ICE/VAPOR RATIO OF ENCELADUS'S PLUME: IMPLICATIONS FOR SUBLIMATION

Susan W. Kieffer[1], Xinli Lu[1], Greg McFarquhar[2], and Kenneth H. Wohletz[3], [1]Department of Geology, University of Illinois at Urbana-Champaign, 1301 W. Green Street, Urbana, IL 61801 (s1kieffer@gmail.com, xinlilu@uiuc.edu), [2]Department of Atmospheric Sciences, 105 S. Gregory St., University of Illinois, Urbana, IL 61801, [3]Los Alamos National Laboratory, EES11 MS 665, Los Alamos, NM 87545

Introduction: The discovery of plumes of H_2O vapor and ice particles erupting from the south pole of Enceladus sparked controversy over whether these plumes are produced by boiling, or by sublimation with subsequent recondensation of the sublimated vapor. The assumption 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 [1]. 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 two new effects, I/V is likely to be <0.1-0.05. This implies that the plume is dominated by vapor and can easily be produced by sublimation with recondensation. Therefore, 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 and are large. **Future interpretations should be done in the context of a multicomponent reservoir, such as a sub-eutectic icy clathrate (ice, clathrate, NaCl•2H_2O), instead of a single-component reservoir.**

Redetermination of the Ice/Vapor Ratio: The key parameter upon which the arguments and inferences about liquid water were made was the ratio of mass of ice to vapor (I/V) in the column which was reported to be I/V=0.42 (I=3×10^{-6} kg m^{-2}, V=7.16×10^{-6} kg m^{-2}) [1]. Data from two separate instruments must be compared to obtain the I/V ratio. Ice was measured at 15 km elevation by the Imaging Science Subsystem, ISS [1], whereas water vapor was measured at 30 km by the UltraViolet Imaging Spectrograph, UVIS [2]. The UVIS data indicated a molecular water vapor abundance of 1.5×10^{20} molecules m^{-2}, which we calculate here to yield a mass of water vapor in the column of 4.5×10^{-6} kg m^{-2} assuming a molecular weight of 18 for the H_2O molecule. The ISS data indicated an ice column abundance of ~6×10^{8} m^{-2}. The mass of ice can be obtained from this by assuming that there is a broad distribution of sizes [1] 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 [1] to ensure a fair fraction of particles greater than 2μm. Our integration of n(r) from 0 to infinity, with the ice density as 1000 kg m^{-3}, yields a mass of 0.94×10^{-6} kg m^{-2}. Thus, using only the material originally reported, our recalculated vapor mass (4.5×10^{-6} kg m^{-2}) is about 2/3 of that originally reported, and our recalculated ice mass (0.94×10^{-6} kg m^{-2}) is 1/3 of that originally 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. This contradicts the assertion that the masses of liquid and vapor are comparable [1], and hence the conclusions about the need for a liquid reservoir.

Sensitivity analysis of the I/V ratio to the assumed analytical particle size distributions has been carried out, holding the value of vapor constant. The effective particle radius, a, seems well-constrained to be ~1 μm [1] or even less (e.g., 0.8 μm, [3]). Two effects favor more ice mass in the column: a narrower size distribution (smaller coefficient b in the distribution), or larger particles (larger a). Two effects favor less ice mass: smaller particles, or a broader size range. Broader size ranges (larger b) give smaller mass because even though more particles with r>2μm 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). We found that the I/V ratio is very sensitive to the choice of a and b. However, because a narrow size distribution (smaller b) contradicts observational evidence and $a \leq 1.0$ micron is more appropriate for particles in the E ring [1], we hypothesize that I/V values are probably less than the 0.21 value calculated above. Further, there are even more uncertainties in I/V 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 [4].

We now consider two additional effects that further lower estimates of the I/V ratio but that are difficult to quantify. First, the measurement of water vapor by UVIS was made at 30 km, whereas the mass of ice was measured at 15 km. Tian et al. [5], using the UVIS data, suggested that at the lower height the vapor abundance may have been 2-3 times the value at 30 km.

This suggests that all values of I/V calculated above should be reduced by an additional factor of 2-3. 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", [1]). 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. 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.

Thermodynamic Analysis on Temperature-entropy Diagram: 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. [1], we assume that the reservoir has 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 cold vacuum above the surface of Enceladus. It is likely that recondensation processes in sublimation will cease due to kinetic limitations if the temperature is significantly below about 190K. We therefore chose 190K as the lower limit of conditions for decompression. Decompression processes from several different reservoirs into a plume is shown in the temperature-entropy diagram (Figure 1). Isentropic decompression is assumed.

On the liquid-water boiling side of the phase diagram, two 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 mass of ice is large compared to the value of 0.1 discussed above: the mass ratio I/V is 7.0 at A' and 1.4 at B'. This 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 [1].

On the vapor side of the phase diagram, two isentropic processes representing recondensation from a sublimated vapor are shown. The sublimated vapor is represented by the reservoir conditions C (273K) and D (220K), and recondensation occurs along the isentropic decompression paths. Decompression of vapor from triple point conditions, C-C', produces a mass fraction I/V~ 0.35, and from D-D', I/V~0.13. Both values are less than the reported estimates of I/V=0.42 by Porco et al. [1] and the value for the colder reservoir D-D' is in the range of our recalculated and preferred values of I/V≤0.2. Producing these values from some even lower-temperature reservoirs is not a problem.

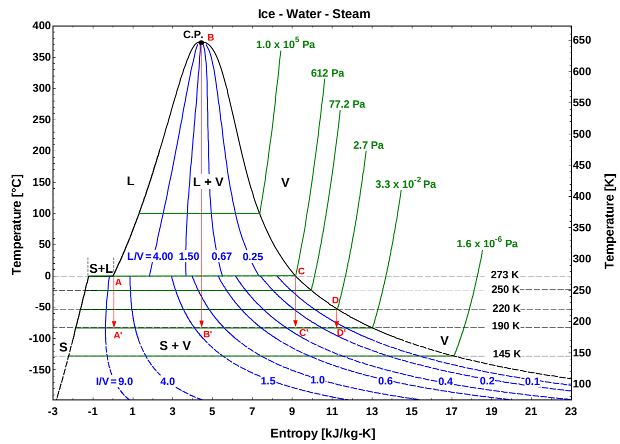

Figure 1: Temperature-entropy diagram for H_2O. S = solid (ice), L = liquid, and V = vapor. Combinations of these indicate the L+V, S+V and S+L two-phase fields. C.P. is the critical point. Green lines: constant pressure; blue lines: constant I/V or L/V ratios. Data below -100 ºC are extrapolated (dashed lines) from the lowest temperature measurements available.

Summary: There is an order of magnitude less ice than vapor in the plume, rather than "comparable" amounts as initially reported. The thermodynamic analysis shows that the measured values can be obtained from sublimation processes, and this 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 [6, 7, 8] should be given serious consideration as alternatives for reservoir conditions. Future interpretations should also be done in the context of a multicomponent reservoir, such as a sub-eutectic icy clathrate, instead of a single-component reservoir.

References: [1] Porco, C. C. et al. (2006) *Science*, *311*, 1393–1401. [2] Hansen, C. J. et al. (2006) *Science*, *311*, 1422–1425. [3] Schmidt, J. et al. (2008) *Nature, 451*, 685-688. [4] McFarquhar, G. M. and Heymsfield, A. J. (1998) *J. Atmos. Sciences 55*, 2039-2053. [5] Tian, F. et al. (2007) *Icarus, 188 (1),* 154-161. [6] Kieffer et al. (2006) *Science, 314*, 1764-1766. [7] Halevy, I. and Stewart, S. T. (2008) *GRL 35*, L12203. [8] Fortes, A. D. (2007) *Icarus, 191*, 743-748.