STOCHASTIC-BALLISTIC PLUMES ON IO: SENSITIVITY OF DEPOSITION TO HIGH EJECTION ANGLES.

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Introduction: Some active volcanoes on Io are associated with bright annular deposits [1]. These annuli are generally thought to be surface deposits of SO_2 frost [2,3,4]. Glaze and Baloga [5] have extended the plume model developed by Cook et al. [6] to describe the emplacement of particles whose motion is controlled by stochastic processes near the vent and deterministic ballistic transport beyond. Assuming that the relative brightness of the surface deposits observed in visible images is directly related to the areal concentration of particles on the surface, this model now provides quantitative constraints on eruption conditions from the brightness distributions of the annuli.

Random effects within the stochastic region could include particle collisions, thermalization, irregularities in vent conditions and phase changes. The random processes of the stochastic regime are expressed as probability distributions for the important transport variables: energy, momentum, and ejection angles. By varying the parameters of the energy and angular distributions, the stochastic-ballistic model can make annuli of high particle concentrations on the surface come and go.

Choosing a narrow normally distributed ejection energy, instead of a single energy, introduces enough dispersion in the resulting areal concentrations to produce broad annuli with dimensions comparable to those observed at Prometheus [5]. Varying combinations of the truncation angle and relative standard deviation for the energy distribution change the shape and magnitude of the surface deposit.

Glaze and Baloga [5] found that the predicted ground concentrations were very sensitive to high ejection angles (as measured from vertical). This is due primarily to the geometry of hemispherical ejection and a singularity in the areal concentration resulting from ballistic transport. Simple truncation of the ejection cone resulted in a wide range of areal concentrations. Here we explore the effects of allowing a small 'tail' at the outer boundary of the ejection cone on the characteristics of the surface deposits.

The Model: The stochastic-ballistic model used here and in [5] divides a plume into two spatial regions. The stochastic region is considered to be a hemisphere near the vent with a radius that is small compared to the overall dimensions of the plume. In general, we assume that the important transport variables (e.g., energy, momentum, ejection angles) have probability distributions. Once particles leave the stochastic region, the randomizing influences on particle motions cease and the subsequent trajectories are purely ballistic. In effect, the probability distributions are quenched when the plume particles exit the stochastic region. The distributions of transport variables for the stochastic region thus serve as initial conditions for ballistic emplacement.

In this work, we are concerned with the areal concentrations of plume particles on the surface of Io that result from different distributions of transport variables in the stochastic region. We will assume that the plume is axisymmetric and use a cylindrical coordinate system to describe particle trajectories. In the simplest case of ejection of N particles with a single energy, the probability that a particle is ejected at an angle, θ, is

$$P(\theta) = \frac{dN}{N} = C_1 \Theta(\theta) \sin\theta d\theta \qquad (1)$$

where C_1 is the normalization constant and $\Theta(\theta)$ is the angular distribution measured from the vertical axis. For isotropic ejection, $\Theta(\theta) = 1$. The areal concentration on the ground as a function of radial distance, ρ (r), is then given by

$$\rho(r) = \frac{1}{2\pi r} \frac{1}{N} \frac{dN}{dr} \qquad (2)$$

Figure 1 indicates a very high concentration peak near the vent for isotropic ejection out to 90°. The particles forming the peak all originate at angles close to 90° that travel only a short distance from the vent. The high concentration is also a result of the small surface area at that point.

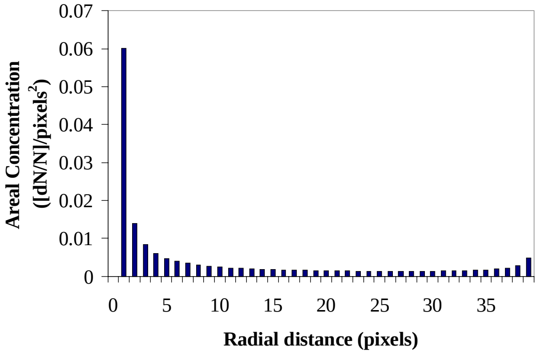

Figure 1. Areal concentration of particles for a single energy and isotropic ejection between 0° and 90°.

Truncating the ejection cone. To examine the sensitivity of the areal surface distribution to the maximum ejection angle, we simply truncate the ejection cone at some angle, θ_o. In general, we will assume that the ejection cone is cutoff at some angle less than 90° and that the distribution is isotropic for $0 \le \theta \le \theta_o$, with relatively few particles ejected beyond θ_o. This approach will allow a small tail in the angular distribution beyond θ_o to some maximum ejection angle.

In the simplest case, no particles are ejected past θ_o. For θ_o = 75°, Figure 2 illustrates how the peak in particle concentration near the vent has been eliminated by cutting off the ejection cone. We see that this results in a broad peak between 20 and 40 pixels from the vent, with a maximum near 40 pixels. Glaze and Baloga [5] have shown that introduction of normally distributed energy with a small relative standard deviation (~8%) results in a broad symmetric peak centered about 30 pixels from the vent that is comparable to the annulus dimensions observed at Prometheus.

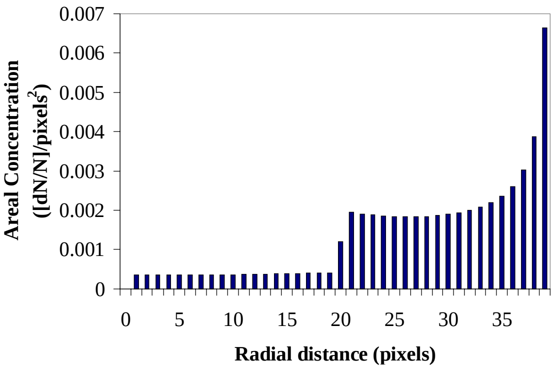

Figure 2. Areal concentration of particles for a single energy and isotropic ejection between 0° and 75°.

The sharp break in the areal concentration (Figure 2) near 20 pixels is a direct result of the cutoff angle. Inside 20 pixels, only the upper plume contributes to the surface deposit. If, however, we allow for a small tail in the angular distribution past the cutoff angle, the surface concentration should have a smoother appearance.

To investigate the influence of a small tail at high ejection angles, we introduce the Fermi function distribution,

$$\Theta(\theta)=\frac{C_2}{1+e^{(\theta-\theta_o)/\varepsilon}} \qquad (3)$$

where ε is the parameter that controls the sharpness and width of the tail. In the limit as ε goes to 0,

$$\lim_{\varepsilon\Rightarrow 0}\Theta\left(\theta\le\theta_o\right)=C_2 \qquad (4)$$

which is simply the isotropic angular distribution up to the maximum ejection angle, and 0 beyond. Otherwise, for finite ε, we need to distinguish between the cutoff angle and the maximum ejection angle. Between these two is the small ‘tail’ of the angular distribution. The maximum ejection angle is taken to be 90°, the physical limit imposed by the surface.

Normalization of (3) leads to the integral

$$1=\int_0^{\pi/2}\Theta(\theta)d\theta=C_2\varepsilon\int_0^{\pi/2}\frac{1}{1+u}\frac{du}{u} \qquad (5)$$

Integrating (5), the normalization constant, C_2, can be found to be

$$C_2=\left[\frac{\pi}{2}+\varepsilon\ln\left(\frac{1+e^{-\theta_0/\varepsilon}}{1+e^{(\pi/2-\theta_0)/\varepsilon}}\right)\right]^{-1} \qquad (6)$$

Substituting (6) into (3) results in the complete probability function that can replace the previous function given in (1).

Figure 3 shows the Fermi function for several choices of ε. Note that although the probability approaches 0 very quickly beyond θ_o, there is some finite probability of ejection at all angles out to 90°.

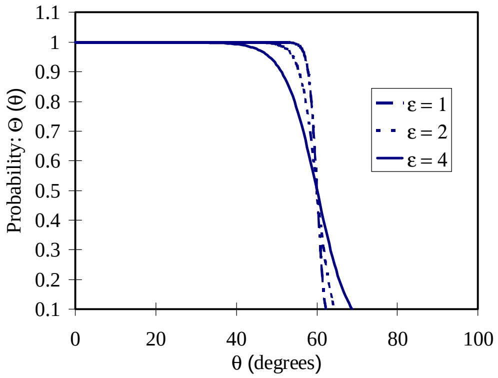

Figure 3. Probability function using Fermi function for ε = 1°, 2° and 4°.

Conclusions: The areal distribution of plume particles on the surface of Io is very sensitive to particles ejected at high angles. Use of the Fermi function, and the limiting process described above, allows us to examine the detailed effects of an ejection cone boundary on annular and other types of areal deposits.

References: [1] A. S. McEwen and L.A. Soderblom (1983) *Icarus 55*, 181-217. [2] T. V. Johnson et al. (1979) *Nature 280*, 746-750. [3] R. G. Strom et al. (1981) *JGR 86*, 8593-8620. [4] A. S. McEwen et al. (1985) *JGR 90*, 12,345-12379. [5] Glaze L. S. and Baloga S. M. (1999) *JGR,*, in review. [6] A. F. Cook et al. (1979) *Nature 280*, 743-746.