Stimulation of electron Bernstein modes by perpendicular ion beams

A. L. Brinca

Centro de Física de Plasmas, Instituto Superior Técnico, Lisbon, Portugal

F. J. Romeiras

Centro de Física de Plasmas, Instituto Superior Técnico, Lisbon, Portugal

L. Gomberoff

Departamento de Física, Facultad de Ciencias, Universidad de Chile, Santiago, Chile

Received 8 April 2003; revised 21 September 2003; accepted 29 September 2003; published 29 November 2003.

[1] This investigation studies the characteristics of electron cyclotron harmonic waves generated by almost monoenergetic perpendicular ion beams. Its motivation is twofold: (1) the new type of free energy source, beams made up of protons, alpha particles, and multiply ionized carbon, nytrogen or oxygen ions, has recently been observed in the geoplasma, and (2) the classical mechanism associated with the stimulation of these electrostatic modes is unable to explain some of their observed features, namely the fine structure sometimes seen in the emission bands and the occurrence of multiple harmonics with the higher branches lying above the upper hybrid frequency. The appropriate dispersion equation supports the developed analysis and determines the properties of this new excitation mechanism. Its characteristics contribute to overcome difficulties encountered by the standard paradigm in the interpretation of several types of electron Bernstein emissions. *INDEX TERMS:* 2724 Magnetospheric Physics: Magnetopause, cusp, and boundary layers; 2772 Magnetospheric Physics: Plasma waves and instabilities; 7867 Space Plasma Physics: Wave/particle interactions. **Citation:** Brinca, A. L., F. J. Romeiras, and L. Gomberoff, Stimulation of electron Bernstein modes by perpendicular ion beams, *Geophys. Res. Lett.*, *30*(22), 2175, doi:10.1029/2003GL017501, 2003.

1. Introduction

[2] The first electron Bernstein modes observed in space were man made. The Alouette satellite generated a pulsed variable frequency signal in the upper ionosphere that excited strong resonances occurring very close to the local cyclotron harmonic frequencies, up to about the tenth cyclotron harmonic [*Calvert and Goe*, 1963; *Lockwood*, 1963].

[3] Later, OGO 5 [*Kennel et al.*, 1970] and many other missions (for example, IMP 6 and 7, Hawkeye, ISEE 1 and 2, GEOS, SCATHA, GEOTAIL) detected several types (upper hybrid, diffuse, multiharmonic, totem pole) of natural cyclotron harmonic electrostatic emissions.

[4] Excluding the more recent SCATHA [*Koons and Fennel*, 1984] and GEOTAIL [*Matsumoto and Usui*, 1997; *Usui et al.*, 1999] observations, the basic features of the electron cyclotron harmonic emissions encountered in the geoplasma were interpreted in terms of a standard model reviewed by *Kennel and Ashour-Abdalla* [1982]: an admixture of cold and hot electron populations neutralized by immobile background ions, with the perpendicular velocity distribution of the hot species providing the free energy, usually associated with a loss cone. Its instability characteristics depended upon the ratios of the temperatures (T_c/T_H) and number densities (N_c/N_H) of the two electron populations, the loss cone properties, and the upper hybrid frequency defined by the cold electron species; they successfully explained simultaneous particle and field observations in GEOS [*Rönnmark et al.*, 1978], for example.

[5] However, this paradigm is unable to justify the fine structure in electrostatic emission bands between electron gyrofrequency harmonics detected by SCATHA and the higher frequency bands of the Totem Pole emissions observed by GEOTAIL (where fine structures are also found). We are thus led to explore other mechanisms that can both excite electron Bernstein modes and eventually provide comprehensive interpretations of heretofore unexplained emission features. We shall study the stimulation of electron cyclotron harmonic waves by perpendicular (with respect to the background magnetic field $\mathbf{B_0}$), almost monoenergetic ion beams recently observed by INTERBALL 1 [*Lutsenko and Kudela*, 1999], stressing at the outset that the aim of the investigation is to obtain the main characteristics of the waves stimulated by this new generation mechanism and not to interpret any specific emission observations, a task to be addressed elsewhere.

[6] Analysis supported by the dispersion equation derived from the linearized Maxwell and Poisson equations shows that these ion beams can excite electron Bernstein modes whose characteristics are reasonably indifferent to the existence of two electron populations, in bands above and below the upper hybrid frequency, and exhibiting fine spectral structure.

2. Model and Dispersion

[7] Although this investigation does not interpret specific observations of electron Bernstein emissions, the adopted medium parameters are compatible with typical values encountered in the vicinity of the dayside magnetopause, with the ion beam properties inferred from the DOK-2 experiment in the INTERBALL 1 spacecraft [*Lutsenko and Kudela*, 1999; *Lutsenko*, 2001]. The envisaged, globally neutral, unperturbed magnetoplasma is made up of an arbitrary number of particle populations permeated by an

0094-8276/03/2003GL017501

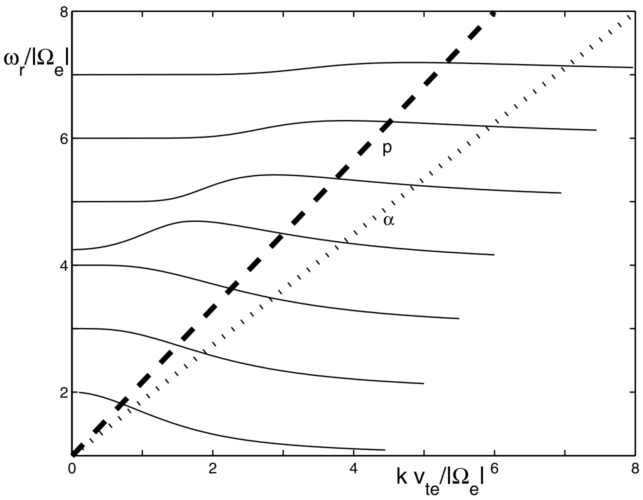

Figure 1. Dispersion of the first seven electron Bernstein flute modes in a hydrogen maxwellian plasma with B_0 = 55 nT, T = 30 eV and N_0 = 0.5 cm^{-3}. The straight lines indicate the perpendicular drift velocities of the proton (dashed) and alpha particle (dotted) beams to be considered in other figures.

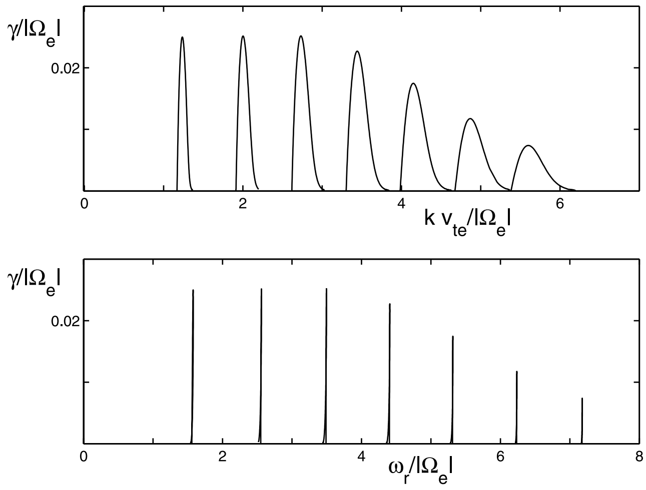

Figure 2. Temporal growth rates of the first seven electron Bernstein flute modes stimulated by a perpendicular proton beam as a function of the wavenumber (upper panel) and the real frequency (lower panel). Model parameters given in the text.

uniform magnetic field $\mathbf{B_0} = B_0\hat{\mathbf{x}}$, with B_0 = 55 nT. Their equilibrium distribution functions are modeled by

$$F_{0s}(\mathbf{v}) = \frac{N_{0s}}{A_s\left(\sqrt{\pi}v_{ts}\right)^3}\exp\left[-\frac{(v_x - V_{bs})^2}{v_{ts}^2} - \frac{\left(v_y - V_{ps}\right)^2 + v_z^2}{A_s v_{ts}^2}\right],$$

so that each species, identified by the subscript s, is characterized by its number density N_{0s}, thermal speed $v_{ts} = (2T_{sx}/m_s)^{1/2}$, temperature anisotropy $A_s = T_{s\perp}/T_{sx}$, and the parallel (V_{bs}) and perpendicular (V_{ps}) drift velocities.

[8] The electrostatic dispersion equation provided below allows for these possibly anisotropic and drifting populations, and arbitrary directions of wave propagation; within the adopted electrostatic and nonrelativistic model, it imposes no restrictions on the frequency or wavenumber ranges, and the particle dynamics (ions, in particular, can be magnetized). In the present study, however, all the species are assumed isotropic (A_s = 1) and to have no parallel drifts (V_{bs} = 0), with the perpendicular drift direction determining the orientation of the wave vectors (according to *Lutsenko and Kudela* [1999], the almost monoenergetic ions are unmagnetized). The sole, nondrifting ($V_{be} = V_{pe} = 0$), electron population has N_{0e} = 0.5 cm^{-3}, T_e = 30 eV, so that $\omega_{pe}/|\Omega_e|$ = 4.12 and (for an hydrogen magnetoplasma) v_A/v_{te} = 0.526, corresponding to a (low) plasma β = 0.002, with the cyclotron angular frequencies defined by $\Omega_s = q_sB_0/m_s$, and v_A and ω_{pe} denoting the Alfvén speed and the electron plasma frequency.

[9] As to the ion (proton and, or, alpha particle) populations, their characteristics depend on the model under analysis, although, because the acceleration mechanism for the solar wind ions invoked by *Lutsenko and Kudela* [1999] is less efficient for lighter particles, we always assume the existence of a nondrifting ($V_{bp_0} = V_{pp_0} = 0$) proton population identified by the subscript p_0, with $T_{p_0} = T_e$; the perpendicular drift parameters of the ion beams are estimated from Figure 1b of *Lutsenko* [2001], T_p = 300 eV, T_α = 500 eV, V_{pp} = 1.33 v_{te}, $V_{p\alpha} = v_{te}$, whereas the ion densities (N_{0p0}, N_{0p}, $N_{0\alpha}$) shall be defined below as the need arises (here the available observations are not helpful and the adopted values are mere reasonable guesses, albeit satisfying global neutrality, $N_{0e} = N_{0p_0} + N_{0p} + 2N_{0\alpha}$).

[10] Previous research on the stability of perpendicular currents in cold [*Brinca et al.*, 2002] and hot [*Brinca et al.*, 2003] plasmas has derived the corresponding electromagnetic dispersion equations from the appropriate (Maxwell, Lorentz, Vlasov) linearized equations and offered algorithms for their numerical solution. Here we are concerned with electrostatic longitudinal (wave electric field parallel to the wave vector) waves, so that the Maxwell equations are

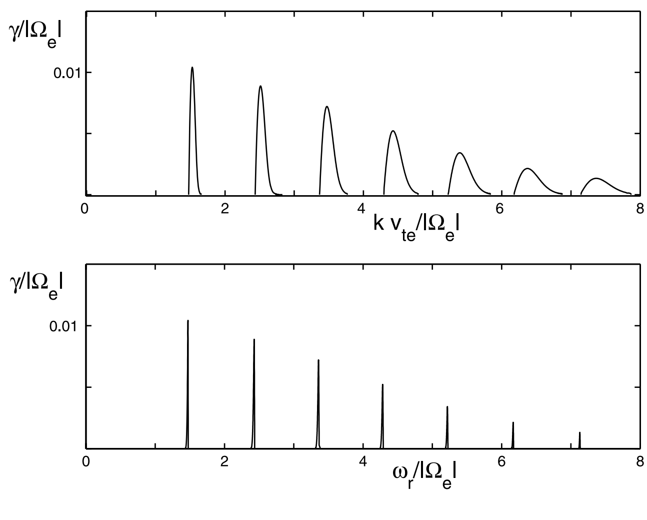

Figure 3. As in Figure 2, but for an alpha particle beam.

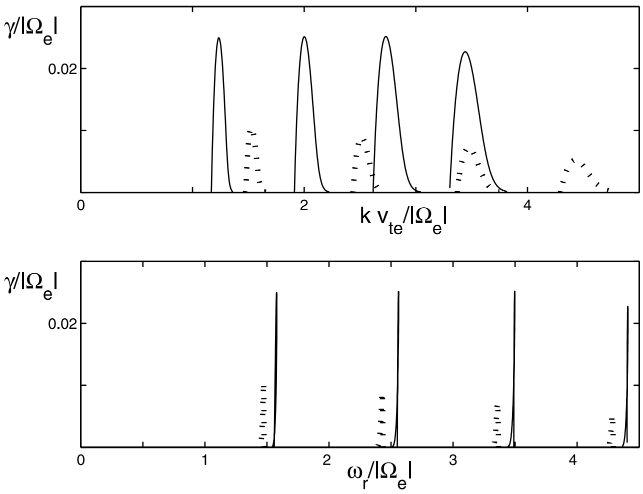

Figure 4. Temporal growth rates encountered in the first four harmonic bands of the electron Bernstein flute modes stimulated by coexisting perpendicular proton (solid lines) and alpha particle (dashed lines) beams, as a function of wavenumber (upper panel) and real frequency (lower panel). Model parameters given in the text.

reduced to the Poisson equation and the following, much simpler, dispersion equation is obtained:

$$-1+\sum_s\left(\frac{\omega_{ps}}{kv_{ts}}\right)^2 e^{-\lambda_s}\sum_n I_n(\lambda_s)Z'(\xi_{sn})-2\sum_s\frac{\Omega_s}{A_s k_x v_{ts}}\left(\frac{\omega_{ps}}{kv_{ts}}\right)^2 \cdot e^{-\lambda_s}\sum_n I_n(\lambda_s)Z(\xi_{sn})=0,$$

where I_n stands for the modified Bessel function of order n, Z' is the derivative of the (Fried) plasma dispersion function Z, $k_\perp$ $\{\cos\phi, \sin\phi\} = k_{\{y,z\}}$, $k^2 = k_x^2 + k_\perp^2$, $\omega_{ps}^2 = N_{0s}q_s^2/(\epsilon_0 m_s)$, $\omega_{ys} = \omega - k_y V_{ps}$, $\omega_{sn} = \omega_{ys} - n\Omega_s$, $\xi_{sn} = (\omega_{sn} - k_x V_{bs})/(k_x v_{ts})$, and $\lambda_s = (A_s k_\perp^2 v_{ts}^2)/(2\Omega_s^2)$.

[11] This equation characterizes the complex dispersion of the medium under investigation. The wave-like perturbations are assumed to vary as $\exp[-i(\omega t - \mathbf{k.r})]$, $\omega = \omega_r + i\gamma$, with the arbitrary orientation of the (initial value problem) real wave vector **k** defined by the angles ϕ and $\theta = \sin^{-1}(k_\perp/|k_x|)$, albeit we recall that here the wave vector is always aligned with the direction of the perpendicular ion drifts, $\mathbf{k} = k\hat{\mathbf{y}}$ ($\theta = \pi/2$, $\phi = 0$); unstable modes have $\gamma > 0$.

3. Wave Stimulation

[12] As a background to the ensuing results, Figure 1 depicts the dispersion of the first seven flute (perpendicular propagation, $k_\| = 0$) electron Bernstein modes in the maxwellian hydrogen plasma associated with the adopted medium ($N_{0p} = N_{0\alpha} = 0$, $T_{p_0} = T_e = 30$eV): the electrostatic waves are stable (no free energy available) but unattenuated (damping arising from wave-particle cyclotron interactions would require electrons with infinite speeds). Also in this figure, the perpendicular drift velocities of the proton and alpha particle beams to be used below are represented, and the upper hybrid frequency, $\omega_{UHF} = 4.24|\Omega_e|$, is implicitly defined as the only starting ($k = 0$) mode frequency that is not a multiple of $|\Omega_e|$.

[13] To model the effects of a proton beam, we assume that in the original isothermal hydrogen magnetoplasma ($T = 30$ eV) half of the proton population ($N_{0p} = 0.25$ cm^{-3}) is transformed into a perpendicular beam with the parameters defined above ($T_p = 300$ eV, $V_{pp} = 1.33\ v_{te}$). The resulting complex dispersion is shown in Figure 2, evidencing the growth of the first seven Bernstein modes at real frequencies that, for the lower harmonics, fall close to $(n + 1/2)|\Omega_e|$, and below this half band value, for the higher branches.

[14] A similar investigation on the stimulation properties of an alpha particle beam adopts $N_{0p_0} = 0.4$ cm^{-3}, $N_{0p} = 0$, $N_{0\alpha} = 0.05$ cm^{-3}, $T_\alpha = 500$ eV, and $V_{p\alpha} = v_{te}$. Again, Figure 3 shows the excitation of the first seven Bernstein harmonics in similar spectral positions but with somewhat smaller temporal growth rates (the alpha beam is much less dense than the proton beam).

[15] Finally, to assess destabilization brought about by the coexistence of proton and alpha particle beams, we use $N_{0p_0} = 0.15$ cm^{-3}, $N_{0p} = 0.25$ cm^{-3}, and $N_{0\alpha} = 0.05$ cm^{-3}, keeping their previously used temperatures unchanged ($T_{p0} = 30$ eV, $T_p = 300$ eV, $T_\alpha = 500$ eV). Figure 4 depicts the resulting complex dispersion and, not surprisingly, the spectra and growth rates basically arise from the combination of the effects already encountered in Figures 2 and 3. In all cases, for these free energy sources, the growth rates maximize at perpendicular propagation ($\theta = \pi/2$). Similar additional effects would have been obtained with the consideration of more, heavier, ion beams.

4. Discussion

[16] The numerical solution of the appropriate dispersion equation demonstrated that the free energy available in perpendicular ion beams is capable of stimulating electron Bernstein modes under circumstances, and with characteristics, that differ from the standard generation model described in the review of *Kennel and Ashour-Abdalla* [1982]. Indeed, this new mechanism dispenses with the need for two, cold and hot, electron populations (and, therefore, with the need for specific ratios between their densities and temperatures), generates flute mode harmonics below and above the upper hybrid frequency, and has the potential to create, via the coexistence of several ion beams, fine structures in the electrostatic emission bands. We stress, however, that the analyzed paradigm should be taken as complementary, and not alternative, to the standard model. The almost monoenergetic ion beams are events of limited duration that do not explain the steadiness of many electron cyclotron harmonic emissions whose basic features are successfully interpreted by the classical mechanism. The novel characteristics provided by the ion beams can, nevertheless, become invaluable interpretation tools for bursty emission observations such as the totem pole waves detected by GEOTAIL; we intend to investigate this issue elsewhere.

[17] **Acknowledgments.** This research was partially performed under the auspices of FONDECYT project nr. 1020152, and one of the authors (A. L. B.) gratefully acknowledges helpful information provided by Dr. V. Lutsenko and support from the complementary FONDECYT project nr. 7020152.

References

Brinca, A. L., F. J. Romeiras, and L. Gomberoff, On the stability of perpendicular particle drifts in cold magnetoplasmas, *J. Geophys. Res.*, *107*(A7), 1090, doi:10.1029/2001JA900169, 2002.

Brinca, A. L., F. J. Romeiras, and L. Gomberoff, On wave generation by perpendicular currents, *J. Geophys. Res.*, *108*(A1), 1038, doi:10.1029/2002JA009375, 2003.

Calvert, W., and G. B. Goe, Plasma resonances in the upper ionosphere, *J. Geophys. Res.*, *68*, 6113–6120, 1963.

Kennel, C. F., F. L. Scarf, R. W. Fredericks, J. H. McGehee, and F. V. Coroniti, VLF emission field observation in the magnetosphere, *J. Geophys. Res.*, *75*, 6136, 1970.

Kennel, C. F., and M. Ashour-Abdalla, Electrostatic waves and the strong diffusion of magnetospheric electrons, in *Magnetospheric Plasma Physics*, edited by A. Nishida, 245–344, Cent. for Acad. Publ. of Jpn., Tokyo, 1982.

Koons, H. C., and J. F. Fennel, Fine structure in electrostatic emission bands between electron gyrofrequency harmonics, *J. Geophys. Res.*, *89*, 3015–3018, 1984.

Lockwood, G. E. K., Plasma and cyclotron spike phenomena observed in top-side ionograms, *Can. J. Phys.*, *41*, 190–194, 1963.

Lutsenko, V. N., Almost monoenergetic ions: New support for Alfvén ideas on the role of electric currents in space plasmas?, *Phys. Chem. Earth (C)*, *26*, 615–619, 2001.

Lutsenko, V. N., and K. Kudela, Almost monoenergetic ions near the Earth's magnetosphere boundaries, *Geophys. Res. Lett.*, *26*(3), 413–416, 1999.

Matsumoto, H., and H. Usui, Intense bursts of electron cyclotron harmonic waves near the dayside magnetopause observed by GEOTAIL, *Geophys. Res. Lett.*, *24*(A), 49–52, 1997.

Rönnmark, K., H. Borg, P. J. Christensen, M. P. Gough, and D. Jones, Banded electron cyclotron harmonic instability—A first comparison of theory and experiment, *Space Sci. Rev.*, *22*, 401–417, 1978.

Usui, H., W. R. Paterson, H. Matsumoto, L. A. Frank, M. Nakamura, H. Matsui, T. Yamamoto, O. Nishimura, and J. Koitzumi, Geotail electron observations in association with intense bursts of electron cyclotron harmonic waves in the dayside magnetosphere, *J. Geophys. Res.*, *104*(A3), 4477–4484, 1999.

A. L. Brinca and F. J. Romeiras, Centro de Física de Plasmas, Instituto Superior Técnico, 1049-001 Lisboa, Portugal. (ebrinca@alfa.ist.utl.pt; filipe.romeiras@math.ist.utl.pt)

L. Gomberoff, Departamento de Física, Facultad de Ciencias, Universidad de Chile, Casilla 653, Las Palmeras 3425, Santiago, Chile. (lgombero@uchile.cl)