Astron. Astrophys. 317, L21–L22 (1997)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

A new whistler-mode and its role in strongly magnetized electron-positron plasmas with charged dust grains

P. K. Shukla[1], **S. Jammalamadaka**[2], **and L. Stenflo**[3]

[1] Institut für Theoretische Physik IV Ruhr Universität Bochum D-44780 Bochum Germany
[2] Max-Planck Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany
[3] Department of Plasma Physics Umeå University S-90187 Umeå, Sweden

Received 7 May 1996 / Accepted 30 May 1996

Abstract. It is shown that the presence of charged dust grains and/or high-Z heavy ions in strongly magnetized electron-positron plasmas can give rise to a novel whistler-like mode. The ponderomotive force of the latter can create large scale density perturbations and cause differential acceleration of dust grains/heavy ions having a variable charge to mass ratio distribution.

Key words: hydromagnetics–plasmas–whistlers

1. Introduction

It is well known (Michel 1982; Rees 1971, 1983) that electron-positron plasmas can be found in many astrophysical and cosmical objects including the polar cap region of pulsar magnetospheres, the inner region of accretion disks surrounding the central black holes in active galactic nuclei, intergalactic jets, as well as the early universe. In addition to the electron-positron pairs, astrophysical and cosmic plasmas also frequently contain a fraction of heavy ions (Weinberg 1972; Hoshino and Arons 1991; Hoshino *et al.* 1992) and dust grains. In contrast to the heavy ions, the extremely massive micron-sized dust grains could be highly charged due to a variety of physical processes (Goertz, 1989; Verheest, 1994).

The study of collective processes (Shukla *et al.* 1986; Iwamoto, 1993; Greaves and Surko 1995) is very important in understanding wave phenomena and particle transport in electron-positron or equal mass plasmas. Recently, it has been shown that the presence of static ions in unmagnetized electron-positron plasmas can cause new phenomena involving the generation of electrostatic wakefields (Berezhiani *et al.* 1992a) as well as localization of strong electromagnetic waves (Rizzato 1988; Berezhiani *et al.* 1992b).

In this Letter, we investigate the properties of electromagnetic waves in magnetized equal mass plasmas with charged dust grains. It is found that the grains support a new whistler-like mode which can play a very important role in creating large scale density perturbations and in producing a differential acceleration of dust grains having different charge to mass ratio distributions.

Send offprint requests to: P. K. Shukla

2. Basic equations

Let us consider the propagation of left-hand circularly polarized electromagnetic waves in an electron-positron dusty plasma in an external magnetic field $B_0\hat{\mathbf{z}}$. The dust grains, which are treated like point charges, are micron-sized and negatively charged. For $\omega \pm \omega_{cj} >> kv_{tj}$ and $\omega >> \omega_{cd}$, where ω_{cj} is the gyrofrequency of the particle species j (j equals e for the electrons, p for the positrons, and d for the dust grains), and v_{tj} is the corresponding thermal velocity, the cold plasma dispersion relation is

$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega+\omega_{ce})} - \frac{\omega_{pp}^2}{\omega(\omega-\omega_{ce})} - \frac{\omega_{pd}^2}{\omega^2}, \tag{1}$$

where $\hat{\mathbf{z}}k$ is the wave vector along the z axis, $\omega_{ce} = \omega_{cp} = eB_0/mc(\omega_{cd} = Z_deB_0/m_dc)$ is electron (dust) gyrofrequency, e is the magnitude of the electron charge,
$m_e = m_p \equiv m$ is the electron or positron mass, c is the speed of light,
$\omega_{pe,pp} = (4\pi e^2 n_{e0,p0}/m)^{1/2}$ is the plasma frequency of the pairs, whereas the dust plasma frequency is denoted by $\omega_{pd} = (4\pi Z_d^2 e^2 n_{d0}/m_d)^{1/2}$. Here $n_{e0} + Z_d n_{d0} = n_{p0}$, where Z_d is the number of charges residing on the surface of a dust grain. For right-hand circularly polarized waves, we have to replace ω_{ce} by $-\omega_{ce}$, whereas for positively charged grains the equilibrium

electron number density n_{e0} is the sum of the positron number density n_{p0} and the grain number density $Z_d n_{d0}$.
Equation (1) yields

$$\omega^4 - \omega^2(\omega_H^2 + \Omega^2) - \omega\omega_{pe}^2\omega_{ce}\frac{Z_d n_{d0}}{n_{e0}} + \Omega^2\omega_{ce}^2 = 0, \tag{2}$$

where $\omega_H^2 = \omega_{ce}^2 + \omega_p^2$, $\Omega^2 = k^2c^2 + \omega_{pd}^2$, and $\omega_p^2 = \omega_{pe}^2 + \omega_{pp}^2$.

Equation (2) is a fourth order polynomial in ω and it can be numerically solved. However, a simple analytical result follows when $\omega << \omega_{ce}$, in which case (2) gives

$$\omega = -\frac{1}{2}\omega_d \pm \frac{1}{2}\left[\omega_d^2 + 4\frac{\Omega^2}{(1+\alpha)}\right]^{1/2}, \tag{3}$$

where $\omega_d = \omega_{pd}^2/\omega_{cd}(1+\alpha)$ and $\alpha = \omega_p^2/\omega_{ce}^2$.

On the other hand, for $k^2c^2 >> \omega_{pd}^2, (1+\alpha)\omega^2$, we have from (2)

$$\omega = \frac{k^2c^2\omega_{cd}}{\omega_{pd}^2}, \tag{4}$$

which is a novel whistler-like mode whose frequency is inversely proportional to the dust number density. Physically, the mode arises because of the finite $\mathbf{E} \times \mathbf{B}_0$ currents caused by the motion of the electrons and positrons in the wave electric field $\mathbf{E}$ in equal mass plasmas with dust grains. This dust whistler mode should be useful for diagnostic purposes, in particular determining the number density of the grains in the ambient plasma. Furthermore, the ponderomotive force of the dust whistlers could produce large scale density bunching as well as differential acceleration of dust grains, as described below.
In the presence of stationary dust grains, very low phase velocity (in comparison with the electron and ion thermal velocities as well as the whistler group velocity) quasi-stationary density perturbations which are driven by the low-frequency ponderomotive force of the dust whistler mode are given by

$$\frac{\delta n}{n_{p0}} = \frac{\omega_{pd}^2}{\omega\omega_{cd}}\frac{|E|^2}{4\pi n_{p0}T}, \tag{5}$$

where T and $\mathbf{E} = E(\hat{\mathbf{x}} - i\hat{\mathbf{y}})$ are the average plasma temperature and electric field vector of the left-hand circularly polarized dust whistlers, respectively. Clearly, the density perturbations are compressional.
The ponderomotive force of the dust whistlers also acts as a piston for the dust grain acceleration, the rate of which along the magnetic field direction is

$$\frac{dv_{dz}}{dt} = \frac{Z_d}{m_d}\frac{\omega_{pe}^2}{\omega_{ce}\omega}\left(\partial_z + \frac{2}{v_g}\partial_t\right)\frac{|E|^2}{4\pi n_{e0}}, \tag{6}$$

where $v_g = \partial\omega/\partial k$ is the group velocity. Equation (6) shows that there is a differential acceleration of dust grains because the acceleration rate is proportional to Z_d/m_d. It is thus obvious that the heavier grains are accelerated slower than the lighter ones. The perpendicular component of the dust whistler wave ponderomotive force can also accelerate the dust grains in a direction transverse to the ambient magnetic field lines.

3. Summary

In summary, we have shown that the presence of negatively charged unmagnetized dust grains (or negative heavy ions) can give rise to a novel whistler-like mode in an equal mass plasma. We note that the present dust whistler mode has the different polarization and the frequency range ($\omega_{cd}, \omega_{ci} << \omega << \omega_{ce}$), in contrast to Shukla and Rahaman (1996) who also found a low-frequency (in comparison with the ion gyrofrequency) whistler-like mode involving the dust particle dynamics. The ponderomotive force of the newly found dust whistlers can create large scale compressional density perturbations, as well as act as a piston to produce a differential acceleration of the dust grains. The results of our investigation also apply to right-hand circularly polarized dust whistlers in equal mass plasmas having either positively charged dust grains or positive heavy ions. Furthermore, we have also found a very low-frequency (in comparison with the dust gyrofrequency) right (or left)-hand circularly polarized dust Alfvén-like mode, the frequency of which is $kc/(1+\alpha+\omega_{pd}^2/\omega_{cd}^2)^{1/2}$.

4. Conclusion

In conclusion, we stress that the present results should be useful for diagnostic purposes in astrophysical, but also in semiconductor plasmas. In the latter case, the positrons in our theory are replaced by the holes and the dust grains are considered as the contaminated impurities which are supposed to be hazardous for the plasma aided manufacture of semiconductors in the microelectronics industry.

Acknowledgements. This work was partially supported by the Commission of the European Community through the Human Capital and Mobility program under the contract No. CHRX-CT94-060.

References

Berezhiani, V. I., Tsintsadze, L. N., and Shukla, P. K. 1992a Physica Scripta **46**, 55.
bibitember2 Berezhiani V. I., Tsintsadze, L. N., and Shukla, P. K. 1992b J. Plasma Phys. **48**, 139.
Goertz, C. K. 1989 Rev. Geophys. **27**, 271.
bibitem[1995]gre Greaves, R. G., and Surko, C. M. 1995 Phys. Rev. Lett. **75**, 3846.
bibitem[1991]hos1 Hoshino, M., and Arons, J. 1991 Phys. Fluids B **3**, 1991.
Hoshino, M., Arons, J., Gallant, Y., and Langdon, A. B. 1992 Astrophys. J. **390**, 454.
Iwamoto, N. 1993 Phys. Rev. E **47**, 604.
Michel, F. C. 1982 Rev. Mod. Phys. **54**, 1.
Rees, M. J. 1971 Nature **229**, 312.
Rees, M. J. 1983 in: G. W. Gibbons, S. W. Hawking and S. Siklos (eds) *The Very Early Universe* (Cambridge University Press, Cambridge).
Rizzato, F. B. 1988 J. Plasma Phys. **40**, 289.
Shukla P. K., Rao, N. N., Yu, M. Y., and Tsintsadze, N. L. 1986 Phys. Rep. **138**, 1.
Shukla P.K. and Rahman, H. U. 1996 Phys. Plasmas **3**, 430.
Verheest, F. 1994 Space Sci. Rev. **68**, 109.
Weinberg, S. 1972 *Gravitation and Cosmology* (Wiley, New York).