MATCHING VARIOUS OBSERVATIONS OF IO WITH DSMC MODELING: PLUME, PLUME SHADOW, SODIUM FIELD AROUND PELE. J. Zhang, D. B. Goldstein, P. L. Varghese, L. Trafton, C. Moore, K. Miki, *The University of Texas at Austin, Austin, TX 78712, (jzhang@cfdlab.ae.utexas.edu).*

Introduction: Volcanic plumes on Jupiter's moon Io are modeled using the direct simulation Monte Carlo (DSMC) method. A parametric study on the "effective" vent gas temperature and velocity is performed to constrain the gas properties at the vent by observables, particularly the plume height and the surrounding condensation deposition ring radius. Also, the flow of refractory 1 nm – 1 μm particulates entrained in the gas is modeled with "overlay" techniques which assume that the background gas flow is not altered by the particulates. The column density along the tangential line-of-sight and the shadow cast by the plume are calculated and compared with Voyager and Galileo images. The possible ejection of sodium from a vent into the circum-planetary region is examined.

Model: Details of the numerical model can be found in [1]. Only a brief description is provided here.

The Direct Simulation Monte Carlo (DSMC) method [2] was used to model the volcanic plume flows. Special effort was expended on modeling the two-phase gas/particle flow. It is assumed that the flow of particles entrained in the gas plume does not alter the gas flow, enabling the use of "overlay" techniques. Condensation effects were examined in [3]. The particles are assumed to be *refractory* so that coagulation and evaporation are neglected in the models. Other assumptions and justifications can be found in [1].

Once the flow field of either gas or particles is obtained, the column density along tangential lines of sight (herein referred to as TCD, i.e. tangential column density) can be calculated by ray tracing. Such calculations are necessary for direct comparison with observations of plume brightness. The column density at viewing angles other than tangential can be projected onto the surface of Io and interpreted as the shadow cast by the plume if the particle plume that cast the shadow is not optically thick. The effects of the plume opacity will be investigated in the future. The elongation of the shadow caused by the spherical geometry of the surface of Io is also taken into account by allowing the solar ray (line of integration) to intersect with the spherical surface.

Results: The vent in our simulation is interpreted as the "effective" vent which represents the location where the gas temperature and velocity reach the modeled values. Therefore, our effective vent may not necessarily be right at the exit of a volcanic tube and may apply to plumes having a lava-frost interaction as the source. Two sets of contours in vent temperature and velocity (V_v, T_v) space are shown in Figs. 1(top and bottom), with one set corresponding to constant shock heights (H_s) and the other to constant ring radii (R_r, at the peak deposition radius, assuming a cold condensing surface). Using the two sets of contours for shock height and peak deposition radius shown in Fig. 1, one can constrain the vent temperature and velocity for large plumes from the observed shock altitude and deposition ring radius by the intersection of appropriate R_r = constant and H_s = constant lines. A reasonable range of vent conditions for Pele type plumes in (V_v, T_v) space is obtained and indicated in Fig. 1(top) by the band between two dashed black lines approximately corresponding to contours of R_r = 550 and 620 km. Note the possibility of a hot lava lake as a source of Pele in addition to a vent. For small Prometheus type plumes, one cannot constrain (V_v, T_v) by this approach as the two sets of contours in Figs. 1(top and bottom) are essentially parallel to each other. Despite this, we have attempted to constrain (V_v, T_v) combinations for Prometheus-type plumes as tightly as possible.

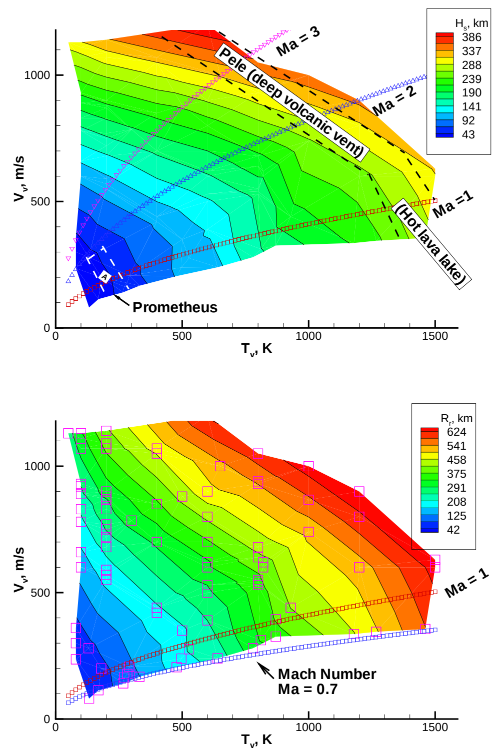

Figure 1: (top) Constant plume height (H_s) and (bottom) constant peak frost deposition radius (R_r) contours in vent velocity-temperature (V_v, T_v) space. Suitable regions of (V_v, T_v) for Pele- and Prometheus-type plumes are indicated. Vent conditions corresponding to Ma = 1, 2 and 3 are also shown by dotted curves in the top figure. A bounding Ma number of 0.7 relevant to lava-lake plume is shown in the bottom figure [1]. The (V_v, T_v) at which the ~90 individual simulations were performed are indicated by the square symbols in the bottom figure.

A nightside plume (surface temperature T_s = 90 K) with vent temperature of 200 K and velocity of 180 m/s (a combination inside the white dashed box in Fig. 1(top)) was chosen for the following discussion on Prometheus. The resulting gas plume with this vent condition is shown in Fig. 2b. The TCD of gas is shown in Fig. 2c. It is seen that the gas TCD contours show very encouraging similarities to the Voyager image (Fig. 2a). In addition to the general shapes and dimensions of the contours, the "hatchet" shape of the contours near the gas shock seen in both the observation and the simulation is promising. It is understood that the observed plume brightness probably arises from scattering of sunlight by fine particulates (refractory or volatile) rather than by the gas. Figure 2d shows that the TCD images of 1 nm refractory particle plumes indeed show convincing similarities to the Voyager image as does the gas. The same calculation was done for the Pele plume and strong similarities between the calculation and observation were found too [1].

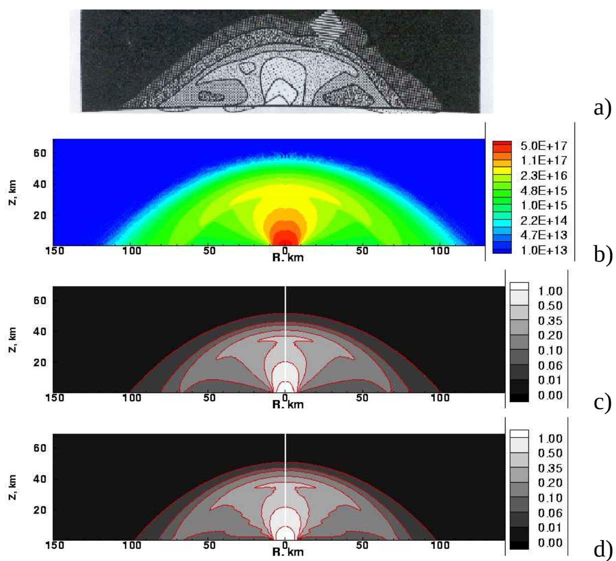

Figure 2: a) Voyager image of the brightness of Prometheus plume, (*From Strom and Schneider (1982) [4], courtesy of Robert Strom*) b) the number density contours of the modeled Prometheus gas plume, c) the normalized (by $6 \times 10^{17} cm^{-2}$) gas and d) 1 nm particle TCD. All figures are drawn to the same length scale.

A remarkable reddish shadow cast by Prometheus is seen in the Galileo image shown in Fig. 3(left). Two components seem to be present with one corresponding to a dark "finger" poking through the cap of a "mushroom". An effort was made to reproduce these features by computing the shadows of particle plumes with particles having different sizes. The solar zenith angle at the Prometheus vent in Fig. 3(left) was $\sim 78^o$ when the image was taken. The column densities projected from the sun onto Io's surface at this angle were calculated for the particle plumes and plotted in Figs. 3(middle and right). The "finger" shape discussed above is found to be best reproduced by a plume of ∼10–100 nm particles. The uniformly dark southern "mushroom" shape may be reproduced by 1 nm particles.

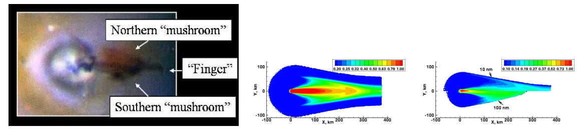

Figure 3: (left) Galileo image of close-up views of Prometheus (http://photojournal.jpl.nasa.gov/catalog/PIA00703); (middle) Computed shadow cast on the surface by 1 nm particles; Shadow of 10 nm (top part of right) and 100 nm particles (bottom part of right). The simulated shadows and the inset of Prometheus in Galileo image are drawn to the same length scale. Refer to [1] for contour levels.

In an attempt to reproduce the atomic sodium number density profiles observed at high altitude by Schneider *et al.* [5], Moses *et al.* [6] obtained sodium densities that seem to be too high at high altitude. In their model, plume dynamics is ignored so that there is no shock at high altitude as in our results. If one accounts for the rapid slowing of the upward moving SO_2 and entrained sodium through the canopy shock, the observed low sodium number density at high altitude may well be reproduced. This is attempted here. The variable hard sphere (VHS) molecular diameter of Na is not provided by [2] so the diameter of Ne is used. Figures 4(left and right) show that although Na is light and tends to have larger thermal velocities than SO_2, it closely follows the bulk SO_2 gas flow, and the Na/SO_2 mixing ratio of 5:95 stays approximately constant throughout the entire plume. It is assumed at the moment that Na does not sublime from the surface at 111K. It is seen that Na is not present in the SO_2 sublimation atmosphere at low altitude. The Na number density is lower than that calculated by Moses *et al.* [6] above the canopy shock at high altitude. Further investigation is needed to finally match the Na density profile at altitudes greater than ∼600 km in [5].

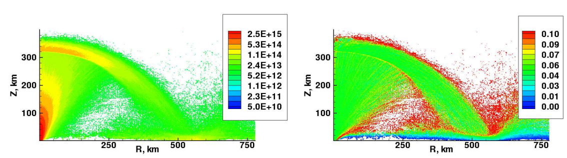

Figure 4: (left) Na number density contours and (right) concentration of Na inside a simulated Pele type plume with 5% (by mole fraction) Na mixed with SO_2 at the vent. The surface temperature is a nominal 111 K.

References: [1] J. Zhang, D. B. Goldstein, P. L. Varghese, L. M. Trafton, C. Moore, and K. Miki, Numerical Modeling of Ionian Volcanic Plumes with Entrained Particulates, submitted to *Icarus*, 2003. [2] G. A. Bird (1994) *Molecular Gas Dynamics and Direct Simulation of Gas Flows*. [3] C. Moore *et al.* LPS XXXIV, Abs. 2102, 2003. [4] Strom, R.G. and Schneider, N.M., Satellites of Jupiter, 1982. [5] Schneider *et al.*, Astrophys. J., 1991a. [6] Moses *et al. Icarus*, 2002.