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A model of the spatial and size distribution of Enceladus' dust plume

Patrick Meier[a,*], Hendrik Kriegel[a], Uwe Motschmann[a,b], Jürgen Schmidt[c], Frank Spahn[d], Thomas W. Hill[e], Yaxue Dong[e], Geraint H. Jones[f,g]

[a] Institute for Theoretical Physics, TU Braunschweig, Germany
[b] Institute for Planetary Research, German Aerospace Center (DLR), Berlin, Germany
[c] Department of Physics, University of Oulu, Finland
[d] Institute of Physics, University of Potsdam, Germany
[e] Physics and Astronomy Department, Rice University, Houston, TX, United States
[f] Mullard Space Science Laboratory, Department of Space and Climate Physics, University College London, Dorking, UK
[g] Centre for Planetary Sciences at UCL/Birkbeck, London, UK

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ABSTRACT

The structure of Enceladus' south polar plume of charged dust is studied by simulations of the dust grain dynamics. The model considers the Lorentz force and charging of the grains by the plasma environment within the plume. Simulated dust plumes are investigated by applying 10 selected sets of dust parameters that include variations of the grain production rate, the slope of the grain size distribution and the start conditions (velocity, direction) of the grains. The modeled dust plume profiles are in good agreement with nanograin data of Cassini Plasma Spectrometer (CAPS). Major results are (1) due to the local plasma environment the nanograins are accelerated by the Lorentz force and form a structured tail; (2) due to the finite charging time the peak dust charge density is located about 0.3–0.6r_E below Enceladus' south pole; (3) nanograins smaller than 10 nm are more than 99% of the produced dust; (4) CAPS data are best matched if the nanograins are launched with high, collimated start velocities; (5) the grain charging time is crucially affected by inhomogeneities in the local plasma environment.

1. Introduction

The icy moon Enceladus (radius $r_E \approx 252$ km) orbits Saturn at a distance of $3.95 r_S$ (Saturn's radius $r_S \approx 60,268$ km) within the inner Kronian magnetosphere. Enceladus is the dominant source of Saturn's E ring ranging from $\sim 3 r_S$ to $\sim 20 r_S$. Its cryovolcanic activity is one of the most spectacular discoveries of the Cassini mission (Spahn et al., 2006). Water vapor and icy dust particles emanate from Enceladus' south polar region (Spahn et al., 2006; Waite et al., 2006; Porco et al., 2006; Hansen et al., 2006). Eight prominent jet sources (Spitale and Porco, 2007) on the south polar "tiger stripe" fissures were identified by Cassini's Imaging Science Subsystem (ISS) in high phase angle images. Their locations coincide with particularly warm areas detected by Cassini's Composite Infrared Spectrometer (CIRS) (Spencer et al., 2006) and they represent the main sources of the material. More, finer jet structures along the tiger stripes were recently announced. The vapor leaves Enceladus' surface with supersonic velocity (Schmidt et al., 2008; Hansen et al., 2008, 2011) and drags the dust particles from the ruptures. The dust grains show diversely chemical composition (Postberg et al., 2011): on one hand, salt-poor particles are seen by Cassini's Cosmic Dust Analyzer (CDA), with mixing ratio $NaCl/H_2O < 10^{-7}$, dominating far from the south pole and in the E ring (Postberg et al., 2009). On the other hand, salt-rich particles with salinities on the percent level dominate closer to the sources. The dust ejection velocity drops with grain size. It is generally lower than the gas velocity which was attributed to decelerating collisions with the rift walls (Schmidt et al., 2008).

Dust and water vapor form a plume towering Enceladus' south pole. The fraction of dust escaping the satellite's gravity eventually feeds Saturn's E ring (Kempf et al., 2010), whereas the vapor replenishes Saturn's neutral gas torus (Johnson et al., 2006). Data of Cassini's Ion and Neutral Mass Spectrometer (INMS) and Ultraviolet Imaging Spectrograph (UVIS) indicate that several hundreds of kilogram of gas are ejected from Enceladus' south polar region (Hansen et al., 2006; Tian et al., 2007; Smith et al., 2010; Tenishev et al., 2010; Dong et al., 2011). Schmidt et al. (2008) infer a production rate of 5 kg s^{-1} for dust larger than about 100 nm. On the other hand, Ingersoll and Ewald (2011) report a much more massive plume from analysis of images, resulting in a production rate of 50 kg s^{-1}. The controversy might be partly solved if a variability is taken into account that was recently detected in data from Cassini's Visible and Infrared Mapping Spectrometer (VIMS) (Hedman et al., 2013). The dust is charged

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[*] Corresponding author.
E-mail address: patrick.meier@tu-bs.de (P. Meier).

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by the surrounding plasma and solar UV (Whipple, 1981; Horanyi, 1996), while the vapor can be ionized by charge exchange with Saturn's magnetospheric plasma or by impact ionization through electrons and photoionization.

The ionized vapor interacts like an ionosphere with Saturn's magnetospheric plasma. This interaction generates Pedersen and Hall currents, which perturb Saturn's magnetic field (Pontius and Hill, 2006). These perturbations yield an Alfvén wing system at Enceladus (Khurana et al., 2007) and are confirmed by Cassini's Magnetometer (MAG) (Dougherty et al., 2006). Without dust the currents are predominantly carried by electrons as the most mobile plasma component. A lack of free electrons compared to the number of ions is detected by Cassini's Radio and Plasma Wave Science instrument (RPWS) (Yaroshenko et al., 2009; Farrell et al., 2009; Wahlund et al., 2009) indicating the importance of dust charging for the total charge balance. Namely, if a substantial fraction of electrons is attached to dust grains in Enceladus' plume and the density of electrons drops below a certain threshold, then the currents are carried by the ions which now play the role of the most mobile plasma component (Kriegel et al., 2011; Simon et al., 2011). While the Pedersen current keeps its direction (following the electric field), the Hall current is reversed, which is called the Anti-Hall effect. Consequently, the magnetic field component along the Saturn–Enceladus–line is reversed within the Alfvén wings when compared to a situation without charged dust. The reversed field perturbation is indeed seen in MAG data obtained in flybys (Kriegel et al., 2011; Simon et al., 2011).

The observed size range of the grains covers several orders of magnitude. Data of CDA (Kempf et al., 2010) as well as VIMS (Hedman et al., 2009) indicate that dust particles in the micron range contribute to the dust plume and the E ring. Only a minor fraction of these grains escapes Enceladus. On the other hand, CAPS detected at close Enceladus flybys a large number of charged particles with energies close to the upper detection limit of the instrument (Jones et al., 2009; Hill et al., 2012). These were interpreted as charged grains of nanometer size, most likely carrying only one elementary charge. Unfortunately, there are no direct dust measurements of the intermediate size range from a few nanometers to the micrometer scale. Shafiq et al. (2011) suggested a model for grains larger 30 nm deduced from RPWS' Langmuir Probe (LP) data that could explain the measured electron–ion imbalance. Farrell et al. (2014) inferred from this model that dust pick-up is a new contribution to the total pick-up currents at Enceladus. Although there is no doubt that there are high ion densities and a significant electron–ion imbalance, the interpretation of LP data may be complicated by the fact that dust currents alter the spacecraft's plasma environment (Hsu et al., 2012, 2013). In addition, the potential structure around the spacecraft is affected by the interaction between the plasma and the spacecraft (Olson et al., 2010; Yaroshenko et al., 2011). Morooka et al. (2011) derived maximum ion densities of $n_i \approx 30,000–100,000\ \text{cm}^{-3}$ from LP data. However, an explanation for these extremely high densities is still an unresolved issue (Kriegel et al., 2014). One of the goals of this study is to constrain the properties of dust in the intermediate range.

In this work we investigate the dust dynamics and develop a model of the spatial and size distribution that is consistent with Cassini measurements. Our dust simulations include the effects of the local plasma environment using results from hybrid plasma simulations in terms of density, velocity, and temperature of watergroup ions as well as the effective electromagnetic field. Hybrid simulations are a special type of plasma simulations that treat ions as particles and electrons as fluid. They have an advantage over common fluid simulations, e.g. by including particle effects while approaching the same computing time. These effects are necessary, if the size of the investigated object is in the same order of magnitude as the ion gyration radius, as in the case of Enceladus. The dust simulations and the plasma simulations cover very different time scales. An iterative procedure is employed until a consistent configuration is achieved. A detailed study of the dust impact on the plasma environment is performed in Kriegel et al. (2014). In this work the dust dynamics in the plume is studied including the effects of the local plasma environment. The impact of the local plasma environment on the grain charge time is investigated and the location of the highest charge density is determined. Especially, we develop a dust size distribution model from CAPS data. Furthermore, the influence of the dust initial conditions, the start velocities and directions, represented by jet and tiger stripe sources, is analyzed.

This paper is organized as follows: in Section 2 the setup of our dust and plasma model and the corresponding simulation methods are described. In particular, we discuss the model constraints for the dust size distribution and the charging processes for the grains. In Section 3 the impact of the local plasma environment on the dust plume structure and the charging processes is studied. The influence of the initial dust conditions represented by jet and tiger stripe sources is analyzed in Section 4. Further, the shape and limits of the dust size distribution model are studied. Finally, the conclusions follow in Section 5.

2. Setup of the dust and plasma simulations

In this section we describe our Monte-Carlo dust model and the hybrid plasma model including their mutual feedback. The Monte-Carlo method operates in three dimensions. It treats the dust grains as macro-particles (a simulated particle represents multiple grains with same physical properties), which are generated on Enceladus' surface at each time step. A newborn macro-particle is given initial position, initial velocity and radius but no charge. The parameter range is discussed in Section 2.1. The grain dynamics are calculated by the Leapfrog method for the Lorentz force and the Euler method for gravitation and inertial forces. Further details are discussed in Section 2.2. The charging process is studied in Section 2.3. Finally, Section 2.4 sketches the modeling of the local plasma environment by plasma hybrid simulations. These define the EM-fields used as an input for the Lorentz force, the ion density n_i and the ion temperature T_i used as an input for the charging routines. Furthermore, the electron density n_e is calculated via the charge neutrality condition from n_i and the dust charge density ρ_c. The electron temperature T_e is chosen to be constant. Two cases for this constant value are discussed. On one hand, we choose $k_B T_{e,high} = 1.35$ eV in agreement with Kriegel et al. (2011); on the other hand we use $k_B\, T_{e,low} = 0.01$ eV corresponding to Enceladus' surface temperature of 180 K (Spencer et al., 2006) as a lower limit.

Because of the different characteristic time scales of the plasma ($\tau_{Plasma} \approx 500$ s, time for a stationary plasma flow through the simulation box in corotational direction) and the dust ($\tau_{Dust} \approx 10,000$ s, time for stationarity of the grains crossing the box from north to south) both simulation methods are not merged in one routine but applied as an iteration loop. Already two iterations yield a consistent state. Further iteration do not yield significant changes in the results for the used parameter settings. The underlying mesh of our simulation box is a hierarchical grid with the resolution from $\Delta L_0 = 0.16 r_E$ for the lowest level (0) cells to $\Delta L_2 = 0.04 r_E$ for the highest level (2) cells. The simulation box has a size of $L_X \times L_Y \times L_Z = 20 \times 20 \times 30 r_E$. The time step is $\Delta t = 0.1$ s in our simulations.

All simulations are performed in the comoving Enceladus Interaction System (ENIS) as sketched in Fig. 1. The *X*-axis points in the corotational direction of the magnetospheric plasma velocity, $\underline{u}_0$. The *Y*-axis aims towards Saturn and antiparallel to the convective electric field $\underline{E}_0 = -\underline{u}_0 \times \underline{B}_0$. The *Z*-axis is perpendicular to Enceladus' orbital plane and antiparallel to the background magnetic field $\underline{B}_0$.