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Ion acceleration by shock surfing

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Collisionless shocks in space conditions are a source of energetic particles. The particles having low velocity along the normal to the surface of the shock front can be multiply reflected from the electric cross potential of a quasiperpendicular shock wave and be accelerated by shock surfing. Shock surfing can provide pre-acceleration of particles for subsequent diffusive shock acceleration. The research of shock surfing is of interest for calculation of injection and element composition of the accelerated particles.

The calculation method of distribution function of the accelerated particles by shock surfing is presented in that case, when the characteristics of the shock front (the cross-shock electric field strength and the width of the shock front) are specified. The calculation results of particle spectra before and behind the shock front depending on initial parameters are shown.

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[1] Speaker

1. Introduction

Shock waves are generated in cosmic events with a great energy release or the interaction of a rapid flux with the environment. Observations show that the shock waves are a source of energetic particles. By far the mechanism of diffusive shock acceleration (regular mechanism, first-order Fermi shock acceleration) [1-3] is the main process for producing the energetic particles. During the acceleration, a particle crosses many times the shock front. However, a particle quantity injected into the acceleration process is a free parameter [4]. In drift shock acceleration, particles can gain just low energies [5]. The acceleration occurs because of their shift along the electric field appearing in magnetized moving plasma. The cause of a shift along the electric field is a magnetic field change at the shock front. The existence of a cross-shock electric field at the shock front gives a new possibility for particle acceleration – surfing acceleration (Multiply Reflected Ions) [6,7]. It is suggested that shock surfing produces the particle injection into an acceleration process [6-8]. Therefore, the research of shock surfing is of interest for a wide class of problems related, in particular, to collisionless shock waves.

Taking into account the shock front structure, the particle spectrum is calculated at a test particle level by analytic [6,7] and numerical [8] studies.

In this paper, the calculation method of the particle distribution function is presented at a test particle level.

2. Model

The calculation method of shock surfing is considered for nonrelativistic ion (proton) acceleration at the perpendicular shock front. Figure 1 shows the coordinate system and the scheme of plasma flow.

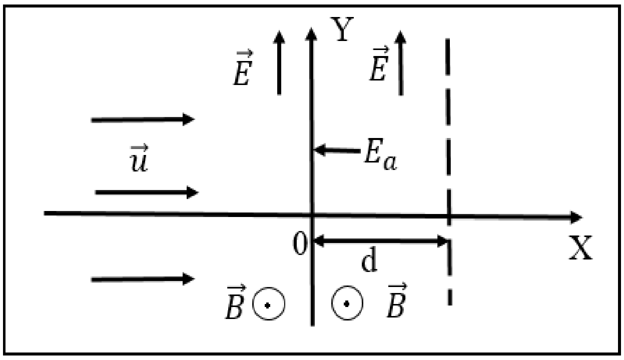

Figure 1: The scheme of plasma flow and the coordinate system.

The initial plasma parameters are: the flow speed $\vec{u} = -\vec{\imath}\,u$, the magnetic field strength $\vec{B} = \vec{k}\,B$, the motional electric field $\vec{E} = \vec{\jmath}uB/c$. The subscript 1 in u_1, B_1 denotes the upstream region ($x<0$) of the shock. Parameters changes in the shock front (the shock ramp, $0 \le x \le d$): $u/u_1 = 1 + (1/\sigma - 1)x/d$, $B/B_1 = 1(\sigma - 1)x/d$. Here $d = \alpha c/\omega_{pe}$ is the shock ramp width, c is the speed of light, c/ω_{pe} is the electron inertial length, α is a numerical coefficient, $\sigma = 4/(1 + 3/M^2)$ is the shock compression ratio, $M = u_1/c_s$ is the Mach number, $c_s = \sqrt{\gamma_g \kappa_B T_1/m}$ is the sound speed, $\gamma_g = 5/3$ is an effective adiabatic constant, κ_B is the Boltzmann constant, T_1 is temperature, m is the proton mass.

The electrostatic cross shock potential is $\varphi = \varphi_a x/d$. The corresponding electric field is $\overrightarrow{E_a} = \vec{\imath}E_a$, where $E_a = -d\varphi/dx = -\varphi_a/d$. The value is specified from $e\varphi_a = eE_a d = \eta m u^2/2$, where $0 \leq \eta \leq 1$; e is the elementary charge. It is supposed that particles coming as a stream to the shock front are described by the Maxwellian distribution $f_{v_0} = (1/\pi^{3/2}v_s^3)\exp(-(\vec{v} - \overrightarrow{u_1})^2/v_s^2)$, where v is the particle speed, $v_s = \sqrt{2\kappa_B T/m}$ is the speed of thermal plasma, T is temperature.

The calculation method is based on the Liouville theorem: the distribution function persists along particle trajectories in the electromagnetic field. This follows from the Boltzmann equation for collisionless plasma $df/dt = \partial f/\partial t + \vec{v}\partial f/\partial\vec{r} + e\big(\vec{E} + (\vec{v} \times \vec{B})/c\big)\partial f/\partial\vec{v} = 0$, where particle trajectories are characteristics of the equation system $d\vec{r}/dt = \vec{v}$, $d\vec{v}/dt = (e/m)(\vec{E} + (\vec{v} \times \vec{B})/c)$.

Straight and back trajectories are used for the calculation of distribution function [9]. The straight (back) trajectories start (end) in the source, i.e. where the distribution function is specified. The main distinction of the straight and the back trajectories consists in the sign of a time step for the solution of the equation system. The step is plus for the straight trajectories and it is minus for the back ones. The system is solved by the Runge-Kutta numerical method of the accuracy fourth order.

3. Results and Discussion

For the calculation, the characteristics of solar wind at the Earth's orbit are used: $u_1 = 4 * 10^7$ cm/s, $B_1 = 5 * 10^{-5}$ G, $T_1 = 10^5$K, $n_e = n_i = 7$ particles/cm^3. The system of moving equations in coordinate and dimensionless form is $dv_x/dt = -E_p + v_y B_z$, $dv_y/dt = u_x B_z - v_x B_z$, $dv_z/dt = 0$, $dx/dt = v_x$, $dy/dt = v_y$, $dz/dt = v_z$. Here $E_p = 0, B_z = 1, u_x B_z = 1$ at $x<0$ and $E_p = E_a c/u_1 B_1$, $B_z = B/B_1$, $u_x B_z = uB/u_1 B_1$ at $0 \leq x \leq d$. The values are used as scales of: speed u_1, time ${\omega_{ci}}^{-1}$, distance u_1/ω_{ci}, where ω_{ci} is the proton gyrofrequency.

Particles after their interaction with the shock front are classified into two groups: 1) passed particles are particles passing the shock front the first time; 2) trapped particles are particles passing the shock front after one or few reflections.

Figure 2 presents the differential particle flow at the region of the downstream (for $\alpha = 1$, $\eta = 0.9$) $J(\varepsilon_\kappa) = (2/m^2)\varepsilon_\kappa \int_\Omega f_v(v, \Omega')cos\theta\, d\Omega'$, where θ is the angle between the particle speed vector and the axis X, Ω is the solid angle, ε is kinetic energy. The initial parameters for the back trajectories are $x=d$ and $v_x > 0$. Speed directions are specified by the solid angle. In the calculation the solid angle Ω = 2π (for $v_x > 0$) is divided into 3308 elements. The trajectory calculation stops when a particle trajectory comes to the source (the downstream). After the shock front about 21% of the upstream flow are trapped particles and 79% are passed ones. The energies of passed particles are less 400 eV. The spectrum has a form of delta-like function. The energies of trapped particles are within 3-4 KeV. This result doesn't correspond with [6,8] where the trapped and passed particle energies locate near.

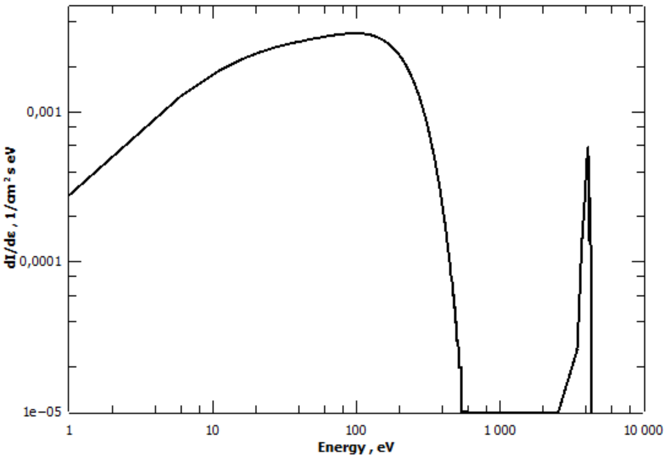

Figure 2: The differential particle flow at the region of the downstream.

Figure 3 shows the differential particle spectrum at the region of the downstream $dn/d\varepsilon_\kappa = \sqrt{2\varepsilon_\kappa/m^3}\int_\Omega f_v d\Omega'$.

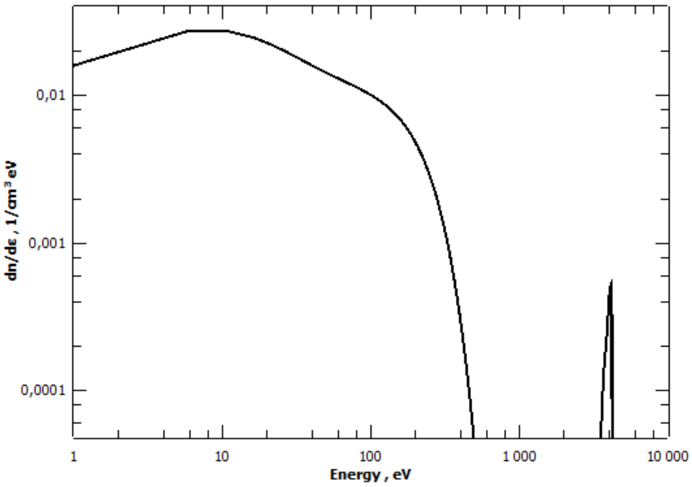

Figure 3: The differential particle spectrum at the region of the downstream.

The efficiency of shock surfing depends on the value η. The trapped particle flow is about 5% of the upstream flow at $\eta = 0.8$, and it is 47% at $\eta = 1$. There are no changes within $1 \leq \alpha \leq 5$.

4. Summary

1. The calculation method of the distribution function of particles accelerated shock surfing is suggested;
2. The ratio between passed and trapped particles depends on the value η: the less the value, the fewer trapped particles;
3. The spectra for two particle groups are determined. It is revealed that trapped particles gain energy about 3-4 KeV and are separated from passed particles by energy.

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