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A novel mechanism for electron-cyclotron maser

D. J. Wu[1], L. Chen[1], G. Q. Zhao[1,2], and J. F. Tang[3]

[1] Purple Mountain Observatory, CAS, 210008 Nanjing, PR China
e-mail: clvslc214@pmo.ac.cn
[2] Graduate School, CAS, 19A Yuquan Road, 100049 Beijing, PR China
[3] Xinjiang Astronomical Observatory, CAS, 830011 Urumqi, PR China

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ABSTRACT

Context. It has been a long-standing puzzle on how to produce natural radio bursts of various cosmic objects, ranging from remote active galactic nuclei and pulsars to the nearest solar radio bursts and terrestrial auroral kilometer radiations.

Aims. An electron-cyclotron maser (ECM) driven by fast electron beams trapped in magnetic fields has been suggested as a dominant mechanism of producing natural high-power radio radiation. However, there have been two serious difficulties: the magnetization condition of requiring the electron gyrofrequency over the plasma frequency and the inversion condition of the perpendicular velocity distribution of the fast electrons, which has held back the popularization of ECM in the astrophysical community.

Methods. By including effects of self-generated Alfvén waves (AW) excited by the beam current, this paper proposes a novel, self-consistent ECM model.

Results. The results show that the self-generated AW can effectively make a density-depleted duct, in which the magnetization condition is easily satisfied, and result in the inversion condition of perpendicular velocity distribution of the beam electrons.

Conclusions. This self-consistent ECM model can effectively overcome the two difficulties, make ECM very easily occur, and, hence, has greatly interesting implications and general significance in radio astrophysics because of its self-consistency, simplicity, and efficiency.

Key words. masers – plasmas – radiation mechanisms: non-thermal – Sun: radio radiation – waves

1. Introduction

It has been a long-standing puzzle on how to produce natural radio bursts of various cosmic objects, ranging from remote active galactic nuclei and pulsars to the nearest solar radio bursts and terrestrial auroral kilometer radiations (AKRs, Treumann 2006). An electron-cyclotron maser (ECM), the process that generates coherent radiation by a beam of fast electrons traveling in a magnetized plasma, has been suggested as a dominant mechanism of producing natural high-power radio radiation (Twiss 1958; Gaponov 1959; Schneider 1959) since it has been employed to explain AKR, which are unique in situ measurable natural radio sources (Wu & Lee 1979). However, there have been two heavy difficulties to hold back the popularization of ECM in the astrophysical community (Wild 1985; Treumann 2006). One is the magnetization condition that requires the local electron gyrofrequency over the local plasma frequency, which is considered rather hard to be satisfied for major cases of natural astrophysical plasmas. The other is the inversion condition of the perpendicular velocity distribution of the fast electrons; nevertheless, the fast electrons initially are accelerated usually along the ambient magnetic field.

The fast electron beam is one of the commonest products in astrophysical activities, ranging from active galactic nuclei and pulsars to solar flares and auroral substorms. When a fast electron beam with a thin density ($n_b \ll n_0$) and fast velocity ($v_b \gg v_A$) along the ambient magnetic field is present in a magnetized plasma, it carries a field-aligned electric current $j_b = -en_b v_b$ passing through the plasma, where n_0 is the ambient plasma density and v_A the Alfvén velocity. This current may cause magnetic fluctuations via the Alfvén waves (AW) instability in the low-frequency ($\omega \ll \omega_{ci}$) and long-wavelength ($k \ll \omega_{ci}/v_{T_i}$) limit (Hasegawa 1975; Hasegawa & Uberoi 1982; Wu 2012), where ω and k are the frequency and wavenumber of AWs, respectively, and ω_{ci} and v_{T_i} the ion gyrofrequency and thermal speed, respectively.

In this paper, taking account of the effects of the self-generated AW excited by the beam current we propose a novel, self-consistent ECM mechanism that can effectively overcome these two difficulties and make ECM very easily occur. Based on the hydromagnetic limit of the kinetic theory, we present the AW instability driven by the beam current and the estimation of its saturation level in Sect. 2. Further, we discuss the effects of the self-generated AW on the ECM emission driven by the fast electron beam in Sect. 3. Finally, discussion and conclusion are presented in Sect. 4.

2. Self-generated AW and estimation of its saturation level

The AW instability driven by the beam current can be dealt with by the hydromagnetic limit of the kinetic theory (Hasegawa 1975; Hasegawa & Uberoi 1982; Wu 2012). For the sake of simplicity, we consider the wave propagating in the direction of the ambient magnetic field $\boldsymbol{B}_0$ along the z-axis, or, the wave vector $\boldsymbol{k} = (0,\ 0,\ k_z)$. For the parallel propagating AW, the dispersion equation that includes the contribution from the fast electron beam reads as (Hasegawa & Uberoi 1982)

$$\frac{\omega^2}{\omega_{ci}^2} + \alpha_Q \frac{\omega}{\omega_{ci}} - (\alpha_J + k_z\lambda_i)\,k_z\lambda_i = 0, \tag{1}$$

and its solution, which is the dispersion relation is given simply by

$$\frac{\omega}{\omega_{\rm ci}} = -\frac{\alpha_{\rm Q}}{2}\left(1 \pm \sqrt{1 + 4\frac{\alpha_{\rm J} + k_z\lambda_{\rm i}}{\alpha_{\rm Q}^2}k_z\lambda_{\rm i}}\right), \tag{2}$$

where the parameters

$$\alpha_{\rm Q} \equiv \frac{n_{\rm Q}}{en_0} = -\frac{n_{\rm b}}{n_0} \text{ and } \alpha_{\rm J} \equiv \frac{j_{\rm b}}{en_0 v_{\rm A}} = -\frac{n_{\rm b}v_{\rm b}}{n_0 v_{\rm A}} = \alpha_{\rm Q}\frac{v_{\rm b}}{v_{\rm A}} \tag{3}$$

are the normalized charge and current density carried by the fast electron beam, respectively, and $\lambda_{\rm i} \equiv v_{\rm A}/\omega_{\rm ci}$ is the ion inertial length.

From this dispersion relation (2), it can be found that the AW becomes unstable, also called the self-generated AW, when

$$\alpha_{\rm J} < -\frac{\alpha_{\rm Q}^2}{4k_z\lambda_{\rm i}} - k_z\lambda_{\rm i} \Rightarrow \frac{v_{\rm b}}{v_{\rm A}} > \frac{n_{\rm b}/n_0}{4k_z\lambda_{\rm i}} + \frac{k_z\lambda_{\rm i}}{n_{\rm b}/n_0} \geq 1. \tag{4}$$

The AW has a frequency

$$\omega = -\frac{\alpha_{\rm Q}}{2}\omega_{\rm ci} = \frac{n_{\rm b}}{n_0}\frac{\omega_{\rm ci}}{2} \ll \omega_{\rm ci}, \tag{5}$$

and a growth rate,

$$\gamma = \omega_{\rm ci}\sqrt{-(\alpha_{\rm J} + k_z\lambda_{\rm i})\,k_z\lambda_{\rm i} - \frac{\alpha_{\rm Q}^2}{4}}. \tag{6}$$

From Eq. (6), when

$$k_z\lambda_{\rm i} = k_{z\rm m}\lambda_{\rm i} \equiv -\frac{\alpha_{\rm J}}{2} = \frac{1}{2}\frac{n_{\rm b}}{n_0}\frac{v_{\rm b}}{v_{\rm A}}, \tag{7}$$

the self-generated AW has its maximum growth rate

$$\gamma_{\rm m} = \frac{\omega_{\rm ci}}{2}\sqrt{\alpha_{\rm J}^2 - \alpha_{\rm Q}^2} \simeq -\frac{\alpha_{\rm J}}{2}\omega_{\rm ci} \gg \omega, \tag{8}$$

where the last approximation is valid for the fast electron beam of $\alpha_{\rm J}/\alpha_{\rm Q} = v_{\rm b}/v_{\rm A} \gg 1$. From Eq. (8), the growth rate of the self-generated AW is directly proportional to the intensity of the electric current carried by the fast electron beam, $|j_{\rm b}| = en_{\rm b}v_{\rm b}$.

As the self-generated AW grows, its wave pressure pushes aside the plasma and results in the formation of a density-depleted duct on the way of the beam traveling. In the density-depleted duct, there is a local Alfvén velocity $v_{\rm AD}$ that is higher than the ambient Alfvén velocity $v_{\rm A}$ by a factor of $\sqrt{n_0/n_{\rm D}}$ because of the density depletion inside it; that is,

$$v_{\rm AD} = \sqrt{\frac{n_0}{n_{\rm D}}}v_{\rm A}, \tag{9}$$

where $n_{\rm D}$ is the plasma density in the duct. In particular, when

$$v_{\rm AD} = v_{\rm b}, \quad \text{i.e.,} \quad \frac{n_{\rm D}}{n_0} = \frac{v_{\rm A}^2}{v_{\rm b}^2} \ll 1 \tag{10}$$

the instability condition of Eq. (4) for the self-generated AW is no longer satisfied inside the duct, which implies that the self-generated AW no longer grows and reaches its saturation. The saturation level $B_{\rm w}^2$ for the self-generated AW can be estimated by the pressure balance between the inside and the outside of the duct. It reads as

$$\frac{B_0^2}{2\mu_0} + \frac{B_{\rm w}^2}{2\mu_0} + n_{\rm D}T_{\rm D} = \frac{B_0^2}{2\mu_0} + n_0T_0, \tag{11}$$

where $T_{\rm D}$ and T_0 are the temperature inside and outside the duct, respectively. In general, one has $T_{\rm D} > T_0$ in consideration of the possible heating effect caused by the fast electron beam in the duct. The balance Eq. (11) leads to

$$\frac{B_{\rm w}^2}{B_0^2} = \left(1 - \frac{n_{\rm D}T_{\rm D}}{n_0T_0}\right)\beta_0 = \left(1 - \frac{v_{\rm A}^2}{v_{\rm b}^2}\frac{T_{\rm D}}{T_0}\right)\beta_0 \lesssim \beta_0 \ll 1 \tag{12}$$

for the fast electron beam of $v_{\rm b}/v_{\rm A} \gg 1$, where $\beta_0 \equiv n_0T_0/\left(B_0^2/2\mu_0\right)$ is the kinetic to magnetic pressure ratio of the ambient plasma.

By including the finite Larmor radius effect (i.e., finite $k_\perp\rho_i$), kinetic AWs can be excited by this AW instability due to the electrostatic coupling (Hasegawa & Uberoi 1982). The relation between the fluctuation level of AWs (or kinetic AWs) and the local plasma β parameter in Eq. (12) is qualitatively consistent with observations associated with AWs in a wide β parametric range. This ranges from the high-β case of $\beta \sim 1$ in the solar wind to the intermediate-β case of $1 > \beta > Q$ in the solar corona and the low-β case of $\beta < Q$ in the auroral magnetosphere, where $Q \equiv m_{\rm e}/m_{\rm i}$ is the electron ($m_{\rm e}$) to ion ($m_{\rm i}$) mass ratio. We infer that the relationship between the AW level and the plasma β presented in Eq. (12) is independent from the excitation and the saturation mechanisms for AWs.

For example, in the auroral plasma explored by the Freja satellite at altitude ~1700 km, the typical ambient parameters are the Earth's magnetic field $B_0 \sim 0.3$ G, the plasma density $n_0 \sim 10^3$ cm^{-3}, and temperature $T \sim 10$ eV, which implies the ambient plasma $\beta_0 \sim 4\times10^{-6} \ll Q$. In the Freja observation, the strength of AWs has typical values of a few tens nT and, hence, has $B_{\rm w}^2/B_0^2 \sim 10^{-6} \lesssim \beta_0$ (Stasiewicz et al. 2000). In particular, these AWs in the auroral plasma often are found to be associated with field-aligned currents carried by fast-precipitating electrons and density cavities (i.e., density-depleted ducts; Stasiewicz et al. 1997, 1998; Bellan & Stasiewicz 1998; Chaston et al. 2007). The ECM emission of these fast precipitation electrons with loss-cone distribution has been extensively accepted as the main AKR source, since the pioneer work by Wu & Lee (1979). In recent work, Treumann et al. (2012) argued that the fine structure of AKRs can be caused by the same mechanism through electron holes predominantly in the upward electron region originating from the ionosphere.

On the other hand, large-amplitude AWs with $B_{\rm w}^2/B_0^2 \sim 1$ in the solar wind with typical values of $\beta_0 \sim 1$ are ubiquitous fluctuations, as shown by in situ satellite measurements in the interplanetary medium (Belcher & Davis 1971). In addition, based on the estimation from remote measurements of the solar atmosphere, the level of AWs in the solar corona, which consists of plasmas with the β parameter ranging between 0.1 and 0.001 (i.e., $1 > \beta_0 > Q$), $B_{\rm w}^2/B_0^2$, is also estimated within the same range with the β parameter (Cranmer & van Ballegooijen 2005; He et al. 2009; McIntosh et al. 2011). Treumann et al. (1990) have shown that various kinds of AWs, including cavities, can be generated in solar coronal plasmas and have pointed out their possible association with solar intermediate drift bursts. The analysis by Wu et al. (2007) also suggested that kinetic Alfvén solitary waves are possibly responsible for the source of solar microwave drifting spikes, which have short lifetimes of several tens of ms, narrow relative bandwidths below 1%, and low frequency drifting rates of a few hundreds of MHz/s.

3. Effects of self-generated AW on ECM emission

A fast electron beam accelerated initially along the ambient magnetic field, in general, cannot directly excite radiation of electromagnetic waves. However, in recent work, Wu et al. (2012), Yoon et al. (2009), and Zhao & Wu (2013) pointed out that the presence of AWs can affect the velocity distribution of the beam electrons via the pitch-angle scattering by the AWs. They showed that the velocity distribution of the beam electrons can evolve quickly into a crescent-shaped distribution, which can be modeled by the following function (Wu et al. 2012; Yoon et al. 2009; Zhao & Wu 2013)

$$f_b(v, v_\perp) = A \exp\left(-\frac{(v - v_b)^2}{V_T^2} - \frac{v_\perp^2/v^2}{V_\perp^2}\right), \tag{13}$$

where A is the normalization constant for the distribution function, V_T is the velocity spread of the beam electrons, and $V_\perp$ is the pitch-angle spread of the beam electrons, which is determined by the AW scattering and can be approximated by (Wu et al. 2012; Yoon et al. 2009; Zhao & Wu 2013)

$$V_\perp \simeq \frac{V_T}{v_b}\sqrt{1 + 2\frac{B_w^2}{B_0^2}\frac{v_b^2}{V_T^2}}. \tag{14}$$

In particular, this crescent-shaped distribution has a typically inverse velocity distribution in the plane perpendicular to the ambient magnetic field and hence satisfies the inversion condition for the ECM instability effectively to excite the ECM emission (Wu et al. 2012; Zhao & Wu 2013). The ECM emission is an induced emission (also called coherent emission in literature) process that can directly amplify radiative electromagnetic waves in the ordinary (O) or the extraordinary (X) modes with the fundamental and the harmonic frequencies via the ECM instability driven by fast electron beams trapped in the local magnetic field. Because of its simplicity and efficiency, the ECM emission is extensively believed to be responsible for short-time, small-scale, and fast-drift radio bursts or spikes from the Sun, planets, and other stars, such as radio radiation from magnetized planets in the solar system, radio bursts, or spike from the Sun and other stars, and the time-varying emission from Blazar jets (see review by Treumann 2006 and references therein for more details). These radio bursts are characterized in observation by the intense nonthermal radiation and extraordinarily brightness temperature, which implies that they should be generated by induced emission processes with a very great radiation efficiency.

Since the pioneering works by Twiss (1958), Gaponov (1959), and Schneider (1959), many nonthermal distribution functions for the fast electrons have been proposed to be responsible for the free driven energy source of the ECM instability, such as the spheric-shell distribution (Bekefi et al. 1961), the bi-Maxwellian distribution (Melrose 1976), the loss-cone distribution (Wu & Lee 1979), the hollow-beam (or ring-beam) distribution (Freund et al. 1983), the ring-shell distribution (Pritchett 1984), and the low-energy cutoff of power-law electrons (Wu & Tang 2008; Tang & Wu 2009). These distributions, however, cannot be formed automatically by the fast electron beam, and their presence depends on some special conditions of local magnetized plasmas. As pointed out above, on the other hand, the crescent-shaped distribution (Wu et al. 2012; Yoon et al. 2009; Zhao & Wu 2013) can be formed self-consistently via the scattering by the self-generated AWs of the fast electron beam.

Another important effect of the self-generated AW on the ECM emission of the beam is to construct a tenuous plasma environment that is more favorable for the ECM emission to work. In order that the ECM can efficiently emit radiation and is independent from its driven-energy sources, the local electron cyclotron frequency (ω_{ce}) needs to satisfy the following magnetization condition (Twiss 1958; Gaponov 1959; Schneider 1959; Treumann 2006)

$$\frac{\omega_{ce}}{\omega_{pe}} > 1 \Rightarrow v_A = \frac{\omega_{ce}}{\omega_{pe}}\sqrt{Q}c > \sqrt{Q}c, \tag{15}$$

which implies a local Alfvén velocity v_A larger than the critical velocity $\sqrt{Q}c$ ($\simeq$7000 km s^{-1} for an hydrogen plasma), where ω_{pe} is the local plasma frequency and c the velocity of light. This magnetization condition is a rather stringently constrained condition for the ECM emission effectively to work. For instance, this requires the plasma $\beta < 10^{-4}$ for the solar corona with temperature of 10^6 K.

In the presence of a fast electron beam in the plasma, however, the self-generated AW driven by the beam can effectively push aside the plasma and excavate a density-depleted duct. In this duct, the condition of Eq. (15) can lightly be satisfied because the local Alfvén velocity inside the duct is equal to the beam velocity; that is, $v_{AD} = v_b$ when the self-generated AW reaches saturation, while the beam velocity v_b usually is well larger than the critical velocity of the ECM emitting radiation, $\sqrt{Q}c \simeq 7000$ km s^{-1}. This indicates that the fast electron beam can self-consistently construct a tenuous plasma environment that is more favorable for the ECM emission to work.

Combining the discussions above, we try to describe a self-consistent scenario for the ECM emission that is driven by a fast electron beam with the self-generated AW. When a fast electron beam with density $n_b < n_0$ and velocity $v_b > v_A$ travels into a magneto-plasma along the ambient magnetic field $\boldsymbol{B}_0$, it can excite AW via the current instability, also called the self-generated AW. Although it has a very low saturation level $B_w^2 \lesssim \beta_0 B_0^2 \ll B_0^2$ for the low-β plasma of $\beta_0 \ll 1$ in general, the self-generated AW can significantly affect the ECM emission driven by the beam via the two aspects below.

First, the self-generated AW pushes aside the plasma due to its wave pressure $B_w^2/2\mu_0$ and makes a density-depleted duct along the way of the beam traveling, which has a density depletion $n_D = \left(v_A^2/v_b^2\right) n_0 \ll n_0$ for the fast electron beam with $v_b \gg v_A$. In particular, there is a much higher local Alfvén velocity $v_{AD} = v_b$ inside the density-depleted duct, which is more favorable for the ECM emission to occur inside the duct where the local Alfvén velocity is $v_{AD} > \sqrt{Q}c \simeq 7000$ km s^{-1}. Thus, the magnetization condition $\omega_{ce} > \omega_{pe}$ is satisfied.

Second, the self-generated AW leads to a velocity distribution of the beam electrons that evolves quickly into a crescent-shaped distribution via the pitch-angle scattering by the self-generated AWs, and this crescent-shaped distribution can efficiently supply the free energy to drive the ECM instability.

To make this ECM mechanism effectively work, however, another unsolved important problem is how the radiation escapes from the duct. One of possible cases is that the radiation is not emitted in an exactly perpendicular direction, so that the radiation trapped in the duct can propagate along the duct and ultimately escape at the location with a lower background density as proposed by Duncan (1979) and Wu et al. (2002). Another possibility is that the motion of the duct toward lower-density regions carries the radiation trapped in the duct into lower-density regions where the lower plasma frequency favors the radiation that escapes, as suggested by Treumann et al. (2012).

4. Discussion and conclusion

Another important instability driven by a fast electron beam is the Langmuir wave (LW) instability, which usually has a much faster growth rate than that of the AW instability. However, this does not imply that the LW instability is more important than the AW instability. The propagation of the LW caused by the thermal pressure of the ambient plasma usually has a phase speed that is close to the kinetic speed of the ambient plasma particles. Thus the LW, in general, has a much faster dissipated rate than the AW. In consequence, the AW has a much longer effective growing time than the electrostatic wave and, hence, has a much higher saturation level than the electrostatic wave. For a long time, it has been recognized that there is a basic difficulty in the propagation of the fast electron beam, sometimes referred to as Sturrock's dilemma (Sturrock 1964). Based on the theory of the Langmuir instability, a fast electron beam should be decelerated considerably within a propagating distance of a few km (or i.e., after $\sim 10^{-5}$ s), which contradicts the result that solar type III radio bursts are observed to last for several seconds and that solar energetic electrons propagate from the Sun to the Earth (Lin 1985). Although many mechanisms have suggested maintaining the beam to propagate it over larger distances and for longer times, the resolution of the Sturrock's dilemma has long been a challenge for plasma physics. We suspect that there possibly is some process, such as magnetic reconnection in the corona or flow convection in the photosphere (Khodachenko 2009), which continually supplies energy to maintain the propagation of the fast electron beam and the current continuity of the current-carrying electron beam.

It is worthy to notice that the physical nature of the AW instability is the macroscopic electric-current instability that does not depend on the kinetic wave-particle interaction, unlike a microscopic kinetic instability, such as the LW instability that driven by the kinetic wave-particle resonant interaction. As shown by the growth rate in Eq. (8), the driven free-energy source for the self-generated AW comes from some macroscopic current system that maintains the electric current carried by the traveling electron beam, $j_{\rm b}$, but not from the non-Maxwell distribution of the beam electrons that drives the ECM instability.

The self-consistent ECM mechanism presented here shows that a fast electron beam along the magnetic filed can self-consistently satisfy the magnetization condition for the ECM radiation and the inversion condition for the ECM instability by including the effects of the self-generated AWs that are excited by the beam current and, hence, overcome the two serious difficulties in the previous ECM theory. This allows ECM to easily occur. Although the present discussion is preliminary, we believe that this novel scenario for the ECM emission, which is driven by fast electron beams, possibly has interesting implications and a general significance for radio bursts from the Sun and the planet and other similar cases, such as the regions near central massive objects and highly magnetized stars (Benz & Güdel 2010; Güdel 2002). This is because of the self-consistency of the model in physics and its simplicity and efficiency.

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