COSMIC RAY ACCELERATION BY STELLAR WIND. SIMULATION FOR HELIOSPHERE

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ABSTRACT

It is shown that the acceleration of the solar wind particles at the solar wind terminal shock is capable of providing the total flux, spectrum and radial gradients of the low-energy protons close to ones observed in the interplanetary space.

1. Introduction. The solar wind deceleration by the interstellar medium may result in the existence of the solar wind terminal shock [1]. In this case a certain fraction of thermal particles after being heated at the shock would obtain enough energy to be injected to the regular acceleration process [2-5]. An analytical solution for the spectrum in the frame ef a simplified model that includes particle acceleration at the shock front and adiabatic cooling inside the stellar wind cavity has been derived in [6].

A more realistic model is discussed in the present paper in order to estimate whether this process might occur the main source of the low-energy cosmic rays in the heliosphere.

2. Model. Let the solar wind velocity $u(r)$ in a steady state spherically symmetric model be equal to u_1=const at $r < R$ and $u_2(R/r)^2$ at $r > R$, where R is the solar wind terminal shock radius, $\sigma = u_1/u_2$ - the compression ratio of the shock. Cosmic ray propagation in the diffusive approximation is governed by the transport equation:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \varkappa \frac{\partial n}{\partial r}\right) - \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 u n\right) + \frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2 u\right)\frac{\partial}{\partial p}(np) = 0 \tag{1}$$

where n(r,p) is the particle number density per unit interval of momentum p, $\varkappa(r,p)$ - cosmic ray diffusion coefficient. At $r < R$ and $r > R$ (subscripts 1 and 2, respectively) it is given by

$$\varkappa_{1,2} = \mathcal{D}_{1,2}(p)\cdot(r/R)^{\beta_{1,2}}$$

The matching conditions are that the particles current and the number density should be continious at the shock. The other conditions are the absence of source or sink at r=0 ($r\cdot n(r,p) \rightarrow 0$ as $r \rightarrow 0$) and a given spectrum at infinity ($n(r,p) \rightarrow N_\infty(p)$ as $r \rightarrow \infty$).

Integrating (1) with respect to r from 0 to R-0 and using the analytical solution to (1) at $r > R$, the matching condition might be reduced to the following:

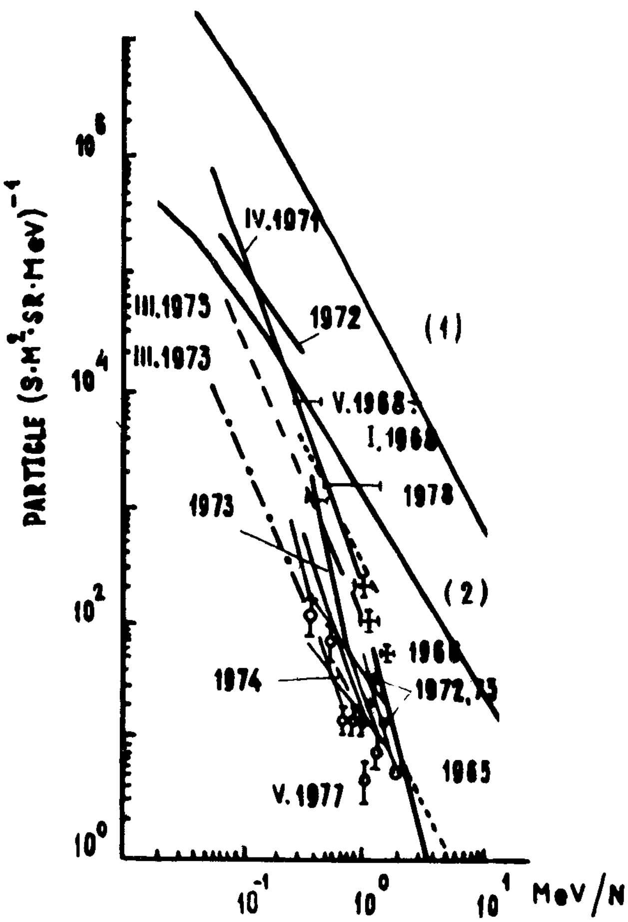
$$\frac{\sigma-1}{3\sigma}\cdot\frac{\partial}{\partial p}[p\cdot n(R,p)] + \frac{n(R,p)}{\sigma[1-\varphi(p)]} = \\ = \frac{1}{u_1 R^2}\int_0^{R-0}\frac{1}{3r^2}\frac{\partial}{\partial r}(r^2 u_1)\frac{\partial}{\partial p}[p\cdot n(r,p)]r^2 dr + \frac{\varphi(p)\,N_\infty(p)}{\sigma[1-\varphi(p)]} \qquad (2)$$

where $\varphi(p) = exp[-u_2 R/(1+\beta_2)\mathcal{D}_2(p)]$

Hence, the problem is to solve the equation (1) at $r \leqslant R$ with respect to the boundary condition (2). The equation (1) is valid at particle momentum p higher than some limiting value, say p_0. One more condition is necessary to make the system (1),(2) being completed, namely $n(R,p_o)=n_o$. This condition relates the injection rate to the spectrum amplitude $p=p_o$.

It has been shown [7-9], that the shock acceleration is efficient enough to transfer a significant fraction (~ 50%) of the inflowing plasma kinetic energy to the accelerated particles. The accelerated particles spectrum takes on the power law form with the index equal to that one given by the linear theory at particles velocity $v \simeq 3\,u_1$ [9]. The corresponding values for the solar wind particles are $T \simeq 10$ keV or $p_o \simeq 3\cdot10^{-3}\,m_p c$. Particles of energy corresponding to the cutoff velocity diffuse far upstream and suffer catastrophic adiabatic cooling.

3. Results and Discussion. The results of the numerical calculations are presented in Figure in comparison with the observational data [10]. The curve labelled "1" is the differential proton flux near the shock, "2"- that one at the orbit of the Earth. The following parameters were used: $u_1=5\cdot10^7$ cm/s, $R=7{,}5\cdot10^{14}$ cm, $\sigma=4$. The solar wind energy density near the shock E_k has been taken equal to 5 eV/cm^3. The value of n_o has been defined so, that accelerated particles ($T \gtrsim 10$ keV) contain 10% of the kinetic energy density E_k. The diffusion coefficients are $\varkappa_1=6{,}5\cdot10^{22}(p/m_pc)^{0,3}\,(r/R)^{0,2}$ cm$^2\cdot$s^{-1}, $\varkappa_2 \ll \varkappa_1$. The diffusion coefficient in the outside vicinity of the shock might be significantly reduced due to the magnetic field compression and convection of the turbulence excited by the accelerated particles. This leads to the strong modulation of the galactic proton flux at $T \lesssim 10$ MeV. Radial gradient $n^{-1}\partial n/\partial r$ takes on a value of 15%/AU at T=10 keV and 5%/AU at $T \simeq (1-10)$MeV.



The comparison of the results with the observations shows that under the above assumptions the acceleration rate (source Q_1) is capable of providing the registered intensity of the low-energy particles in the interplanetary space. In the energy range $T < 100$ KeV the solar cosmic rays might contribute significantly to the total intensity, especially during the maximum of solar activity [11]. This would cause the complicated variations of the low-energy cosmic ray intensity: in the energy range $T < 100$ KeV the intensity is correlated with the solar activity level [10]; at the energy T=6 MeV/nucl. the anticorrelation takes place [11]. The relative contribution of the source Q_1 increases with the heliocentric distance r.

The cutoff energy for the accelerated particles spectrum is determined by $\varkappa_1 (T_{max}) \simeq Ru_1$; on the other hand, $T_{max} \simeq$ 10 MeV/nucl. as is observed for different nuclear species. That shpuld be consistent with our model if $\varkappa$ is a function of T per nucleon only. The verification of this suggestion should be based on the treatment of the cosmic ray chemical composition.

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