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Ion acceleration and Alfvén wave excitation at interplanetary shocks

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Abstract: The selfconsistent theory of ion diffusive shock acceleration and the associated generation of Alfvén waves are presented. The wave intensity satisfies a wave kinetic equation and the ion distribution function satisfies the diffusive transport equation. These quasilinear non-stationary equations are solved numerically for a given speed of the shock, traveling through the inner heliosphere. It is shown, that calculated spectrum of accelerated particles fit the existing measurements in a satisfactory way.

Introduction

Numerous measurements accomplished in interplanetary space demonstrate that intensive acceleration processes take place in the vicinity of interplanetary shock fronts. Some aspects of energetic particle generation and the associated generation of Alfvén waves can be understand in the frame of simplified plane-wave approach of the diffusive shock acceleration theory [1].

At the same time the geometrical factors (finite, increase shock size, adiabatic cooling in the expanding solar wind) essentially influences the acceleration [2]. These factors determine the maximum energy of accelerated particles and its evolution during the shock propagation.

In our previous papers [2, 3]) we developed quasilinear theory of particle acceleration by interplanetary shocks based on the numerical solution of corresponding equations. It was shown for the case of the Earth's bow shock that the time evolution of accelerated particle spectra and selfconsistent spectra of Alfvén waves are sensitive to the employed form of the Alfvén wave grows rate (compare results [4] and [5]).

In this paper we adopt here Alfvén wave grows rate according to Gordon et al. [6], which differs from that one derived by Lee [1] and used in our previous study [2]. It is demonstrated, that calculated particle spectra in a satisfactory way fit the existed measurements [7].

Model

The front of the interplanetary shock, created during the solar flare, has a complicated nonspherical form. One can expect that the most effective acceleration takes place at the front part of the shock, where the shock velocity is the highest and the interplanetary magnetic field (IMF) has a small angle with the shock normal in the inner heliosphere ($r \leq 1$ AU). This part of the shock will be considered as a part of the sphere of radius R_s which increases in time with the constant speed $V_s = dR_s/dt$. We assume that IMF $\mathbf{B}$ as well as the solar wind speed $\mathbf{w}$ is of the radial direction. As far as the transverse size of the acceleration region $L_\perp$ is large enough ($L_\perp \sim R_s$), and fast particles are strongly magnetized ($\kappa_\parallel \gg \kappa_\perp$), the spherical approximation can be used. In this case, the diffusive transport equation for the particle distribution function $f(r, v, t)$ has a form

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\kappa_\parallel r^2 \frac{\partial f}{\partial r}\right) - w\frac{\partial f}{\partial r} + \frac{2w}{3r}v\frac{\partial f}{\partial v} - \frac{f}{\tau_\perp}, \quad (1)$$

where $\kappa_\parallel(\kappa_\perp)$ is the parallel (perpendicular) diffusion coefficient and v is the particle velocity. The last term in the Eq. (1) effectively describes particle leakage from the acceleration region due to the diffusion across the IMF lines with the mean time $\tau_\perp = L_\perp^2/\kappa_\perp$.

We neglected the shock modification by the pressure of accelerated particles. Therefore the shock front is treated as discontinuity at which the medium speed relative to the shock front $u = V_s - w$ undergo a jump from the value u_1 at $r = R_s + 0$ to $u_2 = u_1/\sigma$ at $r = R_s - 0$, where $\sigma = 4[1 + (3/M_e^2)(r_e/R_s)^{2(\gamma-1)}]^{-1}$ is the shock compression ratio, $M = u_1/c_{s1}$ is the Mach number, c_s is the sound speed, γ is the specific heat ratio, the subscript e corresponds to the heliocentric distance $r = r_e = 1$ AU.

At the shock front the distribution function fulfills the boundary condition

$$\frac{u_1 - u_2}{3} v \frac{\partial f}{\partial v} = \left(\kappa_\| \frac{\partial f}{\partial r}\right)_1 - \left(\kappa_\| \frac{\partial f}{\partial r}\right)_2 + Q_0, \tag{2}$$

where

$$Q_0 = \left[u_1 N_{inj}/(4\pi v_{inj}^2)\right] \delta(v - v_{inj}) H(t - t_0) \tag{3}$$

is the source term, which provides the injection of some part $\eta = N_{inj}/N_1$ of medium particles N_1 into the acceleration process; $v_{inj} = 4c_{s2}$ is the velocity of injected particles. We assume that the acceleration process starts at some distance $r = r_0 = V_s t_0 \ll r_e$. As in the previous papers [1, 2] we assume high level of turbulence behind the shock, that provides $\kappa_\|(r < R_s) \ll \kappa_\|(r > R_s)$ and make it possible to neglect the second term in the Eq. (2).

The diffusion coefficients are determined by the relations

$$\kappa_\| = \frac{v^2 B^2}{32\pi^2 \omega_B E\left(k = \rho_B^{-1}\right)}, \qquad \kappa_\| \kappa_\perp = \frac{\rho_B^2 v^2}{3}, \tag{4}$$

where $\rho_B = v/\omega_B$ is gyroradius, $\omega_B = eB/mc$ is the gyrofrequency, m and e are mass and charge of proton, c is the speed of light, $E(k) = d(\delta B^2/8\pi)/d\ln k$ is the energy density of Alfvén waves per logarithm of the wave number k. The wave spectrum $E = E^+ + E^-$ includes the spectra of waves propagating in opposite directions, from (E^+) and towards (E^-) the Sun.

The background Alfvén wave spectrum $E_0^\pm(r,k) = E^\pm(r,k,t = t_0)$ is modified due to the wave excitation by accelerated particles. We describe the wave dynamics within the plane-wave approach:

$$\frac{\partial E^\pm}{\partial t} + u \frac{\partial E^\pm}{\partial x} = \pm \Gamma E^\pm, \tag{5}$$

where the wave grows rate is determined by the expression [6]

$$\Gamma(k) = -\frac{32\pi^3 c_a e^2 \kappa_\|(v = \omega_B/k)}{kmc^2 v^2} \times \times \int_{v_{\min}}^{\infty} dv v^3 \left(1 - \frac{\omega_B^2}{k^2 v^2}\right) \frac{\partial f}{\partial r} \tag{6}$$

$v_{\min} = \max(v_{inj}, \omega_B/k)$, c_a is the Alfvén speed, $x = R_s - r$. Eq. (5) is solved under the boundary condition $E^\pm(x = \infty, t) = E_0^\pm(r = R_s)$.

Note that wave growth rate (6) is by a factor of 8/3 larger than that one derived by Lee [1]. In addition the particle diffusion coefficient $\kappa_\|(v)$ previously [1, 2] was under the integral. Eq.(1)-(6) are solved numerically starting from the initial condition $f(r, v, t = t_0) = 0$.

Results and discussion

The strength of radially-directed IMF has a radial dependence $B = B_e(r_e/r)^2$, where $r_e = 1$ AU. The solar wind proton number density is described by the same kind of dependence $N = N_e(r_e/r)^2$. We take the background Alfvén wave energy density in the form, typical for the solar wind:

$$E_0^\pm(r,k) = E_{0e}^\pm (k/k_0)^{-\beta} (r/r_e)^{-\delta}, \tag{7}$$

where $k_0 = \omega_{Be}/v_{inj}$. We use typical values $\beta = 0.5$ and $\delta = 4$.

We studied the formation of particle and wave spectra, produced by the typical interplanetary shock [3]. Here we use our model in order to compare calculated spectrum of accelerated protons with the existing experimental data.

In order to compare calculations with measurements, performed by Gosling et al. [7], we use the set of relevant parameter values, which corresponds to the observation: $N_e = 8$ cm^{-3} and $\sigma_e = 2.6$ according to [7] and $w = 320$ km/s, $V_s = 474$ km/s and $B_e = 5 \times 10^{-5}$ G according to [8], $M_e = 2.4$ and $\gamma = 1.2$. In the considered case proton injection energy is $\varepsilon_{inj} = 1.2$ keV, and the injection rate $\eta = 10^{-3}$ is needed to fit the data. We also take into account the acceleration of α-particles assuming that the solar wind plasma contains 5% of α-particles relative to protons.

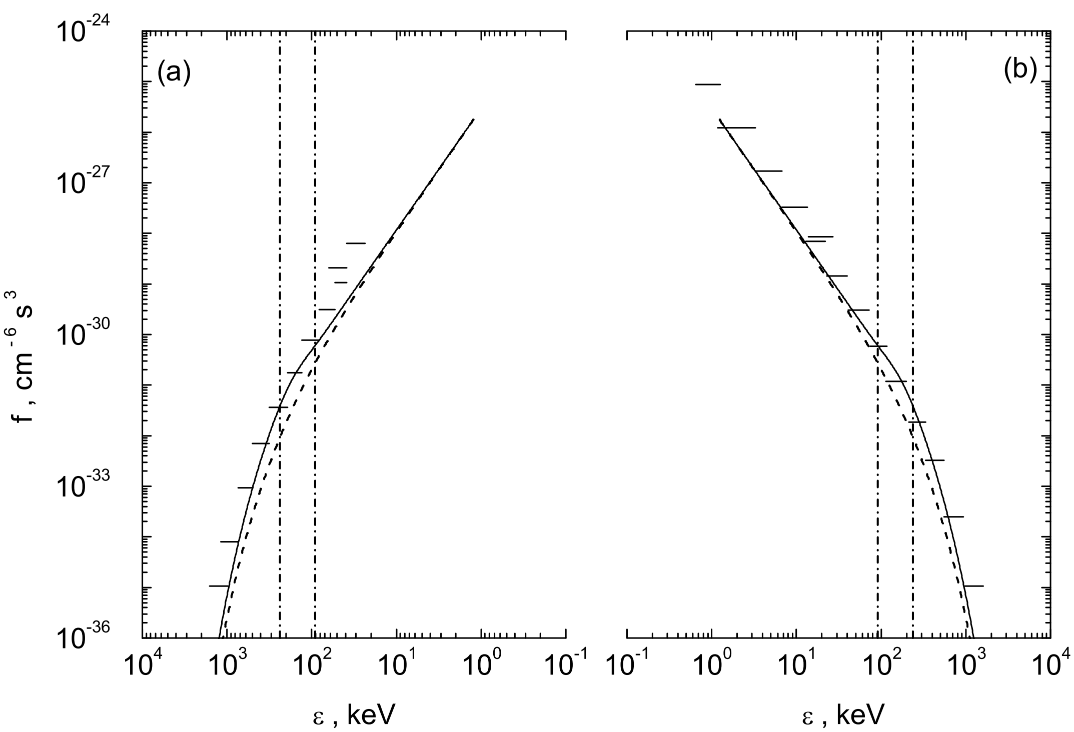

Figure 1: Distribution function of accelerated protons as a function of their kinetic energy separately for protons moving toward the Sun (a) and away from the Sun (b). Experimental data, obtained on August 26-27, 1978 by ISEE 3 [7] are shown as well.

Following Horbury [9] we assume equal number of Alfvén waves propagating in two opposite directions, from and towards the Sun, $E_0^+ = E_0^-$. The value $E_{0e}(k_0) = E_{0e}^+(k_0) + E_{0e}^-(k_0) = 1.1 \times 10^{-13}$ erg/cm^3 is needed to fit the observation.

In Fig.1 and 2 the calculated proton distribution function and the flux $I = \int_{\varepsilon_1}^{\varepsilon_2} d\varepsilon J(\varepsilon)$ of protons with kinetic energies within the interval from $\varepsilon_1 = 91$ to $\varepsilon_2 = 237$ keV are compared with the experimental data Gosling et al. [7].

One can see in Fig.1 that calculations well reproduce the experimental data.

The same calculation has been also performed within the linear approach, where compared with the previous case the increase of Alfvén wave turbulence due to accelerated particles, is ignored. The results are shown in Fig.1 and 2 by the dashed lines. One can see, that intensity of accelerated particles with energies $\varepsilon = 10 - 10^3$ keV calculated in the quasi-linear approach, noticeably higher than in the linear case. This provide the better agreement with the experiment. In Fig.3 we present Alfvén wave spectra $E(\nu) = E(k = 2\pi\nu/w)/\nu$ (here $\nu = kw/(2\pi)$ is the wave frequency, measured by the stationary observer), calculated for six different distances from the shock for the time moment 2 UT of August 27, 1978. It is seen that at $\nu > 0.004$ Hz selfconsistent spectrum near the shock front considerably exceeds the background level.

We conclude that theory of particle acceleration by interplanetary shocks based on the quasi-linear approach fairly well fits the observations.

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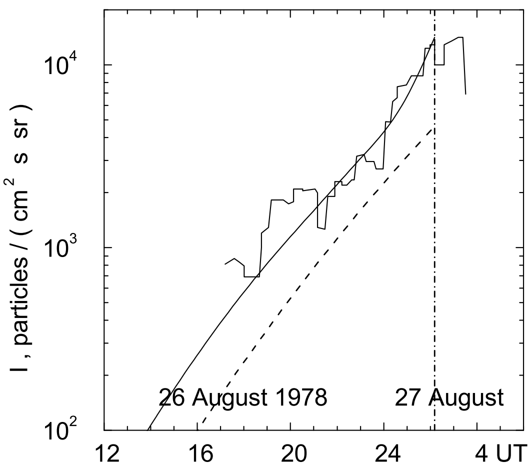

Figure 2: The flux of protons with energies between $\varepsilon_1 = 91$ and $\varepsilon_2 = 237$ keV as a function of time compared with the experiment [7].

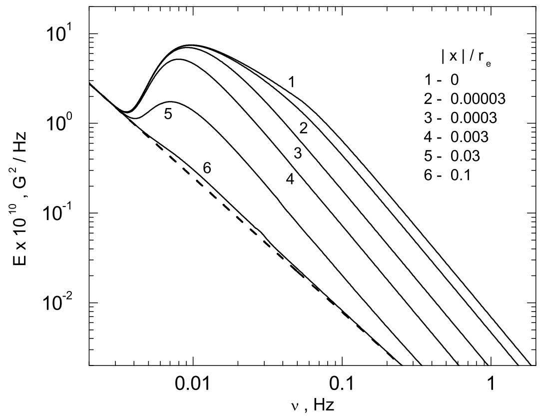

Figure 3: Alfvén wave spectra, calculated for six different distances upstream from the shock for the time moment 2 UT of August 27, 1978.

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