PLASMA EMISSION OF BEAM–PLASMA STRUCTURE IN THE SOLAR CORONA

V. N. Mel'nik* and E. P. Kontar†

Abstract

The plasma emission mechanism is usually used for an explanation of Solar radio bursts at decimetric and longer wavelengths with high brightness temperature. This mechanism needs a high level of Langmuir turbulence generated, for example by fast electron beams or shocks. In recent times it was shown that fast electrons propagate through the plasma in the form of a beam–plasma structure, a new nonlinear object, analogous to a soliton. This structure consists of electrons and Langmuir waves and propagates large distances without energy losses. The energy in Langmuir waves is compared with that in fast electrons, so the beam–plasma structure can be a powerful source of radioemission due to plasma mechanism. In the paper the properties of plasma emission of beam–plasma structure are presented. The application of the results to the explanation of type III burst characteristics is discussed.

1 Introduction

The plasma emission is one of the main mechanisms of radio emission used to explain Solar radio bursts. The high level of Langmuir turbulence, which is necessary for its realization, may be supplied by electron streams or shock waves. Recently [Mel'nik, 1995; Mel'nik et al., 1999b; Mel'nik et al., 2000] it was shown, that fast electron beams of low density propagate in plasma as a beam–plasma structure, a new nonlinear object in plasma physics. The structure consists of fast electrons and Langmuir waves. The energy accumulated in waves is comparable to the energy of particles and consequently the structure may be a powerful source of radio emission via nonlinear plasma processes (for example, $l+i=t+i$, $l+s=t$, $l+l=t$). As shown in [Mel'nik, 1995], beam–plasma structures can propagate with constant velocities without loss of energy and consequently it is an attractive object for the construction of the theory of type III bursts.

*Radio Astronomy Institute, Ukrainian National Academy of Sciences, Chervonopraporna 4, 61002 Kharkov, Ukraine

†Institute of Theoretical Astrophysics, Postbox 1029, Blindern, 0315 Oslo, Norway

In the given work the properties of beam–plasma structure radio emission due to processes with Langmuir waves $l + i = t + i$ and $l + l = t$ are investigated. As is well–known, these processes were introduced by Ginzburg and Zheleznikov for the first time in 1958 [Ginsburg and Zhelezniakov, 1958] for interpretation of harmonic structures of type III bursts, since the first process gives the transverse wave with frequency ω equal to plasma frequency ω_{pe}, and the second process gives rise to the photon at $2 \cdot \omega_{pe}$. Considering the characteristics of type III radio emission (for example, brightness temperature, emission pattern, drift rate, burst duration) one usually proceeds from quality principles as neither a spectrum of Langmuir waves nor the borders of the domain, where waves are generated, are known. Therefore, there has been an essential uncertainty in interpretation of the parameters of bursts and electron streams generating these bursts. In the case of beam–plasma structure, the spectrum of waves in the structure is a universal function, and only the level of Langmuir turbulence and maximum phase velocity are determined by the electron beam density and energy. We hope that the use of the results obtained in the given work enables not only to understand the properties of plasma and fast electron streams, but also the nature of bursts.

2 Beam–plasma structure

If the electrons of a beam has monoenergetic distribution at the initial time moment

$$f\left(v,x,t=0\right) = n'\delta\left(v-v_0\right) exp\left(-x^2/d^2\right), \tag{1}$$

electrons propagate in a plasma as a beam–plasma structure, as was shown in [Mel'nik et al., 1999a]. Note, that the formation of a beam–plasma structure occurs not only for an initially monoenergetic electron beam (1), but also in the case of other initial distribution functions [Mel'nik et al., 1999b; Mel'nik et al., 2000]. Due to fast quasilinear relaxation ($\tau_{qu} = \left(\omega_{pe}\frac{n'}{n}\right)^{-1} << t$, t being the propagation time of electrons in plasma) the electron distribution function has a plateau at every spatial point

$$f\left(v,x,t\right) = \begin{cases} p\left(x,t\right), & v < v_0 \\ 0, & v > v_0 \end{cases}, \tag{2}$$

where

$$p\left(x,t\right) = \frac{n'}{v_0} exp\left(-\frac{\left(x - v_0 t/2\right)^2}{d^2}\right). \tag{3}$$

The spectral energy density of Langmuir waves accompanying the electrons has the following form:

$$W\left(v,x,t\right) = \frac{m}{\omega_{pe}} p\left(x,t\right) v^4 \left(1 - \frac{v}{v_0}\right), \tag{4}$$

where $v = v_{ph} = \omega_{pe}/k$, and k is the wave number of a Langmuir wave. From (4) the maximum value of the spectral energy density W is close to phase velocity

$$v = \frac{4}{5}v_0. \tag{5}$$

The ratio between the energy of waves and electrons in the structure can be found trivially

$$\frac{E}{W} = \frac{\int dv \cdot \frac{mv^2}{2} f}{\int dk \cdot W} = 2, \tag{6}$$

and the total energy of the beam–plasma structure,

$$\int\limits_{-\infty}^{\infty} dx \cdot (E + W) = n'd\frac{mv_0^2}{2} = const, \tag{7}$$

remains constant at the course of its propagation.

Using (3) and (4) one finds that the maximum of electron density $n = \int dv \cdot f$ as well as the maximum of Langmuir waves $W = \int dk \cdot W$ travels with the velocity

$$v_{pl} = v_0/2. \tag{8}$$

3 Fundamental radio emission

Let us consider radio emission of transverse electromagnetic waves by a beam–plasma structure when Langmuir waves are scattered off the thermal ions of plasma $l + i = t + i$. The kinetic equation for the spectral energy density of electromagnetic waves W_t has the form [Tsytovich, 1967]

$$\frac{\partial W_t\left(\vec{k}\right)}{\partial t} = \int \frac{d\vec{k}_l}{(2\pi)^3} w_i^{lt}\left(\vec{k}, \vec{k}_l\right) \left[\frac{\omega}{\omega_l} W_l\left(\vec{k}_l\right) - W_t\left(\vec{k}\right) - \frac{(2\pi)^3}{T_i}\frac{\omega - \omega_l}{\omega} W_t\left(\vec{k}\right) W_l\left(\vec{k}_l\right)\right], \tag{9}$$

where

$$w_i^{lt}\left(\vec{k}, \vec{k}_1\right) = \frac{\sqrt{\pi}\omega_{pe}^2 sin^2\theta}{2nv_{Ti}\left|\vec{k} - \vec{k}_l\right| (1 + T_e/T_i)^2} exp\left[-\frac{(\omega - \omega_l)^2}{2\left|\vec{k} - \vec{k}_l\right|^2 v_{Te}^2}\right] \tag{10}$$

is the probability of the process $l + i = t + i$; k_l, k ,ω_l, ω are the wave numbers and the frequencies of Langmuir and electromagnetic waves, respectively; θ is the angle between $\vec{k}_l$ and $\vec{k}$.

During the initial stage of radio emission $W_t << W_l$ and therefore using (9) we have (including that $(\omega - \omega_l)/\omega << 1$)

$$\frac{\partial W_t\left(\vec{k},t\right)}{\partial t} = \frac{\sqrt{\pi}\omega_{pe}^3 sin^2\theta}{48\pi^2 n v_{Te}^2 \left(1+T_e/T_i\right)^2 k_l}\left[W_l\left(\vec{k_l}\right)+\right.$$

$$\left.+\frac{(2\pi)^3}{T_e}\frac{m}{3M}W_t\left(\vec{k}\right)\frac{\partial}{\partial k_l}k_l W_l\left(\vec{k_l}\right)\right]. \qquad (11)$$

From (11) it follows that spontaneous terms initially determine generation of electromagnetic waves (first term in square brackets). When the level $W_t \approx 3\frac{M}{m}T_e$ is reached, the second term starts to dominate and the generation becomes induced for small wave numbers k_l, where $\frac{\partial}{\partial k_l}k_l W\left(k_l\right) > 0$, i.e. at $k_l \approx k_0 = \omega_{pe}/v_0$ (see Equation (4)). Starting from this moment of time the spectral energy density $W_t\left(k\right)$ can be written as

$$W_t\left(k\right) = 3\frac{M}{m}T_e exp\left(\frac{\chi\tau}{2\tau_{qu}}\right), \qquad (12)$$

where $\tau = \frac{2d}{v_0}$, and χ is given by the expression

$$\chi = 2.5\cdot 10^{-5}\cdot\left(1+\frac{T_e}{T_i}\right)^{-2}\left(\frac{v_0}{v_{Te}}\right)^4. \qquad (13)$$

Equations (12) and (13) show that the spectral energy density of radio emissions strongly depends on velocity v_0, or the velocity of the structure $v_{pl} = v_0/2$. Therefore one can conclude that the most intense radio emission is produced by the fastest beam–plasma structures. It is natural that the intensity of the radio emission also grows with the time width of the structure τ.

4 Harmonic radio emission

To analyze radio emission of a beam–plasma structure at double plasma frequency we use the kinetic equation [Tsytovich, 1967]

$$\frac{\partial W_t\left(\vec{k}\right)}{\partial t} = \omega\int\frac{w_t^{ll}\left(\vec{k}_l,\vec{k}_{l'},\vec{k}\right)}{\hbar}\times$$

$$\times\left[\frac{W_l\left(\vec{k}_l\right)W_{l'}\left(\vec{k}_l'\right)}{\omega_l\omega_l'} - \frac{W_t\left(\vec{k}\right)W_l\left(\vec{k}_l\right)}{\omega\omega_l} - \frac{W_{l'}\left(\vec{k}_l'\right)W_t\left(\vec{k}\right)}{\omega\omega_l'}\right]\frac{d\vec{k}_l d\vec{k}_l'}{(2\pi)^3}, \qquad (14)$$

where the integral in the right hand side of the Equation (14) describes the processes of coalescence of two Langmuir waves $l+l=t$ and decay into two Langmuir waves $t=l+l$

($\vec{k}_l$, $\vec{k}_l'$, ω_l, ω_l' are the wave vectors and frequencies of Langmuir waves, correspondingly). In the Equation (14)

$$w_t^{ll}\left(\vec{k}_{l1}, \vec{k'}_l, \vec{k}\right) = \frac{\hbar e^2 (2\pi)^6}{32\pi m^2} \frac{\left(k_l^2 - k_l'^2\right)^2}{k^2 \omega_{pe}} \frac{\left[\vec{k}_l \vec{k'}_l\right]^2}{k_l^2 k_l'^2} \delta\left(\vec{k} - \vec{k}_l - \vec{k'}_l\right) \times$$

$$\times \delta\left(\omega - \omega_l - \omega_l'\right) \tag{15}$$

is the probability of the process $l + l = t$.

From the energy and momentum conservation laws we find that the wave number of transverse waves is $k = \sqrt{3}\omega_{pe}/c$. Langmuir waves are mostly concentrated in the region of small wave numbers (4) and the coalescence of two Langmuir waves from beam–plasma structures gives a transverse wave if there are two Langmuir waves with wave number $k_l = \sqrt{3}\omega_{pe}/2c$, which corresponds to superluminal velocities $v > c$. There are no such waves in beam–plasma structures and consequently it needs to suppose that waves from the structure should coalescence with the other waves, either thermal or waves scattered from the structure. Devoting index "l" to the waves in beam–plasma structures, and index "l'" to thermal or scattered waves and integrating (14), one obtains

$$\frac{\partial W_t\left(\vec{k}\right)}{\partial t} = \frac{\pi^2 e^2 \omega_{pe} \psi(\theta)}{m^2 v_{Te}^2 c^2 k_l} W_l\left(\vec{k}_l\right) \left[W_{l'}\left(\vec{k}_l'\right) - \frac{1}{2} W_t\left(\vec{k}\right)\right], \tag{16}$$

where $\psi(\theta)$ is the emission pattern [Mel'nik, 1991].

One can conclude that the transformation rate of Langmuir waves into electromagnetic waves is proportional to the level of the waves $W_l(k_l)$. At the saturation the energy density of radio emission $W_t(k)$ determined by thermal or scattered Langmuir waves $W_l(k_l')$ ($W_t(k) \approx W_l(k_l')$). Since the level of the former might be significant, these waves are likely responsible for radio emission at double plasma frequency. The brightness temperature of radio emission is twice the brightness temperature of scattered Langmuir waves. The maximum level of scattered waves is approximately equal to the level of plasma waves in beam–plasma structures. Therefore, the energy density of radio emission at double plasma frequency is

$$W_H = \frac{3M}{2m} T_e exp\left(\frac{\chi\tau}{\tau_{qu}}\right). \tag{17}$$

The detailed consideration of the processes of Langmuir wave scattering off plasma ions $l + i = l + i$ with change of the direction of $\vec{k}_l$ as well as for $l + i = t + i$ shows that the probability quickly increases with phase velocity of waves [Mel'nik, 1991]. Again we have that the most intense radio emission comes from fast beam–plasma structures.

5 Application to the theory of type III bursts

Type III bursts are connected with fast electrons whose velocity of the order of $0.3 \cdot c$, which slowly decreases with the distance from the Sun and approaches $\approx 0.16 \cdot c$ near the Earth [Suzuki and Dulk, 1985]. The brightness temperature of the bursts is generally in the range $10^{10} - 10^{12}K$ [Suzuki and Dulk, 1985] with maximum possible value $10^{15}K$ [Melrose, 1989]. The density of fast electrons generating bursts is considered small $n'/n = 10^{-5} - 10^{-7}$, whereas quasilinear time at various distances from the Sun is essentially less than the electron propagation time $t = l/v_0$. Specifically for this case the gas–dynamic theory of electron beam dynamics in plasma has been developed. From the theory follows that electrons propagate as the beam–plasma structure described in section 2. These structures, as we have seen, travel without loss of energy when nonlinear processes are not taken into account. Inclusion of nonlinear processes [Mel'nik, 1991; Melnik, 2001] leads to the limitation on beam–plasma structure parameters

$$\frac{\chi\tau}{\tau_{qu}} < 15. \tag{18}$$

If the condition (18) fails, the fast pumping of Langmuir waves into non-resonant region takes place and the structure cannot propagate over large distances. It follows from (18) that the maximum velocity of the beam–plasma structure $v_{pl} = v_0/2$ will be approximately $\approx 0.3 \cdot c$. Note that since $T_e/T_i \approx 5$, and $T_e = 3 \cdot 10^5 K$, near the Earth orbit the velocity of the structure following (18), will be $\approx 0.2 \cdot c$. Thus we obtain the required velocities of burst sources.

According to Equation (12), one can conclude that the maximum brightness temperature at the fundamental frequency equals to

$$T_F \approx 10^{13} K. \tag{19}$$

In the case of radio emissions at harmonic frequency, the maximum energy density of scattered waves is reached at the approximate equality (18), and consequently the brightness temperature is

$$T_H \approx 10^{16} K. \tag{20}$$

Thus we see, that radio emission from beam–plasma structures via plasma mechanism supplies the necessary brightness temperatures. Observed weaker brightness temperatures are likely connected with effects of radio wave propagation in corona and the dispersion of the parameters in beam–plasma structures (density, velocity).

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