PROCEEDINGS OF SCIENCE

Influence of region behind the shock front on acceleration of solar energetic particles

PETUKHOV, Ivan[1]
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy of SB RAS
31 Lenin ave., 677980 Yakutsk, Russia

E-mail i_van@ikfia.sbras.ru

PETUKHOVA, Anastasiya
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy of SB RAS
31 Lenin ave., 677980 Yakutsk, Russia

E-mail petukhova@ikfia.sbras.ru

PETUKHOV, Stanislav
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy of SB RAS
31 Lenin ave., 677980 Yakutsk, Russia

E-mail petukhov@ikfia.sbras.ru

Acceleration of solar energetic particles by the shock accompanying a coronal mass ejection is considered. Influence of the region behind the shock front on particle acceleration process is investigated. The external boundary of coronal mass ejection and the shock front are specified as the segments of spherical surfaces with the different radii moving in coordination. Nonstationarity of process, spherical symmetry and adiabatic losses of particle energy in the extending environment are considered in the calculation. The propagation velocity of solar wind is determined by the conservation of matter stream taking into account the known distribution of matter density. Scatterings of solar energetic particles are carried out by Alfven waves moving radially from and to the Sun. The parameters determining the coefficient of particle diffusion are chosen taking into account the available results of theoretical calculations and indirect measurements. Influence of the accelerated particles on dynamics of the system and the turbulence level of the magnetic field isn't considered. The performed numerical calculations show that the influence extent of the region behind the shock front on acceleration process is determined by a ratio between coefficients of particle diffusion in regions behind and before the front. In that case when these coefficients are comparable: 1) rate of acceleration significantly decreases; 2) the considerable part of the accelerated particles is behind the shock front.

The 34th International Cosmic Ray Conference
30 July- 6 August, 2015
The Hague, The Netherlands

[1] Speaker

1. Introduction

It was found that solar energetic particles (SEPs) in gradual events are generated at shock fronts accompanying coronal mass ejections (CMEs) in the solar atmosphere [1-3]. It is confirmed by close connection between CMEs and SEP increases in gradual events as well as the correspondence of elemental abundances and ionization states of SEP ions and the solar corona plasma, on average [1]. Diffusive shock acceleration is used as an acceleration mechanism. Numerous applications of the acceleration mechanism to conditions of the solar corona demonstrated the possibility of SEP generation with the demanded properties [4,5]. However, these works as well as a number of subsequent works [6, 7] contain considerable simplifications limiting application of their conclusions. The calculation results of SEP spectra forming by shock waves within linear and quasilinear approximations with the use of a set of realistic physical parameters of the solar corona are presented in [8,9]. The conclusion that the SEP effective acceleration ends when the shock wave reaches the radius R_s=2-4$R_\odot$ is of significance. In [8,9] it is suggested that the diffusion coefficient behind the shock front region is zero and thus influence of the region on acceleration is excluded.

The purpose of this work is to study the influence of the region behind the shock front on the process of SEP spectrum forming in linear approximation with the use of a set of realistic parameters of the solar corona.

2. Model

The CME is presented as a piston moving with a constant speed V_p. The external border of the piston has a form of a part of the sphere with the radius R_p. The shock front also has a form of a part of the sphere with the radius R_s (R_s>R_p). Speeds of the shock front V_s and the piston are related by $V_s = \frac{\sigma}{\sigma-1} V_p$, where $\sigma = 4/(1+3/M_1^2)$ is the shock compression ratio, $M_1 = V_s - w(R_s+0)/c_{s1}$ is the Mach number, $c_{s1} = \sqrt{\gamma_g k_B T_1/m}$ is the sound speed, $w(R_s+0)$ is the speed of plasma flow near the shock front, $T_1 = 1{,}2 * 10^6$ K is temperature, k_B is the Boltzmann constant, m is the proton mass, $\gamma_g = 5/3$ is the plasma polytrope index. The choice of parameters in the work is the same as in [8,9]. Therefore, the chosen parameters are briefly reviewed in the paper. The detailed argument of the choice is expounded in [8,9].

The magnetic field in the corona is radial and $B/B_0 = (R_{sun}/r)^2$, where $B_0 = 2.3$ Гс, R_{sun} is the solar radius. Particles are scattered by Alfven waves moving along magnetic field lines in opposite directions. The speed of scattering centers in relation to the environment is defined by the ratio $c_c = c_a(E_W^+ - E_W^-)/E_W$, E_W^+, E_W^- are densities of wave magnetic energy moving from and to the Sun, $E_W = E_W^+ + E_W^-$, $c_a = B/\sqrt{4\pi\rho}$ is the Alfven speed. In the region behind the shock front the propagation direction of Alfven waves is assumed to be isotropized $c_c(r<R_s) = 0$.

The diffusive transport equation for the particle distribution function *f(p,r,t)* with spherical symmetry has a form

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\kappa r^2 \frac{\partial f}{\partial r}\right) - w' \frac{\partial f}{\partial r} + \frac{p}{3r^2}\frac{\partial (r^2 w')}{\partial r}\frac{\partial f}{\partial p} + Q,$$

where κ is the radial (parallel) diffusion coefficient, p is the particle momentum, r is the heliocentric distance, $w' = w + c_c$ is the scattering centers speed, w is the speed of plasma flow, $Q = Q_0\delta(r-R_s)$ is the source of particles pointed at the shock front.

The speeds of the environment $u = V_s - w$ and scattering centers $u' = V_s - w'$ in relation to the shock front jump from the values $u_1 = V_s - w_{(R_s-0)}$ and $u_1' = V_s - w'_{(R_s+0)}$ at $r = R_s + 0$ to $u_2 = u_2' = u_1/\sigma$ at $r = R_s - 0$. The indexes 1 and 2 denote the regions before and behind the shock front respectively. The ratio between the distribution functions is derived from the diffusive transport equation for the shock front taking into account the jumps of parameters

$$(\kappa \frac{\partial f}{\partial r})_{|R_s+0} - (\kappa \frac{\partial f}{\partial r})_{|R_s-0} + Q_0 = \frac{u_1' - u_2}{3} p (\frac{\partial f}{\partial p})_{|R_s}.$$

The source of particles $Q_0 = u_1 N_{inj} \delta(p - p_{inj})/4\pi p_{inj}^2$ provides the injection of some of them into the acceleration process $\eta = N_{inj}/N_{R_s+0}$, where N_{R_s+0} is the number density of protons in the upstream plasma. The parameter η, called the injection rate, is a free parameter. As the particle momentum of the injection $p_{inj} = \lambda m c_{S2}$ is used, where λ=4, $c_{S2} = u_1 \sqrt{\gamma_g(\sigma - 1) + \sigma/M_1^2}/\sigma$ is the sound speed behind the shock front. The source of particles specifies the distribution function when the particle momentum coincides with the injection momentum

$$f(p_{inj}, R_s, t) = 3 u_1 \eta N_{R_s+0}/(4\pi(u_1' - u_2) p_{inj}^3).$$

The diffusion coefficient is defined by the expression [10]

$$\kappa = \frac{v^2 B^2}{32\pi^2 \omega_B E(k = p_B^{-1})},$$

where v is the speed of particles, $\omega_B = eB/\gamma mc$ is gyrofrequency, e is an elementary charge, γ is the Lorentz factor, $E(k) = (\delta B^2/8\pi)/d \ln k$ is the differential magnetic energy density of Alfven waves per logarithm of the wave number k. Particles are scattered by Alfven waves with the wave number coinciding with the inverse gyroradius $k = \rho_B^{-1}$.

The solar wind with the observed properties at the Earth is formed due to the energy flow of Alfven waves $F = 10^6$ erg/cm^{2}s at the corona base. The wave energy density is $W = \frac{F}{2c_{a0}} = 1.6 * 10^{-2}$ erg/cm^3 at $c_{a0} = 3.2 * 10^7$ cm/s. The wave spectrum within the range of frequencies $10^{-3} < \nu < 5 * 10^{-2}$ Hz has the form $E(\nu) \sim \nu^{-1}$ Hz. It is expected to be the Kolmogorov-like spectrum $E(\nu) \sim \nu^{-5/3}$ for frequencies $\nu > \nu_0 = 5 * 10^{-2}$ Hz. In this case the region of large frequencies has the energy $0.3W$. The wave spectrum at $\nu > \nu_0$ has the form $E(k) = E_0 (k/k_0)^{-\alpha} (r/R_\odot)^{-\delta}$, where α=2/3, $E_0 = \alpha\, 0.3W = 3.2 * 10^{-3}$ erg/cm^3, $k_0 = 2\pi\nu_0/c_{a0} = 10^{-8}$ cm^{-1}. The spatial dependence coefficient of the diffusion spectrum is a free parameter. Taking into account the assumed parameters, the diffusion coefficient is

$$\kappa = \kappa_0 \frac{\left(\frac{p}{mc}\right)^{2-\alpha}}{\sqrt{1 + \left(\frac{p}{mc}\right)^2}} (\frac{r}{R_\odot})^{\delta - 2(1+\alpha)}, \text{ where } \kappa_0 = \frac{c^3 B_0 m \left(\frac{p_0}{mc}\right)^{\frac{2}{3}}}{32\pi^2 e E_0} = 3.73 * 10^{18} \text{ cm}^2/\text{s at } \alpha = 2/3, \frac{p_0}{mc} = \frac{eB_0}{\kappa_0 m c^2} \approx 73.$$

The diffusion coefficient is used for the region before the shock front in the calculation. For the region behind the shock front $\kappa_2(r < R_s) = \beta \kappa_0 \left(\frac{p}{mc}\right)^{2-\alpha} / \sqrt{1 + \left(\frac{p}{mc}\right)^2}$ is used, where β is a numerical factor. The solar wind flow speed is calculated from the continuity equation of plasma flow $w_1 = w_0 (R_{sun}/r)^2 (n_{sun}/n)$, where $w_0 = 0.52$ km/s, n/n_{sun} is the empirical expression of relative proton number density in the solar wind [11], $n_{sun} = 2.5 * 10^8$ protons/cm^3.

The speed of plasma flow in the region behind the shock front is specified as $w_2(r) = w_{2*} + (V_p - w_{2*})(R_s - r)(R_s - R_p)$, where $w_{2*} = V_s(\sigma - 1)/\sigma + w_{(R_s+0)}/\sigma$.

3. Results and Discussion

The defined task was solved by the numerical method. The results presented in the Figures are calculated for the case: at the initial time $R_{p0} = 1R_{sun}$, $R_{s0} = 1.1R_{sun}$; the ejection speed is constant and equals 1000 km/s; $\eta=10^{-4}$, $\delta=5$, $\beta=1$.

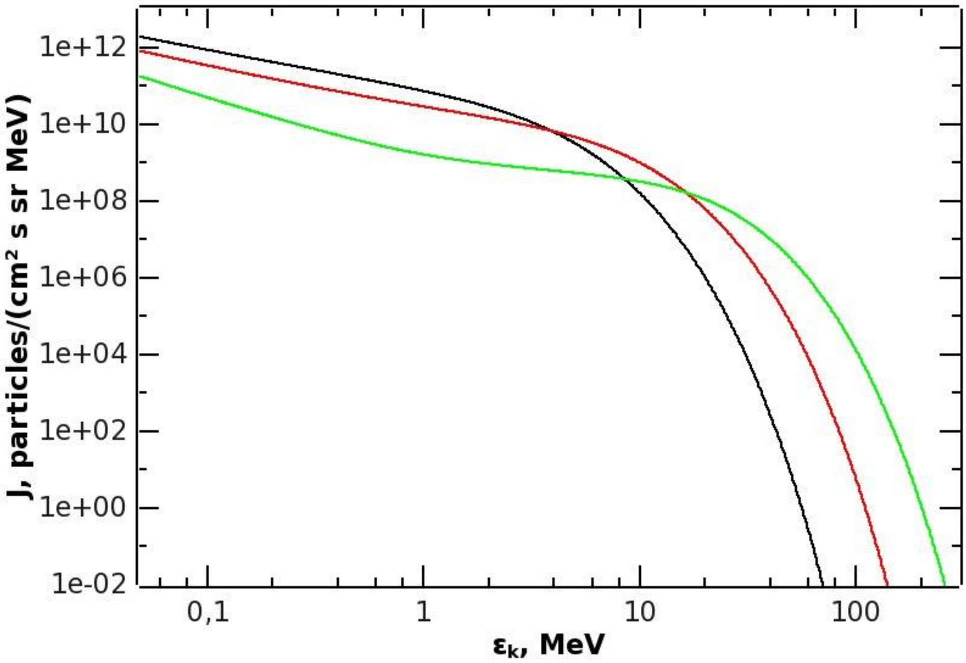

Figure 1. Intensity of the accelerated particles by the kinetic energy. Black line $R_s/R_{sun} = 1.3$; red one $R_s/R_{sun} = 1.5$; and green one $R_s/R_{sun} = 2$.

Figure 1 shows the intensity of the accelerated particles at the shock front $J(\varepsilon_\kappa) = p^2 f(p, R_s, t)$ in relation to the kinetic energy ε_κ for three radius values of the shock front: $R_s/R_{sun} = 1.3; 1.5; 2$. The power region of the spectrum is formed within the range of the energy $\varepsilon_{inj} < \varepsilon_\kappa < \varepsilon_{max}$ and its power increases from 1.1 to 1.4. The parameter increase is caused by the growth of the Alfven Much number. The value ε_{max} increases with the shock propagation like in the case of the flat shock front. The region of exponential decrease filled up by high energy SEPs joins the power region of the spectrum. When the radius value of the shock front reaches the distance $2R_{sun}$, the acceleration stops and $\varepsilon_{max} \approx 20$ MeV. The value ε_{max} is determined by the product of the speed and the size of the shock front, and the diffusion coefficient. Figure 2 shows the quantity of all accelerated particles $\frac{dN}{d\varepsilon_\kappa} = \frac{4\pi p^2}{v} \int_V f(p, R_s, t)\, dV$ by kinetic energy per unit of the solid angle for $R_s/R_{sun} = 2$. Lines denote the quantity of particles before (red) and behind (green) the shock front and, consequently, their sum which coincides with the black line. Distribution of the accelerated particles by regions depends on their energy.

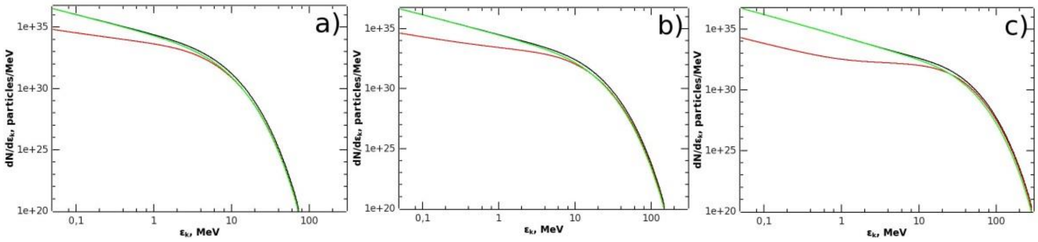

Figure 2. Spektr of all accelerated particles by kinetic energy before (red line) and behind (green line), their sum which coincides with the black line the shock front for three values of shock radius: a) $R_s/R_{sun} = 1.3$; b) $R_s/R_{sun} = 1.5$; and c) $R_s/R_{sun} = 2$.

Most particles within the range $\varepsilon_{inj} < \varepsilon_\kappa < 20$ MeV are located behind the shock front. Thus, the ratio depends on energy: the ratio is 100 times within the range $\varepsilon_{inj} < \varepsilon_\kappa < 1$ MeV, the difference decreases within the range $\varepsilon_{inj} < \varepsilon_\kappa < 20$ MeV. More particles are located before the shock front with a small difference at $\varepsilon_\kappa > 20$ MeV. The spatial particle distribution with the energy near ε_{inj} (3a) and the 20 times higher energy for the three values R_s is illustrated in Figure 3a.

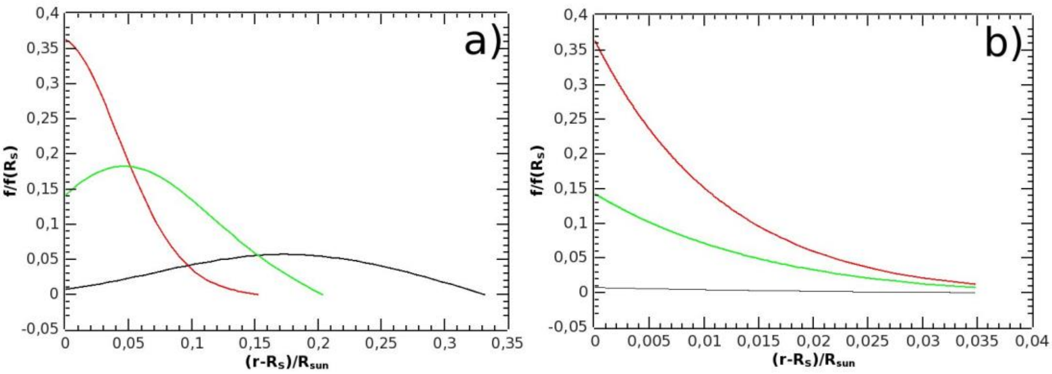

Figure 3. Spatial distribution of accelerated particles for three values of shock radius before (b) and behind (a) the shock front.

The spatial distribution demonstrates temporary dynamics of the particle spectrum with these energies at the shock front. Diffusion of particles in the region behind of the shock front insignificantly influences the distribution as shown. Figure 3b represents similar spatial distributions in the region before the shock front. The ellipses correspond to spatial particle distributions for the flat shock front. The distributions differ insignificantly as shown. Figure 4 illustrates the differential intensity of the accelerated particles at the shock front depending on kinetic energy for the two values radius $R_s/R_{Sun} = 1.44; 1.86$; and the set of values β=1; 0.1; 0.01; 0. The addition of the region behind the shock front reduces the rate of acceleration, shown in the Figure.

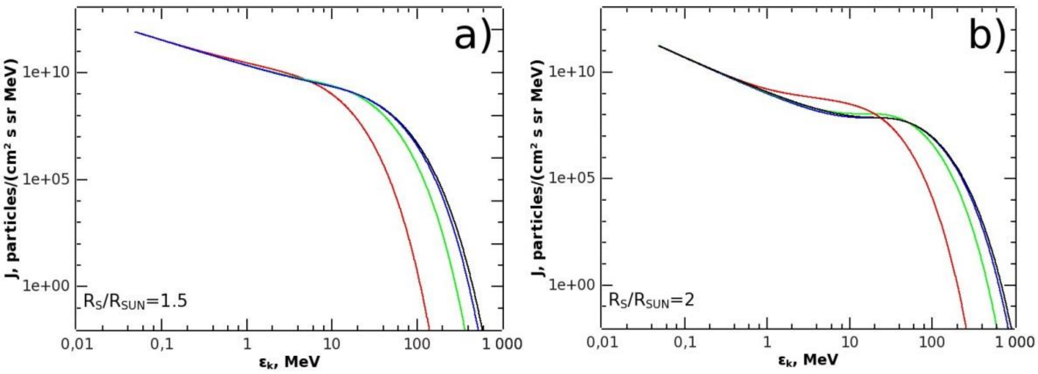

Figure 4. Intensity of the accelerated particles by kinetic energy for two values of shock radius for different values of β: $\beta = 1$ (red line); $\beta = 0.1$ (green line); $\beta = 0.01$ (blue line); and $\beta = 0$ (black line).

Thus, the more the diffusion coefficient in this region, the stronger decrease. The spectrum form in the region of the decrease insignificantly depends on the value β at the end of acceleration process. The higher the value β, the longer the spectrum would form in time. The part of the harder spectrum seen within 1-10 MeV is attribed by the region behind the shock front: the more the value β, the harder the spectrum. The comparison of lines 3 and 4 shows that the region behind the shock front doesn't influence particle acceleration at $\beta \leq 10^{-2}$.

Acknowledgments

This work was supported by the Russian Science Foundation, project no. 14-12-00760.

References

[1] Reames D.V. *Particle acceleration at the Sun and in the Heliosphere*, Space Sci. Rev., **90**, 413 (1999).

[2] Lee M.A. *Coupled hydromagnetic wave excitation and ion acceleration at an evolving coronal/interplanetary shock*, Astrophys. J. Suppl. Ser. **158**, 38 (2005).

[3] Miroshnichenko L.I., *Solar Cosmic Rays*. Dordrecht: Kluwer Acad. Publ., (2001).

[4] Ellison D.C. and R. Ramaty, *Shock acceleration of electrons and ions in solar flares*, Astrophys. J. **298**, 400 (1985).

[5] Lee M.A. and J.M. Ryan, *Time-dependent coronal shock acceleration of energetic solar flare particles*, Astrophys. J. **303**, 829 (1986).

[6] Zank G.P., G. Li, V. Florinski et al., *Particle acceleration at perpendicular shock waves: Model and observations*, J. Geophys. Res. **111**, A06108 (2006).

[7] Ng C.K. and D.V. Reames, *Shock Acceleration of Solar Energetic Protons: The First 10 Minutes*, Astrophys. J. **686**, L123 (2008).

[8] Berezhko, E. G. and S. N. Taneev, *Shock Acceleration of Solar Cosmic Rays*, Astron. Lett., **29**, 530-542 (2003)

[9] E. G. Berezhko, S. N. Taneev, *Shock acceleration of solar cosmic rays*, Astron. Lett., **39**, 393-403 (2013)

[10] Lee M.A., *Coupled hydromagnetic wave excitation and ion acceleration upstream of the Earth's bow shock*, J. Geophys. Res. **87**, 5063 (1982).

[11] Sittler E.C., jr. and M. Guhathakurta, *Semiempirical Two-dimensional Magnetohydrodynamic Model of the Solar Corona and Interplanetary Medium*, Astrophys. J., **523**, 812 (1999).