Energetic Storm Particles in Geomagnetic Storm Forecasting

E. Valtonen, K. Huttunen-Heikinmaa, and T. Laitinen

Space Research Laboratory, VISPA and Department of Physics, University of Turku, FIN-20014 Turku University

Abstract

Coronal mass ejections (CMEs) and their interplanetary counterparts (ICMEs) are known to be the main sources of major geomagnetic storms. Solar energetic particles (SEPs) and energetic storm particles (ESPs) are often accelerated by the (I)CME-driven shocks. SEPs are accelerated close to the Sun, while acceleration of ESPs takes place locally near the observer. We have studied what possible advantages observations of energetic particles, and in particular ESP observations, could bring in geomagnetic storm forecasting. We have shown that the time difference between the onsets of an SEP and the associated ESP event provides a proxy for the transit time of the shocks driven by ICMEs from the Sun to the Earth. For a limited number of moderate and intense (Dst < -50 nT) geomagnetic storms, which can be associated to both SEP and ESP signatures, we found that this transit time correlates with the strength of the storms. Typically, when observable and when associated to a geomagnetic storm, ESPs can be detected several hours before the storm commencement. We have further investigated if ESP observations could improve storm forecasting when used together with solar wind shock observations. A preliminary study has been carried out covering the time period from May 1996 to April 2003 using SOHO/ERNE particle data and including 226 fast forward shock candidates. It was found that if coincident fast forward shock and ESP signals are observed, the probability of occurrence of a moderate or intense geomagnetic storm is 38 % as compared to 21 % when only the solar wind shock observation is used, and that for fast forward solar wind shocks without a coincident ESP signal the probability of causing a moderate or intense geomagnetic storm is only 15 %.

1. Introduction

- CMEs believed to be the main sources of major non-recurrent geomagnetic (GM) storms
  - Full halo (FH) CMEs most probable candidates
- Fast CMEs capable of driving IP shocks are the most geoeffective
  - Most of the FH CMEs belong to the fast (> 900 km/s) population
  - But speeds > 300 km/s sufficient for severe GM storms
- Detection of a FH CME indicates the possibility that the CME is travelling toward the Earth and may be geoeffective
  - But all ICMEs related to FH CMEs do not necessarily encounter the Earth
  - Only about half of the frontside halo CMEs reach the Earth
  - In general, less than 10 % of halo CMEs cause major GM storms

- Question: Can energetic particle observations provide some complementing information in addition to solar and solar wind observations for geomagnetic storm forecasting?

- Prerequisite: Correlation between the occurrence rates of full halo CMEs, energetic particle events and intense geomagnetic storms.

Figure 1 indicates that such correlation exists.

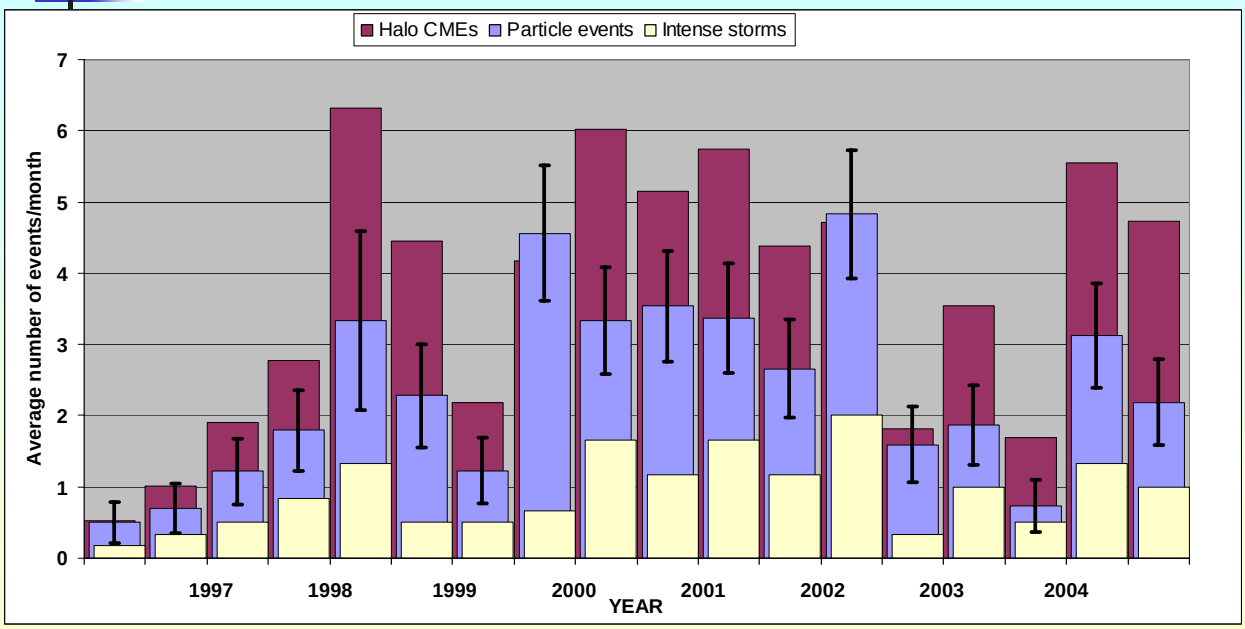

Figure 1. Monthly occurrence rates of full halo CMEs, solar energetic particle events, and intense geomagnetic storms averaged over 6-month periods from 1996 to 2005.

2. Energetic particles

- Solar Energetic Particles (SEPs) are accelerated
  - In solar flare processes low in the solar corona
  - By shock waves driven by fast CMEs high in the corona
    - Often fast rise of intensities, but depends on the source location on the solar disk relative to the observer
    - Onset at the time of flare or CME lift-off
    - Energies up to the GeV-range
    - Velocity dispersion seen in onset times at different energies
- Energetic Storm Particles (ESPs) are accelerated
  - By fast ICME-driven shocks in interplanetary space
    - Gradual rise of intensities often several hours before shock arrival
    - Prominent in the MeV-region
    - No velocity dispersion
    - Fast decay after shock passage to lower than pre-shock levels with spectral softening

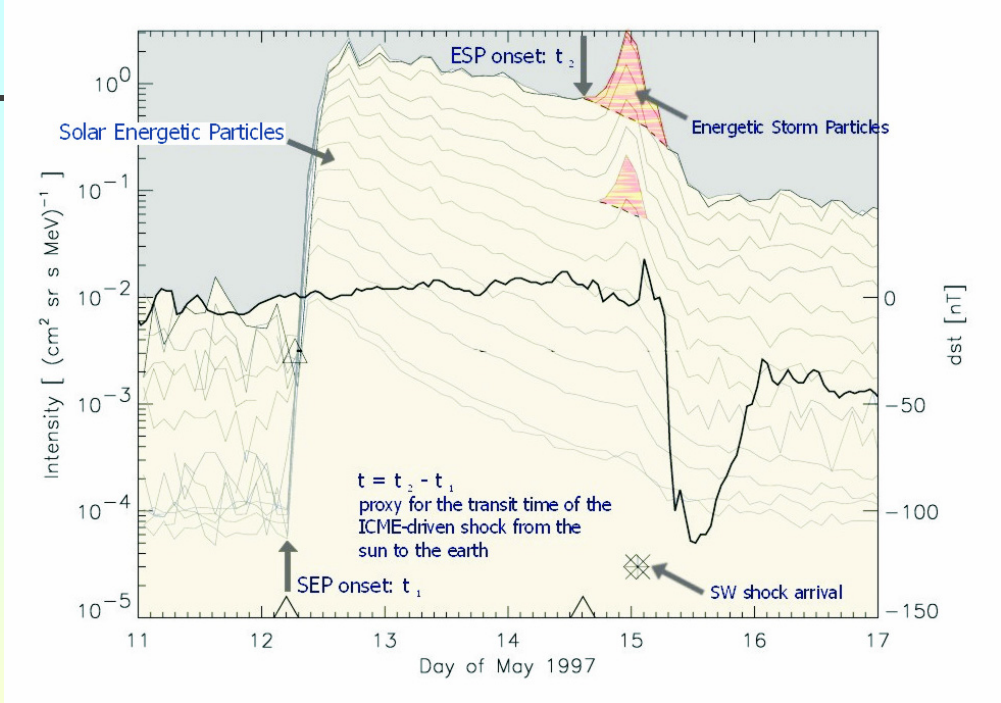

Figure 2. SEP-ESP event on May 1997. Proton time-intensity profiles in the range 1-43 MeV are shown. SEP and ESP event onsets are indicated together with solar wind observations of shock arrival. A study of the SEP-ESP events from August 1999 to July 2000 gave the average lead-time of ESP onset to SW shock observation of 6 hours.

- Energetic particles associated with solar flares and CME-driven shocks
  - Can be helpful in identifying the location of the solar sources
    - Identification of backside/frontside CMEs
  - May provide early warnings of approaching, potentially geoeffective ICMEs
    - SEP: launch of CME
    - ESP: IP shock
  - Can be used as probes of some properties of CMEs and ICMEs
    - Indication of the launch time of the CMEs
    - Relate the shocks and ICMEs with specific solar events
    - Identifying ICMEs and their magnetic topology
      - Magnetic clouds often geoeffective
      - Disordered magnetic structures not causing major GM storms
  - Even absence of energetic particles can be used as indication of the upper limit of the CME transit speed from the Sun to the Earth

3. ESP observations and geomagnetic storms

- ESPs can be helpful in identifying strongly geoeffective ICMEs
  - Improving identification of Earth-directed halo CMEs
    - By assuming that halo CMEs having a particle signature (SEP or ESP) are frontside events
  - Information on the geomagnetic storm strength
    - Average storm strength:Table 1
    - Forecasting storm strength with the lead time of the ESP onset relative to the storm commencement: Figure 2 and Figure 3.

Table 1. Average storm strength associated with various types of IP and energetic particle event in 1996 – 2000.

	Association	Events	Average Dst (nT)	Dst std. dev. (nT)
ICMES	ICME without IP shock	13	-82	25
	IP shock without ICME	6	-64	14
	ICME and IP shock	24	-115	68
	No association with either	16	-65	9
Energetic particles	SEP event without ESP	10	-66	11
	ESP event without SEP	5	-84	22
	SEP and ESP event	12	-125	82
	No association with either	32	-83	32

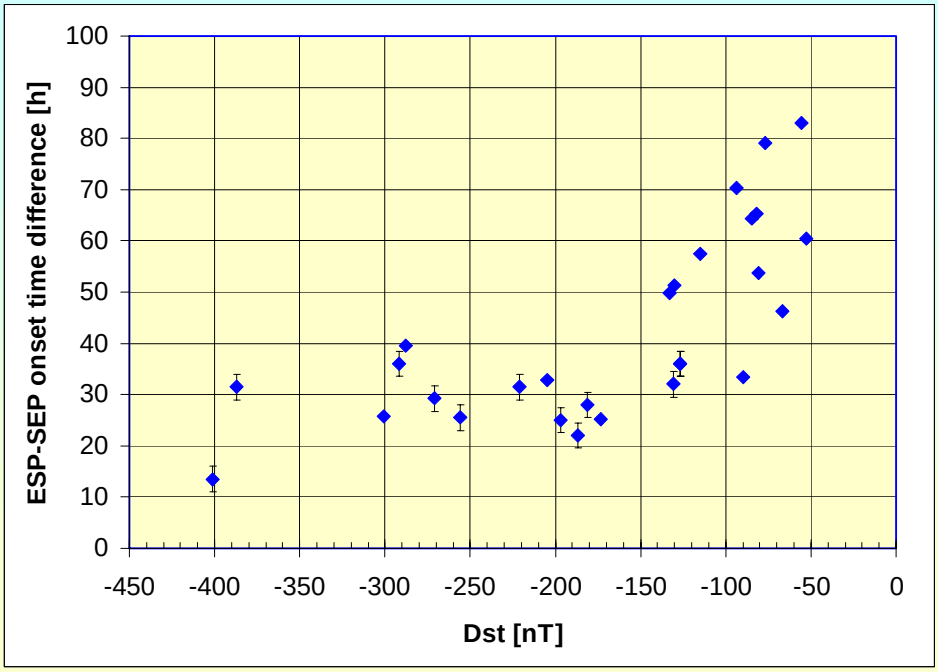

Figure 3. Dependence of the storm strength on the time difference between the SEP and ESP onsets representing the shock transit time from the Sun to the Earth.

- ESPs and geoffectivity of IP shocks
  - Moderate and intense storms (Dst < -50 nT) studied in the time period May 1996 – April 2003
  - 48 solar wind Fast Forward (FF) shocks followed by an onset of a Dst-depression event within the time window of 6 h
    - 21 % probability of solar wind FF shock preceding a storm
  - 26 FF shocks with a clear ESP signal
    - 38 % probability of SW FF shock with ESPs preceding a storm
  - 13 FF shocks clearly without ESPs
    - 15 % probability of SW FF shock without ESPs preceding a storm

4. Conclusions

- Identification of geoeffective halo CMEs needs complementing information to coronagraph observations
- There is a correlation between full halo CME, energetic particle event, and intense geomagnetic storm occurrence rates
- By assuming detection of energetic particles as signatures of frontside halo CME, identification of Earth-directed halo CMEs can be improved
- ESP events have a lead-time of several hours in detecting IP shocks as compared to solar wind observations
- The transit time of ICME-driven shocks, as determined from the difference between SEP and ESP event onset times, correlates with the geomagnetic storm strength
- ESP observations can be used to strengthen the predictive power of solar wind shock observations
  - Observation of a fast forward solar wind shock with a clear ESP signature increases the probability of the occurrence of a moderate or intense geomagnetic storm
  - If no ESPs are associated with a FF shock, the probability for GM storm decreases