DETERMINING LAVA ERUPTION TEMPERATURE ON IO USING REMOTE SENSING: TECHNIQUES, REQUIREMENTS, AND TARGETS FOR A NEW IO MISSION.
A. G. Davies[1], L. P. Keszthelyi[2], and A. S. McEwen[3]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (Ashley.Davies@jpl.nasa.gov). [2]USGS Astrogeology Science Center, Flagstaff, AZ 86001, USA. [3]University of Arizona, Tucson, AZ 85721, USA.

Introduction: One of the most important questions raised in the wake of the *Galileo* mission to Jupiter is that of the composition of the dominant silicate lavas on intensely volcanic Io [1-4]. Some spacecraft and ground-based data have been interpreted to suggest that high-temperature ultramafic lavas have erupted at some locations. Such lavas are the result of a high degree of mantle melting, at higher temperatures than for basalts. As the degree of melting within Io is intimately linked to the location and magnitude of tidal heating, determining lava eruption temperatures is a high priority for any Io-dedicated mission. One way of constraining composition is by measuring the temperature of the lava as it erupts. As noted previously (e.g., [3]), this is not a simple task using only remote-sensing data. To differentiate compositions based on remote observations of temperature requires the careful identification of areas where the highest temperatures can be isolated. This depends on the style of volcanic activity – how lava is physically erupted and emplaced on Io's surface – which can be modeled with multispectral infrared observations, even at low spatial resolutions. Models of thermal emission based on eruption style are then used to determine the temperature and area distribution present. Only certain styles of volcanic activity are suitable, those where thermal emission is from a restricted range of surface temperatures close to eruption temperature. Such processes include large lava fountains [1]; fountaining or vigorous overturn in lava lakes [2]; lava tube skylights [3]; and transient explosions [5]. Eruption characteristics are given in Table 1.

Overcoming observation uncertainties:

Problems… [6, 7]*:* (1) Lava surface temperatures can change very rapidly, potentially more quickly than typical observation integration times and/or the time between acquiring data at different wavelengths. (2) The intensity of thermal emission from Io's volcanism is so much higher than even sunlit scenes that detector saturation is a common problem.

…and solutions [6, 7]*:* (1) Acquire data quickly! Monitoring at 60 Hz in a clear bandpass establishes thermal source stability - if stable, the temperatures derived from colour data acquired at ~0.1-1 second separations will be robust. (2) Focus attention on eruption styles that provide more stable high temperatures (i.e., skylights – see Table 1). (3) Collect data at a variety of wavelengths so the hottest lavas in the scene are not saturated in the shorter wavelengths, while cooler active lavas are still imaged at the longer wavelengths (also yielding the full temperature and area distributions at each location).

We can achieve these solutions by careful instrument and observation design, informed by knowledge of Io's varied styles of volcanic activity, ranging from massive thermal outbursts (e.g., [7]) down to individual lava tube skylights [3].

Recognising useful volcanic eruption styles:

Estimation of lava eruption temperature from remote sensing relies on imaging eruptions where sufficient area at peak temperatures are exposed, even where sources are sub-pixel [7]. Different eruptions have different spectral radiance spectra and magnitudes of thermal emission that can span over six orders of magnitude [6,7]. Desirable eruption styles are shown in Table 1, with some pros and cons. Figures 1 and 2 show how target eruption styles and processes are constrained from measurements of thermal emission at two different wavelengths. Figure 1 shows the magnitude of different eruption types seen on Io. The desirable styles of activity lie within the red ovals, and are described below.

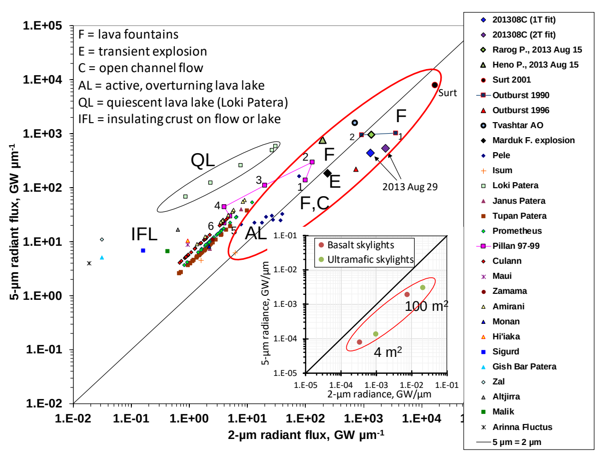

Figure 1: 2- and 5-µm radiant fluxes are used to constrain desired eruption styles. Ratios of other wavelengths also show the same constraints [7]. *The eruption styles in Table 1 fall into the defined areas (red ovals). The inset image shows the modelled thermal emission from lava tube skylights* [3]. *See also* [6, 7].

Prime eruption candidates range from Io's powerful "outburst" eruptions, probably large (>1 km high) lava fountains erupting from rifts, and high-temperature areas exposed by fountaining in lava lakes. The issue with fountains is their temporal variability, which can introduce significant uncertainty in the temperature derivations. The most thermally stable targets are lava streams within highly insulating lava tubes, as imaged through skylights. Lava tubes are likely common on Io as a means of transporting lava great distances (>100 km) at centers such as Amirani, Culann and Prometheus, and *Galileo* data suggest the presence of such skylights. There is a very narrow range of surface temnperatures exposed in a skylight; and thermal emission is stable on a time scale of seconds to hours. If the lava stream is directly observed, a robust temperature constraint can be obtained with data at visible and short infrared wavelengths [3,6].

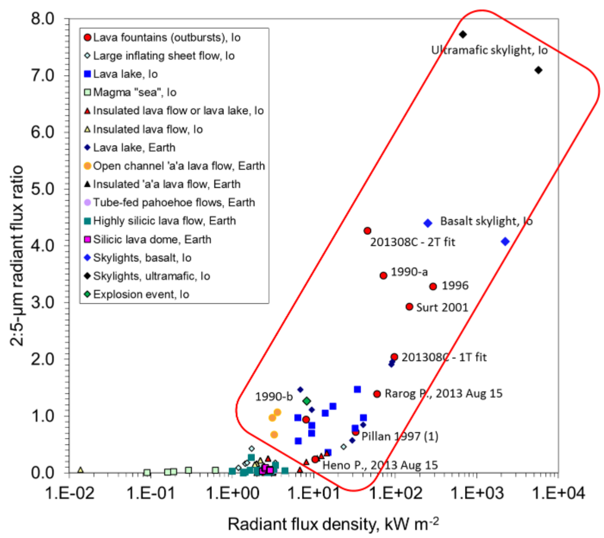

Figure 2: Eruption style is starkly identified by examining radiant flux density against (for example) 2-µm/5-µm ratio. Active lava lakes, lava fountains and skylights, and the Marduk Fluctus explosion event [5] *stand out. Lava fountains are transient; active lava lakes are persistent. The narrow, very high temperature range seen through skylights yields the highest radiant flux densities, and are the best candidates for constraining lava temperature. The stability of thermal emission over minutes removes the necessity of near-simultaneous observations at different wavelengths.*

Conclusions: Previous missions that encountered Io were prevented from robust measurement of eruption temperature due to a lack of knowledge of what was being observed, extreme range to target, instrument degradation, and a generally hostile environment that is now better understood due to the success of these aforementioned previous missions, in particular, *Galileo.* We conclude that **a new mission to Io**, such as the *Io Volcano Observer* concept [8], with instrumentation expressly designed to handle Io's unique eruption volcanoes, will answer the outstanding questions about the current state of Io's interior, and the processes affecting tidal heating of planetary bodies in general. Spectroscopy can also be used to constrain composition, for example, by examining Christiansen Feature position to determine silica content [9].

The mapping of lava eruption temperatures at different locations across Io would reveal the underlying patterns of magma generation and degree of mantle melting, vital to understanding the tidal heating process within Io, and the influence of Io in the evolving tidal resonance with Europa and Ganymede.

Acknowledgements: This work was performed at the Jet Propulsion Laboratory-California Institute of Technology, under contract to NASA.

References: [1] Davies, A. G. et al. (2001) *JGR*, 106, 33079-33104. [2] Keszthelyi, L. P. et al. (2007) *Icarus*, 192, 491-502. [3] Davies, A. G. et al. (2016) *Icarus*, 278**,** 266-278. [4] McEwen, A. S., et al. (1998) *Science*, 281, 87-90. [5] Davies, A. G. et al. (2018) *GRL*, 45, GL077477. [6] Davies, A. G. et al. (2017) *JVGR*, 343, 1-16. [7] Davies, A. G. et al. (2010) *JVGR*, 194(4), 75-99. [8] McEwen, A. S. et al. (2014) *Acta. Astron*., 93, 539-544. [9] Greenhagen, B. T. and D. A. Paige (2016) *LPSC XXXVII*, abstract 2406.

IO VOLCANO OBSERVER

Pre-decisional mission concept: see [8]

Table 1: Desirable styles of volcanic eruptions (see [5,6,7])			
Eruption style	Description	Targeting	Cons
Lava fountain	Extremely powerful (often ≥10 TW); Detectable from Earth.	Aim at: base of fountain Bracket exposure	Rare; detectors saturate; unpredictable, short-lived
Active lava lake	Powerful (500 GW); Detectable from Earth; Long-lived; predictable; unmoving	Aim at: fountains in lake, possibly at base of plumes	Lava lake *has* to be active; resurfacing has to be vigorous
Lava tube skylight	Very small (~few m across) but powerful; may be common on Io. Temporally very stable (mins-hours+)	Aim at: lava stream	Relatively small targets
Volcanic explosion [5]	Powerful (> 1 TW), so easily detected	High-temporal resolution monitoring of Io to catch event	Transient, unpredictable, possibly rare