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# Plasma regions, charged dust and field-aligned currents near Enceladus

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ABSTRACT

We use data from several instruments on board Cassini to determine the characteristics of the plasma and dust regions around Saturn's moon Enceladus. For this we utilize the Langmuir probe and the electric antenna connected to the wideband receiver of the radio and plasma wave science (RPWS) instrument package as well as the magnetometer (MAG). We show that there are several distinct plasma and dust regions around Enceladus. Specifically they are the plume filled with neutral gas, plasma, and charged dust, with a distinct edge boundary region. Here we present observations of a new distinct plasma region, being a dust trail on the downstream side. This is seen both as a difference in ion and electron densities, indicating the presence of charged dust, and directly from the signals created on RPWS antennas by the dust impacts on the spacecraft. Furthermore, we show a very good scaling of these two independent dust density measurement methods over four orders of magnitude in dust density, thereby for the first time cross-validating them. To establish equilibrium with the surrounding plasma the dust becomes negatively charged by attracting free electrons. The dust distribution follows a simple power law and the smallest dust particles in the dust trail region are found to be 10 nm in size as well as in the edge region around the plume. Inside the plume the presence of even smaller particles of about 1 nm is inferred. From the magnetic field measurements we infer strong field-aligned currents at the geometrical edge of Enceladus.



## 1. Introduction

The small icy moon Enceladus is geologically active with long warm fissures at the surface of its south polar region. From there gas and ice grains are continuously being expelled and form a plume (Dougherty et al., 2006; Porco et al., 2006; Spahn et al., 2006; Waite et al., 2006). Many in depth studies have been conducted with various instruments regarding the plume physics based on flyby observations by the Cassini spacecraft (e.g., Spitale and Porco, 2007; Cravens et al., 2009; Krupp et al., 2012). The plume, for instance, has been found to contain partially ionized material including negatively charged nanograins (Jones et al., 2009; Morooka et al., 2011; Shafiq et al., 2011; Hill et al., 2012; Farrell et al., 2012; Dong et al., 2015), where the densities of electrons, ions and negatively charged dust increase to several orders of magnitude compared to the surrounding magnetosphere of Saturn. Newly ejected material from the plume (both ions and charged dust) becomes picked up and accelerated by the Kronian magnetospheric flow (e.g., Tokar et al., 2006, 2008; Pontius and Hill, 2006; Fleshman et al., 2010; Farrell et al., 2012). Enceladus is therefore the primary source of sub-micron sized dust in the E-ring (e.g., Kurth et al., 2006; Spahn et al., 2006), which consists predominantly of negatively charged water ice (Kempf et al., 2006; Hillier et al., 2007), and plays an important role in the dust plasma interaction there (Wahlund et al., 2005, 2009).

Enceladus and its electrically conductive plume act as an obstacle to Saturn's magnetospheric plasma flow, and causes large scale perturbations around the moon (e.g., Dougherty et al., 2006; Saur et al., 2007). The magnetospheric flow slows down due to mass loading of material from the plume, and results in a magnetic field pile-up region upstream of Enceladus' plume (Dougherty

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et al., 2006; Morooka et al., 2011). The neutral-ion collisions generate perpendicular (Pedersen and Hall) currents inside the plume, which are then thought to close along the magnetic field lines (Kriegel et al., 2011; Simon et al., 2014) and cause an auroral footprint in Saturn's ionosphere (Pryor et al., 2011). Clear signatures of accelerated electrons are observed at the edges of the plume, which are associated with auroral hiss emissions (Gurnett et al., 2011; Leisner et al., 2013). However, these are along wedge shaped regions (the so-called Alfvén wings) similar to those observed at Io (Neubauer, 1980). These Alfvén wings are the magnetic wakes caused by a moving plasma flow around a stationary conductive obstacle, in this case the plume.

Extensive modeling of the magnetospheric plasma interaction with Enceladus and its plume has been undertaken using a range of approaches (see e.g. Jia et al., 2010; Kriegel et al., 2009; Simon et al., 2011), Numerical models utilizing both fluid and hybrid approximations have been produced, along with analytical studies (Simon et al., 2011). These models have recently been extended to include various approaches to the inclusion of the observed negatively charged dust component within the interaction region (Kriegel et al., 2011). Notably, the most important result is that the charged dust has a strong influence on the Enceladus plasma interaction and therefore must be included in such models to have their results approach reality (Omidi et al., 2010, 2012). Nevertheless, significant challenges are presented to empirical models, specifically in simulating a negatively charged dust population both accurately and stably (e.g., Kriegel et al., 2014; Omidi et al., 2012).

In this paper we present data from all 20 flybys of Enceladus by the Cassini spacecraft, showing in particular new high temporal resolution electron density measurements from the RPWS Langmuir probe (LP), micron sized dust measurements by the RPWS electric antenna and compare those to magnetic field measurements by MAG. The measurements are presented in Section 2. The data for the regions studied include the Enceladus trail region as well as the edge of the plume, and are presented in Sections 3 and 4. We conclude the paper with a discussion and conclusion in Sections 5 and 6, respectively. Appendices A–C include detailed information on the Langmuir probe calibration, as well as the derivation of electron and ion density from LP sweeps and error estimations.

## 2. Measurement description

### 2.1. Langmuir probe data

The Radio and Plasma Wave Science (RPWS) instrument sensors consists of three electric field antennas, a tri-axial magnetic search coil assembly and a Langmuir probe (LP) (Gurnett et al., 2004). The Langmuir probe is a spherical sensor (diameter $d_{LP} = 5$ cm) located at the end of a 1.5 m boom on the Cassini spacecraft.

The Langmuir probe data used in this study is from two operation modes; a sweep mode, sweeping through $-32$ V to $+32$ V, and a 20 Hz mode with a constant bias potential at $+11.5$ V. By applying a bias voltage to the probe, charged particles are attracted to or repelled from the probe. This results in a current, $I$, to the probe which can be described by the orbit motion limited (OML) theory (Mott-Smith and Langmuir, 1926; Medicus, 1962) for the case $r_{LP} \ll \lambda_D$, where $r_{LP}$ is the probe radius and $\lambda_D$ the Debye length. The OML current due to a particle species $\alpha$ is given by

$$I_\alpha = \begin{cases} I_{\alpha,0}(1-\chi_\alpha), & \text{attractive potentials} : \chi_\alpha < 0 \\ I_{\alpha,0}e^{-\chi_\alpha}, & \text{repulsive potentials} : \chi_\alpha > 0, \end{cases} \quad (1)$$

with subscript $_\alpha$ being either electrons or ions, $q_\alpha$ the charge of the species and $U_{bias}$ the applied voltage to the probe. The equilibrium current, $I_{\alpha,0}$, is approximated by Fahleson et al. (1974)

$$I_{\alpha,0} \approx n_\alpha q_\alpha A_{LP}\sqrt{\frac{q_\alpha T_\alpha}{2\pi m_\alpha} + \frac{v_\alpha^2}{16}} \quad (2)$$

with $n_\alpha$ the density of the sampled particle species, $A_{LP}$ ($= 4\pi r_{LP}^2$) the surface of the Langmuir probe sphere, $T_\alpha$ the particles temperature expressed in [eV], $m_\alpha$ the mass, $v_\alpha$ the bulk speed of the species and

$$\chi_\alpha = q_\alpha \left( \frac{U_{float} + U_{bias}}{T_\alpha + \dfrac{m_\alpha v_\alpha^2}{2q_\alpha}} \right) \quad (3)$$

with $U_{float}$ the floating potential of the probe and $U_{bias}$ the applied potential. For the Cassini LP, the spacecraft potential, $U_{SC}$, relates to the floating potential approximately as

$$(U_{SC} - U_{float}) \approx \frac{5}{6} U_{SC} \cdot \exp(-d_{LP}/\lambda_D) \quad (4)$$

(Gustafsson and Wahlund (2010)) based on inter-calibrations with CAPS/ELS.

A 512 point probe bias voltage sweep between $\pm 32$ V is executed usually every 10 min (every 24 s for targeted flybys). Sweeps can be used to give information on population densities, their temperature and/or drift energy, and the spacecraft potential. See Fig. 1 as an example sweep from flyby E6 taken at the plasma disk just outside Enceladus. The derivation of the electron and ion density can be found in Appendix B.

The main contributions to the LP current in this region are given by

$$I = I_e + I_i + I_{ph}^{s/c} + I_{ph}^{p} + I_{sec}^{s/c} + I_{sec}^{p} + I_d. \quad (5)$$

This includes plasma electrons, $I_e$, plasma ions, $I_i$, and photoelectrons from the spacecraft and the probe, $I_{ph}^{s/c}$ and $I_{ph}^{p}$. Secondary electrons from energetic particle impacts, $I_{sec}^{s/c}$ and $I_{sec}^{p}$, from both spacecraft and probe as well as charged dust, $I_d$, contribute.

The interest of this paper lies in the linear part of the sweep current contribution which is due to plasma electrons, $I_e$. At a positive bias potential, where we take $e = q_e$, the OML current is given by

$$I_e = e n_e A_{LP}\sqrt{\frac{eT_e}{2\pi m_e}}\left(1 + \frac{U_{float} + U_{bias}}{T_e}\right) \quad (6)$$

Between sweeps, the Langmuir probe is in its 20 Hz continuous sampling mode, set to a fixed bias potential, $U_{bias}$, of $+11.5$ V. From Fig. 1 we see that this bias potential, marked by the pink vertical dashed line, is on the attractive (linear) part of the curve (red solid line), so variations of $I_e$ can be taken to reflect variations of $n_e$ in the plasma.

While Eq. (4) takes the effect of the spacecraft on its environment into account, no such considerations are included in the other expressions. To compensate for this, the 20 Hz current is calibrated to electron density by comparison with the RPWS upper hybrid emission data (cf. Appendix A). The associated errors of the presented 20 Hz continuous electron density data are presented in Appendix C.