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Particle-in-cell simulation of spacecraft/plasma interactions in the vicinity of Enceladus

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ABSTRACT

The Cassini Langmuir Probe of the Radio and Plasma Wave Science instrument has measured an electron depletion in a region extending at least 50 satellite radii away from Saturn's small but geologically active icy moon Enceladus. The maximal imbalance between the electron and ion densities was observed in the dust loaded plume and to date is attributed to the electron attachment to abundant dust grains. We report the results from a three dimensional particle-in-cell simulation of a plasma structure formed around a charged spacecraft in the conditions relevant inside the Enceladus torus and in the moon's plume. In addition to the plasma population the plume simulation includes singly charged nanograins detected by the Cassini Plasma Spectrometer. The accompanied spacecraft plasma perturbations can significantly modify an ambient plasma at the Cassini Langmuir probe positions and thus impact the plasma measurements. Our modeling reveals a domination of water group ions over the electron population due to the formation of a conventional plasma sheath at the ram-oriented probe positions in the Enceladus torus and in the plume regions with low dust density ($n_{d0} < n_{e0}$). In the dust-dominated plume ($n_{d0} > n_{e0}$) the plasma perturbations are strongly reduced in the ram direction but can significantly compromise the probe measurements in the orbiter wake. Simulation results can qualitatively explain the long profiles of the electron–ion imbalance registered by the Cassini Langmuir probe during the flybys E2, E3 and E5. In either case, the plasma perturbations associated with the moving Cassini orbiter appear to be important for reliable interpretations of the Langmuir probe measurements.

1. Introduction

The geologically active small moon Enceladus (radius $R_E \simeq 252$ km) represents a significant source of gas from geysers located at the moon's southern pole (Porco et al., 2006). It is assumed that the plumes of gas that extend at least several R_E into space produce a radially narrow $\sim 1R_S$ (Saturn radius R_S = 60,268 km) torus of water-group neutral atoms and molecules centered on Enceladus' orbit (Johnson et al., 2005). The main constituents of a weakly ionized plasma in the moon's torus are co-rotating water group ions and thermal electrons.

Another plasma occurs in the direct vicinity of the eruptive south pole of Enceladus. The plumes of neutral water–vapor interact directly with Saturn's co-rotating plasma, loading the magnetosphere with fresh cold ions and decelerating the co-rotating plasma flow up to its stagnation (Tokar et al., 2006). The Enceladus plumes also contain copious amounts of charged dust. The micron-sized dust was detected by the Cassini Cosmic Dust Analyzer (CDA) instrument (Spahn et al., 2006) and is visible in the forward scattering sunlight images from the Cassini Ultraviolet Imaging Spectrometer (Porco et al., 2006). The smallest, nanometer-sized, icy grains have been registered by the Cassini Plasma Spectrometer (CAPS) (Jones et al., 2009). Hill et al. (2012) reported the number densities up to $\sim 10^3$ cm^{-3} for negatively charged nanograins observed by CAPS at the close moon flybys. Numerous icy grains emanating from the moon interior and charged by an ambient plasma form together with thermal electrons and ions a dust-loaded plasma which is associated with the term "plume". In the direct proximity to the moon's orbit, we thus can distinguish two different plasmas: a co-rotating electron–ion plasma of the Enceladus torus and a dust-loaded plasma of the plume with an almost stagnated plasma flow.

The Cassini spacecraft (SC) has made several targeted Enceladus flybys. The passages E3 (12 March 2008), and E5 (9 October 2008) are of specific interest since Cassini traversed a continuously changing plasma from the Enceladus torus to the dust-loaded

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plume and most instruments were favorably oriented to study variations in the plasma parameters. Since the SC charging process and the wake formation depend on the local plasma characteristics, the electrostatic configuration around the orbiter inevitably exhibits these changes. Indeed, the previous studies show that the SC in Saturn's magnetosphere achieves its equilibrium potential and forms a stable potential configuration during a few ion plasma periods, ω_{pi}^{-1} (Yaroshenko et al., 2011). In the near-Enceladus environment, this process typically develops at time scale $\sim 10^{-3}$ s which is much shorter than the Cassini passage time through the moon's plume $\sim 10^2$ s. The orbiter hence adjusts almost instantaneously to the equilibrium potential following changes in the local plasma parameters. A SC electrostatic configuration governs self-consistently the plasma particle distributions around the orbiter. In this study we present simulations of such a plasma structure when the orbiter passes two characteristic regions within the Enceladus proximity: (A) the Enceladus torus (far away from the south-pole plume) and (B) the dust-loaded plume. To this end we calculate a self-consistent spatial plasma-wake distributions around a spherical SC model employing a three-dimensional particle-in-cell DiP3D code (Miloch et al., 2009; Miloch, 2010). Previously, the SC-plasma configurations in Saturn's magnetosphere have been studied under the assumption that either all plasma species co-rotate with the planetary magnetic field (Olson et al., 2010; Yaroshenko et al., 2011), or involve cold, new-born water group ions (Yaroshenko et al., 2012). Our present simulations now are mostly focused on the specific features of the near Enceladus environment relevant for the Cassini plume flybys E3 and E5, and include an effect of the charged dust species. The main goal of these numerical studies is to highlight significant differences in the plasma-wake configurations formed around SC in the Enceladus torus and in the plume plasmas, and to examine how they could help to explain the Cassini Langmuir Probe (LP) of the Radio and Plasma Wave Science (RPWS) instrument data obtained during the E3 and E5 flybys.

2. Model and numerical code

CAPS, RPWS instrument and Cassini magnetometer data have been used to constrain the parameter space for the modeling of the SC-plasma interactions. Here we consider the cumulative effect of the water group ions, introducing their average mass $m_i = 18$ amu. In the Enceladus frame of reference the rigid co-rotation speed is $V_{cor} \sim 26.4$ km/s. CAPS data however indicate an sub-corotating ion flow velocities ($\sim$80% of co-rotation) in the vicinity of the moon orbit (Wilson et al., 2009). Measurements of the upper hybrid resonance frequency by the RPWS instrument provide estimates of the electron density in the range $n_{e0} \sim (45, 70)$ cm^{-3} at the moon's orbit (Gurnett et al., 2004). It is reasonable to identify these estimates with a total plasma density n_0 in the Enceladus torus. The CAPS observations during a few equatorial flybys of 2005 through the moon's torus, yielded the core electron and ion temperatures $T_e \in (1, 2)$ eV, $T_i \in (20, 30)$ eV, respectively (Tokar et al., 2008, 2009).

In the plume plasma interpretations of the LP measurements predict a local strong enhancement of the ion density up to $n_{i0} \sim 3 \times 10^4$ cm^{-3} (Morooka et al., 2011; Shafiq et al., 2011). It was assumed that some of ions can be trapped within the sheaths of the sub-micron and micron-sized dust particles Wahlund et al. (2009). In any case, the reported high ion densities are not consistent with free ion population inferred from the magnetic field perturbations measured by Cassini during the available Enceladus flybys (Kriegel et al., 2011, 2014). Moreover, recent studies of the RPWS data obtained during a few plume crossings indicate a rather weak local increase of the electron density up to $n_{e0} \sim 10^2$ cm^{-3} (Ye et al., 2014). In our modeling the plasma number density is associated with the ion density (as it would be in the absence of negatively charged dust) and we adopt for the plume region values, $n_0 = n_{i0} \sim 10^2 - 10^3$ cm^{-3}, matching well the Cassini magnetic data (Kriegel et al., 2011, 2014). Admitting a production of the water-group ions from the cold plume neutral exosphere, we assume the ion temperature to be of $T_i \sim 3$ eV. Note that the latter quantity is not constrained by Cassini observations, but is close to the predictions of the plume modeling by Fleshman et al. (2010). Furthermore, we introduce a new plasma species – nanometer-sized dust grains – as negatively singly charged ($q_d/e \sim 1$) heavy ions with mass/charge ratio $\sim 10^3$ amu/e. The nanograin densities, n_{d0}, registered by the CAPS instrument varied in a range $\sim$1–10^3 cm^{-3} deeply inside the plume (Hill et al., 2012). Incorporating charged dust, we consider two plume cases. The first one (B1) describes a more rarefied plasma with $n_0 = n_{i0} \sim 10^2$ cm^{-3} and $n_{d0} \sim 10$ cm^{-3}. As we will see later, even such small amount of dust particles enables significant modifications of the plasma structure around the orbiter. The second case, B2, accounts for the densest part of the plume where the plasma density is assumed to be constrained by the measurements of the Cassini magnetometer, i.e. $n_0 = n_{i0} \sim 10^3$ cm^{-3} (Kriegel et al., 2011, 2014). Simultaneously, we consider the high dust density $n_{d0} \sim 760$ cm^{-3} close to values registered by CAPS (Hill et al., 2012). In both B1 and B2 cases, the plume dust particles are assumed to be cold with temperatures close to the neutral gas and we assign $T_d \sim 0.03$ eV. Table 1 summarizes the input average plasma parameters adopted in the PIC simulations for the regions of the Enceladus torus (A) and plume (B).

The difference between A and B plasmas includes not only variations in the plasma parameters and composition, but also modifications of the "geometry" of SC-plasma interactions. To clarify the geometrical aspect we consider the plume flyby E3 which took place on 12 March 2008 with the closest approach to Enceladus of $\sim$50 km. The projection of the Cassini E3 trajectory onto the *XZ* plane of the coordinate system associated with the moon is shown in Fig. 1. Here we use a so called Enceladus Interaction Coordinate System (EICS), co-rotating with Saturn. Its *Z*-axis is aligned with the moon's rotation axis, pointing roughly toward ecliptic north. The *Y*-axis points toward Saturn. Then the *X*-axis completes the right handed coordinate system in the direction of motion of Enceladus around Saturn. The two panels in Fig. 1 illustrate the difference between the plasma regions A and B. The left one shows a part of the Cassini trajectory, when the orbiter is at large distances $\geqslant 40R_E$ from the moon and when the ion flow, being unaffected by the plume products, is in the azimuthal direction. Since the co-rotating ion flow and the SC velocity vector constitute an angle $\geqslant \pi/2$, this ensures a high relative SC-ion velocity $|\mathbf{V}_i| = |\mathbf{V}_{cor} - \mathbf{V}_{SC}| \sim 30$ km/s. In our simulations for the case A we assign $V_i \simeq 28$ km/s. The latter quantity matches the ion flow velocity at 18:51 UT (12 March, 2008), if the ideal co-rotation velocity is reduced to $V_{cor} \sim 23$ km/s. As Cassini approached the moon's plume (right panel in Fig. 1), the neutral water–vapor reacts with Saturn's co-rotating plasma, loading the magnetosphere with fresh cold ions with subsequent slowing of the co-rotating flow to its stagnation (Tokar et al., 2006). In a central part of the plume we hence assume $\mathbf{V}_{cor} \to 0$, so that the relative ion velocity becomes $\mathbf{V}_i \simeq -\mathbf{V}_{SC}$. Admitting that the plume dust is initially coupled to the neutral gas yields the same relative velocity for the grains, i.e. $\mathbf{V}_d \simeq \mathbf{V}_i \simeq -\mathbf{V}_{SC}$. For the SC velocity in the plume (case B) we take $V_{SC} \simeq 14.4$ km/s close to the Cassini speed at 19:07 UT.

At this stage it is convenient to introduce a local coordinate system (x, y) related to the moving orbiter where a relative plasma