TO THE THEORY OF ELECTRON CYCLOTRON MASER RADIO EMISSION OF ELECTRON BEAMS

V. N. Mel'nik*

Abstract

One of the possible mechanisms of S–radio emission of Jupiter is the electron–cyclotron mechanism on the loss–cone electrons. However there is another possibility, namely, radiation of electron beams injected into the plasma under an angle to the magnetic field. In the paper we show that in this case electrons generate fast magnetosonic (FMS) waves, which act on beam electrons so that a beam–plasma structure is formed. This structure consists of fast electrons and FMS waves. It propagates along the magnetic field with constant velocity and can be a source of emission with the help of the electron–cyclotron maser mechanism. Invoking this possibility allows to explain such characteristics of the S–radio emission as burst duration, lifetime, frequency drift and the radio emission beam.

1 Introduction

The electron cyclotron maser mechanism of radio emission for loss–cone electrons is usually used for interpretation of Jupiter S–bursts [Ryabov and Gerasimova, 1990; Zarka et al., 1997]. Electron distribution function with loss–cone can exist in magnetic tubes, for example, in the Io–Jupiter tube. But the formation time of such a distribution is compared with the time of fast electron passage of the magnetic tube $t = l_{io,J}/v_0$ [Melrose and Dulk, 1982; Fleishman and Melnikov, 1998]. The latter is significantly longer than the S–burst duration so that another source of these bursts should be found. The electron beams, which in one way or another, are ejected into the magnetic tube, can be such sources. To explain the fine structure of the S–bursts one needs to take a finite size of the beams into account.

In this paper propagation and radio emission of space limited fast electron beams, which initially move under some angle to the strong ($\omega_{Be} >> \omega_{pe}$, where $\omega_{Be} = eB/mc$, $\omega_{pe} = (4\pi e^2 n/m)^{1/2}$) magnetic field, $\vec{B}$, are considered. We argue that fast electrons

---

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

propagate along the magnetic field as a beam–plasma structure, a new nonlinear object found recently [Mel'nik, 1993; Mel'nik, 1995; Mel'nik et al., 1999a]. This object consists of electrons and fast magnetosonic waves. Its velocity is constant in time. In the case when $\partial f(v_\perp)/\partial v_\perp > 0$ this beam–plasma structure can be a source of radio emission at the electron cyclotron frequency. Invoking this object for the explanation of Jupiter S–bursts is discussed.

2 Electron cyclotron radio emission of beam–plasma structures

Let there be an electron beam that is ejected into the plasma under some angle to the magnetic field $\vec{B}$ with the electron distribution function

$$f(\vec{v},x) = f(\vec{v})exp(-x^2/d^2), \tag{1}$$

where d is the space size of the beam, OX is the axis parallel to the magnetic field. For the simplicity of analytical consideration let $f(\vec{v})$ be in the factorised form

$$f(\vec{v}) = f(\vec{v}_\perp)f(\vec{v}_\parallel), \tag{2}$$

to say that the electron beam is the flux of oscillators with different Larmor radii [Akhiezer et al., 1974]. In Equation (2) $\vec{v}_\perp$, $\vec{v}_\parallel$ are electron velocities perpendicular and parallel to the magnetic field correspondingly. In a plasma an oscillator flux can interact with the different waves - fast extraordinary, ordinary, fast magnetosonic, slow extraordinary and alfvènic ones. Analysis shows that the interaction time is defined with the next expressions

$$\tau_{FE} \approx (\omega_{pe}\frac{\omega_{pe}}{\omega_{Be}}\frac{n'}{n})^{-1}, \tag{3}$$

$$\tau_{O} \approx (\omega_{pe}\frac{\omega_{pe}}{\omega_{Be}}\frac{n'}{n})^{-1}, \tag{4}$$

$$\tau_{FMS} \approx (\omega_{pe}\frac{n'}{n})^{-1}, \tag{5}$$

$$\tau_{SE} \approx (\omega_{pe}(\frac{\omega_{pe}}{\omega_{Be}})^3\frac{n'}{n})^{-1}, \tag{6}$$

$$\tau_{A} \approx (\omega_{pe}\frac{\omega_{Be}}{\omega_{pe}}\frac{n'}{n}(\frac{m}{M})^4(\frac{v_0}{v_A})^4)^{-1}. \tag{7}$$

Here τ_{FE}, τ_O, τ_{FMS}, τ_{SE}, τ_A are the characteristic times of interaction between electrons and fast extraordinary, ordinary, fast magnetosonic, slow extraordinary and alfvènic waves, $n' = \int f(\vec{v})d\vec{v}$ is the electron beam density, v_0 is a fast electron velocity, $v_A = B/(4\pi Mn)^{1/2}$ is the Alfvèn velocity. From (3)–(7) we see that the fastest process is the electron interaction with fast magnetosonic waves. The longitudinal part of the electron distribution function $f(v_\|)$ is changed at such interaction. The kinetic equations describing $f(\vec{v}_\|)$ and $W(\vec{k}_\|)$ ($\vec{k}_\|$ is the wave vector of FMS wave parallel to the magnetic field), the spectral energy density of FMS waves, are as follows

$$\frac{\partial f(v_\|)}{\partial t} + v_\| \frac{\partial f(v_\|)}{\partial x} = \frac{4\pi^2 e^2}{m^2}\frac{\partial}{\partial v_\|}\frac{W(k_\|)}{v_\|}\frac{\partial f(v_\|)}{v_\|}, \tag{8}$$

$$\frac{\partial W(k_\|)}{\partial t} = \frac{\pi\omega_{pe}}{n} v^2 W(k_\|) f(v_\perp)\frac{\partial f(v_\|)}{v_\|}. \tag{9}$$

These equations are analogous to the kinetic equations of weak turbulence that are relevant for the problem of fast electron propagation in plasma without magnetic field, but instead of FMS waves there are Langmuir waves. As was shown in Mel'nik [1993] and Mel'nik et al. [1999a] in a gas–dynamic approximation (when the propagation time $t = x/v_0$ is significantly more than the time of interaction between electrons and FMS waves τ_{FMS}) the solution of these equations is a beam–plasma structure

$$f(\vec{v}, x, t) = \frac{f(\vec{v}_\perp)}{v_0} exp(-(x - v_0 t/2)^2/d^2), v_\| < v_0, \tag{10}$$

$$W(k_\|, x, t) = \frac{m}{\omega_{pe}}\frac{f(\vec{v}_\perp)}{(k_\|)^4} exp(-(x - v_0 t/2)^2/d^2) \tag{11}$$

for the initial electron distribution function

$$f(\vec{v}, x, t = 0) = f(\vec{v}_\perp)\delta(v_\| - v_0) exp(-x^2/d^2). \tag{12}$$

From (10) and (11) we can see that electrons move at constant velocity $v_0/2$ and they are accompanied by FMS waves. The minimum duration of a beam–plasma structure is defined by the time τ_{FMS} of the plateau formation of the longitudinal electron distribution function. The electron interaction with FMS waves does not influence the perpendicular electron distribution function. But if the distribution function $f(\vec{v}_\perp)$ has a positive derivative $\partial f(v_\perp)/\partial v_\perp$ then the beam–plasma structure can be a source of emission due to the electron cyclotron maser mechanism [Wu and Lee, 1979]. It is well known that the most intensive generation of both fast extraordinary and ordinary waves occurs at the electron cyclotron resonance. The corresponding rates for these processes are

$$\gamma_0 = \frac{\pi^2 e^2 \omega_{Be}}{2m\omega}\int v_\perp \frac{\partial f}{\partial v_\perp}[{v_\|}^2 \frac{{k_\|}^2}{{\omega_{Be}}^2}\sin^2\theta + 2\frac{\omega - \omega_{Be}}{\omega}\cos^2\theta - 2v_\| \frac{k_\|}{\omega}\frac{\omega - \omega_{Be}}{\omega}\sin\theta\cos\theta] \times$$
$$\times\delta(\omega - \frac{\omega_{Be}}{\Gamma} - k_\| v_\|)d\vec{v}, \quad \Gamma = (1 - v^2/c^2)^{-1/2}, \tag{13}$$

$$\gamma_{FE} = \frac{\pi^2 e^2 \omega_{Be}}{2m} \frac{(\omega^2 - {\omega_{Be}}^2)^2}{\omega^3 {\omega_{Be}}^2} \int {v_\perp}^2 \frac{\partial f}{\partial v_\perp} [1 + \frac{2N^2}{2 - N^2} \frac{v_\| k_\|}{\omega_{Be}} \sin\theta \cos\theta] \times$$
$$\times \delta(\omega - \frac{\omega_{Be}}{\Gamma} - k_\| v_\|) d\vec{v}, \quad N = kc/\omega, \tag{14}$$

where θ is an angle between wave vector $\vec{k}$ and the magnetic field $\vec{B}$.

The radiation at frequency $\omega \approx \omega_{Be}$ happens almost perpendicular to the magnetic field direction

$$\theta \approx \arccos \frac{v_0}{c} \approx \frac{\pi}{2} - \frac{v_0}{c} \tag{15}$$

until $\partial f(v_\perp)/\partial v_\perp > 0$. In time $t \approx \tau_{FE}, \tau_O$ the slope of the perpendicular distribution function is decreased to the state with $\partial f(v_\perp) \approx const.$ and the radiation is stopped. Because the whole perpendicular energy of fast electrons is transformed into electromagnetic waves the brightness temperature T_{eff} of emission approximately equals to

$$T_{eff} \approx \frac{W_{FE,O}}{\Delta\Omega}, \tag{16}$$

where

$$W_{FE,O} \approx n' m {v_0}^2 \tag{17}$$

is the energy density of fast extraordinary and ordinary waves and

$$\Delta\Omega \approx 2\pi (\frac{\omega_{Be}}{c})^3 \frac{\Delta\omega}{\omega_{Be}} \Delta\theta \tag{18}$$

is the phase volume in which fast extraordinary and ordinary waves are confined. In the theory of electron cyclotron maser mechanism of radio emission [Wu and Lee, 1979; Mel'nik, 1993] $\Delta\omega/\omega_{Be} \approx v_0^2/c^2$ and $\Delta\theta \approx v_0/c$. From (16)–(18) we have

$$T_{eff} \approx \frac{n' m {v_0}^2}{(\frac{\omega_{Be}}{c})^3 \frac{\Delta\omega}{\omega_{Be}} \Delta\theta}. \tag{19}$$

If electrons propagate in the direction of decreasing magnetic field then their radio emission has negative frequency drift

$$\frac{df}{dt} \simeq -f \frac{1}{B} \mid \frac{dB}{dr} \mid \frac{v_0}{2}. \tag{20}$$

3 Application to Jupiter S–bursts

In the conditions of the Io–Jupiter tube at the plasma density $n = 10^4\ cm^{-3}$, the magnetic field $B = 10\ G$, the density $n' = 10^{-4} n$ and the velocity $v_0 = 0.1\ c$ of fast electrons we find the following characteristics of S–radio emission: the smallest duration of an S–burst at fixed frequency is $\tau \approx 2\ ms$, the whole duration of the electron beams is $t \approx 100\ ms$, the brightness temperature is $T_{eff} \approx 10^{17} K$ and the frequency drift $df/dt \simeq -f(MHz/s)$ at the magnetic irregularity scale $\frac{1}{B} \mid \frac{dB}{dr} \mid = 10^{-9} cm^{-1}$. The radiation occurs into a cone with an angle $\theta \approx 80°$. All these parameters are closely related to Jupiter S–bursts. If this model is correct then the S–burst zoo observed [Ryabov et al., 1997] can be associated with a complex structure of the magnetic field in the place of radiation.

Thus invoking the idea of electron cyclotron maser radio emission of electron beams and using only standard values for plasma and electron beams the main properties of Jupiter S–bursts can be understood.

Acknowledgement: This work was partially supported by INTAS (grant No 97–1964).

References

Akhiezer, A. I., R. V. Polovin, A. G. Sitenko, and K. N. Stepanov, *Electrodynamics of Plasma*, Nauka, Moskva, 1974.

Fleishman, G. D., and V. F. Melnikov, The Solar millisecond radio spikes, *Uspehi fiz. nauk*, **168**, 1265, 1998.

Mel'nik, V. N., Dynamics and radiation of fast electron flux in plasma in strong magnetic field, *Ukr. fiz. zhurn.*, **38**, 1186, 1993.

Mel'nik, V. N., To the problem of "gas–dynamic" flying off of fast electron flux in plasma, *Plasma Phys. Reports*, **21**, 94, 1995.

Mel'nik, V. N., V. I. Lapshin, and E. P. Kontar, Propagation of a monoenergetic electron beam in the Solar corona, *Solar Phys.*, **184**, 353, 1999a.

Melrose, D. B., and G. A. Dulk, Electron–cyclotron masers as the source of certain Solar and stellar radio bursts, *Ap. J.*, **259**, 844, 1982.

Ryabov, B. P., and N. N. Gerasimova, *Decameter sporadic radio emission of Jupiter*, Naukova dumka, Kyiv, 1990.

Ryabov, B. P., P. Zarka, H. O. Rucker, V. B. Ryabov, and M. Y. Boudjada, Recurrent fine structures in Jovian S–burst emission, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, Austrian Academy of Sciences Press, Vienna, 65–89, 1997.

Wu, C. S., and L. C. Lee, A theory of the terrestrial kilometric radiation, *Ap.J.*, **230**, 621, 1979.

Zarka, P., B. P. Ryabov, V. B. Ryabov, R. Prange, M. Abada–Simon, T. Farges, and L. Denis, On the origin of Jovian decameter radio bursts, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, Austrian Academy of Sciences Press, Vienna, 51–63, 1997.