Kinetic instabilities of the suprathermal populations in the solar wind

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Abstract

The kinetic properties of space plasmas, like their temperature anisotropy and the resulting instabilities, are in general studied considering only the thermal (core) populations. The implications of suprathermal (halo) populations is minimized or just ignored, despite the fact that their presence in the solar wind and planetary magnetospheres is permanently reported by the observations for all species of plasma particles (electrons, protons or heavier ions), and their kinetic energy density may be significant. Here we present the results of a preliminary (linear) study of the kinetic instabilities driven by interplay of core and suprathermal populations, when both these two populations exhibit temperature anisotropies. For conditions specific to space plasmas, the effects of suprathermal populations can be more important than those triggered by the core component. In dilute plasmas from space Coulomb collisions are rare and inefficient in the relaxation of kinetic anisotropies, but the anisotropy-driven instabilities should explain the limits of temperature anisotropy measured in the solar wind.

1. Introduction

The in-situ measurements of the velocity distributions (VDs) of plasma particles in the solar wind reveal states out of thermal equilibrium determined by the presence of suprathermal (halo) populations and deviations from isotropy, e.g., temperature anisotropy $T_\parallel \neq T_\perp$ relative to the stationary magnetic field B_0 [1]. In the absence of collisions only the resulting instabilities are efficient in limiting the increase of anisotropy as predicted, for instance, by the expansion of the solar wind, $T_\parallel > T_\perp$, or the magnetic field compression in shocks, $T_\perp > T_\parallel$.

Driven by anisotropic protons with $A_p = T_\perp/T_\parallel > 1$, the electromagnetic ion-cyclotron (EMIC) instability may interact resonantly with protons scattering them back to quasi-equilibrium state, and limiting their anisotropy. The EMIC instability is mainly studied using simplified VDs which minimize the effects of suprathermal populations [2] and leads to questionable results (see [3], and discussions in [4]). However, the instability is highly dependent on the shape of proton distribution [4, 5, 6] which has a dual structure in the solar wind, with a thermal core and a hotter suprathermal halo, see [7] and references therein. Here we present the results of a first refined analysis of the EMIC instability for a realistic model reproducing the main features of the observed proton (nonstreaming) VDs, i.e., a bi-Maxwellian core and a bi-Kappa halo.

2. Governing dispersion relation

For certain conditions (e.g., the absence of beaming components), the VDs of plasma particles (i.e., $\alpha = e, p$ for electrons and protons, respectively) measured in the solar wind present a dual structure, namely, a Maxwellian core (subscript c) and a suprathermal halo (subscript h), which enhances the tails of the distribution and is well described by the Kappa power laws [8, 9].

$$f_\alpha\left(v_\parallel, v_\perp\right) = f_{\alpha,c}\left(v_\parallel, v_\perp\right) + f_{\alpha,h}\left(v_\parallel, v_\perp\right). \tag{1}$$

These two components may be anisotropic, assuming the core bi-Maxwellian while the halo is reproduced by a bi-Kappa [4, 5]. For such a homogeneous and collisionless plasma of electrons and protons, the dispersion relation for the parallel ($\mathbf{k} \parallel \mathbf{B}$) electromagnetic modes reads

$$\frac{c^2k^2}{\omega^2} = 1 + \sum_{\delta=c,h}\sum_{\alpha=e,p}\frac{\omega_{\alpha,\delta}^2}{\omega^2}\left[\frac{\omega}{ku_{\alpha,\delta,\parallel}}Z_\delta\left(\xi_{\alpha,\delta}^{\pm}\right) + \left(A_{\alpha,\delta}-1\right)\left\{1+\xi_{\alpha,\delta}^{\pm}Z_\delta\left(\xi_{\alpha,\delta}^{\pm}\right)\right\}\right], \tag{2}$$

where ω is the wave-frequency, k is the wave-number, c is the speed of light, $\omega_{\alpha,\delta}^2 = 4\pi n_\delta e^2/m_\alpha$ are the plasma frequencies for the core (subscript $\delta = c$) and halo (subscript $\delta = h$), $A_{\alpha,\delta} = \left(T_{\alpha,\perp}/T_{\alpha,\parallel}\right)_\delta$ are the temperature anisotropies, $\pm$ denote the circular polarizations, right-handed (RH) and left-handed (LH), respectively, $Z_c\left(\xi_{\alpha,c}^{\pm}\right)$ is the plasma dispersion function [10] of argument $\xi_{\alpha,c}^{\pm} = (\omega \pm \Omega_\alpha)/\left(ku_{\alpha,\parallel}\right)$, and $Z_h\left(\xi_{\alpha,h}^{\pm}\right)$ is the modified dispersion function [11] of argument $\xi_{\alpha,h}^{\pm} = (\omega \pm \Omega_\alpha)/\left(k\theta_{\alpha,\parallel}\right)$.

Motivating by the recent theoretical and observational results [12, 13], the temperatures are assumed κ-dependent decreasing with increasing the κ-index. Therefore, for the halo component, temperatures $T_{h,\parallel,\perp}^K$ and, implicitly, the parallel plasma beta parameter $\beta_{h,\parallel}^K$ decrease with decreasing the suprathermal populations [4]

$$T_{h,\parallel,\perp}^K = \frac{2\kappa}{2\kappa-3}T_{h,\parallel,\perp}^M > T_{h,\parallel,\perp}^M, \quad \beta_{h,\parallel}^K = \frac{8\pi n_h k_B T_{h,\parallel}^K}{B_0^2} = \frac{2\kappa}{2\kappa-3}\beta_{h,\parallel}^M > \beta_{h,\parallel}^M, \tag{3}$$

3. Results

The general dispersion relations (2) enables us to study different modes and contributing components, and various regimes as conditioned by different anisotropies, relative densities and temperature contrasts. Considering protons as the main driver of the EMIC instability, the interplay of their core and suprathermal (halo) populations can change the linear dispersive and instability properties. For instance, Figure 1 a, b presents a comparison with a simplified model which assumes the core isotropic and only the halo anisotropic with $A_h > 1$ [7], showing an important stimulating effect of the EMIC instability by an anisotropic core with $A_c > 1$. Both the growth-rate and the range of the unstable wave-numbers may be considerably increased. Moreover, for both models (with isotropic or anisotropic core) the instability is enahnced by the suprathermal populations (Figure 1a,b).

An essential role in stimulating or suppressing the EMIC growth rates is also played by the halo–core density contrast $\eta = n_h/n_c$, and these effects are shown in Figure 1 c, d. The growth rates are increased by diminishing this density contrast, and for an anisotropic core with $A_c > 1$ the enhanced growth rates ($\eta = 0.01$) display two distinct peaks, one driven by the halo and another driven by the core at higher wavenumbers. The occurrence of the second peak is directly related to the presence of an anisotropic core. Even for (unrealistically) large anisotropies of the core ($A_c > A_h$) the peak driven by the anisotropic halo is dominant, stressing that for less extreme conditions specific to space plasmas the effects triggered by the suprathermal populations cannot be ignored.

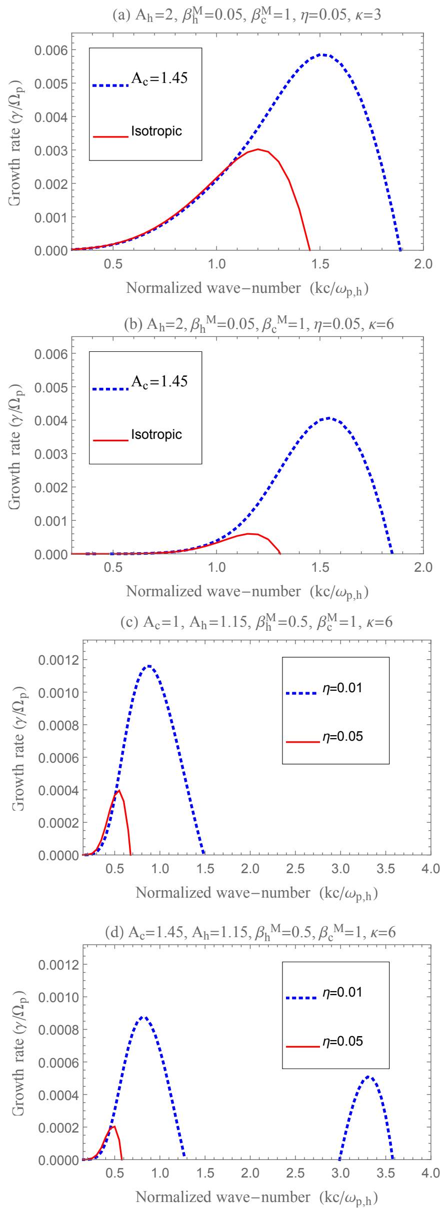

Figure 1: EMIC growth rates. Adapted from Ref. [4].

In order to have a more comprehensive view on the interplay of the core and the suprathermal populations in destabilizing the EMIC modes, we have derived the anisotropy thresholds for two distinct levels of maximum growth rates $\gamma_m/\Omega_p = 10^{-3}$, and 10^{-2} close to the marginal stability $\gamma_m/\Omega_p \to 0$. These thresholds are obtained with an inverse correlation law between the temperature anisotropy A_p and parallel plasma beta $\beta_{h,\parallel}^M$ as $A_h = \left(1 + a/{\beta_{h,\parallel}^M}^b\right) c/{\beta_{h,\parallel}^M}^d$, where a, b, c, and d are the fitting parameters. It's worth to noting that for all the results obtained here the effect of the electrons is minimized, keeping only the zero-order term in the large argument ($|\xi_e|^+ \gg 1$) approximation of their dispersion function. Figure 2 displays these thresholds for both isotropic and anisotropic core models. The effect of the core–halo relative density η is shown in panels a and b for $\gamma_m = 10^{-3}\Omega_p$: the EMIC thresholds increase with increasing η. In the same figure, panels c and d illustrate the effect of the power-index κ for $\gamma_m = 10^{-2}\Omega_p$: the EMIC thresholds are lowered with increasing the suprathermal populations. These effects become important only for regimes of low (parallel) plasma beta $\beta^M_{h,\|} \leqslant 0.1$, which are typical for the suprathermal (halo) component in the solar wind.

4. Conclusions

We have recently proposed an advanced method of characterization of the EMIC instability for conditions typically encountered in the solar wind, where the anisotropic protons exhibit two distinct populations, namely, a bi-Maxwellian core and a bi-Kappa halo [4]. Conditioned by the interplay of these two populations, the instability manifest two distinct peaks of growth rates (Figure 1d), one peak triggered by the anisotropic halo ($A_p > 1$) at lower wave-numbers, and a second peak directly stimulated by the core anisotropy ($A_c > 1$), and the halo–core density contrast. For a fixed anisotropy of the core, the instability thresholds are given by the halo anisotropy, and these thresholds are influenced by the same parameters: the core anisotropy, the core–halo relative density, and the abundance of suprathermal population quantified by the power-index κ. In the new Kappa approach the halo temperature is considered κ-dependent leading to a systematic stimulation of the instability in perfect agreement with the expectations.

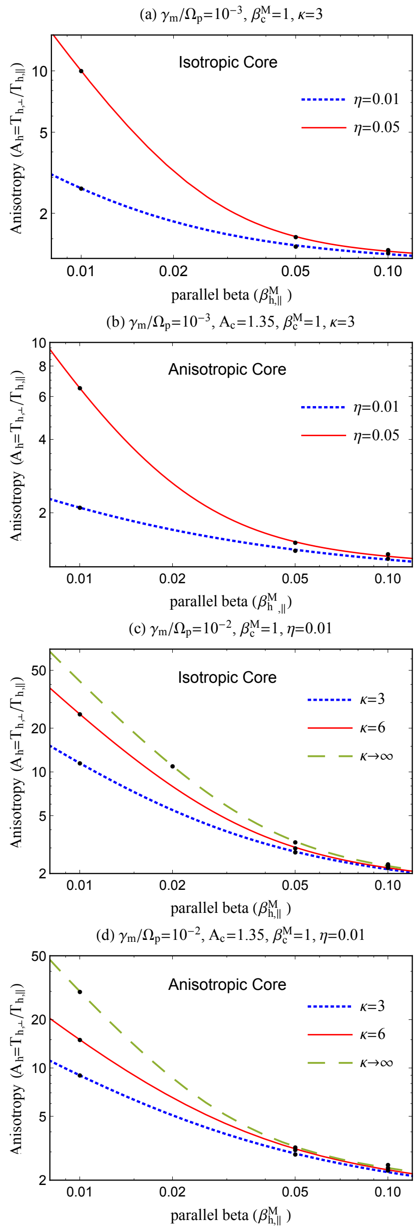

Figure 2: EMIC thresholds conditions for $\gamma_m = 10^{-3}\Omega_p$ (a,b), and $\gamma_m = 10^{-2}\Omega_p$ (c,d).

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