LAVA FLOWS ON IO: MODELLING COOLING AFTER SOLIDIFICATION

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Introduction: We have modeled the cooling of lava bodies on Io after solidification of the lava, a process that has been little explored since Carr (1986) [1]. With recent estimates of lava flow thicknesses on Io ranging from 1 m to 10 m [2, 3], the modeling of thermal emission from active volcanism must take into account the cooling behaviour after the solidification of the lava, which we model using a finite-element model [4]. Once a lava body is fully solidified, the surface temperature decreases faster, as heat loss is no longer buffered by release of latent heat [5]. This is significant as observed surface temperature is often the only clue available to determine lava surface age. We also find that cooling from the base of the lava is an important process that accelerates the solidification of a flow and therefore subsequent cooling. It is necessary to constrain the cooling process in order to better understand temperature-area relationships on Io's surface and to carry out stochastic modelling of lava flow emplacement.

Cooling to lava solidification point: Models of cooling and thermal emission from emplaced lava bodies [1, 6-8] have been applied to remotely-sensed thermal emission data of volcanism on Io. Since temperature is a monotonic function of age, these models have a similar distribution of temperatures. The oldest material is therefore at the coolest temperatures, and by integrating over the entire area of the lava body the temporal evolution of thermal emission and the integrated emission spectrum can be modeled. The observations of thermal emission can be fitted with these model outputs. The models in [6-8] treat lava bodies as semi-infinite half-spaces, with heat lost from the upper surface, with the lava solidifying from the upper surface downwards. While this approach is acceptable for deep lava bodies such as lava lakes, lava flows in all physical cases have finite thicknesses. From the time at which the lava body is completely solid, cooling proceeds at a faster rate, and the aforementioned flow models can no longer be applied.

Additionally, a lava flow cools both from the top and base. A stagnant lava flow will solidify from the base upwards, as well as from the top downwards. Base-crust formation further reduces the time over which the cooling models can be applied.

Cooling after solidification with finite-element modelling: We use the Schmidt graphical method, adapted for the cooling of lava flows on Io [4]. Here, the differential forms of the Fourier equation for the conduction of heat are replaced with finite differences [e.g., 9]. We call the resulting model **CAS**, for Cooling After Solidification. The CAS model requires selection of a primary lava composition. Analysis of Galileo data indicates that the primary lavas on Io are silicate in composition. The CAS model has been run on both basaltic and ultramafic compositions and for different flow thicknesses using thermo-chemical values from [10]. The resulting cooling curves for 1 m, 10 m and semi-infinite ultramafic lavas are shown in Figure 1.

Temporal differences between models: The difference between the 'buffered' (semi-infinite case) and 'non-buffered' models becomes apparent when cooling times are compared. The time taken for a 1 m thick ultramafic flow to reach 150 K is 240 days, using the CAS model, and a 10 m thick flow surface reaches 150 K after 4733 days (13 years). The semi-infinite ultramafic case takes 74,800 days, or 205 years, to reach this temperature, needing a minimum slab thickness of 77 m, the depth of penetration of the solid/liquid interface.

Effect of flow thickness and composition on cooling: The thicker the flow, the longer the time taken for the flow to solidify, and the longer the time taken to reach a target temperature. Basalt flows cool faster than ultramafic flows. For example, a flow 10 m thick cooling from base and top surfaces solidifies in 362 days if basaltic (with an upper surface temperature of 262 K at the point of solidification), and 445 days if ultramafic (with an upper surface temperature at 280 K). The surface temperature of the flow takes a further 1070 days to cool to 200 K if basalt, and 1314 days if ultramafic, a difference of 326 days. This difference increases as surface temperature decreases. From emplacement time it takes the 10 m thick basalt flow 16 years to cool to 130 K, and 66 years for the ultramafic flow to cool to the same temperature.

Model output comparison with observational data: The 1997 Pillan flows were observed in late 1999 and early 2000 by the Galileo Photo-Polarimeter Radiometer [11]. The Pillan 1997 flows had already been determined to be 8-10 m thick [2]. The CAS basaltic outputs for 8 and 10 m thick flows are within the PPR error bars (220 K +/-20 K), while the ultramafic 8 m model is slightly outside this range (18 K too warm). Physically, this might be explained if the bulk of the flows at Pillan were slightly thicker than the 8-10 m derived from SSI data of one point: a small increase in thickness, ~1 m, or less than 10%, would bring the modelled temperatures into parity with the observed temperatures. Other possible technical reasons for this small discrepancy include (1) the model thermo-physical input parameters need adjusting; (2) the PPR-derived temperature came from long-wavelength IR data which was not sensitive to hotter surface areas; and (3) the actual surface temperature distribution is more complicated than the model predicts.

However, and whatever the case, fine-tuning of the model input parameters will allow application of the model generally over the surface of Io.

Future modifications: Future modification of the model will include variations in physical properties of lava due to temperature change; an exploration of parameter space for basaltic and ultramafic compositions; the effects of thermal gradient and effects from multiple (layered) flows, and thec effects of the condensation of sulphur and sulphur dioxide on the flow surface.

Discussions: The application of the finite element cooling model allows cooling after solidification to be modeled. Our first attempts to use this model produce close fits to observed data. Refinement of input parameters can proceed from this point to more closely reproduce observations. Thin flows (such as those seen at Prometheus) solidify and subsequently cool much faster than thick flows do (such as the Pillan 1997 flows). On the surface of Io, flows of basaltic composition cool faster than flows with ultramafic composition. Active lava lakes (Pele, and possibly Loki) exhibit periodic overturning, resetting the surface temperature and cooling clock, and then cooling until the next overturn or disruption event. Complete solidification and subsequent cooling of a stagnant lava lake or ponded flow should also be diagnostic, and determinable from a time series of observations of thermal emission. The same techniques can be applied to terrestrial datasets, obtained from Earth-orbiting platforms (such as ASTER on Terra, and the Hyperion spectrometer on EO-1), from aircraft (for example, TIMS), as well as from *in situ* field observations, so long as different compositional and environmental changes are input. Finally, this approach allows a more stochastic approach to modelling the emplacement of lava flows on Io. Freed from a cooling model limited in its temporal utility, it is possible to calculate the subsequent thermal behaviour of a flow for any set of input parameters (flow composition, flow thickness, subsurface composition and sub-flow thermal gradient). Integrating the model across the flow's areal extent allows the integrated thermal emission from a flow unit to be modeled and the thermal evolution to be determined. Flows can be erupted one on top of another and the resulting heat flows determined. The heat flow characteristics of the material can be changed to reflect those properties of the lavas chemistry and heat transfer properties that change as a function of temperature.

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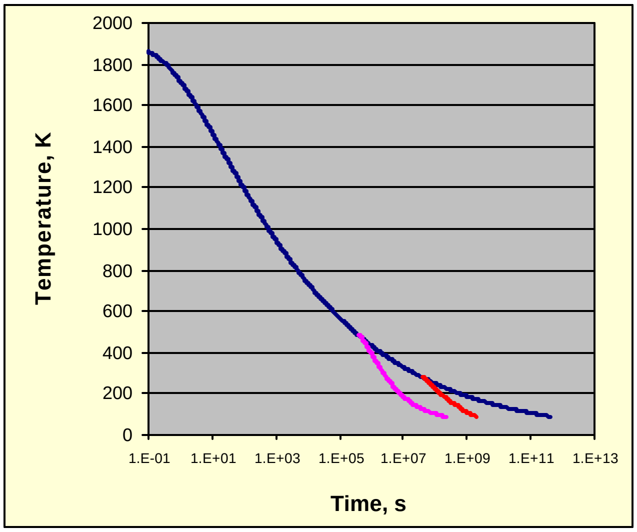

Figure 1. Cooling of ultramafic lavas on the surface of Io. Cooling for all cases follows the blue curve (semi-infinite slab case) until the unit is completely solidified. Cooling after solidification as determined using CAS is shown for 1 m thick (purple line) and 10 m thick (red) flows.