A SIMPLE THERMAL MODEL FOR LAVA FOUNTAINS: APPLICATION TO IO. L. Keszthelyi[1], M. Milazzo[2], A. G. Davies[3], and L. Wilson[4], [1]U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001; [2]University of Arizona, 1629 E. University Dr., Tucson, AZ 85721; [3]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109; [4]Lancaster University, Lancaster LA1 4YQ, UK.

Introduction: The very high temperatures that have been reported for lavas on Io [e.g., 1-4] have proven to be difficult to explain [5,6]. Specifically, the estimates of lava temperatures ≥1600 °C require that the interior of Io either (1) have an extremely unusual chemistry or (2) be almost completely molten. Neither of these possibilities fits within our current understanding of the evolution of the Jovian system [7-12]. If Io has a broadly chondritic composition, then recent tidal heating models suggest that there should be no more than about 20% partial melting of the interior [e.g., 10,11]. This suggests a maximum magma temperature of about 1200 °C.

There are three independent avenues of study that are bringing the interpreted eruption temperatures into line with the theoretical limits. Two of these were discussed by [12] where we showed that ascending Ionian magma could be superheated by 100-200 °C and that the uncertainties in the observations allow temperatures around 1300 °C. Together, this allows the observations to be consistent with the theoretical studies, but eruption temperatures in the range of 1400-1600 °C are not ruled out.

Lava Fountain Thermal Model: The third avenue of study is to improve the models used to convert the observed temperatures to interpreted eruption temperatures. Specifically, earlier studies have used thermal models designed for lava flows. However, the locations where the highest temperatures have been observed (Tvashtar, Pillan, and Pele) all have extensive new dark pyroclastic deposits, indicating that these eruptions included spectacular lava fountains. In the case of Tvashtar, incandescent lava fountains 1-2 km tall were resolved in Galileo SSI images [13,14]. Similarly, the hottest resolved incandescent areas seen at Pele by the SSI camera imaging at night are interpreted to be lava fountains [4]. At Pillan, a 400-km diameter dark pyroclastic deposit formed contemporenously with the highest observed temperatures.

The lava flow thermal models generally utilize assumptions only appropriate for effusive eruptions as discussed by [2,14]. The most serious problem with the thermal models that were used is that they assume that the lava is a semi-infinite half space. While [15] does look at the cooling of a lava flow after solidification, the geometry of a pyroclast is vastly different than that of a lava flow (~spherical vs. ~tabular). Small droplets of lava ejected as pyroclasts should cool much faster than these models would predict.

Here we present a very simple thermal model for lava fountains, building upon work on lunar pyroclastics during the Apollo program [e.g., 16]. The eruption environments for the lunar and Ionian eruptions are remarkably similar in terms of gravity, atmospheric pressure, and likely magma composition. Therefore, it is reasonable to use the lunar data to constrain Ionian lava fountain models. Based on lunar pyroclastics, we expect the Ionian lava droplets to be 0.1-1 mm in radius [17]. Such small droplets can be adequately modeled as isothermal spheres that cool by thermal radiation. The details of radiative heat transfer within a fountain are beyond the scope of this work. Instead, we assume that the fountain is composed of three parts: a hidden optically thick core, an incandescent zone of cooling droplets, and dispersed cold pyroclasts. Only the middle portion is visible in thermal emission to a sensor. This visible part of the fountain will radiate to deep space, the surface of Io, the rest of the fountain, and sometimes Jupiter. We combine all these into a single "ambient" temperature (T_a). With these simplifying assumptions, the temperature T of a droplet as a function of time t is given by

$$\frac{dT}{dt} = \frac{\sigma\left(T^4 - T_a^4\right)}{r\rho C}$$

where σ is the Stephan-Boltzman Constant, T_a is the ambient temperature, r is the radius of the droplet, ρ is the density of the droplet, and C is the heat capacity of the lava. Since the droplets should quench to glass, there is no latent heat of crystallization. After finding that the cooling is not sensitive to the exact value of the background temperature, we used the average surface temperature of Io, -170 °C.

Application to Observations: Of course, there is no practical way to observe the cooling of an individual droplet in a lava fountain. Instead, we must look at the integrated thermal emission from the entire fountain. For application to the Galileo SSI images, we are interested in both the "brightness" and "color" temperatures. The brightness temperature is related to the observed intensity of the fountain in a single filter while the color temperature is computed

from the ratio of the intensities seen through two different filters.

Both types of temperatures can be modeled by convolving the spectral response of the camera with the thermal emission from a fountain that has droplets of all ages (Fig. 1). The SSI camera is relatively insensitive to incandescence from surfaces <600 °C, providing a practical limit for range of droplet temperatures to consider in this calculation. After modeling a wide range of eruption temperatures and droplet sizes, it was found that a good fit between SSI color temperature (from the clear and 1-micron filters) and eruption temperature is provided by the simple linear relationship:

$$T_o = (1.29\ T_c) - 165$$

where T_o is the eruption temperature, and T_c is the SSI clear to1-micron color temperature expressed in °C. This equation is valid for T_o=1200-1600 °C. The response of the Galileo SSI and Cassini ISS cameras are similar enough that this fit should also be applicable to color temperatures derived from ISS.

No such simple fit can be made to the single filter brightness temperatures because brightness temperatures are affected by both the droplet size and the timescale being considered.

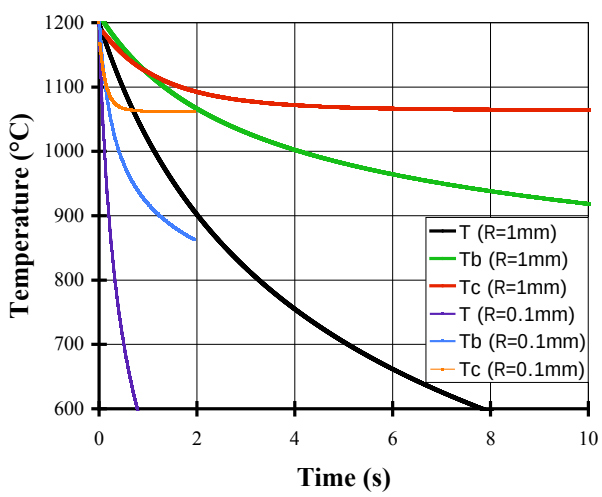

Figure 1. Modeled droplet temperatures (T), SSI clear/1micron filter color temperatures (T_c), and SSI clear filter brightness temperatures (T_b). Note that because the brightness and color temperatures are the integrated flux from droplets of a range of ages, they are always hotter than the coolest individual droplets. Droplets cooler than ~600 °C reduce the observed incandescent flux seen through the clear and 1-micron filters in a proportional manner. Therefore, these dark, cold clasts reduce T_b but not T_c.

Implications for eruptions at Pillan, Pele, and Tvashtar: Using the ≥1200 °C SSI color temperature from [1] for the 1997 outburst at Pillan, we estimate an eruption temperature ≥1380 °C, compared to the ~1600 °C originally reported. In further evaluating the uncertainties in this observation, we find that color temperatures down to 1100 °C (and eruption temperatures of 1250 °C) are allowed by the SSI data. The SSI and ISS color temperatures at Pele (~1000 °C [4, 13]) suggest an eruption temperature of ~1125 °C, rather than the 1400-1600 °C initially estimated [4]. In both cases, we are continuing to evaluate the longer wavelength NIMS data to more fully test these lower eruption temperatures.

In the case of the Tvashtar lava fountains, the only temperature constraint is a clear filter brightness temperature of ~1000 °C. Taking the observation that the incandescent zone is ~1 km tall, and that the pyroclasts were traveling at ~500 m/s [17], we should be looking at ~2 seconds of cooling. Our simple model fits this with lava droplets ~0.25 mm in radius and an eruption temperature of ~1300 °C. Inputting this particle size into the results of [17] indicates an eruption rate of ~3.5 $m^3\ s^{-1}$ per meter of fissure, similar to vigorous terrestrial lava fountains.

Conclusions: Our ongoing evaluation of the highest reported temperatures from Io continue to be consistent with an upper mantle temperature close to 1200 °C. However, further improvements are still needed to (1) fully evaluate uncertainties in the data, (2) model the ascent of magma through Io's unique crust, and (3) better model thermal emission from active volcanism.

References: [1] McEwen, A. S., et al. (1998) *Science, 281*, 87-90. [2] Davies, A. G., et al., (2001) *JGR, 106*, 33079-33104. [3] Lopes, R., et al. (2001) *JGR, 106*, 33053-33078. [4] Radebaugh, J., et al. (2004) *Icarus, 169*, 65-79. [5] Kargel, J., et al. (2003) *EOS, 84*, 313-318. [6] Keszthelyi, L., et al. (2004) *Icarus 169*, 271-286. [7] Consolmagno, G., (1981) *Icarus, 47,* 36-45. [8] Lewis, J. S., (1982) *Icarus, 50*, 103-114. [9] Ross, M. N., and Schubert, G., (1985) *Icarus, 64*, 391-400. [9] Ojakangas, G. W., and Stevenson, D. J. (1986) *Icarus, 66*, 341-358. [10] Moore, W. B., (2003) *JGR, 108*, 2002JE001943. [11] Monnereau, M., and Dubuffet, F., (2002) *Icarus, 158*, 450-459. [12] Keszthelyi, L., et al. (2005) *LPS 36*, Abstract #1902. [13] McEwen, A. S., et al. (2000) *Science, 288*, 1193-1198. [14] Milazzo, M., et al. (2005) *Icarus, 179*, 235-251. [15] Davies, A. G., et al. (2005) *Icarus 176*, 123-137. [16] Hopper, R. W., et al. (1974) *Proc. 5th Lun. Conf.*, 2257-2273. [17] Wilson, L., and Head, J. W., (2001) JGR, 106, 32997-33004.