Simulating Water Vapor Plumes on Europa Using DSMC

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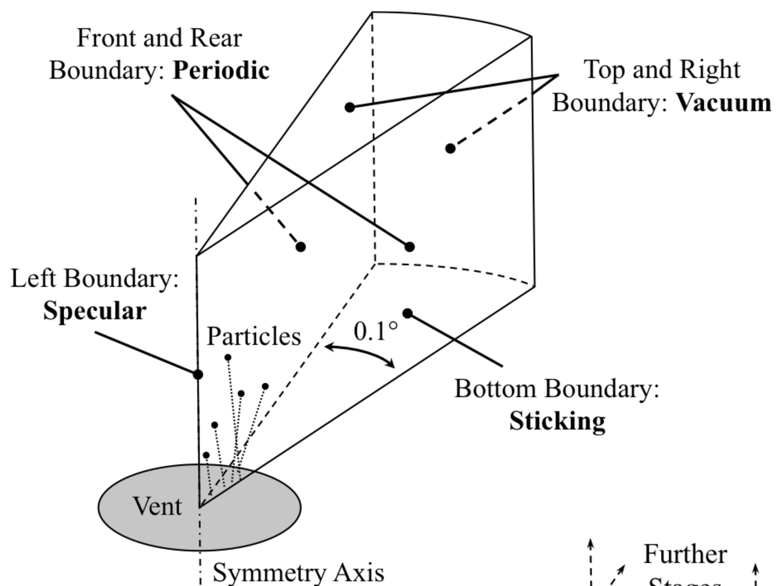
Introduction

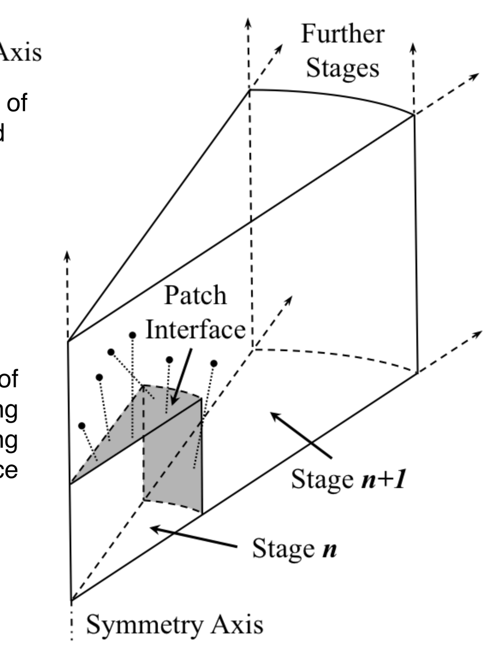
- Active surface processes, a likely subsurface ocean, and conditions favorable to astrobiology make Europa an attractive target for planetary science missions
- Hubble Space Telescope observations by Roth et al [1,2] showed coincident signatures from H (Lyman-α) and O (103.4 nm) indicating presence of water vapor in a plume above the south pole
- Plume height estimated at 200 ± 100 km, H_2O column density ~10^{20} molecules/m^2
- Objective was to develop a Direct Simulation Monte Carlo (DSMC) model of plumes to aid in instrument specification, operations planning, and hazard analysis
- Various vent condition cases were simulated and compared to each other and observations

Modeling Approach

- DSMC represents large numbers (10^{13} – 10^{20}) of actual molecules with each computational particle
- Simulated particles move across meshed domain, collide, and have their properties (velocity, internal energy) updated accordingly
- Plume source is assumed to be a narrow fissure through which water at triple point conditions boils off into vacuum [3]
- Vent modeled as a supersonic isentropic nozzle, with resulting exit conditions used to generate particles with appropriate velocity distribution
- Each domain is an axisymmetric 0.1° wedge with the vent centered on the axis
- Molecules leaving vacuum outflow boundaries are saved and patched into the subsequent stage
- Eight sequential stages allow accuracy and efficiency over large length scale (10^1 – 10^6 m) and particle mean free path (λ) (10^{-5} – 10^5 m) variations
- Solid ice grains of three diameters (0.1, 1, 50 μm) included with momentum coupling to flow [4]
- Photodissociation of water ($H_2O + \nu \rightarrow OH + H$), with daughter species gaining excess energy from dissociation [5,6]



Above: Boundary conditions of axisymmetric, wedge-shaped domain

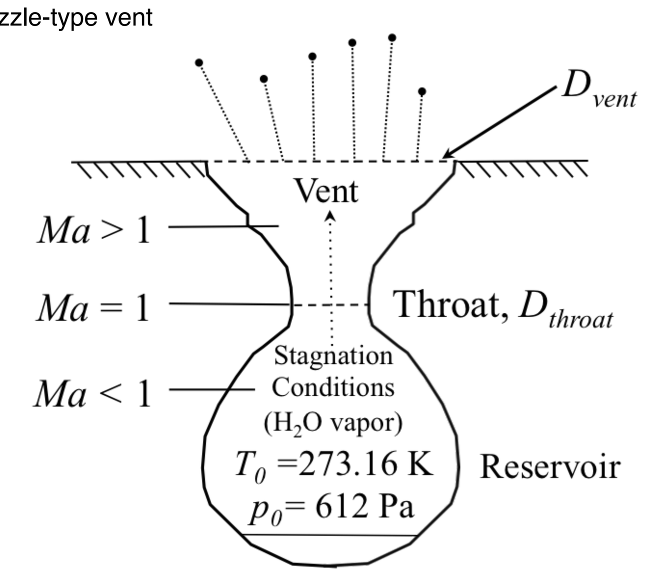


Right: Schematic of domain staging procedure showing patch interface

Properties	Mach 2	Mach 3	Mach 5	Cold	High Mass Flow Rate
Vent-to-throat Area Ratio	1.7	4.8	36.6	4.8	4.8
R_{throat} (m)	1.7	1.7	1.7	1.7	17
R_{vent} (m)	2.2	3.7	10.2	3.7	37
Density (kg/m³)	1.0x10⁻³	3.1x10⁻⁴	3.5x10⁻⁵	3.1x10⁻⁴	3.1x10⁻⁴
Velocity (m/s)	635.3	778	902	778	778
Temperature (K)	163.9	109.26	52.87	87.20	109.26
Pressure (Pa)	79.2	15.8	0.9	15.8	15.8
Mean free path (m)	4.2x10⁻⁵	1.4x10⁻⁴	1.3x10⁻³	1.4x10⁻⁴	1.4x10⁻⁴
Mass flow rate, $\dot{m}_{vent}$ (kg/s)	10.4	10.4	10.4	10.4	1000

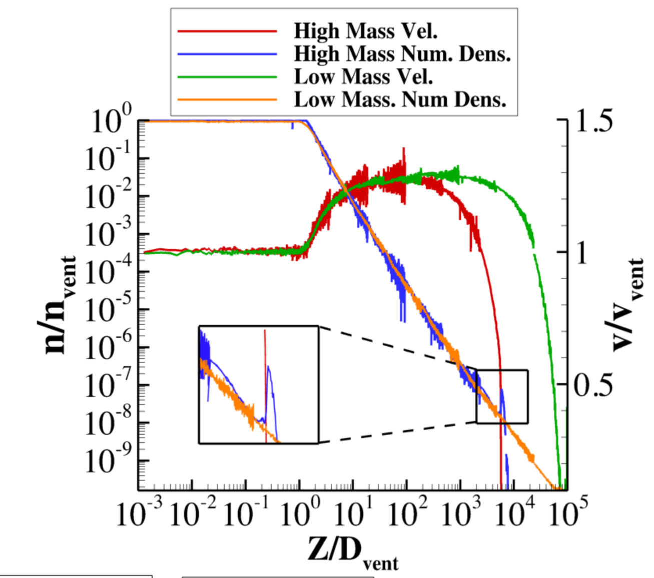
Above: The table shows the various vent cases simulated, with critical changes in parameters highlighted. Mach number is altered by changing the area ratio of the "nozzle" and mass flow rate by changing the size of the throat. The "Cold" case at Mach 3 serves as a proxy for scenarios in which flow energy is lost to the region surrounding the vent resulting in lower vent temperature.

Below: Schematic of nozzle-type vent



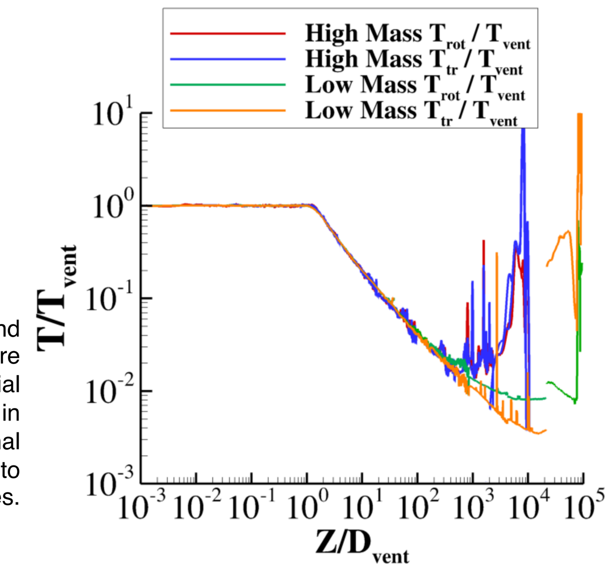
Results

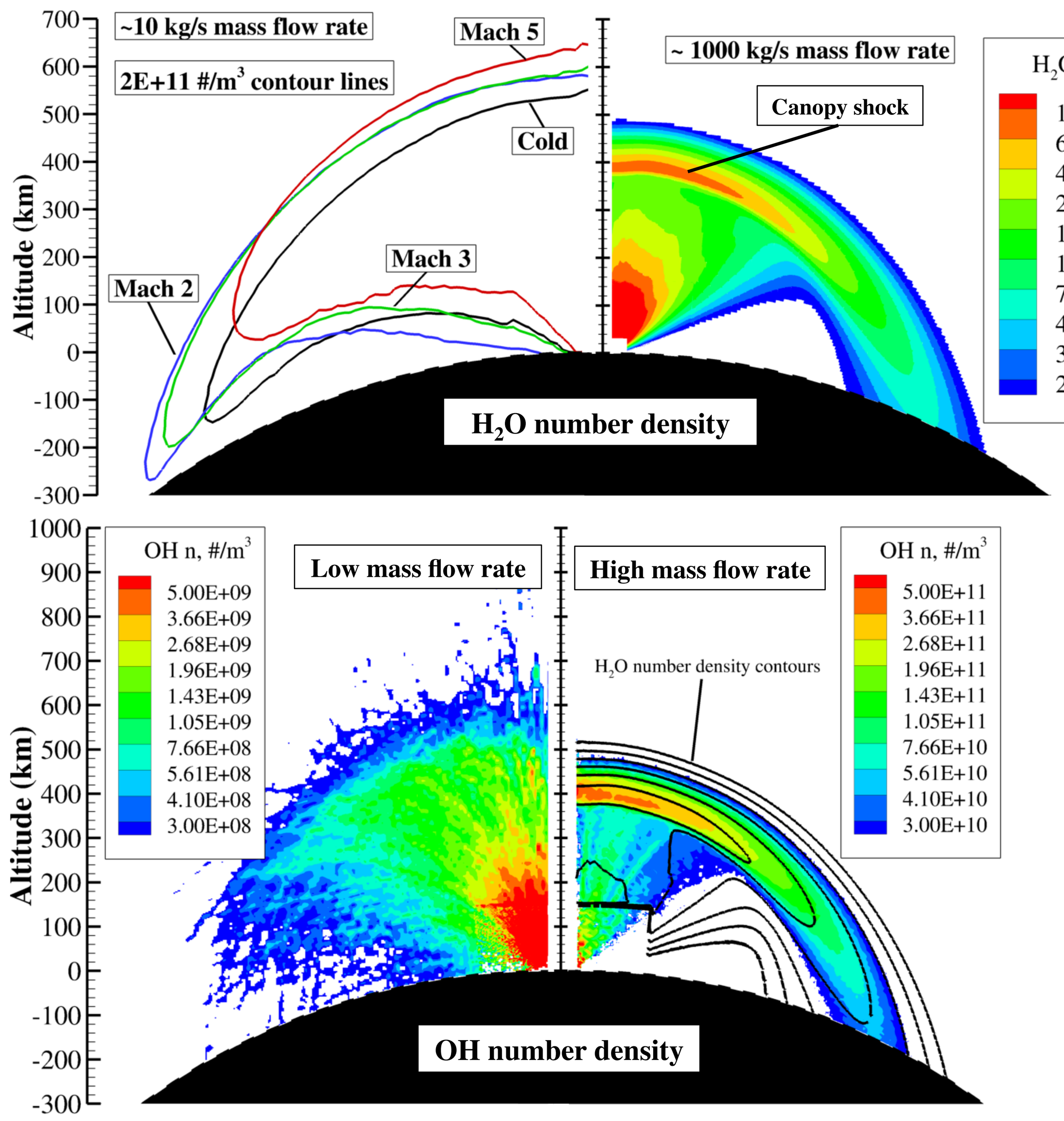
- Plume expands from the vent, rapidly rarefying, cooling, and accelerating to ~1 km/s
- Translational and rotational temperatures diverge as collisions become too infrequent to maintain equilibrium
- Heating at high altitude due to collisions with fast moving photodissociation daughter species

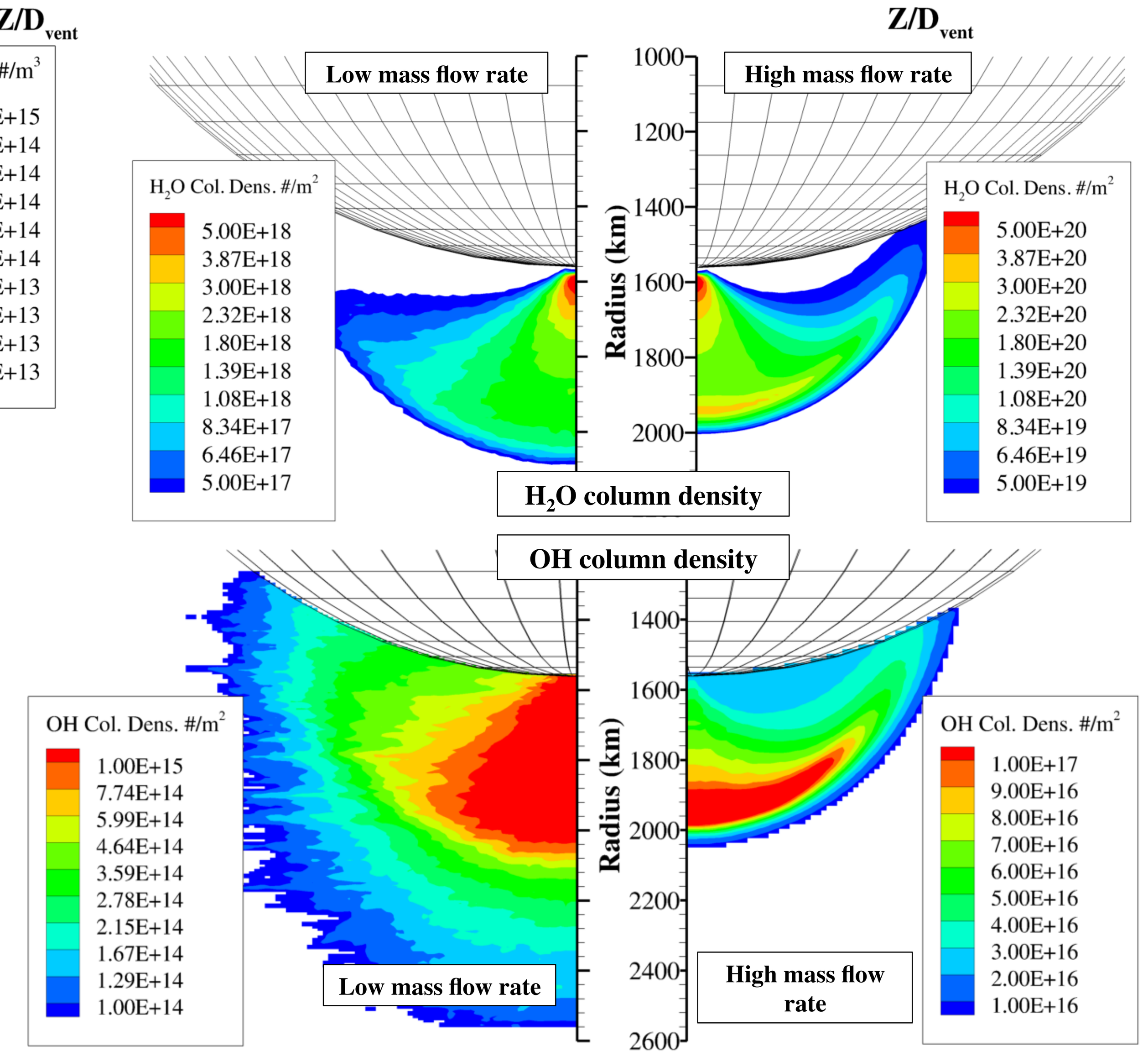


Left: Number density (n) and velocity (v) along the plume centerline normalized by initial vent values. Flat portion is prior to expansion wave crossing centerline. Inset shows density increase from canopy shock.

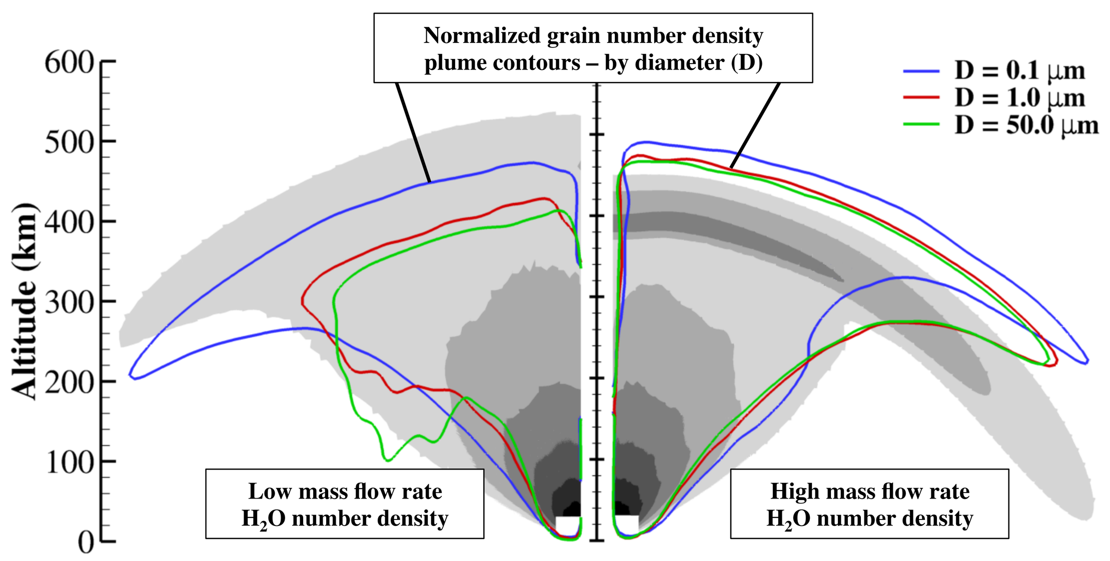
Right: Rotational (T_{rot}) and translational temperature (T_{tr}) normalized by initial vent values. Step in temperatures in final computational stage due to back-falling molecules.







- Increasing Mach number raises plume height and reduces lateral spreading due to more energy being directed vertically
- High mass flow rate leads to a canopy shock due to sufficient number of molecules moving vertically in both directions, leading to more frequent collisions
- Photodissociation products (OH and H) behave similarly and are distributed widely due to large excess energy from creation, unless they are generated and trapped within the denser canopy region
- Ice grains decouple relatively early from the flow and are unaffected by the canopy region
- Smaller grains decouple later, are accelerated to higher speeds and altitude, and spread more laterally by the gas flow



Conclusions

- Mach number and vent temperature changes studied here had modest impact on plume structure and height
- Higher mass flow rates (~1000 kg/s) induce denser canopy shock region, limit plume height, and create column densities corresponding to observation (~10^{20} H_2O molecules/m^2)
- Species resulting from photodissociation disperse widely due to high velocities, except if captured in canopy region
- Ice grains are unaffected by canopy shock and decouple from flow at different altitudes depending on grain diameter

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References: [1] Roth, L., et al, 2014. Science 343, 171–174. [2] Roth, L., et al, 2014. Natl Acad Sci USA 111, E5123–E5132. [3] Schmidt, J., et al, 2008. Nature 451, 685–688. [4] Gallis, M.A., et al, 2001. Phys. Fluids 13, 3482–12. [5] Huebner, W.F., et al, 1992. Astrophysics and Space Science 195, 1–294. [6] Combi, M.R., et al, 2004. Comets II. pp. 523–552.