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Convective Instabilities of Transverse Wave in a Magnetized Chiral Media

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Abstract

Depending on the characteristics of the distribution function, we find that a new mode conversion and instabilities are present for right circularly polarized waves (RCP) due to chiral effect. From the dispersion relations and considering that the chirowave magnetic field may be important when the condition of velocity isotropy is dropped, we find that growing modes (instabilities) can occur at resonance and for frequencies below the electron gyrofrequency. We study, in this paper, the convective instability of RCP waves in a two-component bi-Lorentzian chiroplasma which can model the solar wind particle distributions.

Keywords:

plasma-chiral medium, plane waves, Faraday rotation, helicon waves

1. Introduction

Chirality is a geometrical notion which refers to the lack of symmetry of an object. A chiral media when interacting with an electromagnetic wave can rotate the plane of polarization of the wave to the right or to the left depending on the handedness of the media.

The control of the degree of chirality is one of the main problems concerning chiral media, which can be solved if the medium is anisotropic. This fact renders the plasma an attractive medium, because it is an anisotropic medium due to the presence of the biasing magnetic field [1,2]. For right circularly polarized waves, (RCP), depending on the characteristics of the distribution function, instabilities are found due to the chiral effect. From the dispersion relation and considering that the chirowave magnetic field may be important when the condition of velocity isotropy is dropped, we find that growing modes (instabilities) can occur at resonance and for wave frequencies below the electron gyrofrequency. This is important to explain the measured electron data in the solar wind which can be represented by two components: a core component (nearly Maxwellian) and a halo component which is less Maxwellian in nature so a Kappa distribution may be used to model the solar wind particle. In this paper we study the stability of right circularly polarized electromagnetic waves propagating parallel to the magnetic field in a two component electron plasma, using a bi-Lorentzian distribution: a hot component, which exhibits a temperature anisotropy while the other is temperature isotropic with chiral effect.

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2. Dispersion Relation and Discussion

Here, a chiroplasma consists of chiral objects embedded in a magnetically biased plasma. Chiral plasma or handed media displays an intrinsic asymmetry with respect to the distinction between left and right. On the level of constitutive relations, this is visible in the magneto-electric coupling β, which contains the degree of chirality. For the proposed constitutive relations, following [2], we have that the transverse waves can be described by:

$$\boldsymbol{F}=\boldsymbol{A}+\beta\nabla\times\boldsymbol{A},\ \boldsymbol{B}=\nabla\times\boldsymbol{F},\ \boldsymbol{E}=-\frac{1}{c}\frac{\partial\boldsymbol{F}}{\partial t}, \qquad (1)$$

$$\boldsymbol{E}=\varepsilon^{-1}(\boldsymbol{D}+\beta\nabla\times\boldsymbol{D}),\ \boldsymbol{B}=\mu(\boldsymbol{H}+\beta\nabla\times\boldsymbol{H}), \qquad (2)$$

in which the vector potentials $\boldsymbol{A}$, $\boldsymbol{F}$ satisfies $\nabla\cdot\boldsymbol{F}=0=\nabla\cdot\boldsymbol{A}$ and the wave equation is

$$\nabla\times\nabla\times\boldsymbol{F}+\frac{1}{c^2}\frac{\partial^2\boldsymbol{F}}{\partial t^2}=\frac{4\pi}{c}(\boldsymbol{j}+\beta\nabla\times\boldsymbol{J}). \qquad (3)$$

If $\overleftrightarrow{\sigma}$ is the conductivity tensor operator of the medium under consideration, and after Fourier analysis in time, we have

$$\nabla\times\nabla\times\boldsymbol{F}-(\omega^2/c^2)\overleftrightarrow{K}(\omega)\cdot\boldsymbol{F}=0, \qquad (4)$$

with the dielectric tensor

$$\overleftrightarrow{K}(\omega)=\overleftrightarrow{I}-4\pi(1\overleftrightarrow{\sigma}+\beta\times\overleftrightarrow{\sigma}(\omega))/\mathrm{i}\omega. \qquad (5)$$

For high-frequency waves and propagation along the magnetic field, we have to consider two circularly polarized transverse wave (E normal to the direction z), expressing $J_\pm$ in terms of $E_\pm$ as

$$(1+k_\pm\beta)J_\pm=\frac{\mathrm{i}\varepsilon_0}{\omega}(\omega^2-k_\pm^2c^2)E_\pm. \qquad (6)$$

In cylindrical coordinates we have [3]

$$k_\pm^2c^2=\omega^2-(1+k_\pm\beta)\frac{\omega_\mathrm{p}^2}{n_\mathrm{e}}\int_v\Big(\frac{(\omega-k_\pm v_\parallel)}{\omega-k_\pm v_\parallel\mp\omega_\mathrm{c}}+\frac{\frac{1}{2}k_\pm^2v_\perp^2}{(\omega-k_\pm v_\parallel\mp\omega_\mathrm{c})^2}\Big)f_0\mathrm{d}^3v, \qquad (7)$$

where k_+ is the wave numbers of a circularly polarized wave which drives electrons in the direction of their cyclotron motion, i.e., a right-hand circularly polarized wave (RCP) and k_- corresponds to a left-hand circularly polarized wave (LCP).

For cold chiroplasma we have no instabilities in the right-hand circularly polarized wave (RCP) [2]. Now, by considering the temperature effect, we can find that for an isotropic equilibrium distribution function the last equation reveals that for $k_\pm$ real, ω has an negative imaginary part at the resonance, $\omega/\omega_\mathrm{c}=1$, between the electrons and the RCP wave, leading to a temporal damping of the wave amplitude. However, depending on the characteristics of the distribution function, resonance can also lead to instabilities (which are associated with a positive imaginary part of $\omega(k)$).

If we consider a simple anisotropic equilibrium distribution function which represents a cold electrons in the parallel z direction, but with a Maxwellian velocity distribution function in the plane normal to B_0, it is a simple matter to verify that, for large values of k_+^2, the wave frequency ω becomes complex. Thus in the limit $k_+^2\to\infty$, but $k_+\beta\leq 1$, the denominator of the last equation vanishes and the second degree equation in ω gives [3]

$$\omega=\omega_\mathrm{c}\pm\frac{\mathrm{i}\omega_\mathrm{p}(1+k_\pm\beta)(k_\mathrm{B}T_\mathrm{e}/m_\mathrm{e})^{1/2}}{c}, \qquad (8)$$

which shows that growing modes (instabilities) can occur for $\omega_\mathrm{r}=\omega_\mathrm{c}$.

For a two component bi-Lorentzian plasma where the chiral effect is in the cold component, n_ch, we have the dispersion relation as $c^2k_+^2=\omega^2+D_\mathrm{hot}+D_\mathrm{ch}$, where

$$D_\mathrm{hot}=\omega_\mathrm{ph}^2\frac{\omega}{k_+}\left[\Big(1-\frac{k_+V_\mathrm{g}A}{\omega}\Big)\left\{\frac{Z_\kappa^*(V_\mathrm{g}/\theta_{\parallel\mathrm{h}})}{\theta_{\parallel\mathrm{h}}}\Big(1+\frac{V_\mathrm{g}^2}{\kappa\theta_{\parallel\mathrm{h}}^2}\Big)+\frac{V_\mathrm{g}(\kappa+\frac{1}{2})}{\kappa^2\theta_{\parallel\mathrm{h}}^2}\right\}-\frac{Ak_+}{\omega}\right],$$

and

$$D_\mathrm{ch}=\omega_\mathrm{pch}^2(1+k_\pm\beta)\frac{\omega}{k_+}\left[\Big(1-\frac{k_+V_\mathrm{ch}}{\omega}\Big)\left\{\frac{Z_\kappa^*(V_\mathrm{g}-V_\mathrm{ch}/\theta_\mathrm{ch})}{\theta_\mathrm{ch}}\Big(1+\frac{(V_\mathrm{g}-V_\mathrm{ch})^2}{\kappa\theta_\mathrm{ch}^2}\Big)+\frac{(V_\mathrm{g}-V_\mathrm{ch})(\kappa-\frac{1}{2})}{\kappa^2\theta_{\parallel\mathrm{h}}^2}\right\}\right],$$

where $V_\mathrm{g}=\frac{\omega-\omega_\mathrm{g}}{k_+}$, $A=(1-\frac{\theta_\perp^2}{\theta_\parallel^2})$, V_ch is the drift velocity of the cold chiral component and $\varepsilon=\frac{n_\mathrm{ch}}{n_\mathrm{h}}$. This dispersion relation has, in general, complex solutions. We study the case of convective instability keeping ω real and fixed. This approach can be useful to model plasma distributions with high energy tails. The chiral effect also enhance the growth of plasma waves, especially when the phase velocity of the RCP wave is large compared to the thermal bulk velocity or the drift velocity of the plasma. Such conditions commonly occur in space, in magnetospheric plasmas, and in solar wind. The chiral effect can enhance the temperature anisotropy of the hot species as source of the instability. However, this is restricted to wave frequencies below the gyrofrequency.

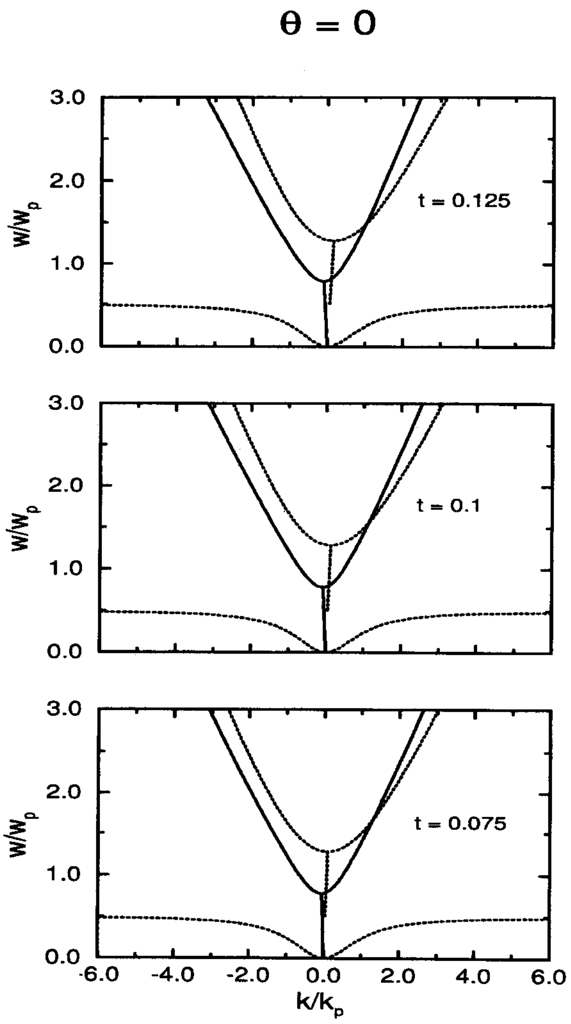

Fig. 1 Dispersion relation for various values of the parameter t (= β) when the direction of the wave propagation is parallel to the magnetic field. The dotted and solid lines correspond to the right and left circularly polarized waves, respectively [8].

As an example, we consider the typical parameters of the solar wind [4] ($B_0 = 7.3\ \gamma$, $\theta_{\|h} = 0.52.10^6\ K$, $\theta_{\|ch} = 0.6\ \theta_{\|h}$, $n_{ch}/n_h = 4.0$), and $T_\perp/T_\| = 2.5$, for a Kappa distribution with a low spectral index $\kappa = k_\pm c/\omega = 4$, and $k_+\beta = 0.3$ and $\varepsilon = 0$. Then, the range where the wave is fully unstable ($\frac{k_i}{k_r} < 0$, for $0 \le \omega/\omega_g \le 0.3$) is similar to the range for a Maxwellian distribution with same parameters except $k_+\beta \simeq 0.5$. For $\kappa = 4$, $\varepsilon = 5$, $v_{ch} = 0.9$ cm·s^{-1}, $\frac{T_\perp}{T_\|} = 10$, we have that the growth rate of the waves increases dramatically. For given values of the drift velocity and $k_+\beta$, the instability increases with increasing ε. As κ increases the wave growth drops sharply. This results is in agreement with the complex ω case dealt with by Thorne and Summers [5].

Taking the limit $\theta \to 0$, the frequency normalized to the plasma frequency, ω/ω_p, the wave number normalized to k_p, k/k_p, ($k_p = \omega_p/c$), and $\frac{v_{te}}{c} = 0.1$, and the ratio between the gyrofrequency and plasma frequency taken to be 0.5, then the β parameter modifies the typical plot of $\omega(k)$ shown by Krall and Trivelpiece [6] and it permits that the waves propagate in a region of frequencies that is forbidden in the case $\beta = 0$. Also the reflection points of the RCP and LCP are shifted [7]. Here the effect caused by the presence of the parameter β is the conversion of modes. In the Figure 1 [8] for $k_+\beta = 0.5 = k_-\beta$, we can also observe that there is a region where both RCP and LCP propagate and for $k/k_p \sim 0.3$ we have a mode conversion from RCP to LCP wave.

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