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Variations of Parameters of Rigidity Spectrum of Cosmic Rays during events of January, 2005

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Abstract: Variations of cosmic ray (CR) rigidity spectrum during Forbush effect on 17 January and solar proton event on 20 January, 2005 (the beginning at 06:36 UT, solar coordinates N14W61) have been researched using the method of spectrographic global survey according to ground-based observations of cosmic ray intensity at the world-wide network of stations. In integrally analyzing ground-based and satellite measurements of protons in the energetic range from a few MeV to tens GeV, parameters of CR rigidity spectrum representing electromagnetic characteristics of heliosphere over the period of the event under investigation have been determined. The analysis provides an explanation of CR variations over a wide energy range.

1. Introduction

The middle of January, 2005, is characterized by a number of events involving the active region 10720. This region developed rapidly and was very active, namely, 17 flares of M class and 5 flares of X class for 10 days from 14 to January 23, 2005. Many of these events are associated with coronal mass ejection (CME) and solar proton events (SPE), one of which, that took place at 06:36 UT on January 20, 2005, in the recovery phase of Forbush decrease, which began on January 17, 2005, is unique by a large variety of properties. Firstly, CORONAS-F registered a gamma flux right up to 100 MeV that can rather rarely be recorded during solar events. Secondly, the CR intensity increase was recorded at the ground-based network of neutron monitors (GLE) and appeared to be one of the strongest increases after the event of February 23, 1956. The aim of this work is to research into manifestations of the whole complex of phenomena in interplanetary space according to variations of cosmic ray (CR) rigidity spectrum, which parameters reflect electromagnetic characteristics of interplanetary me-

dium in line with a model of modulation by regular electromagnetic fields of the heliosphere.

2. Data and method

For the analysis, we used the hour-averaged data of observations of proton intensity over energetic ranges of 4-9, 9-15, 15–40, 40–80, 80–165 и 165–500 MeV, obtained at GOES-11 [2]; and the data for variations of CR intensity of different rigidities, obtained with the method of spectrographic global survey (CGS) [3] according to ground-based measurements at the world network of neutron monitors (35 stations). The CGS method makes it possible to obtain information on variations of angular and energetic distributions of primary CR outside the Earth's magnetosphere, as well as on changes in the planetary system of geomagnetic cutoff rigidities for each hour of observations. To describe the CR rigidity spectrum over a wide range of energies, we employed equation obtained in [1].

$$J(R) = A \left[\frac{(\varepsilon^2 - \varepsilon_0^2)}{(\varepsilon + \Delta\varepsilon)^2 - \varepsilon_0^2} \right]^{3/2} \frac{\varepsilon + \Delta\varepsilon}{\varepsilon} \left[\frac{2\sqrt{(\varepsilon + \Delta\varepsilon)^2 - \varepsilon_0^2} - \sqrt{(\varepsilon^2 - \varepsilon_0^2)}}{\sqrt{(\varepsilon^2 - \varepsilon_0^2)}} \right]^{-\gamma},$$

where ε – total particle energy; ε_0 – rest energy; A and γ – spectral indices of a galactic spectrum; $\Delta\varepsilon$ – variations of particle energy in the heliosphere electromagnetic fields, determined with the following equation:

$$\Delta\varepsilon(R) = \Delta\varepsilon_0 + \Delta\varepsilon_1\left[1 - f(R, bR_0)\right] +$$
$$\Delta\varepsilon_2\left[1 - f(R, bR_0)\right]f(R, R_0) +$$
$$+\left[\varepsilon(1 - e^{\alpha/2}) + \varepsilon - \sqrt{\beta(\varepsilon^2 - \varepsilon_0^2) + \varepsilon_0^2}\right]f(R, R_0),$$

Equation (1) has been derived on the basis of Liouville theorem under the assumption that sources of solar origin particles (SCR) are absent in the considered energy range. If this assumption is broken down, Equation (1) does not describe the observable particle spectrum, and based on these discrepancies a SCR coming can be identified.

Equation (2) has been found from solution of the equation of particle motion in general form as a drift approximation [4] assuming that polarization and vortex electrical fields can be generated in the heliosphere in parallel with an induced electrical field. The generation of polarization electrical fields can take place during propagation of beams accelerated on the Sun in inhomogeneous magnetic fields because of protons and electrons drift in opposite directions. As a consequence there occurs charge separation and, in the presence of special inhomogeneity of accelerated particle density, appears a potential difference between boundaries of the beam along magnetic drift trajectories that results in generation of increasing in time polarization electric field and, as a result, of the polarization drift of background particles of SW plasma, solar corona and GCR along this field, i.e. in acceleration of particles of solar corona and interplanetary medium, which Larmor radius is less than the beam cross size. Owing to origination of depolarization longitudinal currents, there forms current system and is generated a magnetic field and thus a vortex electrical field, accelerating particles through the betatronic mechanism etc. Evidences for appearance of such fields have been obtained at L. Lindberg's laboratory experiments [see 5 and references there]. In such a way energy exchange occurs between accelerated and background particles of the solar corona plasma, SW and GCR, due to this, there are formed current structures of the heliosphere and IMF structure generation, i.e. the process of particle acceleration and propagation in the heliosphere is self-consistent with electromagnetic fields.

Spectrum parameters $\Delta\varepsilon_1$, $\Delta\varepsilon_2$, α, β, and R_0 account for the following heliosphere characteristics: R_0 is a parameter characterizing a scale of structural formations in the heliosphere with nonstationary electromagnetic fields, parameter $\Delta\varepsilon_1$ describes CR energy variations due to gradient and centrifugal particle drifts in the spiral interplanetary magnetic field (IMF) opposite to the induced electric field, and is proportional to IMF intensity, while $\Delta\varepsilon_2$ – in CME fields and proportional to the field intensity in CME and to solar wind velocity (SW) [3]. In $\beta = B/B_0$, B_0 – background IMF intensity, whereas B – time-variable IMF, takes account of the influence of time-nonstationary magnetic fields on the CR spectrum (if particle magnetic rigidity is $R \leq R_0$), while $\alpha = E_{pl}^2/B^2$ – polarization electric fields of E_{pl}. Quasi-stepped functions $f(R,R_0)$, $f(R,bR_0)$, approaching 1 at $R < R_0$ or $R < bR_0$ and zero at $R > R_0$ or $R > bR_0$, have been entered for one or other mechanism of particle energy variation in different energetic intervals to be more significant.

Thus, in determining parameters of the differential rigidity CR spectrum according to the data of its measurements over a wide energy range for each hour of observations, it is possible to perform a monitoring of electromagnetic characteristics of the heliosphere and their dynamics.

3. The analysis results

On fig. 1 at three top panels, triangles present the data of proton intensity observations over energetic intervals 4-9 MeV (0.108 GV), 9-15 MeV (0.223 GV) and 5 GV, whereas solid curves show the results of calculations with model spectrum and obtained values of its parameters. At five bottom panels, there are presented hour-average values of rigidity spectrum parameters R_0, $\Delta\varepsilon_1$, $\Delta\varepsilon_2$, α, and β determined during the period being investigated. On $\Delta\varepsilon_1$ graph, the IMF module values (blue curve) are additionally given for comparison, and on β graph (also blue curve) – SW velocity values shifted to the left by a day and a half. Fig. 2 presents deferential rigidity CR spectra at some moments of the investigated period in combination with the background CR spectrum.
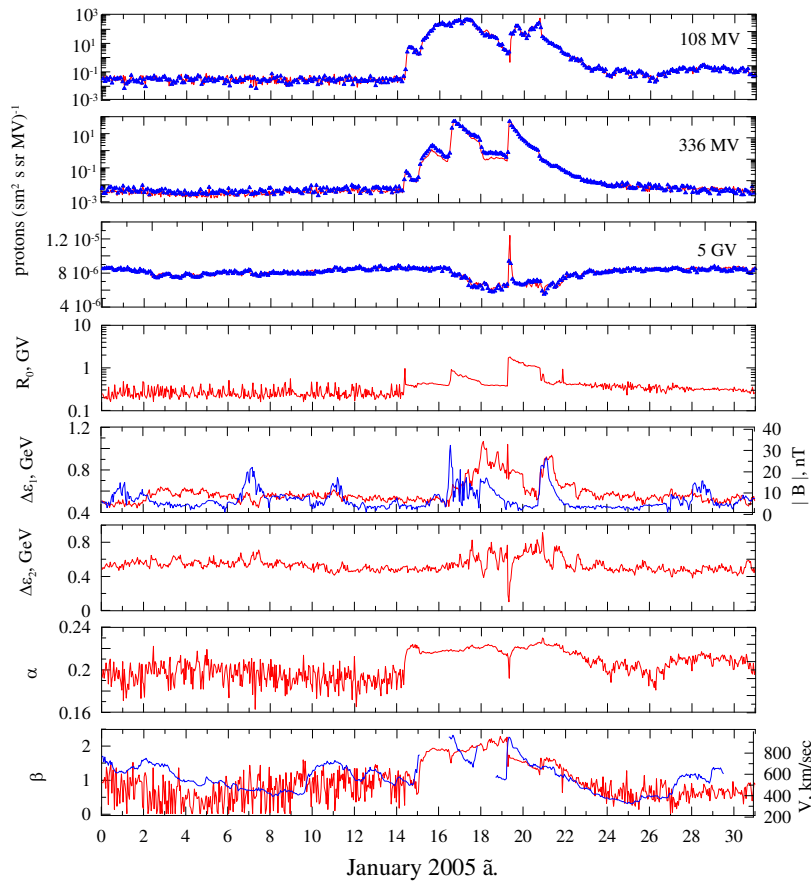
January 2005 ã.

Figure 1

The results of model spectrum calculations at the moments, indicated in these graphs, are denoted by curve 2; triangles show data of the observations. Calculated background spectrum (curve 1) is shown by dotted curve, the observation data – by crosses.

4. Discussion and conclusions

In comparing time variations of parameters of CR rigidity spectrum with time profiles of proton intensity (three top panels in Fig. 1), it is possible to conclude that intensity increase of low-energy particles initially results from acceleration of interplanetary medium particles by the polarization electric fields (α parameter increase), which started at the beginning of 15 January. Then, hand in hand with the acceleration by the polarization electric fields is the CR acceleration at the cost of the betatronic mechanism on account of generation of the heliosphere magnetic fields (the pa-

rameter increase at the beginning of 16 January). The SW plasma accelerates due to the very mechanism as judged from the correlation between β parameter and SW velocity (see Fig. 1). The magnetic field generation results in IMF intensity increase that causes decrease of high-energy particle intensity (increase of $\Delta\varepsilon_1$ and $\Delta\varepsilon_2$ parameters in the middle of 17 January, correlating with the IMF module). Intensity decrease because of the last two parameters is also observed for low-energy particles (see two top panels of Fig. 1), but for particles with $R \ll R_0$ rigidity, acceleration effects in the vortex and polarization electric fields dominate over the effects of energy loss in the induced electric field, in this connection while their intensity decreases, it is nevertheless higher than the background one.

When analyzing the behavior of the CR rigidity spectrum in the event on January 20, one can observe that α and β parameter values differ little from their values in the periods of preceding SPE. Therefore, we can conclude that the polarization and vortex electric fields in the heliosphere were typical, while the increase of high-energy (~5 GeV) particle intensity results from the size of the IMF structures, in which particle acceleration took place under the action of these fields (R_0 parameter increase, see the third and fourth panels of Fig. 1)

From the analysis of Fig. 2 it follows that the employed spectrum type adequately describes observable dependence of the CR intensity on their rigidity on the whole time interval being analyzed except the moment, which took place at 07:00 on January 20, i.e. at the initial stage of GLE.
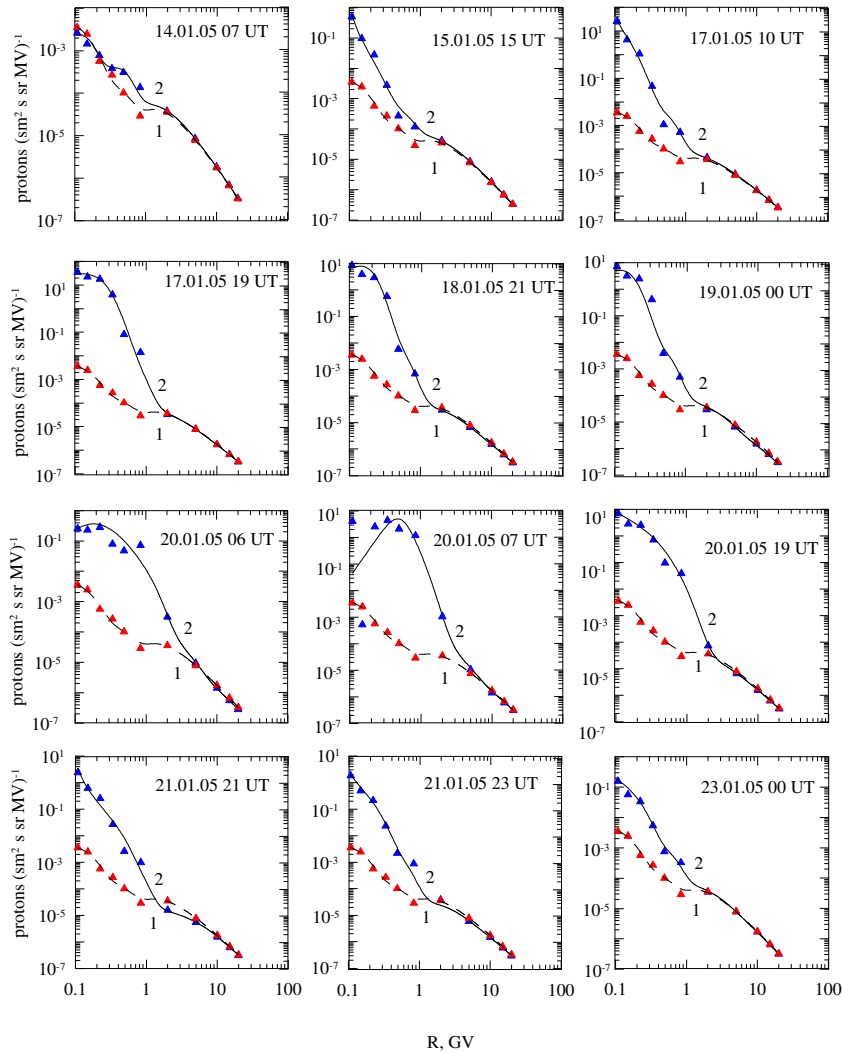
Figure 2

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On the basis of the performed investigations, we can conclude that in the considered energy range the variations of the energetic particle intensity depend upon the variation of the galactic CR energy (GCR) under the action of electromagnetic fields originated in the heliosphere due to SCR propagation, which in its turn move to the region of lower energies and registered only at short-time moments because of energy exchange with GCR and SW plasma particles (for example, at 07:00 UT on January 20, see Fig. 2) as demonstrated by discrepancies between modeling and observable spectra in the low energy region.

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