Icarus 253 (2015) 205–222

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

On understanding the physics of the Enceladus south polar plume via numerical simulation

Seng Keat Yeoh [a,*], Todd A. Chapman [b], David B. Goldstein [a], Philip L. Varghese [a], Laurence M. Trafton [c]

[a] Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, TX 78712, United States
[b] Department of Aeronautics and Astronautics, Stanford University, Stanford, CA 94305, United States
[c] Department of Astronomy, University of Texas, Austin, TX 78712, United States

ARTICLE INFO

Article history:
Received 1 June 2013
Revised 12 January 2015
Accepted 18 February 2015
Available online 26 February 2015

Keywords:
Enceladus
Saturn, satellites
Satellites, atmospheres

ABSTRACT

The Enceladus plume is composed of primarily water vapor and tiny ice grains. Various observations suggest that it most likely originates from vents along the Tiger Stripes. Consequently, understanding the expansion process of the two-phase flow from the vents into vacuum is crucial. Our goal is to investigate the important physical processes and the interaction between the gas and the grains associated with the expansion process. To do so, we compute the expansion flow from the vents out to higher altitudes using the direct simulation Monte Carlo (DSMC) method with two-way coupling between the gas and the grains. The expansion flow passes through multiple regimes, from continuum (very collisional) near the vents to free-molecular (collisionless) at higher altitudes. This transition occurs at a few kilometers high for meter-sized vents and is higher up for larger vents. During expansion, the Mach number increases rapidly in the first few vent diameters mainly due to a drop in gas temperature rather than an increase in gas speed. Collisions at the vent strongly affect the molecular speeds in the far-field (as the flow becomes free-molecular). If the flow is sufficiently collisional at the vent, the molecular speeds approach the ultimate speed of adiabatic expansion, which depends on the source conditions ($\sim$1005 m/s for the triple-point of water). The flow is highly supersaturated as it emerges from the vents, thus condensation grain growth is very likely. We find that condensation growth via heterogeneous nucleation above the vents is proportional to vent size and that fairly large vents several tens to hundreds of meters in size are required to produce the micron-sized grains detected by CDA (radii $\geqslant$1.6 μm) if the grains start with a negligible size at the vents. We also examine how the effects of grains on the gas vary with grain size, grain/gas (ice/vapor) mass ratio and gas–grain velocity difference at the vent. The effects of grains increase with mass ratio and velocity difference at the vent due to greater exchange of momentum and energy. Moreover, smaller grains have a stronger effect for the same mass ratio. However, the effects of grains are minimal for plausible mass ratios $\leqslant$1.0. Our studies show that nanometer-sized grains decouple from the gas at altitudes of 10–100 vent diameters and spread more with the gas while micron-sized grains decouple at <10 vent diameters and remain in collimated beams. Even with large velocity differences at the vent, the micron-sized grains spread by $\leqslant$12°. Consequently, the inferred spreading angles $\geqslant$30° (Ingersoll, A.P., Ewald, S.P. [2011]. Icarus 216, 492–506; Postberg, F. et al. [2011]. Nature 474, 620–622) cannot be caused by velocity difference at the vent alone. Furthermore, nanometer-sized grains are accelerated close to gas speeds while micron-sized grains tend to retain the initial speeds they had at the vent. We determine that the largest grain size that can be accelerated from rest to escape speeds (>240 m/s) is proportional to vent size and that small vents (<1 m) are enough to accelerate large micron-sized grains to escape speeds.

1. Introduction

In 2005, scientists discovered a geologically active region at the south pole of Enceladus (Porco et al., 2006; Spencer et al., 2006) when instruments onboard the Cassini spacecraft observed a thermal signature (Howett et al., 2011; Spencer et al., 2006), a plume consisting of mostly H_2O ($\sim$90%), noncondensable gases and ice grains (Hansen et al., 2006; Spahn et al., 2006b; Waite et al., 2006) as well as perturbations in Saturn's magnetic field and magnetospheric plasma (Dougherty et al., 2006; Tokar et al., 2006). The activity appears to be concentrated along four prominent fractures

* Corresponding author.
E-mail address: skyeoh@utexas.edu (S.K. Yeoh).

http://dx.doi.org/10.1016/j.icarus.2015.02.020
0019-1035/

across the region, dubbed the "Tiger Stripes." Higher-resolution infrared maps combined with visible images of the south polar region showed that the hottest locations lie along these fractures (Porco et al., 2006; Spencer et al., 2006). Distinct gas and dust jets were also observed and their locations correlated with the hot spots (Hansen et al., 2008, 2011; Spitale and Porco, 2007).

The presence of the plume has a significant effect on the saturnian environment. It is the main source of Saturn's E-ring (Kempf et al., 2008; Porco et al., 2006; Postberg et al., 2009; Schmidt et al., 2008; Spahn et al., 2006a), which has a narrow particle size distribution (Horanyi et al., 1992; Nicholson et al., 1996; Pang et al., 1984; Showalter et al., 1991) and an unusual vertical profile, being thinnest but densest near Enceladus' orbit (Hillier et al., 2007; Showalter et al., 1991). Moreover, the interaction of the plume with Saturn's magnetospheric plasma slows the plasma down near Enceladus (Tokar et al., 2006), which leads to the formation of a large circum-saturnian neutral OH torus observed by the Hubble Space Telescope (HST) (Johnson et al., 2006). Additionally, a large fraction of the plume grains are ejected below Enceladus' escape speed (Hedman et al., 2009; Ingersoll and Ewald, 2011; Postberg et al., 2011; Schmidt et al., 2008) and fall back to produce the bright plains in the south polar region (Jaumann et al., 2008; Porco et al., 2006).

The plume also provides a valuable window into the interior of Enceladus. Different mechanisms have been suggested as the plume source. Porco et al. (2006) postulated that liquid water exists near the surface and boils violently when exposed to vacuum. As the vapor rises, it carries some liquid water that freezes to form ice grains. Schmidt et al. (2008) argued that liquid water is present in equilibrium with ice and vapor deep below the surface. The vapor and ice grains escape to the surface via narrow fractures in the overlying ice. The detection of salty E-ring and plume grains supports this model (Postberg et al., 2009, 2011) as the liquid water from which the salty grains originate may have acquired its saltiness from interaction with the rocky core of Enceladus (Zolotov, 2007). Porco et al. (2014) proposed a variation of the deep salty ocean model. Salty liquid water fills the entire subsurface reservoir and the cracks up to the hydrostatic height ($\sim$92% of the distance between reservoir and surface), from which it reaches the surface via a variety of processes, e.g. rapid exsolution of gases (Crawford and Stevenson, 1988; Matson et al., 2012). Some salty water is entrained and freezes, forming salty grains.

Nimmo et al. (2007) attributed the plume production to shear heating along faults (e.g. the Tiger Stripes) due to tidally-driven strike-slip motion of a thick ice shell lying over a subsurface ocean. Shear heating causes the ice along the faults to sublimate. Most of the sublimated vapor then recondenses, with some being entrained with the remaining vapor as ice grains. However, the detection of small-scale ($\sim$10 m) hotspots suggests that it is normal stresses and not shear stresses that drive activity (Porco et al., 2014). Observed variation in plume brightness with Enceladus' orbital position supports this (Hedman et al., 2013; Nimmo et al., 2014) as tidal normal stresses open and close cracks from which eruption occurs on a diurnal timescale (Hurford et al., 2007). However, a simple tidally-modulated model could not fully describe the situation. Based on this model, it appears that there is a delay in the eruption. Nimmo et al. (2014) proposed that the delay may be inherent in the eruption mechanism itself, or due to the viscoelastic behavior of the ice shell, or caused by a 1:1 physical libration of Enceladus, which changes the tidal stress patterns and thus the eruption timing (Hurford et al., 2009). Kieffer et al. (2006) argued that liquid water is not necessary for plume production and proposed clathrate decomposition as the plume source. Clathrates exist under a thick layer of ice and release trapped noncondensable gases when exposed to vacuum. As these gases rise, they entrain some ice that sublimates, producing a mixture of vapor, ice and gases.

The existence of liquid water below the surface of Enceladus depends on the efficiency of the subsurface heat transfer from the source (Ingersoll and Pankine, 2010). Spencer et al. (2006) determined that liquid water would be present within 40 m from the surface if conduction through solid ice were the primary mode of heat transfer. With the newly estimated heat flow that is significantly higher (Howett et al., 2011), liquid water would have to be even closer to the surface, reinforcing the near-surface boiling argument. However, vapor carrying latent heat may provide a more efficient mode of heat transfer (Nimmo et al., 2007; Spencer et al., 2006), thus liquid water may exist farther below the surface. Ingersoll and Pankine (2010) investigated two mechanisms of heat transfer by vapor: diffusion through an icy matrix and hydrodynamic flow in cracks. For vapor diffusion, they found that the ice matrix must be rather porous with large grains or else there would be melting at depth. For hydrodynamic flow, they determined that the cracks must be wider than $\sim$0.1 m and the heat source must be near the cracks or else there would be melting. The temperature of the matrix or the crack walls strongly affects the ability of the vapor to transport heat as the partial pressure of the vapor equilibrates rapidly to the saturation vapor pressure of the surrounding ice.

Since the plume not only influences the dynamics of the saturnian environment but also offers clues into the interior of Enceladus, especially as to whether or not liquid water exists below the surface, it is crucial that the plume be modeled accurately. Many models of the gas component exist, ranging from analytical models (Dong et al., 2011; Saur et al., 2008; Tenishev et al., 2010) to computational models (Burger et al., 2007; Smith et al., 2010; Tian et al., 2007; Waite et al., 2006). The grain component has also been the subject of substantial modeling effort (Degruyter and Manga, 2011; Ingersoll and Ewald, 2011; Juhasz et al., 2007; Kempf et al., 2010; Postberg et al., 2011; Schmidt et al., 2008; Spahn et al., 2006b). However, none of these models have properly treated the expansion of the plume flow from the sources on the surface into vacuum, which is important.

In this work, the direct simulation Monte Carlo (DSMC) method is used to simulate the plume flow as it expands from the surface, where the density is relatively high and the flow is collisional, out to higher altitudes where the density drops so much that collisions cease. DSMC is suitable for this application because the flow passes through multiple distinct regimes during expansion, from near-continuum at the surface to free-molecular at higher altitudes. The coupling between the gas and the grains is two-way, i.e. the gas and the grains affect each other. Other processes e.g. plasma interactions, radiation, ionization, chemistry, and grain charging, which are not essential in our region of interest, can be readily incorporated into DSMC simulations if necessary.

The goal of this work is to investigate the important physical processes associated with the expansion of the plume flow into vacuum in the near-field region directly above the surface. In Section 2, we describe our modeling approach, which includes the subsurface model used to obtain the vent conditions for our simulations above the surface. In Section 3, we present our results and highlight the important physical processes involved, such as collisional and non-equilibrium effects (e.g. the freezing of molecular internal energy modes), grain condensation, and the interactions between the gas and the grains (e.g. the spreading of the grains by the gas and the height at which the grains decouple from the gas and move independently). In Section 4, we conclude with a summary and a short discussion of our results.

2. Model

We adopt a simple analytical subsurface model to obtain the vent conditions for our simulations above the surface. We consider