ION RING BEAM INSTABILITIES IN MAGNETIZED DUSTY COMETARY PLASMAS

N.F. Cramer[1], F. Verheest[2] and S.V. Vladimirov[1]

[1]*Theoretical Physics Department and Special Research Centre for Theoretical Astrophysics, School of Physics, The University of Sydney, N.S.W. 2006, Australia*

[2]*Sterrenkundig Observatorium, Universiteit Gent, Krijgslaan 281, B-9000 Gent, Belgium*

The mass loading of the solar wind by ionized molecules from cometary atmospheres is accompanied by instabilities, giving rise to MHD turbulence. The turbulence is correlated with the presence of energetic heavy ions which result from the ionization by the solar wind particles of cometary neutral molecules in the pickup process [1]. The cometary pickup ions, immediately following ionization, have a gyration velocity and a drift velocity

$$V_{c\perp} \approx V_{SW} \sin\alpha, \quad V_{c\parallel} = V_{SW} \cos\alpha \tag{1}$$

where V_{SW} is the solar wind velocity and α is the local angle between the solar wind velocity and the magnetic field [1,2]. The ions thus form a combined gyrating ring and a field–aligned beam distribution, which has been shown to excite a number of instabilities [2,3,4].

Dust grains may also be present in the plasma where the pickup ions are produced. The dust in the cometary environment can be charged due to radiation, and due to the flow of charged particles onto the grains from the background plasma. Even if the proportion of charge on the dust grains compared to that carried by free electrons is quite small (typically the ratio can be as large as $\approx 10^{-4}$ in cometary atmospheres), it can have a large effect on hydromagnetic Alfvén waves propagating at frequencies well below the ion–cyclotron frequency, [5,6]. For a non–zero charge on the grains the right hand circularly polarized mode (R–mode) experiences a cutoff due to the presence of the dust, while the left hand polarized mode (L–mode) is better described as a whistler or helicon wave extending to low frequencies [7]. Here we consider the effects of the presence of charged dust grains on the instabilities of electromagnetic waves due to ring–beam cometary ion velocity distributions. Every dust grain is assumed to have the same (negative) charge. All species are assumed cold, and overall charge neutrality is assumed.

We obtain the dispersion equation [2]:

$$\frac{V_A^2 k^2}{\sigma \Omega_i^2} + \frac{\omega + kV_{c\parallel}}{\omega + kV_{c\parallel} \pm \Omega_i} \mp \left(\frac{n_e}{n_i} \frac{\omega + kV_{c\parallel}}{\Omega_i} + \frac{n_{ce}}{n_i} \frac{\omega}{\Omega_i} \right) + \frac{Z_c^2 m_i n_{ci}}{m_{ci} n_i} \left(\frac{\omega}{\omega \pm \Omega_{ci}} + \frac{k^2 V_{c\perp}^2}{2(\omega \pm \Omega_{ci})^2} \right) = 0. \tag{2}$$

We define: $z = \omega/\Omega_i$, $q = kV_A/\Omega_i$, $U = -V_{c\|}/V_A$, $V = V_{c\perp}/V_A$, $e = \Omega_{ci}/\Omega_i = Z_c m_i/m_{ci}$, $b = Z_c n_{ci}/n_i$ and $d = Z_d n_d/n_{ce}$. Here Ω_i and Ω_{ci} are the solar wind and cometary ion cyclotron frequencies respectively. The Alfvén speed V_A is based on the combined plasma, excluding the dust, and σ is the ratio of solar wind ion mass density to total ion mass density.

The effects of dust occur at low frequencies, for $d \ll e$, so that there will be little effect of a small amount of dust on resonant instabilities of the L–mode occurring at $\omega \approx \Omega_{ci}$ or Ω_i. However it has been shown using fluid theory [8,9] that the presence of dust affects the non–resonant firehose instabilities of both modes, which occur at low wavenumbers, where the effect of the dust is greatest. Typical unstable solutions of the dispersion Eq. (2) are shown in Fig. 1 (for right hand polarized waves) and Fig. 2 (for left hand polarized waves).

Resonant instabilities can occur where the denominators in Eq. (2) vanish. There is no resonant mode for the right hand polarized wave, because the wave cannot resonate with the (positively charged) cometary ion cyclotron motion. However, there is a non–resonant unstable firehose mode shown in Fig. 1 by the growth rate (the solid curve) extending to low frequencies. This firehose mode is well known in the dust–free case (e.g. Ref. [3], and has been treated in the dusty plasma case in Ref. [9] using the fluid theory. A resonance occurs at $z = e$, i.e. $\omega = \Omega_{ci}$, for the left hand polarized mode. This is a cyclotron resonance in the cometary ions, and it gives rise to the unstable mode shown in Fig. 2 on the right side of the Figure. This mode has maximum growth at $z \approx q \approx e$, and has a higher growth rate than the unstable mode shown in the left of the Figure, which is a non–resonantly unstable firehose mode. It is evident from the Figures that the presence of dust has no effect on the resonant mode.

Even though the firehose mode has a smaller growth rate than the maximum growth rate of the resonant mode, it is dominant at low wavenumbers. In the absence of dust, the requirement for instability to occur can be written as

$$(1 - \sigma)(\sigma U^2 - V^2/2) > 1. \tag{3}$$

This criterion is satisfied for the numerical solutions shown in Figs. 1 and 2.

It was shown in Ref. [8], and may be deduced from Eq. (2), that the presence of dust has two effects on the behaviour of the low–frequency firehose instability. For both the L–mode and the R–mode, an initially unstable solution can be made stable if q is sufficiently small. This lower value of q for firehose instability is shown to increase in the numerical solutions of Figs. 1 and 2 as the amount of dust increases. On the other hand, if criterion (3) is not satisfied and there is no instability in the dust–free case, for the L–mode there is a range of q in the presence of dust where instability occurs. As the amount of dust increases, the range of q for instability changes. The R–mode is always stable in this case. An upper limit to q for the unstable firehose mode appears, in the absence or presence of dust, that is not accounted for by the fluid theory of Ref. [8]. For the L–mode, this upper limit of q occurs before the onset of the resonant mode, but the presence of dust increases the upper limit of q, until the firehose branch merges with the resonant branch. For the R–mode, the firehose growth rate increases with q until $z \approx e$, after which the size of the driving term in V^2 rapidly declines, as does the growth rate. This behaviour is almost independent of the presence of dust.

Acknowledgement

Support for this work has been provided by the Australian Research Council (SVV) and the Fund for Scientific Research - Flanders (FV).

References

[1] R.M. Thorne and B.T. Tsurutani: Planet. Space Sci. **35**, 1501 (1987).

[2] D. Winske, C.S. Wu, Y.Y. Li, Z.Z. Mou and S. Y. Guo: J. Geophys. Res. **90**, 2713 (1985).

[3] C.S. Wu and R.C. Davidson: J. Geophys. Res. **77**, 5399 (1972).

[4] O.P. Sharma and V.L. Patel: J. Geophys. Res. **91**, 1529 (1986).

[5] W. Pilipp, T.W. Hartquist, O. Havnes and G.E. Morfill: Astrophys. J. **314**, 341 (1987).

[6] N.F. Cramer and S.V. Vladimirov: Publications Astron. Soc. Australia **14**, 170 (1997).

[7] D.A. Mendis and M. Rosenberg: Ann. Rev. Astron. Astrophys. **32**, 419 (1994).

[8] F. Verheest and P. Meuris: Phys. Scripta, *in press*.

[9] F. Verheest and P.K. Shukla: Phys. Scripta **T60**, 136 (1995).

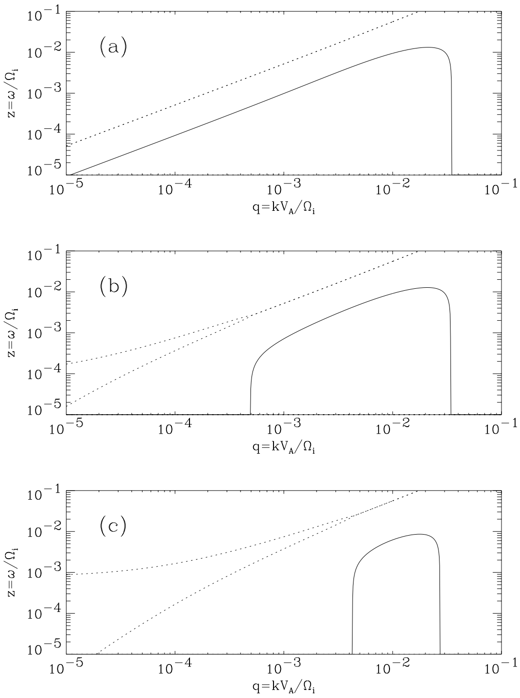

Figure 1. Normalized frequencies (dotted curves) and growth rates (solid curves) for right hand circularly polarized waves in the plasma with non–zero solar wind velocity, plotted against the normalized wavenumber. $U = V = 6$ and (a) $d = 0$, (b) $d = 10^{-2}$, (c) $d = 10^{-1}$.

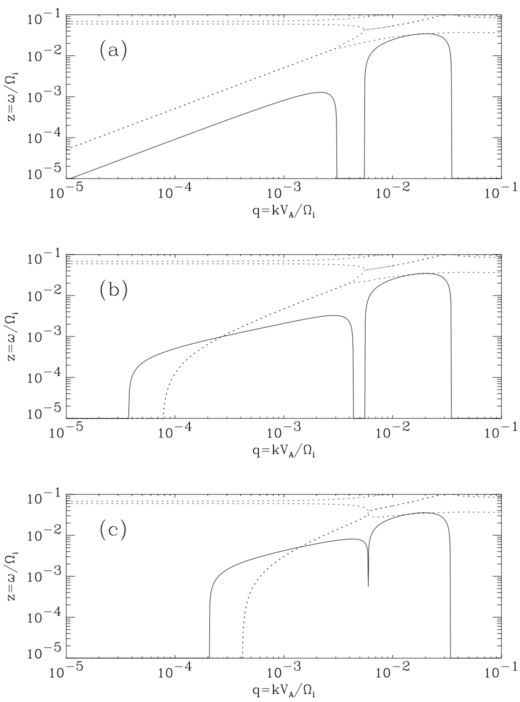

Figure 2. Normalized frequencies (dotted curves) and growth rates (solid curves) for left hand circularly polarized waves in the plasma with non–zero solar wind velocity, plotted against the normalized wavenumber. $U = V = 6$ and (a) $d = 0$, (b) $d = 10^{-1}$, (c) $d = 1$.