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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.
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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 $D_{st} \leqslant -50$ 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;

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