The plasma drag and dust motion inside the magnetized sheath

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The motion of micron size dust inside the sheath in the presence of an oblique magnetic field is investigated by self-consistently calculating the charge and various forces acting on the dust. It is shown that the dust trajectory inside the sheath, which is like an Archimedean spiral swinging back and forth between the wall and the plasma–sheath boundary, depends only indirectly on the orientation of the magnetic field. When the Lorentz force is smaller than the collisional momentum exchange, the dust dynamics is insensitive to the obliqueness of the magnetic field. Only when the magnetic field is strong enough, the sheath structure and, thus, the dust dynamics are significantly affected by the field orientation. Balance between the plasma drag, sheath electrostatic field, and gravity plays an important role in determining how far the dust can travel inside the sheath. The dust equilibrium point shifts closer to the wall in the presence of gravity and plasma drag. However, in the absence of plasma drag, dust can sneak back into the plasma if acted only by gravity. The implication of our results to the usability of dust as a sheath probe is discussed.


I. INTRODUCTION

The experimental work on dust crystals, plasma sheath involving dust, etc., has attracted considerable interest in the last few years.1 For example, controlled experiment with the massive dust inside the plasma sheath provides the access to the spatial and temporal scales hitherto inaccessible to the traditional probe techniques. This has led to the use of dust as a diagnostic tool to explore the sheath characteristics.1–4 As formation of a sheath in the magnetized, collisional plasma depends on the ratio of the cyclotron to the plasma collision frequencies, the trajectory of a charged dust in such a sheath is an implicit function of the plasma parameters.5–7 Often, charge on the dust inside the sheath is inferred by balancing the forces acting on the dust. However, proper consideration of the dust dynamics shows that dust do not come to a halt inside the sheath (as implied by the balance of forces) but oscillates around a small region, whose location is determined by the balance between various forces.7,8

In the absence of plasma drag, micron size grains are not confined inside the sheath but keep oscillating around a small region, which lies across both sides of the plasma–sheath boundary. It is only when plasma drag also acts on the dust that it remains confined to the charged boundary layer. It is known that in the absence of gravity, dust performs an inward slow spiralling motion inside the sheath before settling around a small region.8 Proximity of the dust to the wall is determined by the number of charge on the dust and it can travel much deeper inside the sheath in the presence of gravity, as part of repulsive electrostatic force on the dust is offset by the attractive gravitational force directed to the wall. Further, the equilibrium point around which dust oscillates also shifts closer to the wall. Therefore, plasma drag on the dust plays an important role in determining the dust trajectory inside the sheath.8,9

The dust survives long enough inside the charged boundary layer to feel the effect of the plasma drag.10 For example, unique to the dusty plasma is the formation of stable dust free regions called voids, which are due to an interplay between the repulsive electrostatic force and the ion drag force. The voids have been observed in the plasma processing discharge and plasma crystal experiments.10–14 However, the role of electron plasma drag is overlooked in these analyses. It has been shown recently that both the electron as well as the ion drag forces will be equally important to the dust dynamics.15–17

Role of the magnetic field in the sheath formation has been examined in the recent past.5,6,8,18–24 It is well known that the magnetized collisional plasma sheath characteristic is a sensitive function of the plasma parameters.5 The sheath width decreases with increasing ion-neutral collision frequency or ionization frequency and is also dependent on the magnitude and direction of the magnetic field.5 Dust acquires less number of negative charge when magnetic field is oriented transverse to the wall than when it is parallel to the wall. Therefore, both local plasma parameters as well as the magnetic field orientation play an important role in determining the dust trajectory inside the sheath. We shall investigate the effect of the obliqueness of the magnetic field on the dust dynamics inside the sheath.

The primary motivation of this work is to examine the effect of various forces on the dust trajectory in a nonuniform flowing plasma (which reflects the near wall region of plasma devices) in the presence of an oblique magnetic field. Similar investigation of the dust dynamics has been

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carried out in the past. However, notwithstanding the similarity with past studies, the results of the present analysis are quite different. For example, wide oscillation in plasma parameters seen in the past works is not seen in the present analysis. We believe that this disagreement is primarily due to the unphysical choice of parameters in the past investigations.

This work generalizes our previous work and delineates the role of plasma drag on the dust dynamics. In Ref. 8, we have shown that under the influence of the drag and electrostatic repulsion, dust moves towards the wall. The repulsion of the negatively charged wall supersedes all other forces as dust moves closer to the wall, resulting in dust turning back to the plasma sheath boundary. The dust starts sheath-ward journey all over again once the drag dominates the sheath repulsion. What happens if the plasma drag is sufficiently weak? In the present work, it is shown that in the absence of plasma drag, dust could cross back into the quasineutral region if only gravity partially offsets the repulsion. Thus, in the absence of drag, dust continues oscillating between the sheath and the quasineutral region. As dust moves at a small speed (compared to the ion acoustic speed), this implies that the dust will spend considerable time in the quasineutral region. The obliqueness of the ambient magnetic field does not modify this picture. The strength and direction of the magnetic field affect only the electron flow to the wall and thus the sheath strength in turn affects the dust motion.

II. THE SHEATH MODEL

We shall consider two-component plasma consisting of electrons and singly charged ions in the presence of an oblique magnetic field with $\vec{B}/B = (\sin \theta, 0, \cos \theta)$. A stationary magnetized planer sheath boundary is located at $z = 0$ with the plasma filling the half space $z < 0$. As laboratory sheath experiments with dust include both low ($< 40$ mTorr) as well as high neutral pressure, we shall include both plasma-neutral collision as well as ionization in the sheath region. The dynamics of such plasma is described by the following set of equations for respective species with an equation of state:

$$
\frac{d}{dz}(n_i \nu_{iz}) = \nu_i n_e, 
$$

(1)

$$
\frac{d}{dz}(n_e \nu_{ez}) = \nu_e n_i, 
$$

(2)

$$
\frac{d}{dz}(n_e \nu_{ix}) = \nu_i n_e, 
$$

(3)

$$
\frac{d}{dz}(n_e \nu_{iy}) = \nu_i n_e, 
$$

(4)

$$
\frac{d}{dz}(n_e \nu_{iz}) = \nu_i n_e, 
$$

(5)

$$
0 = \frac{e}{m_e} E_z \nu_{ez} \sin \theta - \frac{\nu_{iz}^2}{m_i} \frac{dn_i}{dz} - \nu_i n_e \nu_{ez}, 
$$

(6)

$$
0 = \frac{e}{m_e} E_z + \omega_{ce} \nu_{ez} \sin \theta - \frac{\nu_{ez}^2}{m_e} \frac{dn_e}{dz} - \nu_e n_e \nu_{ez}, 
$$

(7)

$$
0 = \omega_{ce} (\nu_{ez} \sin \theta - \nu_{ez}) \cos \theta + \nu_e n_e \nu_{ez}. 
$$

(8)

Here, $v_{ij} = \sqrt{k_B T_i/m_j}$ is the plasma thermal velocity with $j = e, i$, $k_B$ is the Boltzmann constant, $m_j$ is the mass, $T_j$ is the temperature of the $j$th species, $\nu_{je}, \nu_{ji},$ and $\nu_{ij}$ are the components of the plasma fluid velocities, $E_z = -d\phi/dz$ is the sheath electric field, and $\omega_{ce} = |e|B/m_e c$ is the plasma cyclotron frequency. While writing Eqs. (6) and (8), the electron inertia term has been ignored implying $d/dt \ll \omega_{ce}$. Note that the above set of Eqs. (3)–(8) are identical to Eqs. (3)–(6) of Ref. 8 in $\theta = \pi/2$ limit when $v_{ex} = 0$. The $\nu_i = \gamma_i n_n$ is the ionization frequency, where the ionization rate, $\gamma_i$, for the argon gas is

$$
\gamma_i = 5 \times 10^{-8} \exp \frac{-15.5}{T_e}. 
$$

(9)

The collision frequency $\nu_{jn}$ is

$$
\nu_{jn} = \frac{\langle |\sigma| v \rangle_j}{m_n + m_j} \rho_n, 
$$

(10)

with the following collision rates:

$$
\langle |\sigma| v \rangle_e = 10^{-15} \text{cm}^2 \left( \frac{128 v_e^2}{9 \pi e^2} \right)^{1/2}, 
$$

(11)

$$
\langle |\sigma| v \rangle_i = 10^{-15} \text{cm}^2 \left( \frac{8 v_n^2}{\pi} + \frac{8 v_{in}^2}{\pi} + (v_i - v_n)^2 \right)^{1/2}. 
$$

(12)

Here $m_n$ and $n_n$ are the mass and number density of the neutral particle, respectively. In the present work, neutral velocity $v_n$ is set to zero.

The electric potential $\phi$ is obtained from the Poisson’s equation

$$
\frac{d^2 \phi}{dz^2} = 4 \pi e (n_e - n_i). 
$$

(13)

While writing plasma momentum equations (3)–(7), we have assumed that the neutrals provide a uniform background. We shall write down the above set of equations in the following normalized coordinates:

$$
\xi = \frac{z}{\lambda_{De}}, \quad \Phi = \frac{e \phi}{k_B T_e}, \quad N_j = \frac{n_j}{n_0}, \quad u_j = \frac{v_j}{c_s}, 
$$

(14)

$$
\nu_i = \frac{\nu_i}{\omega_{pe}}, \quad \nu_e = \frac{\nu_e}{\omega_{pe}}, \quad \nu_{iz} = \frac{\nu_{iz}}{m_i \omega_{pe}}. 
$$

(15)

Here, $c_s = \sqrt{k_B T_e/m_i}$ is the ion-acoustic speed, $\lambda_{De} = \sqrt{k_B T_e/4\pi n_0 e^2}$ is the electron Debye length, and $\omega_{pe} = 4\pi n_0 e^2/m_i$ is the ion–plasma frequency. We shall drop the hat from the collision frequencies and imply, henceforth, that we are dealing with the normalized frequencies. The following normalized set of equations are derived from Eqs. (1)–(8):

$$
\frac{dN_i}{d\xi} = \frac{N_i}{(u_i^2 - \frac{\Phi}{T_e})} \left[ \frac{d\Phi}{d\xi} + \nu_n (u_z + \beta_i u_y \sin \theta) + \nu_i \frac{n_e}{n_i} u_z \right],
$$

(16)
\[ \frac{d\Phi}{dz} = -1 \frac{d\Phi}{dz} - \nu_{in} \left( 1 + \beta_i u_{iy} \sin \theta \right) - \frac{T_i}{T_e} \frac{1}{u_{iz}} \left( u_{iz}^2 - \frac{T_e}{T_i} \right) \]
\[ \times \left[ \frac{d\Phi}{dz} + \nu_{in} \left( u_{iz} + \beta_i u_{iy} \sin \theta \right) + \nu_{r} \frac{n_e}{n_i} u_{iz} \right], \quad (16) \]
\[ \frac{du_{iz}}{dz} = \nu_{in} \beta_i \left( \sin \theta - \frac{u_{ix}}{u_{iz}} \cos \theta \right) - \nu_{r} \frac{n_e}{n_i}, \quad (17) \]
\[ \frac{du_{ix}}{dz} = \nu_{in} \beta_i \frac{u_{iy}}{u_{iz}} \cos \theta - \nu_{r} \frac{n_e}{n_i}, \quad (18) \]
\[ \frac{dN_e}{dz} = N_e \left[ \frac{d\Phi}{dz} - \nu_{en} \left( \frac{1 + \beta_i^2 \sin^2 \theta}{1 + \beta_e^2 \cos^2 \theta} \right) u_{iz} \right], \quad (19) \]
\[ \frac{d^2\Phi}{dz^2} = N_e - N_i. \quad (20) \]

Here,
\[ \beta_i = \frac{e B}{m_i c \nu_{jz}} \equiv \omega_{kj} \nu_{jz} \quad (22) \]

is the ratio of the plasma-cyclotron to the plasma-collision frequencies. This parameter measures the relative strength of the Lorentz force against the collisional momentum exchange.

The above set of Eqs. (15)–(21) will be solved under the following boundary conditions:
\[ N_e = N_i = 1, u_{iz} = 1, u_{iy} = 0, u_{iz} = -0.001, \]
\[ \Phi = 0, \frac{d\Phi}{dz} = -\nu_{in}. \quad (23) \]

A detailed discussion of the above boundary condition is given in Ref. 8. Equations (15)–(21) are solved in various parameter regimes with the boundary condition (23).

## III. THE DUST DYNAMICS

For the dust charging model, for definiteness, we shall assume a spherical dust of radius \( a \). The orbit motion limited (OML) theory of the grain charging can be employed in the presence of the magnetic field provided (a) \( a \ll \lambda_D \) and (b) \( a < \rho_e \equiv \nu_{ce} / \omega_{ce} \). Furthermore in a collisional plasma, it is assumed that the Debye length is much smaller than the collision mean free path, i.e., \( \lambda_D < \lambda_{dpp} \equiv 1 / n_a \sigma \). It can be shown\(^8\) that these conditions are easily met in the present case. Defining \( \Delta \Phi = \Phi_{\text{pl}} - \Phi_{\text{dust}} \), the difference between the plasma and the dust surface potentials, from the ambipolar condition near the grain surface, we get an expression for \( \Delta \Phi \), which can be solved analytically. Thus, the grain charge is given by the following formula: \(^{20}\)

\[ Q = \frac{a k_B T_e}{e} \left[ \frac{4}{\pi} M^2 - \log \left( 1 + \frac{1}{C} \right) \right] \times \left\{ 1 - \log \left( (1 + C) \log \left( 1 + \frac{1}{C} \right) \right) \right\}, \quad (24) \]

for \( \Delta \Phi < 0 \), and

\[ Q = -\frac{a k_B T_e}{e} \left[ 1 + \frac{4}{C} M^2 \log \left( 1 + \frac{1}{C} \right) \right] \times \left\{ 1 - \log \left( (1 + C) \log \left( 1 + \frac{1}{C} \right) \right) \right\}, \quad (25) \]

for \( \Delta \Phi \geq 0 \). Here,
\[ C = \frac{\pi}{4} \sqrt{\frac{m_e n_i}{m_i n_e}} \quad (26) \]

and
\[ C_1 = -\frac{4}{\pi} \sqrt{\frac{m_i n_e}{m_e n_i}} \quad (27) \]

where \( M = \nu_{iz} / c_s \) and the ion velocity \( \nu_i = \sqrt{\nu_{iz}^2 + 2 \nu_i^2} / \pi \) is the sum of random and directed components. The above formulas \( [\text{Eqs. (24) and (25)}] \) are used for the dust charge which is often inferred by numerically solving the ambipolar condition near the dust surface. Only at the initial stage of the charging, when \( C \) \( C_1 \) are not large enough, a small error \( (\sim 3\%) \) occurs when the dust have 1–2 charge.

The dynamics of the dust is determined by solving following set of equations:
\[ \frac{dx}{dt} = v_d, \quad (28) \]
\[ \frac{m_d}{dt} = F_{e,j} + F_E + F_g, \quad (29) \]

where the drag forces \( F_{e,j} \) are due to the electrons and ions. The electrostatic force \( F_E = Q E \) and the gravity \( F_g = m_d g \). The electron and ion drag forces are\(^{15–17}\)

\[ F_e = \pi a^2 m_e n_e \nu_e \nu_i \left[ (2 + z) \exp(-z) + 5 z^2 \right], \quad (30) \]
\[ F_i = \pi a^2 m_i n_i \nu_i \nu_e \left[ (2 + z \tau) + 5 z^2 \tau^2 \right]. \quad (31) \]

Here, \( z = Ze^2 / a k_B T_e \). We have assumed that the value of Coulomb logarithm \( \lambda_{e,j} \approx 10 \) while writing the last term inside respective brackets for \( F_e \) and \( F_i \). In the present work, the sheath width \( \lambda_s \) is much larger than the dust radius \( a \), and thus the correction of the order of \( a / \lambda_s \) to the \( F_e \) has been neglected. Before solving Eqs. (28) and (29), the equations are normalized. The choice of normalization parameter is dictated by Eq. (14).

## IV. NUMERICAL RESULTS

First, we solve Eqs. (15)–(23) for the same set of parameters as in Ref. 8, i.e., \( \beta_i = 0.01, \beta_e = 0.1, \nu_i = 0.001 \nu_{pi}, \) and \( \nu_{in} = \nu_{en} = 0.1 \nu_{pi} \) except now, we vary the magnetic field orientation. Unlike Refs. 19 and 20 where the primary effect of the magnetic field is manifested through the oscillation in the ion density and velocity profile, present results are insensitive to the magnetic field orientation, and thus we do not present them. The insensitivity of the sheath structure to the magnetic field orientation is related to the
smallness of the parameter $\beta_j$, which implies that the plasma is weakly magnetized. However, for large $\beta_j$, i.e., when the Lorentz force dominates the collisional momentum exchange, then the orientation of the magnetic field considerably affects the plasma sheath structure. But before we discuss the dust dynamics inside a strongly magnetized sheath, we shall first explore the effect of gravity and plasma drag on the dust motion in a weakly magnetized sheath.

In Fig. 1(a), the trajectory of a micron size dust inside the sheath is shown for two cases (1) when the dust experiences repulsive electrostatic force along with the plasma drag forces (bold lines) and (2) when in addition gravity also acts on the dust. The sheath parameters are $\beta_i = 0.01$, $\beta_e = 0.1$, $\nu_I = 0.001 \omega_{pe}$, and $\nu_in = \nu_{cen} = 0.1 \omega_{pi}$. As has been noted above, the direction of the magnetic field is unimportant here because the Lorentz force is much smaller than the collisional momentum exchange term. The trajectory of the dust mimics an Archimedean spiral with the centre of the spiral indicating the equilibrium position around which dust continuously oscillates. This feature of the dust dynamics inside the sheath has recently been shown in Ref. 8. Note that the dust moves very slowly inside the sheath with typical dust velocity around only a few percent of the ion acoustic speed. In the absence of gravity, when only plasma drag forces counteract the sheath repulsive field, the dust is unable to travel close to the wall because it feels strong electrostatic repulsion almost halfway down the sheath. However, the presence of gravity allows much closer approach to the wall as repulsive force is partly offset by the gravity. The temporal behaviour of the dust trajectory which is more like a damped harmonic oscillator in the presence of gravity is similar to the case when gravity is absent (Fig. 1(b)). As can be seen from Fig. 1(a), the decrease in the amplitude is related to the localization of the grain in the sheath. The dissipation of the oscillation amplitude is due to the dissipation of energy. For example, while moving towards the wall, negatively charged dust does work against the electric field of the sheath, while gravity and plasma drag are parallel to the dust velocity. The opposite happens when the dust moves backward towards the plasma–sheath boundary. Now, the electric field is parallel while gravity and plasma drag are antiparallel to the dust velocity. As dust approaches the plasma–sheath boundary, the sheath field almost becomes zero and gravity and the plasma drag are the only forces opposing the dust motion. As a result, dust turns back and starts moving towards the wall. Clearly, this back and fourth motion of the dust causes the field to do work against the drag forces and thus, with every turn, the dust loses some amount of energy and the amplitude of the oscillation keeps decreasing with time. Therefore, the dissipative drag causes irreversible loss of energy and ultimate localization of the dust inside the sheath. However, the dissipative loss of energy is minimized as the dust is confined to a smaller region and the amplitude of oscillation asymptotically approaches small mean value corresponding to the equilibrium position of the dust. In Fig. 1(c), the trajectory of a 3 $\mu$m sized dust is shown. In the absence of gravity, the electrostatic repulsion is very strong owing to the presence of large negative charge on the grain.

![Fig. 1](https://example.com/fig1.png)

**FIG. 1.** (Color online) The trajectory of the dust is shown in (a) and (c) for the 1 and 3 $\mu$m sized dust in the absence of gravity (bold line) and with gravity (dotted line). Common to both the case is the presence of plasma drag and electrostatic force. In (b) and (d), the temporal plots for the respective grains are shown.
Thus, the dust is almost tied to the plasma sheath boundary (the bold curve). However, the presence of gravity substantially offsets this repulsion and the dust travels about one third of the distance inside the sheath (dotted curve). In Fig. 1(d), the temporal behaviour of the dust trajectory is shown, which is similar to the previous case, except now the amplitude of the oscillation in the absence of gravity is very small which is indicative of the dust moving very slowly inside the sheath. In Fig. 2, the dust trajectory inside the sheath is plotted against time. As can be seen from the figures, in the presence of gravity, a 1 μm sized dust covers a distance ∼ 5 λD initially before it gets localized to a small region. As noted above, the location of the dust equilibrium position is critically dependent upon the presence of gravity (dotted line in the presence of gravity).

The oscillatory behaviour of the dust inside the sheath was also discussed in the past, and temporal oscillation of the dust trajectory was predicted (Figs. 12(a) and 12(b) in Ref. 19). However, as has been noted in the Introduction, the oscillations in the dust charge which is absent in the present case (Please see Ref. 8 for dust charge profile) might be responsible for the oscillation in the dust trajectory in past studies.

How important is plasma drag to the dust dynamics? As has been noted above, the dust is moving very slowly inside the sheath and thus it will feel significant drag. In order to delineate the effect of the drag on the dust motion, in Fig. 3, we show the dust trajectory inside the sheath for two cases: (1) the plasma drag, sheath electrostatic field, and gravity acts on the dust (dotted curve) and (2) only sheath electrostatic field and gravity is present (bold line). In Figs. 3(a) and 3(b), the spatial and temporal behaviour of a micron size dust is shown. We see from Fig. 3(a) that in the absence of plasma drag, i.e., when conservative forces, namely, repulsive electrostatic field and gravity act on the dust (bold line), the repulsion is so strong that the dust cannot be confined to the sheath region. It crosses the plasma-sheath boundary (z = 0) and enters the quasineutral plasma region (z < 0). Here, the effect of the sheath field diminishes and gravity forces the dust to turn back and move to the wall. The dust will continue this perpetual back and forth motion between the sheath and the quasineutral plasma region because the forces acting on the dust are conservative. The temporal behaviour of the dust trajectory (Fig. 3(b), bold line) shows this undamped oscillation. Further, the value of vD/cs is quite small in this case implying that the dust is moving very slowly. It is only when the plasma drag is also present, that the micron sized dust can move much faster (∼10% − 20% cs) inside the sheath. In Fig. 3(c), the motion of 3 μm sized grain is shown. In the absence of plasma drag force (solid line), we see that, like the micron size dust, the dust is pushed out of the sheath into the quasineutral plasma region before swinging back into the sheath. However, unlike the micron size dust, it is pushed much deeper in the quasineutral region. This is not surprising considering that the larger dust carries more negative charge and thus feels much stronger repulsion. It is only when the plasma drag forces are present that the dust remains confined to the plasma sheath. In Fig. 3(d), the temporal behaviour of the dust trajectory is shown with and without the drag (dotted and bold, respectively), which is similar to the previous case.

V. DISCUSSION

The magnetic field only indirectly affects the dust dynamics inside the sheath. It is the sheath potential and thus
the sheath width that is directly affected by the magnetic field. The sheath size increases with decreasing angle between the field and the wall. This can also be seen if we recall that in the absence of magnetic field, sheath has maximum potential which can be easily inferred by balancing the electron and ion fluxes at the plasma sheath boundary. This yield

\[ \Phi \approx \left(1 + \frac{T_e}{T_i}\right) \left(1 + \frac{k_B T_i}{\pi m_i v_i^2/2}\right) M^2, \]  

(32)

where \( M = v/c_s \) is the Mach number. For typical discharge conditions \( T_e \ll T_i \) and because ions are almost cold, \( k_B T_i \ll m_i v_i^2 \) the wall potential becomes \( \Phi \approx M^2 \). Corresponding sheath width can be estimated by using Child’s law\(^{27}\) which gives \( d \approx M/2 \) in the unit of Debye length. The presence of magnetic field inhibits the plasma motion and changes \( M \). Therefore, depending on the angle between the field and wall, the sheath width can increase or decrease.

The direct coupling of a micron sized dust to the magnetic field, \( \sim v_D \times B \) is much smaller than \( c E \) (here \( c \) is light speed). Therefore, how deep the dust can move in the sheath depends primarily on its charge. In the absence of gravity, dust remains closer to the plasma–sheath boundary as the repulsive sheath field overwhelms the plasma drag forces. However, with the increasing mass and thus size, dust is pinned down to the plasma–sheath boundary. Therefore, there is a trade off between dust size and the plasma parameters regarding its suitability as a probe. If the grain size is big, on the one hand, it can carry large negative charge (implying large repulsion from the wall), while on the other hand, it will feel bigger tug to the wall due to gravity, offsetting partially the large negative repulsion.

The plasma drag plays an important role in confining the dust inside the sheath. In the absence of drag, dust can sneak back into the quasineutral plasma region before falling back to the sheath. Thus, without drag, the confinement of dust inside the sheath is difficult. Often the dust charge is inferred by balancing the repulsive sheath field against the gravity. However, as plasma drag is important and dust speed is 10\%–20\% of the ion acoustic speed, the inference of dust charge by balancing the electrostatic field and gravity should be treated with caution. While investigating the dust dynamics, we have assumed that the plasma-sheath provide a passive background. But because dust can sneak back into the plasma, it may affect the plasma dynamics. In the present investigation, we have not explored this feedback loop.

Following is the summary of our main results.

1. The dust trajectory inside the sheath is unaffected by the magnetic field when the collisional momentum exchange dominates the Lorentz force.
2. The role of magnetic field is limited to the modification of the sheath potential and its width. As dust charge inside the sheath changes with changing sheath potential, the dust dynamics is indirectly affected by the magnetic field.
3. The dust of smaller size can be easily trapped inside the sheath. However, bigger dust can spend considerable time in the quasineutral plasma region before drag and gravity pulls it back to the charged boundary layer.

4. The interplay between gravity and sheath electrostatic force constrains the usability of dust as a sheath probe as there is a trade-off between the dust size and charge.

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1S. V. Vladimirov, K. Ostrikov, and A. A. Samarian, Physics and Applications of Complex Plasmas (Imperial College, London, 2005), Chap. 5.
# Physics of Plasmas

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