INTERPRETING OBSERVATIONS OF VOLCANIC PLUME STRUCTURE IN THE ABSENCE OF AN ATMOSPHERE: EXAMPLE OF TVASHTAR. P. C. Ackley[1], W. A. Hoey[1], D. B. Goldstein[1], L. M. Trafton[2], P. L. Varghese[1]. [1]Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, United States [2]Department of Astronomy, The University of Texas at Austin, Austin, TX, 78712, United States.

Introduction: Supersonic gas/particulate plumes have been well observed on Io, Enceladus, comets, and maybe on Europa. A persistent issue that remains, however, is how to use remote observations to interpret the physical phenomena of the plume source region. During the New Horizons flyby of the Jovian system in 2007, the Long Range Reconnaissance Imager (LORRI) obtained dramatic images of the eruption of Tvashtar on Io [1]. While images of eruptions of the Tvashtar caldera have been captured before, these LORRI images are unprecedented because they include a series of five images taken 2 min apart that constitutes a movie (Figure 1). If we want to draw conclusions about the vent processes that created this plume, we need to infer the constraints indirectly from the plume images.

We know that Tvashtar's plume primarily consists of SO_2 gas and is made visible by light reflected from particles entrained in the gas. However, the geometry of the vent is largely unconstrained by NH surface imagery, and the origin of the intricate structure observed in the plume remains a mystery. Because the SO_2 gas significantly alters the motion of the particles, a simple gravity-ballistic simulation of the particles is not useful. Our group in Austin has developed a sophisticated direct simulation Monte Carlo (DSMC) model for simulating these types of gas-driven plumes, but these simulations are computationally expensive. Thus, we introduce a hybrid method of plume simulation that strikes a balance between the efficiency of a simple ballistic model and the relative physical accuracy of a full DSMC simulation.

Hybrid Simulation Method: Our hybrid simulation method rests on the idea that under certain conditions, it is reasonable to assume that the dust particles are fully entrained in the gas. Using this assumption, we conduct a resolved DSMC simulation of just the gas and then calculate the mean gas velocities at the DSMC cell centers. This velocity field is then exported and stored, and a variety of mass flux functions characterizing different dust distributions at the vent level can be simulated by simply moving the particles according to the gas velocity field while subject to grain sublimation/condensation depending on the gas density and temperature fields.

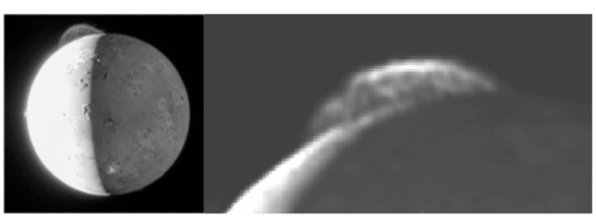

Figure 1: The Tvashtar plume relative to Io (left). The third of the five movie images (right).

While the vent geometry is not well constrained, results from Rathbun et al. [2] and preliminary experiments suggest that a 30 km^2 rectangular vent with a 1280 K stagnation temperature will produce a plume with a canopy height consistent with the LORRI images. As the aspect ratio is still unknown, we simulate four different such vents with aspect ratios 1:1, 3:1, 10:1, and 15:1.

Results: We briefly show how plume images simulated with this method can be used to infer constraints on vent geometry and the spatiotemporal characteristics of the vent processes.

Vent geometry and plume shape. As the aspect ratio of the vent increases, the observed shape of the plume becomes highly dependent on the observer's viewing angle. Specifically, if the observer's line of sight is perpendicular to the vent's long axis, the plume will appear to be much *narrower* than if the line of sight is parallel to the vent's long axis. This is illustrated in Figure 2, which shows a plume simulated with a 15:1 vent with the vent axes appropriately rotated to show both extremes. This difference is due to a gas phenomenon that we refer to as axis switching in which the gas expands much more aggressively in the direction of the vent's *narrow* axis. Thus, if we have images of the plume captured from different viewing angles, we can use this information to determine whether we are dealing with a low- or high-aspect ratio vent. In addition, if we are dealing with a high-aspect ratio vent, multiple views can allow us to infer constraints about the orientation of the vent axes.

Spout. In their *Science* article, Spencer et al. (2007) note that "most Tvashtar plume images show little evidence for a central upgoing column of particles" and state that this suggests that, "the observed particles may condense out of the plume rather than being directly ejected from the vent." Whether an image of a plume exhibits a central upgoing column of particles or a "spout" can depend on many factors. Certainly, if

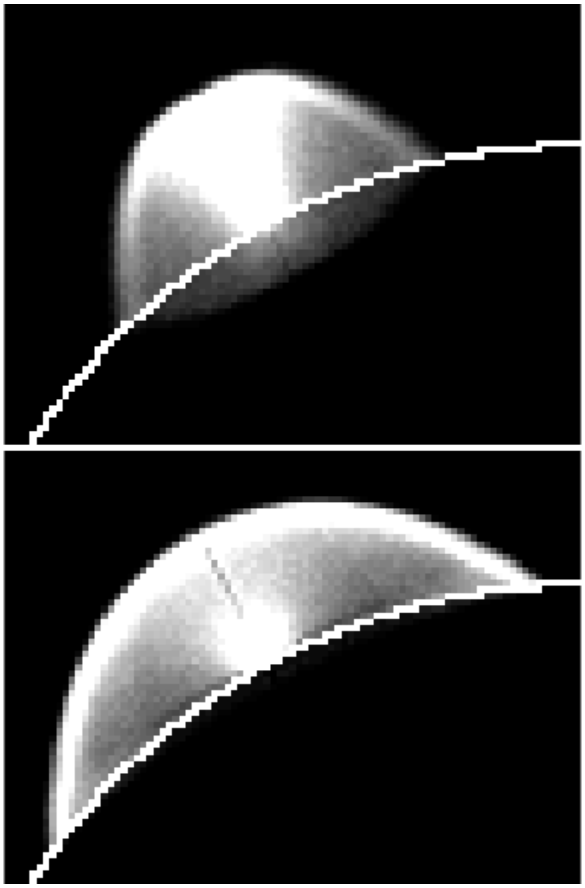

Figure 2: A plume simulated with the 15:1 vent is shown with the observer's line of sight perpendicular to (top) and parallel to (bottom) the long axis of the vent.

particles are continuously ejected from the vent, we would expect there to be a relatively dense region in the center of the plume emanating from the vent. However, whether this manifests as a spout in any particular image depends on several factors including the contrast level of the image and the degree of occlusion of the plume by the planet. Figure 3 shows a plume simulated by continuously ejecting particles uniformly from a 1:1 vent from three different viewing angles and using three different contrast levels. In the bottom row, the vent appears on the limb of Io, and the degree to which the spout extends to the top of the plume depends on the contrast level chosen. The other two rows show the same simulated plume at the same contrast level but from different viewing angles.

To investigate the Spencer et al. (2007) suggestion that the absence of the spout implies that particles predominately condense out of the plume rather than being directly ejected from the vent, we incorporate a rudimentary particle growth model in which particles are permitted to grow/shrink through condensation/sublimation of the SO_2 gas, with the light scattered

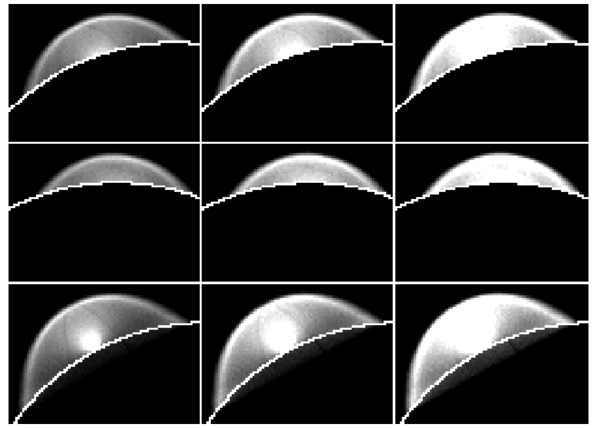

Figure 3: A plume simulated with the 1:1 vent shown from different viewing angles (top to bottom) and with different contrast levels (left to right).

by each particle being proportional to r^6 (in accordance with Rayleigh scattering). In order for this to explain the absence of the spout, the particles would need to grow to a larger size in the canopy than they do in the spout. However, our simulations indicate that the opposite is true for most particles.

Finally, we investigate the idea that a visible spout does not appear in the images because the particles are simply not there. Because the particles slow down significantly once they reach the dense gas canopy, they spend significantly more time aloft in the canopy than in the spout region. As a consequence, a relatively full looking plume can be supported by relatively infrequent pulses of particles. Based on our simulations, we conclude that pulsing input of grains could be a significant part of the explanation for the lack of a visible spout.

Dust distribution in the vent. Some of the Tvashtar plume images reveal interesting and mysterious structures such as a traveling notch that appears on only one side of the canopy and thick, tubelike "tendrils" in the interior of the plume. The relatively efficient nature of our hybrid simulation allows us to quickly simulate a range of different particle distributions at the vent level so that broad conclusions can be drawn about what length and time scales observed in the plume imply about the length and time scales of the vent processes. At LPSC, we will present two possibilities. In the first, we consider a mass flux function in which particles are released according to a traveling sinusoidal wave. In the second, we consider a mass flux function that releases particles in thin strips in infrequent pulses.

References: [1] Spencer et al. (2007) *Science, 318,* 240-243. [2] Rathbun et al. (2014) Icarus, 231, 261-272.