Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 36 (2005) 2295–2302
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

Energetic particle signatures of geoeffective coronal mass ejections

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

Department of Physics and Väisälä Institute for Space Physics and Astronomy, University of Turku, FI-20014 Turku, Finland

Received 19 October 2002; received in revised form 30 August 2005; accepted 31 August 2005

Abstract

We have studied statistically associations of moderate and intense geomagnetic storms with coronal mass ejections (CMEs) and energetic particle events. The goal was to identify specific energetic particle signatures, which could be used to improve the predictions of the geoeffectiveness of full and partial halo CMEs. Protons in the range 1–110 MeV from the ERNE experiment onboard SOHO are used in the analysis. The study covers the time period from August 1996 to July 2000. We demonstrate the feasibility of energetic particle observations as an additional source of information in evaluating the geoeffectiveness of full and partial halo CMEs. Based on the observed onset times of solar energetic particle (SEP) events and energetic storm particle (ESP) events, we derive a proxy for the transit times of shocks driven by the interplanetary counterparts of coronal mass ejections from the Sun to the Earth. For a limited number of geomagnetic storms which can be associated to both SEP and ESP signatures, we found that this transit time correlates with the strength of geomagnetic storms.

Keywords: Solar energetic particles; Coronal mass ejections; Geomagnetic storms

1. Introduction

It is widely recognized that coronal mass ejections (CMEs) and their interplanetary counterparts (ICMEs) are the link between solar activity and non-recurrent geomagnetic storms (Gosling et al., 1991; Tsurutani and Gonzalez, 1997; Webb et al., 2000; Richardson et al., 2001). It is also known, however, that in particular at solar minimum other sources also provide significant contributions to geomagnetic storms and to geomagnetic activity in general (Richardson et al., 2001, 2002). Major geomagnetic storms are most often associated with the Earth-passage of CME material and the shock driven by the ejecta, when the speed difference between the ejecta and the upstream solar wind is sufficient (Gosling et al., 1991; Richardson et al., 2001). The dominant factor contributing to geomagnetic activity is the presence of a strong, long-duration southward interplanetary magnetic field component (Burton et al., 1975, and references therein). Such intense fields can appear either in the turbulent sheath region behind the shock or in the ejecta itself (e.g., Tsurutani and Gonzalez, 1997; Wu and Lepping, 2002).

Halo CMEs having their source on the visible disk of the Sun and presumably moving along the Sun–Earth line are considered potentially geoeffective. However, only a small portion of these CMEs causes geomagnetic activity (Wang et al., 2002; Cane and Richardson, 2003; Srivastava and Venkatakrishnan, 2004), assumably either because they are not actually directed towards the Earth, or their interplanetary counterparts do not posses sufficient southward magnetic field regions (Cane et al., 2000; Zhao and Webb, 2003; Wang et al., 2004). Therefore, when trying to predict the occurrence of geomagnetic storms, the identification of the CME sources by optical and X-ray instruments, and observation of the development of CMEs near the Sun by coronagraphs, need supporting information from all possible sources.

Prediction of the strength of geomagnetic storms is an important issue in space weather studies, and has recently gained considerable attention. Gonzalez et al. (2004) derived a method for peak Dst prediction based on observation

* Corresponding author. Tel.: +35 82 333 5644; fax: +35 82 333 5993.
E-mail address: eino.valtonen@utu.fi (E. Valtonen).

0273-1177/$30 © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2005.08.046

of halo CME expansion speed associated with magnetic cloud events. Smith et al. (2004) evaluated possibilities of using energetic ion (47–65 keV protons) enhancements in forecasting geomagnetic storms. They established a relationship between the maximum flux of energetic ion enhancements and the occurrence of large storms classified by the K_p index. Wu and Lepping (2002, 2005) found in their study of interplanetary magnetic clouds between 1965 and 1998 that the correlation between the Dst index and the magnitude of the southward component of the interplanetary magnetic field increased dramatically for high solar wind speeds, and developed two methods for Dst prediction in magnetic cloud events, one velocity independent and the other velocity dependent.

The purpose of this paper is to study the feasibility of using energetic particle observations in improving the predictions, both the quality and the lead-time, of geoeffectiveness of halo (or partial halo) CMEs. Energetic particles are produced in the flare processes often associated with CMEs, or in the shocks as the CMEs travel through the corona and interplanetary space (e.g., Cane, 1997; Reames, 1999; Kahler, 2001a; Kocharov et al., 2001). Solar energetic particles (SEPs) can be distinguished due to their velocity dispersion at 1 AU from the so-called energetic storm particles (ESPs) (Rao et al., 1967), which are accelerated in an interplanetary shock close to the observer. It is well known that solar wind plasma and magnetic field observations can be used for identifying interplanetary shocks. Frequently, also ICMEs can be identified from the solar wind plasma signatures (Cane and Richardson, 2003, and references therein). However, transient interplanetary shocks can also be detected based on energetic storm particle observations (e.g., Kallenrode, 1996). Furthermore, the presence of CME-related ejecta in interplanetary space can be deduced, e.g., from bi-directional flows of protons (Kahler, 1994, and references therein) and from transient cosmic ray depressions (e.g., Cane et al., 1997, 1998, 1999; Mäkelä et al., 1998). In this paper, we survey statistically the associations of (partial) halo CMEs, energetic particle events, and moderate to intense geomagnetic storms. We also investigate whether specific energetic particle signatures could be defined, which independently of solar wind observations could be used to identify approaching, potentially geoeffective disturbances, and possibilities to estimate the strength of the subsequent geomagnetic storm. The goal is thus to evaluate the usefulness of energetic particles as a tool complementary to solar wind observations to monitor interplanetary conditions potentially causing moderate or intense geomagnetic storms. In order to evaluate their merit as an independent tool, it is necessary in this study to rely on energetic particle measurements only, without taking advantage of the solar wind observations.

The paper is structured as follows. The data sources and temporal associations of solar and interplanetary events are presented in Section 2. In Section 3, we analyze associations of geomagnetic storms with CMEs and energetic particle events, and investigate the feasibility of particle observations as an additional source of information in assessing the geoeffectiveness of halo CMEs. In Section 4, we derive from the particle data a proxy for the shock transit time from the Sun to the Earth, and demonstrate how this correlates with the strength of geomagnetic storms. Conclusions are presented in Section 5.

2. Data sources and event associations

This study covers the 4-year period from the beginning of August 1996 till the end of July 2000, with the exception of the time interval June 25 to October 14, 1998, when SOHO data were not available, and the interval December 19, 1996 to March 4, 1997, when the reliability of the SOHO/ERNE data were questionable due to defective onboard software. This time period covers the solar cycle from the minimum to nearly maximum activity, thus providing a representative sample of events for this feasibility study. For defining geoeffectiveness of CMEs, we use the Dst index. The Dst index is assumed to reflect the variations in the intensity of the magnetospheric ring current, and in terms of the time behavior of this index, a geomagnetic storm can be described to progress in three phases: the initial phase, the main phase, and the recovery phase (Gonzalez et al., 1994). The main phase is characterized by a large decrease of Dst. Activity levels with Dst minimum value between −50 and −100 nT are considered moderate storms, while those with Dst < −100 nT are intense (Gonzalez et al., 1994). In this study, we consider only moderate and intense storms. For the purpose of the present analysis, we assume that a geomagnetic storm commences when the Dst value falls below the moderate storm limit of −50 nT. This assumption introduces only minor delay in the actual time of the storm onset compared to the time windows used to associate storms with ICME arrivals or energetic particle events. Hourly Dst indices for the study period were obtained from the World Data Center C2 (http://swdcwww.kugi.kyoto-u.ac.jp/dstdir/index.html).

For the CME observations, we use the SOHO/LASCO (Brueckner et al., 1995) CME catalogue http://lasco-www.nrl.navy.mil/cmelist.html and http://cdaw.gsfc.nasa.gov/CME_list. Only halo or partial halo CMEs were considered as potentially geoeffective. Partial halo CMEs were defined to be those with widths more than 120° as given in the LASCO catalogues. No limitations were set for the speeds or position angles of partial halo CMEs. Identification of frontside CMEs (source on the visible disk of the Sun) was based on St. Cyr, (2002, personal communication) in the period August 1996 to June 1998, and on inspection of SOHO/EIT (Delaboudiniere et al., 1995) and Yohkoh/SXT (Tsuneta et al., 1991) movies for the latter part of the study period. In addition, solar flare Lyman-α and X-ray observations, as given in the NOAA solar events lists (http://www.sel.noaa.gov/ftpmenu/indices.html), were used in the source identification.