SIMULATION OF POSSIBLE EUROPA PLUMES USING DSMC.

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Introduction: Recent observations of water vapor plumes at Europa [1] may present an exceptional opportunity to study the composition of the subsurface ocean and the geology of the icy crust. The observations made by the Hubble Space Telescope at Lyman-α, 130.4 nm, and 135.6 nm, and indentifed regions of the atmosphere with increased H_2O concentrations relative to background. These emissions are most plausibly explained as radiation from the daughter products of electron impact dissociation. The height of the plume was estimated to be 200 ± 100 km, with a derived vent exit velocity of approximately 700 m/s. Column density and total lofted number of H_2O molecules were also calculated to be $\sim 10^{20}$ molecules/m^2 and $\sim 10^{31}$ molecules respectively. These observations have not yet been replicated. [2]

As geological model of Europa is in part conjectural, multiple scenarios have been put forward that may explain the existence of plumes. One mechanism is explosive volcanism propelled by volatile species dissolved in the water [3]. An alternative is an analogy to plumes on Saturn's moon Enceladus, which may be explained by tidal forces opening cracks or channels in the ice, allowing liquid water to boil near the triple point temperature of 273 K and escape into vacuum [4]. We assume a plume generated in the latter manner.

Having a flexible, physics-based model of plume phenomena is useful for design and planning of a future mission to Europa by serving as both a guide to instrument specification and as an element of hazard analysis.

Method: The Direct Simulation Monte Carlo (DSMC) method employed here is especially useful for modeling flows that transition from continuum to rarefied, such as plumes exhausting into vacuum. DSMC models gas flow by tracking the behavior of individual representative particles instead of relying on continuum fluid equations that fail under rarefied conditions. Every computational particle represents a large number of actual gas molecules, ranging from $\sim 10^{13}$ to 10^{20} in this work. The domain to be simulated is filled with a continuous structured mesh. Given that the flow is composed of particles alone, macroscopic properties including density and temperature are obtained by averaging over the particles in each cell.

The plume source is assumed to be a circular vent, so an axisymmetric simulation is convenient. The domain is a 0.1° wedge with the boundary conditions specified in Figure 1. Directly below the vent, particles are generated in the specified equilibrium state and allowed to pass into the primary domain.

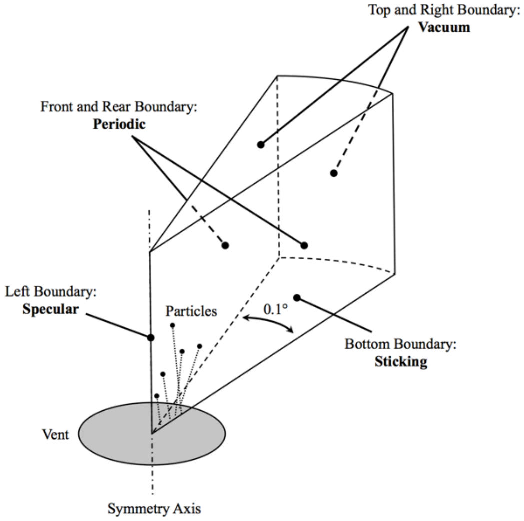

Figure 1 - Simulation domain and boundary conditions.

As mentioned above, the plume expands rapidly from the vent through multiple flow regimes. The mean free path (λ) ranges from ~0.1 mm at the vent to >10 km at ~200 km altitude, requiring eight sequential simulation stages to provide adequate fidelity and statistically sound results. The first stage has the finest spatial and temporal resolution, with following stages progressively coarser. The optimal mesh resolution is dependent on local Knudsen number *Kn* as defined in the gradient local-sense, as the ratio of the mean free path (λ) to the scale length of a macroscopic flow property like density (ρ) determined by $\rho/|\nabla\rho|$.

The expansion of the vapor is assumed to occur through a fissure that behaves as a round, isentropic nozzle having a local area minimum (a throat) not far below the surface. For the baseline case, the sonic nozzle throat conditions are: density, $\rho = 2.56\times 10^{3}$ kg/m^3, speed, v = 373m/s, pressure P = 323 Pa, temperature T = 228 K, as derived from the assumption of isentropic flow from triple point conditions.

Various parameters were manipulated in this study to determine their effect on the final plume structure. The area ratio and throat size are the primary features of an isentropic nozzle that may be altered to change the vent conditions. Three different vent exit Mach numbers (2, 3 and 5) and a "Cold" case were evaluated with a mass flow rate of 10.4 kg/s. The "Cold" case has identical flow properties as the Mach 3 case, except that the flow temperature has been adjusted to

80% of the Mach 3 value to serve as a proxy for possible energy loss from the flow to the conduit walls. The final case has a mass flow rate of 1000 kg/s and a vent velocity of Mach 3, corresponding to a D_{throat} = 34 m. In all cases the vent exit conditions are fully continuum flow.

Photodissociation was also considered. A representative reaction, the creation of OH and H from H_2O, was included to investigate the general behavior of daughter products.

Every time-step, molecules above the surface of Europa are assumed to be in sunlight and part of an optically thin plume. Each has a probability of photodissociation given by:

$$P_{photo} = 1 - e^{(-r_{photo} * \Delta t)}$$

following the model by Prem [5]. Here r_{photo} is the active sun photodestruction rate coefficient of 1.76 × 10^{-5} s^{-1} for the $H_2O + h\nu \rightarrow OH + H$ reaction [6] and Δt is time-step size. The resulting OH and H are retained and tracked until they either leave the computational domain or strike the surface and are absorbed.

Finally, we assume there may be ice grains entrained with the vapor flow as it leaves the vent. Gas and grain interaction is modeled using the one-way coupling method originally developed for monatomic gases by Gallis [7], but is limited to momentum and energy exchange between the gas and the grains. Mass coupling is not modeled, so the grain size does not change and no new grains are formed. However, the conditions relevant to these processes were examined.

Results: All of the cases examined had similar behavior near the vent. During expansion, the gas number density remains at the vent value along the centerline symmetry axis until the first expansion wave crosses it, and then drops rapidly through the expansion wave emanating from the edge of the vent. Consequently, for the same vent conditions, a larger vent leads to the flow becoming free-molecular at a higher altitude.

Simultaneously, the kinetic and rotational energy of the gas molecules is converted into the directed mean kinetic energy of the flow via collisions. Consequently, the gas translational temperature and rotational temperature drop as the gas accelerates.

Changes in the vent Mach number and temperature had very modest effects on the plume height and structure. In contrast, the high mass flow case developed a canopy shock that limited the total height of the plume and also created a region of high density far above the surface (~400 km). The resulting effect on photodissociation daughter products was similarly striking, with the dense canopy capturing and concentrating these molecules in a relatively small region compared to the diffuse distribution in the low mass flow case.

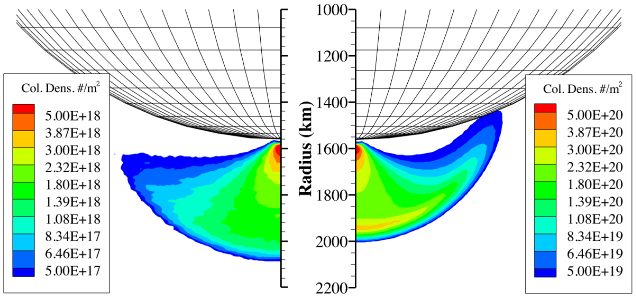

Figure 2 - Comparison of column density for H_2O in the low (left) and high (right) mass flow cases.

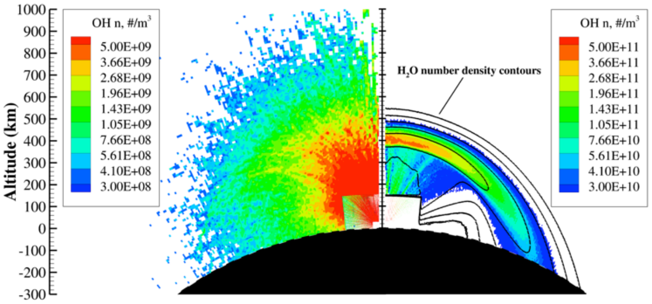

Figure 3 - Comparison of OH number density in low (left) and high (right) mass flow cases.

Conclusions: Changes in vent parameters that affect the speed and temperature of the flow have a limited impact on the final plume morphology. More critical is the mass flow rate, and whether it is high enough to induce a canopy shock. The peak H_2O column densities simulated here (~10^{20} molecules/m^2) are in accord with observations. Ice grain growth and condensation are probable with vents of large diameter (~30 m), such as the high mass flow case here. Grains of the diameters included in this study (0.1-50 µm) uncouple from the flow at low altitudes and are not affected by the canopy.

References: [1] Roth et al. "Transient Water Vapor at Europa's South Pole." *Science* 343, no. 6167: 171–74. [2] Roth et al. "Orbital Apocenter Is Not a Sufficient Condition for HST/STIS Detection of Europa's Water Vapor Aurora." *Proceedings of the National Academy of Sciences* 111, no. 48:E5123–32. [3] Fagents et al. "Cryomagmatic Mechanisms for the Formation of Rhadamanthys Linea, Triple Band Margins, and Other Low-Albedo Features on Europa." *Icarus* 144 (2000): 54-88. [4] Yeoh, Seng Keat. *On Understanding the Physics and Source Conditions of the Enceladus South Polar Plume via Numerical Simulation.* Dissertation, Austin: The University of Texas at Austin, 2015. [5] Prem et al. "Transport of water in a transient impact-generated lunar atmosphere." *Icarus* 255 (2015): 171-174. [6] Huebner et al. "Solar Photo Rates for Planetary Atmospheres and Atmospheric Pollutants." *Astrophysics and Space Science* 195 (1992): 1-294. [7] Gallis et al. "An approach for simulating the transport of spherical particles in a rarefied gas flow via the direct simulation Monte Carlo method." *Phys. Fluids* 13: 3482-3492.