SIMULATIONS OF SOLAR WIND PLASMA FLOW AROUND A SIMPLE SOLAR SAIL

INTERACTIONS OF SPACECRAFT AND SYSTEMS WITH THE NATURAL AND INDUCED PLASMA ENVIRONMENT

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Abstract

In recent years, a number of solar sail missions of various designs and sizes have been proposed (e.g., Geostorm). Of importance to these missions is the interaction between the ambient solar wind plasma environment and the sail. Assuming a "typical" 1 AU solar wind environment of 400 km/s velocity, 3.5 cm$^{-3}$ density, ion temperature of ~10 eV, electron temperature of 40 eV, and an ambient magnetic field strength of $10^4$ G, a first order estimate of the plasma interaction with square solar sails on the order of the sizes being considered for a Geostorm mission (50 m x 50 m and 75 m x 75 m corresponding to ~2 and ~3 times the Debye length in the plasma) is carried out. First, a crude current balance for the sail surface immersed in the plasma environment and in sunlight was used to estimate the surface potential of the model sails. This gave surface potentials of ~10 V positive relative to the solar wind plasma. A 3-D, Electrostatic Particle-in-Cell (PIC) code was then used to simulate the solar wind flowing around the solar sail. It is assumed in the code that the solar wind protons can be treated as particles while the electrons follow a Boltzmann distribution. Next, the electric field and particle trajectories are solved self-consistently to give the proton flow field, the electrostatic field around the sail, and the plasma density in 3-D. The model sail was found to be surrounded by a plasma sheath within which the potential is positive compared to the ambient plasma and followed by a separate plasma wake which is negative relative to the plasma. This structure departs dramatically from a negatively charged plate such as might be found in the Earth’s ionosphere on the night side where both the plate and its negative wake are contiguous. The implications of these findings are discussed as they apply to the proposed Geostorm solar sail mission.

Nomenclature

\[ \lambda_D = \sqrt{\frac{KT_e}{4\pi n e^2}} \]  
plasma Debye length (based on electron temperature)

\( \Phi \)  
electric potential

\( \Phi_s \)  
solar sail to ambient plasma potential difference

\( B_o \)  
solar wind magnetic field

\( d_{sh} \)  
solar sail sheath thickness

\( L_x, L_y \)  
solar sail size
\[
\begin{align*}
\text{solar wind plasma density} & = n_{sw} \\
\text{electron and ion (proton) temperature, respectively} & = T_e, T_i \\
\text{solar wind flow velocity, ion thermal velocity, and electron thermal} & = v_{sw}, v_{ti}, v_{te} \\
\end{align*}
\]

\[
\begin{align*}
I_s(\Phi) &= \text{Total current to/from solar sail; } = 0 \text{ for current balance at potential } \Phi = \Phi_s \\
J_e(\Phi) &= \text{Average electron current per unit area to solar sail at potential } \Phi \\
J_i(\Phi) &= \text{Average ion current per unit area to solar sail at potential potential } \Phi \\
JS_e(\Phi) &= \text{Average secondary electron current per unit area from solar sail at potential } \Phi \\
JS_i(\Phi) &= \text{Average backscattered electron current per unit area from solar sail at potential } \Phi \\
J_{iBs}(\Phi) &= \text{Average ion induced secondary electron current per unit area from solar sail at potential } \Phi \\
J_{p}(\Phi) &= \text{Photoelectron current per unit area from solar sail at potential } \Phi \\
A_s &= \text{Ambient electron impact area} \\
A_i &= \text{Ambient ion impact area} \\
A_{photo} &= \text{Photoelectron emission area}
\end{align*}
\]

**Introduction**

In recent years, a number of solar sail missions of various designs and sizes have been proposed. Indeed various groups, both private and governmental, are in the process of building either flight or prototype solar sails. Of potential importance to these missions is the interaction of the ambient solar wind plasma environment with the sail. To evaluate this interactions and establish a baseline for future studies, we will assume a "typical" 1 AU solar wind environment of 400 km/s velocity, 3.5 cm\(^{-3}\) density, ion temperature of ~10 eV, electron temperature of 40 eV, and an ambient magnetic field strength of 10\(^{-4}\) G. This environment will be used to carry out a first order estimate of the plasma interaction with square solar sails on the order of the sizes being considered for a Geostorm mission (50 m \times 50 m and 75 m \times 75 m corresponding to ~2 and ~3 times the Debye length in the plasma). As will be discussed in more detail below, the first step will be to carry out a crude current balance for the sail surface immersed in the plasma environment and in sunlight to estimate the surface potential of the model sails (the surfaces in this initial study are assumed to be made of thin, uniformly conducting aluminum). A 3-D, Electrostatic Particle-in-Cell (PIC) code is then used to simulate the solar wind flowing around the solar sail. Assuming that the solar wind protons can be treated as particles while the electrons follow a Boltzmann distribution, the electric field and particle trajectories are solved self-consistently to give the proton flow field, the electrostatic field around the sail, and the plasma density in 3-D. The sail is found to be surrounded by a plasma sheath within which the potential is positive compared to the ambient plasma and followed by a separate plasma wake which is negative relative to the plasma. The structure departs dramatically from a negatively charged plate such as might be found in the Earth's ionosphere on the night side where both the plate and its negative wake are contiguous. Finally, the implications of these findings are discussed as they apply to a sample mission, the Geostorm Solar Sail.

**Basic Characteristics**

Spacecraft in the interplanetary environment experience a number of effects from the sun: surface charging (either positive or negative) and/or deep dielectric charging that can result in damaging arcs, UV and radiation effects on materials, and plasma wake or sheath effects that could impact experiments or instruments on the spacecraft. Of importance here are plasma interaction effects due to the solar wind. The solar wind is a fully-ionized, electrically neutral, magnetized plasma that flows outward from the Sun. The solar wind plasma in interplanetary space can vary over a wide range: from <1 cm\(^{-3}\) to ~80 cm\(^{-3}\) in density, from ~200 km/s to over 2000 km/s in velocity, and from 0.5 eV to ~100 eV in temperature. Although the solar wind is highly variable,
in this study we will concentrate on the typical or average solar environment in order to establish a
baseline for future studies. We will thus assume the following “average” solar wind parameters
for our test environment:

\[ v_{sw} \sim 400 \text{ km/s}; \ n_{sw} \sim 3.5 \text{ cm}^3; \ T_i \sim 10 \text{ eV}; \ T_e \sim 40 \text{ eV}; B_0 \sim 10^{-4} \text{ Gauss} \]

(For simplicity, here we only consider the core population for the solar wind electrons and ignore
the halo population.)

Based on these solar wind parameters, the following basic plasma parameters can be
determined:

\[ \lambda_D \sim 25 \text{ m}; \ v_{te} \sim 2.65 \times 10^3 \text{ km/s}; \ v_{ti} \sim 30 \text{ km/s}; \ c_s = (T_i/m_p)^{1/2} \sim 62 \text{ km/s} \]

\[ \Omega_i \sim 1 \text{ rad/s}; \ \Omega_e \sim 1.8 \times 10^3 \text{ rad/s} \]

The basic characteristics of the solar wind flowing around a solar sail are thus the same as that of a
collisionless, mesothermal plasma flowing around an obstacle. That is, since the solar wind flow
is such that \( v_{ti} \ll v_{sw} \ll v_{te} \), the plasma is mesothermal. Moreover, as both the ion gyroradius, \( r_{ci} = v_{sw}/\Omega_i \sim 400 \text{ km} \),
and the electron gyroradius, \( r_{ce} = v_{te}/\Omega_e \sim 1.5 \text{ km} \), are much larger than the
typical solar sail dimension (\( L_{sail} \sim 100 \text{ m} \)), the solar wind flow may be considered as an
unmagnetized, collisionless plasma flow for our problem.

The floating potential of the solar sail relative to the ambient solar wind plasma can be
estimated from current balance (Garrett, 1981). That is, for a thin, conducting aluminum sheet, it
is assumed that current balance is given by:

\[ I_T(\Phi_s) = 0 = -A_e \cdot J_e(\Phi_s, T_e, n_{sw}) + A_i \cdot J_i(\Phi_s, T_i, n_{sw}) + A_e \cdot J_0(\Phi_s, T_e, n_{sw}) + \\
+ A_e \cdot J_{Be}(\Phi_s, T_e, n_{sw}) + A_i \cdot J_{Be}(\Phi_s, T_i, n_{sw}) + A_{pho} \cdot J_{pho}(\Phi_s) \]  \( (1) \)

An accurate calculation of the solar sail floating potential requires knowledge of the detailed
spacecraft specification so that all the current sources can be properly accounted for. In this paper,
we shall consider a very simple geometric model—a conducting flat plate. For the solar wind
conditions listed in section I, the assumed model (Garrett, 1981) estimates that the floating
potential in sunlight ranges \( \Phi_f \sim -6 \text{ V} \) to \( -14 \text{ V} \) based on the details of the current collection (e.g.,
ion ram current, orbit limited, etc.). Hence, in this study, we take the sail potential to be \( \Phi_f = -10 \text{ V} \).

**Simulation Model**

A 3-D, Electrostatic Particle-in-Cell (PIC) code is used to simulate the solar wind flowing
around a solar sail. In this code, the solar wind protons are treated as particles. The electron
component is assumed to be an isothermal fluid and hence its density follows the Boltzmann
distribution. The electric field and particle trajectories are then solved self-consistently. A dynamic
alternating direction implicit (DADI) solver is used to solve the nonlinear Poisson’s equation in a 3-
dimensional space. More detailed description of the code can be found in Wang et al. (2001).

The model setup is shown in Fig.1. When geometric symmetry is considered, the
simulation setup needs to include only a quarter of the sail. The \( x = 0 \) and \( y = 0 \) boundaries are
symmetric surfaces while all other boundaries are “open” boundaries. Macro-particles representing
the solar wind protons are injected into the simulation domain along the \( z \) axis at every time step.
The solar sail is taken to be a conducting, thin plate with the assumed 10 V potential.
Simulation Results

As a base model, we consider a square conducting sail with dimensions of $L_x = L_y$. Table 1 listed the solar sail sizes being considered for the Geostorm mission: $L_x = 50$ m for Sail-1 and $L_x = 75$ m for Sail-2, respectively. If one normalizes the dimension by the electron Debye length, one finds that the two sail sizes are $L_x/\lambda_D \sim 2$ and $L_x/\lambda_D \sim 3$, respectively. For these dimensions and an assumed sail potential to be $\Phi_s \sim 10$ V, the model parameters for Geostorm simulations have been determined and are listed in Table 1 in both normalized units and physical units. A series of test runs with varying resolutions were performed to ensure that the results do not depend on the simulation parameters.

Geostorm Solar Sail Results

The simulations results for the two sails considered are shown in figures 2 and 3. In each figure, the top panel shows electric potential contours on a z-y plane cutting through the center of the sail; the middle panel shows potential contours on a x-y plane containing the sail surface, and the bottom panel compares the potential profile along a z-axis through the center of the sail surface and that along a z-axis through the center of the sail edge. The following conclusions can be drawn from the simulations:

- The sail is surrounded by a plasma sheath (within which the potential is positive compared to ambient) and followed by a plasma wake (within which the potential is negative).
- The plasma sheath in the ram side starts at a distance of $\sim 2 \lambda_D$ in front of the sail, or a distance of $\sim 50$ m in front of the sail for the typical solar wind conditions listed in section 1.
- For the two solar sail sizes considered, the sail size has a minimum effect on the plasma sheath. (Although the potential in the wake region is significantly different.)
- While the plasma sheath extends to a distance of $\sim 50$ m in front of the sail, its effects on solar wind electron measurement made near the sail surface should be minimum. This is because the solar sail floating potential is only about 10 V while the solar wind electron temperature is $T_e \sim 40$ eV. However, the sheath may have some effects on solar wind proton measurements made within the sheath.

Parametric Simulation Results

To better understand the global structure of plasma sheath and wake, we have also performed parametric simulations for various sail sizes and floating potentials. To generalize the results for different solar wind conditions, we will present results in normalized parameters. (Note that the results scale with the plasma Debye length.) This section presents simulation results for a solar sail with a dimension of $L_x = L_y = 8 \lambda_D$ (i.e., $L = 200$ m for the solar wind conditions listed in section 1. For comparison, we also include simulation results for a conducting plate with a negative floating potential. The parametric cases are summarized in Table 2. The results are shown in figures 4 through 8.

It is interesting to compare the plasma interaction of solar sail with that of a large space platform in the ionosphere. A spacecraft in low Earth orbit (LEO) also sees a collisionless, mesothermal plasma flow. However, a LEO spacecraft typically has a negative floating potential. The problem of ionospheric plasma flowing around a large, negatively biased structures has been studied extensively (for instance, Wang and Hastings, 1992a,b; Wang et al., 1994, and references therein). In such a problem, the dominate physics is formation of a plasma wake. When the spacecraft flowing potential is low, the wake is formed through plasma expansion. An expansion fan will be generated at plate edge which serves as a presheath to connect the ambient plasma flow.
and the plasma sheath surrounding the plate. Hence, for a negatively biased sail, the plasma sheath and wake is a unified structure, as shown in Fig.5. On the other hand, for a solar sail with a positive floating potential, the sheath and wake are two distinct regions. In this configuration, the protons are decelerated within the sheath but still undergo the same expansion process in the wake region.

**Conclusions**

We find, for base solar wind plasma conditions, that a solar sail is surrounded by a plasma sheath followed by a plasma wake (within which the potential is negative). The sheath thickness in front of the solar sail is a few Debye lengths thick for moderate charging potentials. Since the solar wind Debye length is in the range of $O(10)\text{ m}$ to $O(10^2)\text{ m}$, comparable to typical solar sail dimensions, one would expect to observe some sheath effects within a distance of tens of meters on the ram side. However, since the solar sail floating potential is found to be moderate (a few volts), sheath effects on solar wind measurements performed near the sail are *not* expected to be significant.

**Acknowledgements**

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**References**


### Tables

#### Table 1: Geostorm Solar Sails

<table>
<thead>
<tr>
<th>Sail</th>
<th>( L_x \times L_y (\lambda^2_p) )</th>
<th>( L_x ) (m)</th>
<th>( \Phi_s (T_e) )</th>
<th>( \Phi_s (V) )</th>
<th>( dsh (\lambda_p) )</th>
<th>( dsh ) (m)</th>
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<tbody>
<tr>
<td>Sail-1</td>
<td>2X2</td>
<td>50</td>
<td>0.25</td>
<td>10</td>
<td>~ 2</td>
<td>~ 50</td>
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<tr>
<td>Sail-2</td>
<td>3X3</td>
<td>75</td>
<td>0.25</td>
<td>10</td>
<td>~ 2</td>
<td>~ 50</td>
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#### Table 2: Parametric Cases

<table>
<thead>
<tr>
<th>( L_x \times L_y (\lambda^2_p) )</th>
<th>( \Phi_s (T_e) )</th>
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<td>1 8X8</td>
<td>.25</td>
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<tr>
<td>2 8X8</td>
<td>-2.25</td>
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<tr>
<td>3 8X8</td>
<td>1.00</td>
</tr>
<tr>
<td>4 8X8</td>
<td>-1.00</td>
</tr>
<tr>
<td>5 8X8</td>
<td>-10.00</td>
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</table>
Figure 1: Simulation Setup. 3-D simulations are performed for a quarter size solar sail. Solar sail is modeled as a thin conducting plate with a potential. Solar wind is injected from the upstream surface along the z direction. Solar wind is modeled as particle protons and fluid electrons.
Figure 2: Simulation Results for Sail-1. Dimension: 50 m X 50 m. Sail Potential: 10V. A: electric potential contours on a z-y plane cutting through sail center. B: electric potential contours on a x-y plane containing sail surface. (contour level difference=2 V) C: potential profile along a z axis through the center of the surface and a z axis through the center of the edge.
Figure 3: Simulation Results for Sail-2. Dimension: 75 m X 75 m. Sail Potential: 10V. A: electric potential contours on a z-y plane cutting through sail center. B: electric potential contours on a x-y plane containing sail surface. (contour level difference=2 V) C: potential profile along a z axis through the center of the surface and a z axis through the center of the edge.
Figure 4: Parametric Case 1. (Potential Isosurfaces. Potential values are normalized by $T_e$. Sail potential: $0.25 T_e$)
Figure 5: Parametric Case 2 (Potential Isosurfaces. Potential values are normalized by $T_c$. Sail potential: $-2.25 T_c$)
Figure 6: Parametric Case 3 (Potential contours and ion velocity vectors. Potential values are normalized by $T_e$. Sail potential : $1 \ T_e$)
Figure 7: Parametric Case 4 (Potential contours and ion velocity vectors. Potential values are normalized by $T_e$. Sail potential: $-1 \ T_e$.)
Figure 8: Parametric Case 5 (Potential contours and ion velocity vectors. Potential values are normalized by $T_e$. Sail potential : $-10 \ T_e$).
SIMULATIONS OF SOLAR WIND PLASMA FLOW AROUND A SIMPLE SOLAR SAIL

INTERACTIONS OF SPACECRAFT AND SYSTEMS WITH THE NATURAL AND INDUCED PLASMA ENVIRONMENT
AGENDA
Geostorm Solar Sail Mission

- Fabrication and Packaging
- Deployment / Jettison in 0 g
- Attitude Control
- Trajectory Maneuvers and Navigation
- Science Measurement and Engineering Diagnostic Instrumentation
- Interstellar Precursor and Interstellar Missions
- Operational Geostorm Warning Missions / Solar Sentinel Mission
- Non-Keplerian Earth Orbit
- Solar Polar Imager
Geostorm Solar Sail Mission
# Solar Wind Parameters

### Solar Wind Parameters at 1 AU

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIN</th>
<th>MAX</th>
<th>AVG</th>
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<td>Flux (NO#/cm²-s)</td>
<td>10⁸</td>
<td>10¹⁰</td>
<td>2-3×10⁸</td>
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<tr>
<td>Velocity (km/s)</td>
<td>200</td>
<td>2500</td>
<td>400-500</td>
</tr>
<tr>
<td>Density (NO#/cm³)</td>
<td>0.4</td>
<td>80</td>
<td>5-10</td>
</tr>
<tr>
<td>T (eV)</td>
<td>0.5</td>
<td>100</td>
<td>20</td>
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<tr>
<td>T_max/T_avg</td>
<td>1.0 (isotropic)</td>
<td>2.5</td>
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<td>Flow Direction</td>
<td>±15° from radial</td>
<td>~2° East</td>
<td></td>
</tr>
<tr>
<td>Alfvén Speed (km/s)</td>
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<td>150</td>
<td>60</td>
</tr>
<tr>
<td>B (γ)</td>
<td>0.25</td>
<td>40</td>
<td>6</td>
</tr>
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</table>

|------------------------------------------|------------------|-------------------|-----------------------|-----------------------|

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*Interstellar Medium*

- Boundary Shell
- Heliosphere
- Sun’s Apex (Shock Transition)
Model Assumptions

- **“Nominal” Solar Wind:**
  \[ v_{sw} \sim 400 \text{ km/s} \quad n_{sw} \sim 3.5 \text{ cm}^{-3} \]
  \[ T_i \sim 10 \text{ eV} \quad T_e \sim 40 \text{ eV} \]
  \[ B_0 \sim 10^{-4} \text{ Gauss} \]

- **Plasma Parameters:**
  \[ \lambda_D \sim 25 \text{ m;} \quad v_{te} \sim 2.65 \times 10^3 \text{ km/s} \]
  \[ v_{ti} \sim 30 \text{ km/s} \quad c_s = (T_e/m_p)^{1/2} \sim 62 \text{ km/s} \]
  \[ \Omega_i \sim 1 \text{ rad/s} \quad \Omega_e \sim 1.8 \times 10^3 \text{ rad/s} \]

- **Spacecraft Potential (Sunlight):**
  \[ \Phi_s \sim 6 \text{ V to } \sim 14 \text{ V} \quad \text{Assume } \sim 10 \text{ V} \]
Model Assumptions

- 3-D, Electrostatic Particle-in-Cell (PIC) code
- Solar Wind protons treated as particles
- Solar Wind electrons treated as isothermal fluid (Boltzmann distributed)
- Electric field/particle trajectories solved self-consistently using dynamic alternating direction implicit (DADI) solver in 3-dimensions [Wang et al. (2001)]
3-D simulations performed for quarter size Sail
Solar Sail modeled as thin conducting plate with a potential
Solar wind injected from upstream surface along z direction
Solar wind modeled as particle protons and fluid electrons.
Simulation Results for Sail (75 m x 75 m) at 10 V Surface Potential

A: Electric potential contours on a z-y plane cutting through sail center.

B: Electric potential contours on a x-y plane containing sail surface.

C: Potential profile along a z axis through the center of the surface and a z axis through the center of the edge.
Solid line--Potential profile along z axis through center of the surface

Dashed line--Potential profile along z axis through center of an edge
Potential Isosurfaces. Potential values are normalized by $T_e$. Sail potential : $0.25 T_e$
Potential Isosurfaces. Potential values are normalized by $T_e$. Sail potential: $-2.25 \, T_e$
Panametric Cases for Potentials of $\pm T_e$

Sail potential: $1 \ T_e$

Sail potential: $-1 \ T_e$

Potential contours. Potential values are normalized by $T_e$. 
Conclusions

- Sail surrounded by positive plasma sheath followed by negative plasma wake.
- Plasma sheath on ram side starts at \( \sim 2 \lambda_D \) or \( \sim 50 \) m for "nominal" solar wind.
- For 50 m and 70 m sails, size minimally effects plasma sheath although wake potential is significantly different.
- Effects on solar wind electron measurements made near sail surface should be minimum as solar sail floating potential is \( \sim 10 \) V while \( T_e \sim 40 \) eV.
- Sheath may effect solar wind proton measurements made within sheath.