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A redetermination of the ice/vapor ratio of Enceladus' plumes: Implications for sublimation and the lack of a liquid water reservoir

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ABSTRACT

The discovery of plumes of H_2O vapor and ice particles erupting from the south pole of Enceladus, the tiny frigid satellite of Saturn, sparked controversy over whether these plumes are produced by boiling, or by sublimation with subsequent recondensation of the sublimated vapor [Porco, C.C., Helfenstein, P., Thomas, P.C., Ingersoll, A.P., Wisdom, J., West, R., Neukum, G., Denk, T., Wagner, R., Roatsch, T., Kieffer, S., Turtle, E., McEwen, A., Johnson, T.V., Rathbun, J., Veverka, J., Wilson, D., Perry, J., Spitale, J., Brahic, A., Burns, J.A., DelGenio, A.D., Dones, L., Murray, C.D., Squyres, S., 2006. Science 311, 1393–1401]. Porco et al.'s analysis that the masses of ice (I) and vapor (V) in the plume were comparable was taken to argue against the occurrence of sublimation and recondensation, leading to the hypothesis that the reservoir was boiling water, possibly as close as 7 m to the surface. Thus, it has been advocated that Enceladus should be a target for astrobiology exploration. Here we show, with recalculations using the original data and methodologies, as well as with new sensitivity studies, that the mass of ice in the column is significantly less than the mass of water vapor, and that by considering three additional effects, I/V is likely to be <0.2–0.1. This means that the plume is dominated by vapor that the thermodynamics permits to be easily produced by sublimation with recondensation. The low I/V ratio provides no compelling criterion for consideration of a liquid water reservoir. The uncertainties on the I/V ratio have not previously been discussed in the literature. Although the I/V ratio is sensitive to particle sizes and size distributions, the masses of ice (I) and vapor (V) are not comparable in any scenario constrained by available observations. We thus discuss the implications of sublimation from a thermodynamic point of view in a context that has not been presented previously. Constraints on I/V ratio from future spacecraft measurements of the plume, in conjunction with consideration of the total plume composition and multicomponent analysis, can help constrain source conditions for the plume.

The plumes erupting from the south pole of Enceladus, the frigid satellite of Saturn, emerge in a terrain where surface temperatures on three Cassini flybys have been reported as 157 ± 24 K (Spencer et al., 2006) and as 200 ± 20 K, and 167 ± 3 K, respectively, in 2008 (John Spencer, personal communication, 3/10/09). The nature of the reservoir that supplies the plumes is the topic of one of the biggest current controversies in planetary science because it has been proposed that there is liquid water in the crust, possibly as shallow as 7 m (Porco et al., 2006), and that Enceladus should therefore be a target for astrobiology exploration. Here we point out that, contrary to this earlier report, sublimation with subsequent recondensation of ice particles cannot be ruled out by the observed ratio of ice to vapor. The key parameter upon which the arguments and inferences about liquid water were originally made in 2006 was the ratio of mass of ice to vapor (I/V) in the column which was reported to be I/V = 0.42 ($I = 3 \times 10^{-6}$ kg m^{-2}, $V = 7.16 \times 10^{-6}$ kg m^{-2}).

The I/V in material exiting from the reservoir and ascending in the plume is the quantity that relates plume properties to a postulated reservoir condition if it is assumed that the plume properties directly mirror the reservoir properties (this assumption is discussed later in the paper). There appear to be errors in calculation of both I and V in the original Porco et al. paper and the purpose of this paper is to clarify the original analysis and to discuss uncertainties in the calculated I/V ratio and the implications of those uncertainties.

In order to obtain the I/V ratio, data from two separate instruments must be compared. We first examine the data as originally reported by Porco et al. (2006). Ice particles were measured at 15 km altitude by the Imaging Science Subsystem, ISS (Porco et al., 2006), whereas water vapor measurements by the UltraVio-

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let Imaging Spectrograph, UVIS reported to range from 7 to 30 km height.[1] The UVIS data indicated a molecular water vapor abundance of 1.5×10^{20} molecules m^{-2} (Hansen et al., 2006), which we calculate yields a mass of water vapor in the column of 4.5×10^{-6} kg m^{-2} assuming a molecular weight of 18 amu for the H_2O molecule. The originally reported water vapor mass would be obtained from the reported molecular abundance if the molecular weight had been assumed to be 28.

An ice column particle abundance was derived from the observed brightness (I/F) by assuming a particle size distribution. This ice particle column abundance is $\sim 6 \times 10^8$ particles m^{-2}. The mass of ice is obtained from this by assuming, after Porco et al. (p. 1401, footnote 30) that there is a broad distribution of sizes given by

$$n(r) = \text{constant} * r^{(1-3b)/b} \exp(-r/ab),$$

where a is the effective radius, and b is a parameter representing the breadth of the distribution. The effective radius, a, was reported as 1.0 μm to be consistent with observations of particle sizes in Saturn's E-rings, and b was taken to be 0.25 in the original work to ensure a fair fraction of particles greater than 2 μm. Our integration of $n(r)$ from 0 to infinity, with the density of ice as 1000 kg m^{-3}, yields a mass of 0.94×10^{-6} kg m^{-2}. For a monodisperse size distribution with radius 1 μm a column mass of 2.5×10^{-6} kg m^{-2}, close to the originally calculated value 3×10^{-6} kg m^{-2} of Porco et al. (2006), is obtained.

Thus, using only the material originally reported, the recalculated vapor mass (4.5×10^{-6} kg m^{-2}) is about 2/3 of that originally reported, and the recalculated ice mass (0.94×10^{-6} kg m^{-2}) is 1/3 of that initially reported. Using these two recalculated values, we find that the I/V ratio is 0.21, half of the initially reported value of 0.42. We thus question the assertion of Porco et al. that the masses of liquid and vapor are comparable, and hence question their conclusions about the need for a liquid reservoir.

To our knowledge, no sensitivity analysis of the I/V ratio to the assumed analytical particle size distributions has been published. Thus, we performed such a sensitivity study, holding the value of vapor constant (Table 1), varying the effective particle radius, a, and the breadth of the particle size distribution, b. For all simulations the scattering cross-section was kept constant, equal to that determined using Mie theory assuming a particle column abundance of 6×10^8 m^{-2}, $a = 1$ μm, and $b = 0.25$. The a seems well constrained to be ~1 μm (Showalter et al., 1991) or predominantly below 1 μm (Postberg et al., 2008) and hence was varied between 0.5 and 2 μm, whereas b was varied between 0.1 and 0.25. The total column ice mass varies by roughly a factor of 2 for these calculations with two effects favoring more ice mass: a narrower size distribution (smaller b), or larger particles (larger a). Two effects favor less ice mass: smaller particles, or a broader size range. The broader size ranges (larger b) give smaller mass because even though more particles with $r > 2$ μm occur, the mode of the distribution is considerably less than a (e.g., the mode is 0.25 μm for $b = 0.25$ and $a = 1$ μm). In addition to uncertainties in a and b, other uncertainties exist because the definition of an effective radius and the calculated mass of the distribution are poorly defined in the presence of non-spherical ice particles (McFarquhar and Heymsfield, 1998). Despite these uncertainties, since the narrow size distribution (smaller b) contradicts observational evidence and $a \leqslant 1.0$ μm is more appropriate for particles in the E-ring (Postberg et al., 2008; Schmidt et al., 2008, p. 687), we conclude that values of I/V are probably 0.2 or less given the initially reported data and assumptions.

Table 1
Sensitivity analysis of the I/V ratio.

a (μm)	b	I (kg m^{-2})	I/V*
2	0.25	2.1×10^{-6}	0.47
1	**0.25**	$\mathbf{0.94 \times 10^{-6}}$	**0.21**
0.8	**0.25**	$\mathbf{0.72 \times 10^{-6}}$	**0.16**
0.5	0.25	0.45×10^{-6}	0.10
1	0.1	0.98×10^{-6}	0.22
1	0.05	1.1×10^{-6}	0.24

* Assuming V is held constant, 4.5×10^{-6} kg/m^2. The values in boldface are those believed to be most consistent with the observations described in the text.

We now consider some additional effects that further lower estimates of I/V but which are difficult to quantify. First, as noted in Footnote 1, the location of the measurement of water vapor by UVIS in 2005 was made at heights reported to be 15 or 21 km, whereas the mass of ice was measured at 15 km (Porco et al., 2006). According to Tian et al. (2007), the vapor abundance at the altitude of 15 km was about two times the value at 21 km. This suggests that all values of I/V calculated above should be reduced by an additional factor of 2. Second, neither the original calculations, nor our recalculations, account for the fact that some of the ice may be falling back toward the vent ("most", Porco et al., 2006, p. 1399). If the ice is falling back toward the vent throughout the whole plume, then it is doubly counted by the ISS, and the I/V ratio in the plume is even lower than discussed above. Third, based on multiphase flow theory, when the vapor velocity is greater than that of the ice particles, the actual mass flow ratio is greater than the measured mass ratio (I/V) in the column. This implies that the I/V "production" ratio is even smaller. We thus conclude that values of I/V ~ 0.2 represent an upper limit for internally consistent assumptions, and that values of less than this by at least a factor of 2–3 are very plausible.

Before examining the implications of these new values for inferred reservoir conditions, we note that if ice falls back to the surface at low elevations, below those of the ISS observations, then I/V observed at tens of kilometers elevation in the plume is smaller than I/V lower in the plume, and is smaller than in an underground reservoir. This effect can only be considered if further measurements at different elevations in the plume become available.

We now examine the implications of these recalculated I/V values on inferred reservoir conditions and consider whether or not sublimation should have been excluded from consideration as a mechanism for describing the source of Enceladus' plume. Following the original assumptions of Porco et al. (2006), we assume that the reservoir is a single-component, H_2O. The two processes available for producing the plume are then (1) boiling to produce vapor plus liquid which then freezes to form ice particles and (2) sublimation with recondensation of vapor to form the ice particles. Either reservoir discharges into the vacuum above the surface of Enceladus. The boiling process produces liquid droplets that will freeze to ice as long as temperature decreases to a certain degree below the freezing point. Thus, there is no lower limit of temperature for generating ice. However, the required recondensation process after sublimation may become limited by a small radius growth rate of an ice particle at low temperature conditions (Lu and Kieffer, 2009, Eq. (9), p. 459). We chose 190 K, in the range of the highest observed temperatures at the South Pole, as a conservative lower limit of conditions for decompression in our analysis of both models.

We illustrate decompression processes from several different reservoirs into a plume on a temperature–entropy diagram shown in Fig. 1. The decompression from the reservoir into an erupting plume is assumed, adiabatic and reversible, i.e., isentropic. To first order, this assumption allows semiquantitative analysis of the fluid

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[1] Later in this paper, we use an average height of 21 km in a qualitative argument. Tian et al. (2007) report a UVIS height of 21 km, and Hansen et al. (2008) report a UVIS height of 15 km.

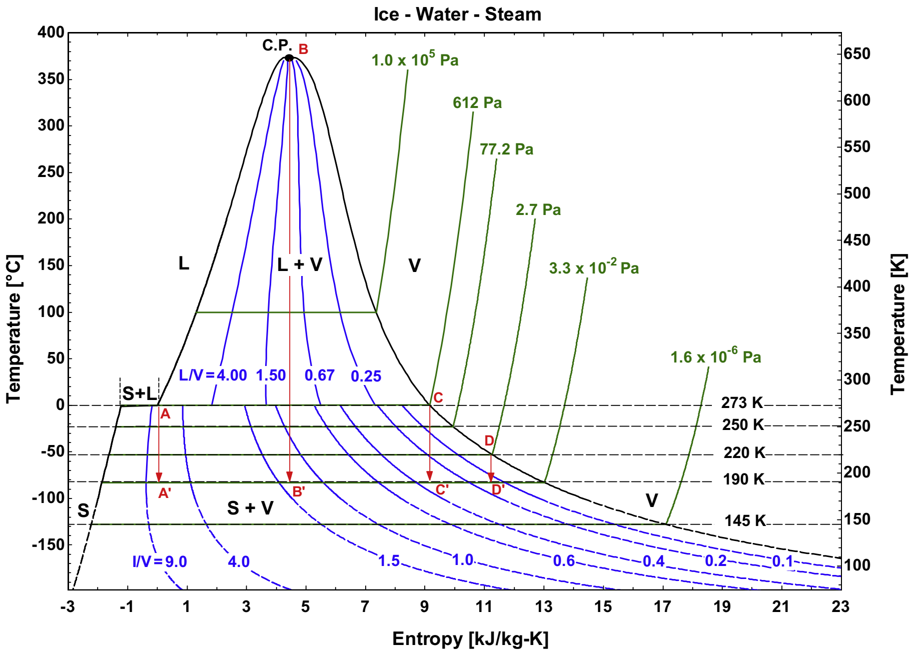

Fig. 1. Temperature–entropy diagram for H_2O. S = solid (ice), L = liquid and V = vapor. Combinations of these indicate the L + V, S + V and S + L two-phase fields. CP is the critical point. Green lines are lines of constant pressure, and blue lines are lines of constant mass ratio: I/V denotes the ice/vapor ratio; L/V denotes the liquid/vapor ratio. Data below −100 °C are extrapolated (dashed lines) from the lowest temperature measurements available. The thermodynamic paths A–A′, B–B′, C–C′ and D–D′ are discussed in the text.

dynamics, e.g., with it Kieffer (1984) showed that the plume composition of Old Faithful Geyser in Yellowstone can be calculated from measured reservoir pressure and conditions. With this assumption, a vertical line connecting the reservoir conditions to the final conditions represents the thermodynamic path and the I/V ratio at all states; irreversible effects would increase the entropy, and the amount of vapor, of the final state.

On the liquid–water boiling side of the phase diagram (analogous to terrestrial hot springs or geysers), two end conditions for boiling are shown. A–A′ represents decompression of a liquid reservoir initially at 273 K (612 Pa pressure) with the formation of a mixture of vapor and frozen liquid droplets (ice). B–B′ represents decompression of a much higher high-temperature liquid from critical point, with the formation of a boiling mixture of liquid plus vapor. This mixture then freezes to a mixture of ice plus vapor when the temperature drops below the freezing point. In both cases, the I/V ratio is large compared to the value of 0.1–0.2 discussed above: the mass ratio I/V is 7.0 at A′ and 1.4 at B′. A similar conclusion led to speculation that if boiling is occurring, ice is left behind in the reservoir or falls back out of the plume near the exit plane (Porco et al., 2006).

On the vapor side of the phase diagram (analogous to terrestrial fumaroles), two isentropic processes representing recondensation from a sublimated vapor are shown. The sublimated vapor is represented by the reservoir conditions C and D, and recondensation occurs along the isentropic decompression paths. Decompression of vapor from triple point conditions, C–C′, produces a mass fraction I/V $\sim$ 0.35, and from D–D′, I/V $\sim$ 0.13. Both values are less than the reported estimates of I/V = 0.42 by Porco et al. and the value for the colder reservoir D–D′ is the range of our recalculated and preferred values of I/V $\leqslant$ 0.2.

Our calculation shows that any isentropic depressurizing process between C–C′ and D–D′ has enough enthalpy trop to accelerate the fluid to get the Enceladus escape velocity of 239 m s^{-1}. Under ice–vapor equilibrium condition, the enthalpy drops from C to C′ and D to D′ are 889 kJ kg^{-1} and 390 kJ kg^{-1}, respectively, corresponding to an upper limit velocities of 1333 and 883 m s^{-1}. Under non-equilibrium condition where an isentropic metastable expansion of vapor occurs (Lu and Kieffer, 2009, p. 457–459), the enthalpy drop can be determined by assuming that the vapor expands isentropically and obeys the ideal gas law. In this case, decompression from 220 to 190 K has an enthalpy drop of 55 kJ kg^{-1}, corresponding to an upper limit velocity of 332 m s^{-1}, while decompression from 273 to 190 K produces a velocity of 553 m s^{-1}, with enthalpy drop of 153 kJ kg^{-1}.

We have addressed the original misconception that sublimation is not permitted by the thermodynamics and that there must be liquid water at shallow depths. At first glance, there appears to be a contradiction between our conclusion that sublimation is permitted and that of the more recent work of Schmidt et al. (2008) that there is a liquid water reservoir at shallow depths. Their kinetic model hinges on the density of the gas phase, and in the pure H_2O system of their analysis, the density of the gas is too low unless the temperature of the reservoir is close to the triple point. However, this argument does not allow for the role that the non-condensible gases (CO_2, CH_4, N_2) play in determining total pressure and density and therefore underestimates their possible contribution to lofting of particles. The criticism of Brilliantov et al. (2008) also makes this same assumption about a single-component system and is therefore not necessarily appropriate to a multicomponent system.

To summarize, although the I/V ratio is sensitive to particle sizes and size distributions, the masses of ice (I) and vapor (V) are not comparable in any scenario constrained by available observations. The recalculation of I/V from the published data shows that there is almost an order of magnitude less ice than vapor in the plume, rather than “comparable” amounts as initially reported. In the single-component H_2O system that was analyzed by Porco et al. (2006) the thermodynamic analysis shows that the measured values of I/V can be obtained from sublimation processes. In that system, the I/V ratio alone provides no compelling reason to postulate a near-surface liquid water reservoir. The sublimation/recondensation process should not have been ruled out by the I/V measurement, and variations of the sublimation model—such as the ice-rich clathrate models (Kieffer et al., 2006; Halevy and

Stewart, 2008; Fortes, 2007) should be given serious consideration as alternatives for reservoir conditions.

Future measurements of I/V, if combined with tight constraints on the particle size and size distributions, may contribute to our understanding of reservoir characteristics if: (1) the relation between measured plume properties and production properties of the reservoir is known; and (2) the relation between the single-component behavior of H_2O and the multicomponent system is defined. Most fluid dynamic analyses are based on assumptions of adiabatic reversible processes, and such processes in multicomponent systems do not imply that each component behaves adiabatically or isentropically. However, the temperature–entropy diagrams of each component can still provide information about the behavior of that component provided that the magnitude of entropy change for each component in the multicomponent system is known. Furthermore, the multicomponent composition of a system has significant influence on conclusions about sublimation by altering the total pressure of the system compared to a single-component H_2O system.

Future simultaneous measurements of I/V by SSI and UVIS, as well as of the plume composition by INMS, and of these properties at different altitudes in the plume, would help constrain the models.

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