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Io: Eruptions at Pillan, and the time evolution of Pele and Pillan from 1996 to 2015

Imke de Pater [a,b,c,*], Conor Laver [d], Ashley Gerard Davies [e], Katherine de Kleer [a], David A. Williams [f], Robert R. Howell [g], Julie A. Rathbun [h], John R. Spencer [i]

[a] Astronomy Department, 501 Campbell Hall, University of California, Berkeley, CA 94720, USA
[b] Faculty of Aerospace Engineering, Delft University of Technology, NL-2629 HS Delft, The Netherlands
[c] SRON Netherlands Institute for Space Research, 3584 CA Utrecht, The Netherlands
[d] Bright Power Inc., 11 Hanover Square, 21st Floor, New York, NY 10005, USA
[e] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[f] School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287, USA
[g] Dept. of Geology & Geophysics, University of Wyoming, 1000 E. University Ave., Laramie, WY 82071, USA
[h] Planetary Science Institute, 1700 E. Fort Lowell, Tucson, AZ 85719, USA
[i] Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302, USA

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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' (Davies, A.G. [1996]. Icarus 124(1), 45–61) Io Flow Model, we find that the oldest lava present is less than 1-2 h 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 ~60 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 µm 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 km^2 was measured. Since that time, however, the radiant flux from what is likely a apparently 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 and an area roughly ~100 km to the SE of the 2002 location.

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

* Corresponding author at: Astronomy Department, 501 Campbell Hall, University of California, Berkeley, CA 94720, USA.

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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 (~0.10" 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 an examination of the 2007 eruption at Pillan and an expanded timeline of observations of both Pele and Pillan. This timeline includes all observations taken with the adaptive optics (AO) system on the Keck telecope 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, in preparation), 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 Δ = 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 Technology.[1] 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 6:41 UT and 6:56 UT. 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 Spectrometer NIRI, coupled to the adaptive optics (AO) system ALTAIR, on the 8-m Gemini-North telescope. NIRI is a 1024 × 1024 ALADDIN InSb array, which we used in its highest resolution mode, with a focal ratio *f*/32 and pixel size of 22 × 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

Fig. 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]

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 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 ephemeris.[3] 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 1/2 pixel (~0.5°) uncertainty in each of the positions. This way we determined that the eruption center is at 245.2 ± 0.7°W and 8.5 ± 0.5°S. For comparison, we determined the position of Pele to be at 257.5 ± 0.9°W and 18.0 ± 0.4°S. The location of the 2007 Pillan eruption, shown in Fig. 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 (GW/sr/μm), 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 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

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

[2] Positions from http://planetarynames.wr.usgs.gov/.

[3] http://ssd.jpl.nasa.gov/horizons.cgi.