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Characteristics of the dust–plasma interaction near Enceladus' South Pole

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ABSTRACT

We present RPWS Langmuir probe data from the third Enceladus flyby (E3) showing the presence of dusty plasma near Enceladus' South Pole. There is a sharp rise in both the electron and ion number densities when the spacecraft traverses through Enceladus plume. The ion density near Enceladus is found to increase abruptly from about 10^2 cm^{-3} before the closest approach to 10^5 cm^{-3} just 30 s after the closest approach, an amount two orders of magnitude higher than the electron density. Assuming that the inconsistency between the electron and ion number densities is due to the presence of dust particles that are collecting the missing electron charges, we present dusty plasma characteristics down to sub-micron particle sizes. By assuming a differential dust number density for a range in dust sizes and by making use of Langmuir probe data, the dust densities for certain lower limits in dust size distribution were estimated. In order to achieve the dust densities of micrometer and larger sized grains comparable to the ones reported in the literature, we show that the power law size distribution must hold down to at least 0.03 μm such that the total differential number density is dominated by the smallest sub-micron sized grains. The total dust number density in Enceladus' plume is of the order of 10^2 cm^{-3} reducing to 1 cm^{-3} in the E-ring. The dust density for micrometer and larger sized grains is estimated to be about 10^{-4} cm^{-3} in the plume while it is about 10^{-6}–10^{-7} cm^{-3} in the E-ring. Dust charge for micron sized grains is estimated to be about eight thousand electron charges reducing to below one hundred electron charges for 0.03 μm sized grains. The effective dusty plasma Debye length is estimated and compared with inter-grain distance as well as the electron Debye length. The maximum dust charging time of 1.4 h is found for 0.03 μm sized grains just 1 min before the closest approach. The charging time decreases substantially in the plume where it is only a fraction of a second for 1 μm sized grains, 1 s for 0.1 μm sized grains and about 10 s for 0.03 μm sized grains.

1. Introduction

The inner magnetosphere of Saturn, which contains the rings and icy satellites, consists mainly of dense (<200 cm^{-3}) and cold ($T_e \sim 0.5$–5 eV) plasma (Wahlund et al., 2005; Jacobsen et al., 2009; Gustafsson and Wahlund, 2010), partly also predicted by models and Voyager observations (Richardson et al., 1990). Saturn's E-ring is one of the most dynamic rings in our solar system (Horányi et al., 1992, 2008; Hamilton and Burns, 1994; Juhász and Horányi, 2002). It has been the focus of many studies ever since its discovery by Feibelman in 1967. It extends from $3R_s$ (R_s is Saturn's radius with $1R_s$=60,268 km) to about $9R_s$ or even beyond (Srama et al., 2006) with embedded icy satellites Mimas, Enceladus, Tethys, Dione and Rhea. The ring consists of sub-micron to micron sized grains and the dust particle density peaks a little bit outside the orbit of Enceladus as noted first by De Pater et al. (2004), and measured *in situ* by Kempf et al. (2008). The ring is the brightest and smallest (in vertical thickness) at the orbit of Enceladus (Showalter et al., 1991; Hamilton and Burns, 1994), which is the main source of E-ring dust grains (Baum et al., 1981; Showalter et al., 1991; Spahn et al., 2006). These dust grains are found to obey a power law of the form $n_d(r_d) \approx r_d^{-\mu}$ with $\mu \approx 4$–5 and with r_d being dust grain radius (Kempf et al., 2008). While the distribution and properties of dust grains in Saturn's E-ring have extensively been reported in the literature lately (Kempf et al., 2008; Yaroshenko et al., 2009; Kurth et al., 2006; Srama et al., 2006), the detection of dusty plasma in Saturn's E-ring inferred from the *in situ* measurements was reported only recently (Wahlund et al., 2009) based on early directions (Wahlund et al., 2005).

Enceladus is the sixth largest satellite of Saturn orbiting at a mean orbital distance of $3.95R_s$ from Saturn. The dynamical connection between the E-ring and Enceladus, which was long suspected and was mainly based on remote sensing techniques, was confirmed recently from the measurements made with the Cosmic Dust Analyzer (CDA) (Spahn et al., 2006) and from the images taken by the ISS instrument onboard the Cassini spacecraft

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(Porco et al., 2006). The CDA measurements point to a significant dust source in Enceladus' South Pole (Spahn et al., 2006; Schmidt et al., 2008; Kempf et al., 2010), which is pouring off streams of ice and water vapors into the E-ring detected both by the Cassini magnetometer (Dougherty et al., 2006) and by the ultraviolet imaging spectrometer (Hansen et al., 2006) onboard the Cassini spacecraft. The density and composition of the neutral gas cloud emanating from Enceladus' South Pole are measured by the Ion and Neutral Mass Spectrometer (INMS) onboard the Cassini spacecraft (Waite et al., 2006). Presence of liquid water against the background plume beneath Enceladus' South Pole using star occultation experiment was discovered recently (Hansen et al., 2008) and was later confirmed both by CDA (Postberg, 2009) and by INMS (Waite et al., 2009). The ejected material from Enceladus is found to be pelting the surfaces of at least 11 other nearby moons of Saturn with ice particles sprayed from its geysers to the surfaces of those moons (Verbiscer et al., 2007). The dust particles ejected from the Enceladus south polar plumes interact with the cold plasma there and collect some negative charges in the process, leading to a decrease in the electron density (Farrell et al., 2009). A similar decrease in electron density in comparison with the corresponding ion density using the RPWS Langmuir probe has been reported recently (Morooka et al., submitted for publication) and the difference is found to be maximum when the spacecraft traverses through the Enceladus plume.

This manuscript is organized as follows: Section 2 contains a short description of the instruments onboard the Cassini spacecraft while Section 3 describes the geometry of the Enceladus flyby under consideration. The RPWS Langmuir probe observations are included in Section 4 and the analysis of the plasma interaction with the plume particles is given in Section 5. Section 6 contains the dusty plasma parameter estimates while the results are discussed in Section 7 and are concluded with a summary in Section 8.

2. Description of instruments

The Cassini spacecraft is equipped with twelve sophisticated instruments, each of them built and designed to measure different physical/chemical properties in the atmosphere of the planet. The present results are from Langmuir probe, which is a part of RPWS instrument onboard the Cassini spacecraft. A full description of the RPWS instruments can be found in the study by Gurnett et al. (2004). The RPWS Langmuir probe experiment methods are described in the study by Wahlund et al. (2009).

The Langmuir probe, spherical in shape and about 5 cm in diameter, has continuously been in operation since July 2004. In order to avoid contamination from the spacecraft photoelectrons, it is placed at a distance of 1.5 m from the main body of the spacecraft. It is connected with a stub, which is charged to the same potential as the probe itself. Depending on the applied probe potential, the current to the probe for electrons or ions is collected. The Langmuir probe provides measurements of several basic physical parameters of importance for the processes occurring in the magnetosphere of Saturn. Among those are the plasma density (N_e), electron temperature (T_e), ion speed (V_i), UV intensity (Ly-α), spacecraft potential (U_{sc}), and characteristics of small-scale plasma structures ($\delta N/N$) up to 3.5 kHz.

3. Geometry of E3 flyby

The third targeted Enceladus flyby during the Cassini prime mission occurred on March 12, 2008. During this flyby, the spacecraft approached the moon from the north and receded towards the south, collecting data from the plume during the passage. The distance between the spacecraft and the moon was just 52 km (32.3 miles) at the point of closest approach at 2008-072T19:06:12 UT. This was the first Enceladus flyby after the discovery of active geysers on Enceladus' South Pole in July 2005 (Dougherty et al., 2006). The trajectory during E3 took the spacecraft deeper into the plume than the July 2005 flyby, allowing for measurements within the plume (Fig. 1).

4. RPWS observations during E3

The Langmuir probe data from the E3 flyby are presented in Fig. 2. Panel a in Fig. 2 shows the calibrated raw sweep data. Electron sampling occurs for positive bias voltage while ion and photoelectron sampling take place for the negative bias voltage. An abrupt increase in both the electron and ion current is observed when the spacecraft passes through Enceladus' plume region (19:06:30–19:08:30 UT). Langmuir Probe sweeps were sampled each 24 s during the E3 flyby.

Electron and ion densities are displayed in panel b (Fig. 2). These densities are exhibited in different colors and are determined using different methods. The blue dots represent electron density obtained from the electron and ion component of the Orbit Motion Limited (OML) theory (Mott-Smith and Langmuir, 1926) fit to the LP voltage sweeps ($\pm$32 V during E3). The black curve represents the electron density obtained from the upper hybrid emissions and the cyan curve is the electron density with a resolution of 20 Hz obtained when the probe current is measured at a fixed bias voltage. The ion density is obtained assuming singly charged water group ions (red dots) and hydrogen ions (green dots). The average electron and ion densities observed before and after the closest approach are found to be 80–100 cm^{-3}. There is, however, a decrease in electron density at the closest approach where it drops from around 80 cm^{-3} at just 1 min before the closest approach to about 10 cm^{-3} at the point of closest approach. It again increases as the spacecraft enters the plume region. It was not possible to get the RPWS data for electron density from the upper

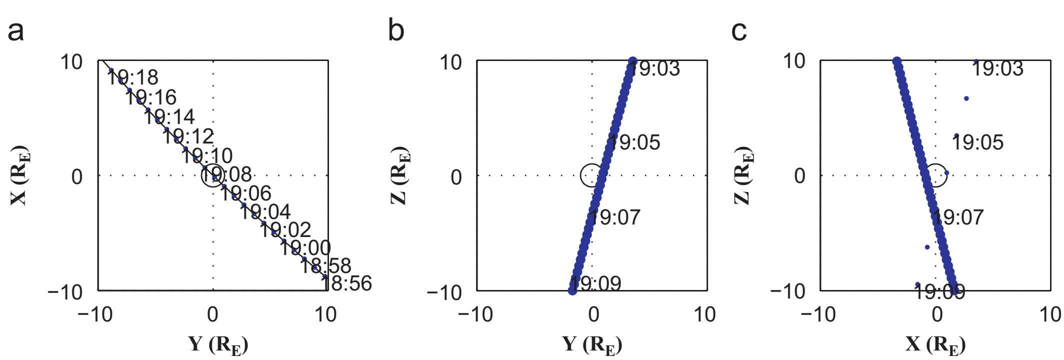

Fig. 1. The geometry for Cassini's trajectory during the third close Enceladus flyby on 12 March 2008.