IDENTIFICATION OF A SHORT-LIVED STROMBOLIAN-LIKE THERMAL EVENT IN *GALILEO* NIMS DATA OF MARDUK FLUCTUS, IO.
A. G. Davies[1], R. L. Davies[2], G. J. Veeder[3], K. de Kleer[4], I. de Pater[5], D. L. Matson[3], T. V. Johnson[1]. [1]Jet Propulsion Laboratory-California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA; Ashley.Davies@jpl.nasa.gov). [2]Oxted School, Bluehouse Lane, Oxted, Surrey, UK. [3]Bear Fight Institute, Winthrop, WA, USA. [4]California Institute of Technology, Pasadena, CA, USA. [5]University of California Berkeley, Berkeley, CA, USA.

Introduction: New analysis of *Galileo* Near Infrared Mapping Spectrometer (NIMS) observations of Marduk Fluctus, an Ionian volcano, reveals a style of volcanic activity not previously identified on Io – a very short-duration (a few minutes), powerful thermal event. The thermal emission rapidly fades, suggesting extremely rapid cooling of small clasts. The duration and evolution of the eruption is akin to what might be expected from a strombolian-like explosion. The presence of such events provides an additional volcanic process that can be imaged with the intent of determining lava composition from lava eruption temperature, an important constraint on Io's internal state [1] and will yield deeper insight into Io's volcanic processes.

***Galileo* NIMS:** The *Galileo* Near Infrared Mapping Spectrometer (NIMS) [2] was well-suited to measuring the thermal emission from Io's volcanoes, being sensitive to surface temperatures from ~220 K to >1000 K [3]. The acquisition and processing of NIMS radiance "tube" and "cube" data is described elsewhere [4]. 27 observations of Io were obtained between 17 and 19 December 1997 during *Galileo* orbit E4. Many of these observations were designed to look for short-term variation in volcanic thermal emission.

Observations: Six usable NIMS observations of Io obtained on 18 and 19 December 1997 included the location of the persistent Marduk Fluctus volcano (209.9º W, 28.4º S). The first observation (e4i007tr) included the Marduk region in daylight, at a spatial resolution of 160 km/pixel, and at an emission angle of 24.3º. Radiance was measured at 96 wavelengths. The other usable data were nighttime observations obtained at spatial resolutions from 376 to 453 km/pixel, and at emission angles of 69.4º to 77.8º. Spectral resolution was low, with measurements at 10 to 12 wavelengths spread evenly across the NIMS wavelength range.

Analysis: NIMS data can, typically, be fitted accurately with a two-temperature, two-area thermal emission model (see [4]). Figure 1 shows the evolution of the thermal event. Data were fitted three ways. Firstly, all data are corrected for emission angle. This represents the upper limit of thermal emission. Secondly, the data showing the thermal spike (e4i017tr, e4i018tr and e4i019tr) are not corrected for emission angle; and thirdly, the thermal spike data are not corrected for emission angle and have the emission angle corrected e4i007tr "pre-event" spectrum subtracted to isolate the spike thermal component; this is the lower boundary of the event thermal emission. The resulting spectra are shown in Figure 1.

Considering data that are corrected for emission angle, within the 136 minutes between observations e4i006tr and e4i017tr, thermal emission increased by more than an order of magnitude at all wavelengths. In the next two minutes and two seconds, between e4i017tr and e4i019tr, thermal emission dropped rapidly, mostly at wavelengths between 3.5 and 5.2 µm. There was an increase in the peak of thermal emission from 2.7 µm for e4i017tr, suggesting an effective brightness temperature T_{eff} of 1035 K (using Wien's Law) to 2.4 µm for e4i018tr (T_{eff} = 1207 K) to 1.8 µm for e4i019tr (T_{eff} = 1610 K). As two-temperature, two-area fits may underestimate the temperature of the hottest areas present; the actual eruption temperature may be well in excess of 1600 K, which would suggest an ultramafic lava composition. Over the same time interval, the hot component area mirrors the rise and fall of thermal emission starting at a fraction of a km^2, rising to an area of 11 km^2, then rapidly decaying to an area of less than 1 km^2 again. After another 23 minutes, thermal emission across short NIMS wavelengths dropped below the pre-event background level at short NIMS wavelengths.

However, at wavelengths longer than 4 µm, a slope develops in the data suggesting an additional larger, cool component is present, one that was not present in the e4i006tr observation. The measured spectral radiance demonstrates a shift in the peak in thermal emission to longer wavelengths (indicating a lower temperature) from e4i019tr to e4i025tr. The e4i019tr data suggest a rapidly dwindling hot area and a new, large, cool area which is still detectable in the e4i025tr data. We note that the model fit to the e4i019tr and e4i025tr data are poorly constrained because of scatter in the sparse data. Fitting the upper boundary of the e4i025tr data yields a cool area of 2000 to 10,000 km^2 at 290 K. This might be a cool plume or blanket of small pyroclastics resulting from the explosion.

Discussion: The radiance from this event changes more rapidly than has been previously seen on Io [e.g., 9-11]. The increase in short wavelength thermal emission can be explained by the exposure of incandescent lava erupting at temperatures well in excess of 1000 K. It could be caused by a new outbreak of lava; a lava fountain issuing forth from a fissure; fountaining in a lava lake; or the rapid overturning and replacement of crust in a lava lake. All of these processes generate strong increases in short wavelength thermal emission [3]. However, this thermal spike is unique in as much as the thermal emission decayed to the pre-event level very quickly (a few minutes). Newly exposed incandescent lava initially cools very rapidly, but the rate of cooling slows as temperature decreases. On Io, basalt cools from 1475 K to 1100 K in about a minute and to 1020 K in two minutes, but it takes another 1.6 hours to cool to 700 K and another 32 hours to cool to 500 K [4]. The thermal signal in the E4 data reverted to the pre-event background level in no more than 23 minutes (the time between e4i017tr and e4i025tr). The replacement of the crust on a lava lake does not cool fast enough to explain the data. The eruption of a new lava flow would have to be very brief (< a few minutes) and still cover multiple km^2 before abruptly stopping – and, again, would not cool fast enough to depress the thermal emission to the observed post-event level.

We propose that this event was a short-duration explosive event – a strombolian-like eruption. Strombolian explosions occur due to buildup in gas within the ascending magma which causes the magma to explode when internal pressure becomes too great to be contained. On Io, as magma ascends through the lithosphere, it will thermally interact with interbedded layers of pyroclastic material, lava flows and plume deposits rich in SO_2 and S, and may therefore add volatiles to any primary volatiles already present in the magma [5]. Such activity probably took place on the early Moon [6]

Given the low spatial resolution of the data, it is not known with certainty if the eruption took place at Marduk Fluctus. However, regardless of location, the detection of this type of explosive activity means that another volcanic process has been identified that designers of Io instruments and missions need to be aware of as a suitable target for determining the eruption temperature of Io's silicate lava. Such a determination would require unsaturated data of such events to be acquired simultaneously (or within ≈0.04 s – see [7,8]) at multiple visible and/or SWIR (≤ 1.5 µm) wavelengths. The chances of observing future events are good as this was a powerful eruption identified in low spatial resolution data at a great distance from Io. We are searching for similar hidden gems in the NIMS Io dataset.

Summary: This explosive event evolved on a much faster time scale than other volcanic processes observed by NIMS, and occured on a shorter timescale and smaller areal scale than the much larger and more powerful "outburst" eruptions, characterized by fountains feeding lava flows [12]. This smaller class of outburst-like eruptions may be more common [13] than outbursts. We note that the temporal resolution of the NIMS data, extraordinary as it is, leaves open the possibility that the peak of thermal emission was not seen. NIMS constrains the onset of the event to within ≈two hours. We do not know how big this event might have been, or how rapid the waxing phase was – but we do observe that the thermal source decayed very fast. An event of this type may be suitable for determining lava eruption temperature by suitable instruments on spacecraft, even at hundreds of thousands of kilometers from Io, if correctly imaged.

Acknowledgments: This work was performed at the Jet Propulsion Laboratory – California Institute of technology, under contract to NASA. © 2018 Caltech. AGD thanks the NASA Outer Planets Research Program for support.

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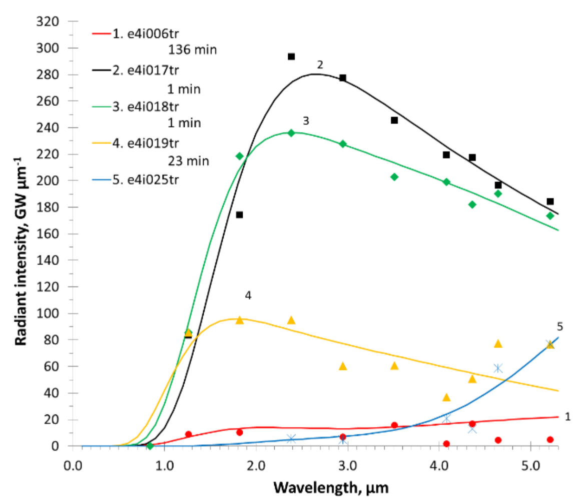

Figure 1: Galileo *orbit E4 NIMS radiances from Marduk region (symbols) and thermal emission spectra (solid lines) synthesized from the best two-temperature, two-area fits to the data. Numbers refer to the order in which the observations were obtained. Time in minutes between observations is also shown. The data shown here are corrected for emission angle. The rapid decay in thermal emission suggests the cooling of small clasts.*