Spacecraft charging in flowing plasmas; numerical simulations

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Abstract. The density and potential variations at and in the vicinity of a spacecraft in flowing plasmas are studied by numerical simulations. The spacecraft charging, wake formation, and their role for the diagnostics of the ambient plasma are addressed. It is demonstrated that the wake features, such as ion focusing, can be altered by photoemission due to directed sunlight. For multiple ion species, the wakes for ions with different ion masses can be separated, with light ions contributing to the ion focus, and heavy ions giving a geometrical shape of the wake. As a specific case, the Cassini spacecraft approaching Saturn is considered. The simulations are carried out with DiP2D and DiP3D codes, the two- and three-dimensional particle-in-cell codes.

1. Introduction

Understanding of spacecraft-plasma interaction is of importance for all space missions and experiments [1-3]. A spacecraft is charged by plasma and also other currents, such as photoemission. With respect to the plasma potential, any isolated object is at floating potential, at which the net current to the object surface is zero. If the spacecraft is much smaller that the Debye length \( \lambda_D \), which is a characteristic length in plasma, its potential can often be approximated by the orbit-motion-limited (OML) theory [1]. However, in intricate plasma environments, such as plasmas with photoelectrons, or multispecies plasmas, the analytic formulas can give incorrect results [4].

Charged objects disturb the surrounding plasma. In the vicinity of the object’s surface a plasma sheath forms, while relative motion of the object and the plasma gives rise to a plasma wake downstream from the object [5-8]. The sheath and wakefield can influence the plasma diagnostics with instruments onboard the spacecraft. Thus, for the analysis of such data, it is necessary to account for the spacecraft potential and its variations in different regions in space. A study of this problem with analytical models is difficult and usually employs linearized models. This has encouraged the use of numerical models, such as particle-in-cell (PIC) simulations [9], which allow us to study the plasma-object interactions self-consistently on a detailed kinetic level, based on first principles.
Numerical simulations reveal that in the presence of a plasma flow, the ion focus can form downstream from the object [5, 10]. Ion focusing is due to electrostatic lensing of ions in the wake region by a negatively charged object. It depends on the material and shape of the object and is more pronounced for large electron to ion temperature ratios [11]. The resulting potential distribution gives rise to a local maximum in the wake, that is located further downstream than the maximum in ion density, consistent with the Poisson equation. Ion focusing has important implications in, for instance, dusty plasmas. It can explain the formation of dust chains from grains suspended in the sheath and presheath of the discharge, where an ion flow is present [12].

We employ DiP2D and DiP3D numerical codes [13, 14], to study the spacecraft-plasma interaction in different plasma environments. The problems addressed here include wake formation in subsonic and supersonic flows, also in the presence of photoemission due to directed sunlight, as well as multiple ion species. As a specific case we consider a set of parameters corresponding to the Cassini spacecraft approaching Saturn.

2. Numerical codes

The DiP2D and DiP3D codes are two- and three-dimensional PIC codes, which have been described in detail in previous works [13, 14], and here we present briefly the main concepts of the model. In DiP codes, two and multicomponent plasmas can be simulated, with the plasma particles (electrons and ions) followed in self-consistent electric fields. For computational efficiency, the codes use a grid for solving the field equations. At each time step, the plasma charge density is built on the grid by weighting individual particles to the nearest grid points. After solving the field equations, the fields are interpolated from the grid points to plasma particles. The particle trajectories are then advanced with the leap frog method characterized by a staggered time mesh [9]:

\[
\begin{align*}
x_k(t + \Delta t) &= x_k(t) + v_k(t + \Delta t/2)\Delta t \\
v_k(t + \Delta t/2) &= v_k(t - \Delta t/2) + f_k(t)\Delta t/m_k
\end{align*}
\]

where \(k\) refers to a plasma particle, \(f_k\) is a force projected from the nearest grid points on the \(k\)-th particle of mass \(m_k\), and \(\Delta t\) is the computational time step.

The plasma particles are initially uniformly introduced with Maxwellian velocity distributions in the simulation box of several electron Debye lengths, \(\lambda_{De}\) in each direction, and they are also injected into the simulation box at each time step according to prescribed particle fluxes. To simulate an open plasma system, the particles can leave freely through the boundaries of the simulation box. The codes use Dirichlet boundary conditions for the potential, and the plasma potential is \(\Phi_{pl} = 0\) V.

A spacecraft, or other finite-sized object, is placed inside a simulation box, and constitutes internal boundary conditions for the plasma particles. The object is initially uncharged, and it is charged self-consistently during the simulation. It can be either made of perfectly insulating or conducting material. For a conducting object, each plasma particle that hits the surface is lost, and it is redistributed on the grain surface to cancel internal electric fields. For an insulating object, the plasma particle that hits the surface remains there for all later times contributing to the local electric fields.

In addition to the plasma currents, the object can be charged by photoemission current due to directed photon flux [15]. The angle of irradiance, energy, and intensity of the monoenergetic photons can be varied. When a photon hits the surface of the object, a photoelectron of energy \(E = E_{hv} - W\) is produced at distance \(l = sv\Delta t\) from the dust grain surface, where \(s\) is a uniformly distributed random number \(s \in (0, 1]\), and \(v\) is the photoelectron speed. For conducting objects, we use the work function \(W < 4.5\) eV, which is typical for many metallic materials [16]. Photoelectron velocity vectors are uniformly distributed over the hemicircle and directed away from the dust grain surface, that is in accordance with Lambert’s law.
3. Results and discussion
With DiP codes we have addressed spacecraft charging under various collisionless plasma conditions. Usually, a spacecraft is in relative motion with respect to plasma, and we focus our analysis on flowing plasmas. For generality, we assume a spherical spacecraft made of conducting material. Thus, the results can also be applied to other plasma-surface interaction problems, such as the plasma probe performance, or dust grain charging [17]. While extended parts, solar panels, or booms can modify the plasma dynamics in the closest vicinity to the spacecraft surface, the spherical approximation generally holds further away from the surface [13].

When a conducting, spherical spacecraft is charged by plasma currents only, its potential can be well approximated with the OML model with stationary electrons and flowing ions, where the current densities to the surface are given by [1]:

\[
J_i = n_i q_i v_d \left[ 1 + \frac{1}{2\xi^2} - \frac{q_i \Phi_{fl}}{kT_i \xi^2} \right] \text{erf} \left( \xi \right) + \frac{1}{\sqrt{\pi} \xi} \exp \left( -\xi^2 \right),
\]

\[
J_e = n_e e \sqrt{\frac{kT_e}{2\pi m_e}} \exp \left[ -\frac{e\Phi}{kT_e} \right],
\]

where \( \xi = v_d/\sqrt{2kT_i/m_i} \), \text{erf} is the error function, \( v_d \) ion drift speed, \( T_{e/i} \) electron/ion temperature, \( e < 0 \) electron charge, \( q_i \) ion charge, \( n_{e/i} \) electron/ion density, and \( \Phi_{fl} \) spacecraft potential.

The floating potential from the simulations of a spherical, conducting object, with radius \( r \) being small in terms of the Debye length (\( r \approx 0.1\lambda_{De} \)), is shown in figure 1. The floating potential calculated with the OML model is also plotted for comparison. The agreement between the results from the simulations and theoretical calculations is very good for supersonic velocities and \( v_d \leq 0.3C_s \), where \( C_s \) is the speed of sound. For \( v_d \in (0.6, 0.9) \) the agreement is worse with deviations up to 10%. Simulations for \( v_d \in (0.3, 0.5) \) did not converge and thus they are not included in figure 1. Note that for insulating objects immersed in flowing plasmas, an electric dipole moment develops [13].

A negatively charged object will act as an electrostatic lens for the plasma particles, and will focus ions into the wake [11, 12]. The ion focus refers to a locally enhanced ion density in the wake of the object, an example is shown in figure 2. The maximum in the ion density is at a distance of few electron Debye lengths \( \lambda_{De} \) downstream from the object, being located further away for increasing velocities. Ion focusing is more pronounced for large electron to...
ion temperature ratios [11], and thus it can be important for the plasma measurements by a spacecraft in planetary environments [18]. Ion focusing can be influenced by the shape of the object, and elongated objects can lead to asymmetric focusing [19].

The plasma flow gives rise to a wake in the potential distribution. In particular, ion focusing can lead to a local potential enhancement. The potential distribution in the wake is shown in figure 3 for subsonic (a) and supersonic (b) flow velocities. For the supersonic flow, the potential distortion in the wake is limited by the Mach cone. Similarly to the linear response calculations of the wake pattern behind the object [20, 21], the simulations with DiP codes show a possibility of forming several potential maxima in the wake. The wake pattern is more pronounced for cold ions, as for the warm ions the focusing is weak and the Landau damping reduces the wake oscillations.

A radiative environment can significantly modify the spacecraft potential [1]. Positively charged objects and photoelectrons will substantially alter the wake pattern [15]. An example of such a wake behind a conducting object is shown in figure 4 [15], where photoemission is due to unidirectional, monoenergetic photons. In contrast to the negatively charged object, there is no ion focusing. Instead, ions are slowed down by the positively charged object, which gives rise to an enhanced ion density in front of the spacecraft, and density depletion in the wake. Photoelectrons contribute to the electron population, and the electrons are no longer Boltzmann distributed in the vicinity of the spacecraft [15]. Charging by photoemission can have important implications for the insulating parts of the spacecraft. Here the angle of incidence with respect to the plasma flow becomes important, and for some angles of incidence, a weak double layer can be formed [22], while spinning objects can lead to strong modulations in the signal received by the spacecraft instruments [23].

The plasma shielding and wakefield behind a charged spacecraft, and associated ion dynamics or photoemission currents, can substantially modify the measurements with the instruments onboard spacecraft, such as electrostatic probes on booms. The results of such measurements can correspond to a locally disturbed plasma, and not reflect the plasma conditions further away from the spacecraft. Both sheath and wake effects need to be accounted for when analyzing the

Figure 3. Potential distribution in the vicinity of a negatively charged object in the plasma flowing with \( v_d = 0.8C_s \) (a), and \( v_d = 0.8C_s \) (b). The potentials with values \( \Phi < -0.8 \text{ V} \) are colored white. The flow is in the positive \( x \) direction. \( n = 10^{13}\text{m}^{-3}, T_e/T_i = 100 \), data is from \( \text{DiP3D} \) code.
data from satellites or rockets. In particular, the ionospheric sounding rockets are the fast spinning objects that can move at sub- or supersonic velocities with respect to the ambient plasma. However, in the studies of ionospheric plasma, one needs to account for multispecies plasma, as well as collisions with neutral background.

To demonstrate the role of multispecies plasma for spacecraft-plasma interaction, we have considered the Cassini spacecraft approaching Saturn [24] with the plasma parameters given in table 1 for $d/R_s = \{3.95, 6.25, 10.2\}$, where $d$ is the distance from the center of Saturn, and $R_s$ is Saturn’s radius. The considered plasma has several components, and we account here for electrons, hydrogen ions, as well as water vapor ions. The water vapor in the Saturn environment is due to icy Enceladus moon [25]. The plasma is co-rotating with Saturn, thus there is a plasma flow with respect to the Cassini spacecraft. Photoemission due to directed sunlight is also included, and the photon angle $\alpha$ changes with $d$.

The study of the Cassini wake reveals that for $d/R_s = 3.95$ and $d/R_s = 6.25$, heavy water vapor ions give rise to geometric wake, while much lighter protons form the ion focus region, see

**Figure 4.** Ion density distribution around the object exposed to a supersonic plasma flow and photon flux. Densities with $n_i/n_{i,0} < 0.5$ are colored white. Data is from simulations with DiP2D code [15].

**Figure 5.** The water ion density around Cassini at $r/R_s = 3.95$. Results obtained with DiP3D code [24].

**Figure 6.** The proton density around Cassini at $r/R_s = 3.95$. Results obtained with DiP3D code [24].
Table 1. The plasma parameters for the Cassini spacecraft approaching Saturn.

| $d/R_s$ (cm$^{-3}$) | $n_e$ | $n_{H^+}/n_{H_2O^+}$ | $T_e$ (eV) | $T_{H^+}$ (eV) | $T_{H_2O^+}$ (eV) | $\alpha$ (deg) |
|---------------------|-------|-----------------------|-----------|----------------|------------------|--------------|
| 3.95                | 50    | 0.05                  | 1         | 0.2            | 3.3              | 62           |
| 6.25                | 30    | 0.5                   | 6         | 0.7            | 8.5              | 52           |
| 10.2                | 0.1   | 2                     | 35        | 2.3            | 22.0             | 35           |

figures 5 and 6. Thus, there is a complex ion wake in the vicinity of the Cassini, extending up to few $\lambda_{De}$ (note that $\lambda_{De}$ changes with $d$). An overall wake in the potential is characterized by a potential reduction extending up to several $\lambda_{De}$, see figure 7. The floating potential of Cassini in this multispecies plasma is $\Phi_{fl} \approx -2.5$ V for $d/R_s = 3.95$, and $\Phi_{fl} \approx -13$ V for $d/R_s = 6.25$. This large difference over a relatively short distance is due to changes in plasma conditions. For the largest considered distance $d/R_s = 10.2$, $\Phi_{fl} \approx 7$ V, meaning that the photoemission current gives an important contribution to the charging in this dilute plasma environment, and hence the wake structure is substantially modified, as shown in figure 8.

4. Conclusions

By numerical PIC simulations it has been shown that relative motion of a spacecraft and plasma leads to the formation of a wake in the density and potential distributions. The details of the wake properties depend on the flow velocity, plasma constituents, and floating potential of the spacecraft. In case of the multispecies plasma, different plasma species can give rise to separate wakes, with heavy ions forming a geometrical wake, and light ions being focused. Photoemission currents can lead to a positively charged spacecraft, thus modifying significantly the plasma properties close to the spacecraft. The floating potential of the spacecraft as well as its wakefield need to be accounted for when analyzing the data from instruments onboard the spacecraft during space missions, in particular for spacecrafts entering planetary magnetospheres, when large differences in the potential and plasma parameters can occur at relatively small distances.

Figure 7. The wake in potential of Cassini at $r/R_s = 3.95$. Results obtained with DiP3D code [24].

Figure 8. The wake in potential of Cassini at $r/R_s = 10.2$. Values above $\Phi = 0.3$ V are colored yellow. Results obtained with DiP3D code [24].
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