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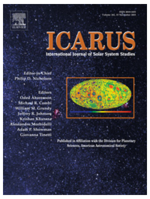

Controlled boiling on Enceladus. 2. Model of the liquid-filled cracks

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ABSTRACT

Controlled boiling will occur on Enceladus whenever a long, narrow conduit connects liquid water to the vacuum of space. In a companion paper we focus on the upward flow of the vapor and show how it controls the evaporation rate through backpressure, which arises from friction on the walls. In this paper we focus on the liquid and show how it flows through the conduit up to its level of neutral buoyancy. For an ice shell 20 km thick, the liquid water interface could be 2 km below the surface. We find that the evaporating surface can be narrow. There is no need for a large vapor chamber that acts as a plume source. Freezing on the icy walls and the evaporating surface is avoided if the crack width averaged over the length of the tiger stripes is greater than 1 m and the salinity of the liquid is greater than 20 g kg^{-1}. Controlled boiling plays a crucial role in our model, which makes it different from earlier published models. The liquids on Enceladus are boiling because there is no overburden pressure—the saturation vapor pressure is equal to the total pressure. Salinity plays a crucial role in preventing freezing, and we argue that the subsurface oceans of icy satellites can have water vapor plumes only if their salinities are greater than about 20 g kg^{-1}.

1. Introduction

Postberg et al. (2009, 2011) made a major advance in our study of the Enceladus plumes with observations that a major fraction of the particles, both in the plumes and in the E ring, are made of salt water ice. Their data eliminate or severely constrain non-liquid models and strongly imply that a salt-water reservoir with a large evaporating surface provides nearly all of the matter in the plume. Both Na-poor and Na-rich grains were detected. The salinities of the latter are in the range 5–20 g kg^{-1}, which Postberg et al. (2009) consider to be a lower limit for the salinity of an Enceladus ocean. They concluded that the area of the liquid–gas interface must be "a few to tens of square kilometers" if it is to supply the observed gas production rate. Our model addresses this last conclusion. We find that freezing of the liquid–gas interface introduces a lower bound on the salinity of all satellite oceans if they are to have plumes.

Nakajima and Ingersoll (this issue), hereinafter referred to as Part 1, considered evaporation of the liquid and the flow of vapor through narrow cracks that vent to space. They introduced the concept of controlled boiling, which arises from the backpressure due to friction with the walls of the crack as the gas flows upward. For narrower cracks and longer paths to the exterior surface, the backpressure increases and ultimately approaches the saturation vapor pressure (SVP) of the liquid, which greatly reduces the evaporation rate. In this paper we show that controlled boiling eliminates the need for large vapor chambers and large areas for the liquid–gas interface. To avoid freezing of the liquid–gas interface, the salinity of the evaporating liquid must be at least 20 g kg^{-1}, and the area of the evaporating liquid must be at least that of a crack 1 m wide extending over the 500 length of the tiger stripes. Freezing of the liquid on the walls of the conduits supplies a low-temperature radiative heat source that extends outward from the tiger stripes to distances of several kilometers. Controlled boiling leads to a new picture of the underground plumbing—the collective surface area of the evaporating liquid, the width of the liquid-filled cracks, and the salinity of the water in the cracks. We discuss the efficiency of convection and the area of the liquid–gas interface in Sections 2 and 3. We discuss freezing of the liquid–gas interface and freezing on the walls in Sections 4 and 5. We present our conclusions in Section 6.

2. Controlled boiling

The implication of controlled boiling is that narrow, liquid-filled cracks with water rising to its level of neutral buoyancy are

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possible. This is different from the view of Postberg et al. (2009), who argue that the area of the evaporating surface is orders of magnitude greater than that of the crack itself. This view is expressed in their Fig. S2, which is reproduced as Fig. 1. They favor evaporation from a large gas-filled chamber as shown in the left panel, although in their model the area ratio of the chamber size to the vent size is much greater than that shown in the figure. They say that a small liquid–gas interface, as shown in the right panel, requires implausibly large temperature gradients in the liquid to maintain the heat flux that is required to support the steady-state gas evaporation. The argument is based on their Eq. (S12), which is from experimental and theoretical work on thermal convection between solid horizontal surfaces maintained at different temperatures, the bottom being warmer than the top (e.g., Malkus, 1954; Kraichnan, 1962; Ingersoll, 1966; Grossmann and Lohse, 2001; Ahlers and Xu, 2001). That equation predicts large temperature differences within the fluid, which seem implausible and led Postberg et al. (2009) to propose large vapor chambers. However, we will argue that the water on Enceladus is boiling, and therefore Eq. (S12) does not apply.

The liquid on Enceladus is boiling if it is vented to space, whether there is a large vapor chamber (left panel of Fig. 1) or a narrow crack (right panel). A liquid boils when its saturation vapor pressure is greater than the total atmospheric pressure. If other gases are present initially, they will be carried off with the vapor until the vapor is the only gas. The total pressure will drop until the condition for boiling is satisfied. If gases more volatile than H_2O like CO_2, NH_3, N_2, and CH_4 are coming out of solution with the water, they will increase the tendency to boil. Their higher saturation vapor pressures will more than offset their higher partial pressures. Thus boiling is occurring for both cases shown in Fig. 1. If the vents are narrow, the boiling will be slow, and that is what we mean by controlled boiling.

Boiling is not confined to the liquid–gas interface; rather it extends into the fluid for a finite distance. For slow boiling, the bubbles make a negligible contribution to the volume of the mixture, and hydrostatic balance becomes $dP/dz = -\rho_{\mathrm{lig}}\, g$, where ρ_{liq} is the density of the liquid. Combining this with the ideal gas form of the Clausius–Clapeyron equation $dP_v/dT = P_v L_v/(R_v T^2)$ where R_v is the gas constant of the vapor and $P = P_v$ is the saturation vapor pressure, we obtain the lapse rate for a boiling liquid on Enceladus:

$$\frac{dT}{dz} = \frac{dT}{dP_v}\frac{dP_v}{dz} = -\left(\frac{R_v T^2 \rho_{\mathrm{liq}} g}{P_v L_v}\right) = -2.70\ \mathrm{K\ m^{-1}} \qquad (1)$$

We are using numbers from Table 1 for seawater, with salinity $S = 35\ \mathrm{g\ kg^{-1}}$, $R_v = 8.314/0.018\ \mathrm{J\ kg^{-1}\ K^{-1}}$, $T = 273\ \mathrm{K}$, $P_v = 599\ \mathrm{Pa}$, and $g = 0.11\ \mathrm{m\ s^{-2}}$. The numbers for fresh water differ by only a few percent. If the surface of the liquid were boiling at the seawater freezing point, which is −1.92 °C, then the liquid 71 cm below the surface would be boiling at 0 °C. Presumably 0 °C is as warm as it gets in the liquid-filled cracks of Enceladus, because the walls are made of ice. Depending on salinity, all the water 10s of cm down from the liquid–gas interface could be boiling at once.

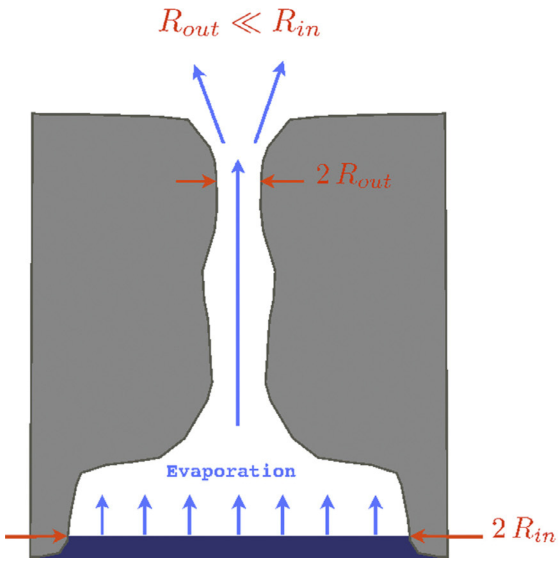

Fig. 1. Contrasting views of gas evaporating from a subsurface liquid flowing through a cylindrical conduit to vacuum. This is Fig. S2 in Postberg et al. (2009). They argue that a large evaporating surface (left panel) is required to avoid implausibly large temperature gradients in the liquid (right panel). R_{in} and R_{out} are the proposed radii of the conduit at the evaporating surface and the vent, respectively.

Table 1
Thermophysical constants for fresh water and seawater. Most of the numbers are from Sharqawy et al. (2010), who give online tables at web.mit.edu/seawater/ for a range of salinities. The expansion coefficient is from the Engineering Toolbox at www.engineeringtoolbox.com/water-thermal-properties-d_162.html.

Quantity	Symbol (units)	Fresh water at 0 °C	Seawater at 0 °C	Fresh water at 100 °C
Density	ρ (kg m^{-3})	1000	1028	958
Specific heat	C_p (J kg^{-1} K^{-1})	4210	3992	4219
Expansion coefficient	α (10^{-6} K^{-1})	−65.5	26	752
Thermal conductivity	k (W m^{-1} K^{-1})	0.572	0.570	0.677
Thermal diffusivity	κ (10^{-6} m^2 s^{-1})	0.136	0.138	0.169
Heat of vaporization	L_v (10^6 J kg^{-1})	2.50	2.41	2.26
Kinematic viscosity	ν (10^{-6} m^2 s^{-1})	1.79	1.85	0.295
Prandtl number	$\sigma = \nu/\kappa$ (none)	13.2	13.4	1.75
Vapor pressure	P_v (10^2 Pa)	6.11	5.99	1013

Further values of the expansion coefficient are given in Table 2.