The water vapor plumes of Enceladus

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[1] The Cassini E3, E5, and E7 encounters with Enceladus probed the south polar plumes, where the Ion and Neutral Mass Spectrometer (INMS) measured neutral H2O molecular densities up to \( \sim 10^9 \) cm\(^{-3} \). We have constructed a physical model for the expected water density in the plumes, based on supersonic radial outflow from one or more of the surface vents. We apply this model to possible surface sources of water vapor associated with the multiple jets observed in the visible dust plumes. Our model predictions fit well with the INMS measurements of neutral H2O density along the E3, E5, and E7 trajectories. The fit is optimized by values of outflow velocity in the range \( \sim 550 − 750 \) m/s and values of total source rate in the range \( \sim 1.5 \) – \( 3.5 \times 10^{28} \) H2O molecules/s. The model can be extended to incorporate the jet features within the plume observed during the E7 encounter.


1. Introduction

[2] Enceladus is a small icy moon orbiting Saturn at 3.95 \( R_S \) and embedded in the neutral OH torus detected by the Hubble Space Telescope (HST) [Shemansky et al., 1993]. (\( R_S \) = Saturn’s equatorial radius \( \approx 60,268 \) km.) The models of Jurac et al. [2001, 2002] and Jurac and Richardson [2005] require a significant source of H2O molecules, up to \( 10^{28} \) per second, at Enceladus’ orbit [Jurac and Richardson, 2005], to account for the production of the OH torus. The Cassini spacecraft entered Saturn’s magnetosphere in 2004, and made three encounters with Enceladus in 2005, labeled E0, E1, and E2. The analysis of these encounters based on the Imaging Science Subsystem (ISS) images [Porco et al., 2006], UltraViolet Imaging Spectrograph (UVIS) observations [Hansen et al., 2006], and E2 Ion and Neutral Mass Spectrometer (INMS) data [Waite et al., 2006] has confirmed that a neutral H2O vapor plume emitted from the warm active south polar region of Enceladus is the missing H2O source suggested by Jurac et al. [2001, 2002, 2005], Johnson et al. [2006] showed that the plume H2O molecules orbit Saturn and form a narrow Enceladus torus peaking at the satellite’s orbit, and are subsequently scattered by charge exchange, neutral-neutral collisions, and dissociation to produce the much broader OH torus [see also Farmer, 2009; Cassidy and Johnson, 2010; Smith et al., 2010].

[3] Cassini INMS directly detected the H2O vapor plume during the E2 encounter, which had a closest approach of 168.2 km from Enceladus’ surface at 19:55:22 UT on 14 July 2005 (the trajectory is shown in Figure 1). Waite et al. [2006] analyzed the E2 INMS data, and suggested a total H2O source rate of \( 1.5 − 4.5 \times 10^{26} \) molecules/s from Enceladus. This source rate may be underestimated because of INMS instrumental effects [Teolis et al., 2010]. The UVIS observation of a stellar occultation by the Enceladus plume during E2 [Hansen et al., 2006] suggested a H2O loss rate of \( 5–10 \times 10^{27} \) molecules/s, depending on the temperature of the south pole source. Tian et al.’s [2007] modeling of this UVIS observation gave a total source rate of \( 4–6 \times 10^{27} \) molecules/s. Burger et al.’s [2007] modeling of both the INMS measurements and the UVIS observation during E2 gave a somewhat larger source \( \sim 10^{28} \) molecules/s.

[4] Individual jet features within the plume have also been observed in Cassini ISS images. Spitale and Porco [2007] studied such images taken in different viewing directions over two years and resolved eight possible dust jet source locations associated with the observed hot spots on the four “tiger stripes” in the Enceladus south polar region [Spencer et al., 2006; Porco et al., 2006]. The UVIS observation of an occultation of the star \( \zeta \) Orionis (Alnitak) by the plume on 24 October 2007 [Hansen et al., 2008] implied H2O gas jets from Enceladus’ south polar region associated with the dust jets suggested by Spitale and Porco [2007], and led to the inference of a total H2O flux from the eight sources \( \sim 6.5 \times 10^{22} \) molecules/s and a vertical bulk jet velocity \( \sim 609 \) m/s.

[5] Cassini’s more recent encounters with Enceladus, E3 (12 March 2008, closest approach 19:06:12 UT), E5 (9 October 2008, c/a 19:06:43 UT), and E7 (2 November 2009, c/a 07:42:00 UT), got much closer to the plume source and produced exciting INMS measurements of the neutral H2O density (trajectories shown in Figure 1). The original data sets from the Planetary Data System (PDS) imply a decrease of the H2O density with distance from the source that was much slower than expected on the basis of radial (albeit angularly anisotropic) expansion from the presumed...
source region. This discrepancy was interpreted as the effect of H₂O vapor absorption by the instrument wall. A Monte Carlo simulation study was used to remove this instrumental effect from the measurement [Teolis et al., 2010], and provided a new version of neutral H₂O density data for the E3 and E5 encounters. Based on the new INMS data, Smith et al.’s [2010] modeling of the neutral H₂O density in the plume requires a total source rate ~6.3 × 10²⁷ molecules/s for E3 and 2.5 × 10²⁸ molecules/s for E5. Tenishev et al.’s [2010] modeling of the new E3 and E5 INMS data and the E2 UVIS data gives a total source rate ~2.6 × 10²⁸ molecules/s.

Several simulation models, as mentioned above, have been applied to Enceladus plume observations (Tian et al. [2007], modeling E2 UVIS observations; Burger et al. [2007], modeling E2 UVIS and INMS observations; Smith et al. [2010], modeling E2, E3, and E5 INMS observations; and Tenishev et al. [2010], modeling E3 and E5 INMS and E2 UVIS observations). In this paper we introduce an analytical physical model of supersonic outflow from a number of specified south polar sources, and we compare the model predictions with E2, E3, E5, and E7 encounter INMS data to infer the required total source rates and outflow velocities from each source. This model was presented by Dong and Hill [2009a, 2009b, 2009c] and Dong et al. [2010]. Tenishev et al. [2010] developed a similar semi-analytical model in their analysis of E3 and E5 INMS and E2 UVIS measurements. The latter paper assumed a flowing Maxwellian velocity distribution equivalent to our equation (1). It did not show an analytic expression for the plume density distribution, but it would presumably be equivalent to our equation (2).

2. Model Description

2.1. Single-Source Model

[7] The multiple jets observed in the visible dust plume [Spitale and Porco, 2007; Hansen et al., 2008] suggest that there are several discrete sources of water vapor at the surface of Enceladus in the south polar region. In this section and in section 2.2, we describe a simple model with a single small point-like source at the south pole. In section 2.3 we generalize this to a multiple-source model.

[8] We assume a radially flowing Maxwellian velocity distribution at the source:

\[ f_s(\vec{v}) = \frac{n_s}{\pi^{3/2} v_{th}^3} \exp\left\{ -\left[ v_x^2 + v_y^2 + (v_z - v_0)^2 \right]/v_{th}^2 \right\}, \]  

(1)

where \( n_s \) is the number density at the source, \( v_0 \) is the flow speed, and \( v_{th} = \sqrt{2kT/m} \) is the thermal speed. The origin is at the center of the source, and the \( z \) axis points in the Enceladus radial direction. Outside the source within a range of tens of Enceladus radii, we assume there are no collisions and neglect Enceladus’ gravity. (The effect of neglecting gravity is discussed in section 6.) Thus the molecules move in straight radial lines from the source. For example, the molecules at the point \((x, 0, z)\) must have the velocity direction given by \( v_x = 0 \) and \( v_{th}/v_{th} = \sqrt{2z} = \tan(\theta) \), as shown in Figure 2, in order to be observable in the \( x-z \) plane. Thus we can derive the density distribution outside the source (see the appendix for the derivation):

\[ n(r > r_s, \theta, M) = \frac{n_s r_s^2}{\pi^{3/2}} \frac{2M \cos \theta}{\sqrt{\pi}} e^{-M^2} \]

\[ + e^{-M^2 \sin^2 \theta} \left[ 1 + 2M^2 \cos^2 \theta \right] \left[ 1 + \text{erf}(M \cos \theta) \right] \]  

(2)

where \( M \equiv v_0/v_{th} \) is the thermal Mach number, the ratio of flow speed to thermal speed. This distribution depends on the distance \( r \) from the source as well as the angle \( \theta \) from the flow direction. The factor \((r_s/r)^2\) accounts for the radial, but not isotropic, expansion from the source. Equation (2) is valid for \( \theta \in [0, \pi] \), if the source is in vacuum. For a source on Enceladus’ surface, \( n(r, \theta, M) = 0 \) for \( \theta \in [\pi/2, \pi] \), accounting for the source molecules lost by impacting Enceladus’ surface.
[9] Our objective is to infer the flow velocity and the total source rate from data-model comparison. The \( n_s r_s^2 \) is the scale factor of equation (2). The total source rate is proportional to \( n_s r_s^2 \), and also depends on the thermal Mach number \( M \) (see section 4). This model is independent of the value of \( r_s \) as long as \( r \gg r_s \). Hence we define a source parameter \( S = n_s r_s^2 \). The two parameters to be determined from the data fitting are then \( S \) and \( M \).

[10] For the single-source model we put the point-like source at the south pole of the satellite. The shape of the density distribution depends only on the value of the thermal Mach number. \( M = 0 \) gives a hemispherical expansion from the source (Figure 3a). For large thermal Mach numbers, \( M = 10 \) for example, the distribution becomes more like a narrow beam (Figure 3b). For \( M = 2 \), the source produces a plume-like distribution (Figure 3c) over the south pole, which resembles the ISS image of Enceladus’ dust plume (Figure 3d). This visual comparison gives us a general idea of the expected value of the best fit thermal Mach number.

Figure 2. A source particle is assumed to travel in a straight line in the \( x-z \) plane to the point \((x, 0, z)\). The \( z \) axis points south. The \( \theta \) is the angle between the particle trajectory and the \( z \) axis.

Figure 3. (a–c) Model plots of the distribution of \( \text{H}_2\text{O} \) vapor density of the plume with different thermal Mach numbers. (d) The ISS image (NASA JPL/Goddard Space Flight Center/Southwest Research Institute/ISS) of the Enceladus dust plume.
This single-source model resembles the general shape of the visible plume, but misses the detailed jet features (see section 3).

2.2. Global Spherical Expansion and Background Density

INMS detected neutral H$_2$O densities up to nearly 10$^6$ cm$^{-3}$ [Waite et al., 2006] during the E2 encounter. However, the E2 trajectory does not really probe the dense part of the plume (see Figure 1). The more symmetric nature of the inbound and outbound parts of the E2 data (Figure 4) compared to the E3 (Figure 5) and E5 (Figure 6) data, and the small increase of H$_2$O density before the spacecraft entered the plume in the E3 and E5 data sets (Figures 5 and 6) suggests that E2 encountered primarily a global spherical expansion of H$_2$O vapor from Enceladus’ surface. Thus we added a global expansion term [Waite et al., 2006; Burger et al., 2007; Tenishev et al., 2010] to our model:

$$n_0 \left( \frac{R_E}{R} \right)^2,$$

where $n_0$ is the uniform component of the H$_2$O density at Enceladus’ surface and $R$ is the distance from Enceladus’ center. Considering the existence of an Enceladus neutral torus [Johnson et al., 2006], we also added a uniform background density $n_{bg}$ [Burger et al., 2007; Tenishev et al., 2010]. The distribution of the H$_2$O density near Enceladus orbit is more complicated than a uniform background, but within about 30 $R_E$ (~0.1 $R_S$) from Enceladus, where the

$M \sim 2$. This single-source model resembles the general shape of the visible plume, but misses the detailed jet features (see section 3).

Figure 4. INMS data from Planetary Data System of the H$_2$O density (cm$^{-3}$) profile along the E2 trajectory compared with the single-source model prediction. The black line shows the data with error bars. The dotted line shows the plume density with $M = 0$ and $S' = 2.4 \times 10^{21}$ cm$^{-4}$. The dashed line shows the plume density with $M = 3$ and $S' = 8.0 \times 10^{21}$ cm$^{-4}$. The blue line shows the sum of the global expansion density and the background density, with the best fit values of $n_0 = 5.7 \times 10^5$ cm$^{-3}$ and $n_{bg} = 1.6 \times 10^4$ cm$^{-3}$. The red line shows the sum of these two terms plus a plume density having $S' = 8.0 \times 10^{20}$ cm$^{-4}$ and $M = 2.5$.

Figure 5. E3 data-model comparison. The black line is E3 INMS data. The error bars are shown only for some data points to avoid clutter. The blue line shows a chi-square fit with the multiple-source model (plume parameters in Table 1, $n_0 = 7.4 \times 10^5$ cm$^{-3}$, and $n_{bg} = 3.3 \times 10^4$ cm$^{-3}$). The red line shows a larger background density ($3 \times 10^5$ cm$^{-3}$) on the outbound trajectory.

INMS data sets studied in this paper were taken, it should not vary too much (see the E3 and E5 inbound data in Figures 5 and 6). In this paper we focus more on the plume, and the assumption of a uniform background is sufficient to give an estimate of the order of magnitude of the background density near Enceladus.

[12] Perry et al. [2010] analyzed the INMS measurements of the neutral species near Enceladus’ orbit at different orbital phase angles from Enceladus. A comparison of the

Figure 6. E5 data-model comparison in the same format as that of Figure 5. The black line is E5 INMS data. The blue line shows a chi-square fit with the multiple-source model (plume parameters in Table 1, $n_0 = 7.2 \times 10^5$ cm$^{-3}$, and $n_{bg} = 2.1 \times 10^4$ cm$^{-3}$). The red line shows a larger background density ($4 \times 10^5$ cm$^{-3}$) on the outbound trajectory.
2.3. Multiple-Source Model

[14] Examination of the jets observed in the visible Enceladus dust plume in Cassini ISS images [Spitale and Porco, 2007] has suggested eight possible sources associated with the hot spots on the tiger stripes. Sources 1, 2, 3, and 6 (corresponding to the Roman numerals of Spitale and Porco’s [2007] paper), all on the Baghdad and Damascus lineaments, are believed to be the strongest candidate dust sources, for they have been identified in a large number of observations of the dust jets and lie near the “tiger stripes.” The UVIS stellar occultation observation [Hansen et al., 2008] implies the association of water vapor jets with the dust jets. In accordance with these results, we have constructed a multiple-source model, a linear superposition of single-source models as described in section 2.1.

[15] The eight possible jet source locations suggested by Spitale and Porco [2007] have been applied to different plume models by Saur et al. [2008], Smith et al. [2010], and Tenishev et al. [2010]. In Smith et al.’s [2010] model, the eight sources are assumed to be identical, for their modeling results are not very sensitive to the variation among different sources. In Saur et al.’s [2008] and Tenishev et al.’s [2010] models, the parameters of each source are allowed to be different and are determined by fitting.

[16] For our model, we have tried a single source at the south pole, eight identical sources, and the four strongest candidate sources suggested by Spitale and Porco [2007], to fit E3 and E5 INMS data. Applying the four strongest candidate sources (sources 1, 2, 3, and 6) gives a better fit than the other two choices with both E3 and E5 data, especially in the region close to the plume sources (see 0–300 s after the closest approach for E3 and 0–200 s after the closest approach for E5 in Figure 7). We also tried applying the nonvertical dust jet directions suggested by Spitale and Porco [2007] to the source flow velocity directions in our model. For nonvertical jets, equation (2) in section 2.1 is still valid if we set the \( z \) direction (\( \theta = 0 \)) to be the jet direction (flow velocity direction). And equation (2) is valid for \( \theta \in [0, \pi] \), if the source is in vacuum. But in this case we need to set the density to be zero below the tangent plane to Enceladus surface at the source location, accounting for the source molecules lost by impacting Enceladus surface. The results show that using the tilted jet directions suggested by Spitale and Porco [2007] does not fit E3 and E5 data as well as using vertical flow velocities. Thus, in our model, we assume that sources 1, 2, 3, and 6 are the four main sources, and that the flow velocity from each source is in Enceladus’ radial direction. The \( \text{H}_2\text{O} \) density distribution of the plume can be expressed as

\[
    n = \sum_i n_i(\mathbf{r}_i'),
\]

where the summation index \( i \) represents one of the eight possible sources, \( \mathbf{r}_i' \) means the position relative to source \( i \), and each term in the summation follows equation (2) in section 2.1. The source parameter \( S' \) and the thermal Mach number \( M \) are first assumed to be the same for each source, which works fine for E3 and E5 fitting. But we adjust these original assumptions for the sources to fit with E7 data (section 3.3). To calculate the total \( \text{H}_2\text{O} \) vapor density near…
Table 1. Best Fit Values of All Model Parameters for E3, E5, and E7

<table>
<thead>
<tr>
<th>Encounter</th>
<th>Sources</th>
<th>$M = v_{bg}/v_{th}$</th>
<th>$S'$ of Each Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3, 12 March 2008</td>
<td>1, 2, 3, 6</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>E5, 9 October 2008</td>
<td>1, 2, 3, 6</td>
<td>1.4</td>
<td>3.2</td>
</tr>
<tr>
<td>E7, 2 November 2009</td>
<td>1, 2, 3, 4</td>
<td>1.8</td>
<td>0.95 (1, 2, 3)$^a$, 1.8 (4)$^b$</td>
</tr>
</tbody>
</table>

$^a$From the chi-square fitting. The numbers in parentheses represent the sources.
$^b$From equating the model and data peak values.

Enceladus, the global expansion term (equation (3)) and the background density $n_{bg}$ are also included.

3. INMS Data-Model Comparison

We compare our model predictions with the INMS data sets of the four encounters E2, E3, E5, and E7.

3.1. E2 Data-Model Comparison

Unlike the other three encounters we study, the E2 trajectory hardly intersected the visible dust plume (see Figure 1), so there is no need to apply the multiple-source model for E2 fitting. Figure 4 shows the comparison of E2 data and the single-source model. For any thermal Mach number, the plume density profile cannot be as symmetric as the E2 data (see the dotted and dashed lines in Figure 4, corresponding to $M = 0$ and $M = 3$, respectively). We therefore conclude that INMS detected mostly the global expansion of H$_2$O molecules from Enceladus’ surface (equation (3)) and the background density $n_{bg}$ during E2. This explains the more symmetric inbound and outbound parts of the E2 data signature compared to E3, E5, and E7. The blue line in Figure 4 shows the result of a chi-square fitting to the sum of the global expansion and background density terms. The best fit values are $n_0 = 5.7 \times 10^5$ cm$^{-3}$ and $n_{bg} = 1.6 \times 10^5$ cm$^{-3}$. If we add a plume density term with $S' = 8.0 \times 10^{20}$ cm$^{-3}$ and $M = 2.5$ for example (red line in Figure 4), there is no obvious improvement of the fit before closest approach, and no difference after closest approach. We conclude that the global expansion source density $n_0$ and the uniform background density $n_{bg}$ were the dominant contributions along the E2 trajectory, even though the plume source rate may have been significantly larger than the global source rate (see section 4), because the E2 trajectory did not probe into the dense part of the plume.

The results of fitting with E2 data may be unreliable for two reasons: the E2 trajectory did not probe the plume, and the INMS instrumental effect [Teolis et al., 2010] has not yet been removed from the PDS version of the E2 data used here. This implies not only an underestimate of the source rate, but also a possible distortion of the density profile (M. E. Perry, private communication, 2010). The results of the E2 comparison give, at best, an estimate of the orders of magnitude of the three terms in our model.

3.2. E3 and E5 Data-Model Comparison

We use the multiple-source model to compare with the new versions of the E3 and E5 INMS data provided by Teolis et al. [2010]. E3 and E5 have similar trajectories, grazing the fringes of the visible dust plume and going from north to south. In each case, the spacecraft entered the plume just after closest approach. There is a sharp increase of the H$_2$O density after closest approach in both E3 and E5 data (see Figures 5 and 6). Before closest approach, the INMS measured primarily the global expansion and background densities. After closest approach, the plume density is dominant.

We first applied a chi-square fitting procedure to the sum of global expansion and background densities for each of the E3 and E5 inbound data sets, where we assume the data are not affected by the plume. This gives best fit values $n_0 = 7.4 \times 10^5$ cm$^{-3}$ and $n_{bg} = 3.3 \times 10^4$ cm$^{-3}$ for E3, and $n_0 = 7.2 \times 10^5$ cm$^{-3}$ and $n_{bg} = 2.1 \times 10^4$ cm$^{-3}$ for E5. We then set $n_0$ and $n_{bg}$ to be fixed at these levels, and applied a chi-square fitting procedure for the plume source parameters $S'$ and $M$ for each of the E3 and E5 outbound data sets. The best fit values of all parameters are shown in Table 1. Figures 5 and 6 show the comparison of the model with the E3 and E5 data sets. The assumption of four main sources (sources 1, 2, 3, and 6) works well for both E3 and E5 data, and the best fit values of the parameters are quite consistent between E3 and E5.

The best fit values of the thermal Mach number $M$ are 1.4–1.6, and the best fit source parameters $S'$ are of the same order of magnitude, $\sim 10^{22}$ cm$^{-3}$. The CIRS detected a temperature of 145K or higher in the south pole troughs [Spencer et al., 2006], and Spencer et al. [2006] suggested an inferred source temperature of 180K or higher if the plume source is the sublimation of water ice and is visible to CIRS. In our model we use 180K as the source temperature. The thermal Mach number $M \sim 1.4–1.6$ then implies a flow velocity at the source of about 550–650 m/s, consistent with the 609 m/s inferred from UVIS observations [Hansen et al., 2008] and the 520–700 m/s from fitting with the E3 and E5 INMS data and E2 UVIS data [Tenishev et al., 2010], and also roughly consistent with Smith et al.’s [2010] result of 720 m/s from E2, E3 and E5 INMS data. All these inferences indicate that most plume particles have velocities considerably larger than the escape velocity (239 m/s), which justifies the neglect of Enceladus’ gravity in our model (see also section 6).

The model predicted density begins to deviate from the data in the more distant portion of the outbound trajectory for both E3 and E5 (after about 300 s in Figure 5 and after about 200 s in Figure 6). This discrepancy is removed if we allow the background density on the outbound trajectories to be different from that inbound, namely, $n_{bg} = 3 \times 10^5$ cm$^{-3}$ for the E3 outbound trajectory and $n_{bg} = 4 \times 10^4$ cm$^{-3}$ for the E5 outbound trajectory, as indicated by the red lines in Figures 5 and 6. These outbound background densities would be 10–20 times larger than those derived from the respective inbound data. The E3 and E5 trajectories both go from north to south. Given that our model gives good predictions of the plume density and assuming that the far outbound disagreements result from the background density, this result might imply a larger background density in the southern hemisphere near Enceladus than in the north. The azimuthal and vertical neutral density distribution near Enceladus orbit has been studied by Perry et al. [2010] on
the basis of INMS measurements, but the background density near Enceladus’ southern hemisphere is not yet clear because of the dominant plume density in that region. The outbound discrepancy may be due to a larger background density in the southern hemisphere near Enceladus, or possibly some other systematic spatial variation of the background density near Enceladus.

3.3. E7 Data-Model Comparison

[24] The E7 trajectory got much closer to the sources in the south polar region than E3 and E5 (see Figure 1). There are at least two main peaks in the E7 INMS data shown in Figure 8, which may indicate jet features in the vapor plume near Enceladus’ surface. To investigate which sources may contribute to the peaks in the E7 data, we plot the H$_2$O density profiles that would be produced by each single source with a thermal Mach number $M \sim 1.5$ (as derived from E3 and E5) to compare with E7 data (Figure 8). This comparison suggests that source 4 may be the most likely one to account for the second main peak in the E7 data, and that some combination of the other sources may produce the first peak.

[25] The E7 data show densities at least tens of times larger than the background and global expansion densities that we have estimated from E3 and E5. In this region the plume density is clearly dominant, so we use these data points to fit for the plume source parameters $S'$ and $M$. First we stay with our assumption of the four main sources, 1, 2, 3, and 6, but add another source 4 and allow a different source strength $S'$ for source 4. The dashed blue line in Figure 9 shows a chi-square fit with sources 1, 2, 3, and 4. The peak values of the model from chi-square fitting are smaller than the data, because there are many more data points at lower values than near the peaks, and the positions of the peaks do not match the data exactly. We also performed a fit by equating the peak values of the model and data, as shown by the red line in Figure 9. The fit values of all the parameters from E7 fitting are shown in

Figure 8. E7 INMS data compared with each source. The black diamonds are INMS data. The color lines show the density profiles produced by each of the eight sources separately with the thermal Mach number $M \sim 1.5$ (as estimated from E3 and E5) and a source strength $S'$ adjusted to equate the peak values of the model and the data.

Figure 9. E7 data-model comparison. The black line is the data with error bars. The dashed blue line shows a chi-square fit with sources 1, 2, 3, and 4. The solid blue line is the result of a chi-square fitting excluding source 6, with parameters in Table 1. The red line shows the same fit after equating the peak values of the model and data (parameters in Table 1).
Table 1. The thermal Mach number $M$ is $1.8$ ($v_0 = 730$ m/s), and the source parameter $S'$ is $\sim 10^{-22}$ cm$^{-2}$ for each source, both generally consistent with E3 and E5. The fit value of $S'$ for source 4 is larger than that for the other three sources.

[26] Figure 10 shows the model plot of the H$_2$O density distribution with the fit values of the parameters for E7 (marked with footnote b in Table 1). This cross section is in the same plane as the E7 trajectory. Sources 1, 2, and 3 together, and source 4 separately, produce the two separate parts of the plume near Enceladus’ surface in this plane. This multiple-source model plot with $M = 1.8$ resembles the ISS image (Figure 3d) better than our previous single-source model plot with $M = 2$. It shows some detailed features at lower altitude similar to those in the ISS image.

[27] There is a small disagreement (~5s) between model and data in the timing of the second main peak. We have used the source location suggested by Spitale and Porco [2007] and assumed the flow velocity to be in the radial direction at each source. There are two possible ways to remove this disagreement: applying a tilted jet direction or adjusting the source location.

[28] According to Spitale and Porco’s [2007] study of the ISS images of the jets, the dust jet from source 4 is actually quite nearly vertical, with a possible zenith angle of only $3.7^\circ$, which makes no visible difference for the second main peak in our E7 model plot. The water vapor jets may not be exactly aligned with the visible dust jets, and either or both may be time variable. But if we adjust the flow velocity direction of source 4 to tilt by $25^\circ$ directly toward the surface projection ([160.3$^\circ$W, 79.7$^\circ$S]) of the position of the second main peak in E7 data (for tilted jets, using the approach described in section 2.3), which is $196.4^\circ$ azimuth clockwise from the local north of source 4 and $25^\circ$ zenith according to the coordinates used by Spitale and Porco [2007], it can predict a timing of the second main peak that exactly matches the INMS data (see the red line in Figure 11).

4. Source Rate

[31] The source rate is defined as the total number of H$_2$O molecules emanating from a given source per unit time. It is an important parameter that describes the strength of the source. Using the velocity distribution $f(r, \theta, v_r)$
Table 2. Source Rates for E3, E5, and E7*  

<table>
<thead>
<tr>
<th>Encounters</th>
<th>E3</th>
<th>E5</th>
<th>E7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources</td>
<td>1, 2, 3, 6</td>
<td>1, 2, 3, 4</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>Total source rate (10^28/s)</td>
<td>0.95−1.2</td>
<td>0.59−0.70</td>
<td>1.9−2.2</td>
</tr>
<tr>
<td>Mass-loading rate (kg/s)</td>
<td>1100</td>
<td>700</td>
<td>1700</td>
</tr>
</tbody>
</table>

*The lower limit of the source rate and mass-loading rate for E7 is calculated with the parameters from the chi-squared fitting (marked “a” in Table 1), and the upper limit is calculated with the parameters from equating the peak values of the model and data (marked with footnote b in Table 1).

Where $S = n_s r^2$ and $M \neq 0$. With the best fit values of the thermal Mach number $M$ and source parameter $S$ (Table 1), and using the source temperature 180K (see section 3.2), we obtain the values of the total source rate for the three encounters shown in Table 2. The total source rates for E3 and E7 fall within a tight range near 1.7 × 10^28 molecules/s. The source rate for E5 is about 2 times higher, ~3.5 × 10^28 molecules/s. The corresponding mass loading rates are ~500 kg/s for E3 and E7, and ~1000 kg/s for E5. The global expansion source rate from E3 and E5 inbound fitting is ~10^26 molecules/s, which is an insignificant contribution to the total source rate for E3, E5 and E7. Our inferred total source rate, based on the most recent INMS data analysis of the E3, E5, and E7 encounters, is significantly larger than the estimate 1.5−4.5 × 10^28 molecules/s based on the E2 encounter [Waite et al., 2006], which is not surprising given that E2 did not really intersect the plume and that the INMS instrumental effect is not yet removed from E2 data. Our fitting results for E2 data in section 3.1 also lead to a total source rate of 10^26−10^27 molecules/s (a plume source rate <10^27 molecules/s and a global source rate ~10^26 molecules/s), consistent with Waite et al.’s [2006] result from E2 data. However, as discussed in section 3.1, the E2 encounter data may not provide good estimates of the plume source.

[32] Our estimates of the total source rates from E3, E5, and E7 (see Table 2) are larger than, but generally consistent with, the values 0.5−1 × 10^28 and 6.5 × 10^27 molecules/s derived from two UVIS stellar occultation measurements [Hansen et al., 2006, 2008], with Burger et al.’s [2007] modeling result ~10^28 molecules/s, and with the “missing source” ~10^28 molecules/s suggested by the HST modeling study of Jurac and Richardson [2005]. It is more consistent with the results based on the new E3 and E5 INMS data, 2.6 × 10^28 molecules/s [Tenishev et al., 2010] and 6.3 × 10^27 for E3, 2.5 × 10^28 for E5 [Smith et al., 2010].

5. Comparison With UVIS Observations

[33] In the previous sections, we have shown that our results of the plume flow velocity and the total source rate are generally consistent with the UVIS results [Hansen et al., 2006, 2008]. More specifically, we also show a rough comparison with the column densities measured by UVIS from a stellar occultation on 24 October 2007 [Hansen et al., 2008]. During this occultation, the ray from UVIS to the star is nearly tangent to Enceladus south polar surface, with a closest distance to the limb of 15 km. The column densities measured by FUV are 1.26 × 10^16 cm^-2 and 1.36 × 10^16 cm^-2 in two 5s time spans, and the maximum column density measured by HSP at ~15 km altitude is 2.6 × 10^16 cm^-2.

[34] First we consider the case where the source radius $r_s \ll h = 15$ km. In this region our plume density model equation (2) would be valid. Assuming a horizontal line crossing the center of a vertical plume, with the closest distance of $h = 15$ km to the source, the column density along this line would be an estimate of the order of magnitude of the UVIS results above. It can be calculated as: $N_c = \frac{n(S)}{h \cos \theta, M \Delta h \tan \theta}$. The actual UVIS line of sight with a closest distance to Enceladus limb ~15 km may not exactly intersect the center of a plume, or it may cross more than one plume’s dense part at a time. So $N_c$ may not be exactly the column density along the UVIS line of sight, but they should be of the same order of magnitude. Letting $M = 1.6$ (an average value from E3, E5 and E7 results), this integral can be calculated numerically: $N_c \approx 3.97 S/h$. Our best fit values for $S$ from INMS data are in the range 1−3 × 10^22 cm^-1 for each source, which gives $N_c \approx 2.6−7.9$ × 10^16 cm^-2. The upper limit comes from the best fit value of $S$ from E5, which may be a more active time for the sources than usual (see section 6). Thus $N_c$ is likely to be closer to 2.6 × 10^16 cm^-2 than the upper limit. It is roughly consistent with the UVIS results [Hansen et al., 2008].

[35] If the source radius $r_s$ is comparable to $h = 15$ km, the ray to the star is getting very close to the sources or may even intersect some, which would make equation (2) invalid in this region. Then a better estimate of the column density along the UVIS line of sight would be $N_c = n_s(2r_s) = 2S/r_s$. The estimates of $r_s \sim h = 15$ km and the best fit values of $S \sim 1−3 \times 10^{22} cm^{-1}$ give the order of magnitude estimate $N_c \sim 1.3−4.0$ × 10^16 cm^-2, which is still consistent with the UVIS results [Hansen et al., 2008].

[36] Thus in both cases, independent of the source size, our model predictions are generally consistent with the UVIS measurements reported by Hansen et al. [2008].

6. Summary and Discussion

[37] We have constructed an analytical multiple-source model for the H2O vapor density in the Enceladus plume, which can be fit quite well to the INMS data for the E3, E5, and E7 encounters. We obtain reasonable best fit values of the source rate $S$, the flow velocity $v_0$, the background density $n_{bg}$, and the global expansion source density $n_0$. We have also calculated the total source rate of H2O molecules
from the model. Our results suggest a flow velocity of 550–750 m/s (thermal Mach number 1.4–1.8) from the source, and a total source rate \( \sim 1.5 \times 3.5 \times 10^{28} \) molecules/s, with an assumed source temperature of 180K. If the source temperature is 140K, both results should be reduced by 12%.

We assumed that the four main sources (sources 1, 2, 3, and 6) identified by Spitalie and Porco [2007] for the visible dust jets are also the main sources of water vapor jets. This assumption works well in fitting E3 and E5 encounter INMS data. Many more (\( \sim 30 \)) dust jets, all from the tiger stripes, have been identified in recent higher-resolution ISS images [Porco et al., 2010], and some of the individual source locations identified by Spitalie and Porco [2007] were found to resolve into multiple sources in the higher-resolution images. The fact that our model fits E3 and E5 data better with just the four main sources 1, 2, 3, and 6 (all on the two tiger stripes Baghdad and Damascus) than with a single source or with eight identical sources may imply that the sources on Baghdad and Damascus are generally more active than other sources, at least during the E3 and E5 encounters [cf. Saur et al., 2008; Tenishev et al., 2010].

Our results for the E3 and E5 encounters are generally consistent with those of Tenishev et al. [2010], who employed a similar model. Tenishev et al. [2010] suggested that sources 1, 2, 3, and 7 are the major contributors to the plume. We agree on sources 1, 2, and 3. We find that sources 6 and 7 are virtually distinguishable on E3 and E5; the combination (1, 2, 3, 6) produces a slightly better chi-square fit for E3 while (1, 2, 3, 7) produces a slightly better fit for E5, but the difference is barely visible in the plots. However, sources 6 and 7 both lie on the Baghdad lineament, so we are in general agreement with Tenishev et al. [2010] in concluding that sources on the Baghdad and Damascus stripes were more significant than other candidate sources during the E3 and E5 encounters.

Our E7 fitting requires a strong source 4 (or at least a strong source nearby) to account for the second main peak in the INMS data. The water vapor jet from source 4 was also observed by UVIS in the stellar occultation reported by Hansen et al. [2008]. Adding a source 4 in our model does not, however, fit well with E3 and E5 data, which may imply an increase in the intensity of source 4 between the E3 and E5 encounters (March and October 2008) and the E7 encounter (November 2009). Our result for the E5 source rate is about 2 times larger than those for E3 and E7. Smith et al.’s [2010] model also shows a significantly higher source rate for E5 than for E3, by about a factor of 4. Their model simulates the \( \text{H}_2\text{O} \) molecules ejected from Enceladus and evolving in Saturn’s magnetosphere for several months. It shows that, with the higher source rate derived from E5, the density of the long-lived \( \text{H}_2\text{O} \) molecules orbiting Saturn near Enceladus (corresponding to the background density in our model) will also be increased. They obtain a better fit with E5 outbound data than with E5 inbound data. The comparison of E3 and E5 inbound measurements with Smith et al.’s [2010] model is also shown by Perry et al. [2010], who indicate that the source rate derived from E3 may be closer than that derived from E5 to the average source rate. Our result for the source rate from E7 also falls back to the same level as E3.

We have neglected Enceladus’ gravity in our model. Our derived flow velocity, 550–750 m/s is significantly larger than the escape velocity at Enceladus’ surface, 239 m/s. Particles with velocity smaller than 239 m/s, which will fall back to Enceladus, account for <1% of our total source rate. For other particles that can escape from Enceladus, the gravity field changes the direction and magnitude of their velocities. A simple numerical study of the particles’ motion under Enceladus gravity (tracking a plume particle with representative initial velocities, such as 239 m/s, \( 2 \times 239 \) m/s, \( v_0 \), etc.) shows that particles with velocity 2 times the escape velocity or larger, which contribute >90% of our total source rate, stay within \( \sim 2^\circ \) of a straight line from the source in the region \( \theta \sim 30^\circ \) (with \( \theta \) defined in section 2 and Figure 2), where INMS measured the dense plume. The data we study in this paper were taken within a range of about 30 \( R_E \) from Enceladus. In this region, the change of the velocity magnitude due to gravity is \( \sim 7\% \) for particles starting with the flow velocity \( \sim 650 \) m/s (an average of the results from the three encounters), and \( \sim 10\% \) for particles starting with a velocity 2 times the escape velocity. Thus the real flow velocity at the source may be slightly larger than that we derived. The numerical trajectory analysis shows that neglecting gravity is an acceptable approximation in our model. We estimate the error due to neglect of Enceladus gravity to be \( \sim 10\% \) for both the flow velocity and the source rate.

The formal error bars from the chi-square fitting procedure are quite small, \( \sim 1–2\% \) for both the thermal Mach number \( M \) and the source parameter \( S' \). We suggest a subjective error bar \( \sim 10\% \) for both \( M \) and \( S' \) because, if either parameter is changed by 10%, there is a noticeable change (at least \( \sim 10\% \)) in the \( \chi^2 \) (see Table 3). So the estimated error bar from fitting is \( \sim 10\% \) for \( M \), and \( \sim 15\% \) for the source rate (derived from error bar propagation from \( M \) and \( S' \)). Including the effect of neglecting gravity, we estimate a total error bar \( \sim 20\% \) for the thermal Mach number and \( \sim 30\% \) for the source rate.

Our estimate of the neutral \( \text{H}_2\text{O} \) vapor loss rate from Enceladus (\( \sim 500 \) kg/s for E3 and E7, \( \sim 1000 \) kg/s for E5) is larger, but not very much larger, than independent empirical estimates of the net rate of production and outward transport of water-group ions from Saturn’s inner magnetosphere [Pontius and Hill, 2006, 2009; Chen et al., 2010]. This comparison suggests that a significant fraction of the neutral cloud content is not lost from the magnetosphere by ballistic neutral escape following charge exchange, but by ionization and subsequent radial plasma transport, as suggested by Johnson et al. [2006].

**Appendix A**

Assume a radially flowing Maxwellian velocity distribution at the outer edge of a hemispherical source \( (r = r_s) \):

\[
f(r_s, \mathbf{v}) = \frac{n_s}{\pi^{3/2} v_{th}^3} \exp\left[-\frac{(v_x^2 + v_y^2 + (v_z - v_0)^2)}{v_{th}^2}\right],
\]

where \( n_s \) is the number density at the source, \( v_0 \) is the flow speed, and \( v_{th} = \sqrt{2kT/m} \) is the thermal speed. The origin is placed at the center of the source, and the \( z \) axis points in the Enceladus radial direction. Outside the source within a range of tens of Enceladus radii, we assume there are no collisions.
and neglect Enceladus’ gravity. (The effect of neglecting gravity is discussed in section 6.) Thus the molecules move in straight lines from the source. The assumed distribution (equation (A1)) is isotropic in the x-y plane, so we can consider only the x-z plane (Figure 2) without loss of generality. It is useful to transform equation (A1) into a cylindrical polar coordinate system (r, θ, y) whose polar axis is the y axis of the Cartesian system (see Figure 2). The coordinate transformation is

\[
\begin{pmatrix}
  z \\
  x \\
  y
\end{pmatrix} = \begin{pmatrix}
  r \cos \theta \\
  r \sin \theta \\
  y
\end{pmatrix},
\]

(A2)

and the velocity transformation is

\[
\begin{pmatrix}
  v_z \\
  v_x \\
  v_y
\end{pmatrix} = \begin{pmatrix}
  \cos \theta & -\sin \theta & 0 \\
  \sin \theta & \cos \theta & 0 \\
  0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
  v_r \\
  v_\theta \\
  v_y
\end{pmatrix}.
\]

(A3)

The Jacobian determinant of the velocity transformation is ±1, so

\[
\int f(v_z, v_x, v_y) dv_z dv_x dv_y = \int f(v_r, v_\theta, v_y) dv_r dv_\theta dv_y.
\]

(A4)

In terms of (r, θ, y) coordinates, the square-bracketed term in equation (A1) becomes

\[
v^2_r + v^2_\theta + (v_z - v_0) = (v^2_r - 2v_0 v_r \cos \theta) + (v^2_\theta + 2v_0 v_\theta \sin \theta)
+ v^2_y + v^2_0,
\]

(A5)

where the right-hand side is grouped into the first two terms in parentheses (dependent only on v_y), the second two terms in parentheses (dependent only on v_0), a third term dependent only on v_y, and a fourth (v_0) term which is constant.

[46] The cylindrical polar coordinate system facilitates the specification of the constraints that apply to molecules observable near the xz plane (= rθ plane). For a true mathematical point source at the origin (r/θ = 0), the mathematical constraints would be v_r/v_θ = 0 and v_θ/v_φ = 0 for r > r_s, and the Maxwellian distribution could be replaced by a Dirac delta function. But this approach would miss important corrections that are of first order in the small but nonzero quantity r_s/r. (To first order in r_s/r, the density at r ≫ r_s would be zero, a valid but uninteresting result.)

[47] The assumed hemispherical source at r = r_s subtends a circular cone of opening (half-width) angle arctan (r_s/r) ≈ r_s/r to first order in r_s/r. The assumption of straight-line trajectories then implies that the allowed range of integration over v_y is −δv_y < v_y < δv_y, where δv_y = (r_s/r)v_y, and similarly for v_θ. The distribution (equation (A1), together with Liouville’s theorem, then implies

\[
f(r \gg r_s, \theta, v) = \frac{\rho_s}{\pi^{3/2} v_\theta} f_1(v_r) f_2(v_\theta) f_3(v_y),
\]

(A6)

where

\[
f_1(v_r) = \exp\left[-(v^2_r - 2v_0 v_r \cos \theta + v^2_0)/v_\theta^2\right], \quad 0 < v_r < \infty,
\]

(A7)

\[
f_2(v_\theta) = \exp\left[-(v^2_\theta + 2v_0 v_\theta \sin \theta)/v_\theta^2\right], \quad |v_\theta| < (r_s/r)v_\theta, \quad 0 \text{ otherwise},
\]

(A8)

\[
f_3(v_y) = \exp\left(-v^2_y/v_0^2\right), \quad |v_y| < (r_s/r)v_y, \quad 0 \text{ otherwise}.
\]

(A9)

The integral of equation (A9) over v_y from −∞ to +∞ is

\[
\int_{-\infty}^{\infty} f_3(v_y) dv_y \approx (2r_s/r)v_y,
\]

(A10)

Table 3. Normalized χ² Values

<table>
<thead>
<tr>
<th>M</th>
<th>S’ (10²² cm⁻¹) for E3</th>
<th>S’ (10²² cm⁻¹) for E5</th>
<th>S’ (10²² cm⁻¹) for E7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3 × (1 – 10%)</td>
<td>1.3</td>
<td>(1, 2, 3): 0.95 × (1 – 10%)</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>(1, 2, 3): 0.95 × (1 + 10%)</td>
<td>(4): 1.8 × (1 – 10%)</td>
</tr>
<tr>
<td>1.6 × (1 – 10%)</td>
<td>2.0</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>1.6</td>
<td>1.3</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>1.6 × (1 + 10%)</td>
<td>1.2</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>1.4 × (1 – 10%)</td>
<td>4.6</td>
<td>2.5</td>
<td>2.2</td>
</tr>
<tr>
<td>1.4</td>
<td>2.1</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>1.4 × (1 + 10%)</td>
<td>1.9</td>
<td>2.5</td>
<td>5.5</td>
</tr>
<tr>
<td>1.8 × (1 – 10%)</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>1.8</td>
<td>1.1</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>1.8 × (1 + 10%)</td>
<td>1.1</td>
<td>1.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

*The χ² values in this table are normalized to that with best fit parameters (as shown in Table 1) for each encounter. The χ² values are calculated with the best fit parameters ±10%. The numbers in parentheses in the E7 rows represent the sources.
correct to first order in $r/r$, and the integral of equation (A8) over $v_\theta$ from $-\infty$ to $\infty$ is
\[
\int_{-\infty}^{\infty} f_\theta(v_\theta)dv_\theta \approx \frac{2r_1}{r_0^2}v_\theta, \tag{A11}
\]
which is also correct to first order in $r/r$, given the first-order asymptotic approximation of the error function for small argument. Integrating equation (A6) over $v_\theta$ and $v_r$, using equations (A10) and (A11), gives the reduced distribution function
\[
f(r \gg r_1, \theta, v_r) \approx \frac{4n_s r_1^2}{\pi^{1/2}4^2} v_r^2 f_\theta(v_\theta), \tag{A12}
\]
which must be integrated over the range $0 < v_r < \infty$ to obtain the number density.

[48] For convenience, let us define $M \equiv v_\theta/v_{\theta 0}$, the dimensionless “thermal mach number” of the flow (equal to the conventional dimensionless sonic Mach number times the dimensionless number $\sqrt{\gamma}/2 \approx 0.91$ for an adiabatic exponent $\gamma = 5/3$), and define $\xi \equiv v_r/v_{\theta 0}$ (a dimensionless measure of the radial expansion speed). With these definitions, equation (A7) can be written as
\[
f_\theta(\xi, \theta, M) = \exp[-(\xi^2 - 2\xi M \cos \theta + M^2)]
\]
\[
\exp\left[-\left(\xi - M \cos \theta\right)^2 - M^2 \sin^2 \theta\right], \tag{A13}
\]
and the integral over $v_\theta$ gives the number density distribution
\[
n(r \gg r_1, \theta, M) = \frac{4n_s r_1^2}{\pi^{1/2}4^2} \exp(-M^2 \sin^2 \theta)
\]
\[
\int_0^\infty \xi^2 \exp\left[-(\xi - M \cos \theta)^2\right]d\xi, \tag{A14}
\]
If we define the new integration variable
\[
\chi \equiv \xi - M \cos \theta, \tag{A15}
\]
than equation (A14) can be written as
\[
n(r \gg r_1, \theta, M) = \frac{4n_s r_1^2}{\pi^{1/2}4^2} \exp(-M^2 \sin^2 \theta)
\]
\[
\int_{-M \cos \theta}^{\chi} \left(\chi^2 + 2M \cos \theta \chi + M^2 \cos^2 \theta\right)
\]
\[
\exp(-\chi^2)d\chi. \tag{A16}
\]
[49] To evaluate this integral, we use the following elementary results:
\[
\int_x^\infty e^{-t^2} dt = \frac{\sqrt{\pi}}{2} [1 + erf(x)], \tag{A17a}
\]
\[
\int_{-\infty}^{\infty} 2te^{-t^2} dt = e^{-x^2}, \tag{A17b}
\]
\[
\int_{-\infty}^{\infty} e^{-t^2} dt = \frac{\sqrt{\pi}}{4} [1 + erf(x)] - \frac{x}{2} e^{-x^2}, \tag{A17c}
\]
giving, altogether,
\[
n(r \gg r_1, \theta, M) = \frac{n_s r_1^2}{\pi^{1/2}4^2} \left\{2M \cos \theta \exp(-M^2)\right. \right.
\]
\[
+ \exp(-M^2 \sin^2 \theta)[1 + 2M^2 \cos^2 \theta \left.\right]\left[1 + erf(M \cos \theta)\right]\}.
\]
\]
For $M = 0$ (no bulk flow), this becomes an isotropic hemispherical expansion (independent of $\theta$). For $M \gg 1$, it becomes a narrow plume with angular half-width $\sin(\theta_0) \sim \theta_0 \sim 1/M$.

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