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Stochastic Acceleration of particles in dust clouds

U.de Angelis, [1], V. N. Tsytovich, [2], A. V. Ivlev,[3] and G. E. Morfill [3]

[1] *Department of Physical Sciences,University of Naples "Federico II", Italy*
[2] *General Physics Institute Russian Academy of Science, Russia*
[3] *Max Planck Institute for Extraterrestrial Physics, Garching, Germany*

Abstract

Stochastic acceleration of electron, ions and dust due to dust charge fluctuations in the particle collisions with dust is analyzed in the frame of generalized kinetic theory of dust which takes into account different sources of ionization, scattering and absorption of electrons and ions on grains. It is found that dust acceleration is enhanced due to resonances in dust screening and the electron/ion acceleration is mainly due to the charging broadening of the resonance diffusion in energies in collisions of electro/ions with grains. Special attention is made to the case of dusty plasmas in the source of intense ultraviolet radiation with electron photo-emission by grains.

1.Dusty plasmas as non-Hamiltonian systems

One of important feature of dusty plasmas is that the charges of grains can be varied both by external sources and in collisions of particles with grains. Such systems are non-Hamiltonian and do not conserve kinetic energy of colliding particles since some of the energy during collisions can be transferred to the charge self-energy of colliding grains. There exist the probability that in collisions with grains the kinetic energy of particles can increase and there is probability that this energy can decrease. In average the particle can be accelerated stochastically. This mechanism does not require the grain movements but in some aspect is similar to stochastic Fermi acceleration by collisions with randomly moving clouds. The first consideration of this effect was made for dust-dust collisions in [1-3] (in [1,2] the Fokker-Planck approach was used, wile in [3] the collision integrals found in the kinetic theory for dusty plasmas developed in [4]). In present consideration we have considered the stochastic acceleration of electrons and ions (which was not considered previously) using the generalized kinetic approach which takes into account the sources of ionization and in particular the photo-emission by strong ultraviolet radiation where the grains are charged positively. This case has application for the astrophysical problems of acceleration of electrons and ions in dust molecular clouds and for problems of dust in edge plasmas in fusion devices.

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2.Resonance acceleration of grains

The new aspects introduced by generalized kinetic theory of dusty plasmas is its extension to the case $\beta = Z_d e^2/aT_i \gg 1$ (met in many existing low-temperature dusty plasma experiments) by taking into account the ion scattering on grain as a fastest process in particle collisions and of dust charge fluctuations. The collisions as previously are proportional to square of effective charge of grains which depends on the distance of the grain with the colliding particle and inverse proportional to the square of effective dielectric constant which screens the particles during collisions. The effect of grain attraction described by the product of scattering and absorption of ions on grains is taken into account. Change of sign of charge of grain interaction inevitably leads to presence of the range of wave numbers (inter-grain distances) where the dielectric function is close to zero which gives an additional enhancement by factor R of stochastic acceleration of grains. The results for stochastic acceleration of grains in dust-dust collisions is

$$\frac{d < E_d >}{dt} \approx R < E_d > 4\pi^2 n_d \lambda_{Di}^3 \frac{\omega_{pd}^2}{\omega_{pi}}; \quad \omega_{pd}^2 = \frac{4\pi n_d Z_d^2 e^2}{m_d} : \quad \omega_{pi} = \frac{4\pi e^2 n_i^2}{m_i} \quad (1)$$

where $\lambda_{Di} = T_i/4\pi n_i e^2$ is the ion Debye radius and $R \approx 1$ for $\beta \ll 1$ as obtained in [3] and $R \approx \lambda_{Di}^4 n_d/a^4 n_i$ ($P = n_d Z_d/n_i$ is of the order of 1 and $a \ll \lambda_{Gi}$). The enhancement could be important for small grain size.

3.Kinetic balance conditions for intense UV source

In kinetic description the dust distribution function $\Phi_{\mathbf{p}}^d(q)$ depends both on dust momentum $\mathbf{p}$ and dust charge q. It is found that by using the kinetic description the condition of balance of UV source of electrons $Q(v,q) = 4\pi a^2 Y_d I \exp(-eq/T_{ph} - m_e v^2/2T_{ph})$ emitted by grains with volume electron absorption on grains can determine the equilibrium electron distribution and the electron current on grain. Here the UV source is characterized by the Yield Y_d, intensity of UV source I and temperature of emitted electrons T_{ph} (usually about several eV). Together with current balance on the grains and condition of quasi-neutrality one obtains two relations for the the dimensionless dust equilibrium charge $z_{eq} = eq_{eq}/aT_{ph}$ and the width Δq of the grain distribution in charges if the latter is assumed to be Gaussian $\Phi_d \propto \exp(-(q-q_{eq})^2/\Delta q)^2$. The width depends strongly on gas pressure due to electron damping on neutrals. The equation found are

$$\exp(-z_{eq}) \frac{\sqrt{2} Y_d I e^2}{a T_{ph} v_{Tp} n_d} \frac{\int_0^\infty \frac{\exp(-y^2)}{y^2+z_{eq}+\nu y} y^2 y dy}{\int_0^\infty \frac{dy (y^2+z_{eq}) y^2 \exp(-y^2)}{y^2+z_{eq}+y\nu}} = z_{eq} \quad (2)$$

$$\frac{(\Delta q)^2}{q_{eq}^2} = \frac{1}{z_{eq}^2} \ln\left(\frac{\sqrt{\pi}}{4\int_0^\infty \frac{y^2(y^2+z_{eq})\exp(-y^2)}{y^2+z_{eq}+y\nu}} \right) \quad (3)$$

where

$$\nu = \frac{\nu^{e,n}}{n_d \pi a^2 \sqrt{\frac{2T_{ph}}{m_e}}} \quad v_{Tp} = \sqrt{\frac{T_{ph}}{m_e}} \quad (4)$$

and $\nu^{e,n}$ is the electron-neutral collision frequency. In numerical solution of these equations it is useful to introduce the normalized intensity $\tilde{I} = 2\sqrt{2} Y_d I e^2/\sqrt{\pi} a T_{ph} v_{Tp} n_d$ of the UV source. The solutions indicate that the equilibrium charge does not depend much on electron-neutral collisions varying from $z_{eq} \approx 0.05; \tilde{I} = 0.1$ up to $z_{eq} \approx$

$1.65; \tilde{I} = 30$ while the width of the dust distribution increase rapidly with $\nu^{e,n}$ reaching $(\Delta d)^2/q_{eq}^2$ about 1 for ν about 1. For $\nu \ll 1$ (see Fig.1) an approximate expression for the width is $(\Delta q)^2/q_{eq}^2 \approx \left(8\sqrt{2}\nu/\sqrt{\pi}z_{eq}^2\right)\int \exp(-x)xdx/(x+z_{eq})$,

These results are sufficient to calculate the charging time or its inverse value, the charging frequency ν_{ch}

$$\nu_{ch} = a^2 v_{Tp} n_d F(z_{eq}, \nu) \tag{5}$$

$$F(z,\nu) = 2\sqrt{2}\pi z \frac{\int_0^\infty \frac{dy(y^2+z)y^2\exp(-y^2)}{y^2+z+\nu y}}{\int_0^\infty \frac{\exp(-y^2)}{y^2+z+\nu y}y^2 y dy}\left(1+\frac{4}{\pi}\int_0^\infty \frac{y^2\exp(-y^2)}{y^2+z+\nu y}dy\right) \tag{6}$$

. The numerical result for dependencies of the factor F on intensity of UV radiation $\tilde{I}$ and on equilibrium charge z_{eq} are given by Fig.2. The value of ν_{ch} determines the stochastic acceleration of electrons and ions.

4.Stochastic acceleration of electrons and ions in collisions with dust grains

Generalized theory of collisions of electrons and ions with grains shows that in the range of quasi-neutral collisions (where the fluctuating field are weak) the stochastic acceleration exists, is proportional to the square of the width of grain distribution in charges and does not exceed the damping existing in the first place due to absorption of electrons and ions on grains although stochastic acceleration decreases the damping and therefore increases the number of electrons and ions created by the source. Ion and electron stochastic acceleration due to interaction with dust is of diffusive type and is described by Fokker-Planck equation with probabilities broadened due to the charging effect and therefore these interaction do not conserve the kinetic electron and ion energies. The equation found is

$$\frac{\partial \Phi^{e,i}}{\partial t} = \frac{\partial}{\partial p_i} 2e^2 \int d\mathbf{k} \frac{k_i k_j |q^{eff}|^2}{k^4|\epsilon^{eff}|^2} \frac{\nu_{ch}}{\pi\left[(\mathbf{k}\cdot\mathbf{v})^2+\nu_{ch}^2\right]} n_d \frac{\partial \Phi^{e,i}}{\partial p_j} \tag{7}$$

where q^{eff} is the effective dust charge and ϵ^{eff} is the effective screening dielectric constant. The mentioned resonances in dielectric function are found to be not important for dust ellectrn/ion collisions. The average energy $< E >$ defined as

$$< E >= \int (m_{e,i}v^2/2)\Phi_{\mathbf{p}}^{e,i} d\mathbf{p}/(2\pi)^3$$

increases due to stochastic acceleration. The law describing this acceleration is

$$\frac{d < E >}{dt} = \alpha < \frac{1}{\sqrt{E}} \int_{\nu_{min}}^\infty \frac{d\nu}{\nu^2+\nu_{ch}^2} > \qquad \alpha = \sqrt{2} z_{eq}^2 a^2 T_{ph}^2 n_d \nu_{ch} \frac{1}{m_{e,i}^{1/2}} \tag{8}$$

Determining ν_{min} by the condition that the energy of the particles is of the order of interaction energy and assuming $\nu_{min} = E\sqrt{E}/\sqrt{m_{e,i}} z_{eq} a T_{ph} \gg \nu_{ch}$ (for large particle energies) we find

$$\frac{d < E >}{dt} = \nu_{ch} n_d a^3 z_{eq}^3 T_{ph}^3 < \frac{1}{E^2} >= n_d^2 a^5 v_{Tp} T_{ph}^3 z_{eq}^3 F(z_{eq}, \nu) < \frac{1}{E^2} > \tag{9}$$

The acceleration is independent on the particle mass (electrons or ions), the threshold is determined by collisions of electrons and ions with neutrals by $-\nu^{e/i,n} < E >$, The acceleration is proportional to n_d^2 and is effective for large grain sizes.

The results are given in the form to be easily used for estimates of electron and ion acceleration for dust molecular clouds in astrophysics where the parameters of dust vary in a broad range and for dust in edge plasma of fusion devised [5]

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References

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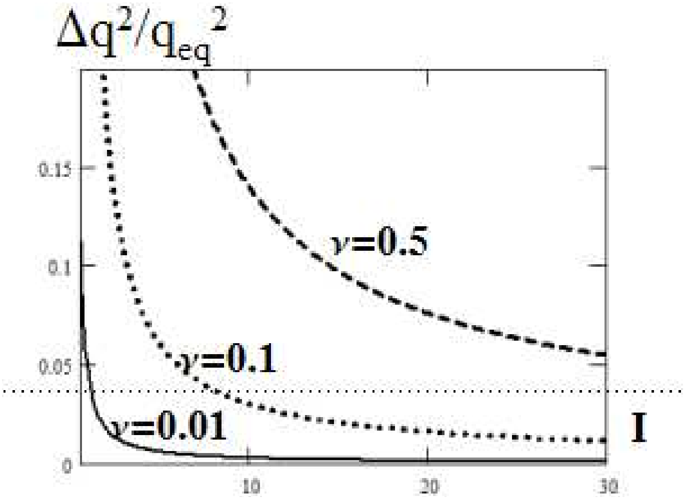

Fig.1

Figure 1. Dependence of the width of the charge distribution on intensity of UV radiation $\tilde{I}$ and the electron-neutral collision rate ν

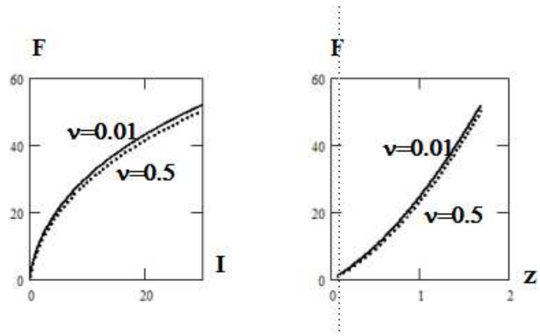

Fig. 2

Figure 2 Dependencies of normalized charging frequency F on intensity of UV radiation $\tilde{I}$ and on equilibrium charge z_{eq} , the solid and dotted lines illustrate that the dependence on the electro-neutral collision rate is weak.