Dust acoustic instability driven by solar and stellar winds

J. Vranjes

Belgian Institute for Space Aeronomy, Ringlaan 3, 1180 Brussels, Belgium

Abstract. A quantitative analysis is presented of the dust acoustic wave instability driven by the solar or stelar wind. This is a current-less kinetic instability which develops in permeating plasmas, i.e.., when one quasi-neutral electron-ion plasma propagates through another quasi-neutral plasma which contains dust, electrons and ions. The cometary dusty plasma in the solar wind appears to be practically always unstable.

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INTRODUCTION

In the presence of a macroscopic electron velocity relative to static singly-charged ions, a kinetic current-driven instability of the ion acoustic mode may develop. The instability may require rather high values for the electron current. A lower instability threshold may be obtained in the case of two interpenetrating (permeating) plasmas, which implies a current-less instability [1]. This will be demonstrated in the example of the solar wind propagating through the cometary dusty plasma.

DERIVATIONS

Using the linearized Vlasov-Boltzmann kinetic equation for the perturbed distribution function, the perturbed number density may be calculated from $n_{j1} = \int f_{j1} d^3\vec{v}$. For the general species j this yields

$$\frac{n_{j1}}{n_{j0}} = -\frac{q_j \phi_1}{\kappa T_j}\left[1 - \mathscr{Z}(\alpha_j)\right]. \tag{1}$$

Here, for non-streaming species we have $\alpha_j = \omega/(k v_{Tj})$, and

$$\mathscr{Z}(\alpha_j) = \frac{\alpha_j}{(2\pi)^{1/2}} \int d\xi \exp(-\xi^2/2)/(\alpha_j - \xi). \tag{2}$$

For the streaming species (that flow with the common speed v_0) the derivation is similar and Eq. (1) is obtained, but instead of α_j and ξ now we have $\beta_j = (\omega - k v_0)/(k v_{Tj})$ and $\zeta = (v_z - v_0)/v_{Tj}$. The quasi-neutrality in the perturbed state $n_{wi1} + n_{ci1} = n_{we1} + n_{ce1} + Z_d n_{d1}$ will directly yield the dispersion equation. The indices c and w stand for the cometary and wind plasma, respectively.

In Eq. (1) for dust the following expansion will be used

$$\mathscr{Z}(\alpha_d) \simeq 1 + \frac{1}{\alpha_d^2} + \frac{3}{\alpha_d^4} + \ldots - i\left(\frac{\pi}{2}\right)^{1/2} \alpha_d \exp(-\alpha_d^2/2). \tag{3}$$

This is valid if $|\alpha_d| \gg 1$ and $|Re(\alpha)_d| \gg |Im(\alpha_d)|$. For the two electron populations we shall use $\mathscr{Z}(\alpha_{ce}) \simeq -i(\pi/2)^{1/2}\alpha_{ce}$, $\mathscr{Z}(\beta_{we}) \simeq -i(\pi/2)^{1/2}\beta_{we}$, that is valid for

$$|\alpha_{ce}| \equiv \frac{|\omega|}{k v_{Tce}} \ll 1, \quad |\beta_{we}| \equiv \frac{|\omega - k v_0|}{k v_{Twe}} \ll 1.$$

The same will be used for the cometary ions, $|\alpha_{ci}| \equiv |\omega|/(k v_{Tci}) \ll 1$. As for the wind ions, the parameter $\beta_{wi} = (\omega - k v_0)/(k v_{Twi})$ contains two terms, where for the first one we expect that $\omega/(k v_{Twi}) \ll 1$, while for the second one

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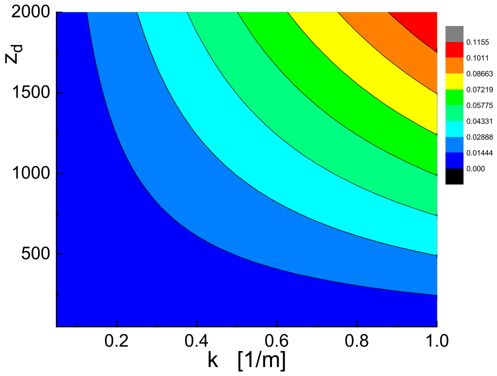

FIGURE 1. The growth rate of the DA mode driven by the slow solar wind.

in this case we assume $v_0/v_{Twi} \gg 1$. Hence, the expansion similar to (3) should be used. The dispersion equation in general form reads

$$\frac{z_{ci}^2 n_{ci0}}{T_{ci}}\left[1+i\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega}{kv_{Tci}}\right]+\frac{n_{we0}}{T_{we}}\left[1+i\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega-kv_0}{kv_{Twe}}\right]+\frac{n_{ce0}}{T_{ce}}\left[1+i\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega}{kv_{Tce}}\right]$$

$$-\frac{z_{wi}^2 n_{wi0}}{T_{wi}}\left\{\frac{k^2v_{Twi}^2}{(\omega-kv_0)^2}-i\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega-kv_0}{kv_{Twi}}\exp\left[\frac{(\omega-kv_0)^2}{2k^2v_{Twi}^2}\right]\right\}-\frac{z_d^2 n_{d0}}{T_d}\left\{\frac{k^2v_{Td}^2}{\omega^2}-i\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega}{kv_{Td}}\exp\left[\frac{\omega^2}{2k^2v_{Td}^2}\right]\right\}=0. \quad (4)$$

The real part of (4) yields the frequency of the dust acoustic mode (where the contribution of the wind ions is negligible)

$$\omega_r^2 \simeq \frac{Z_d^2 n_{d0}}{n_{ce0}}\frac{\kappa T_{ce}}{m_d}\frac{1}{1+\frac{n_{we0}}{n_{ce0}}\frac{T_{ce}}{T_{we}}+\frac{z_{ci}^2 n_{ci0}T_{ce}}{n_{ce0}T_{ci}}}. \quad (5)$$

The growth rate $\gamma \simeq -Im\Delta(k,\omega_r)/[\partial(Re\Delta)/\partial\omega]_{\omega\simeq\omega_r}$ is

$$\gamma=\left(\frac{\pi}{8}\right)^{1/2}\frac{n_{we0}}{Z_d^2 n_{d0}}\frac{m_d m_e^{1/2}}{(\kappa T_{we})^{3/2}}\frac{\omega_r^3}{k^2}\left\{v_0-\frac{\omega_r}{k}\left[1+\frac{z_{ci}^2 n_{ci0}}{n_{we0}}\left(\frac{T_{we}}{T_{ci}}\right)^{3/2}\left(\frac{m_{ci}}{m_e}\right)^{1/2}\right]\right\}. \quad (6)$$

Hence, the instability sets in if

$$v_0 > \frac{\omega_r}{k}(1+a), \quad a=\frac{z_{ci}^2 n_{ci0}}{n_{we0}}\left(\frac{T_{we}}{T_{ci}}\right)^{3/2}\left(\frac{m_{ci}}{m_e}\right)^{1/2}. \quad (7)$$

In application to the solar wind interaction with cometary dusty plasma, the cometary plasma parameters are used from Ref. [2]. These include the following: $T_{ce} = 1.16\cdot 10^5$ K, $T_{ci} = 2.32\cdot 10^4$ K, $T_d = 1.16\cdot 10^2$ K, $n_{ci0} = 10^7$ m^{-3}, $n_{d0} = 10$ m^{-3}, $Z_d = 800$, $m_d = 1.13\cdot 10^{-20}$ kg. As for the electrons and ions from the solar wind, we use the following parameters: $T_{ew} = T_{iw} = 1.5\cdot 10^5$ K, $n_{wi0} = n_{we0} = 5\cdot 10^6$ m^{-3}. The solar wind speed is adopted to be $v_{we0} = v_{wi0} = v_0 = 5\cdot 10^5$ m/s. Singly charged ions are assumed in both systems, and the grains are negatively charged so that $n_{ce0} + Z_d n_{d0} = n_{ci0}$. For these parameters, the threshold velocity v_{th} for the instability is in fact very low. Taking $k = 1$ m^{-1}, and $Z_d = 800$, from (7) we have $v_{th} = 5.3$ km/s only. Therefore, the wind-driven dust acoustic oscillations are always growing. In Fig. 1 the growth rate is given in terms of the wave number and the dust charge number, showing a mode that is practically always growing. In such a multi-component system, the Debye length turns out to be of the meter size. So the largest wave frequency that should be attributed to the DA mode is expected to be of the order of 10 Hz.

REFERENCES

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