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Forecast of the arrival of interplanetary shocks by measuring cosmic ray fluctuations in the interplanetary medium

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Abstract. Here we present a method to forecast the arrival of an interplanetary shock to the Earth's orbit in advance of up to one day, using cosmic ray fluctuations and solar wind parameters measured onboard the ACE spacecraft. The method is based on our previous results [1]. By means of continuous monitoring of the interplanetary space state since April 2010, we conclude that not all shocks can be reliably forecasted by the method. Only those interplanetary shocks, for which a large flux of low-energy particles (10 keV - 10 MeV) of solar or interplanetary origin exists in the upstream region, can be forecasted. This is typically related to quasi-parallel shocks. In the absence of such particles, a forecast cannot be made. This is a typical situation for quasi-perpendicular shocks. Our analysis shows that, on average, an interplanetary shock can be forecasted for several hours up to one day, with the probability about 70%.

1. Introduction

It is statistically shown that Space Weather events, caused by bursts of solar activity, may affect the frequency and severity of sudden health problems (e.g., heart attacks, strokes) and traffic or other types of incidents [2]. Disturbances or even failure of far-distance electric grids or oil pipes can be also provoked by Space Weather events [3, 4]. In order to minimize consequences of such negative influences upon technical systems and human beings, one needs to understand the processes occurring in the interplanetary space and be able to forecast the time and severity of the approaching Space Weather events.

An important factor affecting the Space weather events is related to interplanetary shocks (IPS) propagating in the interplanetary medium. It is important to forecast their arrival to Earth sufficiently in advance. However, the direct forecast based on in-situ measurements of an IPS by spacecraft ACE and SOHO, located in the L-1 Sun-Earth point, has only about 1-hr warning time, which is insufficient for many practical applications. On the other hand, an indirect method based on measurements of cosmic ray (CR) intensities can give much earlier warnings (the exact forecast time is mainly defined by their free path) enabling effective protection measures. Here we present such a method based on measured CR fluctuations. This method makes it possible to forecast the arrival of quasi-parallel IPSs with the forecast time from several hours up to a day. A 2-year test implies that its efficiency is about 70%.

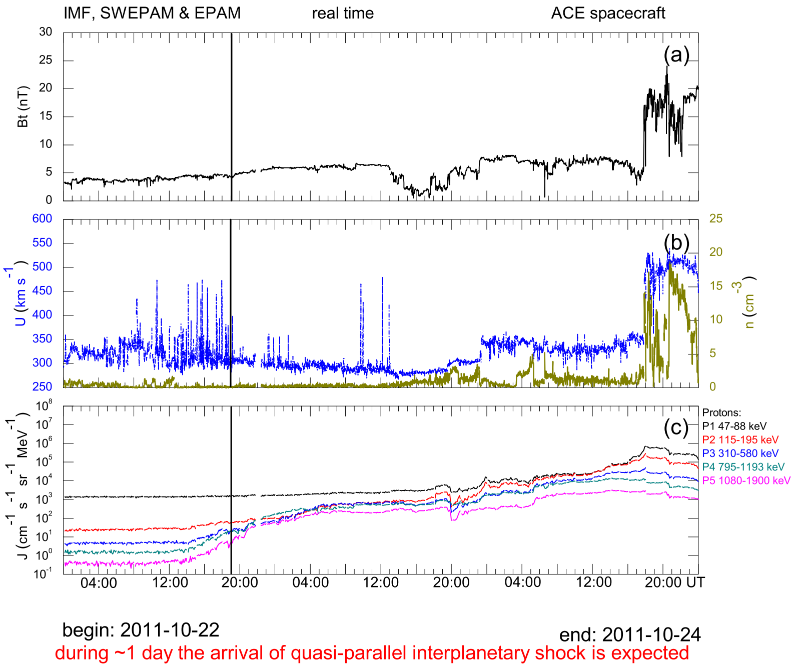

Figure 1. Results of the direct in situ measurements onboard ACE of various SW parameters for the passage of an IPS on October 24, 2011.

2. Data and method

We use 1-min data from instruments MAG and SWEPAM, as well as 5-min data from EPAM onboard the spacecraft ACE. The real time access to the data is obtained via Space Weather Prediction Center (SWPC) at `http://www.swpc.noaa.gov/ftpmenu/lists/ace.html`. Although SWPC does not encourage the use of preliminary data for research purposes, as they may contain errors and gaps, we have to use them for the purpose of Space Weather, entirely realizing the risk of using preliminary unverified data. From the whole dataset of scientific data obtained onboard ACE we employ only the data on the magnitude of the interplanetary magnetic field (IMF) Bt, density n and bulk velocity of the solar U, as well as variations of the differential proton fluxes J in five registration channels (P1 P5) with energies 47-68, 115-195, 310-580, 795-1193 and 1060-1900 keV, respectively. Since the amplitude of fluctuations is small for all the analyzed variables, we apply methods of spectral analysis, by computing the power spectral density (PSD) and the coherence function (defined as a positive square root of the coherence spectrum [5] for different variables). As discussed by [1], the arrival of an IPS to Earth is preceded by appearance of coherent fluctuations of CR in a wide range of energy from 10 keV to 1 GeV. Detection of such fluctuations with the coherence magnitude above 0.8 simultaneously at different frequencies makes it possible to predict the arrival of an IPS to Earth [6].

In order to monitor the geophysical effects caused by IPSs, we also used 1-hour data of cosmic ray intensities measured by a polar ground-based Oulu neutron monitor (`http://cosmicrays.oulu.fi`) and the Dst index of the geomagnetic field from the World Data Center for Geomagnetism, Kyoto (`http://wdc.kugi.kyoto-u.ac.jp`).

3. Results and discussion

Fig. 1 shows an example of an analysis of the IPS for October 22, 2011. Names of the instruments used for analysis, indication of the real time mode, and the name of the spacecraft are indicated on the top of the Figure. Three upper panels depict results of the measurements of the IMF magnitude (Fig.1

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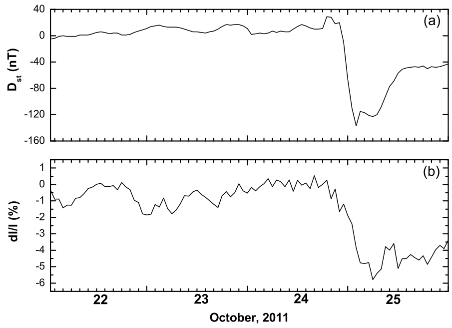

Figure 2. Geomagnetic field disturbance (a) and the Forbush effect (b), caused by the interplanetary shock of October 24, 2011.

a), density and bulk velocity of SW (Fig.1 b) and differential proton fluxes in the five channels (Fig.1 c), respectively, for three days around the event. The X-axis is the time, shown in HH:MM format, the beginning and end of the considered time interval are depicted below. The vertical line in Fig.1 depicts the current time. The arrival of a strong IPS was registered at ACE at 17:49 on Oct. 24, 2011. We have been able to predict this event already at 19:00 on Oct. 22 (vertical line in Fig. 1), i.e. almost 2 days in advance. The forecast was based on the appearance of significant coherent CR fluctuations with the magnitude above 0.8. These fluctuations were caused by fluxes of particles connected to the IPS front (Fig. 1c). We note that this IPS caused an intense magnetic storm (Fig. 2a) and a strong Forbush decrease of galactic CR (Fig. 2c).

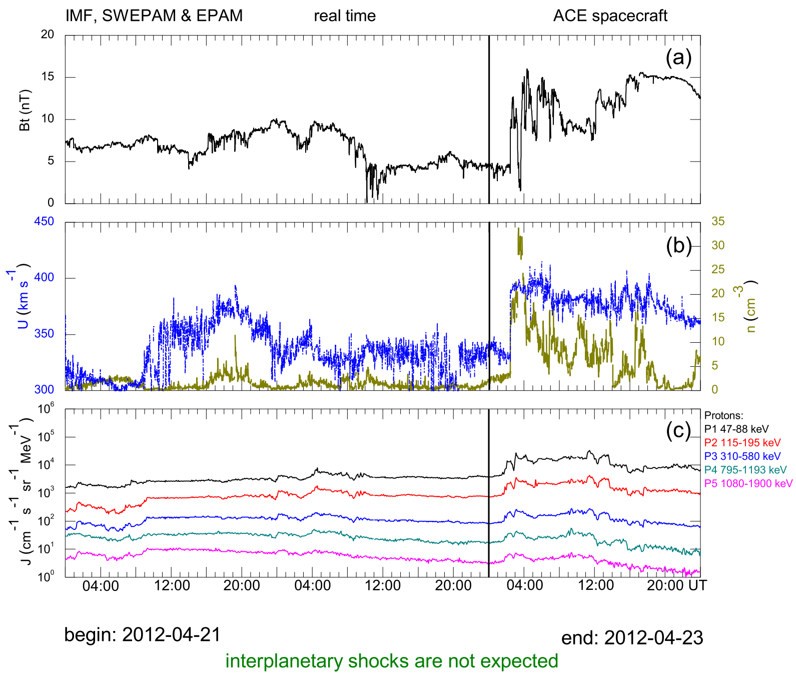

Figure 3. Similar to Fig. 1 but for the IPS of April 23, 2012.

An example of an IPS where our method was not able to give a forecast is shown in Fig. 3. A weak IPS arrived to the ACE spacecraft at 02:25 UT on April 23, 2012. However, in contrast to the previous

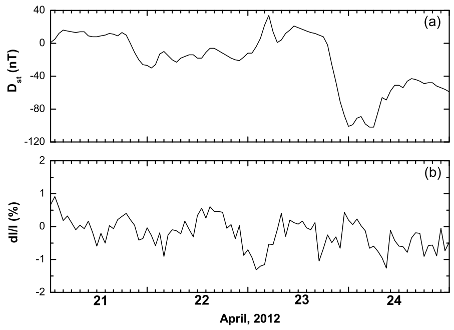

Figure 4. Similar to Fig. 2 but for the IPS of April 23, 2012.

example, there was no increase observed in the intensity of energetic particles accelerated at or reflected from the IPS front. Accordingly, the level of coherence of CR fluctuations remain low (¡0.5) until the IPS arrival, making the reliable forecast impossible. We note that this IPS also caused an intense magnetic storm (Fig. 4a) but not a Forbush decrease (Fig. 4b). This may be related to peculiarities of the relative geometry of the IPS and Earth [7, 8].

4. Conclusion

We have proposed a novel method of prediction for the arrival of an interplanetary shock at Earth that uses an analysis of coherent CR fluctuations. A necessary condition for the occurrence of coherent CR fluctuations is the presence of low energy (10 keV - 10 MeV) particles with high flux and a large gradient, in the interplanetary medium. Our analysis shows that, on average, an interplanetary shock can be forecasted for several hours up to two days in advance, with the probability of about 70%. In order to understand the observed effects of geomagnetic disturbances, one should also know mechanisms of the magnetic storm and Forbush effect formation during large-scale SW disturbances.

Acknowledgments

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