Io: Eruptions at Pillan, and the Time Evolution of Pele and Pillan from 1996 – 2015

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Abstract

Observations obtained with the near-infrared camera NIRC2, coupled to the adaptive optics system on the 10-m W.M. Keck II telescope on Mauna Kea, Hawaii, on 14 August 2007 revealed an active and highly-energetic eruption at Pillan at 245.2 ± 0.7 °W and 8.5 ± 0.5 °S. A one-temperature blackbody fit to the data revealed a (blackbody) temperature of 840 ± 40 K over an area of 17 km^2 , with a total power output of ~ 500 GW. Using Davies' (1996) Io Flow Model, we find that the oldest lava present is less than 1-2 hrs old, having cooled down from the eruption temperature of >1400 K to ~ 710 K; this young hot lava suggests that an episode of lava fountaining was underway. In addition to an examination of this eruption, we present data of the Pele and Pillan volcanoes obtained with the same instrument and telescope from 2002 through 2015. These data reveal another eruption at Pillan on UT 28 June 2010. Model fits to this eruption yield a blackbody temperature of 600-700 K over an area of $\sim 60 \text{ km}^2$, radiating over 600 GW. On UT 18 February 2015 an energetic eruption was captured by the InfraRed Telescope Facility (IRTF) via mutual event occultations. The eruption took place at 242.7 ± 1 °W and 12.4 ± 1 °S, i.e., in the eastern part of Pillan Patera. Subsequent observations showed a gradual decrease in the intensity of the eruption. Images obtained with the Keck telescope on 31 March and 5 May 2015 revealed that the locations of the eruption had shifted by 120-160 km to the NW.

In contrast to the episodicity of Pillan, Pele has been persistent, observed in every appropriate $4.7 \text{ }\mu\text{m}$ observation. Pele was remarkably consistent in its thermal emission from the *Galileo* era through February 2002, when a blackbody temperature of 940 ± 40 K and an area of

6.5 km² was measured. Since that time, however, the radiant flux from this potentially large overturning lava lake has gradually subsided over the next decade by a factor of ~4, while the location of the thermal source was moving back and forth between areas roughly ~100 km to the W of the 2002 location, to an area roughly ~100 km to the SE of the 2002 location.

Keywords: Io, Infrared Observations, Volcanism

1. Introduction

The highly volcanic jovian moon Io is a fascinating body because of the diverse styles of volcanic activity and the large scale of ongoing volcanic eruptions. Ground-based observers are often surprised by the appearance of new hot spots, or old ones that suddenly become active again (e.g., Marchis et al., 2002; Laver et al., 2007; de Pater et al., 2014a; de Kleer et al., 2014). In the summer of 2007 we had several nights to observe Uranus around the time the Earth went through this planet's ring plane (de Pater et al., 2013). On UT 14 August 2007, before Uranus was rising in the sky, we were able to obtain a few images of Io; these revealed renewed activity at Pillan, a site of particular interest as this was the site of a powerful eruption in 1997 that was observed with instruments on the *Galileo* spacecraft (Keszthelyi et al., 2001; Davies et al., 2001; Williams et al., 2001).

The volcanoes Pele and Pillan are in relatively close proximity, separated by only ~400 km (~0.1'' when viewed from Earth), and have been difficult to separate in the past, even with some of the *Galileo* Near Infrared Mapping Spectrometer (NIMS) observations obtained from within

the jovian system (Davies et al., 2001). By using adaptive optics (AO) techniques on the 10-m W.M. Keck telescope we can easily separate the two sources.

Because activity at each volcano is of a quite different nature (a persistent lava lake at Pele, and episodic, large-volume eruptions emplacing extensive lava flows at Pillan – see Davies et al., 2001), we present in this paper, in addition to an examination of the 2007 eruption at Pillan, a timeline of observations of both Pele and Pillan. This timeline includes all observations taken with the adaptive optics (AO) system on the Keck telescope since 2001, supplemented with images obtained with the AO system on the Gemini N telescope since 2013. We also report on an energetic eruption captured with the Infrared Telescope Facility (IRTF) in February 2015. We add these data to older observations taken with *Galileo* NIMS between 1997 and 2001 (Davies et al., 2001; 2010; 2015), as well as an eruption in 2008 reported by Lellouch et al. (2015).

2. Observations and Data Reduction

This paper has been triggered by observations of Io taken on UT 14 August 2007 between 06:10 and 06:39 UT using 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. We observed our target in the narrow band Jcont (1.21 μm), Hcont (1.58 μm), and Kcont (2.27 μm) filters, and the wide band Lp (3.78 μm) and Ms (4.67 μm) filters, as summarized in Table 1.

At the time of these observations, Io was at a geocentric distance $\Delta = 4.88$ AU, heliocentric distance $r = 5.30$ AU, had a visible magnitude of 5.6 and subtended 1.034 arcseconds on the sky. All images were processed using standard near-infrared data reduction techniques (flat-fielded, sky-subtracted, with bad pixels replaced by the median of surrounding pixels). The geometric distortion in the Keck images was corrected using the “dewarp” routines provided by Brian Cameron of the California Institute of Technology¹. The individual images were aligned and co-added to increase the signal-to-noise ratio. A photometric calibration was performed on the standard A2 star HD161903 (~7.0 mag; Elias et al. 1982), observed between 6:41UT and 6:56UT. A correction was made for the difference in airmass between the star and Io. At 1.2-2.3 μm the full width at half peak intensity (FWHM) of the stellar point spread function (PSF) was between 3.5 and 5 pixels, i.e., roughly 0.04”– 0.05”, which is close to the diffraction limit of the Keck telescope (van Dam et al. 2004). As expected, at Lp and Ms bands the FWHM was larger, 0.08” and 0.10”, respectively.

Additional data of Pele and Pillan taken between 2001 and 2015 are summarized in Tables 2 and 3. Most of these data were obtained with the same instrument setup, and the images were processed in identical ways. On non-photometric nights the background intensity of the images was bootstrapped from nights with good photometric calibrations, while accounting for the variations in Io’s heliocentric and geocentric distance.

Some of the data in Tables 2 and 3 were obtained with the Near Infra-Red Imager and

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

Spectrometer NIRI, coupled to the adaptive optics (AO) system ALTAIR, on the 8-m Gemini-North telescope. NIRI is a 1024x1024 ALADDIN InSb array, which we used in its highest resolution mode, with a focal ratio f/32 and pixel size of 22 x 22 milliarcseconds (mas). The images were processed using standard infrared data reduction techniques, and photometry was usually bootstrapped from other well-calibrated images (see, e.g., de Pater et al., 2014b). One additional dataset was taken during a mutual occultation event with the IRTF, and is discussed in more detail in Section 3.

3. Results

3.1 Keck observations of the Pillan eruption on 14 August 2007

Figure 1, panels a–e, shows the 14 August 2007 images of Io in all five filters. The images were slightly sharpened using AIDA, the Adaptive Image Deconvolution Algorithm from Hom et al. (2007). Panel f shows a view reconstructed from the 2001 Kcont (2.2 μm) map of Marchis et al. (2005) using the geometry of the new images, with various volcanoes indicated. A most striking eruption is seen at Pillan, visible even at 1.6 μm . Additional powerful hot spots at 3.5–5 μm are clearly visible at Loki Patera (308.8°W, 13.0°N)², Ulgen Patera (287.2°W, 40.7°S)² and Pele (255.3°W, 18.7°S)². Fainter spots show up at e.g., Dazhbog Patera (301.5°W, 55.1°N)² and Marduk (209.9°W, 29.6°S)².

² Positions from <http://planetarynames.wr.usgs.gov/>

To determine the exact location of the Pillan eruption, we determined the center of the disk manually by centering a circle around the limb of Io in each image, and repeated this for different image stretches and circle sizes. The uncertainty in the disk center is estimated to be less than $\frac{1}{4}$ -th of a pixel. The image was then deprojected using the ephemerides for the sub-observer latitude and longitude as obtained from the JPL ephemeris³. The center of the eruption was assumed to be at the position of peak intensity. We averaged the positions obtained at the four wavelengths (Hcont, Kcont, Lp, and Ms bands). The error was determined from the spread in positions, simultaneously accounting for an adopted $\frac{1}{2}$ pixel ($\sim 0.5^\circ$) uncertainty in each of the positions. This way we determined that the eruption center is at $245.2 \pm 0.7^\circ \text{W}$ and $8.5 \pm 0.5^\circ \text{S}$. For comparison, we determined the position of Pele to be at $257.5 \pm 0.9^\circ \text{W}$ and $18.0 \pm 0.4^\circ \text{S}$. The location of the 2007 Pillan eruption, shown in Figure 2, is relatively close to the eruption observed in 1997 by the *Galileo* spacecraft (Keszthelyi et al., 2001; Davies et al., 2001), and is discussed further below.

The original intention of the deconvolution of the images was to determine the exact flux density, or radiant flux ($\text{GW}/\text{sr}/\mu\text{m}$), of the hotspot (e.g., Marchis et al., 2005); however artifacts introduced by the process rendered the results unsuitable. Due to the crowded and uneven nature of the flux from Io's surface, gaussian fitting of the volcano also proved an unreliable method of determining the absolute flux density of the eruption. Ultimately, we used the method described in detail by de Pater et al. (2014b) on the original (i.e., before deconvolution) images. In short, the radiant flux 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 much flux is lost in the PSF halo, we determined the fraction of the flux lost by determining the radiant flux of the star in

³ <http://ssd.jpl.nasa.gov/horizons.cgi>

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 radiant flux is then divided by the ratio of the stellar flux to the total intensity from the star. To facilitate comparison with previous flux estimates, the results were normalized using the distance to Io at the time of the observation; the resulting numbers are reported in Table 4. These numbers have been corrected for geometric foreshortening, i.e., the numbers as reported were divided by the cosine of the emission angle θ , the angle between the line of sight and the normal to the surface. This was a tiny correction (Table 4). We did not determine the radiant flux in the Hcont filter, as the contrast of the eruption compared to the reflected sunlight in this image is very low (Fig. 1). The hot spot is not seen in the Jcont filter. As shown, the radiant flux peaks at Lp band (3.8 μm) at $\sim 30 \text{ GW/sr}/\mu\text{m}$, or at spectral radiant emittance of 94 $\text{GW}/\mu\text{m}$ (i.e., $\pi \times 30$; e.g., de Pater et al., 2014a). It is slightly less in the Ms band (4.7 μm). Although clearly a relatively bright eruption, it falls short by over an order of magnitude compared to an outburst-class eruption.

3.2 Keck and Gemini observations of Pillan in 2001 – 2015

The Pele/Pillan sites have been observed a few dozen times with the Keck and Gemini telescopes between 2001 and 2015; images in three filters (usually the Kcont, Lp and Ms filters) are shown in Figure 3. In contrast to Figure 1, these images have not been sharpened. In the Lp and Ms band images numerous hot spots are visible; amongst those Loki Patera, Pele and Pillan are indicated. No activity was seen at Pillan on 3 April 2007, 4 months before the bright 2007 August event. Just prior to this, in February 2007, the NASA *New Horizons* spacecraft observed Io in the visible and short-wavelength infrared and did not detect any significant thermal

emission from Pillan either (Spencer et al., 2007).

Unfortunately, after August 2007 the Pillan site was not seen by either the Keck or Gemini telescopes for another two years. In the meantime, however, an extremely vigorous eruption was reported by Lellouch et al. (2015) at a wavelength of $4.0\ \mu\text{m}$; these data were taken with the CRYogenic high-resolution InfraRed Echelle Spectrograph (CRIRES) on the Very large Telescope (VLT). They report a radiant flux of $157\ \text{GW}/\text{sr}/\mu\text{m}$, or an emittance of almost $500\ \text{GW}/\mu\text{m}$ at $4.0\ \mu\text{m}$, which is over a factor of 2 higher than the highest radiant flux measured by Galileo/NIMS. They report a position of $244\pm 1^\circ\text{W}$ and $7\pm 2^\circ\text{S}$, which agrees well with the 2007 location reported in this paper (Fig. 2). We assigned a photometric uncertainty of 15% to this measurement, just like for our own observations.

We determined the radiant flux from Pillan and Pele on all images where these volcanoes were detected, using the same technique as employed above (and by de Pater et al., 2014b). The results are summarized in Tables 2 (Pillan) and 3 (Pele). We typically can measure radiant fluxes if they are above $1\ \text{GW}/\text{sr}/\mu\text{m}$ in Keck Ms and Lp images, and $3\ \text{GW}/\text{sr}/\mu\text{m}$ in Gemini Lp images, for hot spots near the center of the disk (de Kleer & de Pater, 2015).

As shown, the radiant flux varies from less than $1\ \text{GW}/\text{sr}/\mu\text{m}$ up to several $\text{GW}/\text{sr}/\mu\text{m}$ for Pillan. On 28 June 2010, however, one year after the previous observation of the Pillan location, another eruption was seen, with the radiant flux reaching almost the same level as on 14 August 2007. The peak flux, however, is at longer wavelengths than in 2007, indicative of a lower lava surface temperature for the bulk of the exposed lava surfaces than that seen in 2007. Because the eruption site was close to the limb at the time of the observations in 2010, we could not determine the exact location of the eruption. One month later, by 27 July 2010, the eruption had mostly subsided ($\sim 2\ \text{GW}/\text{sr}/\mu\text{m}$ in the Ms filter).

3.3 Mutual occultation events of Pillan observed with the IRTF

On UT 18 February 2015, we fortuitously observed an extremely vigorous eruption at Pillan during a mutual event campaign at NASA's Infrared Telescope Facility (IRTF). We monitored the brightness of Io using the SpeX imaging camera (Rayner et al., 2003) as it was occulted by Europa, and the discrete hotspots are indicated by sudden jumps or drops in the lightcurve. The event lightcurve and the projection of Europa's limb at the time of the Pillan disappearance and reappearance are shown in Figures 4 and 5. The observations were conducted with the Lp filter. From the sudden drop and rise in intensity, the radiant flux has been determined at 5.44% of Io's total flux density -- reflected sunlight + hot spots + Europa's flux density; the latter, however, can be ignored at this wavelength relative to Io. Typical Lp band flux densities observed over the past years with the IRTF, Gemini and Keck telescopes range roughly from 800 to 1100 GW/sr/ μ m. Using 950 GW/sr/ μ m, with a 20% uncertainty, we find a radiant flux for Pillan of 52 ± 10 GW/sr/ μ m. The eruption took place at 242.7 ± 1 °W and 12.4 ± 1 °S, i.e., right at Pillan Patera. After correction for the emission angle effect ($\theta=48.9^\circ$), we find a total radiant flux at Pillan of 80 ± 16 GW/sr/ μ m.

Two weeks prior to the 18 February occultation event, on 4 February 2015, we also observed a mutual occultation event. Although Europa passed slightly too far north to occult Pillan, imaging obtained during the event suggests that the source must have been at least 3 times fainter on this date than on 18 February. A third occultation event, on 15 March 2015, i.e., almost a month after the 18 February event, showed a dramatic decrease in intensity compared to the 18 February event (roughly by a factor of 5). Although we do not have a precise location for

this event, the “disappearance arc” is within 14 km from the 18 February event (Fig. 5), suggestive that no large shift in eruption location occurred. Although we point out that the location could be anywhere along that arc.

Observations with the Gemini and Keck telescopes in late March through early May showed that the flux continued to decrease. However, on 31 March 2015 the location of the eruption was measured to be at 247.4 ± 0.9 °W and 11.8 ± 0.8 °S, and on 5 May 2015 it was at 246.5 ± 0.6 °W and 11.3 ± 0.5 °S, i.e., both to the SW of the 2007 eruptions and to the NW of the 18 February 2015 eruption.

3.4 Keck and Gemini observations of Pele in 2001 – 2015

In contrast to Pillan, Pele was still as active in February 2002 as throughout the Galileo era. In 2002, its flux peaked in the Lp band at a level of ~ 17 GW/sr/ μ m. In the Ms band it reached levels of ~ 13 GW/sr/ μ m. We even see a clear signal in the Kcont filter, at a level approaching that in the Ms band. Its location was at 256.2 ± 0.5 °W, 18.0 ± 0.5 °S (Fig. 2), very close to the main source of emission as observed throughout the Galileo era. Four measurements were taken over the course of the night of 21 Feb 2002. Both the Lp and Kcont values in the first set of data are lower than in subsequent sets; we attribute these variations to effects in atmospheric seeing rather than a physical change in the volcanic activity. In particular, variations in the Kcont band are quite sensitive to changes in seeing (and hence in the point spread function, PSF, which affects the measured intensity). The actual Kcont intensity is most likely near the high end of the observed values, i.e., 12 – 13 GW/sr/ μ m. Unfortunately, no measurements were obtained from 2002 until 2007 (Pele was on the limb in the 29 May 2004 observations; Fig. 3),

and since that time Pele does not appear anymore as one of the strong persistent sources, although in 2010 Pele was a little more active than in prior or later years. In 2011-2015 Pele's overall intensity is roughly $\frac{1}{4}$ that of the 2002 level. Note that the Lp and Ms band radiant fluxes are usually similar, as expected for an overturning lava lake. Pele was observed as an active thermal source in every appropriate *Galileo* observation (Davies, 2007), and throughout the *Galileo* mission showed little variation in thermal emission (Davies et al., 2001; Davies et al., 2008). Based on the implied dynamic nature of eruption style at Pele without the emplacement of cooling lava flows, it has been assumed to be an active, vigorously overturning lava lake (Davies et al., 2001). The subsequent drop in thermal emission indicates a level of variability not previously seen, although a change of a factor of a few in thermal emission is not uncommon even with persistent, active lava lakes on Earth (see Wright and Pilger, 2008; Davies and Ennis, 2011). Intriguing is the fact that the location of the source of emission appears to move from an area of order ~ 100 km to the W. to an area of order 100 km to the SE. of the 2002 location, as indicated in Figure 2. For example, between April and August 2007, the source shifts by about 4° in longitude, or 140 km, from the box East of the 2002 position (Fig. 2) to that on the West of the 2002 location. In early 2013 it is in the W. box; in November 2013 it is in the E. box. In February 2014 it is in the W box, in October-December 2014 it is in the E. box, and in 2015 it is in the W. box. These are large shifts, which have never before been reported. Moreover, this varying position of the main Pele hot spot challenges the previous notion that the main thermal source is fixed in location. Previous data analyses revealed smaller hot spots in SSI (e.g., Radebaugh et al., 2004) and NIMS data (e.g., Davies et al., 2002) close to the main thermal source. The movement of the main thermal source, coupled to the recent reduction in thermal emission are indicators that changes are taking place at Pele.

4. Analysis

Table 5 shows the results of single blackbody temperature (1T) fits to the 2007, 2010, and March 2015 Pillan and the 2002 Pele data. Two-temperature (2T) fits are generally preferred if data are taken at 3 or more wavelengths, since lava lakes and flows usually exhibit a wide range of temperatures and areas, and two-temperature fits are generally a good representation of the total power radiated (the area under the spectrum) as well as being a better representation of surface temperature distributions than a single temperature, single area fit. The 1T and 2T temperature fits for the 2007 Pillan eruption, however, both converged to the same single blackbody temperature of 840 ± 40 K covering an area of about 17 km^2 , indicative of an active, young eruption with a correspondingly relatively narrow range of temperatures present. Although fits were made to three data points, the two-temperature fit converged towards the one-temperature fit because the data straddled the peak intensity, the result of areas at a relatively narrow range of high-temperatures. The 2002 Pele data can also be best matched with a 1T fit, yielding a temperature of 920 K and an area of $6\text{-}7 \text{ km}^2$, as expected for an active, overturning lava lake. The 1T fits to both the 2007 and 2010 Pillan and 2002 Pele data are shown in Figure 6.

The errors on all derived physical quantities (as temperature, area, power, age) were derived from the measurement uncertainties on the intensities (Tables 2 - 4) by also fitting blackbody curves to data points where the measured uncertainty was subtracted from the shortest wavelength data point and added to the longest one, and vice versa, so as to cover the entire possible range of blackbody curves that fit the data. The uncertainties on the physical quantities (Tables 5, 6) are derived from the spread in these blackbody curves, as described by de Pater et al. (2014b).

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.

4.1 Pillan

August 2007: The IFM fit to the 2007 Pillan data results in a total power output in good agreement with the 1T blackbody fits, i.e., roughly a total of 500 GW radiated from an area of $\sim 20 \text{ km}^2$. The oldest surface present is less than 1-2 hrs old, derived from the fact that the oldest radiating surface has cooled down from the eruption temperature of $>1400 \text{ K}$ to $\sim 710 \text{ K}$. Lava is pouring out from a vent or vents at an areal coverage rate of $\sim 6000\text{-}7000 \text{ m}^2/\text{s}$. If the lava flows are similar in thickness to the 1997 Pillan flows ($\sim 10 \text{ m}$; see Williams et al., 2001), this yields an instantaneous discharge (effusion) rate of 6×10^4 to $7 \times 10^4 \text{ m}^3/\text{s}$, comparable with the highly-voluminous outpourings of lava at previous outburst sites such as Rarog and Heno Paterae (de Pater et al., 2014a). Hence, we are observing a vigorous, high-effusion rate eruption at Pillan, not dissimilar to the event observed by instruments on the *Galileo* spacecraft in 1997.

June 2010: In 2010 thermal emission from the Pillan eruption was measured at two wavelengths. The temperature from a single-temperature fit to the data obtained on 28 June 2010 was $640_{-100}^{+200} \text{ K}$ from an area of a few tens of km^2 (Table 5). Over the subsequent months the temperature dropped to below 300 K , while the area covered by lava increased substantially, up to a few 100 km^2 by August 22, and 3 weeks later covering perhaps over $10,000 \text{ km}^2$. If a

circular area, this would be 112 km in diameter. This is an area larger than the 5600 km² covered by lava flows in 1997 (Keszthelyi et al., 2001).

The IFM fits (see Table 6 and Figure 6) show that the 2010 eruption was not as vigorous as the 2007 eruption at the time of our observations. Initially, the lava emplaced is still relatively young, approximately a half day old and covering an area of several tens km². The shape of the spectrum on 2010 June 28 (with a thermal emission spectrum peak around 2.5 μm) is indicative of being dominated by a style of eruption whereby relatively large areas at high temperatures are exposed, indicative of molten silicates – for example, lava fountains, or perhaps a turbulent flow emplacement regime.

February – May 2015: The 18 February 2015 eruption was detected at only one wavelength, Lp band, and hence no blackbody fits could be obtained. On 31 March 2015 the eruption was detected at 3 wavelengths, and an excellent 1T fit was obtained, with a temperature of 358 ± 20 K over an area of almost 1600 km². A 2T fit shows that there is a higher temperature, ~380 K, present over almost 800 km², while the majority of the emission comes from a large area (~14,000 km²) at a relatively low temperature (~250 K), which are likely cooling flows or warm pyroclastic deposits. The 1T fit temperature of 360 K suggests an exposure time, if we are observing lava flows, of ~25 days (Davies et al., 2010), assuming the lava flows are at least 2.5 m thick (thinner flows would cool faster). This is likely a maximum age of the recently-emplaced volcanic material. If the thermal emission is emanating from pyroclastic deposits, then the age could be younger as the pyroclasts would have lost energy and cooled during their flight. Finally, the possibility cannot be ruled out that the material erupted is lower-temperature sulfur.

The locations of activity in February, March and May 2015 point to an increase in

regional thermal emission due to new effusive eruptions, with apparently different eruptions taking place within Pillan Patera (February 2015) and on the plains to the southwest of Pillan Mons in March and May 2015. The lack of detectable thermal emission from Pillan Patera in March 2015 suggests that the lava flows emplaced there may have been thin and rapidly-cooling, or perhaps that activity was confined to a small area such as a lava lake that filled and then drained. Observations immediately following the 18 February eruption would have charted a cooling profile that might have allowed further constraints on eruption mechanism and type, while full time coverage at high spatial resolution might have given insight as to possible connections between the various eruption sites.

4.2 Pele

The IFM fit to the 2002 Pele data (Table 6) is also in excellent agreement with the 1T blackbody fit, with a total power of ~ 270 GW over an area of 7.5 km^2 area. This lava is less than $\frac{1}{2}$ hr old, i.e., extremely young. The surface temperature has only cooled down to ~ 800 K, and lava in the lake is vigorously overturning, exposing new incandescent surfaces at a similar rate as during the Pillan eruption, $\sim 7000 \text{ m}^2/\text{s}$. Again, this is in keeping with other observations of a lava lake overturning at Pele (Davies et al., 2001). However, as mentioned in the previous section, the movement of the main thermal source, coupled to the reduction in thermal emission are suggestive of a much more complicated pattern. Perhaps with the subsidence of the main source of activity after the 1996 – 2002 era, smaller thermal sources away from the main lava lake started to dominate the emission, thermal sources such as were seen along the graben in Galileo NIMS and SSI images (Davies et al., 2002; Radebaugh et al., 2004).

We note one caveat to our model fits and subsequent analysis. In this analysis we always assume an emissivity of 1. Recent work (e.g., Lee et al., 2013) indicates that the emissivity of molten and cooling lava may be lower than commonly assumed. If, for example, the average emissivity of the high-temperature silicates erupting on Io was closer to 0.9, the result would be that the areas implied by our modeling would be larger by about 10%, with a similar sized increase in implied lava discharge rate.

If the ongoing derivations of accurate emissivity behavior as a function of temperature and wavelength for high-temperature silicates from laboratory (Ramsey and Harris, 2015) and field investigations (Vaughan et al., 2015) shows that the variability of emissivity is greater than 10%, then new emissivity values need to be incorporated into our data analysis models.

5. Discussion

5.1 Eruption style and emplacement mechanism

Davies et al. (2010) showed that both the ratio of 2- and 5- μm radiant fluxes and the magnitude of the radiant flux can be used to constrain the likely style of eruption and emplacement of active volcanic activity. Figure 7 shows the 2- μm versus 5- μm radiant fluxes as deduced from the IFM fits for the Pele and Pillan observations (Table 6) alongside similar numbers for a broad range of styles of volcanic activity from data collected for Io (Davies et al., 2010; as updated by de Pater et al., 2014a, b and de Kleer et al., 2014). As shown, both the 2002 Pele and 2007 Pillan placements on the plot are indicative of active eruptions or overturning lava

lakes, as the 2 and 5- μm points are roughly equal (placed near the solid line) and quite substantial -- though displaced quite a ways towards the left along the diagonal line compared to the “outburst” class eruptions near the upper right of the plot. However, the diverging temporal evolutions for these two volcanoes shows that different styles of activity are taking place. The 2007 Pillan eruption is less energetic than that observed near its peak in 1997. The June 2010 eruption is less energetic than in 2007, and decreased substantially in subsequent months, bringing it close to the placement of insulated lava flows (IFL), characterized by a radiant flux that is much larger at 5- μm than at 2- μm . The 2- and 5- μm trends of the 2010 eruption are similar to that seen in 1997 at Pillan (Figure 7). With time passing, the eruption transitions from fountaining to effusive emplacement, insulating crusts develop on the lava flows, crusts that cool with time even as the flow field enlarges. Eventually, the eruption slows and stops, the flow field ceases to enlarge, and the emplaced flows continue to cool and solidify. As cooling proceeds, the level of thermal emission drops and the peak of thermal emission moves to longer wavelengths.

The 2002 observation of Pele is also shown in Figure 7. The Pele point is located within previous Pele measurements derived from NIMS nighttime observations. This location is indicative of continuing vigorous overturning and/or lava fountaining activity in the lava lake (see Davies et al., 2001).

Figure 8 shows a plot of the 2:5- μm radiant flux ratio as a function of the radiant flux density (the energy emitted per unit area) for different styles of volcanic activity from data collected for a broad range of eruption types on both Earth and Io (adapted from Davies et al., 2010; as updated by de Pater et al., 2014a, b and de Kleer et al., 2014). Because this plot shows the relative brightness at two wavelengths compared with the radiant flux density, we have

removed the areal scale of the eruption in this plot. As one can deduce from Figure 7, lava flows with insulating crusts have a low 2:5 μm ratio, while eruptions that fall along the diagonal line in Figure 7 have a 2:5 μm ratio that is equal to unity. Outburst-class eruptions (like the red circles for Io) are characterized by ratios well above unity. The 2007 and 2010 Pillan data show initial high-temperature components; by the August and September 2010 observations, the radiant flux density has dropped, indicative of extensive, cool areas, most probably cool crusts on extensive lava flows. The Pele 2002 datum is located among other Pele points derived from NIMS data, suggesting similar activity in 2002 as during the *Galileo* epoch.

Figure 9 shows the time evolution of Pillan and Pele at 4.6 – 5 μm (Ms band) from 1996 through 2015. Occasional Lp band fluxes for Pillan are indicated as well. In this figure, we combine the *Galileo* NIMS data from the NITED database (Davies et al., 2012, 2015) with the observations reported in this and other papers, as indicated in Tables 2 and 3.

5.2 Pele

Throughout the 1990s and into 2002 Pele has been active; in fact, it was one of few volcanoes that was always visible, even at 2.2 μm (Fig. 3). This changed after 2002, when Pele gradually became fainter, and the distinct bright spot at 2.2 μm disappeared. At times Pele became so faint we could not even measure its radiant flux on the images (i.e., it had dropped below 1-2 GW/sr/ μm in the Ms and Lp bands).

The drop in Pele's thermal emission suggests that less incandescent lava is exposed. If Pele is indeed a lava lake, incandescent lava is exposed where the crust on the surface of the lava lake is disrupted and destroyed, by either vigorous convection in the magma underneath the crust

and/or by explosive gas release (see Davies et al., 2001). A decrease in the gas content of the lava could conceivably decrease lake convection and thus the area of crust disrupted, and this would reduce thermal emission at near-infrared wavelengths. The thermal emission from persistent terrestrial lava lakes may undergo short-term (daily) and longer-term (yearly) temporal changes as the amount of exsolving gas in the magma changes, as local topography changes, as vent and conduit geometry changes, and as a function of variability in the magma supply rate. Persistent terrestrial lava lakes at Erebus volcano (Antarctica), Erta'Ale volcano (Ethiopia), and Nyiragongo volcano (Democratic Republic of Congo) all show variability in thermal emission sometimes exceeding a factor of 10 (see Wright and Pilger, 2008; Davies and Ennis, 2011), while all the time remaining active. The decadal-long but slight decline in Pele's thermal emission together with the apparent shifts in location warrants further study and more observations to see if these trends continue or reverse, and/or if there is any trend in the positional changes.

If the lava in the lake has a reduced gas content, the Pele plume may not be depositing as much red material (likely short-chain sulfur compounds, such as e.g., S₂, S₄, ...) on Io's surface. Red deposits near active vents and large plume deposits are unstable and fade over timescales of just years to decades (McEwen et al., 1998). Visible wavelength observations of Io should show if the extensive (1200-1500 km diameter) red plume deposit is still present.

5.3 Pillan

Galileo captured a large outburst of Pillan in June 1997 (Keszthelyi et al., 2001; Williams et al., 2001; Davies et al., 2001). A sequence of observations over several months was obtained

with NIMS, starting in May 1997, close to the onset of the eruption (Davies et al., 2001). The eruption reached its peak in June 1997, when the thermal signature was that of a likely lava fountain and associated lava flows (Davies et al., 2001; 2010). Subsequent cooling of the emplaced lava flows was recorded by NIMS over the next 2 years. In 2007, 2008, 2010 and 2015 only single events were seen, although we often have only one data point over a period of several months, and hence could have missed other eruptions. In 2007 no activity was seen in early April, ~4 months before the eruption. After the August 2007 observation, approximately one year later, a single data point was obtained by Lellouch et al. (2015) at a wavelength of 4.0 μm . This was an extremely vigorous eruption with a radiant flux roughly twice as large as ever observed before. The next data point was obtained one year later, in 2009, when Pillan was hardly visible. In 2010, one year after the 2009 data point, Pillan was active again; one month after the eruption the radiant flux had considerably subsided. With these one-time data points, it is possible to have missed the onset of the eruption, which may have been much more energetic than what we observed, and it could have been episodic for several months. For the most recent eruption, captured on 18 February 2015, it is clear from the observations we did obtain, that the eruption must have started after the 4-th of February, and already had subsided considerably by the 15-th of March, and continued to gradually subside.

Thanks to the high spatial resolution of the data, it is possible to confine the activity in 2007 to an area located to the south of Pillan Mons and north of Pillan Patera (as shown in Fig. 2), an area ~70 km NW of the 1997 eruption. In 1997, lava flows extended from the base of Pillan Mons to Pillan Patera, which was then flooded with lava (Williams et al., 2001). It is likely that the 2007 eruption followed a similar evolution. Lava most likely erupted from fissures extending from Pillan Mons, creating extensive lava flows on the plain between the mons and

patera. The 2008 eruption reported by Lellouch et al. (2015) was very close to the 2007 eruption site. In 2010, the eruption at Pillan was only seen on Io's limb which prevents location of the main area of activity to the same precision as for the 1997 and 2007 data. Assuming a similar style of activity as seen in 1997 and a location between Pillan Mons and Pillan Patera, given the final extent of the lava flows emplaced in 2010 it may be that Pillan Patera was flooded again. On UT 18 Feb 2015, the location of the eruption was determined from the light curves and the (JPL Horizons) ephemerides (Fig. 5) to be $242.7 \pm 1.0^\circ \text{W}$, $12.4 \pm 1.0^\circ \text{S}$, inside the eastern part of Pillan Patera itself. On UT 15 Mar. 2015 only the Pillan disappearance could be unambiguously identified in the lightcurve and from a single limb arc a unique location cannot be determined. However this disappearance arc passes within 14 km of the 18 February location, giving confidence in the ephemerides and suggesting that no large shift in eruption location occurred. On 31 March and 5 May 2015, while the total radiant flux from the eruptions was fading, the location of the eruptions had shifted $\sim 120\text{-}160$ km to the NW of the 18 February 2015 event (Fig. 2), or ~ 100 km to the SW of the 2007 eruption.

7. Conclusions

In this paper we presented Keck and Gemini AO observations of Pele and Pillan taken over a period from 2001 through 2015, as well as a mutual occultation event of Pillan observed with the IRTF in 2015.

Throughout the 1990s and through early 2002, Pele was a reliable, persistent, hot spot, visible even at wavelengths as short $2.2 \mu\text{m}$. However, after 2002 the radiant flux steadily

decreased (with a noticeable exception in 2010), and the location of the dominant source moved around. The flux levels were typically $\sim 1/4$ that measured in 2002. Additional observations will reveal if this trend continues or if Pele returns to its pre-2002 behavior.

Since the 1997 eruption at Pillan, several new eruptions were recorded. One active eruption on UT 14 August 2007, with a blackbody temperature of 800 – 900 K over an area of 17 km², and a total power output of ~ 500 GW. The implied style of activity, consistent with previous observations of activity at Pillan, is that of lava fountaining. Although the 2007 eruption was not as energetic in an overall sense as that in 1997, it was quite similar when the power output per unit area is considered. Its location was very close to that detected by *Galileo* in 1997.

A second eruption was captured on UT 28 June 2010. This eruption was likely captured at a slightly more evolved stage, because the temperatures observed indicated that older (and therefore cooler) surfaces were present. The area covered was ~ 60 km², suggesting that extensive lava flows were in the process of being emplaced. In addition, a much more vigorous eruption was reported to have taken place in 2008 (Lellouch et al., 2015).

A third eruption reported in this paper via a mutual occultation observation at the IRTF on 18 February 2015 had a magnitude similar to the 1997 eruptions. The February 2015 eruption took place inside the eastern part of Pillan Patera. Subsequent observations with the Keck telescope showed that the location of the eruption had shifted by ~ 120 -160 km to the NW, in the plains to the SW of Pillan Mons.

Judging from a comparison of the *Galileo* observations of the 1997 Pillan eruption with the groundbased observations of the 2007, 2008, 2010 and 2015 eruptions it is clear that most information on eruptions can be derived from a sequence of observations, starting just before the onset of the eruption through its end (see e.g., de Kleer et al., 2014; de Pater et al., 2014a). High

spatial resolution is essential to uniquely identify the eruption source volcano, in particular if there are other nearby volcanic sources, and if the source location is shifting over time. A high frequency of observations is necessary to chart timelines of variability of large effusive eruptions, and to constrain the episodicity of such events. As reported in this paper, we observed a series of effusive events at Pillan, but our data lack the spatial resolution as well as a full coverage over time to understand the fine details of the eruptive activity and if, and how, these events are linked. Although dedicated monitor programs on 8-10 m groundbased telescopes would provide a wealth of information to begin examining repose time and recharge rates of the magma chambers that trigger such eruptions, we ultimately would need a dedicated Io mission making close flybys of Io to provide us with the high spatial, broad frequency and high time resolution needed to fully understand Io's volcanism (e.g., McEwen et al., 2015).

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Figure Captions

Fig. 1. Images of an eruption at Pillan, captured with the Keck telescope on UT 14 August 2007. The contrast in the images is slightly enhanced by using a deconvolution algorithm (see text). Panel f shows the geometry of the images, as reconstructed from the 2001 Kcont map of Marchis et al. (2005). Several volcanoes are indicated.

Fig. 2. Superposition of the locations of the eruptions at Pele and Pillan on a map of Io. The 2007 and 2008 eruptions at Pillan are relatively close to the 1997 eruption. All three eruptions took place in Pillan Mons. The Feb. 2015 eruption is located within the eastern half of Pillan Patera, while the source location of the March and May eruptions took place in the plains to the SW of Pillan Mons. The 2002 emission source at Pele is relatively close to the location as mapped by Galileo NIMS. However, in later years, when the overall emission had decrease in intensity, the location of the main source of emission typically occurred either ~100 km to the W or ~100 km to the SE of the 1997-2002 eruptions. No trend in the location of the emission over time could be identified; the emission moved back and forth between the box to the W and to the E of the canonical lava lake. The figure basemap is the combined *Galileo-Voyager* grayscale mosaic from the Io database, with a spatial resolution of 1 km/pixel (Williams et al., 2011).

Fig. 3a-c. AO-corrected images in the Kcont, Lp and Ms bands obtained with the Keck telescope between 2002 and 2015 (top panel in Fig. 3b, 9 Sep. 2010, was taken with the Gemini telescope). These images all show the Pele/Pillan region. The eruptions in the south in 2014-2015 will be

discussed in de Kleer & de Pater (2015). The images were stretched such as to show the best contrast, which is different for different images.

Fig. 4: The observed flux from Io and Europa as observed on 18 Feb. 2015 as Io is occulted by Europa is shown by the dots. It is superposed on the model flux expected from the sunlit disk and two hotspots with adjustable brightness and position. Below the main curve is an expanded version of the difference between the observations and the disk model and represents the hotspot flux. The sharp drop near 13.9 UT and the rise near 13.13 UT are caused by the disappearance and reappearance of Pillan.

Fig. 5: A simulated image of Io at the time of the 18 February mutual event, with white circles representing the limb of Europa at the times of the hotspot disappearance and reappearance. The hotspot is located at their intersection. The solid curves in the inset are the limb arcs projected onto a map of Io. For orientation purposes, we indicated Pele and Reiden Patera on the disk and the inset. The intersection, at (242.7 W, 12.4S), is within Pillan Patera. Because only the faint disappearance step could be identified in the 15 March lightcurve we only have one arc (dashed) for that date and that hotspot could lie anywhere along that arc. However that arc, passes within 14 km of the 18 Feb. location, a distance which is within our estimated 30 km margin of error.

Fig. 6. Single temperature (1T) blackbody fits (blue line), and IFM (Davies [1996] multi-component model) fit (black line) to a) the 2007 Pillan eruption, b) the 2010 Pillan eruption, and c) the 2002 Pele thermal emission. Also shown are fits to the data showing the uncertainty in the fit (dashed lines), which bracket the solid lines (the best fit to the data). For cases where there

are three data points that strongly constrain the peak in thermal emission, the uncertainty is low (Figs. 4a and 4c).

Fig. 7: Plot of 2- μ m versus 5- μ m radiant fluxes for different ionian volcanoes exhibiting high-energy, vigorous styles of eruption. The positions of Pillan in 2007 (orange square) and 2010 (red squares), and the trend in the 2010 data are similar to the large eruption at Pillan in 1997 (pink squares). The Pillan 2010 data are numbered in sequence (1 to 3), as are the 1997 data (1 to 6). The Pele datum from 2002 plots in the same location as previous analyses of nighttime Pele data (blue diamonds), as seen by *Galileo* NIMS. All other points plotted are either thermal outburst events; detections of possible lava lake overturn or fire fountain activity (Isum, Janus Patera); and Loki Patera, likely an extensive but quiescent lava lake, is shown as an extreme example of a active volcano where thermal emission is dominated by cool crust. Key: F = lava fountains. C = open channel flows. AL = active lava lakes. QL = quiescent lava lakes and flows. IFL = flows with insulated crusts. Numbers refer to a chronological sequence of observations. For Rarog and Heno Paterae, 1 = 2013 Aug 15, 2 = 2013 Aug 20 and 3 = 2013 Aug 22. Base image from Davies et al. (2010); updated most recently by de Pater et al. (2014a, b) and de Kleer et al. (2014).

Fig. 8: Plot of the 2:5- μ m radiant flux ratio against the radiant flux density for different styles of volcanic activity on Io and Earth. The numbers 1-6 on the plot are associated with the Pillan eruption of 1997 through 1998, and show the changing nature of the eruption, from the initial lava fountain phase through a transition to lava flow emplacement, to cooling emplaced lava flows. The 2007 Pillan eruption is slightly less energetic than the initial phase of the 1997 Pillan

eruption, and the 2010 Pillan eruption is less energetic still. The 2002 Pele eruption is very similar to previous analysis of NIMS observations, and is slightly more energetic than the 1997 and 2007 Pillan eruptions. Base image from Davies et al. (2010); updated most recently by de Pater et al., (2014a, b) and de Kleer et al., (2014).

Fig. 9. Time evolution of Pele and Pillan at 4.6-5 μm (Ms band), from 1996 through 2015. The y-axis shows the spectral radiant emittance in $\text{GW}/\mu\text{m}$, i.e., $\pi \times F$, with F the radiant flux in $\text{GW}/\text{sr}/\mu\text{m}$, as given in Tables 2-4. The open symbols are measurements taken with *Galileo*/NIMS, and recorded by Davies et al., (2001; 2012; 2015). The solid symbols are data presented in Tables 2, 3, and 4 in this paper. From 2002 to 2015, Pele shows a decrease in thermal emission from that typically seen during the 1990s. The Pillan timeline clearly shows a very erratic behavior, with five highly-energetic episodic eruptions, including the large extended event recorded in 1997-1999 by *Galileo* NIMS; shorter episodes of activity were observed in 2007, 2008, 2010, and 2015 (both Lp and Ms band data points are indicated for these events).

Table 1: Summary of Keck Observations of the 2007 Pillan Eruption

Date (UT)	Time (UT)	Object	Filter	Wavelength range (μm)	Int Time (images x coadds x s)	Airmass	CML ^a ($^{\circ}$)
Aug 14 2007	06:09	Io	Kcont	2.256-2.285	3 x 5 x 1	1.36	260
Aug 14 2007	06:14	Io	Lp	3.426-4.126	3 x 100 x 0.06	1.36	261
Aug 14 2007	06:16	Io	Ms	4.549-4.790	3 x 100 x 0.06	1.37	261
Aug 14 2007	06:19	Io	Hcont	1.569-1.592	3 x 5 x 1	1.37	261
Aug 14 2007	06:23	Io	Jcont	1.203-1.223	4 x 5 x 1	1.38	262
Aug 14 2007	06:35	HD161903	Hcont	1.569-1.592	3 x 20 x 0.2	1.08	
Aug 14 2007	06:41	HD161903	Lp	3.426-4.126	3 x 100 x 0.06	1.08	
Aug 14 2007	06:44	HD161903	Ms	4.549-4.790	3 x 100 x 0.06	1.08	
Aug 14 2007	06:46	HD161903	Kcont	2.256-2.285	3 x 5 x 1	1.08	
Aug 14 2007	06:48	HD161903	Jcont	1.203-1.223	3 x 20 x 0.2	1.08	

^a: CML = Central meridian longitude; Io-centric latitude is -2.73° .

Table 2: Observations^a of Pillan from 2001 – 2015

Date (UT)	Time (UT)	Latitude °	CML °	θ °	Filter	Radiant Flux ^b GW/sr/ μ m	Comments/Reference
2001/12/26	14:07	1.84	219	29.6	Lp	2.5 ± 0.4	Marchis et al. (2005)
2001/12/26	14:15	1.84	221	27.8	Ms	6.1 ± 0.9	Marchis et al. (2005)
2001/12/28	08:30	1.84	219	29.1	Lp	3.3 ± 0.6	Marchis et al. (2005)
2001/12/28	08:43	1.84	221	27.6	Ms	8.8 ± 1.3	Marchis et al. (2005)
2001/12/28	12:28	1.84	251	17.7	Lp	3.2 ± 0.6	Marchis et al. (2005)
2001/12/28	12:38	1.84	254	19.3	Ms	8.1 ± 1.2	Marchis et al. (2005)
2001/12/28	14:02	1.84	266	27.2	Lp	2.6 ± 0.6	Marchis et al. (2005)
2001/12/28	14:18	1.84	267	28.1	Ms	6.6 ± 1.1	Marchis et al. (2005)
2002/02/21	05:53	1.83	234	29.1	Lp	2.1 ± 0.3	
2002/02/21	06:01	1.83	235	28.4	Lp	2.2 ± 0.3	
2002/02/21	06:05	1.83	236	27.9	Ms	4.2 ± 0.6	
2002/02/21	07:26	1.83	247	12.1	Lp	3.8 ± 0.6	
2002/02/21	07:39	1.83	249	12.5	Ms	4.4 ± 0.7	
2002/02/21	08:54	1.83	260	18.9	Lp	2.9 ± 0.5	
2002/02/21	09:05	1.83	261	20.0	Ms	3.7 ± 0.6	
2002/02/21	10:10	1.83	271	24.4	Lp	2.3 ± 0.3	
2002/02/21	10:22	1.83	272	25.4	Ms	4.1 ± 0.6	
2004/05/29	07:50	-1.31	195	48.2	Lp	3.3 ± 0.5	
2004/05/29	07:55	-1.31	196	47.5	Ms	11.4 ± 1.7	
2007/04/03	14:46	-2.94	259	15.9	Ms	1 ± 0.2	
2007/08/14	06:09	-2.73	260	8.0	Kcont	17.8 ± 2.7	
2007/08/14	06:14	-2.73	261	8.8	Lp	30.3 ± 4.5	
2007/08/14	06:16	-2.73	261	9.2	Ms	23.2 ± 3.5	
2008/07/24	2:24-7:30	-1.51	197-241		4.0 μ m	157 ± 24^b	VLT/CRIRES; Lellouch et al., 2015
2009/07/25	12:08	0.52	198	48.4	Ms	1.1 ± 0.2	
2010/06/28	14:07	2.18	195	51	Lp	23 ± 4	
2010/06/28	14:10	2.18	195	51	Ms	25 ± 4	
2010/07/27	11:44	2.35	316	71.0	Ms	2 ± 1	on limb; Fig. 3 of de Pater et al., 2014a
2010/08/22	10:54	2.42	201	43.0	Lp	2.4 ± 0.4	de Pater et al., 2014a
2010/08/22	10:57	2.42	201	42.6	Ms	5.8 ± 0.9	de Pater et al., 2014a
2010/09/09	09:33	2.40	255	17.2	Lp	2.0 ± 0.3	Gemini; de Pater et al., 2014a
2010/09/09	09:45	2.40	256	18.2	Ms	9.5 ± 1.5	Gemini; de Pater et al., 2014a
2010/09/18	08:52	2.37	281	40.4	Lp	≤ 3	Gemini; Fig. 2 of de Pater et al., 2014a
2011/07/28	14:48	3.23	263	23.2	Ms	2.4 ± 0.4	
2011/11/11	09:36	3.33	195	53	Lp	0.7 ± 0.3	
2011/11/11	09:40	3.33	195	53	Ms	1.9 ± 0.3	
2013/01/20	04:46	2.94	281	38.9	Ms	2.0 ± 0.3	
2013/02/26	05:20	2.80	254	17.0	Ms	1.6 ± 0.3	
2015/01/26	08:40	-0.26	250	14	Lp	≤ 3	Gemini; not visible
2015/02/04	08:50	-0.24	284	42.5	Lp	< 24	IRTF mutual occultation data
2015/02/18	13:05	-0.19	292	48.9	Lp	80 ± 16	IRTF mutual occultation data
2015/03/15	08:25	-0.10	300	58.6	Lp	20 ± 10	IRTF mutual occultation data
2015/03/27	07:17	-0.06	213.2	33.9	Lp	7.8 ± 1.6	Gemini
2015/03/29	05:24	-0.06	244.3	14.1	Lp	7.6 ± 1.5	Gemini
2015/03/31	05:02	-0.05	288	42.1	Lp	5.8 ± 0.9	
2015/03/31	05:06	-0.05	289	42.6	Ms	15.5 ± 2.3	
2015/03/31	05:20	-0.05	291	44.4	PAH ^d	2.5 ± 0.4	
2015/03/31	05:49	-0.05	295	48.4	Lp	5.9 ± 0.9	
2015/03/31	05:52	-0.05	295	48.9	Ms	15.2 ± 2.3	
2015/04/05	07:59	-0.04	250.7	14.1	Lp	5.8 ± 1.1	Gemini
2015/04/21	05:21	-0.03	243.6	16.3	Lp	4.2 ± 0.8	Gemini
2015/05/05	05:56	-0.04	216	36.0	Lp	3.6 ± 0.5	
2015/05/05	05:59	-0.04	217	36.5	Ms	9.8 ± 1.5	

Nondetections were obtained in the Lp and Ms bands with the Keck telescope at $\theta < 60^\circ$ on: 2013/02/28, 2013/08/20, 2013/11/18, 2014/02/08, 2014/10/31, 2014/12/02, with typical upper limits of 1 GW/sr/ μ m (uncorrected for θ). Nondetections were obtained in the Lp band with Gemini at $\theta < 45^\circ$ on: 2010/09/18, 2013/09/03, 2013/09/10, 2013/11/27, 2013/12/04, 2013/12/06, 2013/12/13, 2014/03/10, 2014/10/22, 2014/10/24, 2014/11/25, 2014/11/30, 2014/12/09, 2014/12/16, 2015/01/15, with typical upper limits of 3 GW/sr/ μ m (uncorrected for θ).

^a: Observations are all taken with the Keck telescope, unless otherwise indicated.

^b: Radiant fluxes have been corrected for the emission angle effect; we added a 15% photometric error in quadrature to the estimated measurement error.

^c: No thermal emission detected; emission angle was calculated assuming a latitude and longitude of 8.5° S, 245° W for Pillan.

^d: Wavelength range of PAH filter: 3.2627–3.3282 μ m.

Table 3: Observations^a of Pele

Date (UT)	Time (UT)	Latitude °	CML ^b °	θ °	Filter	Radiant Flux ^c GW/sr/ μ m	Comments/Reference
2001/12/26	14:07	1.84	219	43.0	Lp	7.1 ± 1.3	Marchis et al. (2005)
2001/12/26	14:15	1.84	221	42.2	Ms	6.8 ± 1.1	Marchis et al. (2005)
2001/12/28	08:30	1.84	219	42.5	Lp	8.0 ± 1.3	Marchis et al. (2005)
2001/12/28	08:42	1.84	221	40.9	Ms	10.4 ± 1.6	Marchis et al. (2005)
2001/12/28	12:28	1.84	251	22.8	Lp	9.2 ± 1.4	Marchis et al. (2005)
2001/12/28	12:37	1.84	255	22.3	Ms	8.7 ± 1.3	Marchis et al. (2005)
2001/12/28	14:02	1.84	266	24.0	Lp	6.3 ± 1.3	Marchis et al. (2005)
2001/12/28	14:07	1.84	267	24.5	Ms	8.1 ± 1.3	Marchis et al. (2005)
2002/02/21	05:42	1.83	233	30.1	Kc	4.3 ± 0.6	
2002/02/21	05:53	1.83	234	29.1	Lp	11.5 ± 1.6	
2002/02/21	06:01	1.83	235	28.4	Lp	12.5 ± 1.8	
2002/02/21	06:05	1.83	236	27.9	Ms	10.2 ± 1.5	
2002/02/21	07:16	1.83	246	21.1	Kc	12.9 ± 1.9	
2002/02/21	07:26	1.83	247	21.5	Lp	17.3 ± 2.6	
2002/02/21	07:39	1.83	249	20.9	Ms	11.8 ± 1.8	
2002/02/21	08:44	1.83	258	20.0	Kc	4.3 ± 0.6	
2002/02/21	08:54	1.83	260	20.2	Lp	17 ± 2.5	
2002/02/21	09:05	1.83	261	20.5	Ms	10.1 ± 1.5	
2002/02/21	10:02	1.83	269	23.8	Kc	8.9 ± 1.4	
2002/02/21	10:10	1.83	271	24.4	Lp	16.5 ± 2.5	
2002/02/21	10:22	1.83	272	25.4	Ms	13.3 ± 2.0	
2007/04/03	14:25	-2.94	256	15.1	Kcont	1.5 ± 0.5	
2007/04/03	14:34	-2.94	258	15.1	Lp	5.7 ± 1.0	
2007/04/03	14:46	-2.94	259	15.4	Ms	6.2 ± 1.0	
2007/08/14	04:48	-2.73	248	16.8	Kcont	<2	
2007/08/14	04:59	-2.73	250	16.7	Lp	4.8 ± 0.7	
2007/08/14	05:03	-2.73	251	16.5	Ms	4.8 ± 0.7	
2009/07/25	12:12	0.52	198	59.4	Lp	12 ± 2	on limb
2009/07/25	12:08	0.52	198	59.8	Ms	5 ± 1	on limb
2010/07/27	11:41	2.35	315	61.7	Lp	2.1 ± 0.3	on limb; fig. 3 of de Pater et al., 2014b
2010/07/27	11:44	2.35	316	62.0	Ms	2.1 ± 0.3	on limb; fig. 3 of de Pater et al., 2014b
2010/08/22	10:51	2.42	201	53.8	Kcont	5 ± 1.5	
2010/08/22	10:55	2.42	201	53.6	Lp	8.0 ± 1.2	de Pater et al., 2014b
2010/08/22	10:58	2.42	202	53.2	Ms	8.3 ± 1.3	de Pater et al., 2014b
2010/09/09	09:33	2.40	255	19.8	Lp	6.0 ± 0.9	Gemini; de Pater et al., 2014b
2010/09/09	09:45	2.40	256	20.0	Ms	9.3 ± 1.5	Gemini, non-AO; de Pater et al., 2014b ^d
2010/09/18	08:52	2.37	281	34.7	Lp	1.0 ± 0.2	Gemini; Fig. 2 of de Pater et al., 2014b
2011/07/28	14:41	3.23	262	22.0	Kcont	≤ 2	
2011/07/28	14:45	3.23	262	22.1	Lp	1.6 ± 0.3	
2011/07/28	14:48	3.23	263	22.2	Ms	3.5 ± 0.6	
2011/11/11	09:36	3.33	195	60	Lp	0.6 ± 0.3	on limb
2011/11/11	09:40	3.33	195	60	Ms	2 ± 1	on limb
2013/01/20	04:33	2.94	280	31.5	Kcont	2 ± 1	
2013/01/20	04:43	2.94	281	32.5	Lp	4.5 ± 0.7	
2013/01/20	04:46	2.94	281	32.8	Ms	5.7 ± 0.9	
2013/02/26	05:06	2.80	252	21.5	Kcont	3 ± 1	
2013/02/26	05:17	2.80	253	21.4	Lp	5.4 ± 1.0	
2013/02/26	05:20	2.80	254	21.3	Ms	4.5 ± 0.8	
2013/02/28	04:48	2.79	296	44.5	Kcont	<2	
2013/02/28	04:59	2.79	297	45.7	Lp	3.0 ± 0.5	
2013/02/28	05:03	2.79	298	46.3	Ms	3.0 ± 0.5	
2013/08/20	15:31	2.03	275	30	Lp	1.7 ± 0.3	fig. 2 of de Pater et al., 2014b
2013/08/20	15:40	2.03	276	30	Ms	2.7 ± 0.4	fig. 2 of de Pater et al., 2014b
2013/11/18	15:46	1.11	224	33.0	Kcont	<3	
2013/11/18	15:55	1.11	226	33.8	Lp	3.2 ± 0.5	
2013/11/18	16:12	1.11	228	33.0	Lp	3.1 ± 0.5	
2013/11/18	15:59	1.11	226	32.8	Ms	3.6 ± 1.7	

^a: Observations are all taken with the Keck telescope, unless otherwise indicated.^b: CML = Central meridian longitude.^c: Radiant fluxes have been corrected for the emission angle effect; we added a 15% photometric error in quadrature to estimated measurement error.^d: This number has been corrected from de Pater et al., (2014b).

Table 3: Observations^a of Pele, continued

Date (UT)	Time (UT)	Latitude °	CML ^b °	θ °	Filter	Radiant Flux ^c GW/sr/ μ m	Comments/Reference
2014/02/08	05:24	1.14	271	24.0	Kcont	≤ 2	
2014/02/08	05:27	1.14	272	24.0	Lp	2.9 ± 0.5	
2014/02/08	05:30	1.14	272	24.0	Ms	3.3 ± 0.8	
2014/02/08	05:59	1.14	276	26.9	Lp	2.8 ± 0.5	
2014/02/08	06:03	1.14	277	26.9	Ms	3.0 ± 0.8	
2014/10/31	16:03	0.93	247	20.7	Kcont	≤ 2	
2014/10/31	15:56	0.93	245	20.7	Lp	3.1 ± 0.5	
2014/10/31	15:59	0.93	246	20.7	Ms	3.2 ± 0.7	
2014/12/02	15:38	1.02	272	26.5	Kcont	≤ 2	
2014/12/02	15:41	1.02	273	26.5	Lp	4.2 ± 0.6	
2014/12/02	15:44	1.02	274	26.0	Ms	5.4 ± 1.0	
2014/12/02	16:17	1.02	278	29.4	Lp	4.8 ± 0.7	
2015/03/31	05:02	-0.05	288	34.3	Lp	2.1 ± 0.3	
2015/03/31	05:06	-0.05	289	34.8	Ms	3.0 ± 0.5	
2015/03/31	05:20	-0.05	291	36.4	PAH	1.5 ± 0.2	
2015/03/31	05:49	-0.05	295	40.0	Lp	2.2 ± 0.3	
2015/03/31	05:52	-0.05	295	40.3	Ms	3.6 ± 0.5	
2015/05/05	05:56	-0.04	216	42.8	Lp	2.7 ± 0.4	
2015/05/05	05:59	-0.04	217	42.4	Ms	3.4 ± 0.5	

Nondetections were obtained in the Lp band with Gemini at $\theta < 45^\circ$ on: 2013/09/03, 2013/09/05, 2013/09/10, 2013/11/27, 2013/12/06, 2013/12/13, 2014/03/10, 2014/10/10, 2014/10/24, 2014/11/25, 2014/11/30, 2014/12/09, 2014/12/16, 2015/01/15, 2015/01/26, 2015/03/27, 2015/03/29, 2015/04/05, 2015/04/21, with typical upper limits of 3 GW/sr/ μ m (uncorrected for θ).

^a: Observations are all taken with the Keck telescope, unless otherwise indicated.

^b: CML = Central meridian longitude.

^c: corrected for the emission angle effect; added 15% photometric error in quadrature to estimated measurement error.

^d: This number has been corrected from de Pater et al., (2014b).

Table 4: Viewing Geometry and Flux Densities of the August 2007 Pillan Eruption

Filter	Δ (AU)	r (AU)	W. longitude (°)	Latitude (°)	θ (°)	Radiant Flux ^a GW/sr/ μ m
Hcont	4.88	5.30	246.0 ± 0.5	-8.5 ± 0.5	~ 8	
Kcont	4.88	5.30	245.7 ± 0.5	-9.0 ± 0.5	8.0	17.8 ± 2.7
Lp	4.88	5.30	244.7 ± 0.5	-8.6 ± 0.5	8.8	30.3 ± 4.5
Ms	4.88	5.30	244.5 ± 0.5	-7.9 ± 0.5	9.2	23.2 ± 3.5

^a: Radiant Fluxes have been corrected for the emission angle effect (i.e., divided by the cosine of θ). The uncertainty includes a 15% photometric error.

Table 5: 1T Model Fits to Pele and Pillan

Date	1T fit Temperature K	1T Fit Area km ²	1T Fit Total Power GW
<i>Pillan</i>			
2007/08/14	840±40	17± ⁶ ₄	490±30
2010/06/28	640± ²⁰⁰ ₁₀₀	60± ¹⁴⁰ ₃	540± ³⁰⁰ ₇₀
2010/08/22	375±40	400± ¹⁰⁰⁰ ₂₀₀	450± ⁵⁰⁰ ₂₀₀
2010/09/09	275±25	15,000± ^{40,000} _{8,000}	5000± ⁷⁰⁰⁰ ₂₀₀₀
2015/03/31	358±20	1590± ¹³⁵⁰ ₆₆₀	1475± ⁶⁸⁰ ₄₃₀
<i>Pele</i> ^a			
2002/02/21	920±40	6.5± ² _{1.5}	265±10

^a We used the following radiant fluxes for Pele:

12.9 GW/sr/μm at 2.27 μm;

17.3 GW/sr/μm at 3.78 μm;

11.8 GW/sr/μm at 4.67 μm.

Table 6: IFM Model Fits to Pillan

Date	Total Power	dA/dt	Total area	Oldest Surface age	Oldest Surface temp	2-micron Radiant flux	5-micron Radiant flux	2.5 micron Radiant flux ratio	Flux density
yr/month/day	GW	m ² /s	km ²	hrs	K	GW/micron	GW/micron		kW/m ²
<i>Pillan</i>									
2007/08/14	505 $\pm^{35}_{30}$	6520 $\pm^{2000}_{500}$	21.3 $\pm^8_{45}$	0.9 $\pm^{0.8}_{0.4}$	710 $\pm$ 40	41 $\pm$ 6	71 $\pm$ 6	0.6 $\pm$ 0.15	23.8 $\pm^6_5$
2010/06/28	580 $\pm^{450}_{90}$	1500 $\pm^{700}_{200}$	75 $\pm^{40}_{45}$	14 $\pm^{200}_{9}$	525 $\pm^{200}_{180}$	14 $\pm^{30}_{6}$	75 $\pm^{18}_{11}$	0.18 $\pm^{0.6}_{0.09}$	7.6 $\pm^6_4$
<i>Pele</i> ^a									
2002/02/21	270 $\pm^{14}_9$	7000 $\pm^{3000}_{2000}$	7.5 $\pm^3_2$	0.3 $\pm^{0.3}_{0.15}$	795 $\pm$ 50	32 $\pm$ 4	36 $\pm$ 3	0.88 $\pm$ 0.2	35 $\pm$ 7

^a We used the following radiant fluxes for Pele:

12.9 GW/sr/ μ m at 2.27 μ m;

17.3 GW/sr/ μ m at 3.78 μ m;

11.8 GW/sr/ μ m at 4.67 μ m.

Fig. 1

Fig. 2

Io: 21 February 2002

Io: 29 May 2004

Io: 03 April 2007

Io: 25 July 2009

Io: 28 June 2010

Io: 22 August 2010

Fig. 3a

Io: 09 September 2010 Gemini data

Io: 28 July 2011

Io: 11 November 2011

Io: 20 January 2013

Io: 26 February 2013

Io: 20 August 2013

Fig. 3b

Io: 18 November 2013

Io: 08 February 2014

Io: 31 October 2014

Io: 02 December 2014

Io: 31 March 2015

Io: 05 May 2015

Fig. 3c

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9