Dynamics of dust ejected from Enceladus: Application to the Cassini dust detector

Frank Spahn and Kai-Uwe Thiessenhusen
Department of Nonlinear Dynamics, University of Potsdam, Potsdam, Germany

Joshua E. Colwell
Laboratory of Atmospheric and Space Physics, University of Colorado, Boulder

Ralf Srama and Eberhard Grün
Max-Planck Institute of Nuclear Research, Heidelberg, Germany

Abstract

The satellite Enceladus is obviously the main source of Saturn's E ring. Up to now, different mechanisms of how particles are delivered from this satellite have been suggested. In this paper, we try to answer the question of whether these different launch processes can be distinguished by the cosmic dust analyzer (CDA) aboard the Cassini spacecraft. To this aim, the dynamics of dust particles just launched from the surface of Enceladus is studied numerically. We have integrated the equations of motion for a wide range of initial conditions including ejecta from interplanetary and E ring impactors onto Enceladus. According to our simulations, Cassini will encounter a significant dust stream about the time of closest approach to Enceladus. The duration and intensity of this expected enhanced impact rate onto the CDA depends on the way the particles are ejected from the satellite. The counting rate yields information about the distribution of ejecta sources on the surface of Enceladus. For instance, an anisotropy of the ejecta between the leading and the trailing hemispheres of Enceladus should be detectable, and impactors of different origin should be distinguishable. Furthermore, the vertical component of the ejecta velocities, which results from an earlier study of the impact ejecta physics [*Colwell,* 1993], explains the vertical extent of the E ring.

1. Introduction

The major source of material forming the E ring of Saturn is the satellite Enceladus. The dynamics of this dust is governed by the gravity of Saturn, electro-magnetic forces, and radiation pressure. The combined action of these forces describes roughly the global characteristics of the E ring of Saturn [*Showalter et al.,* 1991; *Horanyi et al.,* 1992; *Hamilton,* 1993]. A quasi equilibrium between micron-sized particles hitting the surfaces of satellites inside the E ring region and the ejecta of dust of about the same size offers a possibility of explaining how this faint ring is sustained [*Hamilton and Burns,* 1994]. However, in these models, the nature of the ejecta process itself as well as the role of the gravity of the parent satellite during the launch was not considered.

We study processes which cause the particles to leave the vicinity of a satellite. This includes the impact ejecta mechanism as well as the subsequent dynamics in the region of the gravitational influence of the satellite (Hill sphere). These processes correspond to different initial conditions for our calculations of the particle trajectories in the close vicinity of the satellite.

One possible mechanism of delivering material into orbit is ejecta caused by high velocity impacts of interplanetary micrometeoroids or E ring particles onto the surface of Enceladus. We will derive criteria from our simulations in order to distinguish between ejecta caused by these different impactor families. These can be used for the interpretation of the measurements of the cosmic dust analyzer (CDA) aboard the Cassini spacecraft during close encounters with Enceladus. Additionally, the results of the simulations can be applied to the orientation of the CDA during such encounters in order to achieve optimal observational conditions.

The paper is organized as follows: In section 2, the equations of motion for dust in Saturn's environment are given. Section 3 deals with the velocity distribution as well as with the anisotropy of the ejecta, which serve as initial conditions of the integration of the model equations. In Section 4, the results of the numerical simulations will be presented, and conclusions are drawn in section 5.

2. Equations of Motion and Model Assumptions

The equations of motion of dust in a Cartesian coordinate system $\mathbf{s} = (x, y, z)$ corotating with and fixed at Enceladus are as follows:

$$\begin{aligned} \ddot{\mathbf{s}} + 2\,\mathbf{\Omega_0} \times \dot{\mathbf{s}} + \mathbf{\Omega_0} \times [\mathbf{\Omega_0} \times (\mathbf{R_e} + \mathbf{s})] \;\; &= \\ -\nabla\left(\Phi_\hbar \,+\, \Phi_e\right) + \frac{Q}{m}\left[\frac{d\,(\mathbf{R_e} + \mathbf{s})}{d\,t} \times \mathbf{B} + \mathbf{E}\right] & \\ + \frac{q_\odot\, Q_{PR}}{m\,c}\left(\frac{R_\oplus}{R_\hbar}\right)^2 \pi r_p^2\, \mathbf{e}_\odot \qquad\qquad . & \qquad (1) \end{aligned}$$

The x- axis points radially outward, y points in the direction of the orbital motion of the satellite, and z is parallel to the spin vector $\omega_\hbar = \omega_\hbar \mathbf{k}$. The orbital angular velocity of Enceladus is given by $\Omega_0 = \sqrt{\frac{GM_\hbar}{R_e^3}}\left[1 \,-\, \frac{3}{2}\,J_2\,P_2(z=0)\,\left(\frac{r_\hbar}{R_e}\right)^2\right]^{\frac{1}{2}} \approx 5.31 \times 10^{-5}$ s^{-1}, where $J_2 = 1.67 \times 10^{-2}$ is the first higher harmonic of the gravity of Saturn due to its oblateness. The mass and radius of Saturn are given by $M_\hbar = 5.7 \times 10^{26}$ kg and $r_\hbar = 60330$ km, respectively.

The terms on the right hand side are in order of their appearance: the gravitational accelerations of Saturn and Enceladus, the Lorentz acceleration, and the solar radiation pressure. The mass of Enceladus is $M_e = 7.3 \times 10^{19}$ kg. The position, mass and the radius of the particle are given by $\mathbf{r} = \mathbf{R_e} + \mathbf{s}$, m, and r_p (assuming spherical particles), respectively. The distances of Earth and Saturn from the Sun are denoted by $R_\oplus$ and $R_\hbar$ with $R_\hbar / R_\oplus = 9.58$, the Solar luminosity measured at 1 AU is $q_\odot = 1.37$ kW m^{-2}, and the vector $\mathbf{e}_\odot$ points to the anti-Sun direction. Q_{PR} is the radiation pressure coefficient which is in the order of 1 [*Burns et al.,* 1979; *Horanyi et al.,* 1992]. The vector $\mathbf{B}$ labels the magnetic field of Saturn and $\mathbf{E} = (\mathbf{r} \times \omega_\hbar) \times \mathbf{B}$ is the electric field caused by the rotation $\omega_\hbar = 1.64 \times 10^{-4}$ s^{-1} of $\mathbf{B}$ fixed with the rotation of Saturn. The grain charge is denoted by Q, where in the E ring region dust of $1\,\mu m$ in size has been assumed to be charged at $U \approx -5$ V (corresponding to 3500 electron charges on the surface of a micrometer-sized grain [see *Horanyi et al.*, 1992]).

The semimajor axis of Enceladus' orbit is $R_e = 2.38 \times 10^8$ m, and c is the speed of light. The magnetic field of Saturn is approximated as a dipole:

$$\mathbf{B} = \frac{\mathbf{B_0}}{r^3} \;-\; 3\,\frac{\mathbf{r}\;(\mathbf{B_0} \cdot \mathbf{r})}{r^5} \qquad (2)$$

with $\mathbf{B_0} = B_0\, r_\hbar^3\, \mathbf{k}$, where $B_0 = -2 \times 10^{-5}$ Vs m^{-2}.

The equations of motion (1) have been solved numerically for a wide range of initial conditions. The latter have been derived from the physics of ejecta released from Enceladus' surface by interplanetary [*Colwell,* 1993] as well as E ring micrometeoroid impactors. It should be noted that for the short-term simulations presented in this paper the influences of the nongravitational forces are rather weak.

3. Initial Ejecta Conditions

A potential source of dust particles in planetary rings is ejecta from hypervelocity impacts onto the surfaces of satellites and larger ring particles, as well as from collisions between these larger particles [*Dobrovolskis and Burns,* 1980; *Banaszkiewicz and Ip,* 1991; Colwell and Esposito, 1990; *Banaszkiewicz and Krivov,* 1997]. In the case of Saturn's E ring, the peak in the optical depth near the orbit of Enceladus points to the former as the main source of this faint ring [*Showalter et al.,* 1991; *Horanyi et al.,* 1992; *Hamilton and Burns,* 1994].

There are different possible families of impactors in the region of the E ring including E ring particles themselves. Other sources of impactors have to be looked for outside of Saturn's system. Colwell [1993] studied the geometry and the physics of interplanetary impactors and derived relations for the distribution of impactors and ejecta on a satellite. Using his results, the interplanetary impactor intensity on the surface of Enceladus has been computed. We studied Oort cloud impactors as well as dust which comes from Centaurs or other short-period comets with semimajor axes in the range $0.85\, R_\hbar \;<\; a \;<\; 1.15\, R_\hbar$, inclinations $i \;<\; 30°$, and eccentricities $e \;<\; 0.3$ [*Colwell,* 1993]. For both interplanetary dust populations, the impactor distributions on Enceladus' surface are nearly identical. The vaste majority of interplanetary dust impacts take place on Enceladus' leading hemisphere [*Colwell,* 1993].

In order to obtain the distribution of E ring impactors, we have performed numerical integrations of the equations of motion of dust (1). To this aim, we assume (for the moment) that the long-term dynamics of an E ring particle is independent of the initial conditions at launch on Enceladus [*Horanyi et al.,* 1992]. Therefore the trajectories of $10,000$ particles (which really leave the Hill sphere later), isotropically ejected from Enceladus, have been followed until they reimpact the satellite. This has been continued until no particle is left. In this way, we obtain information about the distribution of impact velocities of E ring particles on Enceladus.

For this initial "setup" run, and also for all further numerical experiments presented in the section 4 and 5, the following cumulative velocity distribution has been chosen:

$$p(v_{ej}) \;\propto\; \left(\frac{v_{ej}}{v_*}\right)^{-\gamma} \quad , \tag{3}$$

where v_* and γ are parameters. The distribution (3) has been derived from groundbased impact experiments. A detailed theoretical model [*Housen et al.,* 1983] of impact ejecta gives $\gamma \approx 1 - 2$ (depending on surface properties), which is consistent with impact experiments [*Gault et al.,* 1963; *Stöffler et al.,* 1975] (see also *Colwell and Esposito* [1993] for detailed review of the value γ). In this paper we use $\gamma \;=\; 2.0$.

The initial conditions isotropic ejecta and velocities according to (3), chosen for the "setup" run have led to a particle configuration resembling roughly the properties of the E ring of Saturn. This is shown in Figure 1 where the $r - z$ coordinates of every particle are plotted in equidistant time steps. The dashed-dotted line corresponds to the observed radial profile of mean halfthickness of the E ring [*Showalter et al.,* 1991]; the solid line labels the corresponding quantity derived from the simulations. To this goal, the modelring has been divided radially in narrow annuli of Δr, where in each annulus the mean thickness $\langle |z| \rangle$ has been computed by fitting the vertical distribution of numerical data as a Gaussian, the same treatment which has been applied to the observational data [*Showalter et al.,* 1991].

This qualitative reproduction of the basic features of the E ring should be sufficient to set up the distribution of impacts of E ring particles onto the surface of Enceladus.

The distributions related to the interplanetary as well as to the E ring impactors provide the locations and velocity vectors at the impact. In order to derive the corresponding ejecta intensities, a pattern with ejecta confined primarily to a cone with a half-opening angle of 45° has been applied, a property deduced from numerous experimental data [*Cuzzi and Durisen,* 1990; *Colwell,* 1993; *Yamamoto and Nakamura,* 1997].

The ejecta distributions corresponding to interplanetary and E ring impactors are presented in Figure 2 as a function of the surface coordinates Φ and Θ. The longitude Φ is measured between the projection of the ejecta velocity vector onto the orbital plane of Enceladus and the x- axis. In this sense, $\Phi = 0$ and $\Phi = \pi/2$ point in the direction away from Saturn (x axis) and in the direction of Enceladus' orbital motion (y axis), respectively. The latitude Θ is the angle between the orbital plane and the ejecta velocity vector.

The major difference between both displayed ejecta intensities $I(\Phi, \Theta)$ is the variability with the longitude Φ. In the case of interplanetary impactors, many more particles are launched in the direction of the orbital motion of Enceladus with a definite maximum at $(\frac{\pi}{2}, 0)$. This is simply caused by a "windshield" effect, where the satellite sweeps up material with its leading face $(0 \leq \Phi \leq \pi)$ because of its orbital motion.

In contrast to this, E ring impactors preferentially free dust in the Saturn and anti-Saturn directions as indicated by the maxima at $(0, 0)$ and $(\pi, 0)$ on the left in Figure 2. This is plausible because E ring particles move in Keplerian orbits like the target Enceladus does. Thus the largest mean relative velocities between projectiles and Enceladus are found in the region of the surface $(0, 0)$ and $(\pi, 0)$. In addition, there is a weak anisotropy between the leading $(0 \leq \Phi \leq \pi)$ and the trailing face $(\pi \leq \Phi \leq 2\pi)$ of the moon, indicated by the isolevel lines, which comes from the relatively high eccentricities of the E ring particles. The higher the mean eccentricity of the impactor ensemble is the more important the "windshield" effect becomes and the stronger the differences between the leading and the trailing face of the moon get. The distributions represented in Figure 2 and moduli of the ejecta velocities taken from equation 3 will be chosen as initial conditions for the following simulations in order to describe impactor/ejecta as a potential source of the E ring particles.

4. Results

The main goal of this paper is to distinguish between the different possible particle sources of the E ring based on characteristics in the escape pattern of the material leaving the satellite. Furthermore, it should be clarified whether the CDA experiment aboard the Cassini spacecraft can observe significant characteristics which might point to a certain ejecta process.

Thus, numerical experiments have been carried out according to the following initial conditions: (1) isotropic ejecta distribution in Enceladus' frame, (2) ejecta distribution from E ring impacts onto Enceladus, and (3) ejecta distribution from interplanetary impacts onto Enceladus. The outcome of all runs will be compared with each other and also with an estimate of the background of evolved E ring particles. Therefore the resulting distributions of ejected particles are plotted *i)* when projected onto the x-y plane; *ii)* with grey-level plots of the ejecta intensities taken at the Hill sphere (according to Figure 2) versus the angles Θ and Φ; *iii)* at certain distances from Enceladus at the orbital plane; and *iv)* with impact rates derived along a designated trajectory of the Cassini spacecraft at the first encounter with Enceladus.

Figure 3 shows the particles' traces (dots) projected onto the orbital plane of Enceladus for ejecta caused by E ring impactors (item 2). The launch angles measure the deviation from the normal direction with respect to the surface (β_1) as well as the compass direction β_2, which is the angle between the velocity vector projected onto the surface and north, respectively. Both parameters have been chosen at random in the intervals $0 \leq \beta_1 \leq \pi/4$ and $0 \leq \beta_2 \leq 2\pi$, and the velocities are according to the distribution (3). Figure 3 illustrates the geometry of the ejecta with respect to the trajectory of the Cassini spacecraft. This indicates where during an Enceladus flyby dust impacts the CDA.

Figure 4 shows the grey-level-coded density of intersections of trajectories with a sphere of the radius $R = r_e h$ around Enceladus. The values $\mu = M_e/(M_♄ + M_e)$ and $h = \sqrt[3]{\mu/3}$ denote the mass-ratio and the Hill sphere radius of the satellite, respectively. The particles have just been launched from the satellite and are on their way into the E ring.

In the case of the isotropically ejected particles (Figure 4 left), only a weak dependence on Θ and Φ is found. A maximum of the density appears at the Lagrangian point L_2. This is to be expected because there is a local minimum of the "effective potential" of the restricted three body (RTB) problem (see below). A metaphor for this situation might be the spout of a pitcher where the fluid preferentially flows out.

In the framework of the RTB problem, which is sufficient for the description of the dynamics of particles in the Hill sphere, one expects that this behavior should hold for all the cases. However, in order to obtain an escape pattern, where the material leaves the Hill sphere preferentially at L_2 (or also at L_1), the particles must be launched in a very narrow velocity window of about $\Delta v \approx 10$ m s^{-1} width around the escape velocity ($\approx$ 200 m s^{-1}). This can be shown approximately by calculating the difference of the Jacobian C of Lagrangian points L_1 and L_2 (lengths are measured in R_e and velocities are measured in $v_e = \Omega_0 \, R_e$):

$$
\begin{aligned}
C &= v^2 + 2\Phi_{eff} \\
\Phi_{eff} &= -\frac{1}{2}\,(1-\mu+x)^2 - \frac{1}{2}y^2 - \frac{1-\mu}{r} - \frac{\mu}{s} \\
|\Delta v| &\approx \frac{1}{2}\frac{|\Delta C_{1/2}|}{v_{esc}} \approx \frac{2}{7} h v_e \quad .
\end{aligned}
$$

This gives a $|\Delta v| \approx 10$ m s^{-1}, assuming that the radius of Enceladus is $r_e \approx (R_e\, h)/3$. In the case of the power law of the impact ejecta (3), this small range corresponds only to about 5% of all particles which later escape Enceladus. Thus it cannot be expected that particles leave the Hill sphere preferentially at $L_{1/2}$ if many more particles are launched in other directions than the Lagrangian points. This includes particles with higher velocities which are able to leave the Hill sphere anywhere (depending on the velocity vector at launch). In this way, the anisotropy of the ejecta also influences the region where the particles leave the Hill sphere. This is visible in the right of Figure 4. The only case where an enhanced outflow at $L_{2/1}$ can really be observed, and which is purely caused by the gravity of Enceladus, is the isotropic ejecta. Here the particles are evenly launched in all directions from the surface of Enceladus, so that no structure in the ejecta intensity is seen there (see also Figure 5, top-left). Such a situation can again be illustrated by a “pitcher” example. If one fills it up quickly to the upper rim and the pitcher is not tilted, water flows over everywhere but most at the spouts (if there is more than one, analogous to L_1 and L_2). This might serve as an illustration to what happens at the “rim” of the Hill sphere.

The opposite occurs with the interplanetary impactor-ejecta (Figure 4 right). There is a strong anisotropy of the ejecta, and the material will be launched in a direction other than $L_{1/2}$. In this case, because of their high velocities (see Eq. (3)) most of the particles are not strongly affected by Enceladus' gravity, to turn into the directions of the Lagrangian points while moving in the Hill sphere of gravitational influence. The majority of them leave the Hill sphere in the direction of the orbital motion of Enceladus. Again, the “pitcher” example serves as an illustration: If one tilts it strongly in another direction than that of the spout, the outflow will not preferentially take place at the location of the spout.

The middle plot of Figure 4, which corresponds to the E ring impactor-ejecta, shows particles preferentially escaping close to $L_{1/2}$ (Figure 4). However, this is just caused by the initial ejecta conditions at the surface of Enceladus, where maxima of the intensity are also observed pointing in the directions of $L_{1/2}$ (at $(0, 0)$ and at $(0, \pi)$, see Figure 2). In other words, particles mostly leave the Hill sphere at $L_{1/2}$ primarily because of their starting points and directions and not because of the gravity of Enceladus.

The major effect of Enceladus' gravity is to prevent particles from escaping with Jacobian $C < C_2 = C(L_2)$, so that only particles above a certain velocity threshold can leave.

At first glimpse, the middle and the right plots of Figure 4 and the corresponding plots of Figure 2 seem to be identical. In fact, they are very similar, but all features are shifted to lower longitudes Φ, which becomes immediately clear when looking at Figure 3. All trajectories spiral in clockwise direction; that is, a particle drifts to lower Φ, and the drift depends on the velocity relative to the parent satellite.

However, Figure 4 indicates strong differences in the dust stream intensities $I(\Phi, \Theta)$ (number of particles per area and time) of the E ring, and interplanetary impact/ejecta, which might be detectable by the CDA aboard the Cassini spacecraft. It should be noted here, that for interplanetary impactor-ejecta no measurable difference has been found for short-period cometary impactors compared to Oort cloud impactor-ejecta.

Figure 5 shows the rates at which particles cross a certain distance from Enceladus and move close to the plane $\Theta \approx 0$. The comparison between isotropic ejecta (Figure 5 left), the ejecta caused by impacts of E ring particles (middle), and by interplanetary meteoroids (right) are presented. The relative number of particles is plotted (projected onto the $x-y$ plane) in the cases when they cross circles of 1.5, 3.36 (Hill sphere radius, approximately 800 km), 6, and 20 radii (r_e) of Enceladus, corresponding to the plots from top to bottom of Figure 5.

In the case of isotropic ejecta (Figure 5 left), the particle rates do not show significant features in dependence on Φ, especially in the vicinity of Enceladus ($r < 5r_e$). Only the very weak enhancement around $\Phi \approx \pi$ at the Hill sphere ($r \approx 3.36 r_e$) in the left plots of Figure 5 resembles the larger ejecta intensity visible at L_2 in Figure 4.

In contrast to this, close to Enceladus the impact rates caused by the E ring impactors (Figure 5 middle) and interplanetary impactors (Figure 5 right) clearly show different structure $I(\Phi)$. E ring impactors show two maxima at $\Phi \approx 0$ and $\Phi \approx \pi$; interplanetary impactors show a maximum at $\Phi \approx \pi/2$. As already mentioned, such features present the opportunity to distinguish between these two cases and to get information about the origin of the E ring material.

However, if one goes farther away from Enceladus, the differences become weaker (Figure 5 bottom). This means information about the ejecta process can only be obtained close to the satellite. This is because farther away the long-term dynamics of the dust wipes out the influence of the initial conditions, as already mentioned and used in connection with the initial "setup" run in section 3.

The question is as follows: can the different possible ejecta populations be distinguished by the CDA of Cassini? According to the findings described above, these differences can only be detected in the close vicinity of the satellite, that is during an encounter of Cassini with Enceladus. Figure 6 shows the impact rates $n(t)$ along the trajectory of the spacecraft Cassini at its first designated encounter with Enceladus. Figure 6 has been derived from the designated orbital elements of Cassini together with the trajectories of the dust particles obtained from the numerical simulations in the three cases: isotropic, E ring, and interplanetary impactor-ejecta. The dust impacts are counted along an assigned Cassini trajectory (the solid line in Figure 3), where the spacecraft shoots through the Southern part ($z \approx -1.5r_e$) of the Hill sphere of Enceladus coming from the inner Saturnian system.

Apart from the absolute rates, which depend on the fluxes of projectiles and on the orientation of the detector, the effects of E ring and interplanetary impactors could be easily distinguished. E ring particles produce ejecta which will arrive at the spacecraft about 2 min after the closest approach, indicated by the distinct peak in the rate. The expected signal should be much narrower, it should last for 3 min from $t \approx 0$ min up to $t \approx 3$ min.

The ejecta, freed by the interplanetary projectiles, preferentially leave Enceladus in the orbital direction of the satellite. This yields a much broader impact rate at the CDA, and the signal should occur significantly after the closest approach. The signal $n(t)$ is characterized by a moderate increase starting at $t \approx -4$ min, reaching a flat maximum at $t \approx 2-5$ min, and should be easily observable 10 min after closest approach.

A more isotropic distribution of the ejecta would give a broader signal $n(t)$ than the E ring impactor-ejecta; it has a maximum about $t \approx 0$ just around the time of closest approach. Furthermore, the impact rate should be nearly symmetric with respect to the moment of closest approach $t \approx 0$.

The background signal, caused by the E ring dust population, is of the same order of magnitude (or weaker) as the particles coming directly from Enceladus. In order to give a rough estimate of the amount of dust collected by the CDA, which comes directly from Enceladus or from the background, we assume Enceladus to be the only source and sink of dust. This means that these rates must balance (if summed over the surface of Enceladus) at Enceladus, and thus they should also be of the same order of magnitude at the CDA detector during the close encounter of Cassini with Enceladus. A lower estimate (where Enceladus is considered to be the only sink) of the total number of E ring particle impacts can be obtained by the following argumentation: *Showalter et al.* [1991] report a peak optical depth of the E ring near the orbit of Enceladus of 1.6×10^{-5}. Combined with their photometric analysis and determination of a narrow size distribution of micrometer-sized particles, this leads to a vertically integrated number density of 180 particles cm^{-2}. The thickness of the E Ring near the orbit of Enceladus is about 8000 km [*Showalter et al.,* 1991], so the number density of dust at 4 Saturn radii is $\approx 2 \times 10^{-7}$ cm^{-3}.

Assuming optimal orientation of the CDA and depending on the trajectory of Cassini, this leads to an impact rate of micrometer-sized particles on the detector of 100-500 s^{-1} at the orbit of Enceladus. During close flybys of Enceladus, this rate will be modulated by the influence of ejecta directly leaving the surface of the satellite which must at least be of the same order of magnitude. If one considers all sinks in the E ring region, Tethys and companions, Mimas, and the rings, and one accepts Enceladus to be the only effective source of E ring dust, the particle balance (continuity equation) in the E ring requires even more particles being ejected from Enceladus' surface. Furthermore, in contrast to the particle streams just launched at Enceladus, the background signal, derived from our "setup" run, has been found to be nearly featureless. The relative velocities of the ejected dust particles with respect to Enceladus are of the order of $\sim$ 100 m s^{-1} in comparison to about 10 km s^{-1} of Cassini. So, differences in the impact directions are very small compared with the large field of view of the detector. Therefore individual impacts of ejected particles cannot be separated from those of E ring particles. The ejecta can be recognized, however, from the statistical properties of the data $n(t)$ (see Figure 6).

According to this, the CDA will likely be able to distinguish the recently launched ejecta from the usual E ring population, the background signal. This statement holds for most possible encounter geometries where the approach presented above is applicable in an analog manner. Only in a few orbital configurations, the CDA aboard Cassini cannot detect particles being just ejected from Enceladus. Because a reasonable number of close flybys with Enceladus have been scheduled, the chance to distinguish between the different possible origins of the E ring particles is readily available.

5. Conclusions

The main aim of our investigations has been to estimate whether the cosmic dust analyzer (CDA) aboard the Cassini spacecraft can distinguish between different dust ejecta mechanisms at the surface of Enceladus, the major material source for the faint E ring of Saturn. In this context, ejecta which have already been lift off by hypervelocity impacts of micrometeoroids onto the satellites' surface play a favored role.

Our simulations included two different sets of initial conditions for the ejecta from Enceladus: ejecta lifted off caused by impacts of interplanetary micrometeoroids and by impacts of E ring particles (the dominant impactor flux on Enceladus). There are significant differences in the ejecta intensity distributions (Figure 2) at the surface of Enceladus, which remain detectable also in the Hill sphere of the satellite (Figure 4), that is the dynamics of the dust in the vicinity of the moon does not wipe out these significant differences. Thus, the possiblity that the CDA can detect and distinguish certain dust production mechanisms during encounters of Cassini with Enceladus is present.

According to our simulations, an anisotropy of the ejecta with respect to the direction of the orbital motion of Enceladus results in a shift of the CDA signal with respect to the moment of the closest approach of Cassini to the moon. The CDA signal contains information about the number of dust impacts at the detector per time: $n(t)$.

Furthermore, depending on whether the majority of dust is delivered at the leading or trailing face of Enceladus, the main signal at the CDA should occur after or before the closest approach, respectively. Completely isotropic ejecta produce a signal $n(t)$ which is nearly symmetric with respect to the time of closest approach ($t = 0$, see Figure 6). Physically motivated impact/ejecta processes provide more ejecta in the direction of the motion of Enceladus, and thus the maximum of the CDA signal can be expected to occur after the closest approach. This is the case for both impactor-ejecta families investigated in this paper.

According to our simulations, E ring impactor and interplanetary impactor families produce fairly different signals $n(t)$. In the case of interplanetary micrometeorites, a broad and flat signal $n(t)$ will be obtained, which comes up $2-3$ min before the closest approach ($t = 0$), reaches its maximum about $3 - 5$ min after, and should be still observable 10 min after the closest approach. E ring impactors produce a much narrower signal, coming up nearly at $t = 0$, reaching its maximum about 1 min later, and dropping off abruptly, so that the signal vanishes about $3 - 4$ min after the closest approach.

The results presented above are influenced by strong fluctuations in the rate of the impacting micrometeoroids. Furthermore, these micrometeoroid fluxes are not well known. These facts might result in more or less strong deviations of the above findings. Applying the procedure presented here to other encounters of Cassini with Enceladus will improve the reliability of these results.

The CDA will measure both the micrometeoroid flux at Saturn and the flux of E ring particles in the vicinity of Enceladus. The investigations presented above concerning the signal $n(t)$ provide a tool to determine whether interplanetary or E ring impactors are the dominant sources of ejecta from Enceladus or whether perhaps another mechanism serves as a particle source [*Haff et al.,* 1983].

Another result of our simulations concerns the vertical distribution of the dust particles in the E ring of Saturn. The three-dimensional character of the ejecta velocities result in a configuration of the E ring which reflects roughly the vertical structure, thickness as function of the distance from Saturn (see Figure 1). Very similar thickness profiles have been obtained for the interplanetary as well as the E ring ejecta. That means at least the conditions derived by the work of

Colwell [*Colwell,* 1993] and in this paper reflect average realistic conditions of delivering dust particles into the E ring of Saturn.

An interesting fact is that long-term simulations (comparable to the "setup" runs in section 3) show an asymmetric radial optical depth profile of the E ring for ejecta from interplanetary impactors. This is in much better accordance with the observations [*Showalter et al.,* 1991] than the same simulations for ejecta from E ring impactors. A detailed analysis of these questions could not be the subject of this paper. However, it should be mentioned that in this light, the expected results of the Cassini mission are of special scientific interest.

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J. Colwell, Laboratory of Atmospheric and Space Physics, University of Colorado at Boulder, Boulder Co./80 309-0392. (e-mail: colwell@casper.colorado.edu

E. Grün and R. Srama, Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany, (e-mail: gruen@dusty.mpi-hd.de, srama@mpg.mpi-hd.de)

F. Spahn, K.-U. Thiessenhusen, Lehrstuhl "Nichtlineare Dynamik", Institut für Physik, D-14415 Potsdam, Germany. (e-mail: fspahn@agnld.uni-potsdam.de,kai@agnld.uni-potsdam.de)

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Figure Captions

Figure 1. Intersection of the particle trajectories with the $r - z$ plane ($r^2 = x^2 + y^2$) of the "setup" run, which provides the E ring impactor/ejecta. The x- axis denotes the distance from Saturn, the y- axis denotes the distance to Saturn's equatorial plane, both are given in Saturnian radii. This run roughly shows what the distribution of the E ring looks like. There is a maximum of the particle density close to the orbit of Enceladus, and also the mean thickness (solid line) matches the observation (dashed-dotted line).

Figure 2. The grey-level-coded distribution $I(\Phi, \Theta)$ of ejecta versus Θ and Φ for (right) interplanetary as well as the (left) E ring impactors (*left*). The light grey up to white corresponds to the maxima of this intensity, and the solid area labels lowest ejecta intensities. It is obtained by counting the intersections of the particle trajectories with the surface of Enceladus.

Figure 3. Projection of ejecta trajectories from E ring impactors onto the $x - y$ (horizontal) plane. The bold solid line labels the projection of one possible path of the Cassini spacecraft. The units are given in radii of Enceladus (≈ 249 km); Saturn is in the negative x-direction.

Figure 4. Grey-level coded intersection densities, derived from the points of the intersection of the trajectories with the Hill sphere, versus the coordinates Θ and Φ at the Hill sphere for the cases of (left) isotropic ejecta, (middle) ejecta from E ring impactors, and (right) from interplanetary impactors (*right*).

Figure 5. Stream intensities in the $x - y$ plane for different radial distances from Enceladus (labeled above each plot) as a function of the angle Φ with respect to the direction of motion of Enceladus. These rates are displayed for (left) isotropic ejecta, (middle) ejecta from E ring, and (right) interplanetary impactors (*right*). The rates have been normalized so that the average rate equals one in the top of Figure 5.

Figure 6. The relative impact rates at the Cassini cosmic dust analyzer of ejecta caused by different impactor families. The solid, dashed, and dashed-dotted lines correspond to isotropic, E ring, and interplanetary impactor/ejecta, respectively.