Electromagnetic Full-Particle Simulations on Spacecraft Interaction with Near-Sun Plasma Environment

Yohei Miyake and Hideyuki Usui

Abstract—Electric and magnetic field perturbation around the Solar Probe Plus (SPP) spacecraft is examined by using our original electromagnetic particle-in-cell plasma simulation code called EMSES. In the simulations, we consider the SPP spacecraft at perihelion (0.04 AU from the Sun) and important physical effects such as spacecraft charging, photoelectron and secondary electron emission, solar wind plasma flow including the effect of spacecraft orbital velocity, and the presence of a background magnetic field. Our preliminary results show that both photoelectrons and secondary electrons from the spacecraft are magnetized in the spatial scale of several meters, and make drift motion due the presence of the background convection electric field. This effect leads to non-axisymmetric distributions of the electron density and the resultant electric field near the spacecraft. Our simulations predict that a strong spurious electric field can be observed by the probe measurement on the spacecraft due to such a non-axisymmetric effect. We also confirm that the large photo-/secondary electron current alters magnetic field intensity around the spacecraft, but the field variation is much smaller than the background magnetic field magnitude.

Keywords—spacecraft charging; photoelectron emission; secondary electron emission; particle-in-cell simulation; field measurement

I. INTRODUCTION

It is necessary to assess the nature of spacecraft–plasma interactions in extreme plasma conditions for future space explorations. As one of such activities, we study on the physics of spacecraft interaction with near-Sun plasma environment. The spacecraft environment immersed in the solar corona is characterized by the small Debye length due to dense (7000/cm) plasmas and a large photo-/secondary electron emission current emitted from the spacecraft surfaces, which lead to distinctive nature of spacecraft-plasma interactions. For example, Ergun et al. [1] and Guillemant et al. [2] show in their numerical analysis that space-charge effects associated with emitted photo-/secondary electrons lead to a non-monotonic potential profile near the spacecraft surface, which leads to a negative floating potential. This is analogous to non-monotonic potential profiles produced near plane surfaces emitting large fluxes of photoelectrons, predicted by Guersey and Fu [3]. In the context of spacecraft-plasma interactions in the near-Sun environment, full-particle simulations based on an electrostatic approximation and fluid-particle hybrid simulations have been conducted previously [1,2,4,5]. Meanwhile, only a few attempts have been made for a full-particle electromagnetic modeling of the problem [6]. We applied our original electromagnetic particle-in-cell (PIC) simulation code called EMSES to the problem and focus on the perturbation in both electric and magnetic fields around the Solar Probe Plus (SPP) spacecraft.

II. NUMERICAL MODEL AND SETUP

A. Simulation Code

EMSES is an electromagnetic PIC code designed particularly for spacecraft–plasma interaction study [7]. The basic algorithms used in the plasma particle and electromagnetic field solvers are based on the standard PIC method [8]. It allows us to consider an arbitrary number of electrons and ion species, each with user-defined density, temperature, and drift velocity. The simulator can also account for a static background magnetic field as well as a motional electric field, the latter of which is for cases of a plasma flow across the background magnetic field. EMSES employs inner boundary treatments for electric field at the interface between a

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plasma and a conducting spacecraft body, and has capability of simulating spacecraft charging process in space. The function is implemented as the conventional capacitance matrix method [9] in an electrostatic aspect. In addition, a radiation component of an electric field, introduced by the electromagnetic field solver, is also cancelled out on the spacecraft conducting surface [7]. EMSES also includes numerical models of photoelectrons and secondary electron emission, which are reviewed in the next section. According to the models, these electrons are loaded in a simulation domain at each simulation cycle. As it stands now, EMSES supports a uniform Cartesian grid, but it is optimized for well making use of supercomputers and thus has the capability of representing objects with complex shapes.

B. Simulation Model

We simulate the plasma environment near the SPP spacecraft at perihelion. For manageability in the Cartesian grid code, we use a simplified spacecraft geometry as shown in Figure 1. Specifically, SPP is represented by an assembly of three rectangular prisms corresponding to the heat shield, the spacecraft body and a boom. All prisms have a square cross section with dimensions 2 m × 2 m × 0.2 m for the shield, 1 m × 1 m × 3 m for the spacecraft body and 0.2 m × 0.2 m × 4.4 m for the boom. The simplified geometry is similar to that used in Marchand et al. [6], but the size is scaled up twice. We have a simulation domain with sizes of 51 m × 51 m × 51. On the outer boundary of the simulation domain, a Dirichlet condition is imposed for an electrostatic potential solution.

The entire simulation domain, except for the interior of the SPP spacecraft, is initially filled with background solar wind electrons and protons at the SPP perihelion. For Comparative study, we also examine solar wind parameter sets for near-Mercury and Earth regions. Their parameters are summarized in Table I. They are similar to the ones assumed in recent studies by Guillemant et al. [2,4] and Marchand et al. [6]. In addition to the solar wind velocity along z-axis, we take into account a spacecraft orbital velocity of 195 km/s near perihelion along ζ-axis, where ζ-axis is aligned with the diagonal of the square heat shield of SPP (see Figure 1). The composition of the solar wind velocity and the orbital velocity results in an oblique plasma flow in ζ-z plane seen in the spacecraft-reference frame. We also assume a static magnetic field of magnitude 2 μT pointing toward the Sun.

In the series of simulations, only a sunlit face of the spacecraft shield emits photoelectrons throughout the simulations at a rate prescribed by an input parameter. As a reference, we use the photoelectron current density of Jph = 16 mA/m². For simplicity, the velocity distribution of photoelectrons is assumed to follow a single Maxwellian distribution with the temperature Tph = 3 eV.

The present analysis also takes into account the secondary electron emission triggered by electron impact on the spacecraft surface. In order to calculate the emission rate, we use the following expression of the yield δsc for given kinetic energy Eψi and angle θ of the incident (primary) electron:

$$\delta_{sc} = \frac{1.14 \delta_{max}}{\cos \theta} \left( \frac{E_{\psi}}{E_{max}} \right)^{0.35} \left[ 1 - \exp \left( -2.28 \cos \theta \left( \frac{E_{\psi}}{E_{max}} \right)^{1.35} \right) \right]$$

TABLE I. SIMULATION PARAMETERS

<table>
<thead>
<tr>
<th>Solar Wind</th>
<th>SPP perihelion</th>
<th>Near Mercury</th>
<th>Near Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>density: n₀</td>
<td>7000/cc</td>
<td>90/cc</td>
<td>5/cc</td>
</tr>
<tr>
<td>electron temperature: Tₑ</td>
<td>85 eV</td>
<td>20 eV</td>
<td>8.6 eV</td>
</tr>
<tr>
<td>proton temperature: Tᵢ</td>
<td>82 eV</td>
<td>25 eV</td>
<td>8.6 eV</td>
</tr>
<tr>
<td>flow speed: Vₑw</td>
<td>300 km/s</td>
<td>400 km/s</td>
<td>450 km/s</td>
</tr>
<tr>
<td>magnetic field: B₀</td>
<td>2000 μT</td>
<td>55 μT</td>
<td>5 μT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Photoelectron</th>
<th>SPP perihelion</th>
<th>Near Mercury</th>
<th>Near Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>current density: Jₚₘ</td>
<td>16000 μA/m²</td>
<td>700 μA/m²</td>
<td>64 μA/m²</td>
</tr>
<tr>
<td>temperature: Tₚₘ</td>
<td>3 eV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Other parameter

<table>
<thead>
<tr>
<th>SPP perihelion</th>
<th>Near Mercury</th>
<th>Near Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>spacecraft coating material</td>
<td>Indium Tin Oxide ($E_{max} = 300$ eV, $δ_{max} = 2.5$)</td>
<td></td>
</tr>
<tr>
<td>Temperature: Tₑ</td>
<td>2 eV</td>
<td></td>
</tr>
<tr>
<td>spacecraft orbital velocity: V_orb</td>
<td></td>
<td>150 km/s</td>
</tr>
</tbody>
</table>
where $\delta_{\text{max}}$ is the maximum yield at normal incidence, and $E_{\text{max}}$ is the primary electron energy at which the normal incidence yield is maximum. For these constants, we use typical values of $E_{\text{max}} = 300$ eV and $\delta_{\text{max}} = 2.5$ for the ITO material.

The simulation model considers neither of backscattered electron effect and secondary electron emission from ion impact. Previously, impact of these factors was investigated in a cross-comparison study among five simulation codes, and the effects were found to be insignificant for the near-Sun environment [6].

### III. SIMULATION RESULTS

#### A. Spacecraft Floating Potentials

We first reproduce in our electromagnetic simulations earlier predictions on the electrostatic charging of SPP. Table II summarizes the SPP floating potentials computed with the three different environments. For comparison, we list the potential values obtained with a 1/2 scaled model of the SPP spacecraft. (This is identical to the geometry investigated by Marchand et al. [6].) Our electromagnetic simulations produce essentially the same results as the previous investigations on the floating potentials [1,2,4,6]. In all environments considered herein, the photoelectron yield $I_{\text{ph}}$ from the SPP heat shield dominates over the influx $I_0$ of the background solar wind electrons. This results in the positive floating potentials as predicted for the near- Mercury and Earth environments. Note that both $I_{\text{ph}}$ and $I_0$ are increasing functions, and then a ratio $I_{\text{ph}}/I_0$ is a decreasing function of the spacecraft distance from the Sun. The resultant floating potential is smaller near Mercury than near Earth.

The situation is totally different at the SPP perihelion from the other two environments. Despite the large photoelectron emission current, the spacecraft potential is negative. This result is caused by the formation of the potential barrier in front of the spacecraft sunlit surface, which reflects approximately 87% of emitted electrons back to the spacecraft (in case of the reference geometry). That is, the photoelectron emission current is in a space-charge-limited regime with a non-monotonic potential profile, as predicted by Guernsey and Fu [3]. The result is consistent also with the earlier predictions [1,2,4,5,6]. The potential barrier in front of the spacecraft surface is formed under conditions of much greater spacecraft dimensions than the photoelectron Debye length as well as $T_e \gg T_{\text{ph}}$ [11].

Interestingly, the spacecraft potential dependence on the spacecraft size, while the strong dependency is confirmed at the SPP perihelion. In the near-Earth solar wind, the orbital-motion-limited regime is roughly applicable to the plasma and photoelectron currents as functions of the spacecraft potential. In the case, the currents and thus the spacecraft potential are essentially independent of the spacecraft size. This is contrast to the space-charge-limited regime at the SPP perihelion. The result implies that a floating potential can be much different for smaller probes, which require much attention in the instrument development for the SPP mission.

#### B. Plasma and Field Environment around SPP

We next focus on the spatial profiles of field quantities for the SPP perihelion case obtained with the reference SPP geometry. Figure 2 shows solar wind electron and proton densities, photo- and secondary electron densities, electric potential, and magnetic field, as obtained at the steady state.

The overall feature of the field environment around the SPP spacecraft is similar to those obtained in the previous electrostatic modeling (e.g., [6]). The proton density profile clearly shows the presence of a wake downstream of the spacecraft. Generally, the length of the wake is roughly characterized by $V_{\text{flow}}t_{\text{ch}}$, where $V_{\text{flow}} = v_{\text{sw}} - v_{\text{orb}}$ and $t_{\text{ch}}$ is the ion-acoustic velocity. (In the situation considered here, $t_{\text{ch}}$ is comparable to the ion thermal velocity, because ions and electrons are almost iso-thermal.) The resultant wake length, however, is smaller than as predicted from the ratio. This is a consequence of ion focusing due to negative spacecraft potential, which results in focusing the ions at closer to the spacecraft. In contrast to the protons, the solar wind electrons are in a subsonic condition and can enter the downstream of the spacecraft. Nevertheless, the negative potentials of the spacecraft and the proton wake region repel a low-energy portion of the electrons, resulting in the slight depression in the solar wind electron density.

The electric potential profile clearly shows the potential barrier in the vicinity of the spacecraft surface and also the potential well associated with the proton wake. The oblique plasma flow produces the proton wake at $+\xi$ side of the spacecraft. This leads to strong asymmetry of the resultant potential distribution downstream of the spacecraft. Although shown less clearly here, the potential profile shows weak asymmetry also upstream of the spacecraft. The slight asymmetry is due not only to the wake structure but also to the asymmetry in the photo- and secondary electron distributions.

These are shown in panels c and d in Figure 2. In order to obtain clues on pathways by which emitted electrons can escape, we plot these two panels in a logarithmic scale. Although the majority of photoelectrons is reflected back to the spacecraft by the potential barrier, some electrons emitted with energies larger than the barrier can escape from the spacecraft. These photoelectrons are seen as a radial diffusion pattern of its density upstream of the spacecraft. The region downstream of the spacecraft contains electrons emitted near the edge and missing the shield after being reflected by the barrier. The notable feature is apparent left-right asymmetry mainly seen downstream of the spacecraft. This is due to the $E_b \times B_d$ drift to $+\xi$ direction, where $E_b \sim 390$ mV/m represents the motional electric field associated with the spacecraft orbital velocity.

### TABLE II. SPACECRAFT FLOATING POTENTIALS

<table>
<thead>
<tr>
<th>Spacecraft model</th>
<th>Environment</th>
<th>Reference</th>
<th>Near Mercury</th>
<th>Near Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>reference</td>
<td>SPP perihelion</td>
<td>$-20.5$ V</td>
<td>$+9.9$ V</td>
<td>$+12.8$ V</td>
</tr>
<tr>
<td>1/2-scale model</td>
<td></td>
<td>$-10.0$ V</td>
<td>$+10.8$ V</td>
<td>$+12.8$ V</td>
</tr>
</tbody>
</table>
across the static magnetic field. Although not shown clearly, the \( \mathbf{E} \times \mathbf{B}_0 \) drift contributes also to the asymmetry in the photoelectron density upstream of the spacecraft. This slight asymmetry results in the potential asymmetry upstream of the spacecraft.

The secondary electron density shows more peculiar profile. Apparent asymmetry is seen regardless of upstream or downstream of the spacecraft. We recall that solar wind electrons have a thermal velocity that is much larger than the plasma flow velocity in the spacecraft frame. Consequently, the spacecraft should be exposed to solar wind electrons almost isotropically, and thus secondary electrons would be emitted from the entire spacecraft surface. Nevertheless, the secondary electron escape from the heat shield and the right side of the spacecraft main body is strongly prohibited by the potential barrier and the wake potential, respectively. Another thing to note is that a belt-like distribution of secondary electrons is formed at the right side of the spacecraft. It is found that the diameter of this flux tube corresponds to \( 2\rho_{se} \), where \( \rho_{se} \sim 1.7 \) m is the gyro radius of the secondary electrons. Thus, some portion of emitted electrons that are trapped by magnetic field lines at this position and transit up or down along the field lines causes this belt-like distribution. However, an exact reason why such distribution is created at this position is not yet understood.
identified at the time of writing. This will be elucidated by further investigations using the test particle method.

The full electromagnetic modeling enables us to access magnetic field variation in the vicinity of the spacecraft. The magnetic field component normal to \( \xi-z \) plane is shown in Figure 2f. The field variation on the order of nT is seen around the junction of the shield with the SPP main body as well as around the boom. Our simulation found that they are rotational fields, which are supposed to be induced by current flows like black arrows shown in the figure. Specifying an exact source of the field variation requires further breakdown analysis on current flows around the spacecraft. Photoelectron current is confirmed to be maximum in magnitude at the edge of the heat shield, because only electrons emitted there can escape from the shield after being reflected by the barrier. Another possibility other than the plasma current is a conduction current flowing on the spacecraft conductive surface. To ensure the equi-potential over the entire spacecraft body, substantial current should flow from the shield to the spacecraft main body. The presence of the spacecraft conduction current may explain the magnetic field variation seen around the boom, where we do not observe appreciable plasma flows that are consistent with the magnetic field variation. For proper assessment of the spacecraft conduction current, we need to improve our spacecraft model by taking its finite conductivity into consideration, which is left as a future work.

C. Spurious Electric and Magnetic Field Generation

The deformation of the electric and magnetic environment around the spacecraft may lead to spurious fields observed by onboard instruments. The variation of the magnetic field around the boom, where magnetometers are planned to be installed, is a few nT in magnitude. This value is much smaller than the background magnetic field of a few \( \mu \)T. Meanwhile, our analysis predicts that the left-right asymmetry in the electric potential, as described in the previous section, causes a spurious electric field of a few hundreds of mV/m between the probe positions shown with the white circles in Figure 2e. The electric field is not negligible compared with the motional electric field (390 mV/m) and estimated electric field fluctuations at the orbit. The influence of this spurious field to the mission should be further assessed by using a more sophisticated model for the electric probes.

IV. Summary

- We apply the electromagnetic full-particle simulations to the Solar Probe Plus spacecraft interactions with the near-Sun environment.

- The spacecraft floating potentials estimated by our model agree well with those obtained by the previous electrostatic models. We also confirm the strong dependency of the potential on the spacecraft size.

- Plasma and field environments around SPP show considerable asymmetry both upstream and downstream of the spacecraft. The asymmetry principally results from the oblique plasma flow as the composition of the solar wind flow and the spacecraft orbital velocity. As secondary effects, the motional electric field exerts the \( \vec{E} \times \vec{B} \) drift on the photo- and secondary electron dynamics. The resultant asymmetric distributions of these electrons cause the asymmetry in the electric potential profile.

- The magnetic field variation is seen around the junction of the shield with the SPP main body as well as around the boom. The field is rotational and has magnitude on the order of nT.

- The simulations predict a spurious electric field of a few hundreds of mV/m observed by the probe measurement on the spacecraft. Meanwhile, the magnetic field variation is much smaller than the background magnetic field magnitude (a few nT compared to thousands of nT).

ACKNOWLEDGMENT

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REFERENCES


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1. Background

We study on...

- Electromagnetic perturbations near a spacecraft in near-Sun environment
  - Solar coronal plasma of high density (10^3 /cc) and small Debye length (10 cm)
  - Large fluxes of photoelectrons and secondary electrons from SC surface
- Their impact on in-situ field measurements

2. Simulation Model

Computer simulations based on electromagnetic Particle-In-Cell (EM-PIC) modeling

Simulation results on SC potential

- Shortened wake structure due to ion focusing effect
- Slight density depletion around SC and at wake region
- Negative potential barrier
- Asymmetric potential profile

SC potential dependence on SC size

- Strong dependence on SC size in the near-Sun environment

Cross-code comparison/validation made on half-scale SC model (Marchand et al., 2014)

3. Computer simulations using Cray XE6@Kyoto U., 16 ~ 64 nodes (512 ~ 2048 CPU cores & 0.9 ~ 3.6 TB memory)

- SW proton: n_p
- SW electron: n_e
- Electric potential: \( \phi \)
- Photoelectron: \( n_{pe} \)
- Secondary electron: \( n_{se} \)

Simulation parameters

- Background plasma
- Plasma of the Sun
- Electron temperature: \( T_e \)
- Plasma temperature: \( T_i \)
- Proton speed: \( V_p \)
- Photodetronics
- Distance from the Sun: \( D \)
- Temperature: \( T_e \)
- Secondary electron: \( n_{se} \)
- Magnetic field: \( B_0 \)

Secondary electron yield \( \delta \) [Katz et al., 1977]

\[ \delta(T, \theta) = \frac{\delta_{\infty}}{1 + \exp \left( -2.2 \cos \theta \left( \frac{T}{T_{\infty}} \right) \right)} \]

4. Impact on electric/magnetic field measurements

1. Artificial B-field
   - \( B_0 \) (normal to \( \zeta-z \) plane)

2. Artificial E-field
   - Probe potential
   - Spurious E-field \( \mathbf{E}_{sp} \)

4. Summary & future works

- The spacecraft floating potentials agree well with those obtained by the previous electrostatic models. We also confirm the strong dependency of the potential on the spacecraft size.
- Plasma and field environments around SPP show measurable asymmetry both upstream and downstream of the spacecraft. The asymmetry principally results from the oblique plasma flow as the composition of the solar wind flow and the spacecraft orbital velocity. As secondary effects, the motional electric field exerts the \( \mathbf{E}_{\parallel} \times \mathbf{B}_0 \) drift on the photo- and secondary electron dynamics. The resultant asymmetric distributions of these electrons cause the asymmetry in the electric potential profile.
- The magnetic field variation is seen around the junction of the shield with the SPP main body as well as around the boom. The field is rotational and has magnitude on the order of nT.
- The simulations predict a spurious electric field of a few hundreds of mV/m observed by the probe measurement on the spacecraft.

Future considerations:

1. Inclusion of sophisticated model for electric probes
2. Dependency analysis on variation of solar activities
3. Assessment of AC electromagnetic field perturbations