Detection and measurement of ice grains and gas distribution in the Enceladus plume by Cassini’s Ion Neutral Mass Spectrometer

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[1] We report on the measurements of the Cassini Ion Neutral Mass Spectrometer (INMS) of the density and structure of Enceladus’ south polar plume during the E3 and E5 flybys on 12 March and 9 October 2008. Using a Monte Carlo simulation, we analyze the dependence of the INMS gas inlet transmittance on spacecraft pointing and the effect on the measurements at E3. We apply a finite element analysis to correct for water physisorption in the inlet and obtain a maximum plume density almost twice that suggested by the raw INMS data. The results indicate uniform spreading of the plume vapor from the source with a source rate of at least 100 kg/s. We also analyze the detection of ice grains by the INMS and find that, in contrast to the plume vapor component, the grains are concentrated within the plume jets seen in Cassini imaging, supporting the suggestion that the jets are composed of fine-grained ice.


1. Introduction

[2] One of the most remarkable findings of the Cassini spacecraft’s mission to Saturn has been the detection of a cryovolcanic plume of gas and ice grains emanating from Saturn’s icy satellite Enceladus [Dougherty et al., 2006; Hansen et al., 2006; Porco et al., 2006; Spahn et al., 2006; Waite et al., 2006]. The plume is located in the satellite’s southern polar region and consists of several collimated jet-like sources [Spitale and Porco, 2007] emanating from hot spots [Spencer, 2006] located along several prominent elongated troughs or “tiger stripes” [Porco et al., 2006], which scar the surface. Water vapor is the dominant gaseous constituent of the plume (90% ± 1%), but other volatile constituents such as CO₂ and possibly CO and N₂ are present in significant abundance, in addition to trace amounts of hydrocarbons, nitriles, and a population of salt-bearing water ice grains [Waite et al., 2009; Postberg et al., 2008; Schneider et al., 2009]. The plume’s discovery presents a unique opportunity to characterize the composition and active geological processes in Enceladus’ interior and the supply of ice grains to Saturn’s E ring [Kempf et al., 2008; Perry et al., 2010] and ultimately to gain insight into the formation of icy objects in the early solar system. Here we examine the measurements of the Cassini Ion Neutral Mass Spectrometer (INMS) of the neutral density and structure of the plume during the recent E3 and E5 encounters of Enceladus.

[3] The INMS consists of an open ion source for sampling ions, a closed electron impact source for analysis of the neutral gas (Figure 1), a quadrupole mass analyzer, focusing and switching lenses, and two secondary electron multiplier detectors [Waite et al., 2004]. The closed source is equipped with a titanium gas inlet system consisting of an antechamber to capture the neutral gas and a transfer tube to admit a portion of the captured gas into the electron impact ionizer. Molecules enter the antechamber at suprathermal velocities through an orifice faced in the direction of motion of the spacecraft, then thermally accommodate after a few collisions inside the inlet system. Once transmitted into the ionization region, the plume neutrals are ionized through electron impact. The electron impact ionization and fractionation efficiencies are based on laboratory calibration measurements and determine the sensitivity and mass spectra for a particular species.

[4] However, analyses of in-flight data show several phenomena occurring in the inlet system that were not measured during the laboratory calibrations. These phenomena include (1) wall adsorption, (2) enhanced transfer tube transmission at a particular spacecraft orientation, and (3) signal spikes caused by grain impacts in the closed source. In this work, we compare computer simulations to INMS measurements to investigate these processes. The results yield an improved characterization of the Enceladus plume gas-grain density and structure.

2. Transmission Versus Angle

[5] This paper reports on results from two Cassini flybys of Enceladus: E3 and E5, during which INMS pointing was...
optimal (Table 1). During each of these flybys, the spacecraft passed within sufficient proximity to the source of the south polar plume for INMS to obtain measurements of the plume’s structure and composition. Both flybys occurred along an approximate north-to-south trajectory, and thus, both plume encounters took place outbound from Enceladus, with Cassini traveling roughly parallel to the plume. The spacecraft speed relative to Enceladus was more than an order of magnitude faster than the thermal velocity distribution of the molecules in the plume. As a result, the transverse velocity component of the incoming molecules is much less than their forward speed relative to the spacecraft and the sample molecules enter the antechamber as a tightly collimated beam.

Within a few minutes before and after closest approach at E3 and E5, the orientation of the spacecraft was adjusted to maintain a 0 (within $\pm 0.5^\circ$) ram angle, defined as the angle between the direction of the incoming molecular beam and the normal to the antechamber entrance orifice. Outside this time window, $\theta$ was allowed to drift away from zero as other Cassini instruments were given priority, in some cases while the spacecraft was still under the influence of the plume. The principal consequence of the change in $\theta$ is a reduction of the flux entering the antechamber, which varies in proportion to the projected area of the orifice, $\cos \theta$. However, a second effect is an enhancement of the transmittance when the ram direction causes the tightly collimated beam of incoming molecules to enter the transfer tube, which is off-axis to the entrance orifice (Figures 1 and 2). In this orientation, molecules arrive initially inside the tube and have much improved odds of reaching the ionizer.

To quantify the transmittance versus ram direction, we performed a 3-D Monte-Carlo simulation of the molecular trajectories in the inlet system, with the aim of comparing against spacecraft orientation during each Enceladus encounter. We initialized the molecules as a collimated beam originating from the entrance orifice with a direction defined by $\theta$ and the azimuthal angle, then tracked their trajectories inside the inlet system until they escaped the orifice or reached the ionizer. Thermal spreading of the incident beam introduces only a small uncertainty ($\pm 1^\circ$) in the incoming molecule direction and did not significantly affect the results of our simulations. We do not consider

Table 1: Parameters for the Enceladus Encounters Analyzed in This Work

<table>
<thead>
<tr>
<th>Encounter</th>
<th>Date</th>
<th>Speed relative to Enceladus (km/s)</th>
<th>Average H$_2$O Thermal Speed (km/s)$^a$</th>
<th>Close Approach Altitude (km)</th>
<th>Ram Angle in Plumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3</td>
<td>12 Mar 2008</td>
<td>14.41</td>
<td>0.430</td>
<td>50.8</td>
<td>0</td>
</tr>
<tr>
<td>E5</td>
<td>9 Oct 2008</td>
<td>17.73</td>
<td>0.430</td>
<td>25</td>
<td>0</td>
</tr>
</tbody>
</table>

$^a$Here we assume the temperature of the plume vapor to be 157 K: the maximum reported surface temperature in the hot spots [Spencer, 2006], which should be an upper limit.
reentry of transmitted molecules from the ionizer back into the transfer tube (however, we include the effects of return flux in the absolute calibration, discussed later). Upon striking the walls, the molecules exchange energy with the surface atoms and then desorb according to a $\cos\varphi$ angular probability distribution, with $\varphi$ the emission angle with respect to the surface normal. Molecules that reach the ionization chamber have, on average, $\sim 120$ interactions with the instrument walls. We assume no intermolecular collisions, as appropriate for the mean free path, which is tens of kilometers at these densities.

As shown in Figure 3, the transmittance is roughly constant near 8% at angles for which the incoming molecules strike the back surface of the antechamber, i.e., transmission is independent of the point of arrival of molecules in the antechamber. However, the transmission is enhanced by a factor of approximately 3, from roughly 8% to 25% when the incoming molecules arrive at the entrance of the transfer tube, which is at $\theta = 18^\circ \pm 8^\circ$ within $\pm 25^\circ$ azimuth. In Figure 3 we trace the ram direction between 0 and 750 s after closest approach at E3 and find that the direction falls within this range of angle near 470 (±100) s. This causes a transient increase in the sensitivity of INMS which, as shown in Figure 4, enhances the H$_2$O signal at 18 amu by a factor of 1.32 (±0.06) over the continuum baseline. This value is below the predicted threefold increase in transmission, since approximately 60–70% of the mass 18 signal at 470 s is due to outgassing of water adsorbed onto the inlet system walls earlier in the E3 encounter and is unaffected by the change in incident angle.

3. Water Adsorption

Most volatile molecules are transmitted through the inlet system to the ionizer within a few milliseconds
in one sample or integration period, which is 31 ms. By contrast, water molecules adsorb onto the titanium surfaces of the inlet system, a process that extends the transmission time, causing a significant time distortion in the measurements. The distortion is manifested at E3 and E5 as (1) a several-second delay in the appearance of water in INMS relative to other species on Cassini’s arrival at the Enceladus plume; (2) a reduction in the peak count rate (apparent peak density); and (3) a widening of the time profile, including an hours long tail in the mass 18 signal due to gradual desorption of water from the inlet system. To determine accurately the flux of water entering the antechamber versus time requires a model of adsorption in the inlet system.

Cui et al. [2009] have modeled adsorption effects at Titan where N2, the dominant atmospheric constituent, drives the desorption of other species from the inlet through its bombardment of the walls. By contrast, water is itself the dominant constituent at Enceladus, and its adsorption/desorption on the walls is therefore determined by the competition between molecules for surface binding sites. It is therefore necessary to consider the positional dependence of the water surface coverage.

We analyze this system in two steps. First, we infer the water density profile from the INMS data by assuming the plume molecular composition to be homogeneous since, except for water, the relative signals of other major volatile species are constant over the E3 and E5 encounters (Figure 6). Hence, we consider the true water density profile to have the same time dependence as that of other species and normalize the profile amplitude to the total amount of water detected by INMS within 24 h of the encounter.

In the second step of our analysis, we simulate the propagation of water through the inlet system using a finite difference calculation and a model of the antechamber and transfer tube as a surface mesh (Figure A1), then adjust the sticking parameters to match the simulation results with the measured INMS water profile. The sticking is described in terms of two empirical parameters, $\beta$ and $\gamma$ that determine the average sticking time on each element according to equation (A6). The detailed description of the parameters and calculations are described in Appendix A, where we multiply the water density profile by spacecraft speed to obtain the incoming flux $q$ and predict the resultant INMS counts using equation (A10).

Equation (A10) yields good agreement with the data obtained at E3 and E5 with $b$ and $g$ set to $5.3 (\pm 1) \times 10^{17} \text{ s} \cdot \text{m}^2$ and $1.1 \pm 0.3$ (see Figure 7 before 117 s). From equation (A6), these values give sticking times on the order of 0.1–1 s if one assumes $\sigma \sim 10^{16}–10^{17}$ molecules/m$^2$, as is typical during the plume encounter (Figure A1). This corresponds to transmission times of the order of 15–150 s if one considers an average of 120 wall interactions. We show the plume water density profile in Figure 8: the maximum densities, $7.6 (\pm 0.1)$ and $34 (\pm 0.2) \times 10^{13}$ molecules/m$^3$ at E3 and E5 (corresponding to mass densities of $2.3 (\pm 0.03)$ and $10 (\pm 0.06) \times 10^{-12}$ kg/m$^3$), are almost twice the values determined using a straight calibration from the peak

Figure 5. A Monte Carlo estimate of the transmission time distribution for molecules with mass 44 amu that enter the antechamber with $\theta = 0$ at 15 km/s and pass through the transfer tube to the ionization chamber. For this simulation we assume no sticking to the inlet system walls and use a room temperature Maxwell-Boltzmann velocity distribution between wall collisions. We also consider a probability of 0.97 for molecules entering the ionizing chamber to reenter the transfer tube (see text).
INMS count rate. We have corrected the densities to account for conversion of water into H2 (Waite et al., 2009) by impact dissociation and/or chemical reactions in the antechamber by scaling $q$ by $1/(1 - \varepsilon)$; with $\varepsilon$ the conversion efficiency for H2O into H2. The efficiencies are 0.17 and 0.43 at E3 and E5, as determined from the ratio of the H2 mixing ratios seen by INMS over the encounters (0.17 and 0.39 at E3 and E5, respectively) to the total water mixing ratios (0.96 and 0.90 at E3 and E5, respectively) (Waite et al., 2009).

Although the density profiles in Figure 8 provide information about the structure and overall source rate of the plume, in Figure 9 we investigate the expansion of the plume and its relationship to the sources reported by Spitale and Porco (2007). The E3 trajectory passes almost directly over the VIII and II sources (Spitale and Porco, 2007), but the INMS does not measure significant density until approximately 50 s after closest approach, when it is within 20° of source II located in the Damascus vent. This observation is consistent with thermal analysis of CIRS data, which show that the Damascus sulcus is more active than the Cairo sulcus (Howett et al., 2009). The indication that the plume half width is approximately 20° is similar to the results of the studies by Hansen et al. (2008) and Smith et al. (2010).

To further investigate the source and its structure, we scale INMS data by the square of the distance to the planet’s surface, $z$. The scaled density is nearly flat for 400 s after entering the plume. As Cassini was traveling close to the projected direction of source II (Damascus), a $z^{-2}$ density dependence corresponds to uniform spreading within a cone, not the $z^{-1}$ dependence sometimes seen in dust jets and comets (Boice et al., 2002). Using a circular cone with a 20° half angle and the source velocity of 0.6 km/s recently found by Hansen et al. (2008), the source rate is 100 kg/s or $3.5 \times 10^{27}$ molecules/s. This result, which is slightly lower

**Figure 7.** A comparison of the sticking model results (solid lines, left axis) to the measured H2O signal at E3 (circles). Here we show the model results for two cases: an ice grain containing $4.5 \times 10^{12}$ molecules entering INMS 117 s from closest approach and striking the wall (1) 33.5 (black line, left axis) and (2) 4.8 mm (red line) from the exit of the transfer tube. While in case (1) the grain produces a negligible throughput response, case (2) produces the best fit to the observed spike. Also shown is the modeled water vapor input flux into the antechamber used to generate the results (dashed line, right axis), after scaling by $1/(1 - \varepsilon)$ to account for conversion of water to H2.

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**Figure 8.** The source function for the water vapor density at E3 and E5 versus time from closest approach (solid black line, left axis). Also shown is the density given by a direct counts-to-density calibration (dashed red line, left axis, given by $\chi/RS$, with $R$ as the ram enhancement factor) from the peak INMS count rate $\chi$, and the distance of Cassini from the surface of Enceladus (solid red line, right axis), where the average Enceladus radius $R_e$ is 252.1 km. All densities are scaled by $1/(1 - \varepsilon)$ to account for conversion of water to H2.
than those of Hansen (200 kg/s) [Hansen et al., 2008] and Smith (150 kg/s) [Smith, 2010], should be a low estimate because it does not account for emissions that do not intersect Cassini’s trajectory. Estimates of the source rate are also subject to uncertainties, e.g., because current estimates of the source velocity are not well constrained [Tian et al., 2007; Hansen et al., 2008].

4. Ice Grains

INMS detects the signatures of ice grains entering the gas inlet as spikes in several mass channels: 1, 2, 15, 16, 17, 25, 26, 27, 28, and 44 amu, as shown in Figure 10 for H2 at E3. The grains generate bursts of volatile species when vaporized on impact in the antechamber, with the volatiles either (1) present originally as grain constituents or (2) produced in the antechamber through chemical reactions between grain constituents or with titanium atoms ejected during grain impact [Waite et al., 2009]. The transmission time for volatile constituents (Figure 5) is much shorter than the INMS integration period at each mass (0.031 s), and the INMS captures the arrival of a grain within one period as a single spike. The frequency of spikes varies with the number density of the ice grains in the vicinity of Cassini. The number of detected spikes (33 and 41 at E3 and E5, respectively, as shown in Figure 11) is sufficient to allow us to estimate through statistical analysis the density of grains in the Enceladus plume versus time during each encounter. To perform the analysis we group the total number of spikes in all of the volatile mass channels into time bins, then multiply by \( t_{\text{cyc}}/\Delta t \), which is the instrument cycle time (~6.3 s at E3 and E5) divided by the time spent on the required mass channels (the ratios were ~9.0 and ~8.1 at E3 and E5, respectively). Here \( t_{\text{cyc}} \) is the interval between complete mass scans (measured repeatedly according to a pre-set table of mass channels), and \( \Delta t = y \times 0.031 \) s, with \( y \) as the number of volatile mass channel measurements per scan. Dividing by the time bin size, the entrance orifice area, and the spacecraft speed, we obtain a grain density versus time for the E3 and E5 encounter, as shown in Figure 12, where we have used an adaptive time-binning algorithm to maximize resolution near sharp density features while maintaining reasonable counting statistics in each bin. We point out that the densities are likely underestimates, since trace species [1, 8] in the plume vapor and molecules such as H2 and CO produced in the antechamber [Waite et al., 2009] can overwhelm the signatures of small grains during the plume encounter. However, the densities exceed those indicated by the Cassini Cosmic Dust Analyzer (CDA), which may indicate a greater sensitivity of INMS to small grains (less than 1 \( \mu m \) size) (J. Schmidt, Universität Potsdam, unpublished data, 2009). Unfortunately, an estimation of grain size from the spike amplitudes is currently not possible due to uncertainty regarding the degree to which the amplitude reflects the grain composition and/or chemistry in the antechamber and questions about the nature of the chemistry. An example is the H2 spikes appearing in mass 2, which are generated by the reaction of H2O.

Figure 9. The relationship between Cassini’s trajectory, two of the active regions, and the INMS signal during the E3 encounter. The thick line is Cassini’s trajectory in the plane formed by Cassini’s trajectory and Enceladus’ axis of rotation. The tick marks show the seconds from closest approach (CA). A thinner line, with error bars showing 1 \( \sigma \) statistical errors, is the INMS-measured density scaled by the altitude squared (values are on the right-hand axis of the plot). The shaded regions show the extent of the plume and jet emissions if the spreading is ±20°. The INMS data do not support a plume width of ±40°, as indicated by the dotted lines. The INMS density rises as Cassini enters the influence of the active region in Damascus. Cassini travels nearly along the Damascus active region, and the scaled density is nearly flat. Cassini passed directly over the South Pole and intersected the rotation axis.
(vaporized during grain impact) with the ejected titanium [Waite et al., 2009]. Although the amount of hydrogen produced in the antechamber is given by equation (B4b) in Appendix B (with $Y$ in equation (B4b) as the spike amplitude), the grain size required to produce this amount depends on several unknowns, e.g., the fraction of H$_2$O in the grains that reacts to form H$_2$, and the amount of H$_2$ that then binds to unreacted titanium deposited onto the antechamber walls [Waite et al., 2009].

Figure 10. Mass 2 counts per integration period at E3. The circles indicate the spikes corresponding to the arrival of ice grains in the antechamber. At low H$_2$ densities, spikes with counts as low as 15 are distinct from the background, whereas in the dense part of the plume, only larger spikes of at least several hundred counts are discernable. This biases the size-frequency distribution to larger grains.

As shown in Figure 12, a sharp peak of grain density at E3 and several at E5 are consistent with the optical measurements indicating that the Enceladus jets consist of fine-grained ice [Porco et al., 2006]. In Figure 13 we color the E5 ground track according to the grain density and compare with the grain jet locations and directions observed by Spitale and Porco [Spitale and Porco, 2007]. The E5 peak 27 s after closest approach shows good correspondence with Cassini’s passage 24 km from the Baghdad VI jet (see Figure 13). By comparison, the sources of the peak (or possibly two peaks) seen at 17 s (or of the E3 peak at 118 s) are less obvious, but other jet sources cannot be ruled out in light of recent imaging data indicating that the actual number of jets far exceeds the eight analyzed by Spitale and Porco [CICLOPS Press Release, 2010]. Even for the sources analyzed by these authors, knowledge of the jet directions are subject to uncertainty due to angular spreading (roughly 10°) and, in some cases, poorly constrained azimuthal angles [Spitale and Porco, 2007]. The confinement of the grains to discrete collimated jets suggests acceleration by a unidirectional gas flow emanating, e.g., from fissures terminating at Enceladus’ surface [13, 14]. By contrast, the relatively smooth water vapor distribution (Figure 8) is consistent with simulations [Tian et al., 2007; Tenishev et al., 2010] and observations [Hansen et al., 2008] indicating that the thermal velocity distribution of the plume’s gaseous component is of a similar order of magnitude as its forward-directed motion (300–700 m/s; [Tian et al., 2007; Hansen et al., 2008; Tenishev et al., 2010]). We also note the significant density of grains on the inbound portion of the encounters (Figures 11 and 12), several $R_e$ to the north of Enceladus.

Figure 11. The cumulative number of ice grains detected by INMS in all mass channels versus time over the E3 and E5 encounters. A total of 33 and 41 grains were seen at E3 and E5, respectively.

Figure 12. Ice grain density (black squares, left axis) detected by INMS at E3 and E5 versus time from closest approach. Densities are estimated from Figure 11 with an adaptive binning method. Also shown is the distance of Cassini from the surface of Enceladus (red line, right axis), where the average Enceladus radius $R_e$ is 252.1 km. Only larger grains are detected in the densest part of the plume (between 0 and 50 s after CA), and therefore, these densities are a lower bound. Question marks indicate possible jets with unknown sources. We tentatively identify the E5 peak 27 s after closest approach with the Baghdad VI source of Spitale and Porco [2007], based on the comparison of Figure 13.
and well before the encounter with the south polar plume. This may be indicative of grains ejected from the plume close to the Enceladus escape speed (239 m/s) that remain in the satellite’s vicinity, e.g., due to orthogonal oscillations of the grains about Enceladus’ orbital plane [Kempf et al., 2008].

[17] Although water ice is the primary grain constituent [Kempf et al., 2008; Postberg et al., 2008], vaporized H₂O generated by the arrival of a grain has a distribution of transmission times through the inlet on the order of seconds due to wall adsorption (as indicated by equation (A6) for σ ~ 10^{16}–10^{17} m⁻²), and water reaches the ionizer gradually only over many integration periods. This explains the absence of sharp spikes in the mass 18 channel and, in almost all cases, renders H₂O from the grains indistinguishable from ambient water vapor in the plume. However, a notable exception occurs during E3, with a sudden increase in the H₂O signal 117 s after closest approach (Figure 7). Since adsorption precludes the transmission of such fast changes in ambient water vapor density through the entire inlet, this anomaly can be explained only by the sudden arrival of H₂O inside the transfer tube, i.e., due to the arrival of a grain with a sufficient transverse velocity component to impact inside the tube. We have confirmed this with our surface-dependent adsorption model by initializing at t = 117 s from closest approach a sudden increase in water coverage on different individual surface elements to simulate the arrival of a grain at different locations in the inlet. Through optimization of (1) the impact location and (2) the grains’ water content, we find that the height and shape of the observed anomaly (Figure 7) can be approximated only by the impact of an ice grain ~0.5 cm from the exit of the transfer tube containing ~4.5 × 10^{12} H₂O molecules. We note that the optimization somewhat overestimates the signal decay after 117 s, a discrepancy that might result from desorption of water deposited inside the ionizer due to the grain’s close proximity to the tube exit. The assumption of spherical grains yields a diameter of 6.6 μm. This is larger than the...
expected size range based on the measured grain densities (as discussed above) and the CDA measurements (J. Schmidt, Universität Potsdam, unpublished data, 2009) but within the range suggested by the Cassini Visual and Infrared Mapping Spectrometer (VIMS) [Hedman et al., 2009]. The grain impact point requires an entry angle of $\theta = 4.5^\circ - 9.0^\circ$ into the antechamber. This corresponds to a transverse velocity component of 1134–2282 m/s with respect to Enceladus, which is significantly greater than the speeds of a few hundred meters per second suggested by Cassini imaging [2, 6, 13], VIMS [Hedman et al., 2009], and CDA measurements [Kempf et al., 2008]. A possible explanation is the deflection of the grain (or fragmentation of a grain $>6.6 \mu m$ diameter) after a collision with the edge of the antechamber entrance orifice or other spacecraft surface.

5. Conclusions

[18] We have applied detailed computer simulations of the Cassini INMS closed source gas inlet to elucidate the distribution of gas and grains at Enceladus by addressing several poorly characterized anomalies in the results of the Cassini INMS during the E3 and E5 encounters. These are (1) a transiently enhanced transmission of gas through the inlet at E3 due to spacecraft pointing, (2) delayed detection of water vapor due to water adsorption on the inlet walls, (3) spikes observed in multiple mass channels due to the release of volatile species by ice grains impacting the inlet, and (4) a sudden jump in the mass 18 signal at E3 117 s after closest approach due to the arrival of an ice grain inside the inlet transfer tube. Our results provide an interpretation of the in situ, measured density profiles of the Enceladus plumes for the E3 and E5 encounters. The profiles indicate that the density of water vapor, comprising more than 90% of the plume composition [1, 8], is more sharply peaked than indicated by the raw INMS data. The proportionality of the density profile to the inverse square of the distance from the surface of Enceladus indicates uniform spreading of the plume vapor from the source, with a source rate of at least 100 kg/s. Compared to the relatively isotropic emission of water vapor from the plume sources, INMS measurements of the grain density indicate that the grains are ejected into collimated jets that coincide with those seen in Cassini imaging results [Porco et al., 2006; Spitalle and Porco, 2007]. Our findings constitute one of the most detailed descriptions of the gas grain structure of the Enceladus plume to date and will provide valuable constraints for future studies that require quantitative estimates of the plume density profile and magnitude.

Appendix A

[19] Here we give a detailed description of our model of water adsorption in the inlet system and its propagation to the ionizer during the Enceladus encounters. Our approach is to model the inlet system as a surface mesh consisting of 1293 elements and to evaluate the propagation of water through the inlet via a finite difference calculation, taking into consideration adsorption and desorption at each surface element during each time step (Figure A1). The parameters

<table>
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<th>Parameter</th>
<th>Description</th>
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<tr>
<td>(i, j)</td>
<td>Surface element index</td>
<td></td>
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<tr>
<td>(q_i)</td>
<td>Source: number of molecules hitting surface element (i)</td>
<td>molecule/m2/s</td>
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<td>(A_i)</td>
<td>Area of surface element (i)</td>
<td>m2</td>
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<tr>
<td>(\sigma_i)</td>
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<tr>
<td>(t)</td>
<td>Time</td>
<td>s</td>
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<tr>
<td>(T)</td>
<td>Gas temperature in the ionizer</td>
<td>K</td>
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<tr>
<td>(\Phi)</td>
<td>Flux entering the ionizer from the transfer tube</td>
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<td>(\tau(\sigma_i))</td>
<td>Sticking time per molecule (function of (\sigma_i))</td>
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<td>Angle from the surface normal of surface element (i) to surface element (j)</td>
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<td>Angular distribution function for molecules leaving the surface</td>
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<tr>
<td>(b)</td>
<td>Sticking parameter; linear coefficient</td>
<td>s/m2</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Sticking parameter: exponent coefficient</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>(\Delta)</td>
<td>Delay to adjust rise time of simulated water counts</td>
<td>s</td>
</tr>
<tr>
<td>(C)</td>
<td>Conductance to escape the ionization chamber</td>
<td>m3/s</td>
</tr>
<tr>
<td>(S)</td>
<td>INMS sensitivity for a particular molecule</td>
<td>m3/s</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Probability that a molecule entering the antechamber will reach the ionizer</td>
<td>Fraction</td>
</tr>
<tr>
<td>(\chi)</td>
<td>INMS count rate</td>
<td>counts/s</td>
</tr>
<tr>
<td>(v)</td>
<td>Average molecular velocity at temperature (T)</td>
<td>m/s</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Molecular density</td>
<td>molecules/m3</td>
</tr>
</tbody>
</table>
used in the model are shown in Table A1. The model can be described in six parts, as follows:

1. The surface density (coverage) of water \( \sigma_i \) adsorbed onto a surface element \( i \) is controlled by the water input flux and the desorption and adsorption rates:

\[
\frac{d\sigma_i}{dt} = \sum_j F_{ji} - F_i + q_i, \tag{A1}
\]

where \( t \) is time, \( q_i \), \( F_i \), and \( F_{ji} \) are the source, desorption rate, and transfer rate between elements, respectively, and are described below. Because the entrance orifice and tube exit planes do not constitute real physical surfaces, we set \( \sigma_i = 0 \) at all times for elements on these planes. We also assume a clean inlet system, i.e., \( \sigma = 0 \) everywhere, as our initial condition; we investigated using a nonzero surface coverage described in six parts, as follows:

2. The desorption rate \( F_i \) from element \( i \) is given by

\[
F_i = \frac{\sigma_i}{\tau(\sigma_i)}, \tag{A2}
\]

where the average sticking time \( \tau \) is in general a function of coverage (see below). For elements that comprise the plane between the normal to surface element \( i \) and the vector connecting \( i \) and \( j \), the opposing angle \( \theta_{ij} \) between the elements, the angle \( \theta_{ij} \) between the normal to surface element \( i \) and the vector connecting \( i \) and \( j \), the opposing angle \( \theta_{ji} \) to element \( j \), and the angular distribution \( f(\theta_{ji}) \) of desorption from \( j \) evaluated at angle \( \theta_{ji} \), as follows:

\[
F_{ji} = \frac{A_j f(\theta_{ji}) \cos \theta_{ji} F_i}{2\pi \theta_{ji}^2}, \tag{A5}
\]

where we assume a cosine desorption distribution \( f(\theta_{ji}) = \cos \theta_{ji} \). As an exception to equation (A5), we set \( F_{ji} = 0 \) when no line of site exists between \( i \) and \( j \).

3. The transfer rate \( F_{ji} \) from element \( j \) to \( i \) (as explained below), and we have summed \( i \) only over elements on the plane of the transfer tube exit. Equation (A3) ignores the time delay for a molecule to enter the ionization chamber and then find its way back to the transfer tube, but this time is short, as described in the section on ice grains.

4. For the average sticking time we use

\[
\tau = b\sigma^{-\gamma}, \tag{A6}
\]

which yields a power law dependence of the desorption rate on time, as is typical for metals in a vacuum system [Dylla et al., 1993; Toth, 2002]. The \( \sigma \) dependence of sticking time results from the distribution of adsorption binding energies on the inlet system surface, with water molecules migrating by surface diffusion to the strongest available adsorption sites. With increasing coverage, adsorbed molecules have no option but to occupy weaker sites, thus lowering the average sticking time. Although the parameters \( b \) and \( \gamma \) are empirical, the magnitude of \( \gamma \) can be considered a qualitative measure of the width of the binding energy distribution, with the limit \( \gamma \to 0 \) corresponding to the existence of only one binding energy [Toth, 2002].

5. The source function \( q_i \) is equal to the ambient water density times the spacecraft speed. It is zero except on elements located within the circular patch of the antechamber surface directly in the path of the incoming molecular beam. As explained earlier, we assume \( q_i(t + \Delta) \) to have the same shape versus time as the signals of other volatile species and set the amplitude of \( q \) (times the entrance orifice area \( A_0 = 2.173 \times 10^{-5} \text{ m}^2 \)) so that its time integral yields \( C/\alpha S \) times the total number of water molecules detected by INMS. \( C \) is the conductance for gas to escape the ionizer (4.1 \( \times \) \( 10^{-4} \text{ m}^3/\text{s} \)) for H2O at room temperature [Kasperzak, 2009]), \( \alpha = 0.08 \) is the transmittance to the ionizer, and \( S \) is the species-dependent INMS calibration sensitivity factor (~1.48 \( \times \) \( 10^{-10} \text{ m}^3/\text{s} \)) for water [Gell et al., 2009]). The derivation of the factor \( C/\alpha S \) is given in Appendix B. After mass 18 the strongest signals are seen in mass channels 2, 26, 28, and 44 (corresponding to H2, C2H2, CO and/or N2, and CO2 [Waite et al., 2009], as shown in Figure 6. Accordingly, we use these three channels to determine the shape of the source profile by normalizing (after background subtraction and removal of ice grain spikes) and then averaging the signals. The simulation best matches the data with an offset \( \Delta = -12 \text{ s} \). The requirement of an offset suggests either (1) that INMS encounters the water 12 s earlier than the other volatile species (unlikely) or (2) that there is a phenomenon not accounted for in the sticking model such as surface diffusion of adsorbed H2O, which would reduce the water transmission time through the inlet. Further refinement of the model in future work will include additional effects such as diffusion.

6. The INMS signal \( \chi \) (i.e., the count rate) is proportional to the density \( \rho \) of molecules inside the ionizer times the sensitivity:

\[
\chi = S\sqrt{T_i/T_0}\rho, \tag{A7}
\]

where \( S \) is the calibration sensitivity factor for water and \( T_i \) and \( T_0 \) are the ionizer temperature and room temperature, respectively. The correction for temperature is needed since \( S \) was measured in the laboratory with respect to an equilibrium room temperature gas density surrounding the instrument [Gell et al., 2009], which is different by a factor \( (T_i/T_0)^{1/2} \) from the density inside the ionizer. The flux per unit area \( F_i \) reentering the transfer tube (with \( i \) now denoting
only elements on the tube exit plane) is \(\sqrt{\text{v}/4}\) times the density \([\text{Gombosi, 1994}]\), and therefore,
\[
\rho = \frac{4F_i}{\sqrt{\text{v}}} \quad \text{for } i \text{ on exit plane,}
\] (A8)
where \(v\), the average speed of gas molecules in the ionizer, is given by
\[
v = \sqrt{\frac{8kT_i}{\pi m}},
\] (A9)
with \(m\) the molecule mass and \(k\) the Boltzmann’s constant. Using equations (A3), (A4), (A7), (A8), and (A9), one can express the count rate in terms of \(F_i\):
\[
\chi = \beta S \sqrt{\frac{2\pi m}{kT_0}} \sum_{\text{exit}} F_i v_i.
\] (A10)

Here we note that knowledge of \(T_i\) is not required for the model because it cancels from equation (A10).

[26] For \(S\) we use \(1.48 \times 10^{-10}\) m/s for water. This sensitivity is one third the value based on laboratory measurement: analyses show that the total densities derived by INMS in-flight data are consistently lower by a factor of around 3 than those determined by the navigation and attitude-control teams assessing the drag on the spacecraft at Titan (H. Niemann et al., personal communication, 2009). Although the cause of this difference is not certain, the requirement for an adjustment to the INMS sensitivities is clear. \(\beta\) is given by \(C_d/(C_e + C) = 0.97\), where \(C_e = \sqrt{4}/4\) is the gas conductance through the transfer tube exit and \(C_e^*\) is the conductance through all other ionizer escape paths (7.97 \(\times\) 10^{-2} m/s for H\(_2\)O at room temperature [Kasperzak, 2009]).

Appendix B

[27] In the discussion of the source function we multiply by the factor \(C/\alpha S\) to convert the integrated counts into the total number of molecules detected by the INMS, where \(C\) is the conductance for gas to escape the ionizer (4.1 \(\times\) 10^{-4} m/s for H\(_2\)O [Kasperzak, 2009]), \(\alpha = 0.08\) is the transmittance to the ionizer, and \(S\) is the species-dependent INMS calibration sensitivity factor [Gell et al., 2009]. Although we applied the factor for the case of H\(_2\)O, the relationship is valid for any species, provided that the correct \(S\) is used, and that \(C\) is corrected for the molecular mass. To derive the conversion factor we first note that the rate of change of gas density in the ionizer is given by
\[
\frac{d\rho}{dt} = \frac{Q}{V} - \sqrt{\frac{T_i}{T_0} C \rho / V},
\] (B1)
where \(Q\) denotes the arrival rate of molecules into the ionizer and \(V\) is the ionizer volume (0.512 cm\(^3\)) (P. Mahaffy, Goddard Space Flight Center, unpublished data, 2009). We now integrate equation (B1) between times \(t_0\) and \(t_1\)
\[
\rho(t_1) - \rho(t_0) = \frac{1}{V} \int_{t_0}^{t_1} Q dt - \sqrt{\frac{T_i}{T_0} C \int_{t_0}^{t_1} \rho dt}. \] (B2)


Porco, C. C., et al. (2006), Cassini observes the active South Pole of Enceladus, Science, 311(5766), 1393.


Waite, J. H., et al. (2009), Liquid water on Enceladus from observations of ammonia and 40Ar in the plume, Nature, 460, 487.