Charged Particle Effects on Solar Sails—An Overview

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ABSTRACT

The NASA In-Space Propulsion Program is currently sponsoring a comprehensive look at the effects of the charged particle environment on the first generation of Solar Sail propulsion systems. As part of this, a joint NASA MSFC/JPL team is investigating the effects of spacecraft charging on the preliminary ISP Solar Sail mission designs. This paper will begin by reviewing the plasma environments being proposed for such missions—these range from the ambient solar wind at ~1 AU in the ecliptic plane, ~0.5 AU solar-polar orbit, and geosynchronous orbit. Following a discussion of the critical design issues associated with Solar Sails from a charging standpoint, a simple Sail configuration for modeling purposes will be presented. Results for the various environments will be illustrated in terms of the estimated surface potentials for the Solar Sail using the NASCAP-2K charging analysis program. Based on these potentials, representative plasma flow fields and potential contours surrounding the Solar Sail will then be presented. The implications of these results—the surface potentials and plasma flow—will be discussed in the context of their effects on Solar Sail operations and structural configurations. (Note: this paper is intended to provide the overall context for companion poster papers which will cover the detailed aspects of the surface charging and plasma flow around Solar Sails.)

1.0 Introduction

The objective of this paper, in support of the NASA In-Space Propulsion Technologies (ISPT) Program, is to provide an overview of the on-going study "Modeling and Experimental Validation of Solar Sail Charging in the Space Environment". This study is intended as a comprehensive look at the effects of the charged particle environment on the first generation of Solar Sail propulsion systems. The partners in this study are the NASA Marshall Space Flight Center and the Jet Propulsion Laboratory. The team is investigating the effects of spacecraft charging on the preliminary ISPT Solar Sail mission designs. The paper will begin by reviewing the plasma environments for the proposed missions—these range from the ambient solar wind at ~1 AU in the ecliptic plane, ~0.5 AU solar-polar orbit, and geosynchronous orbit. The critical design issues associated with Solar Sails from a charging standpoint and a simple Sail configuration for modeling purposes will be presented. The estimated surface potentials for the Solar Sail design using the NASCAP-2K charging analysis program will be briefly discussed (the detailed model and NASCAP-2K results will be presented in separate papers by other members of the MSFC/JPL team—see references). Based on the NASCAP-2K potential estimates, representative plasma flow fields and potential contours surrounding the Solar Sail are then illustrated using the Virginia Polytechnic Institute and State University's 3-D, Electrostatic Particle-in-Cell (PIC) code.

2.0 Space Environments for ISPT

The first step in evaluating the interaction of a solar sail with the environment is to define that environment. The NASA ISPT Program is currently studying various designs for an advanced Solar Sail spacecraft and has proposed missions in the solar wind at 1 AU in the ecliptic plane and at high solar ecliptic latitudes at 0.5 AU for the solar polar missions. In addition, the more severe charging environments of geostationary orbit are included in our analysis due to the possibility the program may elect to conduct a technology test program in either geostationary or geostationary transfer orbits. Plans for analysis include computation of sail charging as a function of sail orientation relative to the solar wind plasma flow and solar illumination for both mean and extreme plasma conditions.

2.1 Solar Wind

In deriving the plasma characteristics of the solar wind at L1 (approximately 1 AU), data from several different sources were reviewed. The solar wind is a fully-ionized, electrically neutral, magnetized plasma that flows outward from the Sun. Table 1 (updated from Ness, 1968) summarizes many of the characteristics of the solar wind in the ecliptic plane. Perhaps not clear from the table is that the solar wind is highly variable and is coupled to the 11-year solar cycle of activity. Recent years have seen the creation of a modern set of solar wind "weather stations" designed to closely monitor both solar and solar wind activity (e.g., Ulysses, WIND, SOHO, YOHKOH, ACE, and TRACE). One of these, Ulysses, has flown over the poles of the Sun and mapped the solar wind in 3 dimensions (Fig. 1).

It was decided by the team to utilize a median or average environment for the preliminary work reported here rather than determining a worst case for the preliminary phase of the charging analysis because the worst case charging condition is dependent on details of the spacecraft design that have not been finalized by the program. In addition, since the solar wind does not pose the high spacecraft potential threat that the geosynchronous orbit environment does running the additional geosynchronous orbit environment serves as a bounding "worst case" for all environments.

The "average" solar wind parameters assumed for L1 are listed in Table 2 (for simplicity, here only the solar wind "core" population for the solar wind

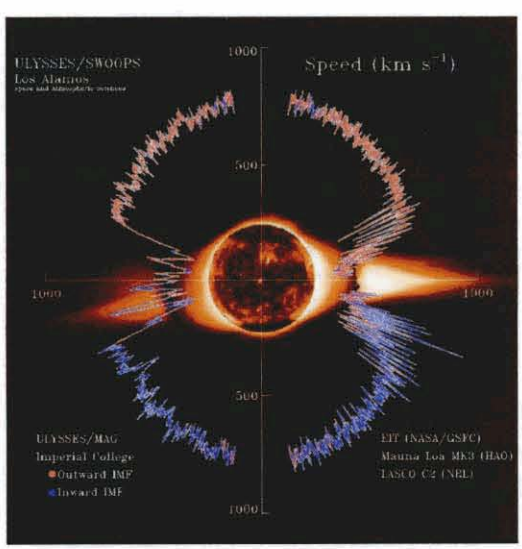


Figure 0. Solar wind velocity as a function of latitude as measured by the Ulysses spacecraft (from McComas et al., 1998).

Table 1. 1 AU solar wind parameters in the ecliptic plane.

	MIN	MAX	AVG
FLUX (#/cm^2-s)	10^8	10^{10}	2-3X10^8
VELOCITY (km/s)	200	2500	400-500
DENSITY (#/cm^3)	0.4	80	5->10
T (eV)	0.5	100	20
T_{max}/T_{avg}	1.0*	2.5	1.4
HELIUM RATIO (N_{He}/N_H)	0	0.25	0.05
FLOW DIRECTION	±15° from radial;		~2° East
ALFVEN SPEED (km/s)	30	150	60
B (g)	0.25	40	6
B VECTOR			
	POLAR COMPONENT:		AVG IN ECLIPTIC PLANE
*isotropic	PLANAR COMPONENT:		AVG SPIRAL ANGLE ~45°

electrons was considered while the electron "halo" population was ignored). Of additional importance to this effort are the solar wind properties for the sub-L1 environment for an out of the ecliptic mission closer to the Sun (0.45 to 0.50 AU; a Solar Polar Imager mission). Nominal solar wind properties for these two environments are listed in Table 2. Based on these median solar wind parameters, the following basic plasma parameters can be determined:

Debye length	$\lambda_D \sim 25\ m$
Electron thermal velocity	$v_{te} \sim 2.65 \times 10^3\ km/s$
Ion thermal velocity	$v_{ti} \sim 30\ km/s$
Acoustic speed	$c_s = (T_e/m_p)^{1/2}$ $\sim 62\ km/s$
Ion cyclotron frequency	$\Omega_i \sim 1\ rad/s$
Electron cyclotron frequency	$\Omega_e \sim 1.8 \times 10^3\ rad/s$

Of special interest are the Debye length (λ_D) and the electron (v_{te}) and ion (v_{ti}) thermal velocities. The Debye length of ~25 m is on the order of one quarter the size of the 100 m solar sail and 0.17 the 150 m sail. This is the distance over which the sail potential is shielded by the plasma and shows that the sail potential extends well out from the sail. The thermal velocity of the ions is much lower than the typical solar wind velocity leading to a deep ion wake behind the sail. In contrast, the electron thermal velocity is much higher than the solar wind and they would

Table 2. Nominal solar wind and worst case geosynchronous plasma environments

PLASMA ENVIRONMENT	0.5 AU	1.0 AU	Geosynch
RE1 (cm^{-3}):	50	3.5	1.2
TE1 (eV):	65	40	24400
RI1 (cm^{-3}):	50	3.5	0.88
TI1 (eV):	40	10	27000
RE2 (cm^{-3}):			0.2
TE2 (eV):			400
RI2 (cm^{-3}):			1.3
TI2 (eV):			300
CPH (nAmps/cm^{-2}):	8	2	2
SAT VELOCITY (km/s):	500	400	3
POTENTIALS:	0.5 AU	1.0 AU	Geosynch
Shadowed (insulator):	-39.06	-45.7	-8144.5
Sunlight (conductive):	6.01	9.23	0.79

normally fill in the wake but are prevented from doing so by the electric field produced by the slower ions. These features characterize the basic structure of the solar sail plasma sheath and wake.

2.2 Geosynchronous Orbit

Although the composition and time evolution of the geosynchronous plasma environment is quite complex, it is standard practice to represent the environment in terms of a temperature and density assuming a characteristic velocity distribution. Assuming a Maxwell-Boltzmann distribution, the geosynchronous environment is typified as a cold, dense plasmaphere (with a "temperature" of about 1-10 eV and a density of 100 particles/cm^3) and a hot, low density plasmasheet component ("temperature" of about 1-10 keV and a density of 1 particles/cm^3). Episodic injections of hot, low-density plasma (1 to 10 particles/cm^3 with energies ranging from 1 to 50 keV) occur near local midnight during geomagnetic substorms with an accompanying loss of the cold plasmasphere component. The substorm environment can charge spacecraft surfaces to sufficiently large potentials that discharges may occur. The hot plasma cloud diffuses in a few hours but is replaced many times during the life of the storm (which may last a day or longer). A "Worst-case" environment for geosynchronous orbit corresponding to a substorm injection are defined in Table 2 based on NASA TP-2361 (Purvis et al., 1984). These values were derived from fits to the plasma distributions observed during three worst-case charging events. The values are particularly useful in estimating the extremes in charging that a geosynchronous spacecraft is likely to encounter.

3.0 Charging Analysis

Evaluation of spacecraft charging conditions for a sail that is thousands of square meters of ultra-thin lightweight, highly reflective material in a geosynchronous or solar wind environment requires calculations that take into account the unique solar sail geometries, material properties and anticipated mission environments. Fig. 2 illustrates the interaction of a typical solar sail membrane with solar wind particles. The various surface currents illustrated in Fig. 2 must balance such that the net current is zero and it is this that determines the potential of the sail surfaces. A first order estimate of the plasma interaction with a solar sail can be determined by assuming it to be made of a thin, uniformly conducting sheet of aluminum. The floating potential of the solar sail relative to the ambient solar wind plasma can then be approximated by the following simple current balance equation (Garrett, 1981):

$$\begin{aligned} I_T(\Phi_s) = 0 = & -A_e \cdot J_e(\Phi_s, T_e, n_{sw}) + A_i \cdot J_i(\Phi_s, T_i, n_{sw}) \\ & + A_e \cdot JS_e(\Phi_s, T_e, n_{sw}) + A_e \cdot JBS_e(\Phi_s, T_e, n_{sw}) \\ & + A_i \cdot JS_i(\Phi_s, T_i, n_{sw}) + A_{pho} \cdot J \end{aligned} \tag{1}$$

where: I = total current; A = the relevant area for current collection; J = the various current densities (see Fig. 2); Φ_s = sail floating potential relative to space; T = plasma temperature; n =plasma number density.

While 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, Eq. 1 can be used to provide a first order estimate for comparison purposed. For the solar wind and geosynchronous conditions listed above, the values for the floating potential in sunlight for a conductive aluminum sheet are: Φ_s ~6 V to ~9 V in the solar wind and ~0 V in geosynchronous orbit (see Table 2) 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 Φ_s ~10 V as a worst case in sunlight. Problems arise, however, if the sail material backing is non-conductive or electrically decoupled from the front surface. In that case, the shadowed back surface can reach potentials of –30 to –40 V relative to the space plasma in the solar wind. These are on the order of arcing onset potentials (reported by some to be as low as 50 V). The real issue is the geosynchronous environment (or its extension down to low altitudes in the auroral zones) where an isolated surface in the dark can reach 1000's of volts. The issue here is simple—make sure the sail material is conductive front to back and end to end if the sail is to be in geosynchronous orbit or in the auroral zone and be very careful with electrically isolated objects in the shadow of the sail.

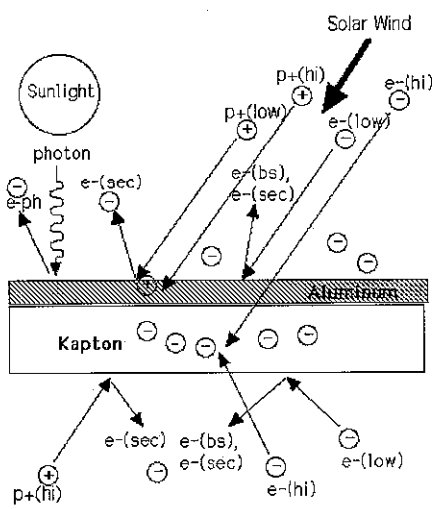


Figure 2. Schematic of currents interactions with a solar sail membrane. They are incident electron and ion currents, secondary and back-scattered electrons, and photoelectrons.

3.1 Critical Charging Issues and Implications for ISPT Solar Sails

This study will advance the state of knowledge of solar sail design by addressing a number of critical charging issues:

- Determine the charging of a solar sail in the solar wind and geosynchronous orbit and the effect that charging has on the sail
- Model the effects of the induced solar sail environment on spacecraft payloads
- Provide guidance in the development and testing of solar sail materials
- Evaluate the behavior of large scale objects in the space environment

The first of these issues, charging in the solar wind, is of concern for the possible effects on scientific observations, for potential effects on the sail surface, and for arc discharges. While large potentials are not expected in the solar wind, even potentials of 10-100 V can effect solar wind observations or cause surface distortions.

Given the potential distributions on a solar sail, the flow field around the sail as a function of the ambient solar wind plasma can be determined. The effects of the plasmas on payloads on and near the solar sail surfaces can then be estimated. As in the case of charging of small spacecraft, limited information can be gained from existing spacecraft. The models being developed can be used to extend these findings to the large dimensions characteristic of solar sails thus allowing the development of mitigation techniques such as placement on booms so as to avoid shadowing or high potential gradients in the fields of view of plasma instruments.

The models can also be used to determine what material characteristics are most likely to be affected by the environment or to have effects on the plasma interactions—thereby pointing the direction as to what tests need to be performed. By varying the composition of the materials, the charging of the solar sail can be altered and the effects estimated. Likewise, the effects of induced conductivity on the charging of different solar sail materials from solar radiation and UV can be estimated. Given the various combinations of materials being considered for the sail surface and its support structures, this should assist in evaluating candidates.

Finally, the unique features of the interactions of truly large structures in the solar wind are yet to be determined. Evidence exists that the region over which a structure affects the environment in its immediate vicinity may scale in a complex manner (see conference proceedings on "Space Technology Plasma Issues in

2001") proportional to its primary dimensions (a tether for example is a one-dimensional object, a solar sail a two-dimensional object, and the Space Station a three-dimensional object). This phenomena can be evaluated using these models.

The solar wind plasma can charge the solar sail surface—if the potential gradients are high enough, this could distort the surface figure or lead to charging-enhanced contamination as was seen on the SCATHA satellite. Likewise, meteoroid impacts may initiate discharges or clouds of contamination that could affect the long term performance of the sail. Radiation will degrade the sail's substrate material over time and change its electrical and mechanical properties. Synergistic effects such as plasma wave coupling with the sail might be possible. In lieu of in-situ measurements, comprehensive models such as proposed here are critical to predicting the behavior of different structural configurations, limiting the environmental effects, and interpreting data from actual test flights. Finally, the impact of the changing plasma sheath, wake, and contamination cloud around the solar sail as a function of solar wind conditions needs to be evaluated so that the proper placement of instruments for measuring the solar wind itself (for the Solar Sentinel class of missions) or for evaluating the plasma sheath and the solar wind interactions with the sail will play a critical role in the final design of these early systems. In these respects, this work forms a vital component of the ISPT Program and provides a direct linkage between theoretical models of the solar sail plasma interactions and the development of this unique, advanced propulsion system. Examples of the anticipated results from the study that address these issues will be presented in the next section.

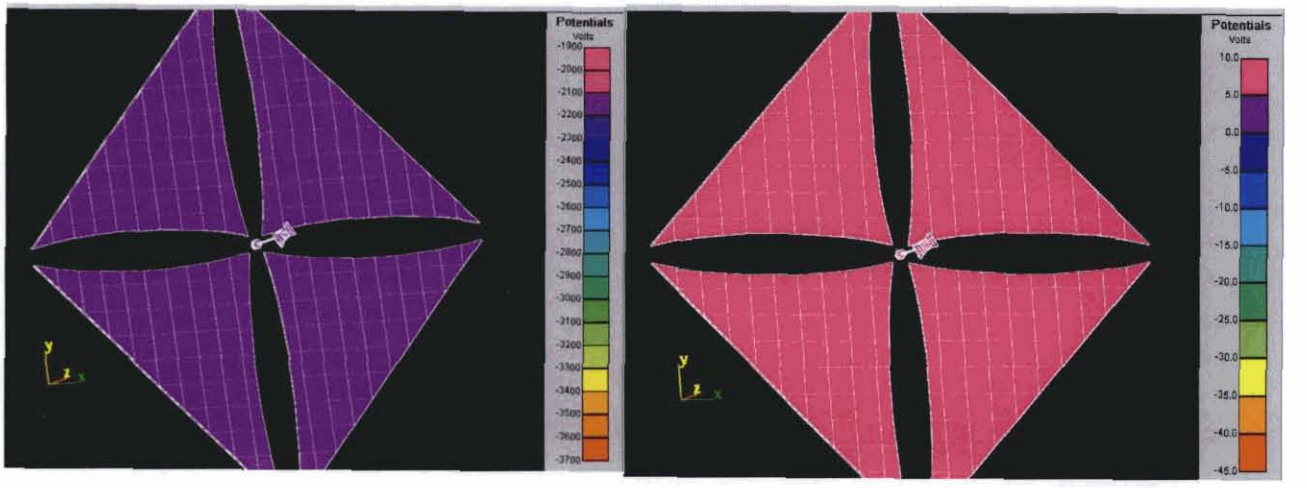
3.2 Nascap-2k Solar Sail Plasma Interaction Modeling

The preceding indicates that a solar sail charges to low levels in the solar wind but can charge during substorms (or in their earthward extensions, the auroral arcs) to dangerous levels in geosynchronous orbit if the surface is not sufficiently conductive. In this section we will briefly review the process for determining how the charging of the solar sail effects the potentials around the sail (plasma flow will be considered in the next section). To accurately determine these effects, much more sophisticated models then that represented by Eq. 1 are required. In particular, the primary tool in current use is the *Nascap-2k* charging code (Mandell et al., 2003; Davis et al., 2003) developed by the Applied Sciences Operation group, Science Applications International Corp. *Nascap-2k* features arbitrarily nested grids to provide spatial resolution, continuous electric fields for accurate particle tracking, models for sheath and wake structures, and the ability to do PIC calculations and dynamics. *Nascap-2k* also includes an interactive *Object Toolkit* (*OTk*) for defining spacecraft surface models for analysis, and an interactive grid generator. It is tailored for building spacecraft surface models and facilitates assignment of material names and conductor numbers to surfaces, as well as the association of material property sets with names.

To accurately model the sail, detailed design information is required for input to the *Nascap-2k* model. For example, electrical properties of materials including relative dielectric constant, bulk conductivity and surface resistively, photoelectron yields, and secondary electron yields due to incident electrons are required for the model as well material thickness and effective atomic number (used in computing the backscattering yield) is required for all surface materials. Design details including the dimensions and locations of conductive or dielectric (insulating) material as well as the electrical properties and the number, location, layout, and material making up all tie points between the sail and support structures. Finally, the physical characteristics of the control satellite including the size, solar array voltage, and surface materials are required as well.

Given this information, *Nascap-2k* can construct a detailed potential model of the solar sail. Sample results from charging analyses are presented in Fig. 3. for geostationary orbit and solar wind environments showing the "grid" nature of the *Nascap-2k* model. The model adopted for the analysis is a 150 meter class sail based on published designs (Jenkins et al., 2004). The solar sail surface materials assumed for both test cases are aluminum coatings on the illuminated surface with a non-conducting Kapton back surface. The spacecraft bus is assumed to be aluminum but the booms (not shown in the figure) are treated as non-conductive Kapton to demonstrate the implications of designing spacecraft with non-conductive materials in the geostationary orbit and solar wind charging environments. Solar arrays are included on the instrument module with solar cell materials facing the Sun and Kapton on the back surface.

Geostationary orbit environments used in Fig 3a for input to the Nascap-2k charging model are single Maxwellian environments with Ne = 1.12 cm-3 and Te = 12 keV for electrons and Ni = 0.236 cm-3 and Ti = 29.5 keV for ions (assumed to be hydrogen), 0.00 km/sec flow velocity (thermal velocities dominate the motion of the plasma or spacecraft), and sunlight from the +z direction (that is, the figure shows the illuminated surface of the spacecraft).



a) b)

Figure 3. Solar Sail Surface Charging Analysis. (a) Geostationary orbit yields extreme differential potentials of -2.1 kV on the illuminated surface (shown) and -3.6 kV on the back surface. (b) Solar wind (1 AU) environments yield more moderate potentials of +0.067 kV on the illuminated surface (shown) and -0.040 kV on the back surface.

The illuminated aluminum coating of the sail material is an equipotential surface since it is a conducting material and therefore the entire surface exhibits a constant potential of $\Phi = -2.13$ kV. The back surface of the sail (not shown) exhibits a maximum negative potential of $\Phi = -3.64$ kV suggesting a differential potential may exist from front to back up to $\Delta\Phi \sim 1.51$ kV although the details will depend on where on the non-conducting Kapton surface the minimum potential actually occurs. Spacecraft bus potentials are the same $\Phi = -2.13$ kV potential as the sail since the bus surface material is a conductor and grounded to the conductive sail in the model. Potentials on the boom structures supporting the sails are $\Phi = -3.64$ kV since the booms are non-conductive and the differential potential $\Delta\Phi \sim 1.5$ kV between the sail and booms suggests a danger of arcing (Purvis et al., 1984). The potential of the front surface of the solar array structure is $\Phi = -2.12$ kV while the Kapton back surface is $\Phi = -2.13$ kV with a more moderate differential potential of $\Delta\Phi \sim 0.01$ kV. The large negative potentials in the geostationary orbit environment are due to collection of an excess number of hot electrons. In contrast, the solar wind environment is characterized by a low density, high speed flow of cold ions and electrons and the charging process is dominated by the photoelectron currents. As a result, the potential on the front surface of the solar sail in the solar wind example shown in Fig. 3b is positive and only a moderate $\Phi = +6.68$ V. Environment parameters used for this analysis are Ne = 12.8 cm-3 and Te = 11.13 eV for electrons and a convective flow speed for both ions and electrons of V = 327 km/s. Ion temperatures are not included in the analysis since the current collection is dominated by the ram current which is simply the product of the ion density and the ion velocity and thermal contributions are of minor importance. Although the thermal energy of the solar wind is relatively low compared to geostationary orbit, the average proton energy due to the convective flow is 0.558 keV at this flow speed. Sunlight is incident from the +z direction illuminating the surface shown in Figure 3b.

There is a differential potential between the front and back sides of the sail in the solar wind case as well since the minimum potential on the back side is $\Phi = -40$ V and a difference as large as $\Delta\Phi \sim 47$ V may exist depending on the location of the potential minimum on the back side. The non-conductive booms in this example also show $\Phi = -40$ V potentials and the conductive spacecraft bus which is grounded to the sail exhibits the same $\Phi = +6.68$ V potential as the aluminum surface of the sail. Potentials on the illuminated surface of the solar array vary from $\Phi = +6.68$ V to $\Phi = -3$ V with a backside potential of $\Phi = +6.68$ V. The small differential potentials in the solar wind case suggest little possibility of damage to the sail or spacecraft structures due to arcing.

It is important to bear in mind that the surface charging results presented here are preliminary and are intended only to demonstrate the range of charging conditions that arise from exposing a solar sail spacecraft to different space environments. Actual worst case

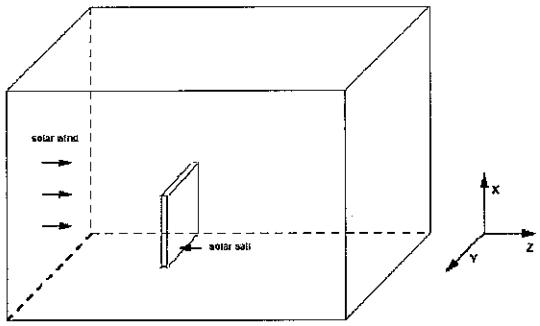


Figure 4. Simulation Setup. 3-D simulations are performed for a quarter solar sail. The solar sail is modeled as a thin conducting plate with a fixed potential. The solar wind plasma, modeled as particle protons and fluid electrons, is injected from the upstream surface along the z direction.

charging conditions depend on details of the spacecraft design and analyses using appropriate materials and design parameters will need to be completed once the details are finalized by the program.

3.3 Plasma Flow Model

Prof. Wang of the Virginia Polytechnic Institute and State University has developed a 3-D, Electrostatic Particle-in-Cell (PIC) code that can be used to simulate the solar wind flowing around a solar sail. In this code, the solar wind protons are treated as individual particles. In contrast, 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 using a dynamic alternating direction implicit (DADI) solver 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). A typical model setup is shown in Fig.4. 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.

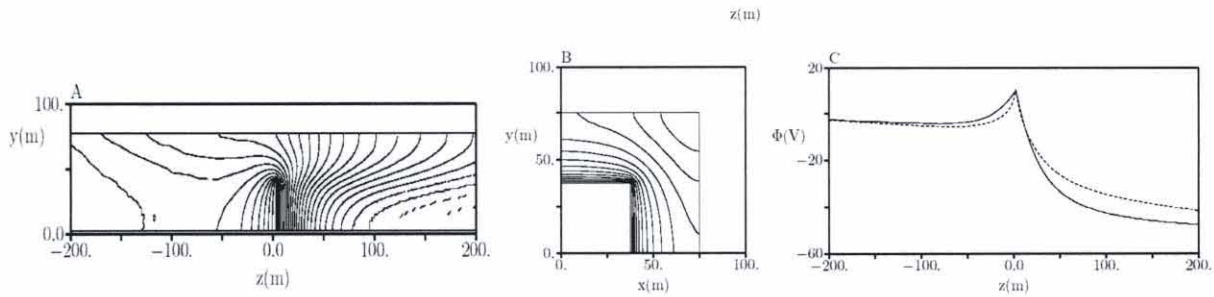
The simulations results are shown in Fig. 5. In the figure, the top panel shows electric potential contours on a z-y plane cutting through the center of the sail; the lower left panel shows potential contours on a x-y plane containing the sail surface, and the right panel compares the potential profile 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 simulation:

- 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 ~$2\lambda_D$ in front of the sail, or a distance of ~50 m in front of the sail for the typical solar wind conditions .
- For the solar sail sizes considered, the sail size has a minimum effect on the plasma sheath. (Although the potential in the wake region can be significantly different.)
- While the plasma sheath extends to a distance of ~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 ~ 40 eV. However, the sheath may have some effects on solar wind proton measurements made within the sheath.

It is interesting to compare the plasma interaction of a solar sail in the solar wind with that of one 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. (Wang and Hastings, 1992a,b; Wang et al., 1994, and references therein). For a negatively biased sail, the plasma sheath and wake is a unified structure, as shown in Fig.6b. On the other hand, for a solar sail with a positive floating potential, the sheath and wake are two distinct regions (Fig 6a).

4.0 Summary

This study has provided an overview of the integrated solar sail charging study be carried out for the ISP program. Initial results from the study are presented in detail in separate papers presented by the team members. Here, as an overview, we find that, for the solar wind and geosynchronous conditions listed, the values for the floating potential in sunlight for a conductive aluminum sheet are: Φ_s ~6 V to ~9 V in the solar wind and Φ_s ~ 0 V in geosynchronous orbit based on the details of the current collection (e.g., ion ram current, orbit limited, etc.). We therefore assume the sail potential to be ~10 V as a worst case in sunlight. Problems arise if the sail material backing is non-conductive or electrically decoupled from the front surface. In that case, the shadowed back surface can reach potentials of –30 to –40 V relative to the space plasma in the solar



a) b) c)

Figure 5. Simulation Results for Sail-2. Sail dimensions are 75 m x 75 m and the sail surface potential is +10V. (a) Electric potential contours on a z-y plane cutting through center of the sail (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.

wind—on the order of arcing onset potentials. The real issue, however, is the geosynchronous environment (or auroral zones) where an isolated surface in the dark can reach 1000's of volts. The solution here is simple—make sure the sail material is conductive front to back and end to end if the sail is to be in geosynchronous orbit or in the auroral zone and be very careful with electrically isolated objects in the shadow of the sail.

Based on this overview, we believe that this effort will advance the state of knowledge of solar sail design in the following areas by:

- Determining the charging of a solar sail in the solar wind and the effect that charging on the sail
- Modeling the effects of the induced solar sail environment on spacecraft payloads
- Providing guidance in the development and testing of solar sail materials
- Evaluating the behavior of large scale objects in the space environment

To accomplish this, however, detailed information on the design of the proposed solar sail and on the electrical properties of the materials making up the sail and its structures are required. With this information and our design tools, we expect to significantly improve the reliability and utility of the first generation of solar sails.

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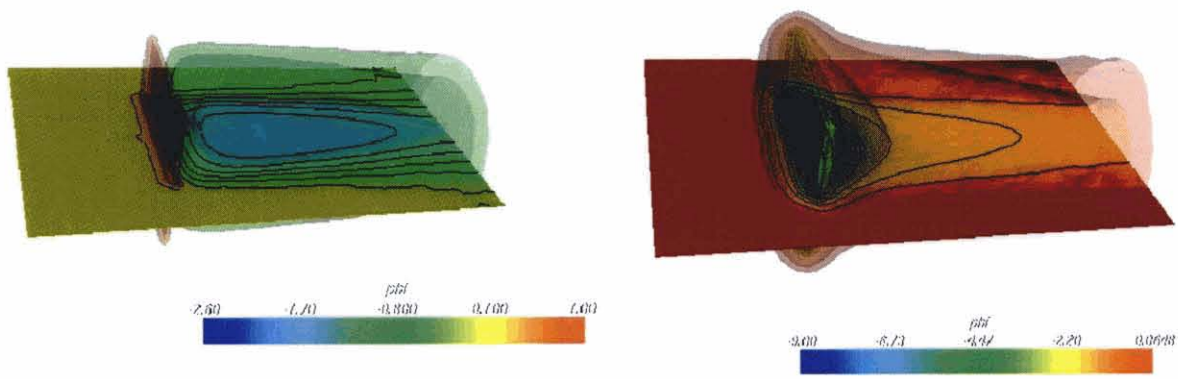

a) b)

Figure 6. Parametric solar sail case studies. (a) Sail in the solar wind with the potentials normalized by 0.25 T_e and (b) sail in the ionosphere for potentials normalized by -2.25 T_e.

Sverdrup/ED44). The effort was supported by the NASA In-Space Propulsion Technologies Project (ISPT) Program.

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