The Forbush effect in the regular magnetic field

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***Abstract*. To explain the origin nature of cosmic ray Forbush-decrease with a hard energy spectrum in the solar activity minimum and in the solar activity maximum in some cases the model of piston shock which appears as a result of sharp increase of solar wind speed with a spiral magnetic field is suggested. The following parameters as the contact speed, compression degree, contact position, ratio of the magnetic field near the contact to a fuse field, maximum momentum of particles susceptible to a modulation, and modulation depth for neutron and muon components of cosmic rays have been calculated. The comparison of theoretical calculations with experimental data has been carried out.**

***Keywords*: cosmic ray, Forbush-decrease**

I. Introduction

In the works (Shafer et al.,1967; Kuzmin et al., 1968) properties of cosmic ray Forbush-decreases during periods of high and low solar activities were studied. As one would expect, during the high activity a decrease amplitude was significantly higher but contrary to the expectations the power spectrum was found to be more rigid during the period of low activity.

A qualitative explanation for such behaviour given in (Krymsky et al., 1981) connects it with the level of magnetic turbulence in the solar wind. It has been a high level of turbulence at high solar activity that has decreased the cosmic ray diffusion coefficient and consequently it leads to the rise of decrease amplitude of their intensity during magnetic storms. On the other hand, the prevalence of small spatial scales in the turbulent magnetic field leads to the fact that the effect at low energies of particles is expressed more strongly i.e. a decrease spectrum becomes soft. Disturbances in the solar wind running at low solar activity under conditions of a low level of turbulence form a main spatial scale affecting particles both of low and high energies. Ideally the spectrum of such disturbances should have a flat appearance with a cutoff at some energy.It is necessary to note that more than 50 years ago the elementary theory of such disturbances with a regular magnetic field (Dorman, 1957), where the flat spectrum of mentioned type was already created. Certainly, the theory contained some arbitrary assumptions quite natural at that time. Since in mentioned works there are indications to the fact that separate events are created by disturbances of solar wind with regular magnetic fields, the construction of more accurate theory and comparison of its conclusions with observation data is worthwhile.

II. Statement of the problem and approximation

The simpliest theory of interplanetary disturbance can be constructed if we assume that the quiet solar wind with a standard spiral magnetic field suddenly increases its speed by leaps as a result of which a piston shock appear. When considering a current in the field of low heliolatitude then one can restrict our consideration to the approach of spherical symmetry. In this case, of fundamental importance is the azimuthal magnetic field which owing to the compression creates a magnetic pressure interfering with further compression. In the indicated statement the problem has a self-similar solution in which instead of the radial distance r the variable $\eta = r/u_\phi t$ is used. Here u_ϕ is the speed of leading edge front assumed to be known. If the fast wind is not very hot, the back front will be also formed. The surface of contact , on which the wind emitted before the moment $t = 0$ with the speed u_- touches the wind emitted after this moment with the speed u_+, moves with the speed

$$u_c \approx (u_+ + u_-)/2.$$

The picture of shockwave in the first approach can be considered symmetric relatively the contact surface having the coordinate $\eta_c < 1$. So only the region of current in front of the contact at $\eta_c < \eta < 1$ will be taken into consideration. The well-known equation of kinematics for the magnetic field

$$\frac{\partial \vec{H}}{\partial t} = rot[\vec{u}\vec{H}]$$

in applying for the azimuthal component H results in the continuity equation

$$\frac{\partial H}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rHu) = 0.$$

A similar equation for density ρ differs by the Lame coefficient which becomes equal to r^2 instead of r. The adiabatic equation for the gas with the pressure p can be written in the form

$$\left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial r}\right)\frac{p}{\rho\gamma} = 0,$$

where $\gamma = 5/3$ is the adiabatic index. As to the dynamic equation, in the region $\eta_c < \eta < 1$ the current is subsonic and a good approach is a simple equality

$$\frac{\partial}{\partial r}\left(p + \frac{H^2}{8\pi}\right) = 0,$$

where derivatives from the medium speed are omited.

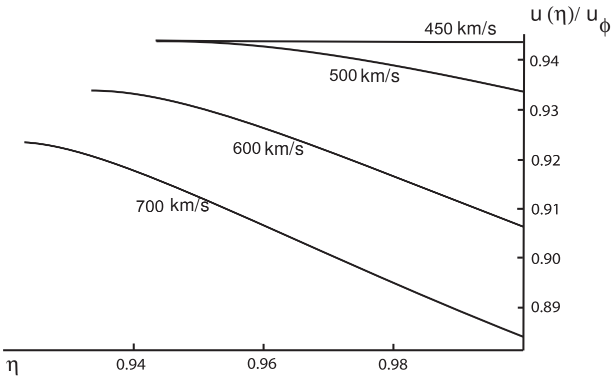

Fig. 1. Spatial distribution of the speed of gas behind the shock front. On the ordinate axis the relation of the speed of gas to the speed of front $u(\eta)/u_{\phi}$ is layed off. On the abscissa axis the relation of the radial distance to the radius of front (η) is layed off.

Since in the solar wind the medium density is proportional to r^{-2}, and the azimuthal field is $\sim r^{-1}$, then the variables with the self-similar coordinate η have the following form $H \sim H(\eta)t^{-1}$; $p \sim p(\eta)t^{-2}$; $\rho \sim \rho(\eta)t^{-2}$; $u \sim u(\eta)$.

In such formulation of the problem the task has been solved in [1].

III. Calculation results.

The profiles of speed $u(\eta)/u_{\phi}$ calculated in [1] are presented in Fig. 1. Numerical calculations have been carried out on the assumption that the speed $u_{-} = 400$ km/sec, the density ρ_0 corresponds to the concentration of protons on the Earth's orbit equal to 8 sm^{-3}, and the complete intensity of the magnetic field is $5 \cdot 10^{-5}$ Oe. The curves correspond to the contact speed $u_c = 450; 500; 600; 700$ km/sec (curves from the top down). Sets of parameters of the shock wave are presented in Table 1 for the complete intensity of the fuse field at the Earth's orbit equal to $5 \cdot 10^{-5}$ Oe . As seen from Tables the compression ratio σ in all variants is significantly less 4. The reason is not very great value of the Mach number. The contact surface is separated from the shock by less than 0.1 shock wave's radius. Correspondingly, the speed of front is little higher than the speed of contact surface.The magnetic field reaches the maximum near the contact surface. This is caused by the fact that when the shock expands, the gas pressure decreases faster than the magnetic one causing the magnetic pressure dominates near the contact surface. Here the value of the field determines the plug relation μ_{max} (the relation of the field near the contact to the fuse field). As seen from the Tables the value μ_{max} depends on the speed of contact surface.

Cosmic ray particles are subjected to the influence of averaged magnetic field whose scale of averaging depends on the particle momentum. Correspondingly, one should average the plug ratio μ_{max} on scales from 0 to $u_{\phi}t(1-\eta_k)$. For each scale L one can determine the inherent momentum $p = e\bar{H}L/c$.

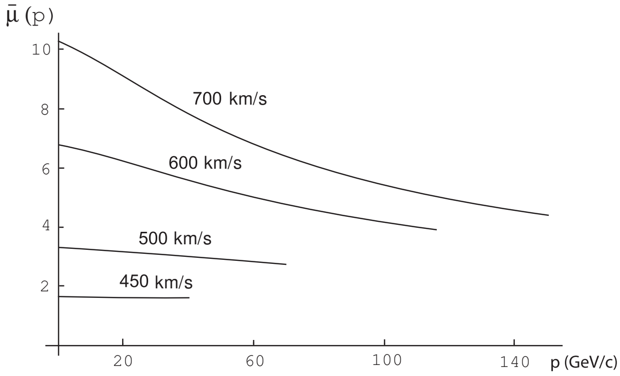

Fig. 2. Dependence of the average plug relation $\overline{\mu}(p)$ from the momentum of particles p for the magnetic field intensity H_0 on the Earth's orbit $5 \cdot 10^{-5}$ Oe.

The maximum value p_{max} corresponds to the main scale of a complete width of shock wave, i.e. to the distance between leading and back shock fronts. This value is also resulted in Table 1. Thus, the dependence of

TABLE I
Parameters of shock wave

u_c, km/s	450	500	600	700
σ	2.06	3.15	3.73	3.88
η_c	0.944	0.944	0.934	0.923
u_{ϕ}, km/s	477	529	642	758
μ_{max}	1.64	3.32	6.77	10.29
pc_{max}, GeV/c	38.3	68.7	115	149

average plug ratio depending on the particle momentum $\mu(p)$ has been found . This dependence is shown in Fig. 2. The dependence found is weak, particularly, when the speed of shock front is not so high.

IV. Decrease of cosmic rays

The shock wave can be considered as a semitransparent shell for cosmic rays which limits the internal volume where the density of cosmic rays n is lowered owing to the expansion. Through the shell only a part of flux falling on it passes which is equal to $1/\mu$. On the moving surface with the speed u the density of falling flux from each side is $nv/4 \pm nu/2$,where v is the particle velocity. So, the change of the particle number in volume limited by the shell will be

$$\frac{dN}{dt} = \frac{S}{\mu}\left[\left(\frac{n_0 v}{4} + \frac{n_0 u}{2}\right) - \left(\frac{nv}{4} - \frac{nu}{2}\right)\right].$$

Here S is the surface of shell, n_0 and n is the particle density outside and inside it.

In the steady case n does not depend on the time and $dN/dt = nSu$. Thus, we have the balance equation

$$\frac{1}{\mu}\left[\left(\frac{n_0 v}{4} + \frac{n_0 u}{2}\right) - \left(\frac{nv}{4} - \frac{nu}{2}\right)\right] = nu.$$

Let's find the depth of cosmic-ray modulation $I \equiv (n_0 - n)/n_0$, which has the following order of magnitude $u/v \ll 1$:

$$I = 4\frac{u}{v}(\mu - 1).$$

The estimation carried out does not take into account the effect of cosmic ray deceleration in the expanding trap giving the additional decrease. Let's consider the ideal trap with an impenetrable wall. Let's write the continuity equation.

$$\frac{\partial n}{\partial t} = -div(n\overrightarrow{u}) + \frac{1}{3}\frac{\partial(np)}{\partial p}div\overrightarrow{u}.$$

The last number describes the deceleration of particles. The density $n \sim p^{-q}$, where $q = 2.5$. In the ideal trap the gradient n is absent and we have

$$\frac{\partial n}{\partial t} = -\frac{q+2}{3}ndiv\overrightarrow{u}.$$

Hence it is seen that the estimated modulation depth should be increased by a factor of $(q+2)/3$. Thus,

$$I = \frac{4}{3}(q+2)\frac{u}{v}(\mu - 1).$$

To estimate the decreasing effect registered with some surface instrument, it is necessary to take into account its coupling coefficient (Krymsky et al., 2003),

$$W(p) = \frac{1}{p_0}\left(\frac{p_0}{p}\right)^{-2} e^{-p_0/p},$$

showing a fraction of cosmic rays with the momentum p, being entered into the intensity registered. The characteristic momentum p_0 for the neutron component and for the ground registration of uons is 9.4 GeV/c and 40 GeV/c, respectively. Estimating the value I, it is necessary to take the plug relation at $p = p_0$, and also to take into consideration that at $p > p_{max}$ the modulation is absent. A cutoff of the modulation gives the additional lowering multiplier which is equal to $e^{-p_0/p_{max}}$. The depth of modulation calculated with regard for aforesaid is resulted in Table 2.

TABLE II
DEPTH OF THE COSMIC RAY MODULATION BY SHOCK WAVE (IN %)

u_c, km/s		450	500	600	700
$H_0 = 5 \cdot 10^{-5}$	neutron	0.45	2.0	6.1	11.7
	muon	0.19	1.1	4.1	8.3

One can cite the comparison of these calculations with observations. Forbush-decreases occurring during periods of three minima and maxima of the solar activity for 1970-2001 by of data of the neutron monitor stations of Alert ((82° 30' N, 62° 20' W), Thule (76° 33' N, 68° 50' W)and muon station of Nagoya (35° 10' N, 136° 58' E) have been analyzed. The duration of each period was accepted to be equal to 3 years. 60 events in the solar activity maximum, and 28 events in the solar activity minimum have been selected. In the average the amplitude of Forbush-decrease in the solar activity maximum in the neutron component is 5.52%, in the muon component it is 2.09%. In the minimum of solar activity these components, on the average, have had values of 3.19% and 1.65%, respectively. The solar wind speed averaged by direct measurements (http://omniweb.gsfc.nasa.gov) in these events is 575 km/s and 520 km/s, respectively, and the wind speed before the onset of disturbance is equal to 399 km/s and 394 km/s, respectively. Reasoning from these data one can think that the speed of contact surface has constituted 575 km/s and 526 km/s. The last value has been obtained by the increase of wind speed before and after the shock front by 6 km/s so that the parameters of the model and the values observed really may coincide. The experimental results are reflected in Fig. 3. It is seen that the decreases during the solar activity minimum are satisfactorily described in the framework of the model of piston shock wave in the regular magnetic field. However, in the solar activity maximum the really observed events have the amplitude more than it is predicted by the model in the neutron component, and in the muon one - less. This can be attributed to the action of magnetic turbulence which strengthens the field on the middle scales and increases a dissipation of particles on large scales.

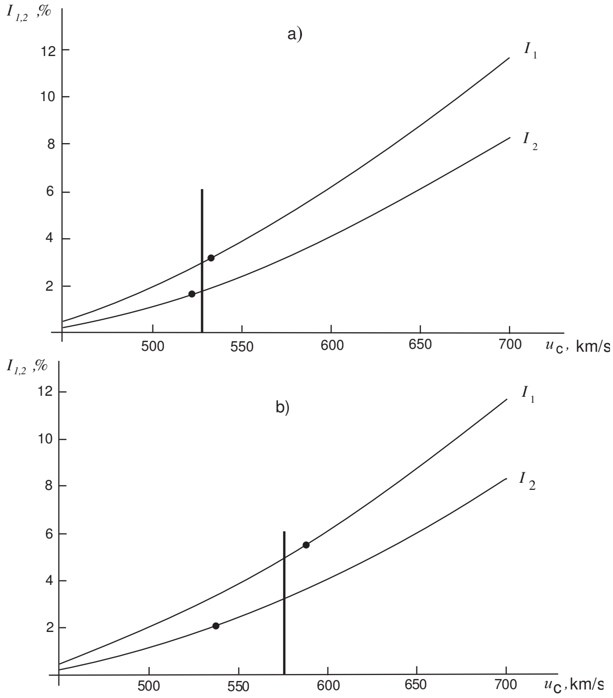

Fig. 3. Dependence of the depth of modulation of the neutron I_1 and muon I_2 components of cosmic rays on the speed of contact surface u_c of the shock wave: a) is the solar activity minimum, b) is the solar activity maximum. The points are the observed average amplitude of Forbush-decreases, the solid vertical line is the observed average speed of contact surface.

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