Arrival of an Interplanetary Shocks at the Earth: a Real-Time Forecast Based on ACE Spacecraft Data

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Abstract: This report concerns the method of predicting geoeffective perturbations of the interplanetary medium due to the passage of interplanetary shocks. The results obtained earlier are the basis of the method. In particular, the method is based on the following results:

1. The strength of registered magnetic storms and Forbush effects strongly depends on the geometry of intersection when interplanetary shocks pass the Earth;

2. Low-energy cosmic rays are accelerated most effectively in the quasi-parallel part of interplanetary shocks;

3. MHD-waves are generated effectively by the accelerated particles in shock pre-front region;

4. The generated MHD-turbulence modulates the cosmic ray flux with the resulting formation of coherent cosmic ray fluctuations in a wide range of energies.

Data of the EPAM, SWEPAM and MAG experiments aboard the ACE spacecraft are used for forecasting purposes. At present the method is tested in real-time and the results are displayed in the Internet at $http://alpha.ysn.ru/\sim starodub/SpaceWeather/ace\_spaceweather\_real\_time.html$.

The first results of forecast for April 2010, February and March 2011 are presented as an illustration.

Keywords: cosmic rays, solar wind turbulence, ACE spacecraft, space weather.

1 Introduction

It is highly important to be able to make short-term forecasts of Space Weather, whose significant effects both in space and at Earth may lead to serious consequences. The Space Weather near Earth is mostly defined by the momentary conditions of the solar wind (SW). On the other hand, one of the most important factors producing SW disturbances is related to propagation of interplanetary shocks (IPS). It is important to predict the time of their arrival to the Earth's orbit. Many research groups are working in that direction [1, 2, 3, 4, 5, 6, 7].

Here we base our study on the following facts:

1. The strength of registered magnetic storms and Forbush effects strongly depends on the geometry of intersection when interplanetary shocks pass the Earth [8, 9].

2. Low-energy cosmic rays are accelerated most effectively in the quasi-parallel part of interplanetary shocks. The MHD-waves are generated effectively by the accelerated particles in upstream shock [10].

3. A region (in the shape of a tongue with a size of 0.1 AU) of enhanced magnetohydrodynamic turbulence is formed in the upstream quasi-parallel parts of the shock front [11].

4. The generated MHD-turbulence (in particular fast magnetosonic wave type) modulates the cosmic ray flux with the resulting formation of coherent cosmic ray (CR) fluctuations in a wide range of energies [12].

We have studied earlier the behavior of CRs, the parameters of the magnetic field and solar wind in the vicinity of 177 interplanetary shocks during the period of 1998-2003 [12]. We have shown that coherent CR fluctuations in the energy range from 10 keV to 1 GeV are often observed at the Earth's orbit before the arrival of IPS. This forms a basis for the proposed method of forecasting, about one day ahead, of the arrival (qausi-parallel) interplanetary shock arrival to Earth, using data of in situ measurements of the interplanetary medium parameters by the ACE spacecraft.

2 Data and Method

The Advanced Composition Explorer (ACE) spacecraft was launched on August 25, 1997 and arrived at the L1 libration point in December 1997. ACE is located at this point for about 14 years, and its instruments are still working very well. Since the L1 libration point is located about 1.5 million km from the Earth Sunwards, it is possible in principle to use the data from the ACE for a sufficiently long time prediction of the arrival of the IPS at the Earth's orbit.

We use 1-min data from the 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.

Form 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.

Since the amplitude of fluctuations is very small for all the analyzed variables, we apply the spectral analysis methods. In order to avoid problems related to inhomogeneous data series, we have normalized all proton data, which may vary by orders of magnitude, to the mean level within each 24-h interval. Data on IMF and SW plasma have been off-set by subtracting the mean value for each 24-h interval. After normalization, detrending and off-setting, the series have been high-pass filtered in the frequency band from 10^{-4} to $2 \cdot 10^{-3}$ Hz and processed by the Blackman-Tukey method [13].

The lower frequency limit (10^{-4} Hz) roughly corresponds to the boundary between energetic and inertial parts of the turbulence spectrum with different properties. The higher frequency bound is defined by the Nyquist frequency. Next, using standard methods, we have computed the power spectral density (PSD) and the coherence function (defined as a positive square root of the coherence spectrum [14] for different variables. The latter is similar to the correlation coefficient but in the frequency domain. Note that the correlation between the fluctuating magnetic field Bt and bulk speed U suggests that the fluctuations correspond to pure Alfvén waves [15, 16], while the correlation between Bt and n implies the presence of fast magnetosonic waves [17].

According to the results by [18, 11, 12], the arrival of a IPS to the 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 magnitude of coherence above 0.8 simultaneously at different frequencies makes it possible to predict the arrival of a IPS to the Earth.

3 Results and Discussion

Figure 1 presents an example of the analysis of the IPS detected at ACE on April 05, 2010 at 07:54 UT. On the Figure's top there are notifications on the names of the instruments used for analysis, indication of the real time mode, and the name of the spacecraft. Three upper panels depict the results of the measurements of the IMF magnitude (panel a), density and bulk velocity of SW (panel b) and differential proton fluxes in the five channels (panel c), for the 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 panel c. Four lower panels presents the results of our computations. Panel d depicts the observed spectrum of the IMF magnitude along with the best-fit least-square approximation (the approximation formula is also shown). Spectra of coherence between Bt and U, and between Bt and n, are shown in panels f and e, respectively. These allow to evaluate relative contributions of Alfven and magnetosonic waves into the observed spectrum of IMF. The coherence between energetic protons measured in channels $P4$ and $P5$ is shown in panel g. The highest energy channels are selected since they contain less errors and failures. The vertical lines in panels $(a - c)$ depict the current time, for which the spectra shown in panels $(d - g)$ are calculated. In case of the operating forecast of an IPS arrival, an indication appears as shown in the bottom of figure 1.

According to the data of the National Geophysical Data Center NOAA ($http://www.ngdc.noaa.gov/stp/geomag/geoib.html$) a sudden storm commencements (SSC), related to the IPS registered by ACE (figure 1), was detected at Earth 32 minutes later, at 08:26 UT. This was observed as a disturbance of the geomagnetic field (figure 2a) and suppression of the CR flux (figure 2b).

This method, based on the direct detection of approaching IPS at L1 point by ACE, can provide only a very short-term prediction of the forthcoming geomagnetic disturbance, which is of little use for the timely notification of special services. The value of a forecast would be greatly enhanced if it could be done for a longer period of time in advance.

On the other hand, an alert of the IPS arrival to Earth was issued by our real-time system already at 09:00 UT April 4, 2010 (figure 1). This forecast was confirmed by the direct observations later. We note that this alarm issued nearly 24 hours before the onset of geomagnetic disturbances at Earth was based on modelling of physical processes in the interplanetary medium. Such a timely alert gives sufficient time for all the potential users to be informed and to take corresponding measures. Similar correct alerts, con-

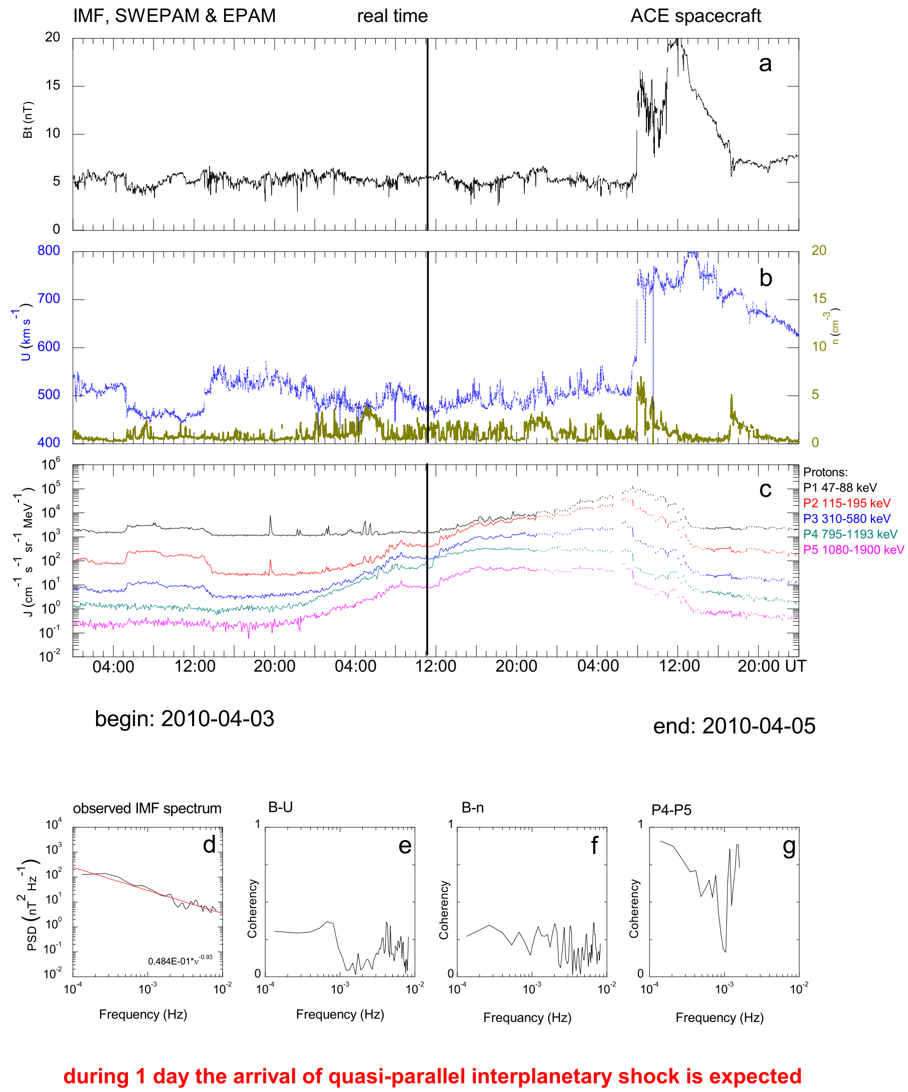

Figure 1: Results of the direct in situ measurements onboard ACE and calculation of the spectral characteristics of various SW parameters, for the passage of an IPS on April 5, 2010.

firmed by the direct observations at ACE and Earth, have been produced by our on-line system for events of February 18, 2011 and March 10, 2011.

The proposed method of the IPS forecast is currently under test in the real-time mode since April 2010. Presently, we are at the beginning of the solar cycle 24, after a prolonged and very quiet solar minimum of cycle 23. There have been no strong magnetic storms during that period. In total, about 20 magnetospheric disturbances with $D_{st} < -80$ nT and about 40 Forbush decreases with amplitude $1-6\%$ were observed. Such a great difference (a factor of two) between their numbers can be interpreted based on the fact that the sources of these events were quite different [8, 9].

We note that during the 1 year of the on-line test of our method we have successfully predicted three events of the passage of a IPS in the Earth's vicinity, as confirmed by direct measurements.

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. The method is based on modelling of physical mechanisms leading to acceleration of cosmic ray particles on the IPS fronts and generation of MHD-turbulence in the forefront region. 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 large gradient, in the interplanetary medium. In order to understand the observed effects of geomagnetic disturbances, one should also know mechanisms of the

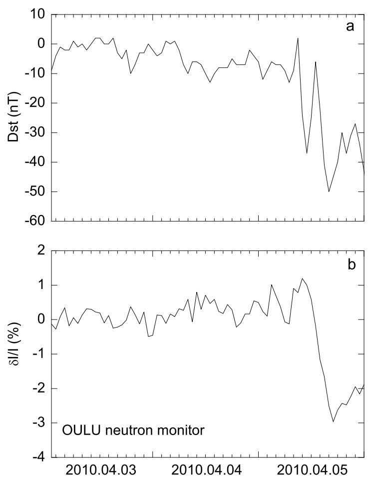

Figure 2: Geomagnetic field disturbance (panel a) and the Forbush effect (Oulu NM data, panel b), caused by the interplanetary shock of April 5, 2010.

magnetic storm and Forbush effect formation during large-scale SW disturbances.

Concluding, all the data of the measured parameters of the interplanetary mediuam, as well as the results of calculation and forecast of the interplanetary shock arrivals are available in Internet at *http://alpha.ysn.ru/~starodub/SpaceWeather/ace_spaceweather_real_time.html*.

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