Are Prometheus-Type Plumes on Io Produced by Lava-SO_2 Interactions at the Flow Fronts?.
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Introduction:

We have investigated how lava-SO_2 interactions could produce Prometheus-type plumes on Io. While most models assume a single source vent for the gas and entrained particles [*e.g.*, 1], the evidence at Prometheus suggests that the plume is created from multiple sources. No central plume vent is apparent in the high-resolution and color images acquired by Galileo in February, 2000. Instead, the images reveal a compound flow field with many active flow lobes, often associated with bright and dark streaks. The medium-resolution color image shows diffuse, blue-colored, regions suggestive of SO_2 gas spread over the flow field. We propose that the plume may originate from SO_2-rich material volatilized by multiple advancing flow lobes [*e.g.*, 2]. The plume is remarkably stable in size, shape and optical properties, seemingly inconsistent with the sporadic behavior of individual flow lobes, but there are tens of active lobes so the cumulative effect could appear constant. We have modeled the interaction between basaltic pahoehoe lava and SO_2 snow on Io during the initial emplacement of a new flow lobe. Using an estimated 5 $m^2\ s^{-1}$ lava coverage rate at Prometheus, we show that the gas production rate of SO_2 at the flow fronts is enough to produce the a resurfacing rate of ~0.24 cm yr^{-1} around Prometheus.

Lava cooling model:

We have developed a model for the heat transfer during the initial contact between a slow moving, thin basaltic flow with a substrate of loosely packed SO_2 snow. The flow is assumed to be basaltic pahoehoe, initially 35 cm thick at a temperature of 1475 K. This flow is extruded onto an infinite half-space of SO_2 snow at an initial temperature of 120 K. Under ~35 cm of basalt on Io, SO_2 will reach its triple point at 197.6 K.

Mathematically, this is described by the following:

$$\frac{\partial T_l}{\partial t} = \frac{\frac{\partial}{\partial z}\left(k_{eff,l}\frac{\partial T_l}{\partial z}\right) + \rho_l L_l \frac{\partial X_{cryst}}{\partial t}}{\rho_l C_{p,l}} \qquad (1)$$

$$\frac{\partial T_l}{\partial z}(z=0,t) = 0 \qquad (2)$$

$$T_l(z,t=0) = T_{o,l} \qquad (3)$$

Where T is temperature, z is depth, t is time, and ρ_l, $C_{p,l}$, $k_{eff,l}$ are the temperature- and porosity-dependent density, heat capacity, and effective thermal conductivity of the lava; L_l is the latent heat of crystallization of the lava; $T_{o,l}$ is the lava initial temperature; $\frac{\partial X_{cryst}}{\partial T_l}$ is the rate of crystallization of the lava [3]. $k_{eff,l}$, the effective thermal conductivity of the lava, modified for vesicularity, is given by:

$$k_{eff,l} = R_v + \frac{k_l[2(1-\Phi)k_l + (1+2\Phi)k_g]}{(2+\Phi)k_l + (1-\Phi)k_g} \qquad (4)$$

Where R_v is the radiation across the vesicles; Φ is the vesicularity of the lava; k_l is the temperature dependent thermal conductivity of basalt; k_g is the temperature dependent thermal conductivity of SO_2 gas within the vesicles. R_v is given by:

$$R_v = 2\Phi\delta\epsilon\sigma T_l^3 \qquad (5)$$

Where δ, ϵ, σ are the vesicle diameter, emissivity across the vesicles, and the Stefan-Boltzmann constant respectively. k_l is given by [4]:

$$k_l = 0.427 + \frac{772}{T_l} - \left(\frac{8.72x10^4}{T_l^2}\right), \qquad (6)$$

k_g is from [5]:

$$k_g = -2.516x10^{-3} + (3.345x10^{-5}T_l) + (2.25x10^{-8} * T_{o,l}^2) \qquad (7)$$

and ρ_l is [*e.g.*, 6]:

$$\rho_l = \rho_{o,l}\left(\frac{1-\Phi}{1+\alpha*(T_l-1450)}\right), \qquad (8)$$

where $\rho_{o,l}$ is the initial density of the lava.

The heating of the SO_2 substrate is described by:

$$\frac{\partial T_s}{\partial t} = \frac{\frac{\partial}{\partial z}\left(k_{eff,s}\frac{\partial T_s}{\partial z}\right) - \rho_s L_s \frac{\partial X_{vap}}{\partial t}}{\rho_s C_{p,s}} \qquad (9)$$

$$\frac{\partial T_s}{\partial z}(z=Z_s,t) = 0 \qquad (10)$$

$$T_s(z,t=0)=T_{o,s} \qquad (11)$$

Where T is temperature, z is depth, t is time, and ρ_s, $C_{p,s}$, are the temperature and porosity dependent density and heat capacity, $k_{eff,s}$ is the effective thermal conductivity; L_s is latent heat of sublimation of SO_2; $T_{o,s}$ is the initial temperature of SO_2; $\frac{\partial X_{vap}}{\partial T_s}$ is the rate of vaporization; Z_s is an arbitrarily deep point in the SO_2 substrate to which heat from the lava does not penetrate. The temperature dependent heat capacity of SO_2 is given by:

$$C_{p,s}=447.719+(0.720T_s)-(3.862x10^{-4}T_s^2)+(7.005x10^{-8}T_s^3) \qquad (12)$$

To conserve energy, we require that

$$q_{out}=k_{eff,l}(z=z_{interf},t)\frac{\partial T_l}{\partial z}|_{z=z_{interf}}, \qquad (13)$$

the heat conducted out of the lava at the interface point into the SO_2 substrate equal

$$q_{in}=k_{eff,s}(z=z_{interf},t)\frac{\partial T_s}{\partial z}|_{z=z_{interf}}, \qquad (14)$$

the heat conducted into the SO_2 substrate at the interface point, z_{interf} (35 cm). The two heat transfer problems are coupled, and therefore must be solved simultaneously.

This problem must be solved numerically, and we have chosen a simple, finite-difference algorithm with 3500 grid points, space .1 mm apart with time steps of 1 ms. We assume that after the triple point is reached, any additional heat is used to convert the solid SO_2 to gas.

For a run of 1 hour, a lobe with 50% vesicularity vaporized approximately 9.2 mm of SO_2 per unit area. Using this result, we can derive an expression for the cumulative vaporization as a function of time:

$$A = (1.53x10^{-4})\sqrt{t} \qquad (15)$$

Where A is the cumulative amount (in meters) of SO_2 vaporized per unit area and time, t, is in seconds.

Change detection observations between I24 and I27 flybys indicate that a lava coverage rate of about 5 m^2 s^{-1} is reasonable at Prometheus. From the lava coverage rate and equation (15), we estimate the amount of SO_2 vaporized as ~1.36 x 10^8 m^3 yr^{-1}. The area of the Prometheus plume deposit annulus is about 5.6x10^{10} m^2. The volume flux estimated here gives us a resurfacing rate of the annulus of about 0.24 cm yr^{-1}.

We will present the results of modelling of the escape of the gas and entrained particles and whether they have enough energy a) to reach the plume annulus, and b) to attain the heights observed in the Prometheus Plumes.

References:

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