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Rapid cosmic ray fluctuations in real-time during the SEP events in December 2006

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Abstract: Cosmic ray fluctuations with periods less than 3 hours are studied using data of the EPAM/LEMS120 instrument aboard the ACE spacecraft. It is shown that the power spectra of cosmic ray intensities undergo significant dynamic changes caused by the presence of fast magnetosonic waves in the solar wind. Evidence for the generation of fast magnetosonic waves by solar energetic particles is presented.

Introduction

Cosmic ray (CR) intensity is measured since decades at the Earth and in space. The measured intensity varies on different time scales from minutes up to 11 years and beyond. The variations of CR intensity can be divided into stationary and non-stationary variations. The former are determined by cyclic processes such as the solar cycle (11- and 22-years), solar rotation (27 days) and the Earth's rotation (diurnal). The latter include CR decreases, ground level enhancement (GLE), solar energetic particle (SEP) events, energetic storm particle (ESP) events as well as short-time variations with the time scale from minutes to few hours called also rapid CR fluctuations (RCRF). While mid- and long-term variations have been intensively studied and are relatively well understood now, RCRF are studied less.

The study of RCRF has a 35-yr long history. The early results indicated a relation of RCRF to interplanetary shocks (IPS) and demonstrated a possibility to forecast, 1-2 days in advance, their arrival at Earth. First successful experiments on forecasting space weather using RCRF were performed at the Tixie Bay polar geophysical observatory in 1982 [1]. The RCRF are still poorly studied in space. Most results obtained during the last 20-30 can be summarized as follows: 1. Significant dynamic changes of RCRF occur before and during large-scale disturbances of the solar wind (SW); 2. Power spectra of RCRF are closely related to the power spectra of IMF fluctuations. This led to the conclusion that RCRF originate from IMF fluctuations; 3. RCRF may be used for diagnostics of the interplanetary medium and space weather forecasts.

Despite advanced analysis results, physical mechanisms responsible for RCRF still remain elusive. Note that the nature of IMF fluctuations is not exactly known either. A possible mechanism of RCRF generation is related to the modulation of CR flux by MHD-waves, either Alfvénic or fast magnetosonic waves, during large-scale disturbances in SW. However, the question how such a modulation depends on the turbulence level of the interplanetary medium is still open. In order to resolve this problem we perform a simultaneous study of both RCRF in space and SW plasma parameters during SEP and IPS events.

Nowadays RCRF can be studied in real time, thanks to the increasing interest in space weather problems as well as to the development of information technology. Since the last decade, it is possible to analyze real-time data from the ACE spacecraft and from different ground-based experiments. This gives a new opportunity to study interplanetary and terrestrial processes and their relations in real time.

Data and methods

In this work we analyze RCRF and IMF parameters observed during December, 2006. The data have been obtained by the instruments onboard the ACE spacecraft which is located in the Lagrangian point L1 (http://www.sec.noaa.gov/ftpmenu/lists/ace.html). Here we analyze 5-min data of CR fluxes (J) measured by the EPAM/LEMS120 instrument, which detects protons in five differential channels (see Table 1). To monitor the IMF and SW plasma parameters we use 1-min data of IMF intensity (B), as well as 1-min data of SW density (n) and velocity (U). Since the amplitude of fluctuations is small for all the analyzed variables, we studied them by means of spectral analysis methods. In order to avoid problems related to inhomogeneous data series, we have normalized all CR data, which may vary (slowly compared to the RCRF period) by orders of magnitude, to the mean level within each 24-hour interval. Data on IMF and SW plasma have been off-set by subtracting the mean value and detrended for each 24-hour interval. After normalization, detrending and off-setting, the series have been high-pass filtered in the frequency band from 10^{-4} Hz to the Nyquist frequency (ν_N) and processed by the Blackman-Tukey method [2]. The lower frequency limit ($\nu_1 = 10^{-4}$ Hz) roughly corresponds to the boundary between energetic and inertial parts of the turbulence spectrum with different properties. Next, using standard methods, we have computed the spectral power density (P) and the coherency (ν) for different variables [3]. The latter is an analogue of the correlation coefficient in the frequency domain.

As a measure of the SW turbulence level, we use the energy density of MHD–waves, which is estimated as follows: $E_W = \frac{1}{8\pi} \cdot \int_{\nu_1}^{\nu_2} P_B(\nu)\, d\nu$. E_W was computed for each 24-hour sub-set and its temporal variations were considered to represent variations of the turbulence level in this frequency range. In addition we make use of 1-hdata of CR count rates (N) at the high latitude neutron monitor of Oulu with geomagnetic cut-off rigidity 0.8 GV, as well as the geomagnetic Dst-index.

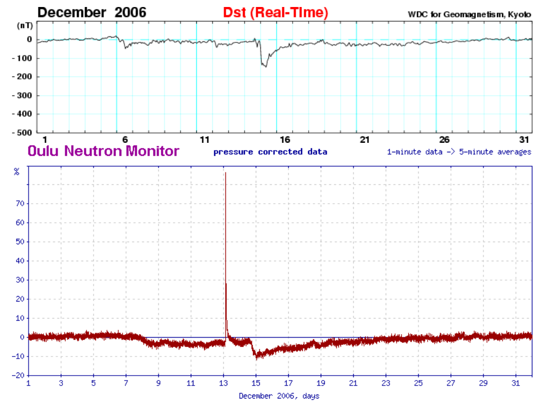

Figure 1: Variations of hourly value of Dst-index (http://swdcwww.kugi.kyoto-u.ac.jp/dst_realtime/200612/index.html) and 5-min value of CR intensity recorded at Oulu station (http://cosmicrays.oulu.fi)..

Results and discussions

Two strong solar flares, accompanied by CME and SEP occurred on December, 6 and 13, 2006. A GLE was detected on December 13, 2006. A series of IPSs were also detected in space. The very fact of such a strong event occurring during the solar minimum epoch is intriguing. Both flares (see Table 2) and the accompanying CMEs originated from the same active region NOAA 10930, in the course of its advance in the solar disc. Subsequently, one may expect severe space weather phenomena and geophysical effects. Particularly hazardous are strong geomagnetic disturbances which may cause damages, e.g., to power grids and pipe lines. Meanwhile, strong fluxes of CR with energy $10 - 100$ MeV may lead to malfunctions of spacecraft electronics and to radiation hazards for astronauts and crews of trans-polar routing aircraft.

One can see from Figure 1 that a storm of class G4 ($K_p > 8$), according to the NOAA space weather scale, began in the evening of December 14, 2006. However, the flare of December 6, was not followed by a significant geomagnetic disturbance. A small disturbance of the Dst–index on December 6

Channel	1	2	3	4	5
Energy(MeV)	0.047-0.068	0.115-0.195	0.310-0.580	0.761-1.220	1.060-1.900

Table 1: Different energy proton channels of the EPAM/LEMS120 experiment onboard ACE spacecraft.

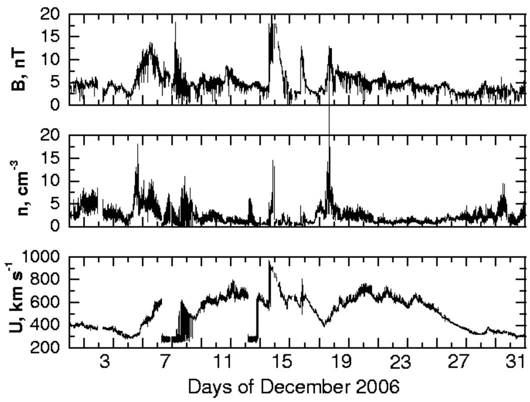

Figure 2: 1-min variations of IMF and solar wind plasma by ACE spacecraft data.

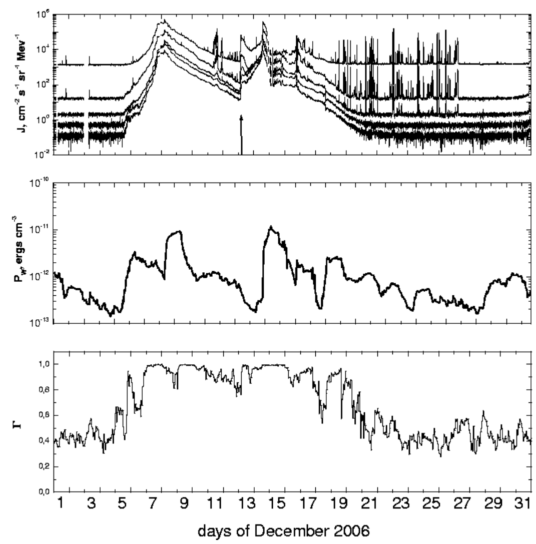

Figure 3: From top to bottom: 5-min fluxes from 5 CR channels, energy density of MHD-waves and coherence between 4-th and 5-th channels in measuring of cosmic rays aboard the ACE spacecraft. The arrow shows the GLE event.

was caused by a fast SW stream (Figure 2). This is consistent with the earlier results [4] that a relation between the Forbush effects and geomagnetic storms can be different depending on the heliolongitude of the source of interplanetary disturbance.

In the studied case, a strong Forbush decrease (about 5%) was observed on December 8 related to the passage of an IPS from the eastern solar flare of December 6. It was not accompanied by a disturbance of the geomagnetic field. A CR decrease (about 10%) and geomagnetic storm (Dst about -150 nT) of December 14 were related to the second flare, which occurred on December 13 near the central solar meridian and caused a GLE. Variations of the IMF and SW parameters as measured onboard the ACE spacecraft during December 2006 are shown in Figure 2. One can see irregularities in the measured parameters of SW during SEP events of December 7–8 and 13. Also IMF intensity was greatly fluctuating during the SEP events. Such fluctuations can be attributed to strong SEP flux in the vicinity of the spacecraft. The upper panel of Figure 3 shows temporal variations of low-energy CR measured by the EPAM/LEMS120 instrument. One can see enhancements of the CR flux during the SEP events of December 06 and 13 as well as an ESP event caused by the passage of a IPS on December 14. Sporadic spikes in three low-energy channels during December 12–28 are probably artifacts caused by the influence of strong SEP fluxes onto the CR detector.

The middle panel of Figure 3 depicts the energy density of MHD-waves in the frequency range $10^{-4} \div 8.33 \cdot 10^{-3}$ Hz. The energy density increases by an order of magnitude during the time of enhanced SEP flux, roughly synchronously with them. Spectral characteristics of RCRF for different energy channels also synchronize during the same periods. For example, the lower panel of Figure 3 shows the coherence between two stable channels #4 and #5. The coherence first increases from 0.4 to almost 1.0 and then decreases back to

NOAA SEC Region	Maximum (Day/UT)	Importance (X ray/Optics)	Location	CME (Day/UT)
10930	Dec 06/1035	X9/2N	S07E79	Halo Dec 06/??
10930	Dec 13/0240	X3/4B	S05W23	Halo Dec 13/0254

Table 2: Characteristics of solar flares in December 2006 (http://umbra.nascom.nasa.gov/SEP/seps.html).

the value of 0.4, in accord with the time profile of the SEP flux. This suggests for modulation of the flux of CR with different energies by magnetosonic waves, which can be generated in the interplanetary medium by SEP or particles accelerated, e.g., at the IPS shock [5, 6].

Conclusion

A study of IMF and solar wind parameters, cosmic ray fluxes and RCRF measured aboard spacecraft can be a useful tool to obtain information about features of the interplanetary medium and for improved diagnostics and forecasts of space weather.

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