Acceleration of dust grains by means of electromagnetic cyclotron waves

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1. Introduction

[1] It is shown that charged dust grains can be accelerated by the nonuniform space charge electric fields that are created by the ponderomotive force of circularly polarized electromagnetic cyclotron waves. The relevance of our investigation to dust energization in the Earth’s mesospheric plasma is stressed.

INDEX TERMS: 7807 Space Plasma Physics: Charged particle motion and acceleration; 7867 Space Plasma Physics: Wave/particle interactions; 7871 Space Plasma Physics: General or miscellaneous; KEYWORDS: dust acceleration, cyclotron waves, ponderomotive force, Earth’s atmosphere, noctilucent clouds, polar mesosphere summer echoes


[2] Dust is an omnipresent ingredient of our universe [Ferrara and Dettmar, 1994; Draine and Lazarian, 1998; Marchant, 2001] and contributes to the occurrence and subsequent understanding of many puzzles in space and astrophysical environments. It is most common in space, particularly in the Earth’s environment, intergalactic and interstellar media, planetary rings, cometary tails, etc. It is now well known that dust particles are not neutral, but are charged due to a variety of processes, namely interaction of dust with background plasmas, secondary electron emission, photoemission, thermionic emission, field emission, etc. [Verheest, 2000; Shukla and Mamun, 2002]. The most important part of the Earth’s environment, where the presence of charged dust particles are observed [Cho and Kelley, 1993; Havnes et al., 1996], is the Earth’s summer mesopause located between 80 km and 93 km in altitude. This is the site of a number of phenomena which are not yet fully understood, for example the formation of Noctilucent Clouds (NLC), the Polar Mesospheric Summer Echos (PMSEs), etc.

[3] PMSEs are strong radar echoes and have been observed at frequencies from 50 MHz to 1.3 GHz with a strongly decreasing backscatter efficiency with increasing frequency [Havnes et al., 2001]. At the heights of PMSEs there also exist layers of electron density depletion and positive ion density enhancement, which are elaborately discussed in some review articles [Thomas, 1991; Cho and Kelley, 1993]. A number of more recent theories involve heavy ion clusters or charged dust particles with total charge density that is significant compared with the electron or ion component [Havnes et al., 1996]. A high charge density on the dust may, in principle, be the result of comparatively few and large highly charged dust particles. A high charge on a dust particle can be possible only if the dust is positively charged by photoemission. On the other hand, if the photoelectron emission is negligible and the dust grain charging is only due to collection of plasma particles, the charge on each dust particle will be low (typically a few unit charges or less) and negative [Havnes et al., 1996].

[4] The role of charged dust particles in creating the conditions for PMSEs was suggested by Havnes et al. [1990, 1992] and Cho et al. [1992], and it was substantially strengthened when Havnes et al. [1996] detected large amounts of subvisual dust particles with negative dust charge densities up to 4500 cm\(^{-3}\) during an event of PMSEs. The ALOMAR RMR lider [Havnes et al., 2001] nearby the Andøya Rocket Range from which the rocket was launched, did not detect any NLC. The rocket did not pass through the radar beam and the horizontal distance was about 20 km when passing the middle of the PMSE layer at about 80 km. The same applies to the results of another rocket launch which detected positive dust [Havnes et al., 1996, 2001] at an occasion when both NLC and PMSEs were detected. The European Incoherent Scatterer (EISCAT) Svalbard Radar (ESR), which operates at 224 MHz, 500 MHz, and 930 MHz frequencies, is also being used for determining the properties of plasmas and fields at the mesospheric altitudes [Chilson et al., 2000; Forme et al., 2001].
[5] In this Brief Report, we consider the nonlinear interaction between intense radar beams with the background plasmas in the Earth’s mesosphere. Specifically, it is shown that charged dust clouds suffer differential acceleration due to nonuniform space charge electric fields that are created by the ponderomotive force of the radar beams. This novel nonlinear phenomenon may contribute to the understanding of the dust layer dynamics and associated PMSEs. The manuscript is organized as follows. In section 2, we show how the space charge electric fields, which are driven by the ponderomotive forces of circularly polarized electromagnetic waves, cause acceleration of dust grains across and along the direction of the geomagnetic field lines. Section 3 contains a summary and an application of our investigation to the dust acceleration in the Earth’s mesosphere.

2. Ponderomotive Forces and Dust Acceleration

[6] We consider the presence of finite amplitude circularly polarized electromagnetic (CPEM) waves in a mesospheric dusty plasma in an external magnetic field \( B_0 \), where \( B_0 \) is the magnetic field strength and \( z \) is the unit vector along the \( z \) axis. The dusty plasma constituents are supposed to be electrons, ions, and micron-sized massive charged dust grains. The wave frequency \( \omega \) and the wave number \( k \) of magnetic field-aligned right-hand CPEM waves satisfy [Stix, 1992]

\[
\omega^2 = k^2 c^2 + \sum_j \frac{\omega_{j,0}^2}{\omega + \omega_{j,0}},
\]

where \( |\omega + \omega_{j,0}/k| \) has been assumed to be much larger than the thermal speed \( v_{th} = (T_j/m_j)^{1/2} \). Here \( c \) is the speed of light in vacuum, \( \omega_{j,0} = (4\pi n_j q_j^2/m_j)^{1/2} \) and \( \omega_{j,0} = q_j B_0/m_j c \) are the plasma and gyro frequencies, respectively, \( m_j \) is the mass of species \( j \) (\( j \) equals \( e \) for electrons, \( i \) for ions, and \( d \) for dust grains), \( q_j \) is the charge (including sign), \( n_j \) is the equilibrium number density, and \( T_j \) is the temperature. In the equilibrium of charged dust grains, the equilibrium quasi-neutrality relation is \( e n_i = e n_e - q_j n_d \), where \( e \) is the magnitude of the electron charge. For left-hand CPEM waves, we replace \( \omega \) by \( \omega_{j,0} \) in equation (1) by \( \omega - \omega_{j,0} \).

[7] In the electromagnetic fields, the plasma particles quiver and experience a ponderomotive force \( \mathbf{F}_{pj} \). The latter is represented by the nonlinear terms in a two-timescale expansion of the momentum equation for species \( j \)

\[
\mathbf{F}_{pj} = -j \mathbf{E} \cdot \nabla \mathbf{v}_{pj} + \frac{q_j}{c} \mathbf{v}_{pj} \times \mathbf{B}_{1j}.
\]

Here \( \mathbf{v}_{pj} \) is the high-frequency quiver velocity of species \( j \) in the wave electric field \( \mathbf{E} = \mathbf{E}(x + iy) \exp(-i\omega t + ilz) \) of the CPEM waves, and the angular bracket denotes averaging over the high-frequency wave periods \( 2\pi/\omega \). The \( +(-) \) designate the right- (left-) hand polarization. The wave magnetic field associated with the plasma high-frequency motion is denoted by \( \mathbf{B}_{1j} \).

[8] For right-hand CPEM waves, the expression (2) for the ponderomotive force can be written in the form [e.g., Washimi and Karpman, 1976; Karpman and Washimi, 1977]

\[
\mathbf{F}_{pj} = \mathbf{F}_{pj\perp} + i \mathbf{F}_{pj\parallel},
\]

where the perpendicular and parallel (to \( z \)) components are denoted by, respectively,

\[
\mathbf{F}_{pj\perp} = -\frac{q_j^2}{m_j (\omega + \omega_{j,0})} \nabla \mathbf{E}^\perp, \\
\mathbf{F}_{pj\parallel} = \left[ \partial_t + \omega_{j,0} \frac{q_j}{m_j (\omega + \omega_{j,0})} \right] \frac{q_j^2 |\mathbf{E}|^2}{m_j c \omega (\omega + \omega_{j,0})},
\]

where \( \partial_t = \partial/\partial t \) and \( \partial_z = \partial/\partial z \). Thus the perpendicular component of the ponderomotive force can be expressed as a gradient of a potential, whereas in the parallel component, besides the gradient of the potential part, there is a time derivative force.

[9] We shall now consider the generation of space charge fields by the ponderomotive force of right-hand circularly polarized EM electron cyclotron and left-hand \( (\omega_{jc} \rightarrow -\omega_{jc}) \) circularly polarized EM ion cyclotron waves. The EM electron cyclotron waves with \( \omega \gg \omega_{jc} \) have

\[
\omega \approx \Omega_e \left[ 1 - \frac{\omega_{pe}^2}{\left( k^2 c^2 + \omega_{pe}^2 \right)^2} \right] \leq \Omega_e,
\]

where \( \Omega_e = |\omega_{je}| \), which for \( k^2 c^2 \ll \omega_{pe}^2 \) reduces to electron whistlers having the frequency

\[
\omega = k^2 c^2 \Omega_e \omega_{pe}. 
\]

On the other hand, for the left-hand circularly polarized electromagnetic ion cyclotron-Alfven (EMICA) waves with \( \omega_{jd} \), \( \omega_{id} \), \( \mathbf{E} \approx \mathbf{0} \approx \mathbf{v} \), the wave frequency is determined from

\[
(\omega - \omega_{jd}) \frac{k^2 c^2}{\omega_{pe}^2} \approx -\frac{\omega}{\omega_{id}} [\omega + \omega_{jd}(1 - \delta)],
\]

where \( \delta = n_j/n_i \equiv 1 + q_j n_j/m_e n_i \) is smaller (larger) than unity for negatively (positively) charged dust grains.

[10] The ponderomotive force of the electromagnetic electron cyclotron waves displaces the background electrons with respect to the ions. The resulting space charge electric fields are obtained by summing the inertia-less electron and ion momentum equations, yielding

\[
q_j n_j \mathbf{E} \approx \frac{1}{c} \mathbf{B} - \nabla p + n_j \mathbf{F}_{pe},
\]

where \( \mathbf{j} = (c/4\pi) \nabla \times \mathbf{B} \) is the current density, \( \mathbf{B} = iB_0 + \mathbf{B}_{1d}, \mathbf{B}_{1d} \) is the magnetic field perturbation associated with the plasma slow motion, and \( p = n_e T_e + n_i T_i \) is the sum of the electron and ion pressures. We have noted that \( n_j \mathbf{F}_e \gg n_j \mathbf{F}_i \) for the electromagnetic electron cyclotron waves.
The space charge electric fields, in turn, act on the dust grains causing their acceleration. In a plasma with uniform plasma and magnetic pressures, we obtain for the rate of change of the dust velocity \( \mathbf{v}_d = \mathbf{v}_{d\perp} + \mathbf{a}_{d\perp} \)

\[
\frac{\partial \mathbf{v}_{d\perp}}{\partial t} = -\frac{\omega_{pe}^2}{4\pi \rho_d (\omega - \omega_e)^2} \nabla_{\perp} |\mathbf{E}|^2, 
\]

(10)

\[
\frac{\partial \mathbf{v}_{d\parallel}}{\partial t} = \frac{k \omega_e}{\omega (\omega - \omega_e)} \frac{\partial}{\partial \omega} |\mathbf{E}|^2, 
\]

(11)

where \( \rho_d = n_e \mu_d \) is the dust mass density. It follows that the dust grain acceleration is quite strong when the wave frequency is close (but smaller) to (than) the electron gyrofrequency.

Next, we consider the dust grain acceleration by the EMICA waves [Guglielmi and Pokhotelov, 1996; Abbasi et al., 1999; Guglielmi and Lundin, 2001]. The acceleration of ions by the ponderomotive force [Pokhotelov et al., 1996; Guglielmi and Lundin, 2001] of the EMICA and Alfvén waves was considered previously [Shukla et al., 1996]. Here, for left-hand circularly polarized EMICA waves, the space charge electric field is reinforced also by the ion ponderomotive force [Shukla and Stenflo, 1985]. Thus, the last term in the right-hand side of equation (9) would contain an additional term \( n_i \mathbf{F}_p \). Correspondingly, we obtain for the dust grain acceleration

\[
\frac{\partial \mathbf{v}_d}{\partial t} \approx \frac{1}{\rho_d} (n_i \mathbf{F}_p + n_i \mathbf{F}_d), 
\]

(12)

which yields

\[
\frac{\partial \mathbf{v}_{d\perp}}{\partial t} = -\frac{\delta \omega_{pi}^2}{4\pi \rho_d \omega_{pi}^2} \left[ 1 + \frac{\omega_{gm}^2}{\delta (\omega - \omega_{gm})^2} \right] \nabla_{\perp} |\mathbf{E}|^2, 
\]

(13)

\[
\frac{\partial \mathbf{v}_{d\parallel}}{\partial t} = \frac{\delta \omega_{pi}^2}{4\pi \rho_d \omega_{pi}^2} \left\{ \left[ 1 - \frac{\omega_{ci}^2}{\delta (\omega - \omega_{ci})^2} \right] \frac{\partial}{\partial \omega} |\mathbf{E}|^2 + \frac{k \omega_e}{\omega (\omega - \omega_e)} \left[ 1 - \frac{\omega_{ci}^2}{\delta (\omega - \omega_{ci})^2} \right] \frac{\partial}{\partial \omega} |\mathbf{E}|^2 \right\}. 
\]

(14)

where \( \omega_{gm} = (\Omega_e \omega_{ci})^{1/2} \) is the lower-hybrid resonance frequency. Equations (10), (11), (13) and (14) are the main results of our paper. They show how nonuniform intensity distributions of circularly polarized electromagnetic waves produce differential acceleration of charged dust grains in magnetoplasmas.

3. Discussion and Applications

We have shown that the ponderomotive forces of right-hand circularly polarized electron cyclotron and left-hand circularly polarized EMICA waves create nonuniform space charge fields, which cause differential acceleration of charged dust grains in a magnetoplasma. It turns out that the perpendicular component of the ponderomotive force is responsible for the transverse (to the ambient magnetic field direction) dust acceleration, which depends strongly on the wave frequency and the gradient of the wave intensity. On the other hand, the magnetic field aligned ponderomotive force causes parallel dust acceleration, the rate of which depends on the wave frequency as well as on the spatio-temporal derivative of the electromagnetic wave intensity. It is obvious that both the transverse and parallel dust acceleration are significantly enhanced when the wave frequencies are close to either the electron or ion gyro frequencies. Furthermore, we note that the dust grain acceleration depends on the shape of the electric field intensity. The latter can be obtained either from observations or from calculations of the preexisting statistically distributed coherent nonlinear structures such as envelope solitons [Shukla and Stenflo, 1985], vortices etc. Hence, we are convinced that intense localized radar beams should be regarded as the most interesting candidate for accelerating charged dust cloud in Earth’s mesosphere.

References


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