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A MECHANISM FOR BURSTY RADIO EMISSION IN PLANETARY MAGNETOSPHERES

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Abstract. Bursty radio emissions are often observed from the polar magnetospheres of the Earth, Jupiter, Saturn, and Uranus in addition to the smooth radio emissions commonly detected. We show that in plasma regimes in which the electron plasma frequency is less than the electron cyclotron frequency, anisotropic electron beams or gyrating electron beams can excite directly broadband electromagnetic radiation. The largest growth is for right-hand X-mode radiation with frequencies above the electron cyclotron frequency. This instability can produce bursty, broadband emission, consistent with some of the properties of the radiation observed from the magnetized planets.

Introduction

Spacecraft explorations in the last two decades have revealed that the magnetospheres of the Earth, Jupiter, Saturn, Uranus, and Neptune are sources of electromagnetic radio emissions. The most intense radiations are generally believed to propagate in the fast extraordinary mode and originate in the high latitude polar regions where the electron plasma frequency (ω_e) is typically smaller than the electron cyclotron frequency (Ω_e). Numerous theories have been proposed to explain the generation of these radio emissions. Of these theories, the cyclotron maser instability, first suggested by Wu and Lee [1979], appears to be the most plausible. One of the strong advantages of this theory is that the electromagnetic radiation is generated directly through wave-particle interactions rather than through mode conversion or other nonlinear processes [see reviews by Grabbe, 1981; Goldstein and Goertz, 1983].

In addition to the smooth radio emissions, bursty emissions have also been observed from Jupiter [Carr et al., 1983], Uranus [Evans et al., 1987, Farrell et al., 1990], Neptune [Warwick et al., 1989], and possibly Earth [Helliwell et al., 1989], and Saturn [Lecacheux and Genova, 1983]. (We refer to radio emissions as being "bursty" if they have been so described by the observers. The reader will note that some of these sources are significantly more "bursty" than others.) The characteristics of all these bursty emissions tend to be quite different from the smooth emissions. The emission is of short duration (the bKOM source at Jupiter may be an exception to this)

and is either narrow or broad band. There is some evidence that these waves propagate parallel to the ambient magnetic field.

The natural question to ask is whether these bursty emissions are generated by the same mechanism as are the smooth emissions. If this is the case, then why are the characteristics of the bursty emission so different from those of the smooth emissions? One possible explanation is to assume that both types of emissions are generated by the same mechanism, but because of variations in the physical parameters in source regions (e.g. different forms of the distribution function and/or different background plasma parameters), the emission patterns are significantly altered. Alternatively, one can look for different generation mechanisms altogether. In this paper we report one example of this latter alternative.

We show below, in a nonrelativistic calculation, that a gyrating electron beam or an electron beam with a temperature anisotropy of the form $T_{\perp} \gg T_{\parallel}$ can generate directly electromagnetic radiation through a cyclotron resonant-wave-particle interaction. The frequencies of the unstable waves can be above Ω_e , depending on the characteristics of the ambient plasma. In fact, this mechanism has been proposed by Goldman and Newman [1987] to explain the "new electromagnetic beam mode" discovered in laboratory experiments reported by Urrutia and Stenzel [1984]. Subsequently, Newman et al. [1988] performed a comprehensive analysis of this instability including numerical simulations. However, in these analyses ω_e was much greater than Ω_e . Thus, the electromagnetic waves generated at frequencies ω between Ω_e and ω_e could not be a freely propagating normal mode of the background plasma. We show below that this same instability also operates in the parameter regime $\omega_e \ll \Omega_e$. In this situation, the excited wave frequency can lie above both the ordinary and extraordinary mode cut-off frequencies. Thus, even in the absence of the beam, the wave, once generated, propagates freely in the background plasma.

Physical Model and Results

The physical model we consider is a gyrating or anisotropic electron beam immersed in a cold background magnetized plasma. Because the frequencies we consider are close to Ω_e , we can ignore the ion contribution to the plasma dielectric. One key question is just how such distributions could be formed, and there are several possibilities that one might imagine. For example, gyrating electron beams in the auroral zone may arise as a consequence of injection from the plasma sheet during a geomagnetic

substorm. If this injection occurs at some angle to the ambient magnetic field, then in the auroral region the electrons will have a gyrating beam distribution. An anisotropic electron beam distribution might arise in a somewhat similar fashion from the propagation of electron beams into the auroral zone along converging magnetic fields.

A general form for the electron distribution function which includes both temperature anisotropy and gyration about the background magnetic field is

$$f_b(v_{\parallel}, v_{\perp}) = \frac{A}{\pi^{3/2} \alpha_{\perp b}^2 \alpha_{\parallel b}} \exp \left[-\frac{(v_{\perp} - v_{\perp 0})^2}{\alpha_{\perp b}^2} - \frac{(v_{\parallel} - v_b)^2}{\alpha_{\parallel b}^2} \right] \quad (1)$$

where $\alpha_{\perp b} \equiv (2\kappa T_{\perp b} / m_e)^{1/2}$, and all other symbols and parameters are defined as in Goldstein and Wong [1987].

The derivation of the growth rates for both left and right-hand modes propagating parallel to \mathbf{B} has been described in Goldstein and Wong [1987, eq. (5)]. In all cases, the waves are predominantly right-hand circularly polarized. The dispersion relation was solved using $\omega_b/\Omega_e = \omega_e/\Omega_e = 0.1$, where ω_b and ω_e are the plasma frequencies of the beam and background electrons, respectively. We present results first for an anisotropic electron beam and then for an isotropic gyrating electron distribution. Three values of the temperature anisotropy were used: $T_{\perp b}/T_{\parallel b} = 6, 15$, and 20 , respectively. The drift speed of the electron beam was $v_b = 3.5$ (in units of $\alpha_{\parallel b}$), the plasma "beta" of the beam was $\beta_{\parallel b} = 5 \times 10^{-5}$ (where $\beta_{\parallel b} \equiv 8\pi n_b \kappa T_{\parallel b} / B^2$). This value was held constant in these solutions while $\beta_{\perp b}$ was varied. The plasma beta of the background electrons was $\beta_{\perp e} = 1 \times 10^{-6}$. The results are shown in Figure 1 in which we plot the real and imaginary frequencies (ω_r and γ , respectively) as functions of wave number. The frequencies are normalized to Ω_e , and the wave number to $\Omega_e/\alpha_{\parallel b}$. Note that ω_r and γ are plotted on linear and logarithmic scales, respectively.

As is evident from Figure 1, the instability exists for $T_{\perp b}/T_{\parallel b}$ as small as 6, but grows rapidly for increasing anisotropy as does the bandwidth of the instability. Note also that the frequency of the unstable waves lies above the X-mode cut-off frequency, which is approximately $1.02 \Omega_e$ for the parameters chosen.

Figure 2 illustrates the behavior of the instability as a function of increasing beam speed for values of $v_b/\alpha_{\parallel b}$ ranging from 3.5 to 9 with a temperature anisotropy of 10. The growth rate increases with increasing beam speed. This increase is accompanied by a shift of the maximum growth to higher wave number (and frequency) together with an increase in the bandwidth of the unstable waves.

In Figure 3, we show the behavior of the instability when driven by an isotropic gyrating electron beam. All the parameters are unchanged except that we varied the ring speed instead of the temperature anisotropy. Note that the instability is qualitatively the same whether driven by a gyrating ring or a temperature anisotropy. This result is expected from the arguments given in Wong and Goldstein [1987] where we showed that for parallel propagating elec-

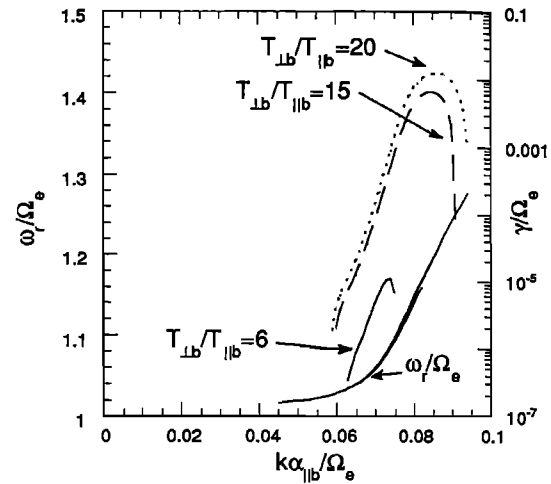


Fig. 1. The real frequency ω_r/Ω_e (linear scale) and growth rate γ/Ω_e (logarithmic scale) for electromagnetic waves driven unstable by an anisotropic electron beam. For these solutions, $\omega_b/\Omega_e = \omega_e/\Omega_e = 0.1$ and the speed of the beam was $v_b = 3.5$ (in units of the parallel thermal speed $\alpha_{\parallel b}$). Unstable roots are shown for three values of the temperature anisotropy.

tromagnetic waves a gyrating ring beam distribution is equivalent to a beam distribution with an effective temperature anisotropy.

Figure 4 shows the variation of the instability with beam density, parametrized by ω_b/Ω_e . The results are shown for $v_{\perp 0}/\alpha_{\perp b} = v_b/\alpha_{\parallel b} = 3.5$. Note that although the growth rate decreases with decreasing beam density, the instability exists even for the very low beam density of $\omega_b/\Omega_e = 0.0125$. In both Figures 3 and 4, all the curves for γ/Ω_e appear at the same value of $k\alpha_{\parallel b}/\Omega_e$, primarily because the beam speed is the same so that the resonance wave number is unchanged. In addition, the upper fre-

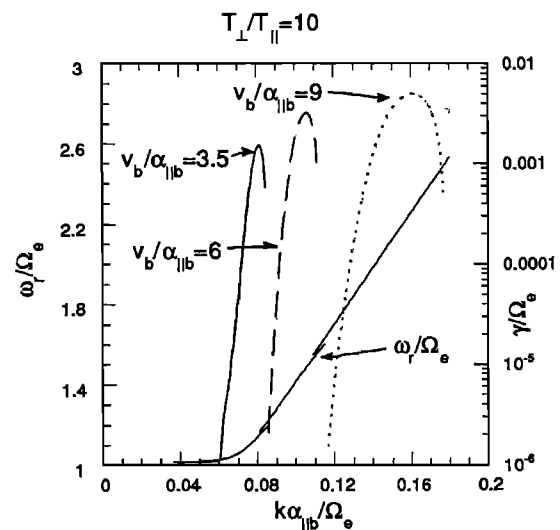


Fig. 2. The variation of the anisotropic electron beam instability with increasing speed of the electron beam. Note the increase in both frequency and wave number bandwidth with increasing values of v_b .

quency cut-off of the instability is approximately the same for all values of beam density, although the lower cut-off shifts to higher wave number as the beam density decreases.

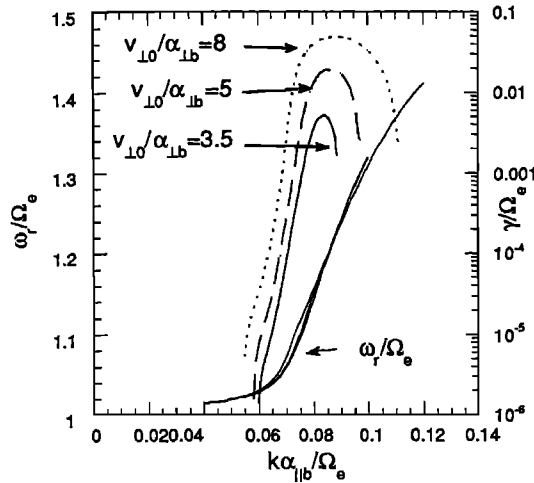


Fig. 3. Growth rates of electromagnetic waves driven unstable by an isotropic gyrating electron beam. The instability is shown for three values of the ring speed, $v_{\perp 0}$.

We have also investigated the behavior of this instability for oblique propagation for both the gyrating ring beam and the anisotropic beam (results not shown). For the parameters used in Figures 1 and 3 the instability has a relatively broad peak centered around $\Theta = 0^\circ$. The most notable feature of the oblique result is the broadband nature of the instability. For nearly parallel propagation, the growth rate was $\gamma/\Omega_e \approx 3.3 \times 10^{-3}$. For propagation at 32° to the field we found that γ/Ω_e had decreased by less than a factor of two, but then fell rapidly for larger propagation angles. For the anisotropic beam, we used the same beam speed, but with a temperature anisotropy of 10, with qualitatively similar results except that the maximum growth rate was smaller (because the ring speed had an

effective temperature anisotropy larger than 10) and the growth rate fell by a factor of ≈ 2 by 25° .

In addition to the right-hand mode, the left hand mode should also be unstable. In the dense plasmas ($\omega_e \gg \Omega_e$) studied by Goldman and Newman [1987] and Newman et al. [1988], the left hand mode actually dominated the development of the instability, at least in the early stages of development. Goldman and Newman found that as a function of wave number the largest growth occurred for the left hand mode, while in the particle-in-cell simulations reported by Newman et al. the left hand mode initially dominated but soon saturated and damped. For the parameters used here the left hand (linear) instability grows at a lower rate than does the right-hand instability. It is interesting, however, that at the values of $k\alpha_{||}/\Omega_e$ for which growth of the “left hand” instability is significant (although still smaller than that of the right-hand mode), the real frequencies are negative so that the waves actually have right-handed polarization. In contrast to the right-hand instability, the growth rate of the left hand instability decreases as the beam speed is decreased. At $v_b = 0$ the situation reduces to that studied previously by Wu et al. [1989].

Summary and Discussion

In this paper we have shown that it is possible for either an anisotropic electron beam or a gyrating electron beam to drive unstable freely propagating electromagnetic radiation in tenuous plasmas in which $\omega_e \ll \Omega_e$. With the proper choice of parameters, the radiation is generated above the X-mode cut-off frequency. The crucial requirement is that the electron distribution include a beam component, i.e. in eq. (1) it is essential that $v_b \neq 0$. This instability arises from a cyclotron resonance between the electron beam and the fast mode. This facet of the instability was used by Goldman and Newman [1987] and by Newman et al. [1988] to explain the laboratory results of Urrutia and Stenzel [1984] which had indicated that the real frequencies were close to $kv_b \pm \Omega_e$. Goldman and Newman [1987] developed the basic theory which was then elaborated and extended by Newman et al. [1988] in their extensive particle-in-cell simulations of the instability in the high density regime ($\omega_e \gg \Omega_e$).

The work reported here extends the Newman et al. analysis into the low density, low plasma beta regime which is very relevant to the excitation of planetary radio emission in the polar regions of magnetized planets. In both the present work and in the earlier references, the instability is excited even though the beam is tenuous. In dense plasmas ($\omega_e \gg \Omega_e$), the beam is first unstable to a “bump-in-tail” electrostatic instability which quickly saturates. The remaining temperature anisotropy then drives the electromagnetic instability. In Figures 1 and 4, we have shown that for low density plasmas, the electromagnetic instability is sensitive to both temperature anisotropy and beam density.

The presence of the beam plays an essential role in possible application to planetary radio emission since it is the beam which provides the Doppler shift necessary to boost the unstable waves above the right-hand cut-off frequency so that they are freely propagating modes and can

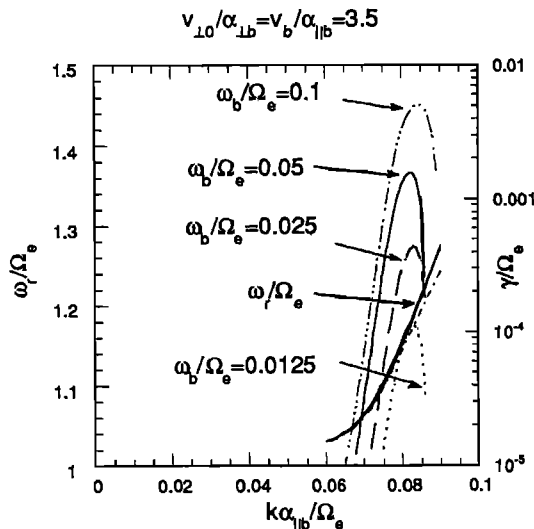


Fig. 4. The variation with density of the electron beam of the instability when driven by a gyrating electron beam.

thus escape the source region when the waves are no longer in resonance with the beam. The fact that the unstable waves can be generated in a relatively broad cone of angles of propagation suggests that the radiation produced by the electron beams can fill a cone of emission with a half width of approximately 30° . The instability is also capable of generating either broad-band or narrow-band emission, depending on the local beam and plasma parameters. Our results also indicate that this mechanism can easily generate radiation a factor of two above the electron cyclotron frequency. Because this instability is driven by electron beams, any intermittence in the beam generation mechanism will immediately lead to the generation of bursty radio emission. In addition, other time dependent features of the beam or ambient magnetic field may cause the line-of-sight of an observer to move in and out of the radiation pattern, which can also be perceived as burstiness of the source.

The work described here is complementary to the recent work of Wu et al. [1989] who considered a similar instability driven by a pure ring distribution. Their work was motivated by the observation of radio waves at frequencies between 150–700 kHz by ground facilities. The unstable waves were typically generated at frequencies below the electron cyclotron frequency and therefore were not freely propagating modes in the absence of the beam. Our work further extends the variety of waves that gyrating and anisotropic electron distributions can generate to include waves propagating above Ω_e ; however, a significant beam component is required.

In this paper our analysis of the electromagnetic beam mode instability was carried out nonrelativistically. To compare quantitatively this mechanism with the cyclotron maser instability [see, for example, Wu and Lee, 1979], one must include relativistic effects in the electromagnetic beam mode. Nonetheless, although we expect that relativistic corrections will be quantitatively important, we do not expect them to be as significant as in the cyclotron maser instability, primarily because the resonant condition is due to the presence of the beam. For the cold gyrating beam, where relativistic corrections can be computed, we have found that the nonrelativistic approximation is satisfactory in that the magnitude of the growth rate is within about 20% of the relativistic analysis. A fully relativistic treatment of this instability is complex and beyond the scope of this Letter, but we hope to have the computational tools appropriate to explore such effects in the future.

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