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# Evidence for Liquid Water beneath the Enceladus Plumes

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## Abstract

We present our analysis of the Enceladus plumes using data from the Imaging Science Subsystem (ISS) on the Cassini spacecraft. The ISS is sensitive to the particles but not to the gas. From the fall-off of brightness with respect to height, we infer the velocity distribution of the particles as they leave the vent. From the variation of brightness with scattering angle and wavelength, we infer the particle size distribution. From integrated brightness, we infer the total mass of particles in the plume and the rate at which particle mass is leaving the vents. Both the mass and the mass rate are comparable to those for the gas inferred from Cassini ultraviolet imaging spectrometer (UVIS) data [1]. Thus the solid/gas ratio is of order unity, which rules out models in which the particles form from the vapor. These data imply that the particles were initially liquid droplets from a liquid water reservoir. The droplets froze when exposed to the vacuum of space. This result is consistent with results from the Cosmic Dust Analyzer (CDA), which detects salt in the icy particles [5]. The result is also consistent with the low speed of plume particles, which is much leas than the thermal speed of the gas and the escape speed of Enceladus. A comprehensive model of liquid water, either evaporating, bubbling, or boiling, with dissolved salt and gases, is needed to explain these observations, but such a model does not yet exist.

## 1. Introduction

We use two sets of data in this analysis. The first set was taken with the ISS narrow-angle camera (NAC) of at a spatial resolution better than 1 km per pixel. These data allow us to study the fall-off of brightness close to the surface, from which we infer the low-velocity component of the distribution. The second data set was taken mostly with the wide-angle camera (WAC) at a spatial resolution no better than 120 km per pixel. The advantage of the WAC data is the low scattering angle, from 2.25 to 5.5 degrees, and the wide wavelength coverage, from 0.42 to 0.918 microns. Observations at these low scattering angles were possible because the spacecraft was in Saturn's shadow and thus was protected from direct sunlight. The data sample the forward-scattering lobe of the phase function and provide strong constraints on the particle size distribution. The one NAC image taken during this eclipse sequence allows us to estimate the rate, in kg/s, at which mass in solid form is leaving the vents.

## 2. Data at high spatial resolution

The NAC data at better than 1 km resolution reveal plumes with scale heights of 18 – 20 km. For the Damascus source #2, we fitted these data to several velocity distributions, including Gaussians, Lorentzians, and exponentials. All of the fits yield mean velocities for the particles of order 35 m/s. This speed is much less than the thermal speed of the gas $(kT/m)^{1/2}$, which is 355 m/s for T = 273 K It is also much less than the escape velocity from Enceladus, which is 235 m/s. Since these micron-sized particles are accelerated quickly to the speed of the gas, either the particles must have formed in the top 10 cm of the vent or the particles must have lost their speed in a collision with the walls in the top 10 cm. A variant of these possibilities is that the particles started out as a large, slow-moving blob of liquid, which broke up when it hit the vacuum of space. A model of flash freezing of liquid water in vacuum is needed, but none exists at present.

## 3. Data at low scattering angles

Despite the low spatial resolution of the WAC data, they are useful because the low scattering angle (phase angle close to 180 degrees) enables one to infer the particle size distribution. We use a differential size distribution of the following form:

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

Here $r_0$ is the median radius, and $M_0$ is the total mass. The parameter $a$ controls the width of the distribution, with $0 < a < \infty$. Small $a$ is a wide distribution, with an infinite number of small particles. Large $a$ is a narrow distribution, clustered about the median radius $r_0$. For particle shapes we tried spheres (Mie theory), oblate spheroids, and prolate spheroids. The best fits are for $a$ = 1 or 2 with $r_0 \approx 3$ μm, which agrees with VIMS results [2]. The total mass of particles $M_0$ is ~1.5 x $10^5$ kg. The fit to the data is not very sensitive to particle shape. From the one NAC image at high phase angle, we infer ~140 kg/s of particles emanating from the vents. This is comparable to the mass rate for water vapour.

## 4. Conclusions

The mass of particles in the plume is comparable to the mass of vapour. This fact is incompatible with models in which the vapour evaporates from the icy walls of the vent and the particles form by condensation from the vapour as it expands and cools [3]. Salt in the ice particles is also incompatible with particles that have condensed from the vapour. The low average velocities are compatible with this scenario only if the particles have collided with the walls or formed from the gas in the top 10 cm of the vent [6]. If they spend more than 10 cm with the gas, the gas would accelerate them to thermal speeds, which is not observed. We conclude that the icy chamber model does not fit the data.

The other models involve liquid water below the surface of Enceladus. If the liquid behaves like geysers on Earth, the models can account for the high solid/vapour ratio. They also can account for salt in the plume particles, if the liquid is salty. Whether or not the liquid is boiling is an open question. If both the liquid and the gas are water, and if the pressure of the gas is equal to or less than the saturation vapour pressure of the liquid, then the liquid will boil provided there are nucleation sites. If it doesn't boil, due to the absence of nucleation sites, it will at least evaporate. Bubbles of other gases breaking at the vapour-liquid interface could inject salty particles into the mixture. These hypothetical processes still have to be worked out in a comprehensive model.

Methane constitutes 1% or more of the gases in the plume, but it has a low solubility in liquid water. This led to the suggestion that the methane is trapped in a clathrate hydrate [4], where the gas to water ratio can be as high as 1:6. The clathrate is supposed to decompose when exposed to vacuum, preserving its ratio of methane to water. The problem is that methane is much more volatile than water: Terrestrial samples of methane clathrate give off their methane but not their water, which either melts or turns into ordinary ice. When exposed to vacuum at $T << 273$ K, clathrate hydrate will decompose into volatile gases and ice, without a large fraction of water vapour.


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