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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 gives new results concerning the sources and acceleration mechanisms of solar energetic particles. Specifically, coronal mass ejections with width >180° (wide) and linear speed >800 km/s (fast) seem they 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 the SPE production rate. From this work, it is outlined that the good relation of the fast and wide coronal mass ejections to proton enhancements seems to lead to a similar conclusion. In spite of the fact that in the case of CMEs the statistics cover 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.

Keywords: Solar energetic particles; Solar flares; Coronal mass ejections; Proton events

1. 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 1 AU 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 $D_{st} \leqslant -50\,\text{nT}$ within 1–5 days later (Whang, 2007; Belov et al., 2007). 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. At the top of them is the ground level enhancement of cosmic ray intensity occurring 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 6th of December, 2006. In particular the big X-ray flare of 13 December 2006 at 02:14 UT with importance X3.4/4B originating from the active region 10930 and from the west side

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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. The same day at 02:54 UT a fast hallo CME with linear speed 1774 km/s was also recorded by the SOHO satellite (Plainaki et al., 2008).

The possible connection of these two parameters of solar activity, soft X-ray flares and CMEs and their results in the interplanetary space and near-Earth as solar proton events is under consideration. Nevertheless, both solar flares and CMEs are the result of rearrangements of the coronal magnetic field, they are often "associated" to 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 an associated CME (Cane et al., 1988).

In order to clarify the role of SXR flares as well as CMEs to proton events generation and propagation at 1 AU, the SPEs are statistically related both to CMEs and SXR flares. One of 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 the IMP-IV and IMP-V satellites were connected and a procedure for identifying the associated flare with solar proton enhancements in interplanetary space was developed. During the last years Belov et al. (2005, 2007) showed that the soft X-ray flares with importance >M5 play an important role in the SPE production rate.

Moreover, Reames (1999) and Kahler et al. (2001) showed that solar energetic particles are also associated with fast CMEs. Gopalswamy et al. (2002) mentioned that most of the large SEP events are associated with wide CMEs having velocities above 400 km/s. Gopalswamy (2006) showed in a detailed study of various properties of CMEs during the time period 1996–2002 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 ground based detectors are connected with the fastest known population of CMEs [average speed ~1798 km s^{-1} (sky–plane)] (Gopalswamy et al., 2005). Up to 15% of the CME kinetic energy goes into the accelerated particles suggesting that the CME-driven shocks are efficient particle accelerators (Emslie et al., 2004).

Most previous work (Reames, 1995; Gopalswamy et al., 2003; Gopalswamy, 2006; Reinard and Andrews, 2006) 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 Belov et al. 2005, 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 enhancements in different energy channels >10 and >100 MeV as well as >500 MeV (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.

2. Data selection and analysis

The database of solar proton enhancements updated and expanded from a previous work covering all the solar cycle 23 is used (Belov et al., 2005). In order to obtain this database, we use the integral proton fluxes measured aboard IMP-8 and GOES 5–12 satellites. In the earlier period 1975–1986 only data from IMP-8 have been available. For the period 1987–2001 data from the IMP-8 and GOES satellites were available and at times during there were gaps in one spacecraft data of the other ones were used. During the period 2002–2006 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).

During the years 1996–2006, a number of 368 solar proton enhancements occurred 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 the SPE rate in these three energy channels during the last solar cycle are presented in Fig. 1. As it can be seen, the frequency of solar proton enhancements in almost all energies follows well the 11-solar cycle variation. The maximum rate in all cases appears in the years 2000 and 2001 that is the maximum solar cycle phase. The number of SPEs during the declining phase of this cycle is also considered.

Coronal mass ejection 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 for unity reasons were used, because C1 was disabled since June 1998. The existing 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). Note that the CME rate increased from less than one per day during solar minimum in 1996 to slightly more than 4.5 ones per day in the year 2002. The mean number of CMEs rate during the declining phase is more than 2.5 CMEs per day, while in 2005 it was three CMEs per day. The year 2005 is characterized by many extreme events as those of January 2005, July 2005, August–September 2005 (Mavromichalaki et al., 2005;

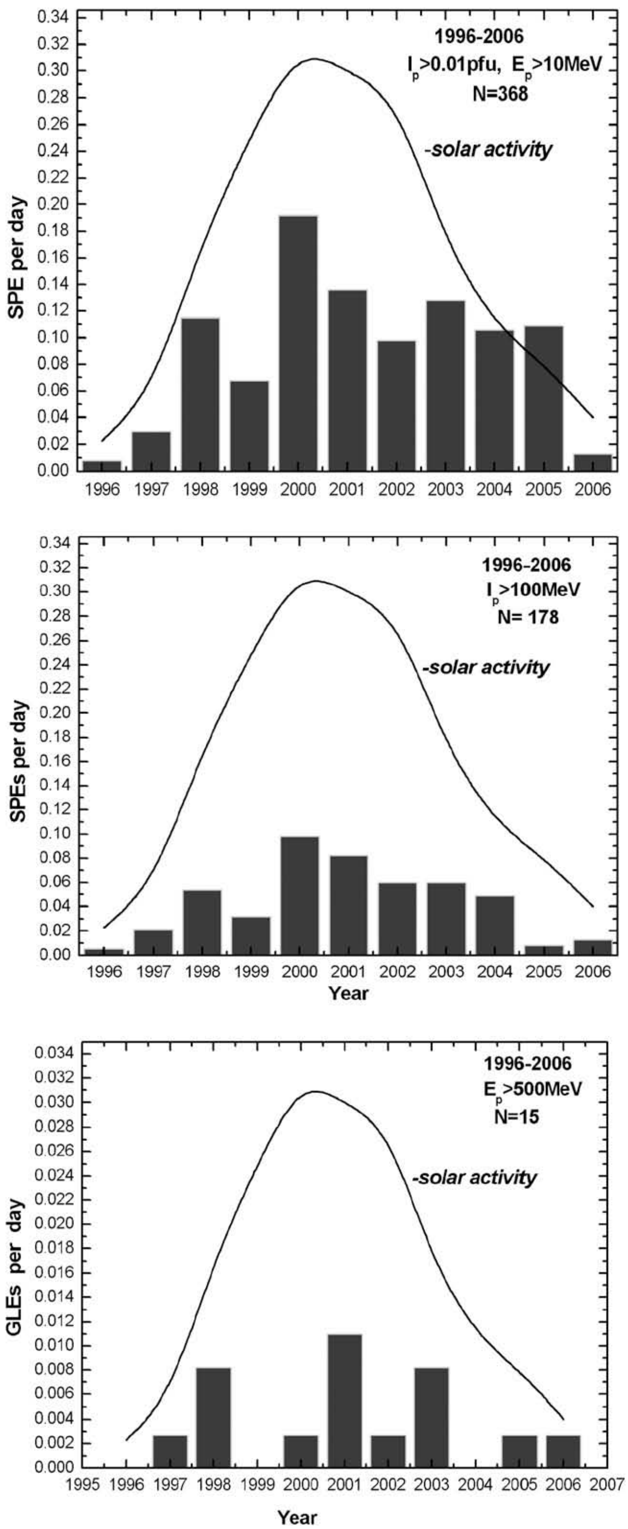

Fig. 1. Time distribution of the daily values of SPEs with $I_p > 0.01$ pfu and energy >10 MeV (top panel), >100 MeV (middle panel) and GLEs >500 MeV (bottom panel).

2007). According to Webb and Howard (1994) and Cliver et al. (1994) 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 occurred in every range of width 90°, the correlation coefficient between them and the rate of SPEs on yearly basis was calculated. It is important to note that the width used in this work is not the accurate width determination described in Michalek et al. (2007), but it is obtained from the measured values of the angular extension of SOHO/LASCO catalogue (http://cdaw.gsfc.nasa.gov/CME_list). 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 with the width of CMEs with a jump for the events with width >180° 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 not to be correlated with SPEs and the correlation coefficient becomes positive for CMEs with speed >400 km/s. A high value of correlation coefficient ($r = 0.78$) was deduced for the case of CMEs with linear speed >800 km/s. 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 (Gopalswamy et al., 2002; Reinard and Andrews, 2006). It is noteworthy to mention that there is a big value of correlation coefficient at the speed region 400–600 km/s. Since the average speed of CMEs is 439.32 km/s, this peak is expected.

Since coronal mass ejections introduce large-scale changes in the corona, which have a 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 earlier indications that solar energetic particles seem to be connected with fast and wide CMEs, their solar cycle variation was examined. Fig. 2 presents the time distribution of all CMEs detected by SOHO (Fig. 2, top left panel) as well as those subsets having a linear speed >800 km/s (“fast”, Fig. 2, bottom left panel), an angular width >180° (“wide”, Fig. 2, top right panel) or qualify as both fast and wide (Fig. 2, bottom right panel). The data are corrected taking into account all the data gaps. This figure shows that the CME rate in all cases follows the 11-year variation of the solar cycle. At the end of the cycle, during the years 2005 and 2006, there is an increase in the CME rate that may be accounted to the unexpected solar extreme events during these years. The time distribution of fast and wide CMEs is more consistent with the solar cycle variation than the unselected sample. The average value of four CMEs per day confirms the measurement by Gopalswamy et al. (2002).

3. Correlation analysis

For our correlative analysis in the time period 1996–2006, only 317 from 11622 detected CMEs seem to have a close temporal association with proton enhancements,

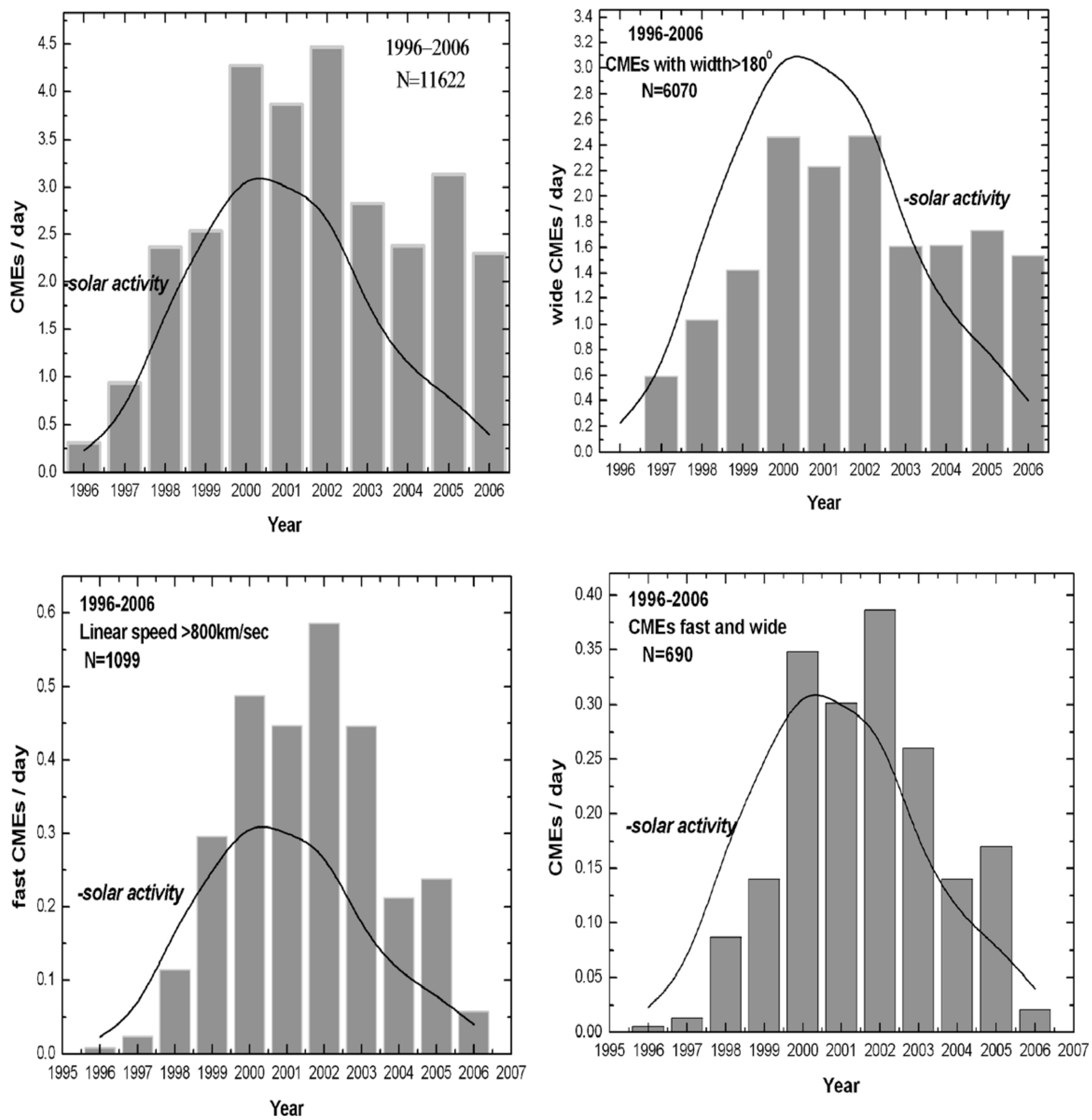

Fig. 2. Time distribution of all detected CMEs (top left panel), fast CMEs (bottom left panel), wide CMEs (top right panel) and fast and wide CMEs (bottom right panel) on a daily basis.

taking into account the gaps in the SOHO data. The term temporal association means that within a window of 4 h before or/and after the SPE appearance, at least one CME detection occurs. The distribution of the time delay between CME detection and SPE is presented in Fig. 4a. As we can see the great majority of CMEs are detected within the time interval from −1 to +1.5 h after the SPEs detection. As obtained from this figure, a great number of SPEs and CMEs appeared with a separation of less than 0.5 h. It is interesting in noting that the fraction of these events to the rest event is 1.26. This is an evidence that the majority of solar energetic particles escapes from the Sun vicinity into interplanetary space with a temporal window of 30 min before/after the detection of CMEs. Minor sub peaks in the distribution may attribute to different source longitudes. However, the general trend of this distribution is a monotonic decrease to greater time delays.

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 that of all detected ones. 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 (Hudson, 2007). The mean flux of SPEs with the speed of the CMEs associated with the proton flares are given in Fig. 4c). It is evident that the fast CMEs seem to be the origin of SPEs.

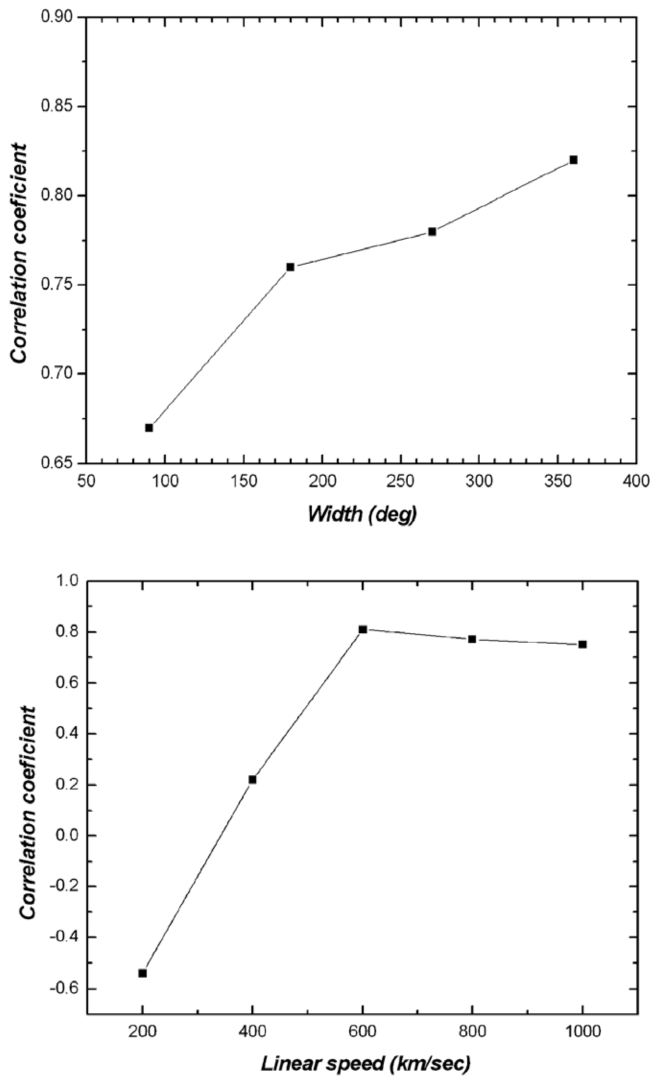

Fig. 3. Correlation coefficient variation of the CMEs in each width range (upper panel) and in each linear speed range (lower panel).

The total rate of CMEs, the CMEs rate having a central position angle ⩾180° (wide), the CMEs rate having speed ⩾800 km/s (fast) and the fast and wide CMEs seem to be well connected with the yearly SPE 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 and >100 MeV for different characteristics of the CMEs is presented in Table 1. The best correlation coefficient occurs in the case of fast and wide CMEs. This is consistent with the results of previous works by Gopalswamy (2006) and Reinard and Andrews, 2006.

4. 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 that a complete solar cycle has been examined in relation to CMEs data. At first

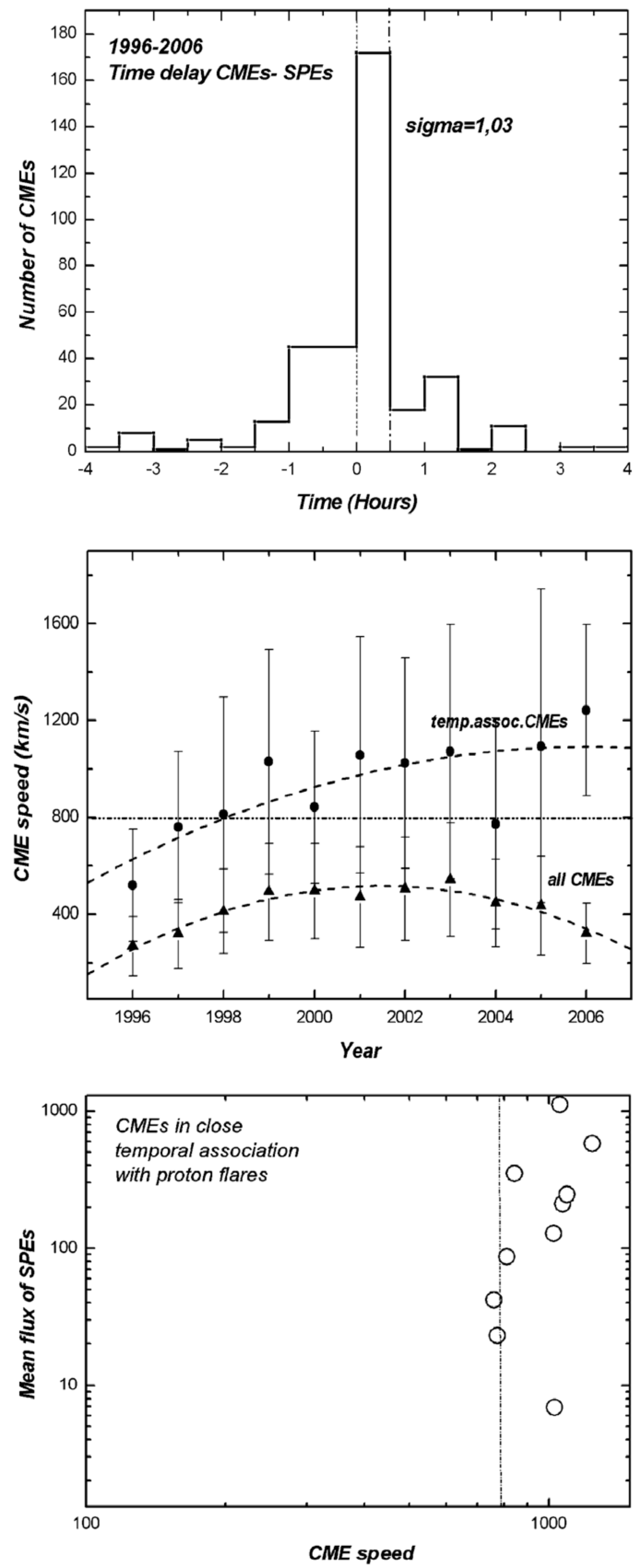

Fig. 4. (a) The distribution of the time delay between the times detection of CME and SEP (upper panel), the yearly average speed of all detected CMEs (triangle data point) in comparison with the yearly average speed of CMEs temporal associated with proton flares (filled cycles) (middle panel) and the mean flux of SPEs versus linear speed of temporal associated CMEs (lower panel) are presented.

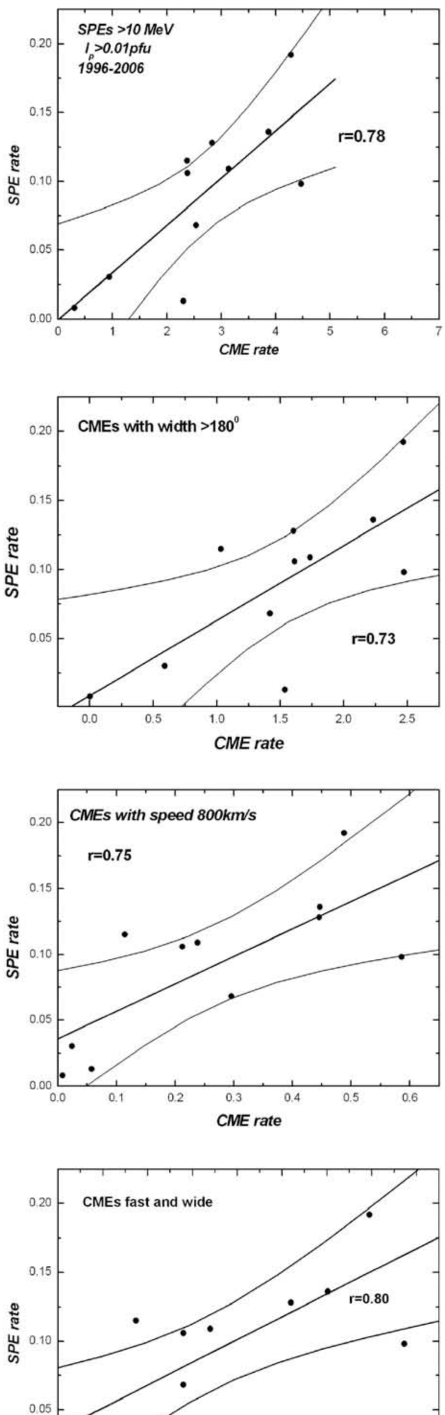

Fig. 5. Scatter plot of the yearly SPE rate versus yearly CME rate (from the top to bottom: all detected, wide, fast, fast and wide) during the period 1996–2006.

we note that all these events follow the 11-year variation. A great number of events of both types occurred in the maximum phase of the cycle, while the declining phase seems to be more productive for SPEs than the ascending one, a feature that was expected if we take into account the differences between even and odd solar cycles (Mavromichalaki et al., 1988).

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

	>10 MeV	>100 MeV
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

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 like their speed and width, we have concluded that those CMEs temporally associated with proton events 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/s (fast CMEs). CMEs with width >180° (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 h.

Moreover, a high correlation coefficient between the rate of fast and wide CMEs and SPEs examined in different energy channels on a yearly basis has been found for the examined time period. It reaches a 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 shows only a statistical connection of them. In order to examine the contribution of CMEs on SPEs production some other properties may be studied, 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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