Is Enceladus' plume tidally controlled?

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[1] Explanations for the plume of gas, water vapor and ice particles jetting from rifts in Enceladus' south polar region include boiling of liquid water and dissociation of clathrate hydrates. In either case, production of the plume may be quasi-static or tidally controlled, with implications for the interior structure and composition of Enceladus. Previous quantification of the clathrate explanation assumed equilibrium dissociation and cannot be used to simulate a tidally generated plume. We present a non-equilibrium clathrate dissociation model, which we use to reproduce past observations and predict the plume's properties during upcoming close encounters. The total mass flux and water to gas mass ratio of a tidally generated plume are predicted to be lower than previous measurements. In comparison, for a quasi-static plume these properties should have values close to previous measurements. This provides an observational means of distinguishing quasi-static from dynamic processes as the plume's source. **Citation:** Halevy, I., and S. T. Stewart (2008), Is Enceladus' plume tidally controlled?, *Geophys. Res. Lett.*, *35*, L12203, doi:10.1029/2008GL034349.

1. Introduction

[2] In 2005, the Cassini spacecraft observed the surface of Enceladus on multiple occasions, including three close flybys. Encounters with the south polar terrain (SPT) revealed an anomalously warm [*Spencer et al.*, 2006], highly fractured surface, separated from the surrounding terrains by a series of sinuous scarps and ranges at a latitude of ~55°S [*Porco et al.*, 2006]. In the interior of the SPT are four subparallel rifts, which are about 130 km long, 2 km wide, 0.5 km deep and bounded by ~100 m ridges [*Porco et al.*, 2006]. In and around these rifts is some of the most crystalline ice observed on the surface of Enceladus [*Brown et al.*, 2006], indicating youth. In contrast with the SPT, the north polar region of Enceladus is cold and heavily cratered. The SPT is the source region of a plume of water vapor, ice particles and a mixture of gases thought to originate from the rifts and feed Saturn's E-ring [*Spahn et al.*, 2006]. The composition of the plume is mostly water (vapor and a little ice) with a few percent CO_2, CH_4, N_2 or CO (a molecule weighing 28 AMU) and trace amounts of simple organic compounds [*Waite et al.*, 2006].

[3] The discovery of an anomalous heat flux from the SPT and the plume jetting from the region, has sparked wide debate about the source of the heat anomaly [*Nimmo et al.*, 2007; *Nimmo and Pappalardo*, 2006; *Meyer and Wisdom*, 2007; *Grott et al.*, 2007], the plume's origin [*Porco et al.*, 2006; *Kieffer et al.*, 2006; *Gioia et al.*, 2007; *Matson et al.*, 2007] and implications for the interior structure and composition of Enceladus. Detection of organic compounds in the plume prompted a suggestion of high-temperature (~500 to 800 K) reactions in the interior of Enceladus at some time in its history [*Matson et al.*, 2007] and an origin of the N_2 and CH_4 by thermal decomposition of NH_3 and Fischer-Tropsch reactions, respectively. It is noteworthy, however, that if the 28 AMU molecule is CO and not N_2, then the composition of the plume is essentially cometary [*Waite et al.*, 2006] and may not require high-temperature reactions at all.

[4] Two main models exist for production of the plume. The first involves decompression boiling of nearly pure liquid H_2O [*Porco et al.*, 2006]. Because Cassini detected no NH_3, a very efficient freezing point depressant, this model requires a shallow reservoir of warm (~273 K) water. Although explanations of the anomalous heat flux [*Nimmo et al.*, 2007; *Grott et al.*, 2007] partly address this issue, the boiling liquid model also has difficulty explaining the plume's composition. This is because N_2 and CH_4 are highly insoluble in liquid water and even if these gases were produced by high temperature reactions, as suggested by *Matson et al.* [2007], their association with liquid water for extended periods of time seems unlikely. An alternative model for the plume is equilibrium dissociation of clathrate hydrates of N_2, CO_2 and CH_4 due to depressurization in the rifts [*Kieffer et al.*, 2006]. The heat of clathrate decomposition is conceivably supplied by the same mechanisms responsible for the thermal anomaly. Advantages of this model are that it does not require a shallow liquid reservoir and that it readily explains the association of N_2 and CH_4 with water.

[5] For both boiling liquid and dissociating clathrate, the demonstration by *Hurford et al.* [2007] that the tidally stressed rifts are under tension for only about half of the diurnal cycle, raises the possibility that production of the jets is periodic rather than stationary. The former may differ from the latter in the source of heat (e.g. tidal shear heating vs. a constant internal heat source), the contributing reservoir (e.g. local melt pockets vs. a deep liquid reservoir) and the nature of the conduits (e.g. periodically vs. continuously open) among other things. Another implication of tidally forced jetting is that dissociation of clathrates, if it occurs, may not be under equilibrium conditions. Here, we use a non-equilibrium clathrate dissociation model to compare the properties of a tidally generated plume to a quasi-static one, allowing discrimination between these cases.

2. A Dynamic Clathrate Hydrate Dissociation Model

[6] To simulate the plume, *Kieffer et al.* [2006] modified a model that was originally constructed to simulate equilib-

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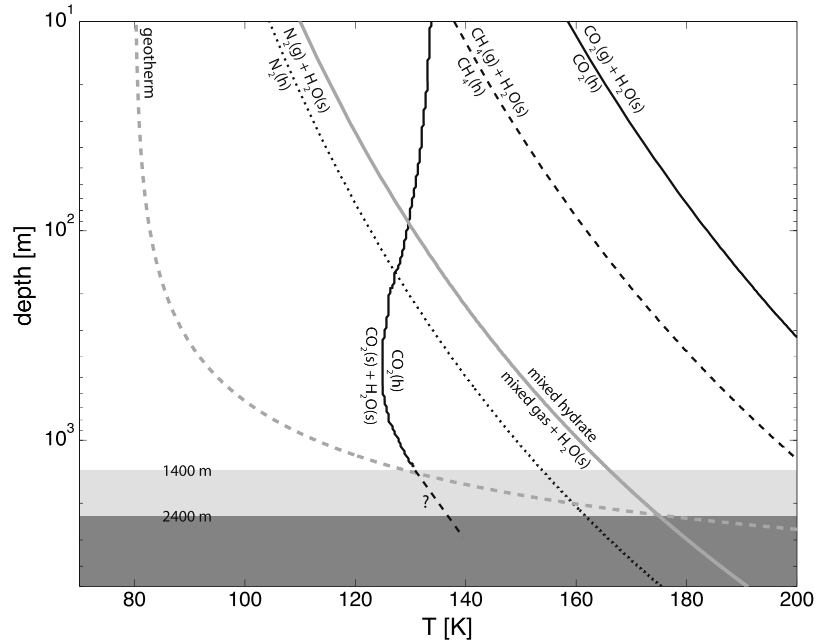

Figure 1. Phase diagram of $H_2O + CO_2$, N_2 and CH_4. The solid gray line is the phase transition between clathrate hydrates and water ice + a mixture of gases of the observed composition [*Waite et al.*, 2006]. The dashed gray line is the geotherm in the SPT, calculated from an average surface temperature of 80 K and an average surface heat flux of 0.25 W m^{-2} [*Spencer et al.*, 2006]. The light gray area is the range of clathrate stability within Enceladus, and the dark gray area is a downward extension of clathrate occurrence if some of the heat flux is advective [*Nimmo et al.*, 2007; *Gioia et al.*, 2007].

rium dissociation of methane hydrates to gas and water, caused by depressurization of a submarine geologic reservoir [*Ji et al.*, 2001]. However, if the rifts are under tension for only part of Enceladus' orbit, as suggested by *Hurford et al.* [2007], then clathrate dissociation may be driven by periodic, short-term exposure of warm clathrate to low pressure alternating with closure of the rifts and an increase in pressure and temperature. Moreover, porosity and permeability in the original model are defined by properties of the geologic reservoir and are constant on both sides of an advancing "dissociation front." In contrast, clathrates under the pressure and temperature of Enceladus' crust are probably quite impermeable [*Schubert et al.*, 2007], while the conduit itself may be entirely open or have a temporally variable permeability controlled by properties of the fault gouge as well as condensation, sublimation and entrainment of particles in the gas flow. Thus, while the existing model may adequately describe a plume generated by steady-state dissociation of clathrates, it cannot account for the potentially important diurnal dynamics on Enceladus.

[7] We constructed a non-equilibrium model of mixed gas clathrate hydrate dissociation, suitable for the conditions of Enceladus and perhaps other tectonically active icy bodies. Clathrates were taken to initially exist wherever the geothermal temperature in the SPT, calculated from an average surface temperature of 80 K and an average surface heat flux of 0.25 W m^{-2} [*Spencer et al.*, 2006], was lower than their dissociation temperature and higher than the temperature of exsolution into separate solids at the local pressure (Figure 1). We assumed that as Enceladus orbits Saturn and the rifts come under tension they do not become clean chasms. Instead, the interior of the rifts is highly constricted with only a few conduits to the surface [*Gioia et al.*, 2007], consistent with observations that the plume is composed of a small number of spatially discrete jets [*Spitale and Porco*, 2007]. We modeled this as a fraction f_{vent} of the walls that is actually exposed to low pressure when the rifts come under tension.

[8] Exposure to near-vacuum destabilizes the warm clathrates and results in their dissociation to gas and water ice along a "dissociation front," which propagates as the clathrate is consumed. The gas diffuses through a layer of empty ice cages [*Takeya et al.*, 2002] and then flows down the pressure gradient (up the conduit), entraining ice particles produced by the dissociation. Collisions with the walls slow the particles down [*Schmidt et al.*, 2008] and also result in some of the ice sticking to the walls. This exposes the ice to relatively high temperatures (150–175 K) for a longer time than if it were immediately ejected from the rifts, causing most of it to sublimate and allowing only a small fraction to reach the surface as solid particles. We calibrated the model to reproduce the observed ice particle flux [*Porco et al.*, 2006; *Spahn et al.*, 2006] and assumed that the rest of the ice produced by clathrate dissociation sublimates and contributes to the flux of vapor. Sublimation of water ice at depths where clathrates do not exist also contributes to the vapor flux. The model is shown in Figure 2 and described in detail in the auxiliary material.[1] For the vertical temperature profile at the rift walls (T_{wall}) we took the steady-state, depth-dependent shear heating temperature of *Nimmo et al.* [2007], which is somewhat higher than the conductive geotherm but still within the stability field of the clathrates. When the rifts open and pressure drops, if

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL034349.

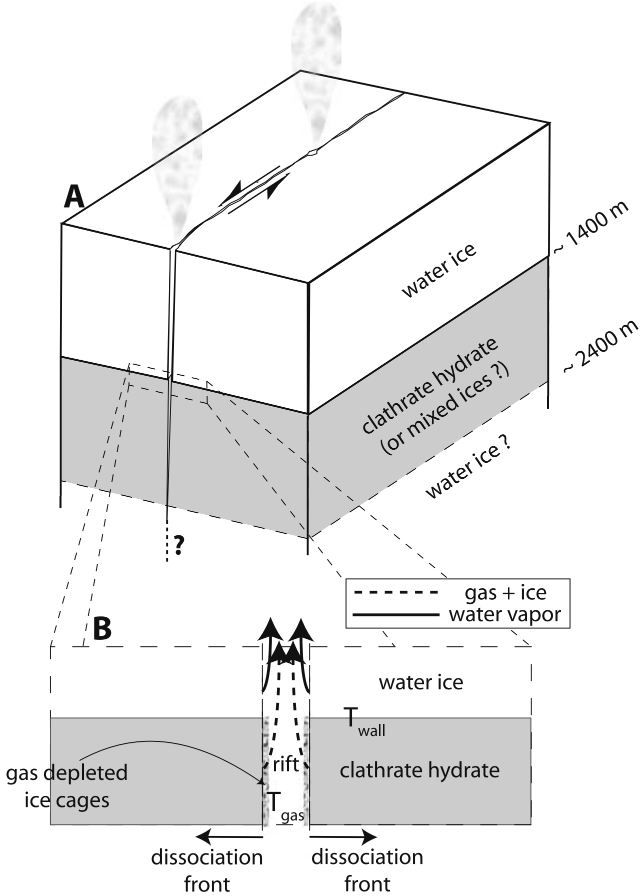

Figure 2. Schematic of the clathrate hydrate dissociation model. (a) Clathrates occur between depths of ~1400 and ~2400 m, in agreement with their stability under a conductive geotherm. If the heat flux is partly advective, then clathrates are stable to greater depth, represented by the dashed lower boundary. The faults are generally constricted, with the plume venting from only a few conduits. It is unclear at what depth the faults terminate and whether they extend below the rheological transition from clathrates back to water ice. (b) An enlarged cross section of a fracture, showing the conduit, a thin coating of gas-depleted ice cages and undissociated clathrate with increasing distance from the fracture axis. Tidal shear heats the ice and clathrate near the rifts to T_{wall} [*Nimmo et al.*, 2007], while the temperature in the open fraction of the rifts, T_{gas}, depends on heat transfer by advecting gas and vapor, which are produced by clathrate dissociation as well as sublimation of ice above and below the clathrate layer.

clathrates destabilize at the dissociation front, then the heat of their dissociation is included in an energy budget, which otherwise contains only conductive and radiative terms, where appropriate. The spatial divergence of this energy budget is used to compute the temperature over the model domain. This way the temperature at the dissociation front gradually approaches the equilibrium temperature of clathrate dissociation, rather than being arbitrarily set to it, as in the study of *Kieffer et al.* [2006]. A similar approach was taken to modeling ice sublimation where clathrates are absent.

[9] The fluxes of gas, water ice and vapor depend, among other parameters, on simulation depth (mainly through the effect of depth on pressure and temperature). Therefore, we carried out simulations at variable depths and integrated the results to give the total fluxes from an entire column of exposed clathrate. Integration over the diurnal cycle is also necessary because the fraction of rifts under tension depends on Enceladus' orbital position [*Hurford et al.*, 2007] and because the fluxes generated by our model are themselves dependent on the time elapsed since opening of the rifts. Using a fit to the simulated fraction of rifts under tension [*Hurford et al.*, 2007], we thus integrated the gas, vapor and ice mass fluxes over time.

3. Results

[10] A successful explanation of the plume must reproduce both the total mass flux ($F_{total} = F_{vapor} + F_{gas}$) and the mass ratio of water vapor to other gases (V:G) at the time in the diurnal cycle of Enceladus when these measurements were made. We calibrated our model to fit estimates of F_{total} between 140 and 210 kg s^{-1} and V:G around 5.8, based on UVIS occultation measurements [*Hansen et al.*, 2006; *Tian et al.*, 2007] and INMS measurements [*Waite et al.*, 2006] made on July 14, 2005 about 27% of an orbit past pericenter. Figure 3 displays F_{total} and V:G as a function of orbital position for venting out of 0.5% of the rifts under tension ($f_{vent} = 0.005$) and for gas temperatures in the rifts of 150 and 175 K. The diffusion coefficient of gas through the ice in these simulations was chosen to be 10^{-9} m^2 s^{-1}, somewhat higher than the value obtained for this temperature range in experiments conducted at Earth's atmospheric pressure [*Takeya et al.*, 2002]. Figure 3 shows that both F_{total} and V:G are within the range of Cassini observation-based estimates for this choice of model parameters. The orbital positions during recent and future close encounters are also marked and a prediction can be made of the expected F_{total} and V:G during these encounters if tidally controlled clathrate decomposition and ice sublimation generate the plume.

[11] In both simulations presented in Figure 3, fitting V:G required an additional contribution of water vapor from sublimation of ice down to a depth of about 3000 m, though it is unknown whether the faults reach this depth. A smaller diffusion coefficient would drastically reduce the required supplement of water vapor to match V:G and the depth of fault penetration. Alternatively, if the dissociating layer is a mixture of clathrates and water ice, then no additional sublimation may be required at all. Further discussion is in the auxiliary material.

4. Discussion

[12] Irrespective of whether the jets are produced by boiling liquid or dissociating solids, in the quasi-static case F_{total} and V:G are not expected to vary much over an orbital cycle. If, on the other hand, the plume's production is controlled primarily by periodic exposure to low pressure, then F_{total} as a function of orbital position is expected to resemble in shape the fraction of faults under tension, as in Figure 3. Furthermore, V:G is expected to steadily decrease from its value at pericenter because in the tidally controlled

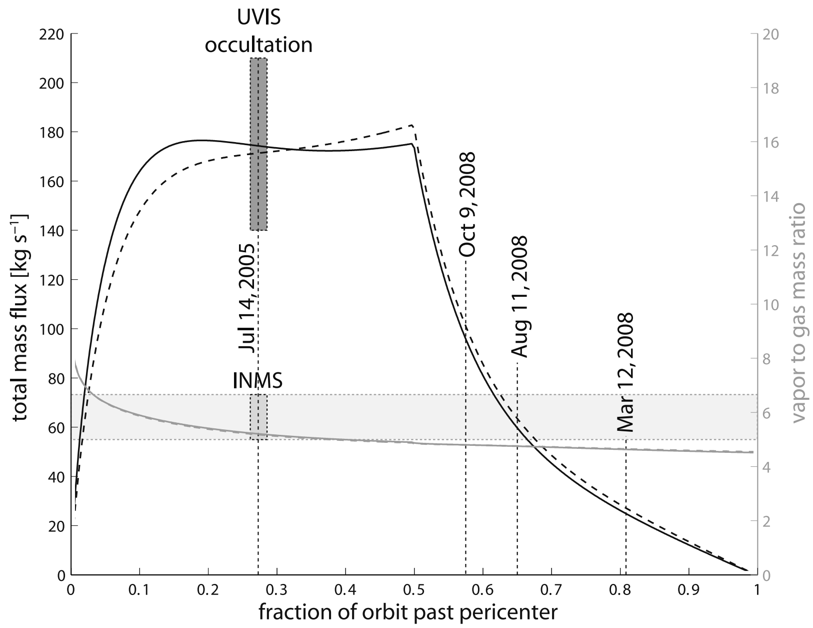

Figure 3. Evolution of the plume over one diurnal cycle. The depth-integrated total mass flux in kg s^{-1} (F_{total}, black) and mass ratio of water vapor to other gases (V:G, gray) for decompression in 0.5% of the rifts under tension (f_{vent} = 0.005) and for gas temperatures of 150 (solid) and 175 (dashed) K. The light and dark gray regions show the range of V:G values from INMS measurements [*Waite et al.*, 2006] and the range of F_{total} values from stellar occultation UVIS measurements [*Hansen et al.*, 2006], respectively. Dashed vertical lines marked with a date represent the orbital position of Enceladus during past and future close encounters. The expected range of V:G during recent and upcoming flybys, if stationary processes produce the plume, is marked by the lightest gray shading. Since the actual fraction of faults under tension exhibits stepwise changes as entire rift segments open and close, observations of F_{total} and V:G would have a more jagged nature than the smoothed curves shown here.

scenarios, V:G depends both on the mass ratio of water to gas in the boiling or dissociating reservoir and on the contribution from sublimation of water ice. The latter depends on the temperature of the walls, which cool by an average of about 20 K over half a diurnal cycle due to radiation of heat into the fracture and the heat of clathrate dissociation and ice sublimation. Consequently, the contribution to the water vapor flux from ice sublimation is high right after pericenter and decreases with time. Thus, INMS measurements of V:G between 4.5 and 5 during the most recent and upcoming encounters (Figure 3) or stellar occultation UVIS measurements of variable water vapor column densities would support a tidally controlled plume, whereas V:G close to previous estimates between 5 and 7 would support a stationary explanation such as equilibrium dissociation of clathrates or boiling of a warm liquid continuously supplied from depth.

[13] Other than additional sublimation of ice, are there ways of elevating V:G to the observed values? Without sublimation, the maximal value of V:G from dissociation of pure clathrate is dictated by the gas occupancy of the ice cages. The obviously active nature of Enceladus and the suggestion of a high temperature source for the N_2 and CH_4 [*Matson et al.*, 2007] imply that clathrates on Enceladus likely equilibrated at moderate pressure and relatively warm temperature. Under these conditions the experimentally observed structure of sparsely occupied (highly hydrated) clathrates is degraded and their long-term stability uncertain [*Sizov and Piotrovskaya*, 2007]. Therefore, we assume hydration values, which maintain a stable clathrate structure and which consequently require an additional source of water to match observations of *V:G*.

[14] It is possible that instead of separate contributions from compositionally layered components, the observed V:G is explained by decomposition of a mixture of water ice and clathrates in the right proportions. Alternatively, if the heat flux is partly advective [*Nimmo et al.*, 2007; *Gioia et al.*, 2007] and the geothermal temperature too low for existence of clathrates, then sublimation of a suitable mixture of ices could explain *V:G.* Since the temperature of water ice sublimation is higher than the sublimation or dissociation temperatures of the other ices or clathrates, the relative contribution of water vapor to the plume would, in either case, decrease as the rift walls cooled. The shape of V:G as a function of time would thus resemble our results (i.e. lower during upcoming encounters) and differ from the case of quasi-static production, still allowing discrimination between the two. Further discussion is in the auxiliary material.

[15] We conclude that the dynamic model presented here may typify tidally-controlled decomposition of solids of various types in the rifts on Enceladus, and perhaps other tectonically active icy bodies. The model reproduces past observations, predicts future plume characteristics and provides an observational means of discriminating between quasi-static and tidal processes as explanations for the plume.

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