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Kinetic theory of dusty plasmas for large angle ion scattering

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Abstract

Kinetic theory of dusty plasma is generalized for the limit of large grain charges where plasma ions are scattered by grains on large angles. The previous approach valid for multiple small angle scattering is also generalized by considering both processes of scattering and charging in the fast fluctuating part of particle distributions. A simple model to describe the large angle scattering is proposed. In the frame of this new kinetic approach in dusty plasmas a general prove of existence of dust attraction at larger distances is given.

1. Achievements of previous kinetic theory of dusty plasmas

Previous kinetic theory of dusty plasmas [1-7] is valid for the condition $\beta = Z_d e^2/T_i\lambda_{Di} << 1$, i.e. if the Coulomb radius is much less then the Debye radius. Generalization of the theory for $\beta >> 1$ is the subject of the present consideration. The condition $\beta \ll 1$ can be fulfilled either for small grain sizes (in laboratory condition less then $0.2\mu\mathrm{m}$) or for the case of large Debye radius (often met in astrophysical conditions). In laboratory experiments β ranges from 5 to $50 - 100$. The necessity of kinetic description of dusty plasmas is well known since at present level of the experiments it is possible to follow individual dust grains and measure (in principle) there distribution functions in space and time. The observed macroscopic properties such as viscosity for inhomogeneous dust flow or friction, diffusion and other transport coefficients can be compared with the results of measurements if the kinetic theory can provide the description of these quantities on the basis of of dusty plasmas kinetic approach. This requires to use a kinetic expressions for the collision integrals in dusty plasmas from which the transport coefficient can be calculated. In the condition often met in most existing experiments $PZ_d \gg 1$ ($P = n_d Z_d/n_i$ is the Havnes parameter and $Z_d \gg 1$ is the grain charge in units of an electron charge) the rate of binary electron/ion collisions with electron/ions is much less than the rate of their collisions with dust grains. The absorption on dust grains and the ionization that is required to compensate this absorption are strongly velocity dependent and create non-thermal electron and ion distributions. This is the main reason of necessity to use the kinetic approach to describe the transport coefficient in dusty plasmas. The main physical processes that makes dusty plasmas different from ordinary plasmas are: 1) during the collisions the grains change there charges which are depending on the distance between the grains and 2) during the collisions the grains change their screening which differs from Debye screening. Plasma physics in absence of dust is based on Landau Balescu collision integrals which serves as the starting point of the modern transport theory. These collision integrals are proportional to the squares of colliding charges and are inverse proportional to the square of dielectric constant describing the screening during the collisions $I_{coll} \propto (e^{\alpha})^2(e^{\beta})^2/|\epsilon_{\mathbf{k},\omega}|^2; \alpha = \{e, i\}$.

Major and basic physical assumption of already developed approach for kinetic theory of dusty plasmas is to take into account only the discreetness of dust component and describe the plasma particles continuously. Developed kinetic theory takes into account self-consistently the dust charging processes and screening (see [1-7]) and gives the collision integrals of grains as functions of $|q^{\alpha,eff}_{\mathbf{k},\omega}|^2|q^{\beta,eff}_{\mathbf{k},\omega}|^2/|\epsilon^{eff}_{\mathbf{k},\omega}|^2$ where q^{eff} is the effective dust charge in collisions and ϵ^{eff} is the effective dielectric constant describing the screening in collisions. Both effective charge and effective screening in [1-7] are found to depend on the grain charging process which is the fastest process in the collisions. For $\beta \ll 1$ (the range of validity of [1-7]) the scattering of ions on grains is a small angle scattering and can be treated by perturbations while the charging effect not. Three major physical achievements were in [1-7] are: 1) the proof of non-elasticity of ion scattering on grains 2)the proof that collective dust charge fluctuations depending on dust density and usually exceeding the standard fluctuations 3) the proof of presence of stochastic dust acceleration due to dust charge fluctuations.

In new developments the basic assumptions are broadened. In the equations averaged on high frequency perturbations the interactions with dust is treated by cross-section. The high-frequency effect in the present approach include the plasma particle scattering, absorption by grains and the drag force on grains due to both absorption and scattering. The scattering is included in the high frequency part and for $\beta \gg 1$ the model of scattering on large angles is used. This approach takes into account the most important sources of ionization including that proportional to the dust distributions, (photo-emission, thermionic dust, radioactive dust, secondary electron-emission). These sources fluctuate with dust distribution and describe the dust charge fluctuations which are determining the collision integrals. We use arbitrary cross-sections of scattering and absorption. The kinetic theory for large angle scattering $\beta \gg 1$ uses a model of backscattering.

2.Model for absorption and ion scattering on large angles

The absorption cross-sections are not changed substantially for $\beta \gg 1$ (as compared to $\beta \ll 1$) due to possible presence of potential barriers [8] and are not much different from standard cross-sections given by Orbit Motion Limited Approach. The cross-section of ion scattering on grain for $\beta \ll 1$ are $Z_d e^2/aT_i$ larger than the absorption cross-section. For $\beta \gg 1$ ion scattering occurs on large angles with important influence of nonlinearity of grain field. The cross-section of scattering found in [9] are $\sigma_{scat} \approx \eta_{scat}\pi\lambda^2_{Di}R^2_{nl}$ where η_{scat} is a numerical coefficient about $0.5 - 0.75$ depending on values of β and model of non-linearity. The R_{nl} is the non-linear screening radius in units of ion Debye screening length. The dependence of R_{nl} on β and on strength of non-linearity is investigated in [9]. Different non-linear models for scattering change somewhat the R_{nl}. In the present approach we assume that the non-linear scattering radius is known. Usually R_{nl} is about $6 - 8$ and β is about $30 - 50$. The cross-section for scattering is still larger than the cross-section of absorption for $R^2_{nl} > \beta a/\lambda_{Di}$. We consider the cross-sections σ_{scat} and σ_{abs} as known in starting the kinetic theory. The rate of plasma particles (electron and ion $\alpha = \{e, i\}$) absorption I^{α}_{abs} is expressed through the absorption cross-section σ^{α}_{abs},

$$I^{\alpha}_{abs} = -\int \sigma^{\alpha}_{abs}(q,v) v f^{d}_{\mathbf{p}'}(q) dq \frac{d^3\mathbf{p}'}{(2\pi)^3} f^{\alpha}_{\mathbf{p}}, \qquad \mathbf{p} = m^{\alpha}\mathbf{v} \tag{1}$$

. Here as in [1-7] we neglect the difference between the particle velocity and the relative particle -dust velocity. For the rate of scattering I^{α}_{scat} for $\beta \gg 1$ we use special model approximating the large angle scattering of ions by back-scattering. The calculations indicate that depending on the impact parameter the scattering can occur on different angles between 0 and π (backscattering) and in average the angle of scattering is $\pi/2$. We can consider the case $\beta \ll 1$ with the effective scattering being the backscattering only approximately with coefficient of the order of 1. This is reasonable since the cross-section of scattering depending on model of non-linearity has the uncertain factor of the same order. We use the I^{i}_{abs} in the form

$$I^{i}_{scat} = -\int \sigma^{i}_{scat}(q,v) v f^{d}_{\mathbf{p}'}(q) dq \frac{d^3\mathbf{p}'}{(2\pi)^3} (f^{i}_{\mathbf{p}} - f^{i}_{-\mathbf{p}}) \tag{2}$$

For isotropic ion distribution the expression (2) is zero, i.e. the scattering is considered to be completely elastic.

2. Basic equations

The averaging with respect to the discreteness of the dust component is used by dividing all distributions in the random and regular parts. The description of general distributions should take into account the scattering and the absorption processes both in the regular and in the random parts of distributions. For the particle distributions we use the equations

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + e_{\alpha}\mathbf{E}\cdot\frac{\partial}{\partial \mathbf{p}}\right) f^{\alpha}_{\mathbf{p}} = S^{\alpha} + I^{\alpha}_{abs} + I^{\alpha}_{scat} \tag{3}$$

where S^{α} describes the source of the plasma particles α. The equations for grains include the process of charging and additional to [1] the drag force acting on grains due to ion scattering

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + \cdot\frac{\partial}{\partial \mathbf{p}}(q\mathbf{E} + \mathbf{F}^{d}_{drag})\right) f^{d}_{\mathbf{p}}(q,\mathbf{r},t) + \frac{\partial}{\partial q}(i_{ext} + \sum_{\alpha} I^{\alpha}) f^{d}_{\mathbf{p}}(q,\mathbf{r},t) = 0 \tag{4}$$

where $I^{\alpha}(q,\mathbf{r},t) = \int e_{\alpha}\sigma^{\alpha}_{abs}(q,v) v f^{\alpha}_{\mathbf{p}}(\mathbf{r},t) d\mathbf{p}/(2\pi)^3$ and
$\mathbf{F}^{d}_{drag} = \int (2\sigma^{i}_{scat}(q,v) + \sigma^{i}_{abs}(q,v)) m_i \mathbf{v} v f^{i}_{\mathbf{p}} d\mathbf{p} d\mathbf{p}'(2\pi)^6$. The averaging on fluctuations gives the collision integral for the regular part of distributions. These expressions are cumbersome.

3.Main results obtained in the generalized approach

1)In the present approach the collision integrals between the grains and grains and plasma particles are found with effective charge and screening include the large angle scattering and different sources of ionization
2) The effective dust charges and the effective screening effects are calculated

3) New effects absent in the previous approach proportional to both absorption and scattering are investigated
3) General kinetic description allows to prove the existence of dust attraction at large distances for any likely charged grains and for any non-equilibrium particle distributions. In the limit of thermal distribution the results coincide with that previously obtained [10-12] (for the thermal distributions in the momentum of the coefficients of drag and charging processes). Previous investigations [10-12] suggest that to prove the existence of dust attraction at large distances it is necessary to find that the ion static dielectric function is changing it sign at small wave numbers k. This result is obtained in the new kinetic approach and the effect is proportional to the product of the absorption ν_{abs} and scattering frequencies ν_{scat} and it cannot be obtained in [1-7]. As an example we demonstrate that for the source of ions $S^i_{\mathbf{p}} = \int \gamma_{\mathbf{p}',\mathbf{p}} f^e_{\mathbf{p}'} d\mathbf{p}/(2\pi)^3$, proportional to the electron distribution function (with γ being the probability of ionizations), the static dielectric constant indeed changes its sign for small values of k which is required for presence of dust attraction at large distances

$$\epsilon^i_{\mathbf{k},0} - 1 = -\frac{4\pi e^2}{k^2} \int \frac{\left((\mathbf{k}\cdot\mathbf{v})^2 \left(\frac{d\Phi^i(\epsilon_p)}{d\epsilon_p}\right) - (\nu^i_{d,abs} + 2\nu^i_{d,scat}) \int \gamma_{\mathbf{p},\mathbf{p}'} \frac{d\Phi^e(\epsilon_{p'})}{d\epsilon_{p'}} \frac{d\mathbf{p}'}{(2\pi)^3}\right)}{\left((\mathbf{k}\cdot\mathbf{v})^2 + \nu^i_{d,abs}(\nu^i_{d,abs} + 2\nu^i_{d,scat})\right)} \frac{d\mathbf{p}}{(2\pi)^3} \quad (5)$$

4) It is found that the zeros of dielectric constant gives the resonances and enhanced the dust-dust interactions described by the dust-dust collision integrals. The broadening of these resonances is determined by imaginary parts of dust effective responses.

4.Conclusion

The result of new approach provide the calculations of transport coefficients which take into account the scattering and absorption of ions and the ion drag on grains. Of special interest are the resonances in the screening due to dust attraction which enhances most transport coefficients.

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