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THE SINGLE PARTICLE AND COLLECTIVE DESCRIPTIONS OF THE ANOMALOUS DOPPLER RESONANCE AND THE ROLE OF ION DYNAMICS

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Abstract

The power $\underline{j} \cdot \underline{E}^*$ dissipated by electrostatic waves interacting with a non-Maxwellian electron velocity distribution is considered. Its component terms illustrate the similarities and differences between collective and single particle treatments of the anomalous Doppler resonance. Examination of the large-k region of wavenumber space - in contrast to the well-known small-k region - shows that ion dynamics are important in stabilising plasmas for which the electron velocity distribution considered alone is destabilising. The sensitivity of theoretical descriptions to the choice of representation of the superthermal electron tail is examined analytically and numerically.

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I. INTRODUCTION

The collective description of the anomalous Doppler effect retains many features of the single-particle description. Consider a system with total relativistic energy E and internal energy U, travelling with velocity βc in a medium with refractive index n. When it emits a photon at an angle θ to its direction of motion, the energy $\Delta E = (h/2\pi)\omega > 0$ supplied to the photon is related to the internal energy change ΔU of the system by[1]

$$\Delta E = \frac{(1 - \beta^2)^{1/2}\Delta U}{1 - n\beta\cos\theta} \tag{1}$$

For motion with $n\beta \leq 1$, Eq.(1) gives the Doppler frequency shift with $\Delta U = (h/2\pi)\omega_o$, where ω_o is the frequency in the rest frame of the system. For superluminal motion with $n\beta > 1$, a positive value for ΔE remains possible within the cone $|\theta| < \theta_o \equiv \cos^{-1}(1/n\beta)$ provided that ΔU is negative. In the case of a superluminal electron in a magnetised medium, the negative ΔU corresponds to an increase in the energy of perpendicular gyration. This is the single-particle anomalous Doppler effect, in which the parallel kinetic energy lost by the electron exceeds that given to the photon (wave), and the balance is transferred to the electron gyromotion.

Consider next a cold beam of electrons in a magnetised plasma. The beam will support waves additional to the bulk plasma waves. These can be negative-energy waves, whose excitation involves a loss in parallel kinetic energy and a smaller gain in perpendicular kinetic energy. When such a wave resonates with a bulk plasma wave, both will grow. Nezlin[2] has pointed out the correspondence between this effect and the single-particle anomalous Doppler effect. There is a net flow from the parallel beam kinetic energy into the perpendicular component of collective motion associated with the beam wave, and into the bulk wave. The diagnostic potential of this process has also been noted.[3]

II. GENERAL PROPERTIES OF THE ANOMALOUS DOPPLER RESONANCE

A collective description of the anomalous Doppler effect arising from the interaction of resonant electrons with electrostatic waves in a magnetised plasma follows from the dielectric response function.[4] We shall show below that ion dynamics play a significant role in wave damping under conditions where the wavenumber is sufficiently large that the ions can be regarded as unmagnetised. For this reason, we include the corresponding ion contribution in the expression for the full dielectric response function:

$$\varepsilon = 1 - \frac{\omega_p^2}{k^2} \sum_{n-\infty}^{\infty} \int_{v_\parallel = -\infty}^{\infty} \int_{v_\perp = o}^{\infty} \frac{2\pi v_\perp dv_\perp dv_\parallel}{n\Omega + k_\parallel v_\parallel - \omega} \left(\frac{n\Omega}{v_\perp} \frac{\partial f}{\partial v_\perp} + k_\parallel \frac{\partial f}{\partial v_\parallel} \right) J_n^2 \left(\frac{k_\perp v_\perp}{\Omega} \right)$$

$$- \frac{\omega_{pi}^2}{k} \int_{-\infty}^{\infty} \frac{dv_i}{kv_i - \omega} \frac{df_i}{dv_i} \tag{2}$$

Here $v_\perp$ and $v_\parallel$ characterise the electron velocity perpendicular and parallel to the magnetic field direction, $f(v_\perp, v_\parallel)$ is the electron velocity distribution function, J_n denotes the Bessel function of order n, and ω_p and Ω are respectively the electron plasma and cyclotron frequencies; $k_\perp$ and $k_\parallel$ are the components of the wavenumber k perpendicular and parallel to the magnetic field direction, $f_i(v_i)$ is the ion velocity distribution function, and ω_{pi} is the ion plasma frequency. For ions of charge Z in a neutral plasma, $\omega_{pi}^2 = Z(m_e/m_i)\omega_p^2$, where m_e and m_i are the electron and ion masses. The real part ε_{real} of ε is in general dominated by cold electron plasma terms which are independent of the exact form of $f(v_\perp, v_\parallel)$. For $(\omega_p/\Omega)^2 \lesssim 0.2$, the electrostatic waves which are roots of $\varepsilon_{real} = 0$ are well described by $\omega = \omega_p k_\parallel/k$ in the frequency range of interest. The imaginary part ε_{im} of ε describes wave-particle resonance, which leads to electrostatic wave growth or damping at a rate given by

$$\gamma = -(\omega_p k_\parallel/k)(\varepsilon_{im}/2) \tag{3}$$

By Eq.(2), a negative contribution from the electrons to ε_{im} arises from the n = -1 term at the parallel resonant velocity $v_{AD} \equiv (\omega + \Omega)/k_\parallel$. This is the anomalous Doppler resonance. If the Landau damping terms are sufficiently weak, wave growth can occur.

The anomalous Doppler effect is of interest as a fundamental limit on superthermal tail formations in tokamak plasmas, and as a probable explanation[5,6] of the relaxation oscillations seen in the soft X-ray signal from Ohmic plasmas[7] and in association with lower hybrid current drive.[8,9] In this application, the divergence of fast-electron motion from the parallel direction as the anomalous Doppler instability proceeds is responsible for the shift in the predominant direction of electron bremsstrahlung, which follows the fast-electron motion. A number of studies[5,6,10-16] have considered such quasilinear development of the instability. The linear instability remains of interest,[17] however, and we shall return to examine this aspect of the phenomenon.

For a wave of given $(\omega, k_\perp, k_\parallel)$, Eq.(3) leads to wave growth if the Landau damping terms associated with $\partial f/\partial v_\parallel$ at $v_\parallel = \omega/k_\parallel$ and df_i/dv_i at $v_i = \omega/k$ in Eq.(2) are so weak that they can be overcome by the anomalous Doppler resonant term involving $\partial f/\partial v_\perp$ at $v_\parallel = v_{AD}$. The latter is proportional to the magnitude, rather than the parallel gradient, of the parallel component of the electron distribution function at the superthermal parallel velocity $v_\parallel = v_{AD}$. Let v_B denote the thermal velocity associated with the isotropic bulk Maxwellian distribution. Electron Landau damping is weak firstly for $v_\parallel \gtrsim 2.5\ v_B$, beyond the main body of the bulk, and also for $v \ll v_B$, deep in the bulk distribution. The first possibility for wave growth has been examined in the literature[5,6,10-17]; the second does not appear to have been studied previously.

Let us consider an isotropic bulk Maxwellian electron distribution, together with a small tail whose distribution in $v_\parallel$ is not yet specified, but which has a fixed perpendicular thermal velocity $v_{T\perp}$:

$$f(v_\perp, v_\parallel) = \frac{(1-\mu)}{\pi^{3/2}\, v_B^3}\, e^{-v_\perp^2/v_B^2}\, e^{-v_\parallel^2/v_B^2} + \frac{\mu}{\pi v_{T\perp}^2}\, e^{-v_\perp^2/v_{T\perp}^2}\, F(v_\parallel) \qquad (4)$$

In general $\mu \ll 1$. We also specify a thermal ion distribution

$$f_i(v_i) = \frac{1}{\pi^{1/2} v_{Ti}} e^{-v_i^2/v^2_{Ti}} \tag{5}$$

where v_{Ti} is the ion thermal velocity. We shall assume the bulk electron and ion temperatures to be equal, so that $v_{Ti} = (m_e/m_i)^{1/2} v_B$.

Substituting Eqs. (4,5) in Eqs.(2,3), we obtain

$$\frac{\gamma}{\omega_p} = \frac{\gamma_{AD}}{\omega_p} - \left(\frac{\gamma_{LB}}{\omega_p} + \frac{\gamma_{LT}}{\omega_p} + \frac{\gamma_{LI}}{\omega_p}\right) \tag{6}$$

$$\frac{\gamma_{AD}}{\omega_p} = \mu\pi^{1/2} \left(\frac{\omega_p}{kv_B}\right)^3 \Lambda_1(\beta_T) \left(\frac{v_B}{v_{T\perp}}\right)^2 \left(\frac{\Omega}{\omega_p}\right) [\pi^{1/2} v_B F(v_{AD})] \tag{7}$$

$$\frac{\gamma_{LB}}{\omega_p} = (1 - \mu)\pi^{1/2} \left(\frac{\omega_p}{kv_B}\right)^3 \Lambda_o(\beta_B) \frac{k_\parallel}{k} e^{-(\omega_p/kv_B)^2} \tag{8}$$

$$\frac{\gamma_{LT}}{\omega_p} = \mu\pi^{1/2} \left(\frac{\omega_p}{kv_B}\right)^2 \Lambda_o(\beta_T) \frac{k_\parallel}{k} \left[- \frac{\pi^{1/2} v_B^2}{2} \frac{dF}{dv_\parallel}\right]_{v_\parallel = \omega_p/k} \tag{9}$$

$$\frac{\gamma_{LI}}{\omega_p} = \pi^{1/2} \left(\frac{\omega_p}{kv_B}\right)^3 Z \left(\frac{m_i}{m_e}\right)^{1/2} \left(\frac{k_\parallel}{k}\right)^2 e^{-[(\omega_p/kv_B)^2 (m_i/m_e)(k_\parallel/k)^2]} \tag{10}$$

Here γ_{AD} is the anomalous Doppler driving term, γ_{LB} and γ_{LT} describe electron Landau damping in the bulk and tail distributions respectively, γ_{LI} describes Landau damping on the ions, $\beta_B = k_\perp^2 v_B^2/2\Omega^2$, $\beta_T = (v_{T\perp}^{\ 2}/v_B^2)\beta_B$, and $\Lambda_n(\beta) = e^{-\beta} I_n(\beta)$, where $I_n(\beta)$ is the modified Bessel function of order

n. The representation in Eqs.(7-10) indicates those features of the instability which are universal, rather than specific to particular choices of parallel electron tail distribution $F(v_\parallel)$.

The dielectric response function ε in Eq.(2) is given in terms of the dielectric tensor ε_{ij} by $\varepsilon = k_i k_j \varepsilon_{ij}/k^2$. In the region of instability it will be shown that the ion contribution to ε_{ij} can be neglected. For the electrostatic waves excited by the anomalous Doppler instability, we have $E_i = |\underline{E}| k_i/k$. Let us take $\underline{k} = (k_\perp, 0, k_\parallel)$. In this case, the rates of energy dissipation by the electrostatic field on the electron motion perpendicular and parallel to the magnetic field are given by

$$P_x = \mathrm{Re}(j_x E_x^*) = \omega \frac{|\underline{E}|^2}{4\pi} \left[\frac{k_\perp^2}{k^2} \varepsilon_{xx}^{im} + \frac{k_\perp k_\parallel}{k^2} \varepsilon_{xz}^{im}\right] \tag{11}$$

$$P_z = \mathrm{Re}(j_z E_z^*) = \omega \frac{|\underline{E}|^2}{4\pi} \left[\frac{k_\perp k_\parallel}{k^2} \varepsilon_{xz}^{im} + \frac{k_\parallel^2}{k^2} \varepsilon_{zz}^{im}\right] \tag{12}$$

From the definition of ε_{ij},[18] Eqs.(11,12) give

$$P_x = \frac{|\underline{E}|^2}{4\pi} 2\gamma_{AD} \frac{\Omega}{\omega} \tag{13}$$

$$P_z = \frac{|\underline{E}|^2}{4\pi} \left[2\gamma_{LB} + 2\gamma_{LT} - (1 + \Omega/\omega)2\gamma_{AD}\right] \tag{14}$$

where we have used Eqs.(7-10). Here $|\underline{E}|^2/4\pi$ is the electrostatic field energy density of the wave, and the factors of 2 arise from the quadratic dependence of power on field amplitude. Eq.(13) describes the field energy dissipated by the wave in increasing the perpendicular kinetic energy of the electrons undergoing the anomalous Doppler resonance. The first two terms of Eq.(14) describe the field energy dissipated by Landau damping on the electrons, which increases their parallel kinetic energy. The final term in Eq.(14) describes the parallel kinetic energy given up by the anomalous Doppler resonant electrons. The net flow of parallel kinetic energy from these electrons to the field and to perpendicular kinetic energy occurs in the ratio 1 : Ω/ω. This reflects the original concept of Kadomtsev and Pogutse,[19] who treated $(h/2\pi)\Omega$ as the energy quantum of perpendicular gyromotion, and $(h/2\pi)\omega$ as the quantum of wave energy, both of which are drawn from the electron parallel kinetic energy. If the energy transfer to the field is sufficient to overcome the Landau damping losses, γ is positive and wave growth occurs: thus, $-(P_x + P_z) = 2\gamma|\underline{E}|^2/4\pi$ as expected. A larger energy transfer occurs from the parallel to the perpendicular component of electron motion. In both these respects, Eqs.(13,14) demonstrate explicitly how closely the collective anomalous Doppler effect follows the single-particle effect described in the Introduction. The essential difference lies in the existence of a threshold, since Landau damping of the wave by the bulk distribution and by the ions, where appropriate, must be overcome in the collective case. This also differentiates the instability of an extended tail from that of a beam in a cold plasma. We note also that the contribution to P_z from the anomalous Doppler term in Eq.(14) is negative, independently of whether the relative magnitudes of γ_{LB}, γ_{LT}, and γ_{AD} are such as to give overall wave growth or damping. It follows that anomalous Doppler resonant electrons may reduce the absorption of driven waves that are undergoing damping, while they increase their perpendicular energy at the expense of their parallel energy.

III. THE EFFECT OF THE TAIL STRUCTURE ON INSTABILITY

Let us return to Eqs.(7-10). We note first that, subject to other constraints, instability is favoured by small values of $k_{\parallel}/k$. Secondly, for $\beta << 1$, $\Lambda_o(\beta) \simeq 1$ and $\Lambda_1(\beta) \simeq \beta/2$; however, for $\beta \gtrsim 2$, $\Lambda_o(\beta) \simeq \Lambda_1(\beta) \simeq 0.2$. There are thus two candidate regimes for instability:

(1) $k_{\perp}$ small such that β_B, $\beta_T << 1$. In this case, ω_p/kv_B can be sufficiently large that the exponential term in Eq.(6d) renders ion Landau damping negligible. The stability of the wave is determined by the electron velocity distribution alone. Electron Landau damping can be weak because the parallel velocity lies beyond the bulk thermal electron distribution. Owing to the factor $\Lambda_1(\beta_T) \simeq \beta_T$, the ratio of γ_{AD} to γ_{LB} is independent of the perpendicular temperature of the tail, and decreases as Ω/ω_p increases at given density.

(2) $k_{\perp}$ large such that β_B, $\beta_T \gtrsim 1$. In this case, the parallel phase velocity ω_p/k can be much less than v_B, and lie in a region where electron Landau damping is again weak. Since $\Lambda_1(\beta_T) \simeq \Lambda_o(\beta_B)$, the ratio of γ_{AD} to γ_{LB} increases with Ω/ω_p, and decreases as the perpendicular temperature of the tail is increased. In this low phase velocity regime, Landau damping on resonant ions becomes a significant phenomenon.

Consider by way of illustration a flat tail which extends as far as a maximum velocity v_M:

$$F(v_{\parallel}) = 1/\pi^{1/2}v_M, \quad 0 < v_{\parallel} < v_M$$

$$= 0 \text{ otherwise} \tag{15}$$

For instability in region (1), combining Eq.(15) with Eqs.(5-9), we obtain

$$\frac{\gamma}{\omega_p} = \pi^{1/2} \left(\frac{\omega_p}{kv_B}\right)^3 \Lambda_o(\beta_B)\left[\mu\left(\frac{v_B}{v_{T\perp}}\right)^2 \left(\frac{v_B}{v_M}\right)\left(\frac{\Omega}{\omega_p}\right)\frac{\Lambda_1(\beta_T)}{\Lambda_o(\beta_B)} - (1-\mu)\frac{k_{\parallel}}{k}\, e^{-(\omega_p/kv_B)^2}\right] \tag{16}$$

provided that $0 < v_{AD} < v_M$, so that

$$k_{\parallel} > \Omega/(v_M - \omega_p/k) \tag{17}$$

In Fig. 1a, the growth rate γ/ω_p given by Eq.(16) is plotted as a function of the dimensionless wavenumber coordinates $(k_{\perp}v_B/\Omega,\ k_{\parallel}v_B/\Omega)$ for a distribution function as in Eq.(15) with $\mu = 0.001$, $v_M = 30v_B$, $v_{T\perp} = v_B$, and $\omega_p/\Omega = 0.4$. The corresponding contour plot is shown in Fig.1b. The dependence of growth rate on tail and plasma parameters has been examined numerically. For a tail fraction $\mu = 0.001$ (0.1% of electrons in the extended tail) we find that

(i) For $\omega_p/\Omega = 0.4$, instability occurs only when $v_M > 15\ v_B$. The growth rate rises to $\gamma = 2 \times 10^{-5}\omega_p$ when $v_M = 30\ v_B$, and thereafter is insensitive to v_M.

(ii) For $v_M = 20\ v_B$, $\gamma = 1.6 \times 10^{-5}\omega_p$ when $\omega_p/\Omega = 0.4$, but γ falls to zero when $\omega_p/\Omega < 0.29$.

(iii) The growth rate is independent of $v_{T\perp}$.

We note from Eq.(2) that the ratio of the anomalous Doppler parallel resonant velocity v_{AD} to the parallel velocity v_L at which electron Landau damping occurs is given by

$$v_{AD}/v_L = 1 + \Omega/\omega \tag{18}$$

Thus, point (i) illustrates the fact that for instability to occur, the tail must extend sufficiently far for electrons to exist at the value of v_{AD} given by Eq.(18) when v_L is a few times v_B, so that Landau damping is weak. Points (ii) and (iii) quantify and confirm remarks made above. For the tail parameters considered, it is possible to suppress the instability by a relatively small increase in magnetic field strength at constant density. Result (iii) holds only for a Maxwellian distribution of perpendicular velocities in the tail. If there were a plateau in the $v_\perp$-distribution in the anomalous Doppler resonant region, it is clear from Eq.(2) that the instability would be significantly affected.

For region (2) we find that no instability occurs. While there can exist a region of wavenumber space - typically at $k_\parallel v_B/\Omega \simeq 0.3$, $k_\perp v_B/\Omega \simeq 3$ - where the anomalous Doppler resonance can overcome the effects of electron Landau damping, this effect is always overcome by ion Landau damping. From Eqs.(8,10), we have

$$\frac{\gamma_{LI}}{\gamma_{LB}} = Z \left(\frac{m_i}{m_e}\right)^{1/2} \frac{k_\parallel}{k} \frac{1}{\Lambda_o(\beta_B)} \exp\left[- \left[\left(\frac{\omega_p}{kv_B}\right)^2 \left\{ \left(\frac{m_i}{m_e}\right)\left(\frac{k_\parallel}{k}\right)^2 - 1 \right\}\right]\right] \tag{19}$$

In the region of wavenumber space indicated, γ_{LI} exceeds γ_{LB} by a factor of order twenty for the case of Hydrogen ions, and this is sufficient to keep γ given by Eq.(6) negative, even though $\gamma_{AD} > \gamma_{LB}$.

Now let us examine the sensitivity to the choice of tail representation. A wide range of monotonically decreasing superthermal tails in the electron velocity distribution can be represented by Eq.(4) when

$$F(v_\parallel) = \frac{1}{\pi^{1/2} v_{T\parallel}} e^{-(v_\parallel - v_D)^2/v_{T\parallel}^2} \tag{20}$$

The parameters (μ, v_D, $v_{T\parallel}$) can be chosen so that the tail structure has a slow, plateau-like decline (Fig. 2a), or a much steeper fall-off (Fig. 2b). In the parameter range of interest, the value of v_D is kept below $4v_B$ in order to avoid describing tails which have a bump rather than monotonic decrease. We have also taken steps in our code to preclude spurious effects arising from a positive γ_{LT} given by Eq.(9) near $v_\parallel = 0$, where γ_{LB} is small. Physically, these constraints ensure that the electron distribution function is monotonically decreasing in $v_\parallel$ throughout its range. For all these distributions, it is clear from Eq.(7) and the exponential dependence of Eq.(20) that the anomalous Doppler effect can play a significant role only for those electrons for which v_{AD} is close to the characteristic drift velocity of the tail. This has two consequences. Firstly, the anomalous Doppler resonance condition can be written $k_{\parallel} v_D \simeq \omega_p k_{\parallel}/k + \Omega$ so that $k_{\perp}^2 \simeq k_{\parallel}^2[\omega_p^2/(k_{\parallel} v_D - \Omega)^2 - 1]$. The requirement that $k_{\perp}^2 > 0$ therefore gives

$$\frac{\left|k_{\parallel} - \Omega/v_D\right|}{\Omega/v_D} \lesssim \omega_p/\Omega \tag{21}$$

and under the conditions of interest, $\omega_p/\Omega \lesssim 0.5$. We conclude that for a wide range of monotonically decreasing tail formations, any unstable region in $\underline{k}$ - space must be localised around $k_{\parallel} = \Omega/v_D$. This conclusion applies independently of the particular region of velocity space in which Landau damping occurs. Secondly, since $v_{AD} \simeq v_D$, it follows from Eq.(18) that in general the corresponding value of v_L will be so small that it lies within the region of strong Landau damping by the bulk electron plasma. These considerations suggest that monotonically decreasing tails described by Eqs.(4) and (20) are stable against the anomalous Doppler effect. We have confirmed this result numerically.

IV. CONCLUSIONS

The components parallel and perpendicular to the magnetic field of the power $j.\underline{E}^*$ dissipated by an electrostatic wave interacting with a non-Maxwellian electron velocity distribution have been considered. They show

how the parallel kinetic energy given up by anomalous Doppler resonant electrons is partitioned between the electrostatic field and the perpendicular component of electron motion. This process can occur both when the wave is growing, and when a driven wave is undergoing damping due to the dominance of Landau damping terms over the anomalous Doppler resonance term, provided that the latter is non-zero. We have indicated the role of ion Landau damping in stabilising plasmas against the emission of electrostatic waves in the large-k region of wavenumber space, where the anomalous Doppler growth term can exceed the electron Landau damping term. The sensitivity of stability calculations to the choice of representation of the superthermal electron tail has been examined analytically and numerically.

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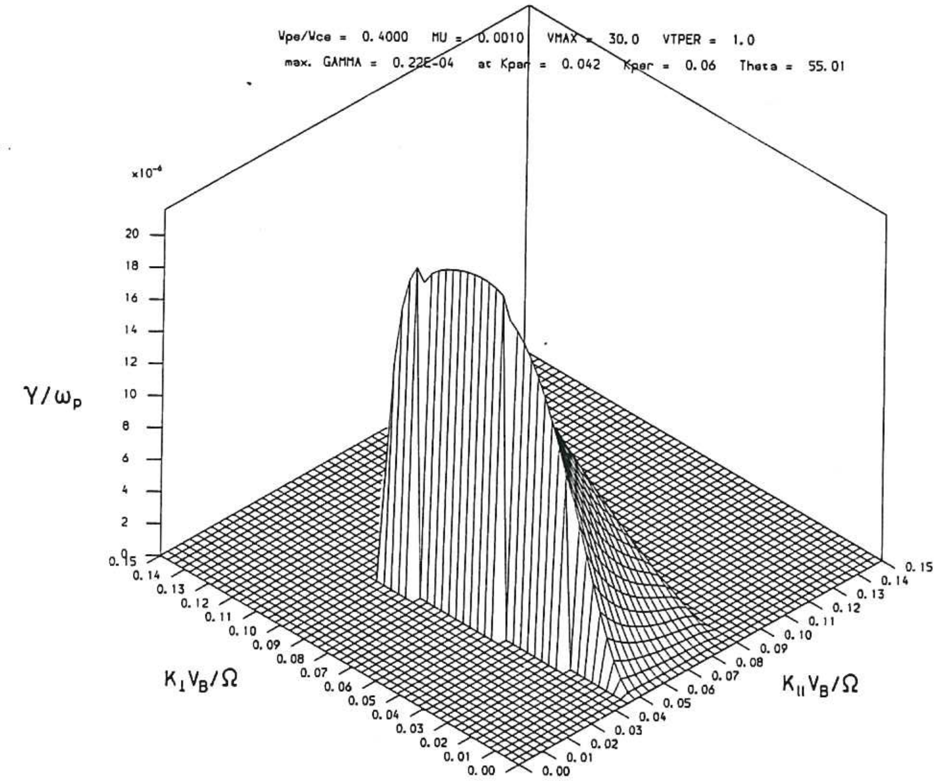

Fig. 1a Growth rate γ/ω_p as a function of $k_\perp v_B/\Omega$ (left axis) and $k_\parallel v_B/\Omega$ (right axis) for a flat tail with parameters displayed.

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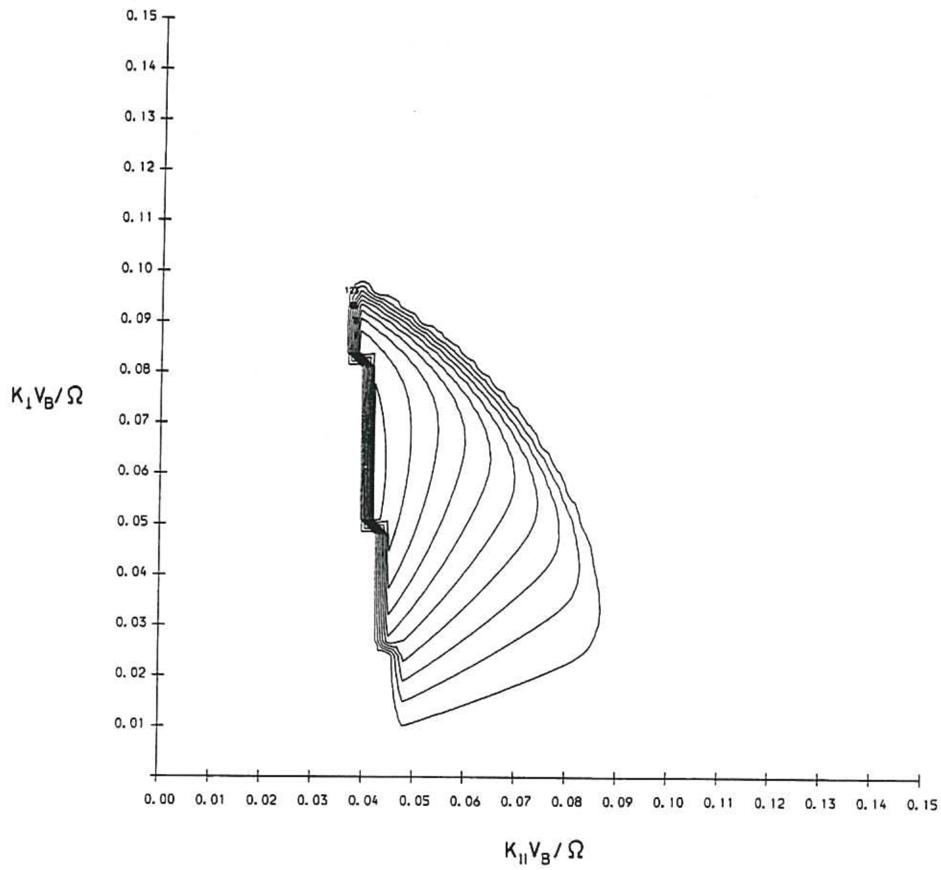

Fig. 1b Contour plot for Fig. 1a.

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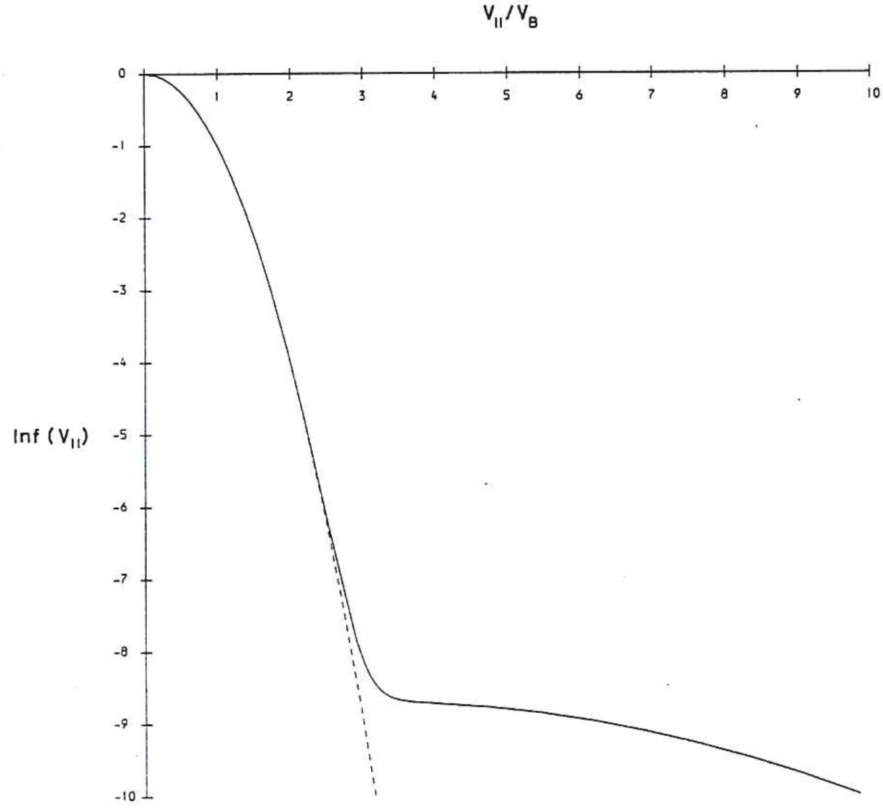

Fig. 2a Use of a drifted Maxwellian component to represent a plateau-like monotonically decreasing tail, with $\mu=0.001$, $v_D=3v_B$, $v_{T\parallel}=6v_B$, $v_{T\perp}=v_B$.

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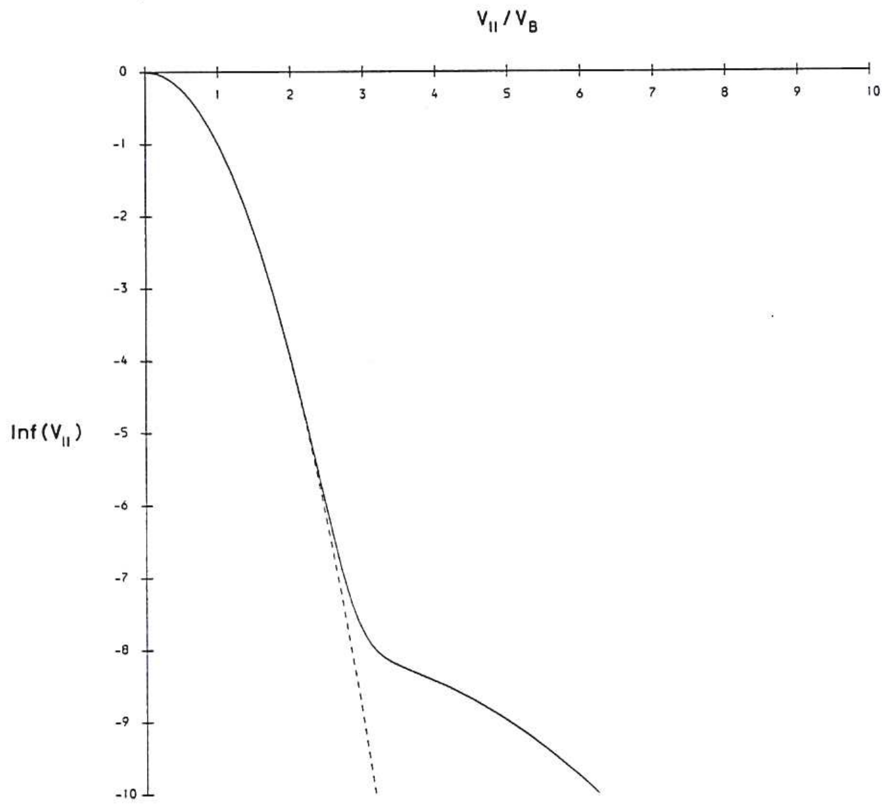

Fig. 2b Use of a drifted Maxwellian component to represent a more steeply monotonically decreasing tail, with $\mu=0.001$, $v_D=2v_B$, $v_{T\parallel}=3v_B$, $v_{T\perp}=v_B$.

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