources and acceleration mechanisms of solar energetic particles. Specifically, coronal mass ejections with width >180^0 (wide) and linear speed >800 km/sec (fast) seem to have the best correlation with solar proton enhancements. The study of some specific solar parameters, such as soft X-ray flares, sunspot numbers, solar flare index etc. has showed that the soft X-ray flares with importance >M5 may provide a reasonable proxy index for SPE production rate. From this work, it is outlined that the good relation of the fast and wide coronal mass ejections to the proton enhancements seems to lead to a similar conclusion. In spite of the fact that in the case of CMEs the statistic covers only the last solar cycle, while the measurements of SXR flares are extended over three solar cycles, it is obvious for the studied period that the coronal mass ejections can also provide a good index for the solar proton production.**

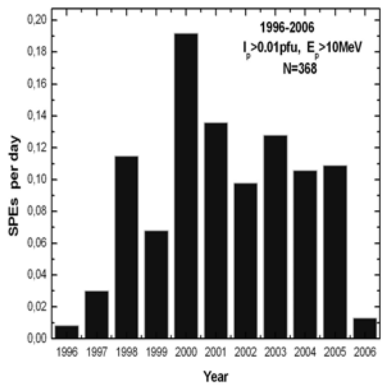
***Key Words*—solar energetic particles, solar flares, coronal mass ejections, proton events**

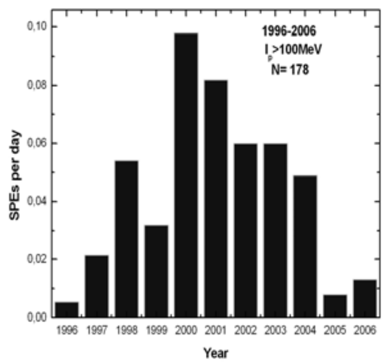
I. INTRODUCTION

The appearance of solar energetic particles having high fluxes at the Earth's space environment or/and in any point of heliosphere is of great interest and usually these particle storms are called solar extreme events. A component of these events is the solar proton events (SPE) recorded by satellites at 1AU as well as by the ground level neutron monitor network.

During extreme solar events as big flares or/and energetic coronal mass ejections, high energy particles are accelerated by the shocks formed in front of fast interplanetary coronal mass ejections (ICMEs). These CMEs also give rise to large geomagnetic storms which have significant effects on the Earth's environment and human life. Around 15 ground level cosmic ray intensity enhancements (GLEs) events were recorded by neutron monitors during the solar cycle 23 and all but one of them were always followed by a geomagnetic storm with D_{st}<=-50nT within 1-5 days later ([1], [2]). It is notable that during the decay phase of this solar cycle and in particular almost at the very end of this, a number of such events was observed. In the top of them is the ground level enhancement of cosmic ray intensity occurred on 13th of December, 2006 during a magnetically disturbed period manifested by a series of Forbush decreases of the cosmic ray intensity at neutron monitors starting from 6 of December, 2006. In particular the big X-ray flare of 13 December 2006 at 02:14 UT with importance X3.4/4B originated from the active region 10930 and from the west side of the Sun (S06W23) resulted in a big proton flux increase at 1 AU reaching the flux value of 695pfu at energy range >10 MeV and 86 pfu at energy >100 MeV, as it was recorded by GOES-11 satellite. The same day at 02:54 UT a fast hallo CME with linear speed 1774 km/sec was also recorded by SOHO satellite ([3])

The possible connection of these two parameters of solar activity, soft X-Ray flares and CMEs and their results in the interplanetary space and at the Earth as solar proton events is under consideration. Nevertheless, both flares and CMEs are the result of rearrangements of the coronal magnetic field, they are often "associated" one another in some way. However, a major controversy still exists as to whether the particle acceleration occurs in the flare itself or the particles are accelerated by associated CME ([4]).





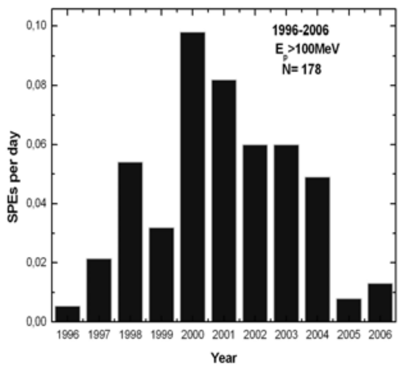


Fig. 1. Time distribution of daily values of SPEs with I_p >0.01pfu and energy >10MeV (top panel), >100 MeV (middle panel) and GLEs >500 MeV (bottom panel).

In order to clarify the role of SXR flares as well as of CMEs to proton events generation and propagation at 1AU, the SPEs are statistically related both to CMEs and SXR flares. From the first studies in this direction was that of Van Hollebeke et al. (1975) in which the flares and the SPEs data from the Goddard cosmic ray experiment on IMP-IV and IMP-V satellites were connected and a procedure for identifying the associated flare with solar proton enhancements in interplanetary space were developed. During the last years, [2], [6] showed that the soft X-ray flares with importance >M5 play an important role in the SPE production rate.

Moreover, [7] and [8] showed that solar energetic particles are also associated with fast CMEs. [9] mentioned that most of large SEP events are associated with wide CMEs having velocities above 400 km/sec. [10] in a detail study of various properties of CMEs during the time period 1996-2002 showed that the fast (average speed >1500 km s^{-1}) and wide (mostly full or partial halo) CMEs are associated with SEPs. 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)) ([11]). Up to 15% of the CME kinetic energy goes into the accelerated particles suggesting that the CME-driven shocks are efficient particle accelerators ([12]).

Most previous works ([10], [13], [14], [15]) 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 by [6], 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 1976-2006.

In this work, using this extended database of solar proton events for proton enhancements in different energy channels >10 MeV and >100 MeV as well as >500MeV (GLEs) and the complete catalogue of CMEs (http://cdaw.gsfc.nasa.gov/CME_list), we try to study the possible connection of the SPEs and the coronal mass ejections for the entire time period of solar cycle 23 (1996-2006). Specifically the characteristics of CMEs associated with SPEs are considered and compared with previous results.

II. DATA SELECTION

The database of solar proton enhancements updated and expanded from a previous work covering all the solar cycle 23 is used ([6]). In order to obtain this database, we use the integral proton fluxes measured onboard IMP-8 and GO 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 2002-2006 only GOES data are available. GOES corrected integral fluxes were extracted for proton energies >10 MeV, >30 MeV, >60 MeV and

>100 MeV (see http://spidr.ngdc.noaa.gov/spidr/) as well as IMP-8 >10 MeV, >30 MeV 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)

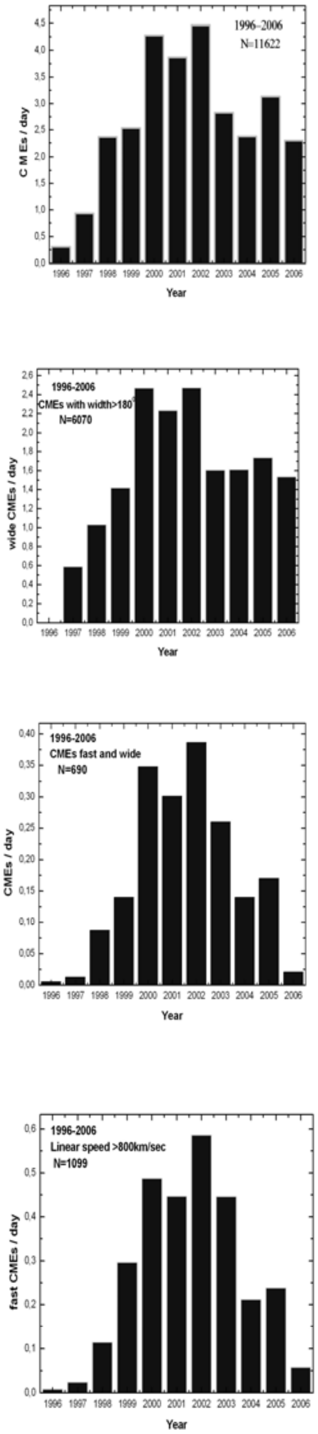


Fig. 2. Time distribution of all detected CMEs (top panel), fast CMEs(bottom panel), wide CMEs (second panel) and fast and wide CMEs (third panel) on a daily basis.

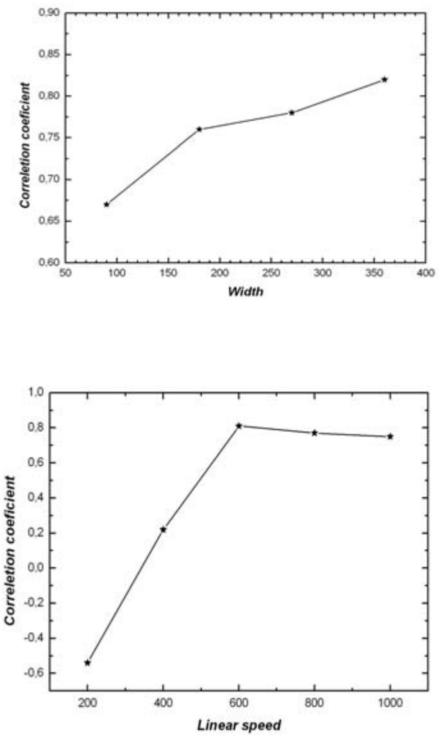


Fig. 3. The calculated correlation coefficient of the CMEs a) in each width range and b) in each linear speed range.

During the years 1996-2006, a number of 368 solar proton enhancements 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-off energy ≈500 MeV known as GLEs. The time distributions of SPE rate in these three energy channels during the last solar cycle are presented in Fig. 1. As it can be seen solar proton enhancements in almost all energies follows well the 11-solar cycle variation. The maximum rate in all cases is appeared in the years 2000 and 2001 that is the maximum solar cycle phase. The great number of SPEs during the declining phase of this cycle is also considered.

Coronal mass ejections data were taken from the Large Angle and Spectrometric Coronograph (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 existed data gaps were taken into account in our calculations.

A total number of 11622 CMEs were selected and the time distribution on a daily basis for the time span 1996-2006 is given in Fig. 2 (upper left panel).

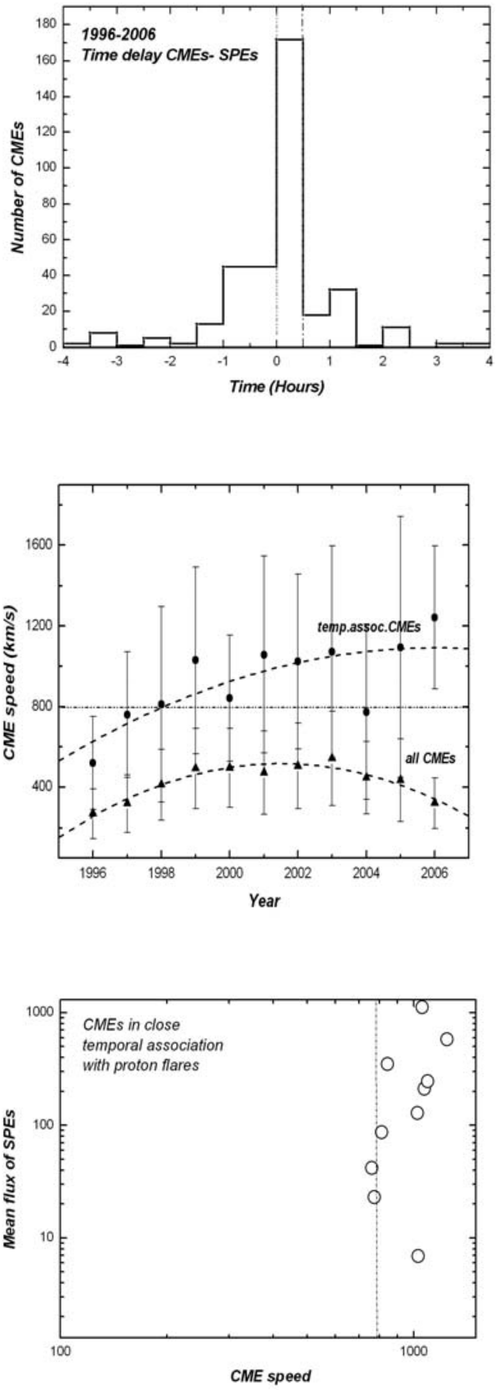


Fig. 4. a) Distribution of the time delay between time detection of CME and SEP (upper panel) b) Yearly average speed of all detected CMEs (triangle data point) in comparison with yearly average speed of CMEs temporal associated with proton flares (filled cycles and) (middle panel) c) Mean flux of SPEs versus linear speed of temporal associated CMEs (lower panel).

Note that CME rate increased from less than 1 per day during solar minimum in 1996 to slightly more than 4.5 in 2002. The mean number of CME rate during the declining phase is more than 2.5 CMEs per day, while in 2005 it was 3 CMEs per day.

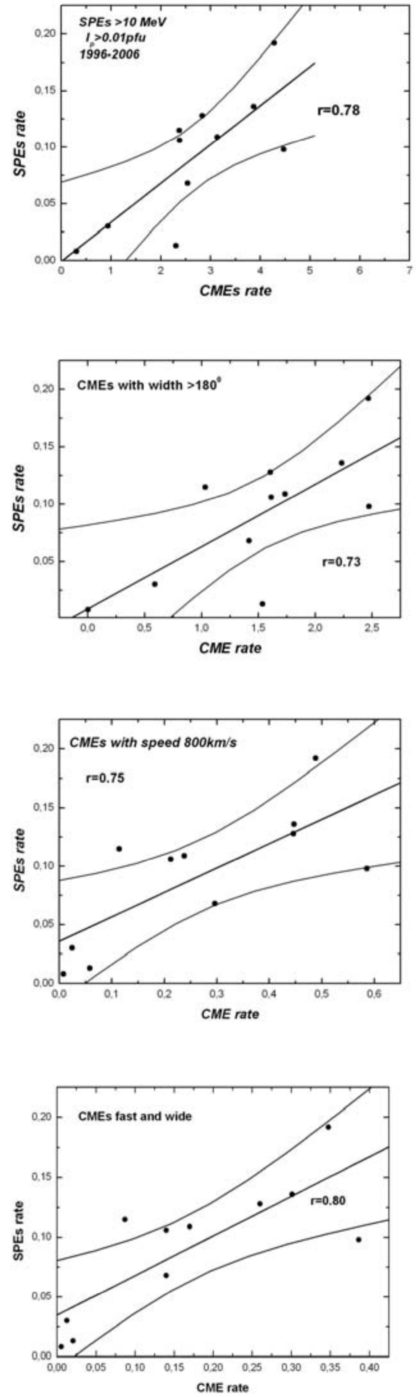


Fig. 5. Scatter plot of yearly SPE rate versus yearly CME rate (from the top to bottom: all detected, wide, fast, fast and wide) during the period 1996-2006.

This year is characterized by many extreme events as those of January 2005, July 2005, August-September 2005 ([16], [17]). According to [18] and [19] the rate during solar maximum is much higher than the highest corrected rate (3.11 per day) reported in previous cycles.

Separating the number of CMEs that were occurred in every range of width 90^0, the correlation coefficient between them and the rate of SPEs on yearly basis was calculated. Results of the calculated correlation coefficient in each width interval are presented in Fig. 3a (upper panel). As it can be seen the correlation coefficient is growing up with the width of CMEs with a jump for the events with width $>180^0$ called wide CMEs. The same procedure concerning the speed of CMEs is also applied. The results are presented in Fig. 3b (lower panel). It is evident from this figure that slow CMEs with linear speed <200 km/s seem to be not correlated with SPEs and the correlation coefficient becomes positive for CMEs with speed >400km/s. A big value of correlation coefficient (r=0.78) is appeared for the case of CMEs with linear speed >800km/sec. This fact in combination with the result obtained from Fig. 4c, where the speed of CMEs that are in close association with proton flares seems to be greater than 800 km/sec, leads to the conclusion that the fast CMEs are well connected with SPEs. This conclusion is also consistent with previous works where smaller time periods were investigated ([9], [15]).

Since coronal mass ejections bring large-scale changes in the corona, which have fundamental implication for the evolution of magnetic-flux of the Sun, it is interesting to examine the long-term behaviour of the CMEs. Based on the previous results that solar energetic particles seem to be connected with fast and wide CMEs, their solar cycle variation was examined. The time distribution of all detected by SOHO CME rate as well as of the CMEs having linear speed >800 km/s, CMEs with width $>180^0$ as well as CMEs having linear speed >800 km/s and width $>180^0$, called fast and wide during the last solar cycle are presented in Fig. 2. The data are corrected taking into account all the data gaps. This figure shows that all CME rate in all cases follows the 11-year variation of solar cycle. At the end of the cycle, during the years 2005 and 2006 there is an increase at the CME rate that may affect to the unexpected solar extreme events during these years. The time distribution of fast and wide CMEs is more consistent to the solar cycle variation. It is noted that an average value of four CMEs per day is observed near solar maximum ([9]).

III. CORRELATION ANALYSIS

For our correlative analysis in the time period 1996 to 2006, only 317 from 11622 detected CMEs seem to have a close temporal association with the proton enhancements, taking into account the gaps on SOHO data. 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 the time delay between CME detection and SPE is presented in Figure 4a. As we can see the great majority of CMEs are detected within the time interval from -1 to +1.5 hours after SPEs detection. As it is obtained from this figure, a great number of SEPs and CMEs appeared in the time interval 0-0.5 hour. It is interest to note that the fraction of these events to the rest event is 1.26. Minor observed sub peaks in the distribution may attribute to different source longitude. However, the general trend of this distribution is a monotonic decrease of this to greater time delays.

	>10 MeV	**>100MeV**
Total CMEs-SPEs	**0.78**	**0.72**
Wide CMEs-SPEs	**0.73**	**0.69**
Fast CMEs-SPEs	**0.75**	**0.76**
Fast and Wide CMEs -SPEs	**0.80**	**0.77**

Table 1. Correlation coefficient of the yearly CME rate and the yearly SPE rate in different energy channels.

A comparison of the yearly average linear speed of all detected CMEs with the yearly average speed of CMEs having close temporal association with proton flares is presented in Fig. 4b. It is noted that the average speed of associated CMEs is much greater than all detected ones. The average speed of CMEs having close temporal association with proton flares is greater than the critical value of 800 km/sec. The time profile of the average speed of all detected CMEs seems to be consistent with the solar cycle variation, while the yearly average speed of temporal associated CMEs deviates at the end of the cycle. This result reflects on the number of solar proton events detected during the years of solar minimum 2005-2006 ([20]). The mean flux of SPEs with the speed of the CMEs associated with the proton flares are given in Fig. 4c.). It is evidence that the fast CMEs seem to be cause of SPEs production.

The total rate of CMEs, the CMEs rate having central position angle $>=180^0$(wide), the CMEs rate having speed >=800km/sec (fast) and the fast and wide CMEs seem to be well connected with the yearly SPEs rate with energy >10 MeV during the last solar cycle (see Fig. 5).

The correlation coefficient of the solar proton enhancements in energy channels >10 MeV and >100 MeV with the different characteristics of the CMEs is presented in Table I. The best correlation coefficient is appeared in the case of fast and wide CMEs. This is consistent with the results of previous works by [10] and [15].

IV. Discussion - Conclusions

In this work a comparative analysis of 368 solar proton enhancements and 11622 CMEs during the last solar cycle has been performed. It is the first time examined a complete solar cycle in relation to CMEs data. At first we note that all these events follow the 11-year variation. A great number of both these parameters is appeared in the maximum phase of the cycle, while the declining phase seems to be more productive than the ascending one. It was expected if we take into account the differences between even and odd solar cycles ([21]).

In order to clarify the connection between SPEs and CMEs extending our previous studies on SPEs and Soft X-rays flares, studying some special properties of the CMEs as their speed and width, we have concluded that the temporal associated with proton events CMEs, have linear speed much greater than all other detected CMEs. The critical value of CMEs speed that are well connected with solar proton enhancements seems to be >800 km/sec (fast CMEs). CMEs with width $>180^0$ (wide CMEs) are also well associated with solar proton enhancements. The calculated time delay between the detection of CMEs and the onset time of the proton flares reveals a pronounced maximum of this time delay from 0 to 0.5 hours.

Moreover a high correlation coefficient between fast and wide CMEs rate and SPEs examined in different energy channels on an yearly basis has been found for the examined time period. It reaches the value of 0.80 for the case of SPEs with energy >10 MeV and 0.77 in the case of the ones with energy >100 MeV. This correlation one by one does not provide a correct picture for their association as cause and effect, but appears only a statistical connection of them. In order to examine the contribution of CMEs on SPEs production, it may be studied some other properties of them, such as the total energy, the ejected mass of CMEs etc. Nevertheless, studying only some characteristics of CMEs, we can say that CMEs present an important effect on SEP related and non-related events. Extending this work to other properties of CMEs, it will be possible to have a more complete knowledge of this connection for a better understanding of the Solar-Terrestrial phenomena and Space Weather applications.

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