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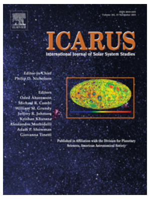

Controlled boiling on Enceladus. 1. Model of the vapor-driven jets

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ABSTRACT

Plumes of water vapor and ice particles have been observed from the so-called tiger stripes at the south polar terrain (SPT) of Saturn's satellite, Enceladus. The observed high salinity (~0.5–2%) of the ice particles in the plumes may indicate that the plumes originate from a subsurface liquid ocean. Additionally, the SPT is the source of strong infrared radiation (~4.2 GW), which is especially intense near (within tens of meters) the tiger stripes. This could indicate that the radiation is associated with plume activity, but the connection remains unclear. Here we investigate the constraints that plume observations place on the widths of the cracks, the depth to the liquid-vapor interface, and the mechanisms controlling plume variability. We solve the fluid dynamics of the flow in the crack and the interaction between the flow and ice walls assuming that the flows of water vapor and ice particles originate from a few kilometers deep liquid ocean. For a crack with a uniform width, we find that our model could explain the observed vapor mass flow rate of the plumes when the crack width is 0.05–0.075 m. A wider crack is not favorable because it would produce a higher vapor mass flow rate than the observed value, but it may be allowed if there are some flows that do not reach the surface of Enceladus due to condensation onto the ice walls or the crack is significantly tortuous. The observed heat flow can be explained if the total crack length is approximately 1.7 × 500 km. A tapering crack (a crack which is ~1 m wide at the bottom of the flow and sharply becomes 0.05–0.075 m at shallower depths) can also explain the observed vapor mass flow rate and heat flow. Widths of 1 m or more are necessary to avoid freezing at the liquid-vapor interface, as shown in our paired paper (Ingersoll and Nakajima [2016] Icarus). The observed intense heat flow along the tiger stripes can be explained by the latent heat release due to vapor condensation onto the ice walls near the surface. The resulting buildup of ice causes the vents to seal themselves on time scales less than a year. We also find that the ice to vapor ratio of the plumes is sensitive to the ice mass fraction at the bottom of the flow (liquid–vapor interface). We find that the total mass flow rate of the plumes becomes larger when the crack width is larger, which is consistent with the observation that the flow rate increases near the orbital apocenter, where the crack is expected to be widest.

1. Introduction

Water plumes were first detected by Cassini near the south polar terrain (SPT) of Saturn's satellite Enceladus (Porco et al., 2006). These plumes consist of vapor and ice particles that emanate from the four prominent fractures, the so-called "tiger stripes", which are approximately 500 km long in total (Porco et al., 2014; Spitale and Porco, 2007). The vapor is mostly water but contains small fractions of volatiles (e.g., 5% CO_2, 1% CH_4, and 1% NH_3, Hansen et al., 2011; Waite et al., 2009; 2011). The vapor production rate is reported as $\sim 200 \mathrm{kgs}^{-1}$ based on the measurements of the Ultraviolet Imaging Spectrometer (UVIS) (Hansen et al., 2011; Tian et al., 2007). The ice particles in the plumes are also dominated by water along with ~0.5–2% of salt (Postberg et al., 2011). The high salinity of the plumes suggests that the plume source is liquid water because ice particles condensed from vapor could not reach this high salinity (Postberg et al., 2011). Additionally, the reported ice to vapor ratios (I/V ratios) range from < 0.1–0.2 (Gao et al., 2016; Kieffer et al., 2009) to 0.3–0.7 (Hansen et al., 2006; Hedman et al., 2009; Ingersoll and Ewald, 2011; Porco et al., 2006). This variation stems from the difference in modeling the scattering of light by the ice particles. The I/V ratio is an important indicator of the plume source, given that a flow evaporating from ice cannot have a high I/V ratio (< 0.05, Ingersoll and Pankine, 2010; Schmidt et al., 2008).

The tiger stripes are the source not only for the plumes, but also for strong infrared radiation. Based on the Cassini's

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Composite Infrared Spectrometer (CIRS), the total heat flux from the SPT was estimated to be as low as 5.4–5.8 GW (Abramov and Spencer, 2009; Spencer et al., 2006) and as high as 15.8 GW (Howett et al., 2011). This high heat flow may include the contribution from surrounding areas, which is difficult to distinguish from re-radiated sunlight. Recently, Spencer et al. (2013) have reported that the heat flow could be ∼4.2 GW after eliminating these contributions. The thermal emission is especially strong near the tiger stripes (Porco et al., 2006; Spencer et al., 2006). Analyzing data from the Visual and Infrared Mapping Spectrometer (VIMS) show that the thermal emission is most intense near the stripes, in the form of small-scale hot spots (∼10 m) (Blackburn et al., 2012; Goguen et al., 2013; Spencer et al., 2012). Thus it appears that the thermal emission along the tiger stripes is associated with the plume activity (e.g., Ingersoll and Pankine, 2010; Blackburn et al., 2012; Spencer et al., 2012; Goguen et al., 2013; Porco et al., 2014).

Another key observation is that the plume activity depends on the orbit of Enceladus. The plume brightness, caused by the scattering of light by ice particles, reaches its maximum near the apocenter (Hedman et al., 2013; Nimmo et al., 2014; Ingersoll and Ewald, 2016). This is probably because the cracks are most widely open at the apocenter, as predicted by the tidal-opening model (Hurford et al., 2007), and they lead to higher plume mass fluxes. This model is further supported by the correlation between the locations of the most active plumes and high normal tidal stresses (Nimmo et al., 2014; Porco et al., 2014). There is some time lag between the apocenter and the maximum plume brightness. Several mechanisms have been suggested regarding this issue (Běhounková et al., 2015; Kite and Rubin, 2015; Nimmo et al., 2014).

In summary, these observations performed by Cassini seem to indicate that water vapor and ice particles are evaporating from a subsurface liquid ocean and that the hot spots are associated with the plumes. However, we still do not have a clear understanding of the connection between the plume dynamics and these observations. In this paper, we attempt to build a dynamical model that can explain the observed vapor mass flow rate, heat flow from the tiger stripes, and I/V ratio of the plumes. We assume that the plumes originate from a liquid-vapor interface a few km deep. The water evaporation rate from the liquid ocean is controlled mainly by the back pressure arising from the friction of the walls (discussed in Section 2.2). We call this a controlled boiling mechanism in this paper. We use similar assumptions to those of Ingersoll and Pankine (2010) (IP10 hereafter), but one of the major difference is that we assume a subsurface liquid ocean and that the evaporation is controlled by the back pressure, whereas IP10 assumes that the plumes originate from vapor sublimation from the ice walls. Using this model, we attempt to clarify the following connections: Can a subsurface ocean explain the observed heat flow, the vapor mass flow rate, size of the hot spots, and the ice to vapor ratio? We propose that the evaporation of water does not freeze the liquid ocean, as discussed in Section 4.3. This is further discussed in our paired paper (Ingersoll and Nakajima, 2016, herein Part 2). It should be noted here that the ratio of the heat flow and the vapor production rate determines the ratio of radiated heat to latent heat carried with the vapor (approximately 10:1), which has been discussed in previous literature (e.g., Ingersoll and Pankine, 2010).

2. Model

We solve steady-state equations of the flow and flow–wall interaction. Water vapor and ice particles evaporate from the liquid ocean and ascend towards the ice surface. Along the way, part of the vapor condenses onto the surrounding ice walls and releases its latent heat to the walls. The heat is transported by conduction in the ice and eventually reaches the ice surface. Subsequently, the heat is released into space by radiation. The parameters used here are the crack width δ, crack depth D, and solid mass fraction at the bottom of the flow (liquid–vapor interface) s_0. Here, the crack width is the distance between the ice walls, and the crack depth is the distance from the liquid surface (vapor–liquid boundary) to the surface of the ice (Fig. 1). We consider vertically uniform and nonuniform crack widths.

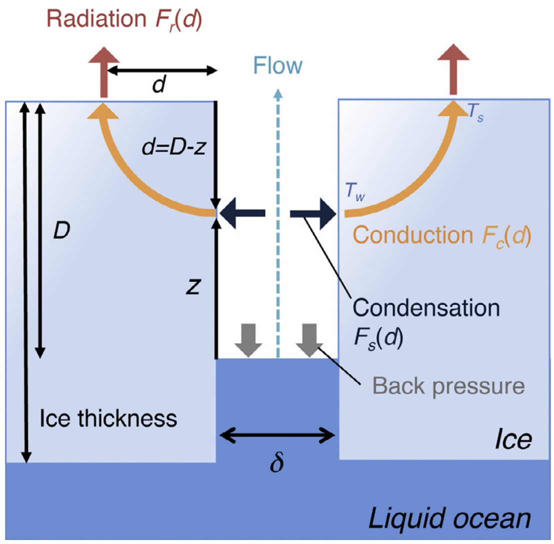

Fig. 1. Schematic view of our model with a uniform crack width ($d\delta/dz = 0$). The evaporation is controlled by the back pressure of the flow. At each depth d, some of the vapor condenses onto the ice walls and emits its latent heat to the ice walls ($F_s(d)$). The heat is conducted in the ice ($F_c(d)$) and eventually emitted to space ($F_r(d)$).

2.1. Governing equations

The conservation equations of mass, momentum, and energy of the flow are solved simultaneously. The mass conservation is written as

$$\frac{d}{dz}(\rho v \delta) = E, \tag{1}$$

where z is the upward coordinate, ρ is the density, v is the velocity, and E is the vapor mass flux from the ice walls to the flow (i.e., $E < 0$ when vapor condenses onto the ice walls). Eq. (1) can be written as

$$v\delta\frac{d\rho}{dz} + \rho\delta\frac{dv}{dz} + \rho v\frac{d\delta}{dz} = E. \tag{2}$$

The momentum equation is

$$\frac{d}{dz}(\rho v^2 \delta) = -\delta\frac{dp}{dz} - \tau - \rho g\delta + v(E - E^*), \tag{3}$$

where p is the pressure, g is the gravitational acceleration, and $E^* = E$ when $E > 0$ and $E^* = 0$ when $E < 0$. τ is the stress from the wall ($= 12\eta v/\delta + 2C_d\rho v^2$, where η is the dynamic viscosity and C_d is the drag coefficient). The four terms on the right hand side represent the contribution from the pressure gradient, stress from the walls, gravitational force, and the momentum loss due to vapor condensation onto the walls, respectively. Using the relation that $\frac{d(\rho v^2\delta)}{dz} = Ev + \rho v\delta\frac{dv}{dz}$, Eq. (3) can be written as

$$\rho v\delta\frac{dv}{dz} = -\delta\frac{dp}{dz} - \tau - \rho g\delta - vE^*. \tag{4}$$

The energy equation is

$$\frac{d}{dz}\left[\rho v\delta\left(u + \frac{p}{\rho} + \frac{1}{2}v^2 + gz + L(1-s)\right)\right] = E\left(u + \frac{p}{\rho} + gz + L\right) + \frac{1}{2}v^2(E - E^*) - \frac{\tau}{v}C_p\Delta T, \tag{5}$$

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