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Dust in magnetized sheath

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The presence of dust in the plasma provides an important diagnostic tool. For example, in a bounded plasma, sheath characteristics can be studied in considerable detail by using fine dust probes (Samarian & James, 2005). This is due to the fact that the charge on the grain is a function of local plasma conditions and thus, studies of the dust dynamics in such a surrounding can provide information on the electron and ion fluxes, on the sheath potential and on the electric field. Therefore, the investigation of the charged dust behaviour provides useful guide in measuring the sheath characteristics.

The present study will focus on investigating the dust dynamics in a magnetized sheath in the presence of magnetized electrons and ions. By predicting the grain size and charge in levitation equilibrium, the sheath characteristics can be predicted accurately. This study aims to undertake such an investigation by first, elucidating the dependence of the magnetized sheath on various plasma parameters and then consistently calculating the charge on an isolated grain inside the sheath and corresponding levitation position. The planer sheath structure in the presence of a magnetic field parallel to the wall is investigated in this work. Although, the electron inertia is neglected from the present formulation, effect of the electron-neutral collision is retained in the dynamics. The ionization frequency is also included. The effect of Lorentz force and collision terms is compared on the structure of the plasma sheath. The charge on the dust grain inside the sheath is calculated self-consistently and effect of the magnetic field strength and plasma-neutral collision on the grain charging is delineated.

Two-component plasma consisting of electrons and singly charged ions is considered in the presence of a magnetic field that is parallel to the wall. Due to the formation of the sheath near the boundary, there exists two regions in the bounded plasma: (a) The quasi-neutral bulk plasma, where the electron and, ion number densities are equal: $n_i = n_e$, and, (b) The sheath at the boundary where the electron number density will be much smaller than the ion number density. A stationary magnetized planer plasma sheath boundary is located at $z = 0$ with the plasma filling the half space $z < 0$. The simplest description of such plasma, consisting of the electrons and ions is given in terms of continuity and momentum equations for respective species with a suitable closure model, viz., an equation of state. The normalized equations are

$$\frac{dN_i}{d\xi} = \frac{N_i}{\left(u_{iz}^2 - \frac{T_i}{T_e}\right)} \left[\frac{d\Phi}{d\xi} + \nu_{in}\left(u_{iz} + \beta_i u_{iy}\right) + \nu_I \frac{n_e}{n_i} u_{iz}\right], \tag{1}$$

$$\frac{du_{iz}}{d\xi} = -\frac{1}{u_{iz}}\frac{d\Phi}{d\xi} - \nu_{in}\left(1 + \beta_i \frac{u_{iy}}{u_{iz}}\right) - \frac{T_i}{T_e}\frac{1}{u_{iz}}\frac{1}{\left(u_{iz}^2 - \frac{T_i}{T_e}\right)} \times \left[\frac{d\Phi}{d\xi} + \nu_{in}\left(u_{iz} + \beta_i u_{iy}\right) + \nu_I \frac{n_e}{n_i} u_{iz}\right], \tag{2}$$

$$\frac{du_{iy}}{d\xi} = \nu_{in}\left(\beta_i - \frac{u_{iy}}{u_{iz}}\right), \tag{3}$$

$$\frac{dN_e}{d\xi} = N_e\left[\frac{d\Phi}{d\xi} - \nu_{en}\left(1 + \beta_e^2\right) u_{iz}\right], \tag{4}$$

$$\frac{du_{ez}}{d\xi} = -\left[\frac{d\Phi}{d\xi} - \nu_{en}\left(1 + \beta_e^2\right) u_{iz}\right] u_{iz} + \nu_I \tag{5}$$

$$\frac{d^2\Phi}{d\xi^2} = N_e - N_i\,. \tag{6}$$

Here $\beta_j = \frac{eB}{m_j c \nu_{jn}} \equiv \frac{\omega_{cj}}{\nu_{jn}}$, is the ratio of plasma-cyclotron to the plasma-collision frequencies. This parameter measures the relative importance of the Lorentz force against the collisonal momentum exchange in the plasma momentum equation. We following normalization have been used $\xi = \frac{z}{\lambda_{De}}, \Phi = \frac{e\phi}{T_e}, N_j = \frac{n_j}{n_0}, u_j = \frac{v_j}{c_s}, \hat{\nu}_I = \frac{\nu_I}{\omega_{pi}}, \hat{\nu}_{in} = \frac{\nu_{in}}{\omega_{pi}}\, \hat{\nu}_{en} = \frac{m_e \nu_{en}}{m_i \omega_{pi}}$, where $c_s = \sqrt{T_e/m_i}$ is the ion-acoustic speed, $\lambda_{De} = \sqrt{T_e/4\pi n_0 e^2}$ is the electron Debye length, and $\omega_{pi} = 4\pi n_0 e^2/m_i$ is the ion plasma frequency. The plasma number density n_0 correspond to the qusineutral density at the plasma sheath boundary $z = 0$. The set of Eqs. (1) - (6) is supplemented with the following boundary conditions $N_e = N_i = 1, u_{iz} = 1, u_{iy} = 0, u_{ez} = 0, \Phi = 0, \frac{d\Phi}{d\xi} = \nu_{in}$. We shall employ the set of Eqs. (1) - (6) with the above boundary condition to investigate the sheath structure in various parameter regimes. We assume argon as the discharge gas parameters[9] $T_e = 1\,eV, T_i = T_n = 0.05\,eV, n_0 = 10^8\,cm^{-3}$.

In Fig. 1(a) the sheath potential is shown for $\nu_{in}/\omega_{pi} = 0, 0.1$ and 0.2 respectively. For $\nu_{in} = 0$ wall potential reaches -4 V for $T_e = 1\,eV$ at $z = 15\,\lambda_{De}$. Thus for $\lambda_{De} = 0.07$ cm, the sheath width is 1 cm. The increase in the collision frequency leads to the decrease in the sheath thickness. For $\nu_{in} = 0.1\,\omega_{pi}$ the sheath potential is, $\phi_W = -5V$ and sheath width is $Z = 0.5$ cm. The experimental results on the collisonal magnetic sheath (Kim et al. 1995) suggests that when $\lambda_{mfp} \equiv 1/n_n\sigma < c_s/\omega_{ci}$, the sheath width is approximately $\sim (0.5 - 0.6)\,\lambda_{mfp}$. For an argon discharge, $c_s = 2.36 \cdot 10^5$ cm and $\omega_{ci} = 2.78 \cdot 10^4\,\mathrm{sec}^{-1}$ and thus $\lambda_{mfp} \sim 1\,\mathrm{cm} < c_s/\omega_{ci} \sim 10\,\mathrm{cm}$

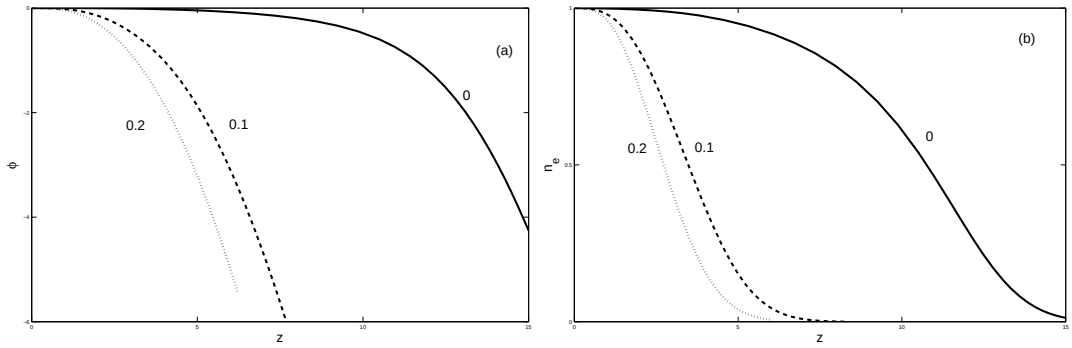

Figure 1: The potential (a) and electron density (b) profiles for parameters $\beta_i = .01\,, \beta_e = .1\,, \nu_{ioniz} = .001\,, \nu_{en} = .1$ with changing ν_{in}.

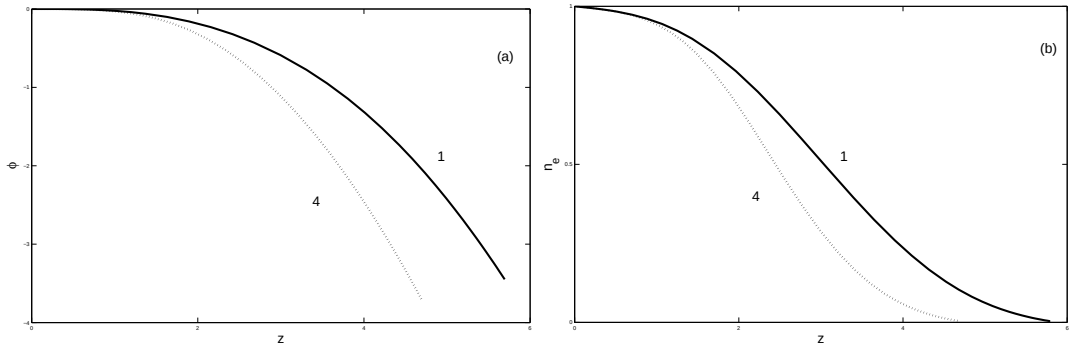

Figure 2: The parameters $\nu_{in} = \nu_{en} = 0.1\,, \beta_e = 5\,, \nu_{ioniz} = 0.001$. The sheath potential (Fig. 2(a)) and the electron density (Fig. 2(b)) is shown in the figure for varying β_i.

and the sheath width is $\sim 0.6\,$cm. Thus present sheath width for $\nu_{in} = (0-0.2)\,\omega_{pi}$ falls in the range of experimental observations. We see that the electron number density decrease faster with the increase in the ion-neutral collision frequency.

The change in the sheath potential (Fig. 2(a)), for $\omega_{ci} = \nu_{in}$, is $\phi_W = -5.8V$ and sheath width is $0.4\,$cm. When $\omega_{ci} = 4\,\nu_{in}$, sheath potential changes to $\phi_W = -3.71V$, and, the width of the sheath reduces to $0.33\,$cm. With the increase in β_i, the corresponding electron number density profiles, Fig. 2(b), is shown.

The orbit motion limited (OML) theory of the grain charging can be employed in the presence of the magnetic field provided (a) $a \ll \lambda_{De}$ and (b) $a < \rho_e \equiv v_{te}/\omega_{ce}$. Furthermore in a collisional plasma, $\lambda_{De} \ll \lambda_{mfp} \equiv 1/n_n\sigma$ is also assumed. By equating the sum of the electron and ion currents to zero, i.e. the charge on the grain surface is stationary, and calculating the potential $y = \Phi_p - \Phi_s$ (Sorasio et al. 2001) and thus charge $Q = (k_B T_e\, a y)/e$ the levitational equilibrium of the grain $Q\mathbf{E} = m_g\,\mathbf{g}$, can be used to calculate the location and the size of the grain inside the sheath. In Fig. 3(a) the charge on the gain is given in the unit of $10^3\,e$. In Fig. 3(b) the size distribution for the spherical grains of radius a is obtained by solving the levitation equilibrium

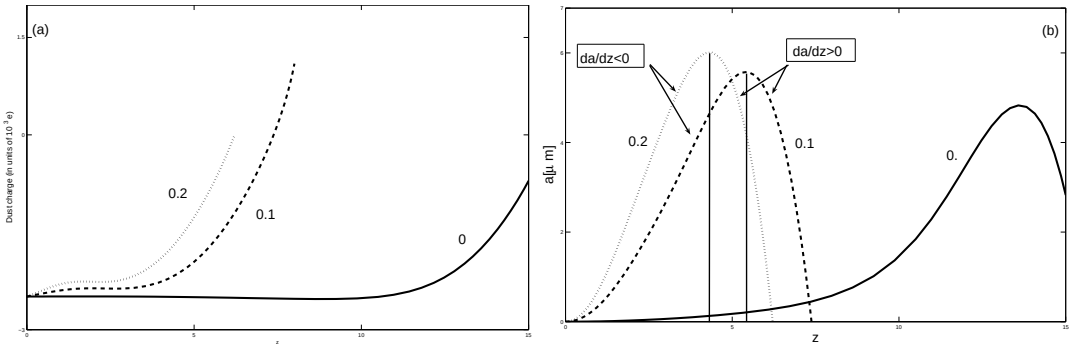

Figure 3: Same as in Fig. 1.

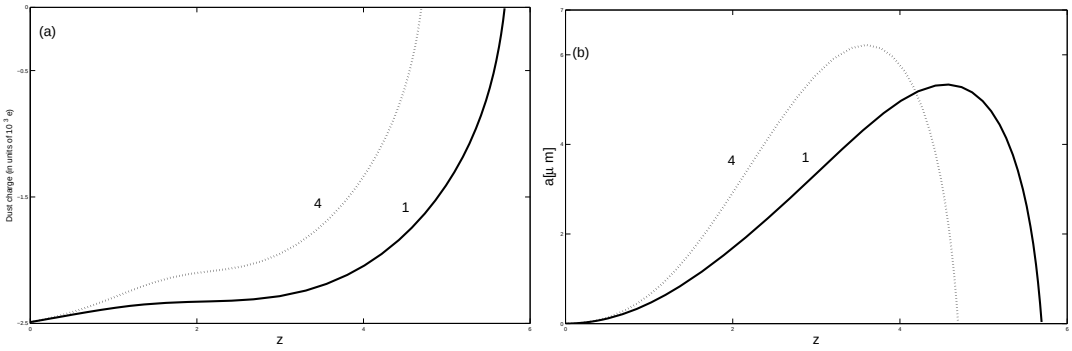

Figure 4: Same as in Fig. 2.

inside the sheath. The spatial derivative da/dz provides the clue to the stability of the grain inside the sheath. When $dQ/dz < 0$ or $da/dz < 0$, the grains are in an stable equilibrium inside the sheath. We see from Fig. 3(b) that in the absence of ion-neutral collision, grain is practically present right up to the sheath wall except when there is not enough charge of the grain to keep it in equilibrium.

In Fig. 4 β_i is varied. The increase in the ion-magnetization (β_i) inhibits the free flow of ions to the grain surface. This results in the grain setting up stronger repulsive field against the sheath with fewer electrons than is otherwise possible. Therefore increase in β_i is accompanied with the grains having less negative charge (Fig. 4(a)). The corresponding distribution of the different sizes of the grain displays a shift towards bigger stable grains with increasing β_i. Since the sheath width becomes smaller and shifted, the stable equilibrium of the levitated grains as well shifts towards the plasma-sheath boundary.

References

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