Modeling the Gas/Particle Plume of Enceladus

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Introduction: Cassini first detected a water vapor composite plume near the warm, ice-covered south polar region of Enceladus in 2005 [1, 2, 3, 4]. Since then, more flybys have been made to collect data and capture images of the plume, with the most recent ones occurring at the end of 2009. The plume consists of gas and entrained ice particles [3, 5]. We present a hybrid model of the gas/particle plume that divides the plume into two regimes. The direct simulation Monte Carlo (DSMC) method is used to simulate the region of the plume close to the vent where it is relatively dense, while a less-expensive free-molecular model is used for the far-field where collisions are negligible.

DSMC Method:

- Uses a representative number of computational molecules to model the flow stochastically; the collisions and movements of sample molecules mimic real gas molecules [6].
- Plume is assumed to originate from a series of smaller vents along the tiger stripes [1].
- Each vent is an axisymmetric source with a radius of 250 m and gas flow rate ~1 kg/s.
- Water vapor issues from the vent in thermal equilibrium at 145 K [4].
- Surface frost sublimation is negligible due to the low surface temperature of 75 K [4].
- 10 nm and 1 micron ice particles are considered, at source $V_{particle} = V_{gas} = 300$ m/s.

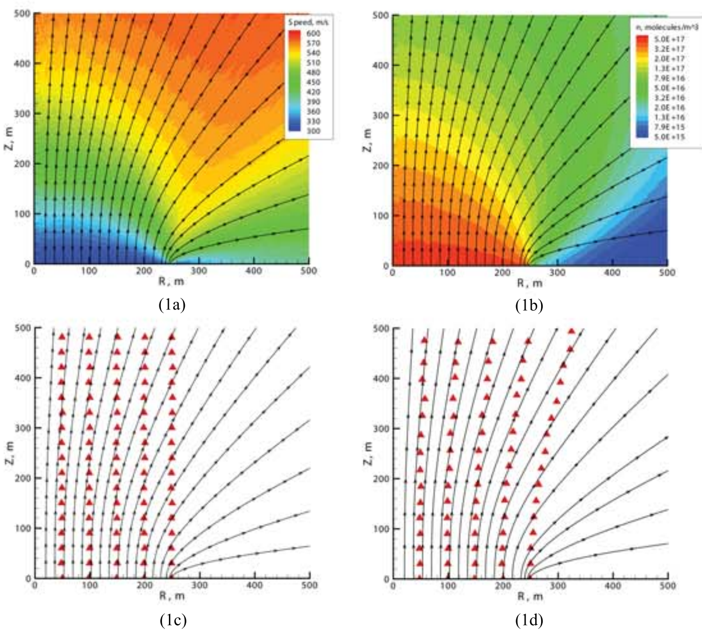

Figure 1abcd: Close-up view of a DSMC simulation of a plume, with gas velocity stream lines shown (black solid lines with arrow heads). (a) The speed of the gas flow. (b) The number density of the gas. (c) Trajectories of 1 micron ice particles (red triangles); they move straight up. (d) Trajectories of 10 nm ice particles (red triangles); they bend noticeably due to the gas flow.

DSMC Results:

- Figure 1a: Gas accelerates to supersonic speeds > 500m/s (V_{escape} ~ 239 m/s).
- Figure 1b: Gas density falls by two orders of magnitude as it expands to the far-field; mean free path increases from O(1 m) to O(100 m).
- Figures 1c and 1d: Larger particles are only slightly affected by the flow; smaller particles are turned by expanding gas.
- This difference may be attributed to the higher inertia of the larger particles.

References: [1] Porco C. C. et al. (2006) Science, 311, 1393-1401. [2] Hansen C. J. et al. (2006) Science, 311, 1422-1425. [3] Waite J. H. et al. (2006) Science, 311, 1419-1422. [4] Spencer J. R. et al. (2006) Science, 311, 1401-1405. [5] Spahn F. et al. (2006) Science, 311, 1416-1418. [6] Bird G. A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flow*, Oxford University Press, 1994. [7] Spitale J. N. and Porco C.C. (2007) Nature, 449, 695-697. [8] B. D. Teolis, J. H. Waite Jr. and the Cassini INMS team, personal communication. [9] G. Fletcher, personal communication. [10] D. Seal (2003), Cassini Mission Plan Document, JPLD-5564.

Free-Molecular Model:

- The far-field plume model is constructed from 8 point sources in the tiger stripes near the south pole [1].
- Two sources are placed on Damascus Sulcus, three on Baghdad Sulcus, two on Cairo Sulcus and one on Alexandria Sulcus (locations indicated in Figure 2a) [7].
- Sources eject gas molecules at a combined mass flow rate of ~100 kg/s.
- Gas molecules leave the surface with a presumed $\cos^2(\delta)$ distribution and merge with a simulated global sputtered atmosphere and background E-ring gas.
- In-situ H_2O gas density measurements (INMS data [8]) and spacecraft trajectory data [9] from the E3 and E5 flybys of Enceladus are used to constrain vent orientations, strengths and the overall 3-dimensionality of the vapor plume.
- During the E3 flyby (Figure 2b) Cassini passed within 50 km of Enceladus [10] and flew directly through the composite plume.

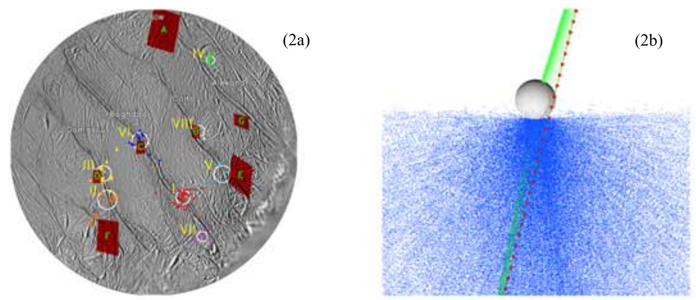

Figure 2ab: (a) Image of Enceladus' south polar terrain showing the 8 main sources (white circles) identified by Spitale and Porco [7]. (b) Visualization of E3 Enceladus flyby by the Cassini spacecraft simulated in the free-molecular regime. The Cassini trajectory is marked by the green line and red arrows and the merged plume can be seen ejecting gas molecules from the 8 sources identified in (2a).

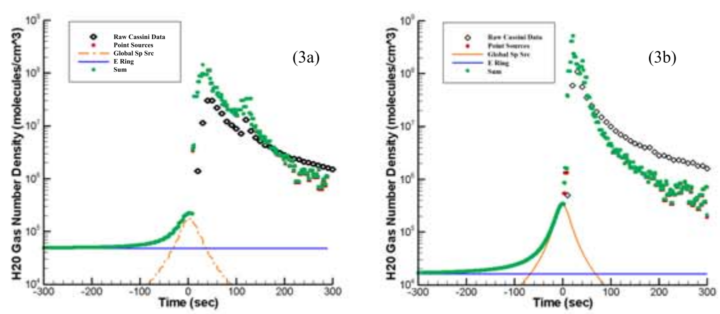

Figure 3ab: Comparison between in-situ density data and free-molecular model results for the E3 (a) and E5 (b) flybys. The Cassini INMS data can be seen as the black diamonds. The free-molecular model superimposes the eight point sources (red dots), a global sputtered source (dot-dash orange line) and a background E-ring density (blue line) to create a total H_2O simulated number density (green dots) to compare with Cassini data.

Free-Molecular Results:

- Simulations agree well with raw Cassini INMS data obtained in E3 and E5 flybys.
- Figure 3a shows the comparison between in-situ INMS H_2O density data and the simulated H_2O density provided by the free-molecular model.
- Discrepancies seen in the peaks and tails of each signal may be attributed to H_2O adsorption and desorption in the antechamber of the INMS instrument [8].
- Secondary density peak at 120 sec in the E3 flyby is also observed by the simulation shown in Figure 3a. E3 groundtrack shows that the spacecraft was directly overhead of the Damascus II source at 120 sec.
- The Enceladus plume exhibits 3-dimensionality and discrete effects can be observed when the spacecraft nears source locations.

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