Surface Deposition of the Enceladus Plume and the Angle of Emissions

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Abstract

Since the discovery of an ice particle plume erupting from the south polar terrain on Saturn’s moon Enceladus (Porco et al., 2006; Spahn et al., 2006; Spencer et al., 2006), the geophysical mechanisms driving its activity have been the focus of substantial scientific research. The pattern and deposition rate of plume material on Enceladus’ surface is of interest because it provides valuable information about the dynamics of the ice particle ejection as well as the surface erosion. Surface deposition maps derived from numerical plume simulations by Kempf et al. (2010) have been used by various researchers to interpret data obtained by various Cassini instruments. Here, an updated and detailed set of deposition maps is provided based on a deep-source plume model (Schmidt et al., 2008), for the eight ice-particle jets identified in Spitale and Porco (2007), the updated set of jets proposed in Porco et al. (2014), and a contrasting curtain-style plume proposed in Spitale et al. (2015). Methods for computing the surface deposition are detailed, and the structure of surface deposition patterns is shown to be consistent across changes in the production rate and size distribution of the plume. Images are also provided of the surface deposition structure originating in each of the four Tiger Stripes. Finally, the differing approaches used in Porco et al. (2014) and Spitale et al. (2015) have given rise to a jets vs. curtains controversy regarding the emission structure of the Enceladus plume. Here we simulate each, leading to new insight that, over time, most emissions must be directed relatively orthogonal to the surface because jets “tilted” significantly away from orthogonal lead to surface deposition patterns inconsistent with surface images.

Data for maps is available in HDF5 format for a variety of particle sizes.

Keywords: Enceladus, plume, surface deposition

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1. Introduction

In 2005 the Cassini mission made the exciting discovery of a water-vapor and ice-particle plume erupting from the south polar terrain on Saturn’s icy moon Enceladus (Dougherty et al., 2006; Hansen et al., 2006; Porco et al., 2006; Spahn et al., 2006; Spencer et al., 2006). Multiple Cassini traversals through the plume allowed Cassini in-situ instruments to collect samples of the emerging vapor (Waite et al., 2009) and ice particles (Postberg et al., 2009), which most likely originate from the boiling surface of the moon’s subsurface ocean (Postberg et al., 2011). Since then much research has been devoted to understanding the Enceladus plume and its driving mechanism, for example, see Brilliantov et al. (2008); Gao et al. (2016); Hurford et al. (2007); Schmidt et al. (2008). There is convincing evidence that the plume is by far the strongest source of E-ring particles (for example, Spahn et al., 2006; Horányi et al., 2009) and also the dominant source of the resurfacing of Enceladus (for example, Jaumann et al., 2009; Kempf et al., 2010). However, there remain open questions about the plume, some of which may be addressed by examining surface deposits.

The purpose of this work is two-fold. First, we provide simulated surface deposition data resulting from the three primary proposals for plume emission structure: the eight jets identified in Spitale and Porco (2007), an updated set of approximately 100 sources identified in Porco et al. (2014), and a contrasting “curtain-like” plume proposed in Spitale et al. (2015). Multiple particle sizes from 0.6 – 10 µm are simulated for each source location, and data are generated on the impact rate in particles/sec and mass deposition in mm/year across the surface of Enceladus. Initial simulated maps of surface deposition from the Enceladus plume published in Kempf et al. (2010) have received interest from the larger research community (for example, Di Sisto and Zanardi, 2016; Nahm and Kattenhorn, 2015; Scipioni et al., 2017) and, here, we provide a more complete set of maps and data with respect to source location and particle size. Using the newly generated surface data for a curtain-style plume (Spitale et al., 2015) and the ~ 100 discrete jets proposed in Porco et al. (2014), we provide new insight into the zenith angle of plume emissions, that is, the “tilt” of the jets. Specifically, comparing simulated surface deposition patterns with the surface pattern seen in IR/UV images (Schenk et al., 2011) indicates that most highly tilted jets (zenith angle $\gg 15^\circ$) identified in Porco et al. (2014) do not contribute to surface deposition. This is likely due to a combination of short lifetimes for highly tilted jets, generally higher particle velocities for discrete jets over curtain emissions, and potentially some “phantom jets,” where a jet does not exist and was (falsely) identified due to an inadvertent spacecraft viewing angle relative to emissions, creating the appearance of a jet (Spitale et al., 2015). In any case, over a long timeframe, most emissions must be directed approximately orthogonal to the surface.

A background on the plume model and simulations is given in Section 2, along with a description of the data. Details on computing impact rate and surface deposition can be found in the Appendix. Images of surface deposition as a function of time are given in Section 3 and all associated data cubes,
stored in HDF5 format (The HDF Group, 2010). Section 4 introduces the jets vs. curtains controversy and provides evidence that, regardless of whether emissions originate from discrete jets or in a continuous curtain-style emission, the zenith angle of emissions is largely close to orthogonal to the surface. Implications and other open questions that surface deposition may provide insight towards are discussed in Section 5.

2. Plume model

Here we assume that the Enceladus plume is fed by a deep-source mechanism (Brilliantov et al., 2008; Schmidt et al., 2008; Postberg et al., 2011), where fractures in Enceladus’ icy crust extend down to a liquid-water reservoir. Particles then condense and are accelerated though a back-pressurized gas flow exiting the fracture, for which the particle velocity upon ejection takes the following distribution

\[ p(v|r) = \left( 1 + \frac{r}{r_c} \right) \frac{r}{r_c v_{gas}} \left( 1 - \frac{v}{v_{gas}} \right)^{r_c - 1}, \tag{1} \]

where

\[ \int_0^{v_{gas}} p(v|r) dv = 1. \tag{2} \]

Note that the velocity distribution (Equation (1)) assumes that particle velocities cannot be larger than the gas velocity \( v_{gas} \), hence the normalization integral in Equation (2) over \([0, v_{gas}]\). Evidence of a deep-source plume mechanism can be found in Schmidt et al. (2008); Postberg et al. (2011) and Yeoh et al. (2015). In Equation (1), \( v_{gas} \) is the gas velocity, and \( r_c \) the so-called critical radius, which is effectively a measure of the length of time a particle has to be reaccelerated by the gas between its final collision with a fracture wall and ejection. Particles \( r < r_c \) are efficiently accelerated to velocities approaching \( v_{gas} \), while particles \( r > r_c \) move in the gas flow at average velocities less than \( v_{gas} \). A detailed look at the critical radius, \( r_c \), and gas velocity, \( v_{gas} \), can be found in Schmidt et al. (2008) and Southworth et al. (2015). Here we use values for \( r_c \) and \( v_{gas} \) based on simulations of the venting process by Schmidt et al. (2008).

The size-dependent speed distribution is consistent with a chemically stratified plume, as evidenced by data from the Cassini Cosmic Dust Analyzer (CDA) (Postberg et al., 2011), as well as surface deposition patterns that depend on particle size (Kempf et al., 2010; Scipioni et al., 2017). Particle ejection angles are assumed to be azimuthally uniform and follow a \( \cos^2(\theta) \)-zenith angle distribution over \( \theta \) between 0° and 15°. A maximum half-angle of 15° is consistent with opening angles seen in Spitale et al. (2015) as well as the widths of plume gas estimated in Hansen et al. (2008), and the \( \cos^2 \)-distribution indicative of the

\[ ^5 \text{Eq. } 1 \text{ includes a correction of } 1/v_{gas} \text{ that was omitted in Schmidt et al. (2008). That correction also appeared without comment in Southworth et al. (2015).} \]
smooth onset, peak and decline of particle impact rates as seen by CDA (Kempf et al., 2010). A plume source is simulated by launching millions of particles from a given location and integrating their trajectories in a Saturn-centered quasi-inertial frame until each particle has either collided with Enceladus, or escaped from Enceladus and established orbit about Saturn. The equations of motion account for Saturn’s gravity, Enceladus’ gravity, and particle charging (Horányi, 1996) in a Z3-Voyager magnetic field about Saturn (Connerney, 1993). We have also implemented a local magnetic field about the plume as proposed in Simon et al. (2011), which considers the effects of the Enceladus plume on the corotating plasma in Saturn’s magnetosphere. Although the local model in Simon et al. (2011) reproduces data from the Cassini magnetometer (MAG) instrument more faithfully than a global magnetic field about Saturn, aggregate plume dynamics for the particle sizes considered here (> 0.6 µm) are nearly identical using a Z3-charging model, a local charging model, and no particle charging. In particular, surface deposition patterns are not affected by a change in the charging equations considered. Further details on the software used to run simulations as well as the equations of motion and underlying distributions can be found in Schmidt et al. (2008); Kempf et al. (2010); Southworth et al. (2015).

Particle sizes between 0.6 − 10 µm are simulated for each source location, leading to $10^5 - 6 \cdot 10^5$ simulations per particle size (larger particles take on a smaller range of initial velocities and do not require as many simulations) and $10^6 - 10^7$ particle simulations per source (depending on the number of sizes considered for a given source). Particle trajectories are integrated until either the particle establishes a stable orbit about Saturn or collides with the surface of Enceladus. When a particle collides with Enceladus, its position and velocity at the time of collision are saved with respect to an Enceladus-centered inertial frame (these data are available on request). All collisions for a given particle size and source location are then grouped into $1^\circ$-latitude × $1^\circ$-longitude bins, covering the surface of Enceladus. At the meridian, one bin covers an approximate square with dimensions 4.35 km × 4.35 km and a surface area of approximately 19 km$^2$; at the poles, one bin covers a surface area of approximately 0.17 km$^2$. Bins are then normalized to give the contribution of a single ejected plume particle to impact rate per m$^2$ in each bin. Data for each simulated particle size and jet location are stored in 360 × 180 arrays, corresponding to planetographic coordinates in western longitude. Scaling the impact rate for each bin by the size of the bin, and summing over the entire array gives the ratio of simulated particles that collided with the surface. For particles larger than 1 µm, this is close to one (that is, most particles larger than 1 µ do not escape Enceladus’ gravity). These arrays are available in HDF5 format (The HDF Group, 2010).

Details on computing the impact rate in particles/sec and surface deposition in mm/year can be found in the Appendix. It is assumed that particles follow a power-law size distribution with slope $\alpha$, $p(r) \sim r^{-\alpha}$, and the plume has a total mass production rate $M^+$ kg/sec. Values for the size-distribution slope and mass production are based on CDA data Kempf et al. (2010); Southworth et al. (2017), but surface deposition patterns are shown to be consistent across
changes in $\alpha$ and $M^+$ (Section 3). In any case, because data arrays are stored for individual particle sizes, deposition and impact rate can be re-weighted with arbitrary size distribution models and mass production.

Source locations consist of the eight sources initially identified in Spitale and Porco (2007) and the updated 98 sources identified in Porco et al. (2014), all simulated as published with a given direction and source strength. A curtain is simulated via discrete sources spaced evenly along the tiger stripes, approximately 5-6 km apart, directed orthogonal to the surface. Although this is not a true “curtain,” at sufficiently high altitudes above Enceladus’ surface it appears as a curtain, and this choice offers greater numerical flexibility in adjusting the production rate along fractures a posteriori. Relative production rate of each source in the curtain is based on the average activity of emissions along the Tiger Stripes, measured through images of the plume in Spitale et al. (2015).

3. Surface maps

This section provides maps of surface deposition for various particle sizes and model parameters. It is important to note that our simulated deposition depth assumes perfect compaction of particles and particle density equal to that of water ice. Evidence for “fluffy” (less dense) particles (Gao et al., 2016) and the fact that particles are unlikely to pack perfectly on the surface suggests that deposition may be greater than presented here; nevertheless, here we present a safe lower bound on deposition. Figures 1, 2, and 3 are based on the original eight sources identified in Spitale and Porco (2007), and Figure 4 is based on a continuous curtain emission over each individual fracture. Maps for jet sources proposed in Porco et al. (2014) and a full curtain scenario as proposed in Spitale et al. (2015) are given in Section 4.

Figure 1 maps the particle impact rate per m$^2$ per sec and surface deposition in mm/year for particles $0.6 - 15$ $\mu$m, and Figure 2 breaks the total deposition down into particle size ranges starting at $0.5 - 2.0$ $\mu$m, and increasing up to

![Figure 1: Cumulative plume particle deposition on Enceladus’ surface in mm/year for the eight sources proposed in Spitale and Porco (2007), particle sizes $0.6 - 15$ $\mu$m, assuming a mass production rate of $M^+ = 20$ kg/s, and slope of the power-law size distribution $\alpha = 3.$](image)
For each of these figures, we choose $r_{\text{min}} = 0.6 \, \mu\text{m}$ and $r_{\text{max}} = 15 \, \mu\text{m}$, a mass production rate of $M^+ = 20 \, \text{kg/s}$, and a size distribution slope of $\alpha = 3$. All results presented use these parameters, unless stated otherwise.

The mass production and size distribution slope are directly motivated through CDA data on low-altitude flybys Southworth et al. (2017), which provide the most direct measurements to date of large particles in the Enceladus plume. Results are also relatively consistent with estimates of mass production in Meier et al. (2015); Porco et al. (2017). Note that in fixing $r_{\text{min}}$ and $r_{\text{max}}$, $M^+$ corresponds to the mass production of particles in this size range. A maximum particle size must be chosen so that the average mass of a particle is well-defined; here we choose $r_{\text{max}}$ to be sufficiently large that plume particles of that size or larger are very unlikely and increasing $r_{\text{max}}$ has a small effect on results. We only consider micron-size particles (formed through condensation in gas flow) because the assumed power-law size distribution does not necessarily propagate back to nano-grains. Nano-grains can also be formed through supersonic nucleation bursts at the narrowest channel points, which can occur at various depths, leading to a bi-modal or multi-modal size distribution. In any case, it is easily

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6The last bin contains a large range of sizes because there are very few particles of that size, and they do not travel far from the fractures.

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Figure 2: Plume particle deposition rates on Enceladus’ surface in mm/year for the eight sources proposed in Spitale and Porco (2007) and for particle sizes $0.6 – 2 \, \mu\text{m}$, $2 – 4 \, \mu\text{m}$, $4 – 6 \, \mu\text{m}$, and $6 – 15 \, \mu\text{m}$. Mass production rate is $M^+ = 20 \, \text{kg/s}$ and the slope of the power-law size distribution is $\alpha = 3$.  

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verified that the total ejected mass and the total redeposition mass are dominated by large particles, so extending $r_{\text{min}}$ to nano-grains also does not have a significant effect on results. Although there is evidence that plume strength varies over time (Hedman et al., 2013; Nimmo et al., 2014; Southworth et al., 2017), in considering mass deposition on the surface, we need only consider an average mass production.

In Equation 11 of the appendix, we show that mass deposition depends linearly on the mass production rate and, thus, the structure of surface deposition is consistent across changes in $M^+$. Similarly, Figure 3 shows that the structure of the surface deposition pattern is not strongly affected by changes in size distribution slope, $\alpha$, either. A steeper size distribution (larger $\alpha$; see $\alpha = 3.5$, Figure 3) results in more small particles ejected, which tend to have higher ejection velocities (Schmidt et al., 2008; Hedman et al., 2009) and travel larger distances from the source, leading to an increase in deposition away from the pole. Conversely, a flatter size distribution slope (smaller $\alpha$; see $\alpha = 2.5$, Figure 3) results in more large particles ejected, which have slower initial velocities and impact the moon closer to the source location. Then, there are increased deposition rates close to the source, and decreased deposition rates far from the source. In any case, the structure of plume resurfacing seen in Figures 1, 2, and 3 is consistent on some scale, regardless of $\alpha$ and $M^+$.

So far we have only considered the eight sources published in Spitale and Porco (2007). Figure 4 shows the deposition from a curtain-style emission (see Section 4.2) isolated to the four main Tiger Stripes of the Enceladus plume. Due to three-body effects and the angle of ejection, emissions from the outermost fractures, Alexandria and Damascus, are most likely to reach the north polar region and would likely dominate resurfacing there. Here we have assumed emissions are directed orthogonal to the surface; note that highly-tilted emissions from Baghdad or Cairo may also be likely to reach the north pole, but in Section 4 we discuss that such emissions are generally not active for long periods of time. Further images of deposition from a curtain-style plume (Spitale et al., 2015) and the jets proposed in Porco et al. (2014) can be found in Section 4.
4. Jets vs. curtains and tilting of emissions

4.1. Competing theories of emission structure

The structure and location of plume emissions on Enceladus’ surface was first studied by triangulating images of observed jetting activity from various angles, and projecting the result back to an approximate source location (Spitale and Porco, 2007). Spitale and Porco (2007) identified eight distinct jet sources that are largely consistent with thermal emission signatures measured by the Cassini Composite Infrared Spectrometer (CIRS) (Spencer et al., 2006); however, the image resolution was relatively coarse and the accuracy of proposed source locations no better than 10 to 20 km. This led to a set of follow-up observations at lower altitudes to better resolve the emission structure of the plume. Porco et al. (2014) analyzed six years of imaging data from the Cassini Imaging Science Subsystem (ISS) using a triangulation-based approach, resulting in the identification of approximately 100 discrete “jets.” Results from Porco et al. (2014) are consistent with temperatures measured across the south polar terrain by CIRS (Howett et al., 2011) as well as localized hot spots identified in Cassini Visible and Infrared Mapping Spectrometer (VIMS) observations (Goguen et al., 2013).

More recently, Spitale et al. (2015) noticed that much of the plume activity actually appears as a relatively continuous glow in ISS images, as opposed to

Figure 4: Plume particle deposition rates on Enceladus’ surface in mm/year for particle sizes 0.6 – 15 µm and all particles emitted in a curtain-style plume (Spitale et al., 2015) from a single fracture. Mass production rate is $M^+ = 20$ kg/s and the slope of the power-law size distribution is $\alpha = 3$. The fractures can be seen in the dark green region of each image where deposition rate is highest.
discrete jet-like features as proposed in Porco et al. (2014), and that finer structure within the plume is difficult to reliably identify over successive ISS images. This motivated a different analysis applied to many of the same data sets used in Porco et al. (2014), where a continuous “curtain” emission is simulated over fractures and compared with images of the plume to identify active regions. One result that came out of that study is that so-called “phantom-jets” may appear in an image of a sinuous fracture, corresponding to regions where continuous curtain emissions overlap in the line of sight and (falsely) appear as discrete jetting activity. Although many jets identified in Porco et al. (2014) are undoubtedly real and have shown to be consistent with other data (Howett et al., 2011; Helfenstein and Porco, 2015), it is likely that some of the jets identified in Porco et al. (2014) are phantom jets.

The differing approaches and results of Porco et al. (2014) and Spitale et al. (2015) have stimulated an in-depth review of the interpretation of ISS images and plume emission structure. Here, we simulate the jets proposed in Porco et al. (2014) as well as an approximate curtain, consistent with Spitale et al. (2015). Although the results presented here do not favor either approach, a comparison with surface color maps (Schenk et al., 2011) does provide constraints on the angle or “tilt” of emissions relative to the surface.

4.2. Surface deposition and highly-tilted emissions

In Schenk et al. (2011), near-global, high-resolution color maps of Enceladus were constructed using data from the Cassini ISS in three colors, UV, Green, and near-IR. Looking at the IR/UV ratio provides a color contrast, where a “reddish” area on the surface appears bright, and a “blueish” area, potentially corresponding to unaltered water ice, appears darker (Schenk et al., 2011). It is generally believed that Enceladus’ unique color pattern, differing from other Saturnian satellites, is a result of surface re-deposition due to plume activity (Hendrix et al., 2010; Kempf et al., 2010; Schenk et al., 2011), which agrees with comparisons of surface maps and simulated deposition patterns. Here, we assume that the surface pattern seen on Enceladus and shown in Figure 5 does indeed result from plume deposition and use this as a basis for expected surface deposition patterns in simulated plumes.

The Enceladus plume model and structure can be constrained by ensuring that data collected by spacecraft are reproducible. Here, we use IR/UV images (Figure 5) as a reference to compare simulated surface deposition profiles. Figure 6 shows simulated global surface deposition profiles of plume particles size 0.6 – 15 µm, for both a curtain-style plume (Spitale et al., 2015) and discrete jet sources (Porco et al., 2014). Each simulated plume leads to a surface deposition pattern that is largely consistent with the IR/UV ratio seen in surface images of Enceladus (Figure 5). However, the discrete jets proposed in Porco et al. (2014) do not reproduce the finer structure of surface deposition, while the curtain-style plume does. In particular, jets from Porco et al. (2014) lead to surface deposition features not seen in surface images.

In looking at the simulated curtain- and jet-style plumes, the fundamental difference between the two is the direction that jets are pointing. Like the
jets, the curtain is also “discrete” and not simulated as a truly continuous curtain, and both models have emissions primarily aligned on the Tiger Stripes. However, all sources simulated for the curtain are directed orthogonal to the surface, while each of the jets proposed in Porco et al. (2014) have a given zenith and azimuthal angle. A number of the proposed zenith angles are as large as 30–62° (measured from orthogonal to the surface). Such strongly tilted jets lead to very distinct deposition patterns on the surface, which do not always agree with observed deposition. As an example, Jets 23 and 95 from Porco et al. (2014) originate in close proximity to each other, but Jet 23 has a near-orthogonal zenith angle of 3°, while Jet 95 has a large zenith of 42°. Figure 7 compares the deposition pattern for Jets 23 and 95.

Surface deposition from Jet 23 is consistent with surface IR/UV maps, but Jet 95 has a long, narrow deposition pattern, aligned effectively the opposite direction as the pattern seen in IR/UV maps. Although this is partially due to the proposed azimuthal angle as well, in fact, most highly tilted jets lead to deposition patterns that are at odds with the observed IR/UV maps. A natural conclusion from this is that, for the most part, highly tilted jets are not contributing to surface deposition. Figure 8 shows the jet-plume surface deposition rates for jets and curtains.
deposition for three scenarios: all jets in Porco et al. (2014), jets with zenith angle less than 30°, and jets with zenith angle less than 20°. We can see that by simply removing highly-tilted jets, the surface deposition pattern is now consistent with that of the simulated curtain and, more importantly, IR/UV images of the surface.

There are several possible explanations as to why highly-tilted emissions are not contributing to surface deposition. The first is that many of the highly tilted jets, which are the source of surface patterns that differ from observed IR/UV ratios, are phantoms. Less than 30% of jets proposed in Porco et al. (2014) have a zenith angle greater than or equal to 20°, and only about 10% have a zenith angle greater than or equal to 30°. A few of these high-tilt jets lead to surface deposition patterns that are consistent with the patterns seen in surface images (for example, Jet 5), and we can reproduce surface IR/UV patterns well using approximately 80% of jets proposed in Porco et al. (2014), leaving about 20% that are candidate phantoms in this scenario. Although surface deposition of tilted jets is largely inconsistent with observed IR/UV ratios, the distinct angle of such jets, differing from most plume emissions, does decrease the probability
of these being phantom jets (Spitale et al., 2015). The tilted jets also tend to be highly prominent in images, further arguing against a phantom origin.

A second possible explanation is that highly tilted jets are not active long enough (at least for a fixed direction of emission) to create visible surface patterns. Roughly, particles covering the surface should be visible in images when their depth is greater than the reflectivity wavelength (on the order of nanometers). All figures shown use a minimum value for the deposition profile of 1 nm/year. Looking at Figures 7 and 8, one can faintly notice the deposition pattern of Jet 95 in the aggregate deposition pattern, contributing on the order of 1 nm per year in particle deposition. Thus, for certain deposition contributions from Jet 95, particularly areas that do not overlap with the deposition of other jets, to be visible in surface images, Jet 95 would have to be continuously active for approximately one year or longer.

Although the plume itself has been active for much longer than one year, there is evidence for temporal variability of plume emissions in several forms. There has long been speculation and confirmation of tidal stresses along Enceladus’ orbit modulating the emissions (Hansen et al., 2008; Hedman et al., 2013; Hurford et al., 2012, 2007; Nimmo et al., 2014), as well as evidence of long-term change in emission rates between 2005–2015 (Ingersoll and Ewald, 2017). Recent images show prominent jets in the plume suddenly turning on or off in successive images, while the curtain-emissions remain relatively constant (Spitale and Southworth, 2017). It is plausible that highly-tilted jet sources do not stay active for significant periods of time, either turning on and off or changing direction sufficiently often that their deposition signature cannot be seen in IR/UV maps. An interesting open question is whether highly-tilted jets are more susceptible to variability and short lifespans compared with jets near orthogonal to the surface.

Finally, the large heights of many of the tilted jets in ISS images suggest that discrete jet sources identified in Porco et al. (2014) have higher emission velocities than the continuous curtain emissions proposed in Spitale et al. (2015). Because of this, it is expected that a larger percentage of particles from discrete jet sources escape Enceladus’ gravity and do not land back on the surface compared with curtain emissions. This would lead to a slower rate of surface deposition, which may further explain why deposition patterns from highly-tilted jets in Porco et al. (2014) are not apparent in surface images. However, it is important to note that higher emission velocities alone are not sufficient to explain why tilted jets do not contribute to surface deposition. The model for particle dynamics used here and, in particular, the size and speed distributions (Equation 1), are based on prominent jetting activity observed in the plume. Even with a higher gas velocity, the speed and size distributions indicate that many emitted particles would still land on the surface. In fact, they would then populate the tail of deposition patterns at a higher rate, which are exactly the prominent features seen in simulation data that do not appear in IR/UV images.
5. Conclusions

This work provides the first detailed look at surface deposition from the Enceladus plume, providing simulated impact and deposition data for emissions proposed in Spitale and Porco (2007); Porco et al. (2014) and Spitale et al. (2015), for particle sizes between $0.6 - 10 \mu m$. The larger structure of deposition patterns is shown to be stable with respect to variations in model parameters, total plume mass production, and size distribution slope, and deposition patterns are consistent with IR/UV images of Enceladus’ surface. Images are used as a reference to compare simulated deposition patterns for the jets proposed in Porco et al. (2014) and a curtain as proposed in Spitale et al. (2015).

The deposition pattern resulting from highly tilted jets is not consistent with the pattern seen in color maps of Enceladus’ surface. This indicates that highly tilted jets are not active long enough to contribute visible particle deposition patterns on the surface. Due to the higher velocity of discrete jets compared with curtain emissions, more of these particles are likely to escape Enceladus’ gravity, which reduces their expected contribution to surface deposition. Nevertheless, results here indicate that, in a long-term average, most emissions are directed relatively orthogonal to the surface.

There remain open questions on the Enceladus plume to which surface deposition may provide insight. Estimates on the depth of resurfaced particles would allow for estimates on the plume’s lifetime, based on resurfacing rates presented here. Surface deposits also indicate where plumes have been active, and whether there have been emissions from other areas on Enceladus’ surface. Finally, reproducing surface patterns provides validation for models of plume particle dynamics (Kempf et al., 2010; Southworth et al., 2017; Schmidt et al., 2008; Southworth et al., 2015) and insight into the structure of plume emissions at the interface between subsurface vents and particle ejection (Porco et al., 2014; Spitale and Porco, 2007; Spitale et al., 2015).

Appendix: Particle flux and surface deposition

In considering resurfacing of Enceladus from plume particles, we are interested in two rates: the particle collision rate in particles/sec and the depth of particle deposition in mm/year. First, define $p_{size}(r) = Cr^{-\alpha}$ as the power-law particle size distribution, where $C$ is chosen such that $\int_{r_{min}}^{r_{max}} p_{size}(r)dr = 1$, $r_{min}$ is the minimum particle radius, $r_{max}$ is the maximum particle radius, and $\alpha > 0$ the size-distribution slope. Assuming spherical particles, the average

\[ \text{Note that for a well-defined size distribution and average plume particle mass, we must choose some minimum and maximum particle radius, } r_{min} > 0 \text{ and } r_{max} < \infty. \]  

The minimum size particle is largely based on the mechanical origin of the particle, of which we are interested in frozen ice grains from the subsurface ocean. A separate population of nano grains likely result from supersonic bursts through Laval nozzles in the fractures, and corresponding to a different size distribution. A maximum size is necessary to bound the average mass of particles, but also makes sense physically because ejecta particle size is at least limited by the channel width of fractures from which particles are emitted (and likely much smaller).
volume of a plume particle is given by

\[ V_{av} = \int_{r_{\text{min}}}^{r_{\text{max}}} \frac{4}{3} \pi r^3 p_{\text{size}}(r) dr = \begin{cases} 
\frac{4\pi(\alpha-1)(r_{\text{max}}^{\alpha-1} - r_{\text{min}}^{\alpha-1})}{3(\alpha-4)(r_{\text{min}}^{\alpha-4} - r_{\text{max}}^{\alpha-4})} & \alpha \neq 4 \\
\frac{4\pi(\alpha-1)(\log(r_{\text{max}}) - \log(r_{\text{min}}))}{3(r_{\text{min}}^{\alpha-4} - r_{\text{max}}^{\alpha-4})} & \alpha = 4 
\end{cases} \tag{3} \]

and average mass \( M_{av} = \rho V_{av} \), for particle density \( \rho \). Note that \( r_{\text{min}} \neq 0 \) and \( r_{\text{max}} \neq \infty \) must be fixed for \( V_{av} \) to be well-defined. Now consider the particle impact rate, \( r_{\text{imp}}(\lambda, \phi) \), as a function of surface location, for longitude \( \lambda \) and latitude \( \phi \). Let \( M^+ \) denote the plume mass production in kg/sec and \( N^+ = \frac{M^+}{M_{av}} \) the expected plume production rate in particles/sec. Impact rate can then be written as \( r_{\text{imp}}(\lambda, \phi) = N^+ \hat{r}_{\text{imp}}(\lambda, \phi) \), where \( \hat{r}_{\text{imp}}(\lambda, \phi) \) is the normalized contribution of a single plume particle to the impact rate at location \((\lambda, \phi)\). Impact rate can be obtained by integrating the normalized impact rate over the size distribution as a function of particle radius \( r \):

\[ r_{\text{imp}}(\lambda, \phi) = \frac{M^+}{\rho V_{av}} \int_{r_{\text{min}}}^{r_{\text{max}}} \hat{r}_{\text{imp}}(\lambda, \phi, r) p_{\text{size}}(r) \, dr. \tag{4} \]

Now, given \( r_{\text{imp}}(\lambda, \phi) \) expressed in geographical coordinates, suppose we want the expected deposition height of plume particles covering some area \( S(\lambda_0 \leq \lambda \leq \lambda_1, \phi_0 \leq \phi \leq \phi_1) \) per second. The expected total volume of particles per second is given by the product of the average volume of a plume particle \( \text{impacting in } S \), \( V_{av,S} \) (generally not equal to \( V_{av} \)), with the expected number of particle impacts in area \( S \) per second, \( n_S = \int_S r_{\text{imp}} \, dS \). To compute the average volume of impacting particles at a given location \((\lambda, \phi)\), we define the normalized size distribution of particles impacting at \((\lambda, \phi)\) as \( p_{\text{imp}}(\lambda, \phi, r) := \frac{\hat{r}_{\text{imp}}(\lambda, \phi, r)}{r_{\text{imp}}(\lambda, \phi, r) p_{\text{size}}(r) \, dr} \). Then, averaging over \( S \),

\[ V_{av,S} = \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \frac{4}{3} \pi r^3 p_{\text{size}}(r) \cos(\phi) \, r \, d\lambda \, d\phi \]

\[ = \frac{\int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \frac{4}{3} \pi r^3 p_{\text{imp}}(\lambda, \phi, r) \cos(\phi) \, r \, d\lambda \, d\phi}{\int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \cos(\phi) d\lambda d\phi} \tag{5} \]

Let \( R_E = 249.1 \) km be Enceladus’ radius. Volume of particles per second in \( S \) is then given by:

\[ V_S = V_{av,S} n_S \]

\[ = V_{av,S} \cdot \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} R_E^2 \hat{r}_{\text{imp}}(\lambda, \phi) \cos(\phi) \, d\lambda d\phi. \tag{6} \]

The depth or height of surface deposition if we assume perfect compaction of particles is given by \( h \) such that the volume of particles (Equation 6) is equal to the volume of \( S \) integrated to height \( h \):

\[ \int_{R_E}^{R_E+h} \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} R^2 \cos(\phi) \, r \, d\lambda d\phi dr = h \left( R_E^2 + R_E h + \frac{h^2}{3} \right) \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \cos(\phi) \, d\lambda d\phi \]

\[ = h \left[ R_E^2 \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \cos(\phi) \, d\lambda d\phi + O(R_E h + h^2) \right]. \tag{7} \]
Here, $h$ is expected on the order of mm or $\approx 10^{-7}R_E$, which justifies dropping terms $O(R_Eh + h^2)$, and we find that

$$h \approx \frac{M^+}{\rho} \cdot \frac{V_{av,S}}{V_{av}} \cdot \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \int_{r_{min}}^{r_{max}} \hat{r}(\lambda, \phi, r)p_{size}(r) \cos(\phi) \, d\lambda d\phi \frac{\rho \int_{\phi_0}^{\phi_1} \cos(\phi) \, d\phi}{\int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \cos(\phi) \, d\phi}. \quad (8)$$

Note that dropping terms $O(R_Eh + h^2)$ is equivalent to estimating the total volume as the surface area times height. To estimate $h$ over the moon’s surface, we consider a mesh on the moon’s surface of $1^\circ$ longitude $\times$ $1^\circ$ latitude cells and approximate Equation 8 for each cell. Cells are sufficiently small that we assume $\hat{r}_{imp}$ to be constant over each cell, denoted $\hat{r}_{imp}(\lambda, \phi)$, with units $1/m^2$. Average volume of impacting particles (Equation 5) reduces to

$$V_{av,S} = \frac{\int_{r_{min}}^{r_{max}} \frac{4}{3} \pi r^3 \hat{r}_{imp}(\lambda, \phi)(r)p_{size}(r) \, dr}{\int_{r_{min}}^{r_{max}} \hat{r}_{imp}(\lambda, \phi)(r)p_{size}(r) \, dr},$$

and we can then separate integrals in Equation 8 to get:

$$h(\lambda, \phi) \approx \frac{M^+}{\rho} \cdot \frac{V_{av,S}}{V_{av}} \cdot \frac{\int_{r_{min}}^{r_{max}} \hat{r}_{imp}(\lambda, \phi)(r)p_{size}(r) \, dr \cdot \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \cos(\phi) \, d\lambda d\phi}{\rho \int_{\lambda_0}^{\lambda_1} \int_{\phi_0}^{\phi_1} \cos(\phi) \, d\lambda d\phi} = \frac{M^+}{\rho V_{av}} \int_{r_{min}}^{r_{max}} \frac{4}{3} \pi r^3 \hat{r}_{imp}(\lambda, \phi)(r)p_{size}(r) \, dr. \quad (9)$$

Notice that the (approximate) total volume (Equation 9) takes a similar form to the impact rate (Equation 4), but now we are integrating over particle volume, $\frac{4}{3} \pi r^3 dr$. Each can be approximated using some quadrature method with sample particle sizes \{${r_0, ..., r_k}$\} and data \{$\hat{r}_{imp}(\lambda, \phi)(r_i)$\}$_{i=0}^{k}$:

$$\hat{r}_{imp}(\lambda, \phi) \approx \frac{M^+}{\rho V_{av}} \sum_{i} \hat{r}_{imp}(\lambda, \phi)(r_i)p_{size}(r_i)w_i, \quad (10)$$

$$h(\lambda, \phi) \approx \frac{4\pi M^+}{3\rho V_{av}} \sum_{i} r_i^3 \hat{r}_{imp}(\lambda, \phi)(r_i)p_{size}(r_i)w_i, \quad (11)$$

for quadrature weights \{${w_i}$\}. We use a simple trapezoid method to approximate (10) and (11). Although more accurate methods could be used for quadrature as well as higher resolution (non-constant) estimates of $\hat{r}_{imp}$, the underlying physical model is not sufficiently resolved to warrant such accuracy. The function $\hat{r}_{imp}(\lambda, \phi)(r_i)$ is exactly what we build from simulation data and store in $360 \times 180$ arrays corresponding to $1^\circ$ longitude $\times$ $1^\circ$ latitude areas on the moon’s surface.

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