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Some features in the time series of energetic protons measured at L1 during November 2001

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Abstract. Extreme events originating on the Sun induce various processes in the heliosphere, such as shock waves and particle acceleration. In this work, we studied the impact of extreme solar events on the flux of energetic particles measured at Lagrange point L1. In many cases, the enhanced flux of energetic particles can be clearly associated with a specific source and involves a well-known acceleration mechanism. However, in some instances, this connection is not as easily established. We examined and compared structures in energetic proton time series where a clear source is not immediately obvious, with structures clearly related to the concurrent passage of an ICME by analyzing the event-integrated fluence of energetic protons during November 2001 to potentially gain insight into the origin of such events.

Key words: solar energetic particles – solar activity – fluence spectra

1. Introduction

The study of transient phenomena caused by solar activity is of great importance, as these events can affect Earth's magnetosphere, environment, technological infrastructure and systems (Kataoka et al. (2018); Belov et al. (2022); Kolarski et al. (2023) and references therein). With the rising phase of the current Solar cycle 25, a better understanding and study of these transient phenomena are of great importance. Extreme events originating on the Sun, like solar flares (SF) and coronal mass ejections (CME) induce various processes in the heliosphere, such as shock waves and particle acceleration (Waterfall et al., 2023). All these processes can lead to the acceleration of charged particles (both of local and solar origin), resulting in an increased flux of these particles. The enhanced flux of solar energetic particles (SEP) during extreme solar events can be, in many cases, associated with a specific source (i.e., the passage of an interplanetary CME (ICME) related shock in heliosphere). However, this connection can be questionable in some instances. There are two major physical mechanisms of SEP acceleration based on the research conducted during several solar cycles

(Reames, 2013). One of the mechanisms is associated with type II radio bursts from coronal and interplanetary shock waves. It is driven by fast CMEs and it is proton-dominated. This mechanism produces "gradual" SEP events that have high SEP flux intensity near Earth, which can last for days. The second mechanism is predominantly connected to magnetic reconnection with open magnetic field lines and resonant wave–particle interactions in impulsive SFs and jets. It is associated with type III radio bursts produced by streaming electrons and produces "impulsive" SEP events that last for hours. In this work, we compared the features of different structures observed in energetic proton flux time series by analyzing the event-integrated fluences at L1 during November 2001, aiming to gain insight into their origin.

2. Data sets and event overview

2.1. Data sets

For this study we used data measured in-situ at Lagrange point L1 by SOHO and WIND probes. Data from Energetic and Relativistic Nuclei and Electron (ERNE) sensor unit onboard the Solar and Heliospheric Observatory (SOHO) (Torsti et al., 1995) was used to provide hourly data of energetic protons and interplanetary magnetic field and solar wind speed data were provided by the Global Geospace Science WIND spacecraft from OMNIWeb Plus repository (King & Papitashvili, 2005). For event selection, we used online CME, ICME and major SEP events catalogs (CDAW (2024); Richardson & Cane (2024))

2.2. Extreme events during November 2001

During November 2001 there has been a heightening activity of the Sun (Gopalswamy et al. (2010); Falkenberg et al. (2011); Rawat et al. (2006)). Four X-class solar flares have been reported (November 4, 8, 22, 28), along with two strong geomagnetic storms (November 6, 24) and several CME/ICME and SEP events in succession. At the beginning of November a series of three halo CME with most pronounce on November 4, originated from active region 9684 with an initial speed of $1810\,\mathrm{km\,s^{-1}}$ produced ICME. A strong interplanetary shock on November 6, characterized by abrupt increase in solar wind speed and total interplanetary magnetic field (IMF) and proton flux was recorded by WIND and SOHO/ERNE (Fig. 1). Later during November 2001, the activity of the Sun risen again. On 17 November a halo CME was observed with an initial speed of $1379\,\mathrm{km\,s^{-1}}$ and the ensuing ICME was observed at Earth and even Mars two days later. Two halo CMEs were emitted from the Sun on 22 and 23 November with that merged into one ICME at near-Earth location and produce geomagnetic storm and an increase in solar wind parameters, as shown in Fig.1

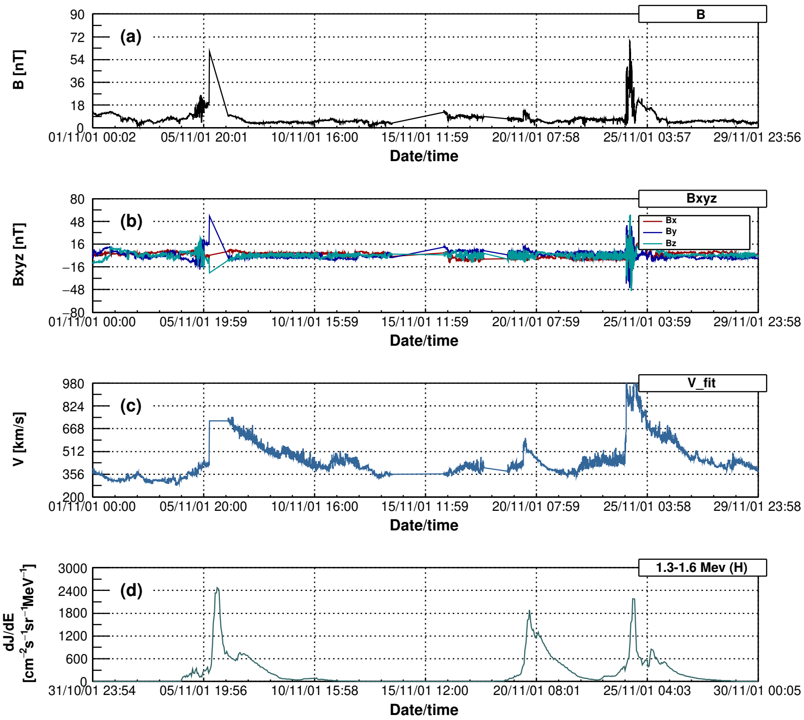

Figure 1. Time series of selected solar wind parameters measured by WIND and SOHO/ERNE proton flux data for November 2001: (a) IMF, (b) IMF components, (c) solar wind speed, and (d) energetic proton flux in the 1.3–1.6 MeV energy channel.

3. Analysis and discussion

The data provided by the instruments onboard the WIND spacecraft were used to establish a link and precise timing between the passage of an ICME and its effects on the onset and duration of the increased energetic proton flux. We found that the most useful parameters for this purpose are the time series of the IMF and the solar wind velocity. As WIND data are missing at the beginning of November, around the time of one of the extreme events, this period has been omitted from the analysis. Instead, the focus is on the second half of November, where all the necessary data are available. During the second half of November 2001, the arrival of the ICME shock is clearly observed in both the time series of IMF data and the flux of energetic protons (Fig. 1). One particularly interesting feature is a significant increase in proton flux that precedes the second ICME shock and cannot be directly associated with any perturbation in the IMF parameters. This structure is interesting because the measured flux exhibits a different energy dependence compared to the structure directly associated with the shock, which is especially evident in the higher-energy channels (Fig. 2).

Time intervals marking the ICME shock/interaction were determined based on the IMF and CME data. Based on these intervals proton flux was integrated in all SOHO/ERNE energy channels for three enhancements observed in the second half of November. The procedure is illustrated in Fig. 2, where cyan color is used for the two structures that can be more directly associated with concurrent disturbances in IMF and solar wind velocity, while the red is used for the structure mentioned in the previous paragraph where that is not the case.

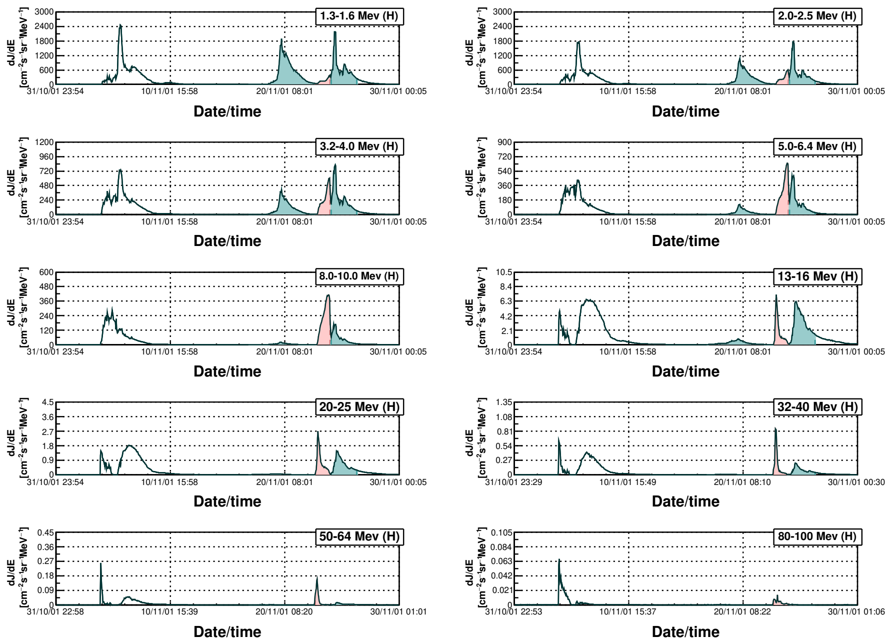

Figure 2. Energetic proton flux in ten selected SOHO/ERNE energy channels for the November 2001 event. The two cyan areas on each graph represent the measured flux during the passage of two ICMEs, while the red area between them represents the measured flux during a non-ICME-related structure.

The obtained values were used to form event-integrated fluence spectra. These spectra, calculated for the three proton flux enhancements occurring in the second half of November 2001, are shown in Fig. 3.

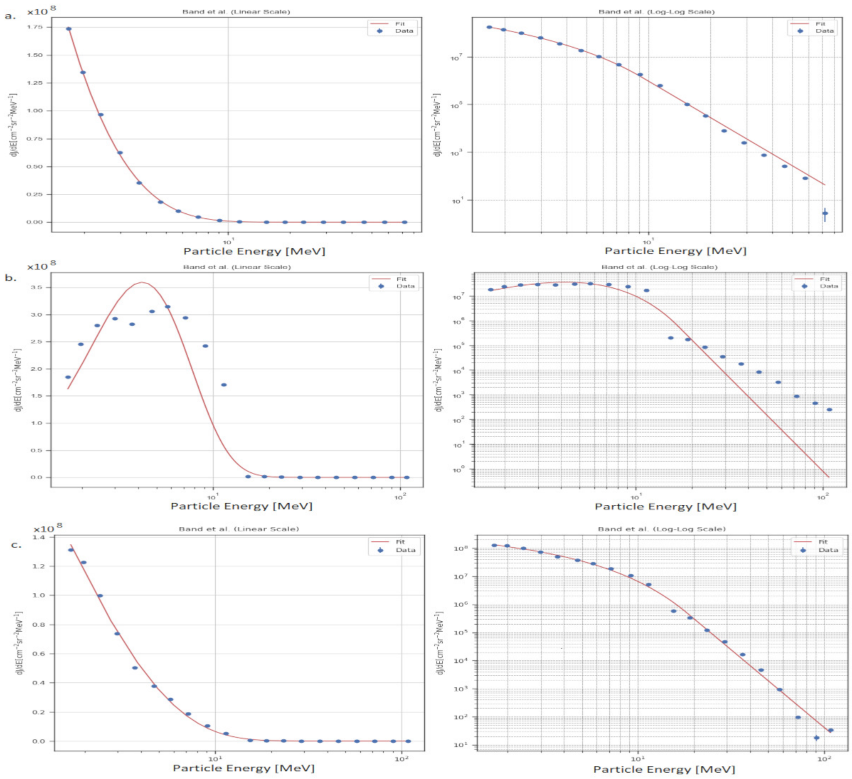

Figure 3. Event-integrated fluence spectra for three analyzed events, presented on a linear scale (left) and a log–log scale (right): (a) ICME on 17 November 2001, (b) SEP event on 22 November 2001, and (c) ICME on 24 November 2001. The red line represents the fit using the Band function.

To characterize the observed flux enhancements, event-integrated fluence spectra were fitted with a function based on the model proposed in (Band et al., 1993), which takes the form of a double power law:

$$\frac{dJ}{dE} = \begin{cases} AE^{\alpha} \exp\left(-\frac{E}{E_B}\right) & E \leq (\alpha-\beta)E_B, \\ AE^{\beta}\left[(\alpha-\beta)\,E_B\right]^{\alpha-\beta} \exp\left(\beta-\alpha\right) & E > (\alpha-\beta)E_B, \end{cases} \quad (1)$$

Here, E represents the particle energy, E_B is the "knee" energy, α is the power-law index characterizing the low-energy part of the spectrum, β is the power-law index characterizing the high-energy part of the fluence spectrum, and A is the spectral coefficient. A more detailed explanation of the procedure is provided in (Savić et al., 2024).

This model effectively describes the spectra of energetic particles accelerated by shocks, whether their origin is solar or due to local acceleration (both phenomena described in more detail in (Desai & Giacalone, 2016)). With this in mind, analyzing the spectra presented in Fig. 3, we observe that the events on 17 November and 24 November, which can be directly associated with the passage of concurrent ICMEs and related disturbances in the WIND data, are well modeled by the Band model. In contrast, the event on 22 November, which shows no observable disturbance in the WIND data, is poorly modeled. This discrepancy suggests that the origin of the flux enhancement on 22 November may not be attributed to shock acceleration.

Additional insights may be gained from the profiles shown in Fig. 4, which further highlight the differences in energy dependence between the observed structures in the energetic proton flux.

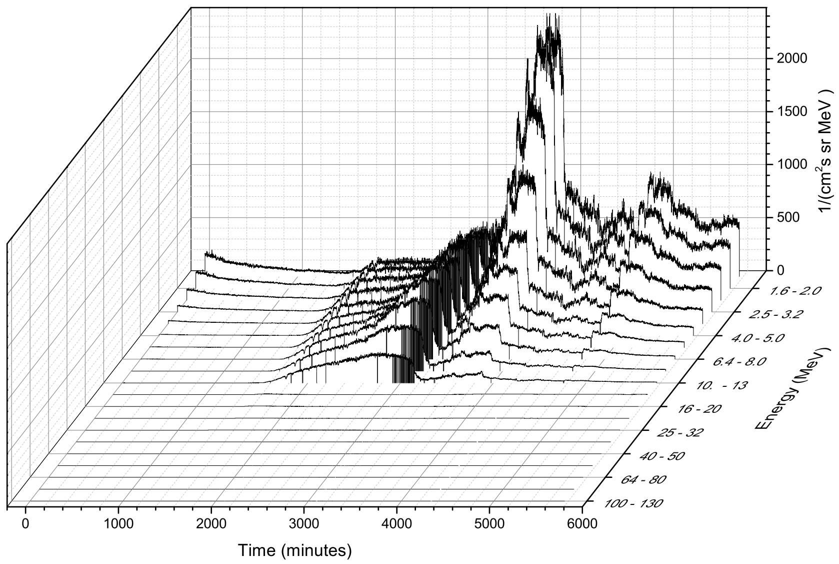

Figure 4. Energetic proton flux in various SOHO/ERNE energy channels during the time interval of 22–25 November 2001.

The analysis of fluence spectra can only indicate that the 22 November event cannot be clearly attributed to the passage of an ICME and shock acceleration, but does not provide a straightforward explanation for the origin or the mechanism responsible for the observed proton flux enhancement. Furthermore, similar enhancements of unclear origin have been observed preceding or following other ICME-related SEP events, highlighting the need for additional systematic investigations in the future to better understand their nature.

4. Conclusion

To analyze the nature and impact of CMEs/ICMEs on the near-Earth environment, time series data from twenty different energy channels of proton flux measured by the SOHO/ERNE detector at Lagrange point L1 were used. WIND IMF and solar wind velocity data were used to precisely determine the times of ICME shocks and interactions. Based on this, SOHO/ERNE proton flux time series were integrated to obtain event-integrated fluence spectra. These spectra, corresponding to three apparently separate events, were modeled using the Band function. The two events where proton flux enhancement could be more directly associated with the passage of ICMEs were well modeled, whereas the event for which no concurrent disturbances in the IMF or CME velocity were observed did not fit the model as well. This suggests that the particle acceleration leading to the observed enhancement in this event cannot easily be attributed to interaction with an ICME shock, and alternative sources should be considered. Moreover, numerous similar enhancements observed in the SOHO/ERNE proton flux time series show the need for a more detailed systematic investigation.

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