A Simple Model of Cosmic Ray Modulation in the Heliosphere

Krymsky G.F., Krivoshapkin P.A., Gerasimova S.K. and Grigoryev V.G.
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677891 Yakutsk, Russia

Abstract

The cosmic ray modulation by the interplanetary magnetic field of simple geometry is considered. The turbulent component of field is assumed to be proportional to the total field intensity with a proportional coefficient independing on the coordinates but varying with the 11-year cycle. The expected variations are compared with the ground-based results for many years.

1. Methods

The heliosphere as a region occupied by the solar wind and interplanetary magnetic field is of interest, first of all, from the point of view of the cosmic ray astrophysics. Characteristics of the heliosphere are manifested in the galactic cosmic ray modulation where aside from the solar activity level, the geometry of interplanetary magnetic field and its alternating property are embodied [1].

In view of the complication in the modulation picture, the presence of many peculiarities and acting factors, it is appropriate to have a greatest simplified model with the minimum number of free fitted parameters which, however, would reflect main peculiarities, in particular, a sign-change of the magnetic field. Here such a model of the heliosphere has been suggested, and its influence on high-energy cosmic rays is investigated.

The solar wind is assumed to have a radial and constant speed u_0 in magnitude which occupies a sphere of radius R around the Sun equal to 100 AU in order of magnitude. The interplanetary magnetic field has a radial component which changes a sign in the equator plane of the Sun, and its value doesn't depend on the heliolatitude ψ and longitude. The azimuth component predominate almost in the whole volume of the heliosphere is caused by the rotation of the Sun and equals to

$$H_\varphi = \mp H_0 \frac{r_0}{r} sign\psi, \qquad (1)$$

where H_0 is its value at the distance r_0, which is determined in such a way that the radial and azimuth components of the field are equal to each other. At $u_0 \approx 400$ km/s we have $r_0 = 1$ AE and $H_0 \approx 3.5 \cdot 10^{-5}$ Gs. The sign "$-$" corresponds to the

pp. 3799–3802

positive polarity of a general magnetic field of the Sun. Accordingly, a sign of the field is varied in each cycle of solar activity during the moment of its maximum.

The presence of a turbulent magnetic field superposed on the above regular field leads to the appearance of cosmic ray diffusion. The simplified diffusion model is obtained if we consider the scattering of particles to be instantaneous and isotropic and occurring with a frequency $\nu = \omega/k$, where ω is a gyrofrequency of cosmic ray particles, $k = const$ is a parameter reflecting a ratio of the regular a to turbulent field:

$$k \approx H_{reg}/H_{turb}. \tag{2}$$

The main supposition simplifying the model lies in the fact that k is assumed to be independent of the coordinates but changing only with a solar activity cycle.

In the framework of the above suppositions, the diffusion coefficient is a tensor with longitudinal, transverse and Hall coefficients [2]

$$\kappa_{\|} = \frac{vr_0}{3}\frac{p}{p_0}\frac{H_0}{H}k, \kappa_{\perp} = \frac{\kappa_{\|}}{k^2+1}, \kappa_H = \frac{\kappa_{\|}k}{k^2+1}. \tag{3}$$

Here v and p are the velocity and momentum of particles, respectively and parameter p_0 is $\frac{eH_0r_0}{c}$ (e is a charge of electron). At the above numerical values, $p_0 \approx 150$ GeV/s.

The transport equation of cosmic rays for the distribution function $f(p, \vec{r})$: $\frac{\partial f}{\partial t} = \nabla(\kappa\nabla f) - \vec{u}\nabla f + \frac{1}{3}\nabla\vec{u}p\frac{\partial f}{\partial p}$ in the case of high-energy particles is essentially simplified from the fact that their modulation depth (and correspondingly, a varied part of the distribution function) can be considered to be a small value. Therefore, we use the stationary approach linear in speed $\vec{u}$. The term with the Hall diffusion coefficient can be written in the form of convective form $\vec{u}\nabla f$, where the coefficient named as a drift speed is

$$\vec{u}_= \frac{v}{3}\frac{k^2}{k^2+1}\frac{pc}{e}rot\frac{\vec{H}}{H^2}. \tag{4}$$

Neglecting the magnetic field radial component, the substitution of the above values gives the equation for the distribution function

$$\frac{1}{2k}\nabla f - \frac{1}{k}\frac{\partial f}{\partial \lambda} + \frac{\partial f}{\partial \lambda}\delta(\psi) + \frac{\partial f}{\partial \mid \psi \mid} = b_1 \cos\psi. \tag{5}$$

Here $\lambda = lnR/r$, $b_1 = \frac{2(\gamma+2)}{3}\frac{u_0}{v}\frac{p_1}{p}f_0$, $p_1 = \frac{3}{2}\frac{k^2+1}{k^2}p_0$, $\gamma = 2.5$ is the index of cosmic ray differential spectrum, f_0 is an invariable part of distribution function. The Laplacian operator affects the variables λ, ψ as it does the Cartesian coordinates. The distribution function is an even function of ψ which has the singularity at $\psi = 0$. For $\psi > 0$ the equation is of following form

$$\frac{1}{2k}\nabla f - \frac{1}{k}\frac{\partial f}{\partial \lambda} + \frac{\partial f}{\partial \psi} = b_1 \cos\psi, \qquad (6)$$

and at $\psi = 0$ we have the following boundary condition: $\dfrac{1}{k}\dfrac{\partial f}{\partial \psi} + \dfrac{\partial f}{\partial \lambda} = 0$. At the heliopause at $\lambda = 0$ the boundary condition must reflect the behavior of electric potential in the heliosphere: $f = f_0 + b_1 \dfrac{k^2}{k^2+1}\left(-\dfrac{1}{2} + \sin\psi\right)$. At $\psi = \pi/2$, $f = (b_1/2)k^2/(k^2+1)$ and it doesn't depend on λ.

Here the equation and boundary conditions are written for the positive polarity of a general field of the Sun. The transition to the negative polarity is realized by a change of sign for k and b_1.

The solution of equation at given boundary condition critically depends on the polarity sign and correspondingly on the drift direction of particles. At positive polarity the drift is directed from high latitudes to the equator plane, and the influence of the heliopause may be neglected. In this case the solution for the varied part of function doesn't depend on λ.

At the negative polarity the particles drift into the heliosphere along the equator plane and in the direction of high latitudes. Therefore, vice versa, one can neglect the influence of high-latitude region.

In the case of small $| k |$, when both channels for the arrival of particles can give the comparable contribution, one should take the solution being a harmonic sum of the two solutions.

If we now specify the condition how the parameter k changes in time, then one can calculate the changes of cosmic ray intensity during a solar cycle.

In order not to relate the model to concrete set of experimental data we postulate simple features of the magnetic field in a solar cycle. Let the turbulent field intensity rises linearly in time from some minimum value determined through the fitted parameter k_{max}, to the maximum value during the rising phase of cycle (3,5 Years) and then it linearly falls up to the onset of next solar activity minimum. The regular component of field behaves contrariwise but in such a way that the total field remains constant. During the solar maximum the turbulent field is predominant so in this moment $k \approx 0$. In actually, the total field also changes with a solar cycle but its each component changes more significantly. So the supposition on a constancy of a total field is justified.

The calculation of modulation in the framework of the above simplified conditions for three values of k_{max} is presented in the Figure. It is assumed that the Earth is in the solar equator plane. At the bottom of the Figure the modulation picture for two sequential 22-year cycles is presented.

It is seen that 11-year cycles of modulation essentially differ from each

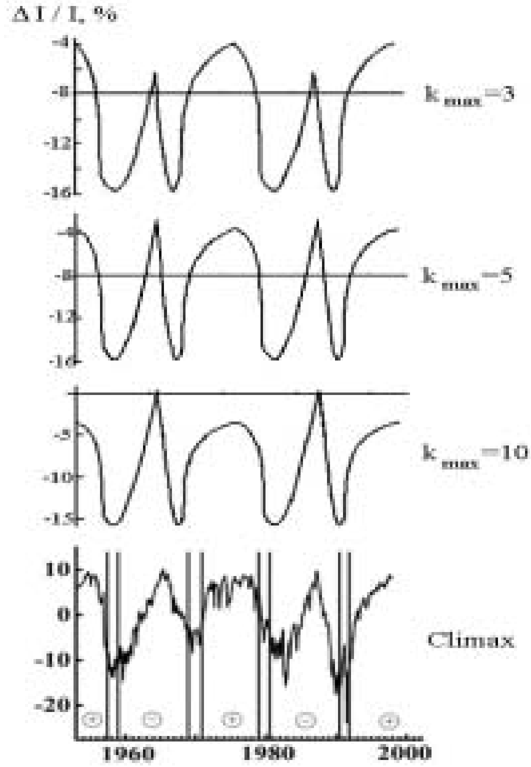

Fig. 1. Expected and observed 11-year cosmic ray variations.

other. The cycles of a sign change from "plus" to "minus" (odd cycles of solar activity) are of longer period of cosmic ray decreases (wide minimum) and the consequent recovery of intensity is more short-term (acute peak) than in the cycles following them. This difference is caused by the cosmic ray drift and it clearly seen in observation data.

Cosmic ray neutron component intensity is given in the Figure taken from [3]. These data are obtained from observations on the mountain of Climax for almost 50-year period. The comparison with the above calculations shows the general correspondence.

The work has been carried out at the support of grant of Leading Scientific School N 422.2003.2.

2. References

1. Levy E.H. J. Geophys. Res., v.81, 2082, 1976
2. Krymsky G.F., Kuzmin A.I., Krivoshapkin P.A. et al. Cosmic Rays and Solar Wind. Novosibirsk.: Nauka, 1981 (in Russian)
3. Jokipii J.R., Kota J. Proc. 25^{th} ICRC, 8, 151, 1997