A Hybrid Simulation of the Gas/Particle Plume of Enceladus

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Introduction: Cassini first detected a water vapor plume near the warm, ice-covered pole of Enceladus in 2005 [1, 2]. Since then, flybys over the moon have yielded not only spectacular images but also details of the plume structure and composition [3, 4, 5] as well as the possible locations of the contributing sources [6]. Observations found that the plume is actually composed of multiple jets [7] located along long fractures known as the "Tiger Stripes" which straddle the south polar region of Enceladus. A hybrid model of the gas/particle plume is constructed with several discrete "jet" sources. Simulation results can be used to constrain the physical conditions at the plume sources, such as temperatures, velocities, vent geometry, and plume generation mechanism.

Hybrid Model: The hybrid model of the gas/particle plume is divided into two regimes: collisional and free-molecular. The Direct Simulation Monte Carlo (DSMC) method is used to model the region near the vent source where the plume is relatively dense and collisional. As the gas expands out into the far-field, its density drops and collisions become negligible. Therefore, the assumption of non-collisional dynamics is adequate and the free-molecular model is used in the far-field of the plume. The output of the DSMC model (collisional flow) is fed as an input to the free-molecular model.

DSMC Model:

- The plume source is modeled as a series of small axisymmetric vents along the tiger stripes [6, 7].
- The conduit beneath each vent is modeled as a converging-diverging nozzle (Figure 1).
- Two vent exit Mach numbers are chosen: $Ma_E = 5$ and $Ma_E = 10$.
- DSMC is used to simulate the expansion of the gas from the exit into vacuum until the flow becomes mostly collisionless or free-molecular.
- DSMC uses a representative number of molecules to statistically approximate the movements and the collisions of real gas molecules [8].
- Three dust particle sizes are incorporated into the gas flow: 10 nm, 100 nm and 1 micron.
- A low dust mass loading is assumed; gas affects dust, but dust does not affect gas.
- The dust particles exit the vent at the same speed as the gas.

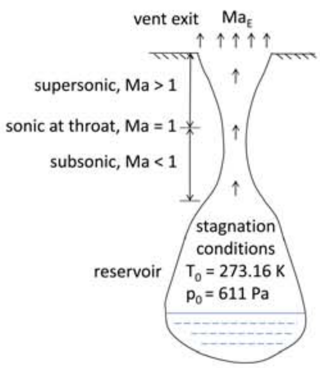

Figure 1: Water vapor is assumed to expand isentropically through the conduit, modeled as a converging-diverging nozzle, from stagnation conditions in the reservoir out of the vent exit into vacuum. The stagnation conditions are chosen as the triple point of water.

Free-molecular Model:

- The free-molecular model is constructed from eight sources located along the tiger stripes.
- Two sources are placed on Damascus Sulcus, three on Baghdad Sulcus, two on Cairo Sulcus, and one on Alexandria Sulcus, in accord with observations [6].
- The sources are assigned pre-determined orientations with respect to surface normal [6].
- The gas is modeled as purely water vapor since the plume composition is ~90% H_2O [4].
- The velocities of the gas molecules at the satellite surface are initialized by two ways: (i) a $\cos^2(\delta)$ mass flux distribution [8], and (ii) a velocity distribution from DSMC.

DSMC Results and Conclusions:

- The Mach-10 jet is narrower than the Mach-5 jet; the Mach-5 gas is deflected more than the Mach-10 gas, as shown by the gas streamlines (Figures 2a and 2b).
- Observations of the jets can be used to infer the conditions at the individual vents making up the plume; the narrower the jet, the higher the vent exit Mach number.
- The smaller dust particles are deflected more by the gas than the larger ones in the Mach-5 flow (Figure 2c).
- Dust particles of all sizes are barely deflected by the gas in the Mach-10 flow (Figure 2d); the dust particles mostly shoot straight up as initialized.
- The degree to which the dust particles are affected by the gas depends on not only the gas speed but also the gas density since the Mach-10 flow, though faster, is two orders of magnitude less dense than the Mach-5 flow.

References: [1] Porco C.C. et al., *Cassini Observes the Active South Pole of Enceladus*, Science, 311, 1393-1401, 2006. [2] Spencer J. R. et al., *Cassini Encounters Enceladus: Background and the Discovery of a South Polar Hot Spot*, Science, 311, 1401-1405, 2006. [3] Hansen C. J. et al., *Enceladus' Water Vapor Plume*, Science, 311, 1422-1425, 2006. [4] Waite J. H. et al., *Cassini Ion and Neutral Mass Spectrometer: Enceladus Plume Composition and Structure*, Science, 311, 1419-1422, 2006. [5] Spahn F. et al., *Cassini Dust Measurements at Enceladus and Implications for the Origin of the E Ring*, Science, 311, 1416-1418, 2006. [6] Spitale J. N. and Porco C.C., *Association of the jets of Enceladus with the warmest regions on its south-polar fractures*, Nature, 449, 695-697, 2007. [7] Hansen C. J. et al., *Water vapour jets inside the plume of gas leaving Enceladus*, Nature, 456, 477-479, 2008. [8] Bird G. A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flow*, Oxford University Press, 1994. [9] Teolis B. D. et al., *Detection and measurement of ice grains and gas distribution in the Enceladus plume by Cassini's Ion Neutral Mass Spectrometer*, J. Geophys. Res., 115, 2009.

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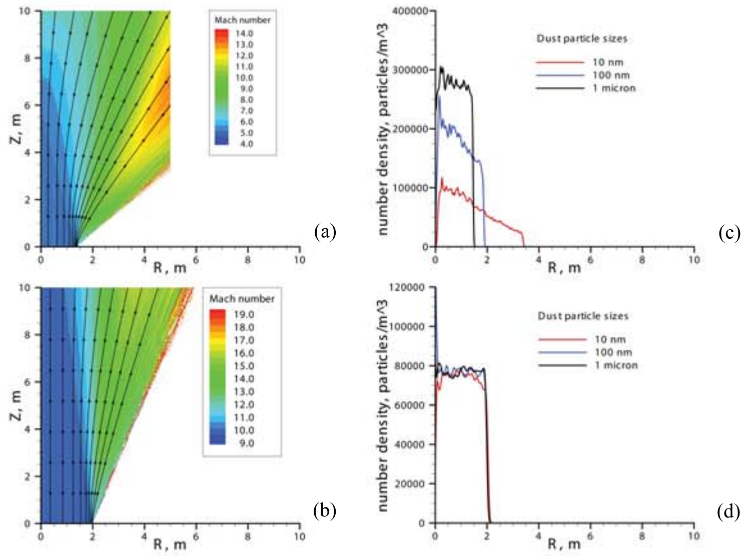
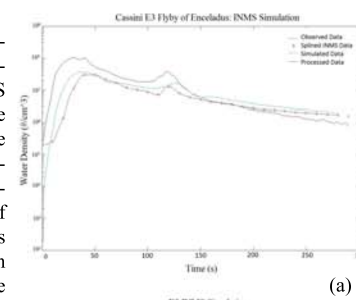
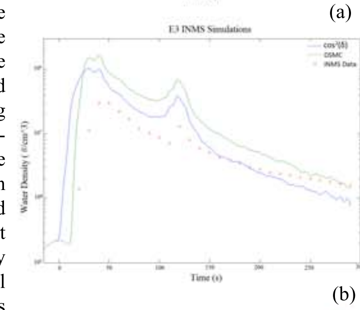


Figure 2abcd: (a) The Mach number contours for the Mach-5 flow with gas streamlines; the jet is wider. (b) The Mach number contours for the Mach-10 flow with gas streamlines; the gas expands out into a narrower angle. (c) The dust density distribution for the Mach-5 flow at 10 m above the vent exit; the smaller dust particles are spread out wider than the larger particles. (d) The dust density distribution for the Mach-10 flow at 10 m above the vent exit; dust particles of all sizes are barely deflected by the gas.

Free-molecular Results and Conclusions:

Raw simulation results from a simulated Cassini plume fly-through agree well with the general magnitude and shape of the *in-situ* INMS density profiles. The simulation with the DSMC input yields a delayed initial rise time but exhibits similar results to the $\cos^2(\delta)$ distribution. Comparison to INMS data shows noticeable discrepancies in the peaks and tails of both simulations due to instrument delay effects [9]. Results are post-processed by convolution with an instrument function that describes the antechamber adsorption phenomenon. We divide the Fast Fourier Transform (FFT) of the observed E5 data by the FFT of the simulated E5 data. Then, the inverse FFT of the resulting function is taken to acquire the instrument function of the INMS device. Convolution with the simulated E3 results yields a close correlation between the observed data and the processed simulation, indicating a realistic instrument function is obtained. Discrepancies are likely due to imperfections in the gas plume model and actual plume time variability. Also, for this simulation, DSMC was not run to a point where the flow becomes free-molecular before the output was passed to the free-molecular model.





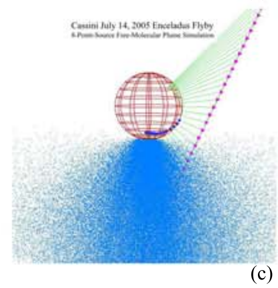


Figure 3abc: (a) E3 simulation showing results of post-processing; convolution with the instrument function accounts for instrument delay effects. (b) Comparison between the *in-situ* INMS data and the results from using a $\cos^2(\delta)$ distribution and a DSMC velocity distribution. (c) 3-D plume model showing the E3 trajectory of the Cassini spacecraft through the south polar plumes of Enceladus.

Some Future Work:

- Investigate the effects of different dust initial speeds.
- Run DSMC calculation to the point where the flow becomes essentially non-collisional before passing the output to the free-molecular model.
- Use different sub-surface conduit models to obtain different new vent parameters.