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PROPAGATION OF ELECTRON BEAMS IN SOLAR CORONAL LOOPS

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It is shown that electron beams propagate into coronal loops as accelerated beam-plasma structures. Definitions of electric fields in loops from observed asymmetry of X-ray emission generated by fast electron beams as well as plasma temperature from electron beam velocity are proposed.

It is thought [3] that energy is released during solar flare in the cusp of coronal loops. High energy electrons accelerated in the flare propagate through plasma in the form of simple beams [2]. It is known that under such conditions beam instability occurs and the Langmuir waves are generated. In turn these waves influence electron dynamics.

In recent papers [4, 6, 8] it was shown that for quasilinear approximation electrons propagate as a nonlinear object of beam-plasma structure, consisting of electrons and the Langmuir waves. The velocity of the structure is constant and equals half maximum of electron velocity determined by electron distribution function for plateau in velocity space. Formation of this soliton-like object takes place because of generation and absorption of the Langmuir waves, correspondingly, at front and back of the structure.

The presence of electric fields in the coronal loops must be taken into account in analysis of quasilinear propagation of electrons. In 1967 Ryutov [9] considered the problem, in which he studied plateau formation at electron distribution function in an external electric field. However, it can be shown that for solar conditions quasilinear relaxation is a fast process and electron movement in electric field is a slow one. So, we suppose that the plateau of the electron distribution function is instantly

$$f(v, x, t) = \begin{cases} p(x, t), & v < u(x, t), \\ 0, & v > u(x, t), \end{cases}$$

established at every point and height $p(x, t)$ and maximum velocity $u(x, t)$ is changing slowly under electric field. The spectral energy density of the Langmuir waves is generated in the form

$$W(v, x, t) = \begin{cases} W_0(v, x, t), & v < u(x, t), \\ 0, & v > u(x, t). \end{cases}$$

For functions $p(x, t)$, $u(x, t)$, and $W_0(v, x, t)$ the gas-dynamic equations

$$\frac{\partial p}{\partial t} + \frac{u}{2}\frac{\partial p}{\partial x} = 0,$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} - \gamma = 0,$$

$$\frac{\partial}{\partial v}\frac{1}{v^3}\frac{\partial W_0}{\partial t} = \frac{m}{\omega_{pe}}\left(\frac{\partial p}{\partial t} + v\frac{\partial p}{\partial x}\right)$$

with boundary conditions

$$\frac{\partial W_0}{\partial t} = 0, \qquad v = u, \qquad \frac{\partial u}{\partial t} W_0 = 0, \qquad v = u$$

are derived from the quasilinear equations

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} + \frac{eE}{m}\frac{\partial f}{\partial v} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v}\frac{W}{v}\frac{\partial f}{\partial v},$$

$$\frac{\partial W}{\partial t} = \frac{\pi\omega_{\text{pe}}}{n}v^2 W\frac{\partial f}{\partial v}, \omega_{\text{pe}} = kv$$

by standard way [6].

The solution of these equations in the case of boundary monoenergetic beam

$$f_{\text{b}}(v, t) = f(v, x, t)\Big|_{x = 0} = f_0\delta(v - v_0)\psi(t)$$

is [7]

$$pl(x, t) = p(T) = \begin{cases} \dfrac{f_0 v_0 \psi(-T)}{(v_0 - \gamma T)^2(v_0 - 2\gamma T)}, & T < 0, \\ \dfrac{f_0(_0 + 4\gamma T)\psi(T)}{v_0^2(v_0 + 2\gamma T)}, & T > 0, \end{cases} \tag{1}$$

$$T = t - \frac{2}{\gamma}(u - v_0), \tag{2}$$

$$u = \sqrt{2\gamma x + u_0^2}, \tag{3}$$

$$W_0(v, x, t) = \frac{m}{\omega_{\text{pe}}}\left[p(x, t)v^4\left(1 - \frac{v}{u}\right) + \frac{v^5}{u}p\left(\frac{v_0 - u}{\gamma}\right)\right]. \tag{4}$$

If electrons are injected during time tau and the source function $\psi(t)$ can be presented as

$$\psi(t) = \exp(-t/\tau),$$

then we find solution of the equations (1)—(4) in the form of accelerated beam-plasma structure. Indeed, it follows from (1) that maximum electron density propagates according to law

$$x = \frac{\gamma t^2}{8} + \frac{u_0 t}{2}.$$

That is to say, the acceleration of beam-plasma structure is four times smaller than for a single particle.

Electron number in the structure

$$N = \int dx \int dv f$$

is proportional to $u^2(x, t)$ owing to both structure width and plateau width in velocity space and proportional to $u(x, t)$. An increase of particle number in accelerating field is connected with phenomenon of «pulling out» particles from the thermal region. In decelerating field electron number in beam-plasma structure is decreased because of electron slowing down to thermal velocity. Variations of fast electron density can be exhibited in the asymmetry of hard X-ray emission from footpoints of magnetic loops. For asymmetry $\rho = \dfrac{F_+ - F_-}{F_+ + F_-}$ (F_+, F_- are X-ray intensities of footpoints where electrons are accelerated and decelerated, correspondingly). Taking into account that $F \propto n©\sigma v$, where $\sigma \propto 1/E \propto 1/v^2$ we find

$$\rho \approx \frac{|\gamma|(x_+ + x_-)}{2v_0^2}. \tag{5}$$

The electric fields in coronal loops can be estimated from observed asymmetry ρ and distance $d = x_+ + x_-$ between loop footpoints

$$E = \frac{2m}{e}\frac{\rho v_0^2}{d}.$$

From data presented in [1] we derived the electric fields in the range from 10^{-8} to $7 \cdot 10^{-8}$ CGSE.

As it was shown in [5] nonlinear processes of the Langmuir wave scattering on plasma ions ($l + i = l + i$) limit the maximum velocity of the beam-plasma structure

$$v_{pl} \approx 14 v_{Te}(1 + T_e/T_i)^{1/2}, \tag{6}$$

where T_e, T_i are temperatures of electrons and ions, correspondingly. For the isothermal plasma this enables to find plasma temperature knowing beam velocity. For example, for electron velocity $v_{pl} = 5 \cdot 10^9$ cm/s in the magnetic loops [2] we derive $T_e = 4 \cdot 10^5$ K from (6).

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