Characteristics of the plasma sheath and the charging near the ion engine of the spacecraft

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Abstract

New sheath structures near the ion engine of the spacecraft are investigated by numerical calculation. We show the double sheath potential, the space charge density and the double electric field by the dust grains and secondary electrons. Temporal evolution of the grain charge near the ion engine is simulated by the conservation law of the electric charge–current equation. It turns out that the control of the plasma sheath near the ion engine of the spacecraft is possible. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The presence of particulate contaminants in etching, sputtering and deposition processors remains a major problem in engineering [1–4] and space plasmas [5–7]. In most cases, dust grains do not have well-defined mass, charge and size, and it is often quite difficult to understand plasmas having such dust grains or fine particles. The particulates occur in the range of sizes, 0.01–10 μm being the most common although grains of 10 μm or larger are also possible. The particulates grow in size and vary in charge while in the discharge due to various chemical processes and the nonlinear interaction between the plasma and the wall. Particulates such as BaTiO₃ are used as the insulating material of the cathode or the insulator of the electrode in the ion engine [8]. Since BaTiO₃ is generally negatively charged due to the adhesion of the faster moving electrons than the positive ions, we assume it as the dust grains. These phenomena can have the appearance of clouds associated with particulates suspended above or near the wall of the ion engine of the spacecraft. A sheath with electron emission from the wall has been considered in a plasma with negative dust grains [9–11]. However, not many theoretical works on the effects of the sheath structure and the time-dependent grain charge have been done in plasmas near the ion engine of the spacecraft. We investigate the effects of the negatively-charged dust grains to understand the behavior of the sheath including dust grains such as BaTiO₃ emitted from the cathode or the insulator of the electrode in the ion engine. As a result of numerical calculation, we demonstrate the new properties of the sheath potential, the space charge density and the electric field, and show the dust grain-charge depending on the plasma parameters.

2. Modeling

We show a one-dimensional model of a dusty plasma near the wall of the ion engine. Fig. 1 illustrates a model of the hollow cathode type of an ion engine. Dust grains emitted from the cathode or the insulator are generated in the discharge chamber and are discharged from an outlet. Part of exhausting gas goes back to the outside wall of the engine and collides the outside wall of the ion engine, which is negatively charged. In Fig. 1, the discharging plasma is generated in the chamber drawn with meshed line, and dusts are emitted from the cathode or the insulator of the electrode. The region modeled in numerical calculation is the negatively charged, outside wall of the ion engine. The outside wall of the spacecraft is usually negatively charged by the interaction between the spacecraft and space plasma.

The electron, positive ion, secondary electron and dust grain densities at the sheath edge denote \( n_e, n_i, n_s \) and \( n_d \); the potential in the sheath, the bulk plasma potential and the wall potential are \( -\Phi_e \) and \( -\Phi_w \); the initial velocity of positive ions entering the sheath is \( u_0 \); the electron, positive ion, secondary electron and dust grain temperatures are \( T_e \)
$T_b$, $T_i$, and $T_d$, respectively. Poisson’s equation is given as
\[ \varepsilon_0 \frac{d^2 \Phi}{dx^2} = e(n_e - n_i - n_s + Z n_0) = \rho, \]  
(1)
where $\rho$ is the space charge density. The density of electrons $n_e$ forms the Boltzmann distribution
\[ n_e = n_{e0} \exp \left( \frac{e\Phi}{T_e} \right). \]
(2)

The flux of ions is assumed to be continuous across the sheath in the collisionless model. The ion density $n_i$ is supposed to be as follows due to the flowing ions with the velocity $v_i$,
\[ n_i = \frac{n_{i0}}{\sqrt{1 - \frac{2(e\Phi/T_e)}{(m_{Xe}/m_p)(M^2 - 1/T_e)}}}, \]
(3)
where the Mach number $M = v_i/v_{sc}$, $v_{sc}$ is the ion acoustic velocity and Xenon and proton mass ratio is $m_{Xe}/m_p$ [8–10]. The secondary electron density $n_s$ produced by the secondary emission
\[ n_s = \frac{j_i}{e} \frac{m_e}{2e\Phi_w(1 - (\Phi/\Phi_w))} \]
(4)
where $j_i = n_{d0}e\nu_s$ and $\Phi_w$ are the current density of secondary electrons and the potential of the wall, respectively. When the Xenon gas burns in the engine room, a large number of the particulates are emitted from the cathode or the insulator composed of the ceramics such as BaTiO$_3$. The particulates become negatively-charged due to the adhesion of electrons. The dust grain density $n_d$ is assumed to be the Boltzmann distribution
\[ n_d = n_{d0} \exp \left( \frac{Q_d \Phi}{T_d} \right) \]
(5)
near the wall of the engine, where $Q_d = e|Z|$ and $T_d$ denote the magnitude of the dust charge with the charge number $|Z|$ and the dust temperature, respectively. For the wall potential, $|\Phi_w| \gg T_d/e$ holds. We define the distance from the wall as $\xi = x/\lambda_D$, where $\lambda_D = (e_0 T_e/e^2 n_{d0})^{1/2}$ is the Debye length. Quasineutrality condition at the sheath edge is $n_{e0} + Z n_{d0} = n_{i0} + n_{s0}$. The boundary conditions are set as follows. The derivative of the space charge density $\rho$ is

Fig. 1. Schematic diagram of our model.
assumed to be zero at the sheath boundary: $\partial \rho / \partial \phi = 0$. The electric field is assumed to be 0 at the boundary. In this case, integration of Poisson’s equation gives rise to the electric field.

In order to study time-series of the grain-charge, we consider the conservation law of the electric charge–current equation in the bulk plasma. In this case, the particle potential is determined by balancing the currents of electrons $J_e$, positive ions $J_i$ and secondary electrons $J_s$ to dust grains. The charge number of dust grains can be obtained by solving $\partial Q_d / \partial t = J_e + J_i + J_s$, where

$$J_e = -4\pi r^2 e \sqrt{T_e/2\pi m_e} \exp(e\Phi/T_e)n_e,$$

$$J_i = 4\pi r^2 e \sqrt{T_i/2\pi m_i}(1 - e\Phi/T_i)n_i$$

and

$$J_s = 4\pi r^2 e \sqrt{T_e/2\pi m_e} \times 14.8(\delta_m/E_m)J_e.$$

The parameters $r$, $\delta_m$ and $E_m$ are the average radius of dust grains, the coefficients of the maximum secondary emission and the maximum energy of the secondary electrons, respectively. Here we use the orbital limited motion theory [8–10] for positive ions. We illustrate the forms of the sheath, the space charge density and the electric field, and simulate one dimensional temporal-evolution of the grain-charge in Section 3.

3. Numerical results

We attempt to calculate the nonlinear structure of the sheath, space charge density and electric field in the sheath region, and simulate temporal-evolution of the grain charge in the bulk plasma.

First, we investigate the sheath structure because the sheath is closely connected with the control of the plasma by the potential of the wall. In the sheath, since the electrostatic potential is negative, we assume that the normalized potential $\phi = -e\Phi/T_e$ for numerical calculation of the
Fig. 3. (a) Spatial profile of the sheath potential for \( J_e/J_e^* = 0.5 \) (solid line), 1.0 (dotted line) and 2.0 (solid and dotted line), respectively. (b) The space charge density in the sheath for \( J_e/J_e^* = 0.5 \) (solid line), 1.0 (dotted line) and 2.0 (solid and dotted line), respectively. (c) Profile of the electric field as a function of the distance, for \( J_e/J_e^* = 0.5 \) (solid line), 1.0 (dotted line) and 2.0 (solid and dotted line), respectively.

sheath. Fig. 2a shows the sheath potential \( \Phi \) depending on the ion density near the wall for \( n_i/n_i^* = 10 \) (solid line), 100 (dotted line), and 500 (solid and dotted line), where the fixed parameters are \( \Phi_e = -20, \ Z = 500, \ T_i/T_e = 0.1, \ T_d/T_e = 0.05, \ J_e/J_e^* = 0.5 \) and \( T_e = 2 \) eV, respectively. It turns out that the shape of the sheath potential varies in the range of \( 0.9 \lambda_D < x < 1.1 \lambda_D \) for \( n_i/n_i^* = 10 \) by the presence of dust grains and secondary electrons. In Fig. 2a, a magnified area is also illustrated in the range of \( 0.8 \lambda_D < x < 1.2 \lambda_D \) for \( n_i/n_i^* = 10 \). We think that dust grains are trapped in this range. We illustrate the space charge density \( \rho \) in the sheath for the same parameters in Fig. 2b. The structure of the electric field \( E \) in the sheath is shown in Fig. 2c, where we use the same parameters as employed in Fig. 2a. We see that the electric field forms the double humped structure, which is newly found in this sheath. Positively charged Xenon ions are frequently accelerated and decelerated by this electric field, and are drastically accelerated near the wall. Fig. 3a illustrates the potential depending on the ratio of the secondary electron and main electron current densities \( J_e/J_e^* \). The solid, dotted, and solid and dotted lines imply \( J_e/J_e^* = 0.5, 1.0 \) and 2.0, respectively. We show the magnified figure in the range of \( 0.7 \lambda_D < x < 1.16 \lambda_D \) in Fig. 3a. The space charge density is shown in Fig. 3b for the same parameters in Fig. 3a. Similarly, we illustrate the electric field in Fig. 3c. When there are no dust grains and secondary electrons, we cannot show the deformation of the potential, an enhancement of the space charge density and the double electric field structure. These structures do not depend on the ion and dust temperatures even if we change the ion temperature in the range of \( 10 < n_i/n_i^* < 500 \) and the dust temperature in the range of \( 0.05 < T_d/T_e < 0.5 \), where the radius of dusts \( r = 1 \) μm. Hence dust grains and secondary electrons are the major effects in this plasma.

Next, in order to investigate temporal-evolution of the grain-charge, we perform a simulation of the grain-charge depending on the ion temperature and density. Fig. 4 shows
temporal-evolution of the grain charge for \( T_i/T_e = 0.3 \) (solid line), 0.5 (dotted line), 0.7 (solid and dotted line) and 0.9 (long dotted line), which implies that dust grains take \( \sim 0.3 t_0 = 8.9 \mu s \) for \( T_i/T_e = 0.3 \) to saturate its charge, whereas \( \sim 0.6 t_0 = 15.5 \mu s \) for \( T_i/T_e = 0.9 \), where \( t^* = t_0 T_e \), \( t_0 = \omega_{\text{pe}}^{-1} \lambda_{\text{D}}/r = 132/\pi \sqrt{\epsilon_{\text{D}}/m_{\text{D}}} \), \( r \) is the average radius of the dust grains, \( T_e = 2 \text{ eV} \), \( \epsilon = e^2/4\pi \varepsilon_0 T_e = 1.5 \times 10^{-4} \), \( \phi = e\Phi/T_e = 0.2 \), \( n_{\text{D}}/n_{\text{O}} = 100 \), \( n_{\text{D}}/n_{\text{O}} = 0.5 \), \( m_{\text{D}}/m_{\text{O}} = 133.29 \) and \( n_{\text{O}} = 10^{15} \text{ m}^{-3} \), respectively. We show the dependency of the dust charge on the ion density in Fig. 5 for \( n_{\text{D}}/n_{\text{O}} = 100 \) (solid line), 200 (dotted line), 300 (solid and dotted line) and 500 (long dotted line), respectively, where we use the same parameters in Fig. 4. We understand that if the ion temperature and density increase, the dust grain charge increases.

4. Discussion

In this paper, we have used a one-dimensional model of the sheath near the ion engine to calculate time-independent, self-consistent spacial profiles for the sheath potential, space charge density and electric field, and showed the time-dependent grain charge in the plasma with secondary electrons. When we assume BaTiO₃ as the particulates emitted from the cathode or the insulator of the electrode, we obtain the interesting results. If we don’t consider the dust grains and secondary electrons, we cannot find the modification of the sheath potential and the double electric field. These effects give rise to the remarkable change of the profiles of the sheath potential, space charge density and electric field. We understand that the time constant of the grain charge becomes long and the charge number increases due to the ion temperature. The ion density grows the dust charge and shortens the time constant. As a problem, the presence of the strong sheath bends the orbit of the exhaust gas composed of the plasma ions, and consequently decreases the velocity of the spacecraft. We show that the results presented here may be applicable to the control of the sheath by modifying the potential of the wall and selecting the materials of the cathode or the insulator of the electrode of the ion engine. This fact is also closely connected with the problems of the electric damage of satellites or spacecrafts. Therefore this investigation is important in understanding the problems near the wall of the ion engine and the spacecraft charging.

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