Identification of a Short-Lived Strombolian or Vulcanian Thermal Event at Marduk Fluctus, Io, using *Galileo* NIMS Data

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Key Points:

- We identify a powerful, short-lived thermal event in the vicinity of Marduk Fluctus in *Galileo* NIMS Io data.
- The temporal evolution of this event is consistent with an explosion, with rapid cooling suggesting the generation of small clasts.
- Similar events imaged from spacecraft will constrain lava eruption temperature if data are obtained simultaneously at multiple wavelengths.

Abstract

Analysis of *Galileo* Near Infrared Mapping Spectrometer (NIMS) observations of Marduk Fluctus, a volcano on the jovian moon Io, reveals a style of volcanic activity not previously seen there – a powerful thermal event lasting only a few minutes. 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 or vulcanian explosion. The presence of such events provides an additional volcanic process that can be imaged with the intent of determining lava composition from eruption temperature, an important constraint on the internal composition of Io. These data promise to be of particular use in understanding the mechanics of explosive volcanic processes on Io.

1 Introduction

The highly-volcanic jovian moon Io exhibits many different modes of eruption and emplacement of lava onto the surface (e.g., Davies, 2007; Davies et al., 2010). Observed and implied styles of eruption are similar to those seen on terrestrial basalt volcanoes (active, overturning lava lakes; pahoehoe-like insulated flows; open-channel flows; lava fountaining) (Davies, 2007). Ionian volcanic activity is typically on much larger areal and volumetric scales than contemporary terrestrial eruptions. Observations of thermal emission from Io's erupting volcanoes can be used to constrain the composition of Io's lavas (Davies et al., 2001; 2017; McEwen et al., 1998). This is important as the composition of the erupting lava reflects the degree of melting in the upper mantle (Keszthelyi et al., 2007), which is a direct consequence of the depth and magnitude of tidal heating due to the Laplace resonance. However, only eruption styles that reveal relatively large areas at temperatures very close to the eruption temperature are suitable for this purpose. The best targets for instruments on spacecraft flying close to Io include targets such as the bases of lava fountains (Keszthelyi et al., 2001) and the lava stream within a lava tube as viewed through a skylight (Davies et al., 2016). *Galileo* Near Infrared Mapping Spectrometer (NIMS) data obtained in 1997 but only recently examined in detail reveal another process that may be used for determining eruption temperatures: transient, short-wavelength thermal events reminiscent of a large eruption on Io's surface. Such an event was observed at or near to the active volcano Marduk Fluctus.

2 Observations

2.1 *Galileo* NIMS and observations of Io

The *Galileo* NIMS instrument (Carlson et al., 1992) was well-suited to measuring the thermal emission from Io's volcanoes, as the 0.7 to 5.2 μm wavelength range meant that NIMS was sensitive to surface temperatures from ~220 K to >1000 K (Davies et al., 2010). The

acquisition and processing of the high-precision NIMS radiance data is described in detail by Davies (2007). NIMS obtained 190 Io observations between 1996 and 2001. 27 observations of Io were obtained during *Galileo* orbit E4 between 17 and 19 December 1997. Many of these observations were designed to look for short-term variations in volcanic thermal emission. Six observations of Io obtained on 18 and 19 December 1997 covered much of the trailing hemisphere of Io (180º W to 360º W), including the location of Marduk Fluctus (209.9ºW, 28.4ºS), a powerful and persistent volcano. Planetary Data System NIMS raw radiance "tube" products were used to measure radiance, and "cube" products, which have improved navigation, to identify hot spots (e.g., Davies et al., 2012).

2.1.1 Marduk Fluctus

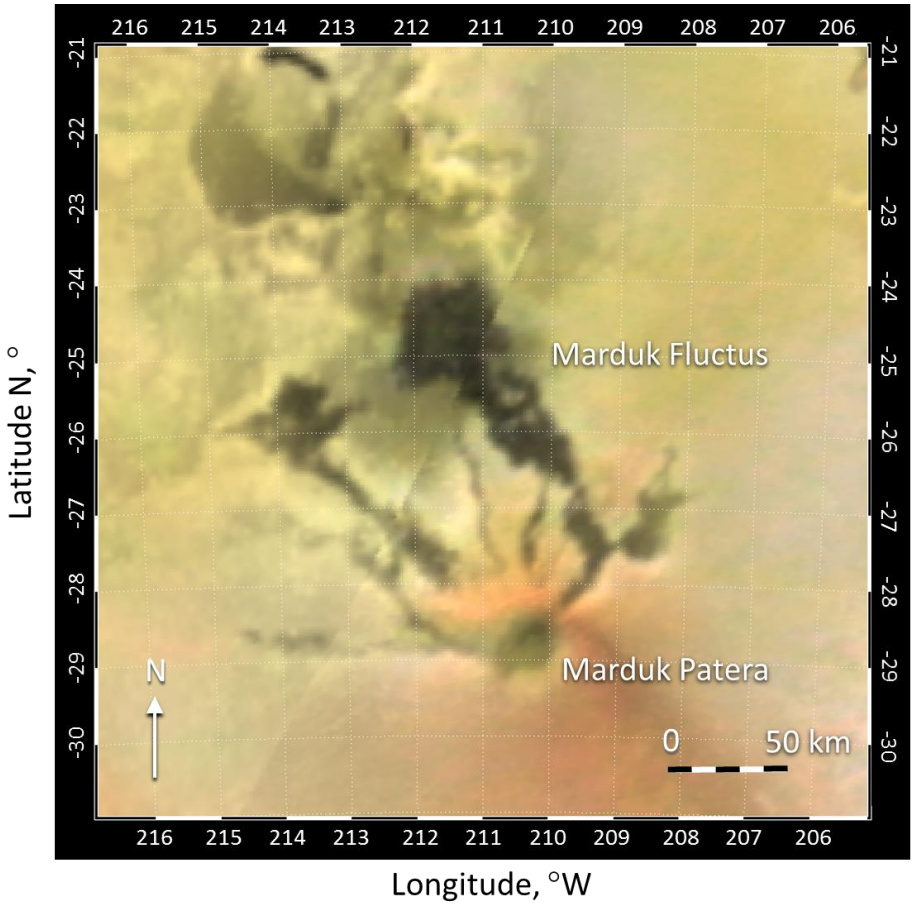

Figure 1. The Marduk Fluctus volcanic complex as seen by the *Galileo* Solid State Imaging experiment. Flows originate in a patera (a caldera-like volcanic depression) in the south of the image and flow northwards. The reddish deposit is rich in sulfur. This image is taken from the Io global mosaic of Becker and Geissler (2005).

Marduk Fluctus (Figure 1) has an extensive flow field identified early in the *Galileo* mission at Jupiter as a thermal source by both the *Galileo* Solid-State Imaging experiment (SSI)

(observation G1ISIOECLI02) (Belton et al., 1996; McEwen et al., 1997) and NIMS (Lopes-Gautier et al., 1997). The Marduk region was identified as a plume source in 1979 *Voyager* data (Strom et al., 1981), and SSI observed changes between the first two *Galileo* orbits in 1996. Marduk Fluctus has been identified as a thermal source in ground-based telescope data (e.g., de Pater et al., 2014b). SSI data show Marduk Fluctus as consisting of a series of at least six lava flows emanating from a patera and likely flowing downslope, consistent with the flows spreading laterally into a broad fan as the gradient decreases. Around the vent is a reddish plume deposit, likely rich in short-chain sulfur allotropes. The presence of these short-lived deposits is an indication of ongoing high-temperature (silicate) volcanic activity. The area is marked by what are presumably older flows which have cooled to the point where sulfur and SO_2 condense on the surface, yielding higher albedos than the active flows. The area of the young, black lava flows is ≈3600 km^2 (Veeder et al., 2009; 2012).

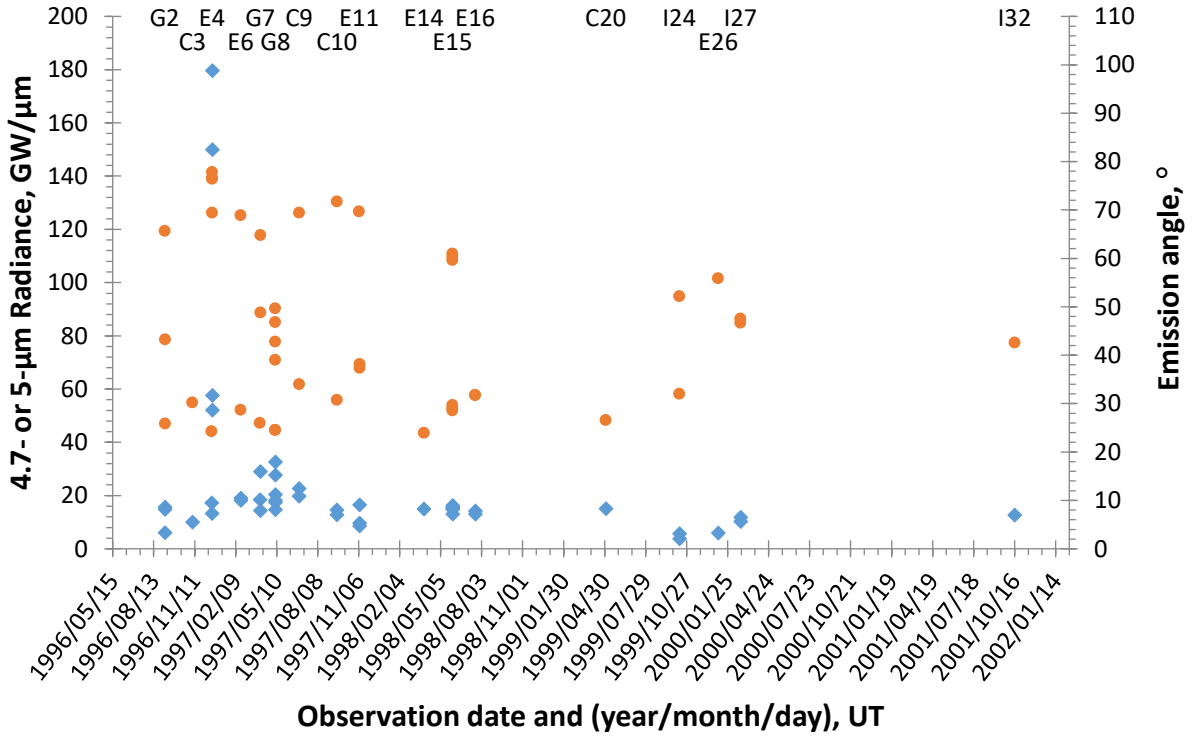

Figure 2. 4.7 or 5 µm radiances (blue diamonds), which are corrected for emission angle (angles shown as red circles) from NIMS observations that include Marduk Fluctus. *Galileo* orbit designations are also shown. The orbit E4 radiance values are unmatched, even in other observations taken at high emission angles.

2.1.2 Marduk Fluctus E4 NIMS observations

Between 1996 and 2001 NIMS obtained 44 Io observations that included Marduk Fluctus. Six E4 observations (see Table 1) were obtained where thermal emission was detected from Marduk Fluctus on 18 and 19 December 1997. Marduk Fluctus was in darkness in the five latter observations, which were made on the outbound portion of *Galileo*'s orbit. At a range of 319,480 km, spatial resolution was 160 km/pixel for the first, day-lit observation (e4i007tr), which had an emission angle of 24.3º. NIMS observation e4i007tr measured radiance at 96 wavelengths across the full NIMS range. The five usable nighttime observations were obtained at ranges from 752,083 km to 905,805 km, yielding 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. Poor spectral resolution is problematic as radiation-induced spikes in the NIMS data are often detectable by their deviation from other data close by in the spectrum. Also, problems with NIMS detectors 1 and 2 (< 1 µm) render these data unreliable. Where data have been fitted with the black-body thermal emission model (see below), an effort was made to ensure that most data fall on or below the resulting curve to maximize the integrated thermal emission (Davies, 2003). The uncertainty of the de-spiking and the inherent scatter within the e4i006tr and e4i025tr data reduces confidence in the temperature derivations such that a strong constraint on lava eruption temperature is not possible. However, the present analysis is based on the comparison of the overall shape of the thermal emission spectra and relative intensity of thermal emission from observation to observation, tasks for which the data are well suited. There was no clear detection of Marduk Fluctus in another nine observations obtained during E4 at high emission angles and low spatial resolution, especially where data were so heavily impacted by radiation as to render them unusable. Usable NIMS E4 Marduk Fluctus nighttime data are shown in Figure 3a.

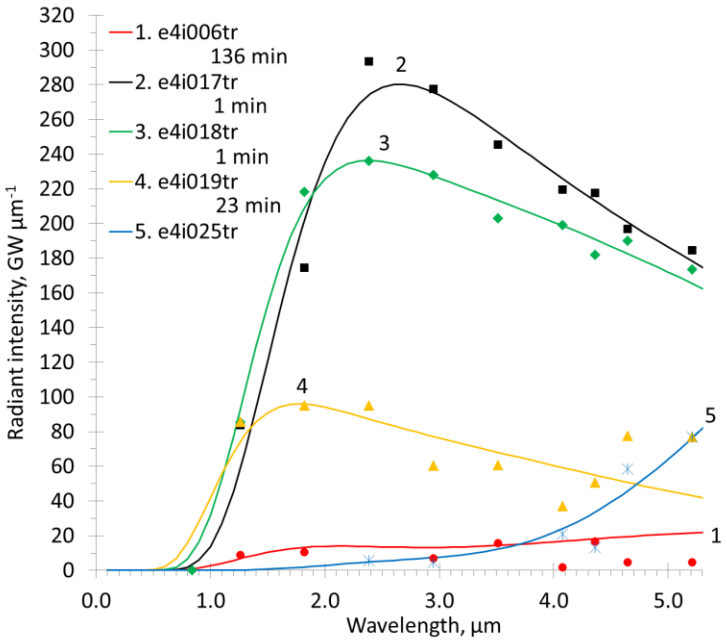

Figure 3a. Radiances from Marduk Fluctus (symbols) and thermal emission model spectra (solid lines) synthesized from the best two-temperature, two-area fits to the data using the temperatures and areas in Table 1. The numbers refer to the order in which the observations were obtained. Data are corrected for emission angle. The intervals between observations are also shown.

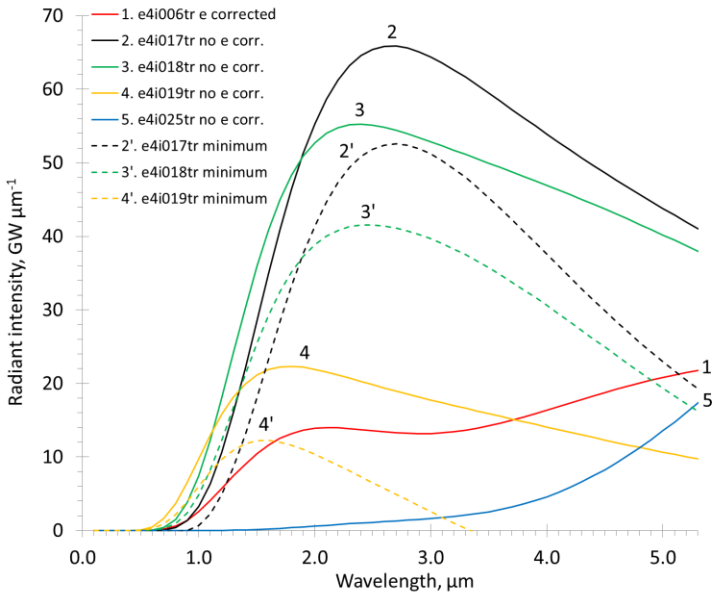

Figure 3b. Radiances uncorrected for emission angle *e* (solid lines). The lower boundary of thermal emission is obtained by subtracting the pre-event *e*-corrected e4i006tr radiance (1) from the uncorrected radiance spectra from the "explosion" observations (e4i017tr, e4i018tr and e4i019tr, denoted by 2', 3' and 4').

3 Methods

NIMS radiance data are processed by adding radiances from adjacent pixels to account for the NIMS point-spread function (e.g., Davies, 2007). Obvious radiation-induced spikes are removed. An emission angle correction is applied. If the thermal emission source was essentially a flat plate (a broad lava flow or a lava lake surface), and thermal emission was Lambertian, then dividing the radiances by the cosine of the emission angle would be appropriate to determine the actual emitting areas and thermal emission. However, as lava flows are not two-dimensional and thermal emission can be detected at emission angles >>70º, then the cosine correction may exaggerate the power and area of the thermal source. Additionally, if the thermal source was above the surface – a lava fountain, for example, or clasts from an explosion – then a cosine correction should not be applied. The suitability of applying the cosine correction in this particular case is discussed below. The NIMS data are fitted with a two-temperature, two-area ("2-T, 2-A") model (e.g., Davies et al., 1997; 2001). The model minimizes the residuals between the data and the model output. The resulting relatively small, hot area is the sum of the hot vent (if present), young lava surfaces including new lava breakouts, lava fountains, incandescent open

channel flows, and areas within a lava lake or pond where the crust is being disrupted. The lower temperature component, a much larger area in these cases, corresponds to the cooling and insulating crust that forms on lava flows and lava lakes.

4 Results

The NIMS data are mostly well constrained by the "2-T, 2-A" model. Figure 3 shows the evolution of the thermal event. Data are processed in three ways to account for uncertainty in the vertical extent of the lava (and hence the appropriate emission angle correction to use), and all three processed datasets are fitted with the 2T, 2A model (Table 1). 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 left uncorrected 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. This isolates the spike's thermal component from the background and is the lower boundary of the event's thermal emission. The resulting spectra are shown in Figure 3b.

Considering data that have been corrected for emission angle, at some time in 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 decreased 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 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 tracks 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 has dropped to 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 (suggesting a lower temperature) from e4i019tr to e4i025tr. The e4i019tr data suggest a rapidly dwindling hot area and a new, large, cool area that is still detectable in the e4i025tr data. We note that the model fits to the e4i019tr and e4i025tr data are poorly constrained because of scatter of the sparse data. It is apparent that some of the data are impacted by noise. We do not know which points are the noisy ones. Fitting the upper boundary of the e4i025tr data yields a cool area of 10,000 km^2 at 290 K. This might be a cool plume or blanket of small pyroclastics resulting from the explosion. We can only speculate as to what this

may represent. The lack of a 200-km diameter low-albedo (silicate-rich) deposit in subsequent *Galileo* imagery suggests that this deposit either does not exist or was buried under later, higher-albedo, sulfur-rich plume fallout. Fitting by weighting the lower data points between 3.5 and 5.2 μm yields a smaller cool component area covering 190 km^2 at 395 K. In any event, the low level of thermal emission in e4i025tr shows rapid cooling, consistent with the explosion hypothesis discussed below.

5 Discussion

The radiance from this event, with such rapid waxing and waning in radiance at all wavelengths and with such large variations in intensity, changes more rapidly than has been previously seen on Io (Blaney et al., 1995; Davies, 1996; Sinton et al., 1983). We can speculate as to what physical process generates this thermal signal evolution. 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. This could be caused by a new outbreak of lava, a lava fountain issuing 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 (Davies et al., 2010). However, the E4 thermal spike is unique with the thermal emission returning to the pre-event level very quickly (a few minutes). Newly exposed incandescent lava initially cools very rapidly, but the rate of cooling decreases 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 (Davies, 1996). The thermal signal in the E4 data reached the pre-event background level in no more than 23 minutes (the time between e4i017tr and e4i025tr). A replaced 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 would still not cool fast enough to depress the thermal emission to the observed post-event level.

The observations were obtained at high emission angles, and so thermal emission from the surface may be blocked by topography (e.g., de Kleer and de Pater, 2017; Radebaugh et al., 2002). The emission angle changed from 69.4º to 77.8º during the five E4 observations. The "background" level of thermal emission does decrease slightly at short wavelengths after the thermal event, but the emission angle difference is <2º from that of the peak of the eruption and so topographic control is unlikely. The thermal emission from the Marduk Fluctus lavas, likely from lava flows dominated by a relatively cool insulating crust, is visible at high emission angles and is therefore not shielded by topography. Likewise, if the thermal emission from Marduk Fluctus is emanating from a lava lake, then the lava lake surface is not topographically shielded either. Of the 40 other NIMS observations of this area, the thermal emission at 5 μm is constant at about 15 ± 6 GW/μm over a wide range of emission angles (excluding the E4 thermal event data). The E4 data cannot be explained simply by the emplacement of a new lava flow or the quiescent replacement of the crust in a lava lake.

The E4 event had to be caused by a different style of activity. We propose that this event was a short-duration eruption event – a strombolian or vulcanian explosion. It is unlike most terrestrial strombolian activity in as much as this appears to be a single event, and terrestrial strombolian eruptions are episodic. However, poor temporal resolution over much of the duration of the *Galileo* mission may have prevented other similar events from being detected; alternatively other such events simply have not yet been identified in the NIMS data.

Strombolian events are driven by the abrupt release of gas that has accumulated within the ascending magma when the pressure becomes too great to be contained. On Io, as magma ascends through the lithosphere, it can thermally interact with interbedded layers of pyroclastic material, lava flows and plume deposits rich in SO_2 and sulfur, and may therefore add volatiles to any primary volatiles already present in the magma (Leone et al., 2011).

Such explosions have been observed in the phonolite lava lake of Erebus volcano, Ross Island, Antarctica (e.g., Gerst et al., 2013). The contents of the lava lake, which in December 2005 was 38 m across (Davies et al., 2008), were entirely evacuated and disrupted into fragments. These fragments, ranging in size typically from mm to in excess of 1 m in diameter are ejected at velocities often exceeding 50 m/s (Gerst et al., 2013). In 2005-2006, bombs were distributed as far as 600 m from the lava lake (Gerst et al., 2008), and explosions occurred every 6 to 9 hours. After such an explosion, the lava lake quickly refilled and within a few minutes (as witnessed by the lead author), appeared as it did before the explosion.

An explosion in a lava lake can also be caused by the fall of material from the crater wall into the lava lake. This has been observed repeatedly at the lava lake that began forming in 2008 in Halema'uma'u, Kilauea volcano, Hawai'i. The lava lake enlarges through failure of the undermined walls of the pit in which it resides. Rockfall into the lake apparently triggers the abrupt release of volatiles in lava close to the surface, possibly by runaway decompressive vesiculation, leading to an explosion (Orr et al., 2013). The explosion, possibly exacerbated by the formation of a rebound-splash Worthington jet (Orr et al., 2013), and the generation of an ash cloud that includes juvenile tephra, is followed by powerful roiling of the lava until equilibrium is restored. Eventually, the lava lake surface temperature distribution returns to pre-eruption levels.

On Io, such a gas-driven explosion would be enhanced by the environment. The lack of a substantial atmosphere allows unrestrained expansion of the gas, increasing the fragmentation of the lava and increasing ejection velocity over a similar eruption on Earth. The lower gravity on Io increases the range (Wilson and Head, 1983).

Phreatomagmatic activity can also cause explosions on basaltic volcanoes. A rootless explosion may be caused by the thermal mobilization of surface ices underneath a thick lava flow. Such an explosion was observed during the Eyjafjallajökull, Iceland eruption in 2010 (A. Hoskuldsson,

pers. comm. 2010). In 1924 and 2008, ground water interacting with hot rock caused ash-rich explosions on Kilauea volcano, Hawai'i (e.g., Houghton et al., 2011; Mastin, 1997).

Rather than being strombolian, the explosion may be vulcanian in nature. Although vulcanian eruptions are generally associated with more viscous lava than basalt, the collection of gas-rich lava under the cooled crust of a lava lake or lava flow could build up pressure to the point that an explosion occurs.

An explosion of some kind best explains the *Galileo* orbit E4 NIMS Marduk Fluctus data. A powerful explosion would generate clasts that, if very small, would cool rapidly. On Io, a basalt clast of radius 1 mm would cool from 1480 K to 700 K in less than a minute (Keszthelyi et al., 2007), and would cool to 520 K in two minutes and to 290 K in just over 12 minutes. The explosive generation of small clasts, initially erupted at a liquidus temperature at or above 1400 K, would generate the observed thermal spike and subsequent rapid thermal decay as the clasts were widely dispersed and rapidly cooled. Similar small clasts formed during lava fountaining events that took place on the early Moon (Wilson and Head, 1981; 1983).

The emitted power P from each clast = $4\pi R^2 \sigma T^4$, where R is the clast radius, T is absolute clast temperature, and σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m K^{-4}). If R = 0.001 m and T = 1400 K, P = 2.73 W per clast. Estimates of radiated power from the event during e4i017tr are 1735 GW (cosine-corrected data); 256 GW (uncorrected data); and 29 GW (uncorrected, subtracting corrected e4i006tr data). Each clast has a volume of 4.12×10^{-9} m^3 and a mass of 1.09×10^{-5} kg, assuming a density of 2600 kg m^{-3}. Assuming we see radiation from half the clasts present, the volume of material ejected spans 89 to 5310 m^3 (mass = 2.31×10^5 to 1.38×10^7 kg). These volumes are orders of magnitude smaller than the volumes erupted (6-13 km^3) from larger, longer duration fire fountain eruptions elsewhere on Io (Davies et al., 2001; de Pater et al., 2014a).

Given the low spatial resolution of the data, it is not known with certainty if the eruption took place exactly at Marduk Fluctus, within Marduk Patera, or nearby. Rata Patera, another active volcano detected by NIMS, is located at 200°W, 36°S, and may contribute to the observed radiance in the high emission angle data. Nevertheless, Marduk Fluctus seems to be the most likely candidate, based on the constancy of thermal emission as seen in these and higher spatial resolution data. Regardless of exactly where this event took place, the detection of this style of activity means that another volcanic process has been identified that designers of future Io instruments and missions need to be aware of as a suitable target for determining the eruption temperature of Io's silicate lava. Such observations would require unsaturated data of such events to be acquired simultaneously (or within ≈0.04 s – Davies et al., 2011; 2017) at multiple visible and/or infrared (≤ 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 currently searching for similar hidden gems in the NIMS dataset.

Summary

This explosive event evolved on a much faster time scale than other volcanic processes observed by NIMS, and occurred on a shorter timescale and smaller areal scale than the much larger and more powerful "outburst" eruptions, characterized by fountains feeding lava flows (Davies et al., 2001). This smaller class of outburst-like eruptions may be more common (de Kleer and de Pater, 2016) 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 quickly (in a few minutes). Such an event may be appropriate for determining lava eruption temperature by instruments on spacecraft, even at hundreds of thousands of kilometers from Io, if correctly imaged.

Acknowledgments

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Table 1. Characteristics of NIMS E4 observations including Marduk Fluctus and boundary two-temperature, two-area model fits.

Observation	Observation id	Date, time	No. of NIMS λ	Range	Emission angle	Temp 1	Area 1	Temp 2	Area 2	Power area 1	Power area 2	Total power[a]
				km	°	K	km^2	K	km^2	GW	GW	GW
e4i007tr (1)	E4INHRSPEC01[b]	12/18/96 21:29	96	319480	24.3	284	3600	-	-	1328	-	1328
e4i006tr (1)	E4INCOOLCV02C	12/19/96 13:40	10	752083	69.4	1400	0.2	440	100	44	213	256
e4i017tr (1)	E4INWARMCV03A	12/19/96 15:56	10	880418	76.4	1144	10.8	496	201	1047	689	1735
e4i017tr (2)	E4INWARMCV03A	12/19/96 15:56	10	880418	76.4	1144	2.52	496	46.9	245	161	406
e4i017tr (3)[c]	E4INWARMCV03A	12/19/96 15:56	10	880418	76.4	1085	2.71	-	-	212	-	212
e4i018tr (1)	E4INWARMCV03B	12/19/96 15:57	10	881752	76.5	1332	4.2	567	142	741	834	1575
e4i018tr (2)	E4INWARMCV03B	12/19/96 15:57	10	881752	76.5	1332	0.98	567	33	175	193	368
e4i018tr (3)	E4INWARMCV03B	12/19/96 15:57	10	881752	76.5	1368	0.49	899	2.22	98	82	180
e4i019tr (1)	E4INWARMCV03C	12/19/96 15:58	10	882869	76.5	1722	0.5	714	15.0	238	221	459
e4i019tr (2)	E4INWARMCV03C	12/19/96 15:58	10	882869	76.5	1722	0.12	714	3.5	60	52	112
e4i019tr (3)[c]	E4INWARMCV03C	12/19/96 15:58	10	882869	76.5	1800	0.05	-	-	29	-	29
e4i025tr (1)	E4INWARMCV04A	12/19/96 16:21	10	905805	77.8	830	1.4	290	$1x10^4$	38	4010	4048
e4i025tr (2)	E4INWARMCV04A	12/19/96 16:21	10	905805	77.8	830	0.29	290	2133	8	847	855

Notes:
a An emissivity *e* of 1 is used.
b e4i007tr temperature and area derived from 4.999 μm radiance of 17.26 GW/μm from an area of 3600 km^2 (Veeder et al., 2012).
c Data best fitted with single component.
(1) Model fits to data corrected for emission angle.
(2) Model fits to "explosion" data not corrected for emission angle.
(3) Model fits to "explosion" data not corrected for emission angle, having subtracted emission angle corrected e4i006tr data.

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