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Aggregate particles in the plumes of Enceladus

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ABSTRACT

Estimates of the total particulate mass of the plumes of Enceladus are important to constrain theories of particle formation and transport at the surface and interior of the satellite. We revisit the calculations of Ingersoll and Ewald (Ingersoll, A.P., Ewald, S.P. [2011]. Icarus 216(2), 492–506), who estimated the particulate mass of the Enceladus plumes from strongly forward scattered light in Cassini ISS images. We model the plume as a combination of spherical particles and irregular aggregates resulting from the coagulation of spherical monomers, the latter of which allows for plumes of lower particulate mass. Though a continuum of solutions are permitted by the model, the best fits to the ISS data consist either of low mass plumes composed entirely of small aggregates or high mass plumes composed of mostly spheres. The high particulate mass plumes have total particulate masses of $(166 \pm 42) \times 10^3$ kg, consistent with the results of Ingersoll and Ewald (Ingersoll, A.P., Ewald, S.P. [2011]. Icarus 216(2), 492–506). The low particulate mass plumes have masses of $(25 \pm 4) \times 10^3$ kg, leading to a solid to vapor mass ratio of 0.07 ± 0.01 for the plume. If indeed the plumes are made of such aggregates, then a vapor-based origin for the plume particles cannot be ruled out. Finally, we show that the residence time of the monomers inside the plume vents is sufficiently long for Brownian coagulation to form the aggregates before they are ejected to space.

1. Introduction

Enceladus' plumes provide an indirect way to study the subsurface. In particular, the ratio of ice particle to vapor mass can serve as an important constraint of ice particle formation and transport (Ingersoll and Ewald, 2011, henceforth IE11). IE11 examined Cassini Imaging Science System (ISS) images of the plumes at small scattering angles from 2.2° to 5.3°, where forward scattering is dominated by ice grains as opposed to water vapor. They then fit the resulting phase curves to various mass and shape distributions, assuming that the ice grains are solid spherical or ellipsoidal particles. However, the large particle to vapor mass ratio calculated by IE11 could not be easily explained by any existing theoretical models. Furthermore, recent results from the Cassini Cosmic Dust Analyzer (CDA) (Kempf, S., Cassini Project Science Meeting, January 22, 2015, and private communication) indicate that the particulate mass may be a factor of ten lower than the estimates of IE11. Since the defining property of the plume particles is strong forward scattering, an alternative model for the plume is one made up of aggregates.

An aggregate is a particle of irregular shape composed of smaller subunits (or "monomers") stuck to each other. The monomers are usually composed of simpler shapes, such a spheres, plates, or columns, depending on the formation mechanisms. Aggregates form under many different settings. For example, the hazes in the atmospheres of Jupiter and Titan are thought to be composed of hydrocarbon aggregates (West and Smith, 1991; Tomasko et al., 2008; Zhang et al., 2013); Saturn's F-ring is likely populated by ice aggregate particles (Vahidinia et al., 2011); and cirrus cloud particles on Earth take on a variety of non-spherical shapes, ranging from fernlike and fractal geometries to aggregates of irregular shapes (Yang and Liou, 1998). In particular, ice clouds that form as a result of strong vertical motions are dominated by aggregate particles (Heymsfield et al., 2002). Since aggregates form under such a wide variety of conditions, it is plausible that they could form in the plumes of Enceladus.

Thanks to the diversity of instruments on Cassini, the plumes are well studied. There are good estimates of water vapor mass from the Ultraviolet Imaging Spectrograph (UVIS) instrument (Tian et al., 2007; Hansen et al., 2011, for example), as well as that of other minor gaseous constituents, such as carbon dioxide, methane, ammonia, and argon from the Ion and Neutral Mass Spectrometer (INMS) (Waite et al., 2009). Data from Cassini CDA

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suggests that the ice particles in the plumes can be broadly classified into two types: slow, large, salt-rich grains that tend to fall back onto the surface, and fast, salt-poor grains that escape into the E-ring (Postberg et al., 2011). Ice particle velocity distributions were measured using the Visual and Infrared Mapping Spectrometer (VIMS) (Hedman et al., 2009) and ISS (IE11). However, the shapes of the particles remain mostly unconstrained by observations and are usually assumed to be spherical or oblate/prolate, such as in Porco et al. (2006) and IE11. In this study, we derive estimates for the total particulate mass of the Enceladus plumes by extending the range of possible particle shapes to aggregates.

2. Aggregate model

Aggregate particles are defined by two parameters: their fractal dimension D and their monomer radius r_m. These two quantities are related to the number of monomers that make up the aggregate N_m and the radius of the aggregate particle r by

$$N_m = \left(\frac{r}{r_m}\right)^D. \tag{1}$$

A typical value of D for aggregates in the Solar System is around 2. For example, it has been shown that $D = 2$ is a good approximation for the aggregate particles in the Titan hydrocarbon haze, where the actual dimension may vary between 1.75 and 2.5 (Cabane et al., 1993). $D = 2$ is also appropriate for snowflakes and cirrus cloud ice crystals on Earth, which have variations in D between 1.9 and 2.3 (Westbrook et al., 2006; Schmitt and Heymsfield, 2010). Zhang et al. (2013) further showed that $D = 2$ aggregates can be used to fit Cassini ISS observations of the Jupiter stratospheric aerosols. Such particles have masses that scale linearly with surface area, like a sheet, though the particle itself is a three dimensional object. As a result, these particles tend to have small masses associated with large scattering cross sections.

By comparison, r_m values vary considerably across different types of aggregates. For example, $r_m = 10$ nm for the stratospheric aerosols of Jupiter (Zhang et al., 2013) and 40 nm for Titan's haze aggregates (Tomasko et al., 2009), but these values are easily dwarfed by that of Saturn's F ring particles, which can reach a few microns (Vahidinia et al., 2011), while ice crystal monomers on Earth can be hundreds of microns across (Kajikawa and Heymsfield, 1989). We will therefore leave r_m as a free parameter in our model that will be varied to best fit the data. As a simplification, we assume that all aggregates in the plume have monomers of the same r_m.

Eq. (1) leads to a minimum size r_{min} for an aggregate of

$$r_{min} = 2^{\frac{1}{D}} r_m \tag{2}$$

where we have chosen $N_m = 2$ as the minimum number of monomers an aggregate can have. Particles with $r < r_{min}$ are assumed to be spherical with radius r. To simplify the problem and reduce the number of free parameters, we further assume that both spherical and aggregate particles "share" the same particle size distribution

$$\frac{dN}{dlnr} = N_0 (r/r_0)^{f-3} / [1 + (r/r_0)^{2f}], \tag{3}$$

which is the number of particles in the natural log of radius interval $dln(r)$, with N_0 as a parameter that scales with the particle number density, f as a positive width factor, and r_0 as the median radius of the particle mass distribution given by

$$\frac{dM(r)}{dr} = \frac{2M_0}{\pi r_0} \frac{f(r/r_0)^{f-1}}{1 + (r/r_0)^{2f}}, \tag{4}$$

where

$$M(r) = \frac{2M_0}{\pi} \arctan\left[\left(\frac{r}{r_0}\right)^f\right] \tag{5}$$

is the total mass of particles with radius between 0 and r, and M_0 is the total mass of particles. r_0 splits the mass distribution into equal halves, with the width of the distribution governed by f; small f values indicate wide distributions while large f values indicate narrow distributions. M_0, r_0, and f are free to vary in the model during optimization of the fit to the data. Eqs. (3)–(5) are the same distribution functions given in IE11, which were chosen due to their relative simplicity and their ability to capture both sharply peaked and asymptotic functional forms with only two free parameters. Fig. 1 shows a schematic of how the aggregate and spherical particles "share" the $dM(r)/dr$ distribution in our model. Particles with $r > r_{min}$ are assumed to be aggregates with radius r given in Eq. (1) and r_m defined by Eq. (2); they follow the size distribution of Eq. (3) with some given r_0 and f values. Particles with $r < r_{min}$ are assumed to be spheres of radius r that follow the same size distribution as the aggregates, with the same r_0 and f values. With these definitions, $dM(r)/dr$ has a discontinuity at $r = r_{min}$. This is caused by the different ways the mass of single particles (aggregate or spheres) scales with r while keeping N_0 fixed for both the aggregate and spherical sections of the size distribution. The discontinuity is not shown in Fig. 1, and we avoid it in our calculations, as discussed below.

3. Observations and model setup

Following the procedure of IE11, we use the following relationship to estimate total plume particulate mass (Eq. (4) of that paper):

$$R(\theta) = \frac{M_0}{4\rho_{ice}} \int \frac{A_p Q_{sca} P(\theta)(dN/dln(r))dln(r)}{V_p(dN/dln(r))dln(r)} \tag{6}$$

where M_0 is now the total particulate mass of the plume; A_pQ_{sca} is the scattering cross section of the particle, which, for spherical particles, can be split into the geometric cross section of the particle $A_p = \pi r^2$ and the scattering efficiency Q_{sca}; $P(\theta)$ is the scattering phase function; θ is the scattering angle, which is given in Table 1 of IE11; V_p is the solid volume of each particle, given by $(4/3)\pi r^3$ for spheres and $(4/3)\pi r_m^3 N_m$ for aggregates; $\rho_{ice} = 0.917$ g cm^{-3} is

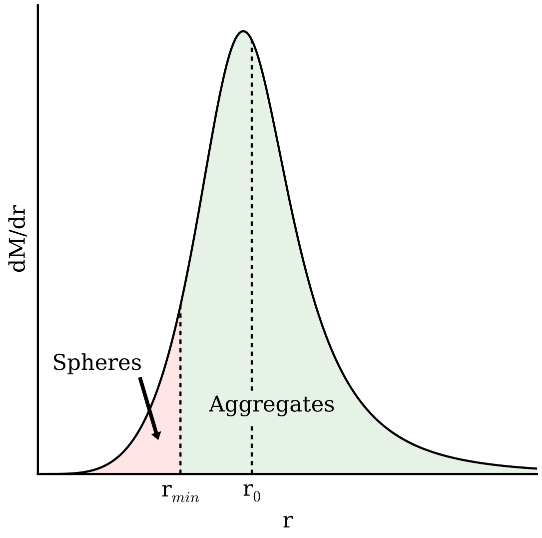

Fig. 1. A schematic of the plume particle mass distribution dM/dr as a function of the particle radius r, with the median particle radius r_0 and minimum aggregate radius r_{min} labeled.