Numerical Analysis of Potential Structure around Solar Sail in Solar Wind Plasma

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We had numerically analyzed the charged particle profiles and the potential structure around a solar sail at 1.0 AU. The quantitative estimation of these issues can be of importance for the payload design of a solar sail such as the location of onboard scientific instruments and solar arrays. In addition, estimation of the electrostatic force on the IKAROS spacecraft was made to determine whether the force was significant for the deformation of the membrane. A 3-D electrostatic, full-Particle-In-Cell code was used to study precise charged particle behaviours around a solar sail, and MUSCAT, a spacecraft charging analysis tool, was additionally used to obtain differential voltage of the sail. The numerical results showed that a wake potential was formed due to a large ion wake in the downstream of a sail obstructed the diffusion of the photoelectrons to the downstream surface. The size of the photoelectron cloud around a sail was estimated to be 17.5 m in the upstream hemisphere at 1.0 AU. The floating potential of the sail was +8.3 V, where double Maxwellian photoelectron spectrum model was adopted in the computation. The reduction of the electron sheath due to the photoelectron cloud was recognized. The differential voltage on the insulator surface of the sail of -15.8 V was obtained by the MUSCAT computation, that showed the charging of a solar sail itself was not serious in this environment but would affect the photoelectron diffusion and the wake potential. The electrostatic force at the numerical grid on the membrane assuming the IKAROS spacecraft was estimated under the observed real plasma environment. The magnitude of the force was of 10^{-8} N at the edge of the insulator that could not be negligible to a small-scale deformation on the membrane during the flight.

Key Words: Solar Sail, Spacecraft-Plasma Interaction, Spacecraft Charging, 3D Particle-In-Cell Code, Solar Wind Plasma

Nomenclature

I	: current
J	: current density
V	: voltage
ϕ	: electric potential
A	: relevant area of current collection
n	: density of charged particle
T	: temperature of charged particle
e	: elementary charge
m	: mass of charged particle
k	: Boltzmann constant
ω_{pe}	: Electron cyclotron frequency

Subscripts

0	: initial
i	: ion
e	: electron
s	: spacecraft
ph	: photoelectron

1. Introduction

Solar sail is a next-generation spacecraft that is regarded as a candidate for interplanetary flight. Today, JAXA had launched the IKAROS spacecraft¹⁾, the first demonstration spacecraft of solar power sail, in May 2010 into the Venus transfer orbit. The IKAROS spacecraft had achieved the

interplanetary flight for more than 11 months for April 2011²⁾. Solar sail consists of a large membrane that is typically made of aluminum-coated polyimide. The conductive surface of the membrane reflects the solar radiation, which results in converting the solar radiation pressure into the spacecraft thrust. The scale of the membrane is estimated from $10 \times 10 \text{ m}^2$ to $100 \times 100 \text{ m}^2$ to obtain sufficient thrust from the solar radiation pressure, (e.g. 10^{-6} Pa at 1.0 AU). During interplanetary flight, a solar sail is exposed to the solar wind plasma whose density and temperature vary depending on the solar activity and the distance from the sun. Photoelectron current from the sunlit surface of a spacecraft that is the dominant current source in the environment also varies depending on the solar flux intensity. In addition to the Debye length of the solar wind plasma is comparable to the scale of the sail, the charged particle profiles such as the photoelectrons are unique around a solar sail. Hence, the sail is expected to have the significant potential structure in the vicinity of itself. Therefore, it is of importance to study the potential structure around the sail for its payload design, such as the locations of scientific instruments and solar arrays. Garrett and Minow had provided an overview on the charging issue of solar sails³⁾ by using NASCAP-2K⁴⁾, a spacecraft charging analysis program, and a Particle-In-Cell⁵⁾ (PIC) code⁶⁾ for a solar sail in the solar wind and in the ionosphere. We tried a further investigation of the interactions between charged particles and a solar sail by using a three-dimensional electrostatic full-PIC code we had been developed⁷⁾. The

analyses were performed focusing on the potential structure around the sail including the space charge effect of photoelectrons as well as the solar wind. We also performed charging analysis using MUSCAT^{8,9)}, a spacecraft charging analysis software, to estimate the differential voltage between the local insulator component and the body potential of the spacecraft. In this paper, we will report the characteristics of the charged particle profiles and the potential structure around a solar sail. We also analyze those to a numerical model of the IKAROS spacecraft using the measured solar wind environment. In the IKAROS model analysis, we considered the electrostatic force works on the membrane that could affect the deformation of the membrane.

2. Characteristics of Interactions between Solar Sail and Solar Wind Plasma

The fundamental structure of a solar sail is a huge thin membrane that is typically made of aluminum-coated polyimide. The first order estimation of the plasma interaction with a solar sail can be determined by assuming the sail as a thin conducting aluminum sheet. The floating potential of the solar sail relative to the ambient solar wind plasma is determined so that the net current onto the sail is equal to zero at the floating potential of the sail^{3,10)},

$$\begin{aligned} I_{net}(V_s) &= 0 \\ &= I_e + I_i + I_{ph} \\ &= -A_e \cdot J_e(V_s, T_e, n_e) + A_i \cdot J_i(V_s, T_i, n_i) \\ &\quad + A_{ph0} \cdot J_{ph}(V_s, T_{ph}, J_{ph0}) \end{aligned} \quad [1]$$

Equation [1] only includes the current balance between ambient solar wind plasma and photoelectron. Other current sources such as secondary electron are neglected in this study. We can easily estimate each current component in Eq. [1] considering the characteristic parameters of the solar wind plasmas and the solar sail geometry at zero potential of the spacecraft. For typical solar wind plasma at 1.0 AU whose density is $6 \times 10^6 \text{ m}^{-3}$ and temperature is 10 eV with the drift velocity of 470 km/s, the thermal velocities for the electron and ion (H⁺) are $1.87 \times 10^6 \text{ m/s}$ and $4.37 \times 10^4 \text{ m/s}$, respectively. Thus, the current density of the thermal electron onto a solar sail can be estimated as $5.08 \times 10^{-7} \text{ A/m}^2$ by the following equation¹¹⁾,

$$J_e = -e \cdot n_e \cdot \frac{1}{4} (8kT_e / \pi m_e)^{1/2}, \quad [2]$$

for ions, on the other hand, we can simply estimate the current density as $4.51 \times 10^{-7} \text{ A/m}^2$ by the product of its charge, density and drift velocity because the drift velocity is much greater than the thermal velocity. Meanwhile, the photoelectron current density for aluminum at 1.0 AU is of the order of 10^{-5} A/m^2 that is about 100 times greater than the electron and the ion current densities. Hence, the floating potential of the solar sail saturates at a positive potential as a result of the current balance described Eq. [1]. The spacecraft at a positive potential is shielded by the ambient electrons and its characteristic scale is almost comparable to the solar sail. Figure 1 shows the schematics showing the steady state of the charged particle distributions around a solar sail and potential structure. In the upstream region of the sail, existence of the

photoelectron cloud would affect the potential structure. In the downstream region, an ion wake is formed and that will make a wake potential.

Fig. 1. Schematics of the charged particle profiles and the potential structure around a solar sail. Space charge effects on the potential structure are expected; 1) electron sheath, 2) ion wake, and 3) photoelectron cloud. If we consider an insulator on the downstream surface of a sail, the negative differential voltage to the spacecraft body is expected.

3. Numerical Analysis of Interactions between Solar Sail and Solar Wind Plasma

We performed numerical experiments in order to determine the charged particle profiles and the potential structure around a solar sail in 1.0 AU solar wind plasma environment using a conventional three-dimensional electrostatic full PIC code that we had developed⁷⁾. The motion of individual ions and electrons is explicitly solved, and the electrostatic field is computed self-consistently in the code. We focused on the quantitative analyses of the charging status of a solar sail, space charge effect of the photoelectrons in the upstream region, and wake potential in the downstream region. The differential voltage on the downstream insulator surface of the sail was optionally computed using MUSCAT, a spacecraft charging analysis tool. Table 1 shows the computation parameters and Fig. 2 shows the numerical domain of the simulation. The plasma parameters used are also shown in Table 1. The sail is assumed an aluminium conductor plate whose area is of $14 \times 14 \text{ m}^2$ and thickness is of 0.5 m. The thickness of the sail model is comparable with the Debye

Table 1. Numerical parameters used in the computation.

Plasma density [m^{-3}]	6×10^6
Plasma temperature [eV]	10
Plasma drift velocity [km/s]	470
Photoelectron (PE) current flux [A/m^2]	40
PE1 temperature [eV]	1.5
PE2 temperature [eV]	5.0
Flux ratio, PE1:PE2	9:1
mass ratio (m_i/m_e)	1836
Numerical domain [grid]	$256 \times 128 \times 128$
Object size [grid]	$1 \times 28 \times 28$
Grid size, dx, dy, dz [m]	0.5
Time width, dt [10^{-7} s]	1.0
$\omega_{pe} \cdot dt$	0.0138

length of the photoelectrons but much smaller than that of the ambient plasma. The direction of solar flux and the ambient plasma flow is normal to the surface of the sail in this simulation. As simplicity, we neglect ambient magnetic field. The emitting photoelectrons are considered to have double Maxwellian distribution as a better representation of the distribution in tenuous plasma environment.^{12,13)}

Fig. 2. Numerical domain of the PIC code computation. The rectangular object located at the center indicates the conductor sail model.

In this solar wind plasma environment at 1.0 AU, the Debye length of the plasma is 9.6 m that is corresponding to 0.69 times the scale of the sail. The ratio of the solar wind drift velocity to the ion thermal velocity is 10.8. Figure 3 shows the numerical results of the spatial distribution of the charged particles: ambient electrons, ambient ions, photoelectrons, and the electric potential at 2500 time steps. The saturation value of the floating potential of the sail is determined to be +8.3 V by the computation. A large ion wake structure is formed in the downstream region of the sail as shown in Fig. 3 (b). The number density of the ambient electrons shown in Fig. 3 (a), on the other hand, decreased in the vicinity of the sail and in the wake region, although degradation of the density is much smaller than that of the ions. A wake potential whose minimum value is -3.0 V is formed due to the difference of the charge density between ions and electrons shown in Fig. 3 (d). The emitted photoelectrons from the upstream surface diffuse around the sail even to the surface although the negative wake potential obstructs the diffusion shown in Fig. 3 (c). The dense layer of the photoelectrons whose magnitude is up to $3.8 \times 10^8 \text{ m}^{-3}$ in 1.5 m thick from the emitting surface is recognized in the figure. We define a photoelectron cloud as the diffusing photoelectron region whose density is more than 1/10 of the ambient electron density. The size of the photoelectron cloud in the upstream hemisphere is about 17.5 m from the emitting surface.

We had determined the space charge effect of the photoelectron cloud on the potential structure around the sail by the comparative computations with or without photoelectron emission. The computation without photoelectrons was performed at the fixed spacecraft potential of +6.2 V that had been obtained as the floating potential of the sail by the computation using the single Maxwellian photoelectrons whose temperature was 1.5 eV. Figure 4 shows

the one-dimensional distributions of the electric potential with or without photoelectron emission in X-axis at $Y=Z=64$ at 3000 steps. The significant potential drop is shown with photoelectron emission in the region between $X=80$ and $X=131$ compared to the result without photoelectron emission. (Note that the location of the photoelectron emitting surface in the upstream region is $X=131$.) It is assumed that the photoelectron cloud can lead to the reduction of the electron sheath, in other words, the compression of the potential near the sail.

Fig. 3. Spatial distributions of the charged particles and the electric potential at 1.0 AU at 2500 time steps. Contours show a) the number density of the ambient electrons, b) the ambient ions, c) the photoelectrons and d) electric potential in XY-plane at $Z=64$ from the top in this figure.

A robust charging analysis to estimate the differential voltage on the insulator surface of the sail had been made using MUSCAT, a spacecraft charging analysis software. We

obtained the differential voltage of -15 V on the insulator surface of Kapton[®] whose relative dielectric constant and thickness are of 3.5 and 7.5×10^{-6} m, respectively. Although the magnitude of the differential voltage is not serious for charging-arc problem, the differential voltage would affect the wake potential and suppress the diffusion of the photoelectrons to the downstream region.

Fig. 4. One-dimensional distributions of the electric potential with or without photoelectron emission in X-axis at $Y=Z=64$ at 3000 steps.

4. Estimation of the Electrostatic Force on the IKAROS Spacecraft

We have numerically analyzed the charged particle profiles and the potential structure around a solar sail at 1.0 AU in Sec. 3, and we found that the magnitude of the electric field in the vicinity of the sail was up to 10 V/m in the computation. Considering a solar sail interacting with the solar radiation pressure of the order of 10^{-6} Pa, the electrostatic force works on the sail could not be negligible for the large membrane to maintain its shape. In this section, we have numerically estimate the electrostatic force on the IKAROS spacecraft model under the observed solar wind plasma environment in order to evaluate whether it is significant for deformation of the membrane. The schematic of the IKAROS spacecraft is shown in Fig. 5.

Fig. 5. Schematics of the IKAROS spacecraft.

4.1. Solar wind parameters

The solar wind parameter is the key issue to estimate the precise electrostatic force works on a solar sail. Hence, we used the real observed parameters by the WIND spacecraft¹⁴⁾ as the input parameters of the computation. We selected a specific data at the time when the IKAROS spacecraft was on orbit. In the data archive of the WIND observation¹⁴⁾, the distribution function of the solar wind plasma is described using Kappa distribution, although we use a Maxwellian-type distribution function in the computation. We extracted the plasma parameters from the Kappa distribution by fitting this with two Maxwellian distributions for the electrons and one Maxwellian distribution for ions. Figure 6 shows the original Kappa distribution and the Maxwellian-type fitting curves for the electrons. The extracted plasma parameters are shown in Table 2.

Fig. 6. Solar wind electron distribution described with Kappa distribution and Maxwellian fitting curves. The original data was obtained on June 14, 2010 by the WIND spacecraft.

Table 2. Extracted solar wind parameters used in the computation.

ion density [m^{-3}]	4.05×10^6
ion temperature [eV]	4.90
electron (1) density [m^{-3}]	2.65×10^6
electron (1) temperature [eV]	9.21
electron (2) density [m^{-3}]	0.75×10^6
electron (2) temperature [eV]	44.05
Plasma drift velocity [km/s]	470

4.2. Computations for estimation of the electrostatic force

In order to evaluate the electrostatic force on the membrane of a solar sail at the steady state of charging, we need to determine both the local electric field and the local charge on the membrane of a solar sail. We found from the MUSCAT computation in Sec. 3 that the magnitude of the differential voltage was relatively high because ions could hardly exist in downstream region of the sail. Thus, we first performed the computation using MUSCAT to estimate the electrostatic force mainly on the insulator surface at the steady state. The computation model of the IKAROS spacecraft is a simple aluminum plate same as that of used in Sec. 3 but has an

insulator surface of Kapton® whose relative dielectric constant and thickness are of 3.5 and 7.5×10^{-6} m, respectively. The insulator surface has the hemming of the conductor of 0.5 m (1 computation cell) as the IKAROS spacecraft did. The solar wind plasma parameters in Table 2 and numerical parameters in Table 1 are used in the computation. In this computation, we had updated the charging status only by the net current of the charged particles onto the sail without considering their space charge effect. It is, however, almost appropriate to obtain the magnitude of the electrostatic force on the downstream insulator surface because the magnitude of the wake potential is relatively small compared with the insulator charge as estimated in Sec. 3. The electrostatic force on the upstream surface was specially estimated by the PIC computation that takes into account the enhancement of the electric field as a result of the sheath reduction by the space charge effect of the photoelectron cloud.

Fig. 7. Vectors of the electrostatic force on the IKAROS spacecraft model facing the wake region at the numerical grid at 460 s. Contours show the normalized charge on the surface (times 4.58×10^{-13} , in Coulomb). The maximum magnitude of the electrostatic force is of the order of 10^{-8} N, and the estimated pressure on the unit cell by the force is of 10^{-7} Pa, which is about one tenth of the solar radiation pressure.

Fig. 8. Normal component of the electric field on the sail model shown as E_x facing the wake region at 460 s. The maximum magnitude of the electric field is up to 50 V/m at the corner of the insulator.

Figure 7 shows the electrostatic force on the downstream surface of the IKAROS model at the steady state. The solar

wind flows from positive X direction to negative X in the coordinate. Vectors show the electrostatic force at the numerical grid on the numerical model, and contours show the normalized charge collected on the surface. Significant electrostatic force can be recognized at the edge of the insulator, especially at the corner of the insulator. The maximum magnitude of the electrostatic force is of the order of 10^{-8} N. If we compare the maximum pressure by using the electrostatic force on the unit numerical cell of 0.25 m^2 with the solar radiation pressure, the order of the pressure is of 10^{-7} Pa, which is about one tenth of the solar radiation pressure. Figure 8 shows the normal component of the electric field on the sail model at the numerical grid shown as E_x on the downstream surface at 460 s. The maximum magnitude of the electric field is up to 50 V/m at the corner of the insulator. The magnitude of the electric field at the edge of the insulator is of the order of 10 V/m.

Figure 9 shows, on the other hand, the normal component of the electric field on the sail model shown as E_x (top) and the normalized charge (bottom) on the upstream surface at 460 s. Both the magnitude of the electric field and the charge on the upstream surface are much less than those of on the downstream surface. The magnitude of the electrostatic force at the numerical grid on this surface is of the order of 10^{-11} N.

Fig. 9. a) Normal component of the electric field shown as E_x (top), and b) the normalized charge (times 4.58×10^{-13} , in Coulomb, bottom) on the sail model facing the ram region at 460 s.

We estimated the electric field on the upstream surface with photoelectron emission using the PIC code at the steady state of its body potential. The electric field was almost uniform on the surface and was of -7 V/m, whose magnitude was about 7 times greater than that without photoelectron emission shown

in Fig. 9 (a). Thus, the electrostatic force on the upstream surface with the photoelectron cloud can be estimated to be of the order of 10^{-10} N at the numerical grid, which is much less than the maximum magnitude of the electrostatic force on the downstream surface shown in Fig. 7.

5. Conclusion

We had numerically analyzed the charged particle profiles and the potential structure around a solar sail at 1.0 AU. The quantitative estimation of these issues can be of importance for the payload design of a solar sail such as the location of onboard scientific instruments and solar arrays. In addition, estimation of the electrostatic force on the IKAROS spacecraft was made to determine whether the force was significant for the deformation of the membrane. Followings are obtained in this paper.

- 1) A wake potential is formed due to a large ion wake in the downstream region of a solar sail. The minimum value of the wake potential is of -3.0 V. The potential obstructs the diffusion of the photoelectrons to the downstream surface of a sail.
- 2) Photoelectron cloud is formed around the sail including the downstream region of the sail. The photoelectron cloud can lead to the reduction of the electron sheath, in other words, compression of the potential in the vicinity of the sail.
- 3) The spatial scale of the photoelectron cloud whose density is more than 1/10 of the ambient electron density is 17.5 m in the upstream hemisphere.
- 4) The density and the thickness of the dense layer of the photoelectron cloud in front of the emitting surface are $3.2 \times 10^8 \text{ m}^{-3}$ in 1.5 m, respectively.
- 5) We obtained the charging status of the solar sail as follows; the floating potential is +8.3 V and the differential voltage is -15.8 V. The magnitude of the differential voltage is not serious to spacecraft charging problem, however that will affect the wake potential and suppress the diffusion of the photoelectrons to the downstream region.
- 6) The electrostatic force at the numerical grid on the membrane assuming the IKAROS spacecraft was estimated in the observed real solar wind plasma environment. The significant force was observed at the edge of the insulator surface. The maximum magnitude of the electrostatic force is of the order of 10^{-8} N, and estimated pressure on the unit cell by the force is of 10^{-7} Pa, which is about one tenth of the solar radiation pressure. The electrostatic force could not be negligible to a small-scale deformation such as wrinkles on the membrane but can be for a large-scale deformation of a solar sail.

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