Keck Observations of Eruptions on Io in 2003 – 2005

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Abstract

We report observations of four energetic volcanic eruptions on Io: at Tupan Patera on UT 8 March 2003; Tung Yo Patera on UT 28 May 2004; Sui Jen Patera on UT 2004 May 30; and south of Babbar Patera on UT 31 May 2005. The Tung Yo, Sui Jen and south of Babbar Paterae eruptions are in locations where no activity had been seen before. Our observations were obtained at near-infrared wavelengths (1.2-4.7 μm) with the 10-m Keck telescope equipped with adaptive optics. We report single and two-temperature blackbody fits, as well as single-component and dual-component Io Flow Model (IFM) fits (Davies, 1996, *Icarus*, 124, 45-61) to all four eruptions where applicable. We use 2- μm and 5- μm radiant fluxes, the 2:5- μm radiant flux ratio, and radiant flux density of each thermal source to constrain the likely style of volcanic eruption. All eruptions are characterized by a high temperature IFM component (ranging from 1475 to ~ 900 K) from a relatively small area (<1 km^2 to several tens of km^2), and a lower temperature component with a more extensive surface area. The relationship of the areas at the highest temperatures to the cooler, more extensive area is of particular importance in deriving eruption style. Model fits to the Sui Jen Patera data are strongly suggestive of lava fountaining, although not at a level consistent with a large “outburst” eruption. Activity at Tupan Patera suggests that the entire floor of the patera may have been resurfaced with silicate lava in 2003.

Keywords: Io, Infrared Observations, Volcanism

1. Introduction

Volcanic eruptions are ubiquitous on Io, as testified by numerous observations from spacecraft (*Voyager*, *Galileo*, *Cassini*, *New Horizons*), and from the ground (e.g., Marchis et al., 2000, 2005; Macintosh et al., 2003; de Pater et al., 2004, 2014). However, rarely do we capture an eruption near its onset, nor at wavelengths as short as 1.6 μm . In this paper we report an eruption near Sui Jen Patera ($\sim 3^\circ\text{W}$, $\sim 19^\circ\text{S}$) observed with the 10-m W.M. Keck telescope on UT 30 May 2004 at a wavelength as short as 1.6 μm . We further report on the continuing volcanic activity at Tupan Patera on UT 8 March 2003, and an eruption to the south of Babbar Patera on UT 31 May 2005. This is the latest step in our project to populate the timeline of volcanic eruption detections, quantifying the thermal emission, examining eruption processes, constraining lava discharge rates, and charting the variability of activity of Io's volcanoes with a view to future missions to the jovian system.

2. Observations, Data Reduction and Results

Observations were carried out with the NIRC2 camera coupled to the Adaptive Optics (AO) system on the Keck II telescope at the W.M. Keck observatory in Hawaii (Wizinowich et al. 2000). NIRC2 is a 1024×1024 Aladdin-3 InSb array, which we used in its highest angular resolution mode, i.e., the NARROW camera at 9.94 ± 0.03 mas per pixel (de Pater et al. 2006), which translates roughly into 35 km/pixel at the center of Io's disk in May 2004. The

78 observations are summarized in Table 1.

79
80 All images were processed using standard near-infrared data reduction
81 techniques (flat-fielded, sky-subtracted, with bad pixels replaced by the median
82 of surrounding pixels). The geometric distortion in the Keck images was
83 corrected using the “dewarp” routines provided by Brian Cameron of the
84 California Institute of Technology¹. The individual images were aligned and co-
85 added to increase signal to noise. Photometric calibration in May 2004 was
86 performed on the standard star HD129655 (Elias et al., 1982; Leggett et al.,
87 2003); on the other dates the background intensity of the images was
88 bootstrapped from well-calibrated images (e.g., from de Pater et al., 2014b) while
89 properly accounting for the variations in Io’s heliocentric and geocentric distance.
90 Since Io’s background intensity is primarily caused by reflected sunlight, we do
91 not expect this to change over time; indeed, we have not seen variations in the
92 background intensities on photometrically calibrated images by more than a
93 few %. Hence, by using well-calibrated images at approximately the same
94 viewing aspect, the photometric accuracy is preserved. We adopt a conservative
95 photometric uncertainty of ~10-15% for all our observations.

96
97 Figure 1 shows the results for all 4 days: the two top rows show the images
98 obtained on UT 28 and 30 May 2004; the third row shows the images from UT 8
99 March 2003, and the last row show those obtained on UT 31 May 2005. The
100 latter images are of a poor quality, since the AO system did not work properly,
101 which resulted in a double point spread function (PFS), as best shown at 2.27 μm .

¹<http://www2.keck.hawaii.edu/inst/nirc2/forReDoc/post-observing/dewarp/nirc2dewarp.pro>

At the longer 3.78 and 4.67 μm the PFS appears to be quite elongated, due to the same problem.

On each day, several bright hot spots are visible at 3.78 and 4.67 μm ; only the largest eruptions are also detected at the shorter wavelengths. All bright hot spots are indicated with a number (1 – 11), and the identification is given in the legend. These identifications are based on the position of the hot spots, which were determined by reprojecting the individual images (for details, see de Pater et al., 2014a,b) and using the sub-earth longitude and latitude as obtained from standard ephemerides². A typical uncertainty in the location of a hot spot near the center of the disk is $\sim 0.5^\circ$.

The locations and identifications of the bright eruptions are summarized in Table 2; those of additional hot spots are listed in Table 3. The spectral intensity of each of the spots was determined using the technique described by de Pater et al. (2014b). In short, the intensity is integrated over a small circle centered on the hot spot, and the background is determined from an annulus immediately surrounding the hot spot. Since a considerable fraction of flux is lost in the PSF halo, we determined this by determining the spectral intensity of a star in the exact same way as for the hot spot (same size circle centered on the star, and annulus around the star). Io's hot spot intensity is then divided by the ratio of the stellar intensity to the total intensity from the star. We repeated the measurements with slightly different radii for each hot spot (and star); the uncertainty in the measurement has been derived from the dispersion in the values, augmented with a 15% photometric uncertainty (in quadrature). To facilitate comparison with previous flux estimates, the results were normalized

² <http://ssd.jpl.nasa.gov/horizons.cg>

using the distance to Io at the time of the observation; the resulting numbers are summarized in Tables 2 and 3 together with the location of the hot spots. The intensities as listed are corrected for the emission angle effect, i.e., the observed values are divided by the cosine of the emission angle of the volcanic hot spot.

3. Results and Discussion

3.1 Large Eruptions in 2003 – 2005

In the following we give a brief discussion of the large volcanic eruptions at Tung Yo Patera, Sui Jen Patera, Tupan Patera, and to the South of Babbar Patera. A preliminary report on the first two eruptions was provided by Marchis et al. (2004). Below, after the name of the volcanic site, we indicate in brackets the location of the geologic features (e.g., patera, fluctus) as listed by the USGS³; we note that this may differ slightly from the positions of the hot spots as measured on our images, which were listed in Table 2.

Tung Yo Patera (0.9° W, 18.3° S) and ***Sui Jen Patera*** (2.56° W, 19.2° S). On 28 May 2004 we detected a very bright eruption at 3.78 and 4.67 μm in the area near Tung Yo, Sui Jen, and Ilmarinen Paterae. This was the first detection of volcanic activity at this location. Although not quite in the “outburst” class of observations when we detected it, this eruption was very powerful with an intensity ~25% of Io’s total reflected sunlight component at ~5 μm . “Outbursts” are defined as events that double Io’s 4.8–5.0 μm flux (Blaney et al., 1995; Spencer

³ <http://planetarynames.wr.usgs.gov/>

and Schneider, 1996). We do not know when the eruption started; it could have been much more energetic at its onset, which could have been just hour(s), days, or weeks prior to our observations. Two days later, on 30 May 2004, the eruption is still prominent, visible even at 1.6 μm , although its output was waning. The locations of the eruption on both days are indicated on Figure 2; we derived an average location for each day, assuming that the location of the eruption is independent of wavelength. On May 28 this puts the eruption at $0.8 \pm 0.9^\circ \text{W}$ and $17.5 \pm 0.9^\circ \text{S}$. closest to Tung Yo Patera; on May 30 the source of thermal emission was ~ 100 km to the west, at $4.2 \pm 0.3^\circ \text{W}$ and $17.5 \pm 0.6^\circ \text{S}$, closer to Sui Jen Patera. It might be possible that these sites are somehow connected at depth, and that the eruption at Tung Yo Patera triggered the second eruption.

Half a year later, in January 2005, and again in October 2008, we also see strong thermal emission from this general area (see Fig. 7 of de Pater et al., 2014b); however, these thermal sources are to the north-west of the May 2004 eruptions, closer to Grian Patera (12.0°W , 11.9°S) (Table 4).

Table 5 shows the results of both single (1T) and two-temperature, two-area (2T) blackbody fits to the spectral intensities listed in Table 2. Table 6 shows the results of using the Davies (1996) Io Flow Model (IFM), which quantifies the thermal emission spectrum from the surface of a steadily spreading, and cooling, basaltic lava body. Details of this model are provided by Davies (2007), and were most recently summarized by de Pater et al., (2014b). This model is best used for data of active, ongoing lava emplacement. Fits to the data are shown graphically in Figure 3a.

179 The errors on all derived physical quantities (as temperature, area, power,
180 age) were derived from the measurement uncertainties on the intensities (Tables
181 2 and 3) by also fitting blackbody curves to data points where the measured
182 uncertainty was subtracted from the shortest wavelength data point and added to
183 the longest one, and vice versa, so as to cover the entire possible range of
184 blackbody curves that fit the data. The uncertainties on the physical quantities
185 (Tables 5--7) are derived from the spread in these blackbody curves, as
186 described by de Pater et al. (2014b).

187
188 The observations near Sui Jen Patera on UT 30 May 2004, where the
189 spectral intensity was measured at 4 wavelengths between 1.6 and 4.7 μm ,
190 provide a better characterization of the volcanic activity compared to the
191 observations at Tung Yo Patera 2 days earlier. Figure 3a compares the data
192 obtained on 2004 May 28 at two wavelengths, 3.78 and 4.67 μm , with data
193 obtained two days later on 2004 May 30 at four wavelengths, 1.58, 2.27, 3.78,
194 4.67 μm . Figure 3a also shows the results of fitting the 2004 May 30 data with
195 1T, 2T and IFM model fits. With only two data points for 2004 May 28, only a 1T
196 or IFM fit is justified. The 2T fit to the 2004 May 30 data is superior to any single
197 component fit, reflecting the complex temperature and area distribution present.
198 The high-temperature component is 1165 ± 25 K with an area of 5.5 ± 1 km^2 ; this
199 high a temperature alone is indicative of silicate volcanism. The erupted lava has
200 spread over Io's surface as indicated by the lower temperature component, $480 \pm$
201 30 K, with an area of $\sim 500\text{-}900$ km^2 . Although the IFM fit does yield some insight
202 into the eruption process, the fit is rather poor – since only one component was
203 used in the IFM fit, it resembles the 1T curve rather than the 2T fit (Fig. 3).

Two-component IFM fit. With data obtained at four wavelengths, a more sophisticated application of the IFM is possible using two IFM components, in the same manner as a two-temperature, two-area fit is superior to a single temperature, single area fit. The dual-component IFM fit yields as good a fit as a two-temperature, two-area fit, but yields considerably more information as to the physicality of the eruption, as the temperature ranges revealed are now directly related to the exposure times of the lava, the areal coverage rate, and the duration of the eruption. This dual-IFM approach was previously used to process multispectral data obtained by *Galileo* NIMS of thermal emission from Pillan and Pele in 1997 (Davies et al., 2001). Figure 3b shows the fit to the Sui Jen Patera data obtained on 2004 May 30. Table 7 shows the 2-component IFM best-fit eruption parameters. The results are highly illuminating in discerning the physical structure of the ongoing eruption.

Our interpretation of the model fit suggests that the first component consists of thermal emission from an intense thermal source, such as that produced by lava fountains. This interpretation is based on the following eruption parameters: a relatively small area ($\approx 7 \text{ km}^2$) with a very high temperature range (1475 K to 995 K) and an accordingly young age range with the oldest emitting surface no older than ~ 100 seconds. The inferred areal coverage rate is extremely high, at over $65000 \text{ m}^2/\text{s}$. The radiant flux density (80 kW/m^2) is relatively high, and the total thermal emission is 555 GW. The exact geometry of the emitting area is not known, but the simplest explanations are either lava fountains or a vigorously overturning lava lake, where a cool crust has no time to form. No lava lake had been previously observed at Sui Jen Patera, but a temporary lava lake could have formed over the vent, a roiling cauldron of rapidly overturning lava that feeds an expanding lava flow field. This precise scenario was observed during

the 2014-2015 eruption of Nornahraun volcano, Iceland, where a large cauldron over 100 m long and 60 m wide containing roiling lava formed directly over the vent, building levees nearly 70 m high. The lava cauldron, fed at a rate of between 50 and 100 m³/s [M. T. Gudmundsson and T. Thordarsson, 2014, pers. comms.] fed an expanding lava flow field that ultimately was ~20 km long and ~10 km across the widest part of the flows.

We now consider the model fit to IFM component 2. The second component is much larger in area, covering over 2800 km². The coolest areas are modelled to be at temperatures as low as 315 K. The assumed constant areal coverage rate is about 630 m²/s through an eruption duration of about 52 days. The component 2 total thermal emission of nearly 3 TW is much larger than from component 1, but the greater area of component 2 means that the radiant flux density of 1 kW/m² is considerably lower than that of component 1. Our interpretation of component 2 is that this is an extensive area of active lava flows dominated by cooled crust but with some small but still incandescent areas, and the lava flows are being fed by either lava fountains or from an above-vent cauldron. The implication here is that this eruption had been progressing for some time when observed on 2004 May 30. It is not known if lava fountains persisted for this entire time, or if this was a new episode of fountaining. Alternatively, an active vent with ponded but roiling lava could also explain the component 1 thermal emission and the shape of the thermal emission spectrum. We note that the dual-IFM fit suggests that the extensive component (component 2) had been active for 52 days when we observed it. Our observations two days earlier, on 28 May 2004, however, showed that the center of activity was closest to Tung Yo Patera. The spatial resolution of the data, though, is low enough that

we cannot exclude the presence of warm lava near Sui Jen Patera during an eruption episode near Tung Yo Patera.

The distinctive thermal signature at Sui Jen Patera has been seen before on Io at other locations. The 1990 thermal outburst, thought to be in the Loki region (Veeder et al., 1994; Blaney et al., 1995) was interpreted by Davies (1996) as resulting from large lava fountains that decreased in area over the course of two hours but which continued to feed expanding and cooling lava flows. The same interpretation of fountain-fed lava flows explained NIMS data of Pillan in 1997 that resulted in lava flows covering 5600 km² (Keszthelyi et al., 2001) (but not the Pele data obtained at the same time, suggesting a different eruption style at Pele), and *Galileo* SSI data of Tvashtar in February 2000 showed 1-km-high lava fountains that led to the emplacement of a lava flow field (Keszthelyi et al., 2001) covering 150 km² (“Tvashtar B” in Veeder et al., 2012).

Eruption rate. If the areal coverage rate is 630 m²/s and the lava flow field is 10 m thick, the time-averaged discharge rate (TADR, also known as the eruption rate) is 6300 m³/s, very high for terrestrial effusive eruptions (e.g., see Davies, 2007) but much less than that encountered at two outburst eruptions observed in August 2013 at Rarog Patera (TADR of 1.2×10^4 m³/s) and at Heno Patera (TADR = 2×10^4 m³/s) (de Pater et al., 2014). This is consistent with our interpretation of the Sui Jen Patera eruption as not being quite as energetic or voluminous as recent outburst eruptions. The peak effusion rate at Sui Jen Patera may have been an order of magnitude greater than the TADR.

Error analysis. Figure 3c shows the result of fitting the Sui Jen Patera data for 2004 May 30 data using the dual-component IFM to test the limits of the

uncertainties in the data. The hotter component is well constrained by the 1.58 μm datum, the fits yielding a range of power output from ~ 450 to ~ 600 GW from an area of ~ 5 to ~ 7 km^2 , that is only of order 1 minute old. The larger, cooler IFM component 2 is less well constrained; the peak of thermal emission is at a longer wavelength than 4.67 μm . The wide range of the derived parameters within uncertainty limits reflect this lack of constraint but without impacting our interpretation of the data as suggestive of an extensive, active, crust-dominated lava flow field. The range of areas within the uncertainty limits spans 2000 to 70,000 km^2 , and the age of the oldest surfaces spans ~ 1 month up to ~ 6 years. The range of IFM component 2 thermal emission ranges from 1.6 TW to 9 TW. A single datum at thermal infrared wavelengths (for example, 8.7 or 12 μm) would strongly constrain model fits for the cool IFM component.

Figure 4 shows the model-derived 2- and 5- μm radiant fluxes for Tung Yo Patera on 2004 May 28 for the IFM fit (labeled “A”) and for Sui Jen Patera on 2004 May 30 (labeled “B”). The letters C1 and C2 indicate the locations of the individual components of the 2-component IFM fit to Sui Jen Patera on May 30. The location of point C1 close to the 2- μm radiant flux = 5- μm radiant flux line suggests an eruption with a relatively large area at incandescent temperatures (Davies et al., 2010). The presence of a vigorous eruption, likely including some lava fountains that have already fed an extensive lava flow field, is indicated by the closeness of the data points to those of Pillan in 1997, as measured by *Galileo* NIMS (see Davies et al., 2001, 2010; de Pater et al., 2015). Together with the recently detected set of eruptions in the vicinity of Pillan Patera and Pillan Mons that changed location by ~ 100 – 200 km from observation to observation (de Pater et al., 2015), the Tung Yo and Sui Jen Paterae eruptions present another example of eruptions in relatively close proximity that may be

connected through some as yet unknown mechanism, such as a shared magma source.

Figure 5 shows the 2:5 μm radiant flux ratio plotted against radiant flux density for the two eruption sites. The data can be compared with the the radiant flux densities and 2:5- μm radiant flux ratios for different styles of volcanic activity on Earth and Io, as derived from previous data analyses. This plot is useful as it allows comparison not on the magnitude of thermal emission (as in Figure 4), but by the thermal characteristics of the emitting surfaces per unit area. The point labeled A is for the 1-component IFM fit to the Tung Yo Patera 2004 May 28 data, and the point labeled B is for Sui Jen Patera on 2004 May 30.

For Tung Yo Patera, the position of the datum in Figure 4 suggests an extensive area of relatively cool surfaces, such as cool crust on lava flows or a quiescent, non-overturning lava lake. This is supported by the low radiant flux density and 2:5- μm ratio in Figure 5.

For Sui Jen Patera, in Figure 5, the point labelled B is for a single IFM fit to the data. The points labelled C1 and C2 are for the individual components in the superior dual-IFM fit to the Sui Jen Patera data. The position of the C1 datum on 2004 May 30 is suggestive of an active, high-temperature area, while the C2 data point is indicative of an extensive lava flow field, dominated by cool crust. However, the overall style of the eruption depends on the combination of these two components (B), in conjunction with the relatively small 2- and 5- μm radiant fluxes (Figure 4). The location of point B suggests that there is an area of relatively cool lava flows or lava lake crust, and a smaller high temperature area or areas that may correspond to an active vent or vents, break-outs of lava along a lava flow, an area of crustal overturning in a lava lake, and possibly very small

lava fountains. As in other cases, our data allows only a broad constraint on the likely style of lava eruption at Sui Jen Patera.

Tupan Patera (141 °W, 19 °S). Located on the anti-jovian hemisphere of Io some 40° in longitude from the sub-jovian point, Tupan Patera is one of Io's most colourful features (Fig. 6). What is known about this persistent active volcano in the wake of the *Galileo* mission has most recently been summarized by Davies (2007) and Davies and Ennis (2011). The patera is 75 km x 50 km in size, and about 900 m deep (Turtle et al., 2004) and was imaged at a spatial resolution of 132 m/pixel by *Galileo* SSI in October 2001. The bright red material that covers much of the floor of the patera and as diffuse deposits on the surface outside of the patera, especially to the east and southeast, is thought to be rich in short-chain sulphur allotropes (Keszthelyi et al., 2001, Turtle et al., 2004). As seen by SSI, dark silicates cover the eastern half of the patera floor and in patches in the western half. In NIMS data obtained in 2001, these dark areas are the warmest; the central "island" is cold (Lopes et al., 2004). NIMS data obtained in 1996 revealed that part of the floor was at a temperature exceeding 1100 K, a clear indication of silicate volcanism (Davies, 2003b). As discussed in Davies and Ennis (2011), it is not known for certain how Tupan Patera is resurfaced – whether it is a lava lake (Radebaugh et al., 2002) that regularly overturns, or whether the patera floor is resurfaced with lava flows (e.g., Davies, 2003b). The shape of the feature-integrated thermal emission spectrum as seen by NIMS (Fig. 7a) shows an almost linear spectrum between 1.7 and 5.2 μm. This departure from a Planckian curve cannot be adequately fitted with a single temperature and area combination, instead requiring a more complex temperature and area distribution. This spectrum, taken in June 1996 during *Galileo* orbit G1, was fitted with a 2T model that yielded a small (0.01 to 0.25

km²) high temperature area at ~950 K to >1100 K, and a larger area at ~440 K
 covering ~30 km² (Davies and Ennis, 2011). A two-component IFM fit (Fig. 7c)
 shows that the temperature has cooled from the eruption value of 1475 K down
 to only 1175 K over an area equal to 0.04 km² over a timespan of 14 seconds, at
 an implied areal coverage rate of almost 3000 m²/s. The total power of this
 component is 5.5 GW. The second, low-temperature component shows that a
 surface area equal to ~34 km² has cooled down until 385 K over ~9 days, at an
 areal coverage rate of ~40 m²/s. These numbers are in good agreement with
 those obtained from the previous 2T fit both in terms of the magnitude of thermal
 emission and the implied temperature and area distributions. The dark, low-
 albedo areas on the floor of Tupa Patera, at least when observed by *Galileo*,
 cover 789 km² and have an averaged temperature of 272 K (Veeder et al., 2011).
 The relatively small active area from our 2-component fit, therefore, suggest that
 NIMS observed an expanse of cooling lava with a fractional area of ~0.1% made
 up of extremely hot lava, as might be found either at the vent of a lava flow,
 crusts and breakouts, or as cracks in the crust of a relatively quiescent lava lake
 revealing hot lava beneath, as has been proposed for Loki Patera (Rathbun et
 al., 2002; Davies, 2003a; Rathbun and Spencer, 2006; Matson et al., 2006). The
 ~4% of surface area covered by the lower ~400 K temperature would also be
 consistent with either the crust on a lava lake or cool crust-dominated lava flows.

On UT 8 March 2003, we measured a 4.7 μm radiant flux of 85±13
 GW/μm (i.e., πF, with F the observed spectral intensity in GW/sr/μm; see de
 Pater et al., 2014b), higher than ever measured before at Tupa Patera. The
 average 4.7- or 5-μm radiant flux during the *Galileo* era was 6.3±2.6 GW/μm
 (Davies and Ennis, 2011), while the maximum radiant flux detected by *Galileo*

NIMS was almost 14 GW/ μm for observations taken at emission angles $<70^\circ$. One NIMS measurement at an emission angle of 83° showed a radiant flux of 37 GW/ μm .

Table 5 shows the results of fitting the Keck data with 1T and 2T models. As with the NIMS G1 data, the Keck data are poorly fitted with an isothermal area. The 2T fit yields a high temperature component at 920^{+90}_{-3} K over an area of $5.5^{+0.7}_{-2.5}$ km²; and a lower-temperature component at 287^{+35}_{-15} K with an area of $\sim 14,000$ km². This implies a total radiated thermal emission of ~ 5 TW. Most of this thermal emission is at wavelengths longer than 5 μm , and the model fits are unconstrained at these wavelengths. However, we can impose limits on the variables by limiting the total area of the components. For example, using the dark area of 789 km² measured by Veeder et al. (2011), a 2T fit yields, in one example (Fig. 7b) a high-temperature area at 1065 K and of size 2 km², and a lower-temperature area at 402 K over an area of 787 km². In this case, the total thermal emission is 1.3 TW. Although this is smaller than the value of 5 TW mentioned above, it is much higher than the average total thermal emission of 70 ± 29 GW determined from the *Galileo* NIMS observations (Davies and Ennis, 2011).

A 1-component IFM fit (Table 6) resembles the 1T curve in Fig. 7b, and does not provide a good fit to the data. We provide a 2-component IFM fit in Table 7 and Fig. 7d. There is a very small component (0.8 km²) at high temperatures, suggesting young, newly-exposed and therefore hot lava: our calculations indicate that the lava has cooled from its eruption temperature of 1475 K down to 1140 K (which only takes about 20 seconds). The total area and

417 young age suggest a very high areal coverage rate ($\sim 40000 \text{ m}^2/\text{s}$) to allow this
418 area to persist, but, as with other fits of this nature, we cannot with certainty say
419 what the distribution of hot and cold areas are relative to each other. The hot
420 area described above may be localized in one spot: an active vent, fountains, a
421 portion of a lava lake that is fountaining or vigorously overturning, an open-
422 channel flow; or the hot area may be distributed across the cooler crusted area in
423 the form of cracks in the crust of a lava flow (or lava lake), and the style of
424 emplacement is relatively quiescent, such as inflating pahoehoe flows, or a
425 quiescent lava lake with a stable crust and only small areas at high temperatures.

426 Nonetheless, the total power from this hot component alone is 106 GW,
427 on the high end of that measured by *Galileo* NIMS for the entire patera (Davies
428 and Ennis, 2011), indicating an increase in volcanic activity in 2003. Both the
429 surface area and areal coverage rate are over an order of magnitude larger than
430 that measured by *Galileo* NIMS. The second component exhibits a much larger
431 range of temperatures, from the eruption temperature down to 265 K, and covers
432 an area as large as the entire patera ($\sim 5000 \text{ km}^2$). This component of the
433 emission is at least 7 months old, and because of its sheer size, the total power
434 radiated from this surface is $\sim 2.5 \text{ TW}$, much larger than that measured by
435 *Galileo* NIMS ($\sim 70 \text{ GW}$).

436
437 As shown in Figure 6, the location of the emission measured in 2003 is not
438 in one of the dark patera regions imaged by *Galileo* SSI. This may explain the
439 difference in emission characteristics between those seen by *Galileo* NIMS and
440 in 2003, both in the total radiant flux and resulting model fits. Still, the general
441 shape of the 2003 spectrum is remarkably similar to that seen by *Galileo* NIMS,
442 and this is interpreted, as in Davies and Ennis (2011) as a generally unchanging
443 style of activity within the patera, but now over a larger area; more of the same

style of volcanism as previously seen.

In 2003, from the dual IFM component fit (as with the two-temperature and two-area model fits) we see a high temperature-range (and therefore young) component with a small area, less than 0.02% of the entire active area, while the lower temperature-range component covers the entire area of the patera (4900 km²). What is important to deriving eruption style is the distribution of the “hot” component among the “warm” component. Is the hot component a stand-alone vent area, or is it the sum of hot cracks, the vent area, new lava lobe breakouts? The shape of the thermal emission curve, and the comparison with the spectra of lava flows at, for example, Prometheus, Zamama and Culann (see Davies and Ennis 2011), suggest the latter.

However, the same thermal signature can be found with the crust on a relatively quiescent lava lake, so, as with previous analyses, we cannot definitively say what the resurfacing style of volcanic activity is at Tupa Patera.

For illustrative purposes, the individual components of the Tupa Patera dual-IFM model fit are plotted on Figures 4 and 5. The combined output of the dual IFM fit, the true classification metric on these plots, suggests a surface covered by lava dominated by cooling crust.

From our output it appears that Tupa Patera has completely resurfaced itself. In order to determine the style will require more observations, ideally at higher temporal resolution, to chart the evolution of thermal emission and subsequent eruption episodes. Repeated higher spatial resolution data should clearly reveal the nature of resurfacing Tupa Patera, but these data are only obtainable from a spacecraft making a close flyby.

471

472 ***S. of Babbar Patera*** (272 °W, 40.8 °S). On UT May 31 2005 an eruption was
473 detected at 2.2, 3.8, and 4.7 μm to the south of Babbar Patera. Assuming the
474 emission at the different wavelengths to come from the same location, we
475 averaged the values in Table 2 to get a position at 277.2 ± 2.5 °W and 50.7 ± 1.0
476 °S. This position is indicated on the USGS map in Figure 8; interestingly, there is
477 no sign of any prior volcanic activity at this location, i.e., no surface features
478 anywhere. Although the performance of the AO system was far from optimal, the
479 presence of an energetic eruption is quite obvious and real, even though the
480 morphology (2-lobed structure) is an artefact. The location of the eruption,
481 assumed to be at the center of the hot spot, could be pinpointed to within a few
482 degrees (Table 2). Also, since the same double-lobed structure was seen on
483 stellar images, we are quite confident that the spectral intensities reported in
484 Table 2 are trustworthy, although the uncertainties in the numbers are higher
485 than for the other hot spots, as shown. Interestingly, the intensity is almost flat
486 from 2-5 μm , indicative of a high temperature (Fig. 9). Indeed a 1T fit shows a
487 value of 925 ± 100 K over an area of $\sim 30 \text{ km}^2$, very similar to the 1T fit for the Sui
488 Jen Patera data from UT 30 May 2004. (No reliable 2T fits were found). The IFM
489 fit shows a very active eruption: The oldest lava is only about 20 min (between 6
490 and 100 min including the uncertainties) old, derived from the fact that the oldest
491 radiating surface has cooled down from the eruption temperature of >1400 K to
492 ~ 800 K. With this short a cooling time, we note that it is possible that the relative
493 radiant fluxes changed over the duration of our observations.

494

495 Plotting 2- and 5- μm radiant fluxes (Fig. 4) derived from the IFM fit to the
496 data shows that the temperature distribution is weighted heavily towards high

temperatures and is suggestive of lava fountains or a vigorously overturning lava lake. Plotting the 2:5 μm radiant flux ratio against the radiant flux density (Fig. 5) shows that the power emitted per unit area and shape of the thermal emission spectrum is almost identical to that of the Pele lava lake. The lack of detection of this hot spot in subsequent observations to date rules out that this was an active lake, instead suggesting a single, though voluminous, eruption episode.

3.2 Other Bright Hot Spots in 2003 – 2005

Several other bright hot spots were detected on the four days we observed (Fig. 1). As before, after the name of the volcanic site, we indicate in brackets the location as listed by the USGS³.

On UT 8 March 2003, we observed a relatively low level of activity at Prometheus (153.9° W, 1.5° S), a volcano that is known for its episodic behavior (see Davies et al., 2006, for a detailed description of Prometheus and observations obtained by *Galileo* NIMS). In addition to the episodic behavior observed by *Galileo* NIMS, low level activity at Prometheus was also observed with the Keck AO system in Dec. 2001 (Marchis et al., 2005) and in July-August 2010 (de Pater et al., 2014b). The level of activity reported here ($\sim 16 \text{ GW}/\mu\text{m}$ at 4.7 μm) is very similar to that observed in 2001 and 2010. The location of the emission reported in this paper is right at the center of the large flow field in the north-west (Fig. 10), referred to as C in Davies et al. (2006).

Three quite active volcanic centers were seen on UT 28 May 2004:

i) *Amaterasu Patera* (306.5° W, 38.1° N), a volcanic center which was detected before by Voyager/IRIS (e.g., Pearl, 1985) and by Galileo/NIMS (Lopes-Gautier et al., 1999). Geissler et al. (2004) reports that the surface darkened noticeably between Galileo orbits G1 and E6.

ii) *Creidne Patera* (342.5° W, 53.0° S). Thermal emission from this patera had been detected before by Voyager IRIS and Galileo NIMS (Lopes et al., 2001); we see thermal emission from the north side of the patera.

iii) *Loki Patera* (308.8°W , 13.0°N) was detected both on 28 May 2004 and on UT 31 May 2005. Loki Patera is assumed to be a massive lava lake, emission of which has been seen in every relevant observation from the ground and from spacecraft (e.g., Rathbun et al., 2002; Davies, 2003a; de Pater et al., 2004; Marchis et al., 2005; Matson et al., 2006; Davies et al., 2012; de Pater et al., 2014b; Conrad et al., 2015). The spectral intensities reported by us are quite typical for the 2003-2007 time period, when the lake was relatively quiescent (Rathbun and Spencer, 2010).

On UT 30 May 2004, we detected *Masubi Fluctus* (58.1°W , 50.5°S). Both Voyager 1 and 2 detected plumes above Masubi Fluctus (Strom and Schneider, 1982). Plumes with associated surface deposits were also detected during several Galileo orbits (e.g., C21, 22; Keszthelyi et al., 2001) and during the New Horizons flyby, at which time two simultaneous plumes were seen, one at the source vent, and one at the distal flow front (Spencer et al., 2007). Thermal emission from hot spots in Masubi Fluctus has been detected on various occasions from Galileo NIMS, New Horizons, and groundbased observations (e.g., Geissler et al., 2004, and refs therein). In December 2001, a spectral intensity of ~ 4 GW/sr/ μm was measured at 3.8 μm , and ~ 7 GW/sr/ μm at 4.7 μm (Marchis et al., 2005; de Pater et al., 2004), very similar to the numbers reported

in this paper. On UT 18 December 2001 an intensity of ~ 0.8 GW/sr/ μm was measured at $2.2 \mu\text{m}$ when Io was in eclipse. Two-temperature fits to the 2001 data yield a temperature of ~ 620 K over an area of $\sim 12 \text{ km}^2$ and ~ 400 K over $\sim 200 \text{ km}^2$ (de Pater et al., 2004). The numbers reported by us in 2004 are suggestive of a similar temperature distribution. A second hot spot was detected on UT 30 May 2004 at *Euboea Fluctus* (351.0° W, 45.0° S). Activity has been reported from this site in 2001, while Io was in eclipse (de Pater et al., 2004).

7. Conclusions

In this paper we reported four relatively large eruptions during the 2003 – 2005 period. No emissions had been reported before from three of the eruption sites: Tung Yo Patera, Sui Jen Patera, and an area to the south of Babbar Patera where no obvious surface features (volcanic or otherwise) were seen during the *Voyager* and *Galileo* epochs. The third eruption was at Tupan Patera, from a location within the patera that was apparently inactive during the *Galileo* epoch. Our data form a useful extension of the observation timeline of Tupan Patera, and suggest that after the *Galileo* mission the patera floor was resurfaced in its entirety, invoking a comparison, at least in appearance, with Loki Patera.

From all four sites we detected a high temperature component of over 900 K, over areas of $< 1 \text{ km}^2$ up to several 10's km^2 , clearly indicative of ongoing silicate volcanism. Most of the sites exhibited a larger (typically several 100 km^2) at temperatures of order 300-500 K. We were able to obtain two-component IFM fits to the Sui Jen and Tupan Paterae, only possible because energetic volcanic eruptions were taking place yielding data at more than two wavelengths.

To interpret the IFM model fits to the data, we again use the 2- μm and 5- μm radiant fluxes, the 2:5- μm radiant flux ratio, and the radiant flux density to constrain the likely style of eruption at each of the locations studied (Davies et al., 2010). The plot of 2- μm and 5- μm radiant fluxes (Figure 4) place different eruptions in order of the magnitude of thermal emission, with the most energetic eruptions located in the upper right of the plot. As demonstrated in previous analyses (e.g., Davies et al., 2010) different styles of lava eruption plot in different regions of data space. High-temperature and high thermal emission events such as large “outburst” eruptions as seen at e.g., Surt (Marchis et al., 2002), Heno and Rarog Paterae (de Pater et al., 2014a), and 201308C (de Kleer et al., 2014) are located here. These eruptions are often characterized by a lack of a relatively cool component, implying that the bulk of thermal emission is from incandescent areas, typical of lava fountains. These events are also transient and can transition to a thermal signature characteristic of flows with a cooling crust. A relatively quiescent lava lake with a surface dominated by a relatively cool and well-developed crust, implying older surfaces, usually emits less total energy than outburst events, and emits considerably more energy at 5- μm than at 2- μm due to the mostly lower surface temperatures present. Further constraints to eruption style are therefore imposed by considering the 2:5- μm radiant flux ratio, as well as the radiant flux density (kW/m^2). The greater the proportion of “hot” areas to “warm” areas, the greater the radiant flux density, so lava fountains have a high 2:5- μm radiant flux ratio and a high radiant flux density as shown in Figure 5 (see Davies et al., 2010). Combining the information in Figures 4 and 5 yields more constraints on an eruption type, combining the size of the eruption (Figure 4) and the style of the eruption by considering what the

surface area of the eruption looks like on average (Figure 5).

The individual characteristics of the IFM components for individual volcanoes have been added to Figures 4 and 5. Note, however, that for other eruptions plotted in these figures, the parameters described above are derived from the integrated thermal emission spectrum of the eruption, the sum of the thermal emission from all of the emitting areas over a wide range of surface temperatures. For direct comparison between eruptions, the 2 and 5 micron data and radiant flux densities for Tupa, Sui Jen and Tung Yo Paterae must be from the total values, not from the individual values of the IFM component fits. For example, the Sui Jen Patera Keck data yield a relatively small hot area and a larger, relatively cooler area. In Figure 5, the hot area radiant flux density plots as a lava fountain would – but this area only makes up a small fraction (~1%) of the total emitting area, and this is reflected by the position of Sui Jen Patera as derived from the integrated thermal emission spectrum (point B in Figure 5). The location of point B in Figure 4 does suggest an energetic eruption is taking place, however, with a position close to the $2\text{-}\mu\text{m} = 5\text{-}\mu\text{m}$ radiant flux line (point B in Figure 4). The dual-component IFM fit offers an interpretation of the physical nature of the eruption. The high-temperature component (Table 7) (C1 in Figure 4) suggests lava fountains or some other form of highly-active, high-temperature vent. The low-temperature component (C2 in Figure 4) suggests a large area of still-active flows dominated by a cool, insulating crust. Combining components C1 and C2 lead to the location of point B, located at a point between two Pillan 1997 eruption data when lava fountains were transitioning to a flow emplacement regime (Davies et al., 2001).

This may be the simplest interpretation of the data. A better understanding can be gained, with further constraints, by continual observations as eruptions evolve. Ideally, of course, a mission to Io is required, providing

high-resolution observations to truly constrain eruption styles and parameters.

We note that longer wavelength (8 – 12 μm) data would help tremendously in constraining the model fits, but such data are usually difficult to obtain simultaneously with the shorter wavelength measurements since they require different detectors, and ground-based telescopes are typically designed to accommodate only 1 detector at the time. A dedicated Io mission with a suite of instruments spanning visible, mid- and thermal-infrared wavelengths is needed to fully understand Io's magnificent volcanoes.

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Figure Captions

Fig. 1. Images of eruptions in 2003 – 2005, as indicated. Various volcanoes are indicated on the images; the legend is provided in the figure. The images are stretched in contrast such as to best show the contrast on the disk and the hot spots. The rings around some of the bright hot spots result from the point-spread function (PSF) of the telescope (Airy rings).

Fig. 2. Superposition of the location of the 2004 eruptions on a map of Io (USGS³). The red squares show the location with errorbars of May 28 (0.8 ± 0.9 °W, 17.5 ± 0.9 °S) and on May 30 (4.2 ± 0.3 °W, 17.5 ± 0.6 °S).

Fig. 3. a) Tung Yo Patera data from 2004 May 28 (diamonds, thin error bars) and Sui Jen Patera data from May 30 (stars, thick error bars), with 1T, 2T and IFM fits to the Sui Jen Patera data. The error bars for the 3.78 and 4.67 μm data overlap.

b) Dual component IFM fit to the Sui Jen Patera data from 30 May 2004.

c) Fitting the uncertainties in the Sui Jen Patera data of 2004 May 30. Error fit 1 = subtracting uncertainties at short wavelengths and adding uncertainty at long wavelengths. Error fit 2 = adding uncertainties at short wavelengths and subtracting uncertainties at long wavelengths.

Fig. 4. 2- and 5-micron radiant fluxes for the large eruptions discussed in this paper, as compared to previous eruptions and different classes of eruptions. The Tung Yo Patera data for 2004 May 28 (A) and Sui Jen Patera data for 2004 May 30 (B) fitted with the IFM model. The points labeled as C1 and C2 are the individual components of the dual-IFM fit to the Sui Jen Patera data of 2004 May 30. C1 is the active vent area and C2 is the extensive flow field. The powerful eruption detected to the south of Babbar Patera on 31 May 2005 is also close to the 1997 Pillan eruption and the 2- μ m radiant flux = 5- μ m radiant flux line. The 8 March 2003 eruption at Tupan, fitted with the IFM model is close to the waning phase of the 1997 Pillan eruption (point 3 in the 1997-sequence), indicative of a large expanse of mostly cooling flows. Blue and green squares and circles show the placements of the individual components of the dual-IFM fit to both the Tupan Patera *Galileo*/NIMS (green) and Keck (blue) data, as indicated in the legend. Other labels on this plot refer to different styles of volcanic eruption. F= lava fountains. F, C = lava fountains and channelised flows. AL = active lava lakes. QL = quiescent lava lakes (e.g., Loki Patera). FL = Flows with insulated crusts. See Davies et al. (2010) for derivation of eruption styles based on 2- and 5- μ m radiances and evolution. Base image after Davies et al. (2010).

Fig. 5. Plot of radiant flux density against 2:5- μ m radiant flux density for the large eruptions discussed in this paper, compared to other styles of volcanic activity on Earth and Io, and also some specific ionian eruptions. The IFM fit to the Tung Yo Patera 2004 May 28 data is labeled A, and the IFM fit to the Sui Jen 2004 May 30 data is labeled B. C1 and C2 are the individual components of the dual-IFM fit to the Sui Jen Patera data. C1 is indicative of fire fountaining, and C2 of a quiescent extensive flow field. The location of the eruption to the south of Babbar Patera of 2005 May 31 shows that the eruption has a 2:5 μ m ratio and

radiant flux density almost identical to that of the Pele lava lake in 2002 and at other times. The dual-component IFM fit to both the 2003 March 8 and *Galileo*/NIMS eruption at Tupan shows one component as being extremely vigorous (it plots well above C1, close to the 201308C-1T fit) and a second one more similar to C2. It is necessary to compare the location of these eruptions on both Figs. 4 and 5 to interpret the characteristics of these eruptions. After Davies et al. (2010).

Fig. 6. Tupan Patera on Io as seen by *Galileo* SSI (left) and *Galileo* NIMS in the near infrared (right) at approximately the same picture scale. The NIMS data are scaled so that areas with the greatest thermal emission appear red and white. The white box on the SSI image shows the approximate location of the UT 8 March 2003 eruption. North is up. Credit: NASA PIA03601.

Fig. 7. a) *Galileo*/NIMS G1 (28 June 1996) spectrum (data with blue line) with a 2T model (solid black line), and a 1T fit (red line). “Area 1, Temp 1” and “Area 2, Temp 2” refer to the two components of the two-temperature fit. Temperatures and areas are given in the text. Also shown are the thermal spectra for the high-temperature component (dotted black line) and the low-temperature component (dashed black line) of the 2T fit. (From Davies and Ennis, 2011).

b) A 1T and 2T fit to Tupan Patera Keck data from 8 March 2003. For the 2T fit we limited the total area to 789 km^2 , as described in the text.

c) Dual component IFM fit to the *Galileo*/NIMS Tupan Patera data. Both the high-temperature and low-temperature component fits are shown.

841

842 d) Dual component IFM fit to the Tupan Patera data from 8 March 2003,
843 with uncertainties obtained by subtracting the uncertainties on the data at short
844 wavelengths and adding uncertainties at long wavelengths.

845

846 Fig. 8. Image of the area near Babbar Patera (USGS³), with the location
847 as measured on UT 31 May 2005 indicated.

848

849 Fig. 9. Observed spectrum of the eruption S. of Babbar Patera from 31
850 May 2005 with the 1T (dashed line) and IFM (solid line) fits superposed.

851

852 Fig. 10. Galileo mage of Prometheus (NASA/JPL/University of Arizona,
853 PIA02565), with the location as measured on 8 March 2003 indicated. The area
854 shown is roughly 5° east-west and 4.5° north-south. The entire region is shown
855 on the inset in the lower right corner.

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Table 1: Observations of Eruptions in 2003 – 2005

Date (UT) year/month/day	Mid-time hr:min	airmass	Filter	Wavelength range μm	Obs-long $^{\circ}$	Obs-lat $^{\circ}$	r AU	Δ AU
2003/03/08	09:01	1.03	Lp	3.426-4.126	153.2	0.19	5.321	4.506
2003/03/08	09:14	1.04	Ms	4.549-4.790	155.1	0.19	5.321	4.506
2003/03/08	09:26	1.06	Kcont	2.256-2.285	156.7	0.19	5.321	4.506
2003/03/08	09:39	1.08	Hcont	1.569-1.592	158.6	0.19	5.321	4.506
2004/05/28	05:24	1.03	Lp	3.426-4.126	330.7	-1.31	5.434	5.295
2004/05/28	05:28	1.04	Ms	4.549-4.790	331.1	-1.31	5.434	5.295
2004/05/30	07:36	1.40	Lp	3.426-4.126	36.1	-1.31	5.434	5.328
2004/05/30	07:39	1.42	Ms	4.549-4.790	36.6	-1.31	5.434	5.328
2004/05/30	07:43	1.44	Kcont	2.256-2.285	37.1	-1.31	5.434	5.328
2004/05/30	07:46	1.47	Hcont	1.569-1.592	37.6	-1.31	5.434	5.328
2004/05/30	07:52	1.50	Jcont	1.203-1.223	38.3	-1.31	5.434	5.328
2005/05/31	05:32	1.10	Kcont	2.256-2.285	307.1	-2.63	5.457	4.893
2005/05/31	05:57	1.09	Lp	3.426-4.126	310.6	-2.63	5.457	4.893
2005/05/31	06:61	1.08	Ms	4.549-4.790	311.2	-2.63	5.457	4.893

Columns 4 and 5 show the central meridian longitude (CML) as seen by the observer and the observer's latitude; r = the heliocentric distance, Δ = geocentric distance.

Table 2: Locations and Intensities of the 2003-2005 Eruptions

Date (UT) Year/month/day	Filter	W. Longitude °	Latitude °	Emission angle °	Intensity ¹ GW/sr/μm
Tupan					
2003/03/08	Kcont	141.5±0.5	-17.6±0.5	23.4	11±1.7
2003/03/08	Lp	141.3±0.5	-18.0±0.5	21.3	17.5±2.6
2003/03/08	Ms	141.9±0.5	-17.6±0.5	22.3	27±4
Tung Yo Patera					
2004/05/28	Lp	0.7±1.0	-18.0±1	34	72±12
2004/05/28	Ms	1.1±2.0	-16.6±2	34	94±15
Sui Jen Patera					
2004/05/30	Jcont				not detected
2004/05/30	Hcont	4.0±0.5	-18.3±0.5	37	25±4
2004/05/30	Kcont	4.3±0.5	-17.4±0.5	36	49±8
2004/05/30	Lp	4.3±0.5	-17.1±0.5	35	59±9
2004/05/30	Ms	4.5±1.0	-16.8±1.0	36	71±12
S. of Babbar					
2005/05/31	Kcont	279±3	-51.7±1.4	53.3	63±15
2005/05/31	Lp	278.6±2.0	-49.8±2.0	54.8	57±14
2005/05/31	Ms	274.6±2.0	-50.2±2.0	55.0	72±15

¹ These numbers have been corrected for the emission angle effect.

Table 3: Locations and Intensities of Other Bright Hot Spots in 2003–2005

Volcanic Center Year/month/day	Filter	W. Longitude °	Latitude °	Emission angle °	Intensity ¹ GW/sr/ μm
2003/03/08					
Prometheus	Lp	155.1±0.5	-1.1±0.5	1.3	3±0.5
Prometheus	Ms	155.1±0.5	-1.2±0.5	1.3	5.3±0.8
2004/05/28					
Loki Patera	Lp	309.0±1.0	13.0±1.0	25.8	14.5±2.2
Loki Patera	Ms	309.8±1.0	15.0±1.0	26.6	41±6
Amaterasu Patera	Lp	306.0±1.5	37.0±1	45	5.5±1.0
Amaterasu Patera	Ms	308.0±2.0	40±2	46	28±4
Creidne Patera	Lp	340±2	-51±2	50	15±3
Creidne Patera	Ms	342.4±2.0	-49.2±2	49	53±8
2004/05/30²					
Masubi Fluctus	Lp	58.8±2.0	-43.5±2.0	46	3.9±0.6
Masubi Fluctus	Ms	57.8±2.0	-41.0±2.0	46	6.8±1
Euboea Fluctus	Lp	355±3	-50±3	59	8.6±1.5
Euboea Fluctus	Ms	355±3	-45±3	59	17.6±3.5
2005/05/31					
Loki Patera	Lp	311.0±1.4	15.4±1.4	17.6	10.7±2.6
Loki Patera	Ms	309.2±1.4	14.6±1.4	17.6	49±9

¹ These numbers have been corrected for the emission angle effect.

² Janus and Kanehekili were reported by de Pater et al., (2014b).

Table 4: Additional observations of the Tung Yo Patera environment¹

Date (UT) Year/month/day	Filter	Obs-long °	Obs-lat °	r AU	Δ AU	W. Longitude °	Latitude °	Emission angle °	Intensity ² GW/sr/ μm
2005/01/15	Lp	48.7	-2.83	5.456	5.246	6.4 $\pm$ 1.4	-11.1 $\pm$ 1.0	44	5.9 $\pm$ 1
2005/01/15	Ms	49.4	-2.83	5.456	5.246	5.5 $\pm$ 1.4	-11.1 $\pm$ 1.0	44	13.7 $\pm$ 2
2008/10/09	Lp	44.2	-1.44	5.146	5.088	9.6 $\pm$ 1.4	-11.5 $\pm$ 1.0	35	5.1 $\pm$ 0.8
2008/10/09	Ms	44.6	-1.44	5.146	5.088	10.7 $\pm$ 1.4	-11.7 $\pm$ 1.0	35	8.8 $\pm$ 1.4
2009/07/26	Lp	28.7	0.52	5.049	4.087				ND ³
2009/07/26	Lp	29.2	0.52	5.049	4.087				ND ³

¹ The images of these data were published in de Pater et al. (2014b).

² These numbers have been corrected for the emission angle effect.

³ ND = Not Detected

Table 5: 1T and 2T Model Fits to Eruptions

Date	1T fit Temperature K	1T Fit Area km ²	1T Fit Total Power GW	2T Fit Temperature A K	2T Fit Area A km ²	2T Fit Temperature B K	2T Fit Area B km ²	2T Fit Total Power GW
Tupan								
2003/03/8	690 ⁺⁸⁵ ₋₁₆₀	37 ⁺³⁰⁰ ₋₁₅	470 ⁺⁵³⁰ ₋₈₀	920 ⁺⁹⁰ ₋₃	5.5 ^{+0.7} _{-2.5}	287 ⁺³⁵ ₋₁₅	13,825 ⁺²⁶⁰⁰ _{-6,600}	5,000 ⁺⁵⁰ ₋₁₄₀₀
2003/03/8 ¹				1065	2	402	787	1300
Tung Yo Patera								
2004/05/28	550 ⁺¹³⁰ ₋₈₀	480 ⁺¹²⁰⁰ ₋₃₀₀	2460 ⁺¹⁸⁰⁰ ₋₅₀₀	~ 1075 ²	~ 6.6 ²	~ 450 ²	~ 1300 ²	~ 3500 ²
Sui Jen Patera								
2004/05/30	884±70	34 ⁺²⁰ ₋₁₂	1164 ⁺¹⁶⁰ ₋₁₂₀	1165±25	5.5±1	480±30	650 ⁺³⁰⁰ ₋₁₀₀	2000±500
S. of Babbar								
2005/05/31	925±100	28.5 ⁺²³ ₋₁₀	1175 ⁺¹²⁰ ₋₆₅					

¹ For this calculation we constrained the total surface area to 789 km², as explained in the text.

² This fit is not statistically justifiable as only two data points are available; however, we provide approximate numbers for comparison with 30 May 2004.

Table 6: 1-component IFM Model Fits to Eruptions

Date (2013)	Total Power GW	dA/dt m ² /s	Total area km ²	Oldest surface age hrs	Oldest surface temp K	2-micron radiant flux GW/micron	5-micron radiant flux GW/micron	2.5 micron radiant flux ratio	Flux density kW/m ²
Tupan									
2003/03/08	563^{+1000}_{-140}	1370^{+1400}_{-600}	77^{+1200}_{-40}	15.5^{+700}_{-10}	522^{+110}_{-140}	13.2^{+8}_{-6}	75^{+25}_{-18}	$0.18^{+0.2}_{-0.10}$	7.4^{+8}_{-4}
Tung Yo Patera									
2004/05/28	2800^{+4000}_{-800}	2680^{+5000}_{-800}	800^{+7000}_{-400}	80^{+1500}_{-60}	430^{+140}_{-90}	28^{+35}_{-10}	308 ± 60	$0.09^{+20}_{-0.04}$	3.5^{+7}_{-2}
Sui Jen Patera									
2004/05/30	1215^{+190}_{-140}	$20,000^{+11,500}_{-6,000}$	44^{+30}_{-15}	$0.61^{+1.1}_{-0.35}$	741 ± 70	114 ± 20	167 ± 30	$0.68^{+0.3}_{-0.2}$	28^{+12}_{-7}
S. of Babbar									
2005/05/31	1210^{+180}_{-70}	$30,000^{+40,000}_{-14,000}$	34^{+40}_{-13}	$0.3^{+1.6}_{-0.2}$	793 ± 110	140 ± 45	160^{+35}_{-20}	$0.87^{+0.5}_{-0.35}$	35^{+22}_{-14}

Table 7: 2-component IFM Model Fit to the Sui Jen and Tupan Paterae

Date (2013)	Total Power GW	dA/dt m ² /s	Total area km ²	Oldest surface age	Oldest surface temp K	2-micron radiant flux GW/micron	5-micron radiant flux GW/micron	2:5 micron radiant flux ratio	Flux density kW/m ²
Sui Jen Patera Component 1									
2004/05/30	555 ⁺⁵⁵ ₋₁₀₀	65,000 ^{+30,000} _{-5,000}	6.9 ^{+0.1} _{-1.4}	1.2±0.5 min	1000 ⁺⁴⁰ ₋₁₀	115 ⁺²⁰ ₋₁₅	62 ⁺⁴ ₋₁₅	1.8 ^{+0.2} _{-0.1}	80 ⁺¹⁵ ₋₅
Sui Jen Patera Component 2									
2004/05/30	2900 ⁺⁶⁰⁰⁰ ₋₁₃₀₀	630 ^{+12,000} ₋₃₆₀	2800 ^{+50,000} ₋₁₀₀₀	1.7 ⁺⁷⁰ _{-0.7} months	315 ⁺⁶⁰ ₋₈₅	6.6 ^{+5.8} _{-2.5}	160 ⁺³⁸ ₋₃₀	0.04 ^{+0.02} _{-0.01}	1.0 ⁺¹ _{-0.6}
Tupan Patera Component 1									
2003/03/08	106 ⁺⁸ ₋₁₉	40,000 ^{+14,000} _{-2,000}	0.8 ^{+0.01} _{-0.2}	20±5 sec	1140 ⁺³⁰ ₋₅	28 ⁺³ ₋₄	10.4 ^{+0.5} _{-1.8}	2.7 ^{+0.14} _{-0.06}	130 ⁺¹⁰ ₋₄
Tupan Patera Component 2									
2003/03/08	2550 ⁺⁸⁰⁰⁰ ₋₁₃₅₀	260 ⁺⁴⁰ ₋₃	4900 ^{+3,000} ₋₇₅₀₀₀	220 ⁺³⁰⁰⁰ ₋₁₅₀ days	265 ⁺⁸⁰ ₋₆₀	3.0±0.3	85±20	0.03 ^{+0.02} _{-0.01}	0.5 ⁺¹ _{-0.3}

28 May 2004

- 1: Tung Yo Patera (28 May 2004)
 1: Sui Jen Patera (30 May 2004)
 2: Loki Patera
 3: Creidne Patera
 4: Amaterasu Patera
 5: Kanehekili Fluctus
 6: Janus Patera
 7: Masubi Fluctus
 8: Euboea Fluctus
 9: Tupan Patera
 10: Prometheus
 11: S. of Babbar Patera

30 May 2004

8 March 2003

31 May 2005

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10