



Modeling the total dust production of Enceladus from stochastic charge equilibrium and simulations

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ABSTRACT

Negatively and positively charged nano-sized ice grains were detected in the Enceladus plume by the Cassini Plasma Spectrometer (CAPS). However, no data for uncharged grains, and thus for the total amount of dust, are available. In this paper we estimate this population of uncharged grains based on a model of stochastic charging in thermodynamic equilibrium and on the assumption of quasi-neutrality in the plasma-dust system. This estimation is improved upon by combining simulations of the dust component of the plume and simulations for the plasma environment into one self-consistent model. Calibration of this model with CAPS data provides a total dust production rate of about 12 kg s^{-1} , including larger dust grains up to a few microns in size. We find that the fraction of charged grains dominates over that of the uncharged grains. Moreover, our model reproduces densities of both negatively and positively charged nanograins measured by Cassini CAPS. In Enceladus' plume ion densities up to $\sim 10^4 \text{ cm}^{-3}$ are required by the self-consistent model, resulting in an electron depletion of about 50% in the plasma, because electrons are attached to the negatively charged nanograins. These ion densities correspond to effective ionization rates of about 10^{-7} s^{-1} , which are about two orders of magnitude higher than expected.

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1. Introduction

Enceladus is Saturn's sixth largest moon with a radius of $r_E \approx 252 \text{ km}$. It is cryovolcanically active, expelling water vapor and icy dust particles from an anomalously warm region around the south pole (Spencer et al., 2006). The plume formed by the ejected material above the south polar region was detected by various instruments aboard the Cassini spacecraft (Dougherty et al., 2006; Spahn et al., 2006; Waite et al., 2006; Porco et al., 2006; Hansen et al., 2006). The output of heat (Spencer et al., 2006) and the cryovolcanic activity are concentrated along Enceladus' "tiger stripe" fissures. Eight prominent jet sources were first identified in images taken by Cassini's Imaging Science Subsystem (ISS) (Spitale and Porco, 2007), while a later analysis of a larger set of high resolution images identified more than 100

jets along the tiger stripes (Porco et al., 2014). Among these, various jets were found to be intermittent, turning on and off between images taken at different times. A recent analysis of Cassini images from the plume suggests that ejection occurs more uniformly along larger segments of the tiger stripes (Spitale et al., 2015).

Cassini's measurements indicate a subsurface ocean at Enceladus (Nimmo et al., 2007; Postberg et al., 2009a, 2011; Iess et al., 2014; Hsu et al., 2015). Water vapor emanates from the tiger stripes, forming Enceladus' gas plume, partly at supersonic speeds (Hansen et al., 2006, 2008, 2011; Waite et al., 2006; Dong et al., 2011), replenishing Saturn's neutral gas torus (Johnson et al., 2006). Cassini's Cosmic Dust Analyzer (CDA) measured number densities of dust grains as well as radial and vertical profiles of the E-ring in the vicinity of Enceladus, formed by particles that have escaped Enceladus' gravity. CDA also performed a compositional analysis of E-ring grains, showing that the population is dominated by grains with a low but significant salt content of a mixing ratio $\text{NaCl}/\text{H}_2\text{O} < 10^{-7}$ (Postberg et al., 2009b, 2009a), while a

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smaller fraction ($\sim 5\%$) shows a salinity on the order of one percent. The salt poor grains can condense from the vapor in the subsurface vents of Enceladus (Postberg et al., 2009a). They are transported to surface in the gas, if the gas is sufficiently dense (Schmidt et al., 2008), but are expected to move, on average, more slowly than the gas, possibly due to decelerating collisions with the rift walls. CDA data obtained during a plume traversal by the spacecraft showed that the fraction of salt rich grains, with salinities on the percent level, increases close to the south polar sources (Postberg et al., 2011). Importantly, these particles were found to dominate the rate of dust production by mass. Deep in the plume the CDA instrument is saturated by the high number of dust particles in the sub-micrometer range (Kempf et al., 2008), so that the production rate of these grains is extrapolated from measurements at greater distances and modeling (Schmidt et al., 2008; Kempf et al., 2010). Generally, during Enceladus flybys, the smallest particle size that CDA can detect is on the order of $0.3 \mu\text{m}$. As a consequence, the rate of dust production in the smaller grains, and thus the total rate, is unknown. But knowledge of this rate is important to establish a more detailed understanding of Enceladus' outgassing, the dust to gas ratio in the plume, the condensation of dust grains from the gaseous phase, and ultimately the rate of material delivered to the E-ring.

A lower limit of Enceladus' gas production rate of $\sim 100 \text{ kg s}^{-1}$ was inferred from data obtained by Cassini's Ion and Neutral Mass Spectrometer (INMS) (Smith et al., 2010; Tenishev et al., 2010; Dong et al., 2011) and the Ultraviolet Imaging Spectrograph (UVIS) (Hansen et al., 2006; Tian et al., 2007). Dust production rates are suggested from 8 kg s^{-1} for particles larger than about 100 nm by Schmidt et al. (2008) based on CDA data and ISS images to 50 kg s^{-1} by Ingersoll and Ewald (2011) from the analysis of ISS images. Dong et al. (2015) inferred a grain mass production in the range $15\text{--}65 \text{ kg s}^{-1}$ from data of CAPS, INMS and Cassini's Radio and Plasma Wave Science instrument (RPWS), dominated by grains in the nanometer size range. Furthermore, tidal-induced variations in the production rates of dust were found using images of Enceladus' plume taken by Cassini's Visible and Infrared Mapping Spectrometer (VIMS) (Hedman et al., 2013). These variations were detected consistently in ISS images (Nimmo et al., 2014).

Once the water vapor is ejected from Enceladus, it can be ionized by impact ionization through electrons and photoionization as well as charge exchange processes with Saturn's magnetospheric plasma. This process induces an ionospheric perturbation of Saturn's magnetic field that was detected by measurements of Cassini's magnetometer (MAG); this yielded the first indication of the presence of Enceladus' plume (Dougherty et al., 2006). This interaction can be classified as an Alfvén wing (Neubauer, 1998; Saur et al., 1999). The plasma environment of the Alfvén wing is also affected by the dust grains, particularly through the attachment of electrons to these particles. When the fraction of free plasma electrons drops below a certain threshold, currents associated with the Alfvén wing are carried by plasma ions instead of electrons and the Alfvén wing is significantly modified (Simon et al., 2011; Kriegel et al., 2011, 2014). In particular, analytical and numerical estimates of the perturbation in the magnetic field component along the Saturn-Enceladus-line are in agreement with measurements of the magnetic field by Cassini MAG only if the effect of electron absorption by dust is taken into account. A corresponding depletion of free electrons in the plume plasma was also seen in data obtained by RPWS (Yaroshenko et al., 2009; Farrell et al., 2009; Wahlund et al., 2009; Morooka et al., 2011).

CDA (Kempf et al., 2010) and VIMS (Hedman et al., 2009) are sensitive to dust sizes in the micron range when sampling Enceladus' plume and Saturn's E-ring. Another population, charged nanograins, were detected by CAPS (Jones et al., 2009; Hill et al., 2012). In particular, the peak in the nanograin size distribution was

estimated to be about 2 nm in CAPS measurements (Hill et al., 2012; Dong et al., 2015). These data indicate that the majority of dust grains are smaller than 10 nm . These nanograins were found to dominate the modification of Enceladus' Alfvén wing (Kriegel et al., 2014; Meier et al., 2014). In turn, the electromagnetic fields of the Alfvén wing feed back on the motion of the charged nanograins, leading to the formation of multiple dust tails at Enceladus. However, since CAPS is only able to detect charged grains, the size distribution inferred from these data does not contain any information about the uncharged grains. Thus, to date the inferred dust production rate only represents a lower limit.

In this work we give an estimation of the fraction of uncharged grains in Enceladus' plume as well as of the total grain production rate. First, in Section 2 a stochastic equilibrium model for the nanodust charge distribution is derived from basic equations of grain charging and the assumption of quasi-neutrality. In this approximation the amount of uncharged dust particles is connected to the abundances of negatively and positively charged grains, providing us with a first estimate of this population's extent. After Section 3, where the simulation method is described, we use a self-consistent combination of plasma and dust simulations to improve these estimates. Results from the simulations are compared with the stochastic equilibrium model and CAPS data in Section 4 and Enceladus' total grain production rate and a global profile of uncharged nanograins in the plume are determined. Finally, we present the conclusions in Section 5.

2. Transition probability between dust charge states

The CAPS instrument is designed to measure plasma electrons and ions. Surprisingly, it also detected negatively and positively charged nanograins in Enceladus' plume (Jones et al., 2009; Hill et al., 2012). However, it is not clear from these data, how many nanograins populate the plume in total, because uncharged grains cannot be detected. In this section we present an analytical model to determine the number of neutral grains from the number of those that are negatively and positively charged. The starting point of this analysis is a small test volume V in the center of the plume, as illustrated by the cube in Fig. 1, assumed to be small enough to contain plasma and dust with homogeneous densities. Within this volume, ionization and charge exchange with neutral gas, as well as inflow of plasma, are sources for electrons and ions (Kriegel et al., 2014). The outflow of plasma from V and dust grain charging are the sinks. In Enceladus' plume the ion loss by grain charging is very small compared with the outflow (Meier et al., 2014). Hence, we can assume within this model a well defined plasma background.

2.1. Equilibrium charge for continuous states

A dust grain in a plasma environment is charged by electron (I_e) and ion (I_i) collection currents

$$I_e = I_{0e} \begin{cases} \exp\left(\frac{e\Phi}{k_B T_e}\right), & \Phi \leq 0 \\ 1 + \frac{e\Phi}{k_B T_e}, & \Phi > 0 \end{cases} \quad (1)$$

$$I_i = I_{0i} \begin{cases} 1 - \frac{e\Phi}{k_B T_i}, & \Phi \leq 0 \\ \exp\left(-\frac{e\Phi}{k_B T_i}\right), & \Phi > 0 \end{cases} \quad (2)$$

with $I_{0k} = 4\pi R^2 n_k \sqrt{k_B T_k / 2\pi m_k}$, $k \in \{e, i\}$ (Whipple, 1981). Boltzmann's constant and elementary charge are denoted by k_B and e . The number density, the temperature and the mass of the respective

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