Forecast of the Solar Proton Events according to the Rigidity Spectrum Variations of Cosmic Rays

V.M. Dvornikov, M.V. Kravtsova, A.A. Lukovnikova, V.E. Sdobnov

Institute of Solar-Terrestrial Physics SB RAS, Irkutsk

dvornikovl@iszf.irk.ru

Abstract: According to the temporal variations of CR rigidity spectrum parameters the dynamic processes are researched in the interplanetary space and it is found that the variation of electromagnetic characteristics of heliosphere begins up to the sporadic phenomena on the Sun. In particular, it is shown that before the sporadic phenomena the generation of local polarization electric fields, magnetic fields intensity decrease in the small-scale heliosphere structures and also the increase of potentials difference between the pole and the surface of ecliptics take place. Use of the given features combination allows carrying out the forecast of solar proton events with the advance term from several hours up to several tens of hours with a high degree of defense.

Introduction

Carrying out the forecast of solar proton events (SPE) is concerned with sufficient difficulties conditioned by the set of complicated circumstances general of which is the absence of theoretically proved algorithms for the given problem solution. Because of this reason we cannot determine the necessary and sufficient features for the identification of the pre-flare situation on the Sun. But, even in the case if this problem was solved there would appear the difficulties with the forecast of localization fluxes of accelerated particles in the interplanetary space and, consequently – with the forecast of their reaching the Earth. Almost the only possible situation where the problem of SPE forecasting can be solved is the situation when the accumulation of the flare energy takes place as a result of the dynamics of current systems localized not only in solar corona, but spreading up to some distances in heliosphere. In this case it is worth trying to find the SPE precursors on the basis of heliosphere diagnostics according to the effects in cosmic rays (CR). Moreover, such diagnostics is carried out in the field lines of interplanetary magnetic field (IMF) that bind at the present moment the Earth with the corresponding regions on the Sun. Notes for the existence of such situations are taken from the works [1-3]. The goal of the proposed work is the realization of such an opportunity.

Data and method

For the analysis we had used the middle-hour observation data of protons intensity of the energetic scales 4-9, 9-15, 15–40, 40–80, 80–165 and 165–500 MeV obtained at the satellite GOES-10 [4] and the CR intensity variations data of various rigidities obtained by the method of spectrographic global survey (SGS) [5] according to the ground measurements at the global network of neutron monitors (38 stations).

When analyzing, for describing the CR rigidity spectrum in a wide range of energies, we had used the analytical expression obtained in the supposition that the rigidity spectrum in the Galaxy is described by the degree function from the CR rigidity and their intensity variation in the interplanetary space takes place (because of the energy change in regular electromagnetic fields of heliosphere) in accordance with the Liuville theorem, i.e. on condition of constant density of particles along the traveling trajectories in the phase space [6]

$$J(R) = A\left[\frac{(\varepsilon^2 - \varepsilon_0^2)}{(\varepsilon + \Delta\varepsilon)^2 - \varepsilon_0^2}\right]^{3/2} \frac{\varepsilon + \Delta\varepsilon}{\varepsilon}\left[\frac{2\sqrt{(\varepsilon + \Delta\varepsilon)^2 - \varepsilon_0^2} - \sqrt{(\varepsilon^2 - \varepsilon_0^2)}}{\sqrt{(\varepsilon^2 - \varepsilon_0^2)}}\right]^{-\gamma}, \quad (1)$$

where ε is the total energy of particles; Δε is the change in the electromagnetic fields of heliosphere; ε_0 is the rest energy; *A* and γ are the spectral indices of the galactic spectrum.

Within the limits of drift approximation the particle energy change can be obtained by the integration of the equation [8]:

$$\frac{d\varepsilon}{dt} = \vec{E}\left\{\frac{mc v_\perp^2}{2B^3}\vec{B}\times\nabla\vec{B} - \frac{mc}{B^2}\left[\frac{\partial\vec{V}}{\partial t} + (\vec{V}\nabla)\vec{V}, \vec{B}\right]\right\} + \frac{mc v_\perp^2}{2B}\frac{\partial\vec{B}}{\partial t}. \qquad (2)$$

Here $\varepsilon = \frac{m}{2}(v_\parallel^2 + v_\perp^2 + v_E^2); \vec{V} = v_\parallel\frac{\vec{B}}{B} + \vec{v}_E;$ *m* is particle mass; $v_\parallel$ and $v_\perp$ are transverse and longitudinal velocity components relative to $\vec{B}$ of interplanetary magnetic field (IMF); B is the IMF intensity; $\vec{E}$ is electric field intensity; $v_E = \frac{c}{B^2}\vec{E}\times\vec{B};$ *c* is the light velocity.

The first member in the equation (2) characterizes the energy change due to particle magnetic drift along or transversely (depending on IMF gradient) to electric field; the second member describes particle acceleration due to drift under the action of inertial force $-m\left[\frac{\partial\vec{V}}{\partial t} + (\vec{V}\nabla)\vec{V}\right]$ along electric field with its increasing in time; the third member describes the same due to variability of magnetic fields in time.

For the spiral IMF and induced electric field $\vec{E} = -\frac{1}{c}\vec{u}\times\vec{B}$ of homogeneous stationary SW, and from the equation (2) solution the expression is obtained:

$$\Delta\varepsilon_{pt} = \frac{z_e\Omega B_0 r_0^2}{c}(1-\cos\lambda_E), \qquad (3)$$

where Ω is the angular velocity of Sun's rotation; B_0 is the intensity of radial IMF component at the distance of r_0, and λ_E is the Earth's heliolatitude.

As follows from the equation (3) the particle energy losses under potential electric field do not depend on particle rigidity, and are of ~ 200 MeV at typical IMF intensity.

If the electromagnetic fields of heliosphere are not stationary the particle energy changes should be taken into account which are described by second and third members of the equation (2). The corresponding energy changes are determined by the following expressions:

$$\Delta\varepsilon_{pl} = \varepsilon(1-e^{-\alpha/2}), \qquad (4)$$

where $\alpha = \frac{E_{pl}^2}{B^2}$, E_{pl} is the polarized electric field and

$$\Delta\varepsilon_{rot} = \varepsilon - \sqrt{\beta(\varepsilon^2-\varepsilon_0^2)+\varepsilon_0^2}, \qquad (5)$$

where $\beta = \frac{B}{\langle B\rangle}$, $\langle B\rangle$ is the background field intensity, and *B* is the variable magnetic field intensity.

Supposition for existence of such fields is based on the Lindberg laboratory experiments on researching the flux movement of accelerated plasma in the curved magnetic field [9 and references there]. In particular, it is shown in the given work that in a definite range of the flux parameters when plasma reaches the region of curved field there the charges division takes place as a result of electrons and protons drift in opposite direction. Polarization electric field appears orthogonally to magnetic field depolarizing the longitudinal currents and longitudinal electric fields, under the influence of which the anomalous deflection of the flux takes place, the flux transforms from the cylinder into the flat one and the depolarizing currents distort the initial magnetic field.

It is reasonable to suppose that the energy change takes place through such fields between the accelerated particles and the background particles of solar wind plasma and CR in heliosphere, and as a result there happens the transformation of rigidity spectrum of background CR. This circumstance was taken into account when deriving an analytical expression for rigidity spectrum used in analysis.

To describe the dependence Δε(*R*) it should be assumed that the mentioned mechanisms are of different efficiency for particles of different rigidities. The energy changes of high-energy particles take place in accordance with the equation (3) and depend on large-scale IMF intensity. If the Earth enters the "magnetic cloud" the CR intensity changes are determined by superposition of the background IMF and the magnetic cloud field, as well as by the SW velocity [7]. This effect should be observed for particles the Larmor radius of which is less than magnetic cloud sizes (a few GV). At lower energies the effects dominate which are described by the expressions (4), (5) because the magnetic drift velocity of these particles is considerably less than that for high-energy CR.

We can obtain the expression for particle energy change from the solution of the motion equation in general form:

$$\Delta\varepsilon(R) = \Delta\varepsilon_0 + \Delta\varepsilon_1\left[1 - f(R,\, bR_0)\right] + \Delta\varepsilon_2\left[1 - f(R,\, bR_0)\right] f(R,\, R_0) + \\ + \left[\varepsilon(1 - e^{\alpha/2}) + \varepsilon - \sqrt{\beta(\varepsilon^2 - \varepsilon_0^2) + \varepsilon_0^2}\,\right] f(R,\, R_0), \qquad (6)$$

where $\Delta\varepsilon_0$ = 0.1 GeV; R_0 is the parameter, characterizing the scale of the structural formations in heliosphere with nonstationary electromagnetic fields;

$f(R,\, R_0) = \left[\exp\left(\dfrac{R - R_0}{aR_0}\right) + 1\right]^{-1}$ is quasi-step function which approach 1 at $R < R_0$ and 0 at $R > R_0$ (a<1); $\Delta\varepsilon_1$, $\Delta\varepsilon_2$ are the parameters characterizing the energy changes of the high-energy particles ($\Delta\varepsilon_1$ at $R > bR_0$, b = 2.5, and $\Delta\varepsilon_2$ in rigid interval $[R_0, bR_0]$ when the Earth gets into "magnetic cloud").

The rigidity spectrum parameters R_0, $\Delta\varepsilon_1$, $\Delta\varepsilon_2$, α, and β were determined for every hour of observation throughout the entire period under study with used expression (1) taking into account (6).

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

While using this method the monitoring of interplanetary environment was carried out for the period October–November, 2003 and 2004.

Analysis results

In the fig. 1 at three upper panels the observations data of proton intensities in energetic intervals 4-9 MeV (0.108 GV), 9-15 MeV (0.223 GV) and 5 GV are represented by the triangles, and the calculation results with the use of model spectrum and obtained values of its parameters by the bold curves. At the fourth panel the Dst-index values are represented. At the four lower panels the average hour values of parameters of rigidity spectrum $\Delta\varepsilon_1$, α, β, and R_0 are represented. They are determined for the researched period.

On the basis of the comparing of the temporal variations of CR rigidity spectrum parameters with the temporal profiles of low energy CR intensity (the first two panels in the fig. 1) we can make a conclusion that on the day before the solar proton events the changes of heliosphere electromagnetic characteristics take place. In particular, we can see that for several hours or tens of hours before SPE the generation of local polarization electric fields takes place (parameter α increase), decrease in intensity of magnetic fields in small-scale structures of heliosphere (parameter β decrease), and also the increase of intensity of a large-scale helical IMF (parameter $\Delta\varepsilon_1$ increase).

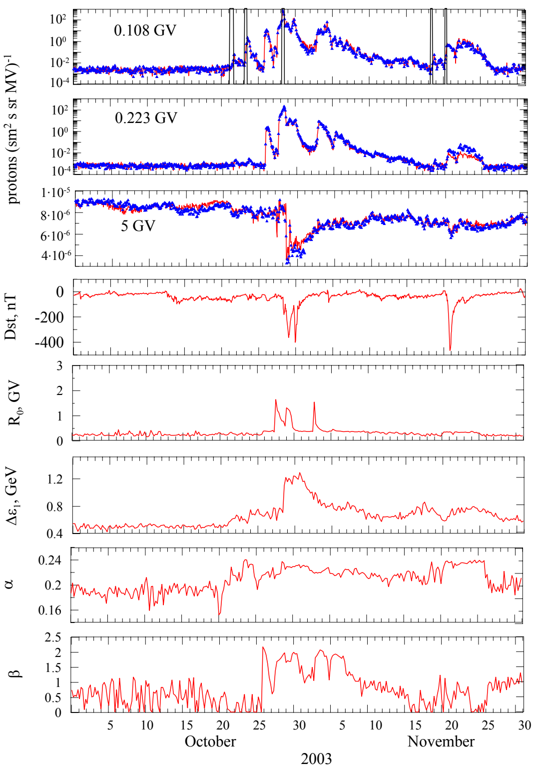

Figure 1: Temporal profiles of CR intensity with R=0.108, 0.223 and 5 GV (bold line – calculation, triangles – observations data), Dst-index and parameters of CR rigidity spectrum R_0, $\Delta\varepsilon_1$, α, β for the period October – November, 2003. Moments of SPE predictors' manifestation are marked by the vertical lines at the upper panel.

This circumstance allows us hope to have an opportunity for the SPE forecast when monitoring the electromagnetic characteristics of heliosphere (in the real time regime) according to the effects in cosmic rays.

Combination of these three features was used for the SPE forecast at the two-month data selection in October – November, 2003. At the upper panel in the fig. 1 realization moments of the shown features are marked by the vertical lines that are predictors for given events. In the fig. 2 the similar information for the 2004 period is represented that demonstrates the high level (about 90 %) of truth for the worked out method of forecast.

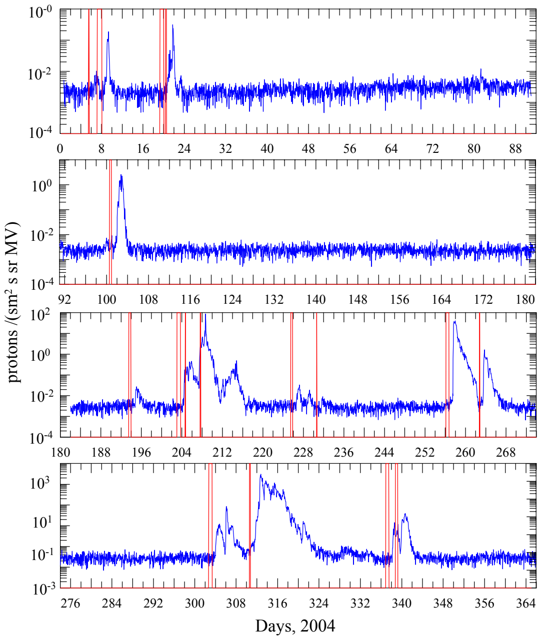

Figure 2: Time profile of CR intensity in energetic range 4–9 MeV in 2004. Moments of SPE predictors' appearance are shown by red vertical lines.

Conclusion

Diagnostics of electromagnetic conditions in the interplanetary space according to the effects in CR allows carrying out the forecast of solar proton events in advance time of several hours up to several tens of hours with high level of truth. And that shows us the adequacy of the used modulation model and of the validity of obtained information about dynamic processes in heliosphere.

Acknowledgements

This work is provided by the complex integration project SB RAS-2006 □3.10 and the program of Presidium RAS «Neutrino physics» in the frames of the project «Research of modulation effects of cosmic rays by the method of ground and stratosphere monitoring».

References

[1] Volodichev N.N., Kuzhevsky B.M., Nechaev O.Y., Savenko I.A. Zaderzhka vyhoda solnechnyh protonov vysokoj energii v mezhplanetnoe prostranstvo. *Kosmicheskie issledovaniya, V. 23. Edition 5. P. 748-753,1985.*

[2] Dvornikov V.M., Sdobnov V.E., Sergeev A.V. Rekurrentnye dvojnye vspleski pitch - uglovoj anizotropii kosmicheskih luchej i ih svyaz' s solnechnymi protonnymi sobytiyami. *Rep. AN USSR. Ser. Phys, V. 48, N 11. P. 2140-214*2, 1984.

[3] Dvornikov V.M., Sdobnov V.E., Sergeev A.V. Anomal'nye variacii kosmicheskih luchej v zhestkostnom diapazone 2-5 GV i ih svyaz' s geomagnitnymi vozmuscheniyami. *Rep. AN USSR. Ser. Phys, V. 52, N 12. P. 2435-2437, 1988.*

[4] http://spidr.ngdc.gov/spidr/index.html.

[5] Dvornikov V.M., Sdobnov V.E. Time variations of the cosmic ray distribution functions during a solar event of September 29, 1989. *Journal Geophys.Res., V. 102, N A11. P. 24209-24219, 1997.*

[6] Dvornikov V.M., Kravtsova M.V., Sdobnov V.E. Uskorenie kosmicheskih luchej v geliosfere. *Baikal International School on Fundamental Physics. Irkutsk, P. 167-169, 2005.*

[7] Dvornikov, V.M., Sdobnov, V.E. Variations in the rigidity spectrum and anisotropy cosmic rays at the period of Forbush effect on the 12–25 July1982. *International Journal of Geomagnetism and Aeronomy, V. 3, N 3. P. 217, 2002.*

[8] Voprosy teorii plazmy. Vyp. 2 / pod red. M.A. Leontovicha. M.: Gosatomizdat, 1963. 264 s.

[9] Alven Kh. Space plasma. M.: Mir. 1983. 213 p.