Large Volcanic Event on Io Inferred from Jovian Sodium Nebula Brightening

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Abstract

Using narrow-band images recorded on over 150 nights by the 35 cm coronagraph that comprises the Planetary Science Institute’s Io Input/Output Facility (IoIO), we detected a 6-month long enhancement in the Jovian sodium nebula. The onset of the enhancement occurred in the mid 2017 December–early 2018 January timeframe. Sodium emission over the Io(IO 0°4 field of view was seen to increase through 2018 January and peak in 2018 early March. By early June 2018, the surface brightness of the emission returned to the value seen in 2017 April–June, making this the longest such event observed by this technique and comparable in length to that observed by the Galileo Dust Detector in 2000. A new infrared hot spot was found on Io near Susanoo/Mulungu Paterae between January 2 and 12, however this hot spot was neither bright nor long-lasting enough to have been independently identified as the source of a major sodium nebula enhancement. Furthermore, no other report of this event has been made despite a significant number of observations of the Jovian system by and in support of NASA’s Juno mission. This detection therefore places those observations in valuable context and highlights the importance of synoptic observations by facilities such as IoIO, which provide a global view of neutral material in the Jovian magnetosphere.

Key words: instrumentation: miscellaneous – planets and satellites: individual (Jupiter, Io)

Supporting material: animation

1. Introduction

Io’s volcanism was first hinted at by a fortuitous observation in the 3–5 μm region of the infrared (IR; Witteborn et al. 1979), though it was not understood as such until after Voyager 1 observations confirmed the presence of plumes (Morabito et al. 1979; Sinton 1980). This volcanism helped to place in context earlier fortuitous observations of Io’s ionosphere (Kliore et al. 1975), a sodium cloud near Io (Brown & Chaffee 1974), and ionized sulfur emission near Jupiter (Kupo et al. 1976); Io has an atmosphere that ultimately derives its source from volcanic activity and supplies Jupiter’s magnetosphere with a substantial amount of material (∼1 ton s−1, e.g., McGrath et al. 2004; Schneider & Bagenal 2007). As discussed in these references, material that is ionized forms the Io plasma torus (IPT), which encircles Jupiter near Io’s orbital radius. It is the bright line of singly ionized sulfur at [S II]6731 Å that led to the initial detection of the IPT and has enabled it to be imaged by ground-based coronagraphs with apertures as small as 30 cm (Nozawa et al. 2004). Interaction between the IPT and Io’s atmosphere via processes such as sputtering, charge exchange, and dissociative recombination result in the energetic ejection of neutral material. Although a minor component of the material that is released, sodium has such a bright doublet emission at 5890 and 5896 Å that it has been imaged by ground-based coronagraphs with apertures as small as 10 cm (e.g., Mendillo et al. 1990, 2004; Yoneda et al. 2009, 2010, 2014, 2015).

Mendillo et al. (2004) used of order one wide-field (6°) sodium cloud image per year between 1990 and 1998 and a literature search of available Io IR measurements to suggest there was a general correlation between the sodium nebula brightness and Io’s disk-averaged IR brightness (their Figure 2). Long-lived volcanic hot spots, particularly Loki Patera and Tiermes Patera, were identified as the primary causes of this correlation (their Figure 1). Subsequent work by de Kleer et al. (2016) used three years of higher-cadence sodium cloud images (up to one per day) and much higher spatial resolution IR monitoring and failed to confirm this correlation. Rather, de Kleer et al. (2016) suggested that some, but not all, bright transient IR events traceable to individual volcanic eruptions may trigger sodium cloud brightening. Loki Patera and Tiermes Patera are lava lakes, which are not known to produce high eruptive plumes (e.g., Rathbun & Spencer 2006; de Pater et al. 2017). Rather, explosive events produced by volcanoes such as Pele, Tvashtar, Pillan (e.g., Jessup & Spencer 2012) would seem more likely to result in the ejection of material, though it is not clear if plume material from these eruptions can be ejected directly beyond Io’s atmosphere or if sublimation of the large ejecta blankets observed around these volcanoes is responsible for increase in ejection rates. Finally, Johnson et al. (1995) have suggested that SO2 geysers may create “stealth plumes,” undetected by methods that monitor Io surface or near-surface properties, as they would not have strong IR or dust signals. Regardless of the precise physical mechanism operating, Io’s volcanic nature is ultimately responsible for the release of gas into Jupiter’s magnetosphere. Therefore, for the purposes of this work, we will call such a release of gas a volcanic event.

Using a spectroscopic study that lasted an entire Jovian opposition, Brown & Bouchez (1997) showed that when there was a large increase in sodium emission in the inner Jovian magnetosphere, the IPT also became brighter and shifted to the east. The sodium peak brightness was seen before the IPT peak brightness. Brown & Bouchez (1997) attributed this behavior to an eruption of a volcanic plume on Io and the resulting radial and antisunward diffusion of material through the Jovian magnetosphere.
Yoneda et al. (2010) used the Nozawa et al. (2004) [S II] IPT observations and contemporaneously recorded small-aperture coronagraphic sodium nebula images to establish a correlation between IPT brightness and sodium nebula brightness in the same sense as that found by Brown & Bouchez (1997). Extreme ultraviolet (EUV) observations of the IPT have also shown evidence of correlation with indicators of volcanic eruption of material from Io (Krüger et al. 2003; Stefl et al. 2006; Yoneda et al. 2015; Kimura et al. 2018).

Motivated by the success of the small-aperture ground-based coronagraphic observations of the IPT and Jovian sodium nebula by Nozawa et al. (2004), Mendillo et al. (2004), and Yoneda et al. (2009, 2010, 2014, 2015), and the numerous open scientific questions in inner Jovian magnetospheric studies, we created the Io Input/Output facility (IoIO). Described in more detail in Section 2, IoIO is comparable in aperture size to the coronagraphs used by Nozawa et al. (2004) so that detection of the IPT in [S II] is possible. This makes the IoIO aperture area ~10-times that of the wide-field sodium nebula studies of Mendillo et al. (2004) and Yoneda et al., with a comparable reduction in field of view. The larger aperture, yet still relatively large field of view (0.4) simultaneously enables IoIO to study the detailed 3D structure of the sodium nebula near Io and Jupiter (Figure 1 and online animation) and, like Yoneda et al., measure the average surface brightness of the Jovian sodium nebula with a nightly cadence. As detailed in Sections 2–5, our reduction techniques are sufficient to demonstrate the detection of a large and long-term enhancement in the sodium nebula; however, removal of the effects of passing clouds is not yet as sophisticated as those of Yoneda et al. As a result, the scatter our data is greater and the sensitivity to small enhancements is less. This will be addressed in subsequent iterations of our reduction pipeline. In Sections 4–5 and Figure 2, we show that IoIO detected a substantial increase in the amount of sodium within ~25 Jovian radii (R_J) of Jupiter starting in the 2017 mid-December–2018 early January timeframe. In Section 6, we suggest this was caused by a volcanic event on Io.

2. Observations

The IoIO consists of a 35 cm Celestron telescope feeding a custom-built coronagraph, a boresight-mounted 80 mm guide telescope and an Astro-Physics 1100 GTO German equatorial mount. IoIO is located at the San Pedro Valley Observatory, a hosting site situated in a dark location 100 km east of Tucson, Arizona, USA. The coronagraph imaging system is telecentric: A Kodak Wratten ND3 gelatin neutral density filter cut ~1.5 mm wide is placed at the focal plane of the Celestron telescope so that Jupiter is attenuated rather than occulted, allowing for astrometric and photometric calibrations. The diverging light from the f/11 beam then passes through one of the five filters listed in Table 1, which are standard bandpasses for this work. The filters are hard metal oxide coated to maximize durability and minimize central wavelength (CWL) temperature drift (<0.1 Å C−1). The narrow-band Fabry–Pérot type filters, fabricated by Custom Scientific, have a very flat-top profile with >90% peak efficiency. The sodium on-band filter was constructed such that both the Na D lines are transmitted with <1% change in efficiency over the entire FOV and nighttime temperature range expected at our hosting site. After the filters, the light passes through a field lens which focuses the telescope pupil onto the pupil of a Nikon Nikkor 60 mm F/2.8 camera lens. Finally, the light is collected by a Starlight Xpress SX694 medium format CCD camera. The effective focal length of IoIO is 1200 mm, the FOV for sodium nebula observations is 0.4 or 64 R_J × 84 R_J, depending on Jupiter’s geocentric distance and pixels are 0.78 arc seconds per side.

Sodium observations are recorded in on-band/off-band pairs for five minutes and one minute, respectively, every ~30 minutes. On- and off-band images of the Io plasma torus in [S II] 6731 Å are recorded on a 6 minute cadence in the

Figure 1. Two images of the inner 0.4 (~50 R_J) of the Jovian sodium nebula recorded by IoIO. Left panel: image recorded 2018 February 27 08:26:11 UT, during the period when the extended Jovian sodium nebula was bright. Right panel: image recorded 2018 June 12 04:40:37 UT, during a period when the nebula was at baseline value. The images have been down-sampled by a factor of four and then rebinned by another factor of four. The boxes indicate the apertures used to construct Figure 2 (left panel). The innermost aperture (blue) is a square area 15 R_J on a side containing points approximately within approximately 7.5 R_J from Jupiter (blue triangles in Figure 2, left panel). The next concentric aperture (orange) is a square aperture 30 R_J on a side containing points <15 R_J from Jupiter (orange squares in Figure 2, left panel). The square annular area, between the outermost two (green) rectangles, was used to calculate the surface brightnesses shown as the green Xs in Figure 2 (left and right panels). This corresponds to points 20 R_J < r < 25 R_J, which is comparable to the 25 R_J aperture used by Yoneda et al. (2009). An animation, lasting 1.5 minutes, of the data set is found in the online Journal and shows the 3D structure of the “banana,” “jet,” and “stream” features discovered by Schneider et al. (1991) and modeled in detail by Wilson et al. (2002). Individual frames of the animation have been processed with the histogram equalization method to enhance contrast of low surface brightness features. Frames with high background light (average surface brightness >250 R) have been removed, as have frames where the image of Jupiter moved more than 5 pixels between the on-band and off-band images. The later effect does not materially affect our aperture surface brightness values, but it does detract cosmetically from the animation. In the animation, values above 8 kR have been set to zero and Jupiter has been scaled up by a factor of 100. A long-term ongoing archive of all raw and reduced images collected by IoIO will be kept at NASA’s Planetary Data System (PDS).

(An animation of this figure is available.)
intervals between the Na observations and will be reported in another work.

3. Data Reduction

Because the sodium nebula is a field-filling source for our field of view (FOV), we take some care in reducing the data. This starts with the bias and dark subtraction of our on- and off-band images. The IPT is a much smaller target than the sodium nebula, so as a cost-savings measure we used 32 mm diameter band images. The IPT is a much smaller target than the sodium nebula recorded by IoIO and processed as described above. Data were recorded on more than 150 nights between IoIO observations.

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Sky flats show that white light vignetting is ~10% starting beyond the region we use for our analyses, so we ignore the effect. Similarly, we ignore small-scale variation in biases, flats, and darks because our primary results are derived by averaging over large areas of pixels.

After bias and dark subtraction, we subtract the off-band image recorded closest in time from each on-band image. A factor, OFFSCALE, is multiplied by each off-band image. OFFSCALE is the product of the flux in the central 10 × 10 pixel (7°8 × 7°8) areas of Jupiter in the on- and off-band images times. An additional factor of 0.80 is applied to remove over-subtraction consistently seen in the images. OFFSCALE typically varies by ~20% each night and there was a systematic drop of 20% during April attributable to improvements that we were making in the guiding system: because on-band images have longer exposure times than off-band, improved guiding reduced smearing of Jupiter preferentially in the on-band images, hence raising OFFSCALE. We show in Section 5 that the systematic change in OFFSCALE has no effect on our results.

We derive a factor, ADU2R, to convert pixel values to the surface brightness unit of rayleighs (R) where

\[
ADU2R = \frac{\text{on\_jup} \times \text{ND}}{\text{MR}}.
\]

Here, on\_jup is the average pixel value of the 10 × 10 pixel box centered on Jupiter in the on-band images. This area represents pixels within ~0.2 R\_J of the center of Jupiter. ND is the attenuation factor provided by our neutral density filter. R-band measurements of GSC5017:78 on 2018 March 20 UT show ND = 730 ± 70. MR is the surface brightness of Jupiter over our 12 Å wide bandpass on-band filter. To account for the deep sodium Fraunhofer absorption lines, this is calculated using jovian albedos from Woodman et al. (1979) and Karkoschka (1998, see also PDS: ESO-J/S/N/U-SPECTROPHOTOMETER-V2.0) and the Kurucz (2005) solar flux atlas. MR varied from 52.6 MR to 54 MR over the IoIO observations.

Figure 1 shows two of the over 700 images of the sodium nebula recorded by IoIO and processed as described above. Data were recorded on more than 150 nights between IoIO commissioning in 2017 March and the end of the Jovian opposition in 2018 July. Subsequent work will address the “banana,” “jet,” and “stream” features described in the caption of Figure 1. For our current work, we concentrate on the diffuse emission in the images, which can be studied using the surface brightness in various apertures centered on Jupiter. In Section 4 and Figure 2, we present the time evolution of these surface brightness values to show that there was a large modulation in the emission detected by IoIO during the 2018 Jovian opposition. In Section 5, we demonstrate that this emission was from the Jovian sodium nebula.
4. Results

Figure 2 shows that there was a significant and long-lasting enhancement in emission detected by IoIO during the 2018 Jovian opposition. The left panel of the Figure shows via large colored triangles, squares, and Xs, the nightly medians of the average surface brightnesses within the three regions indicated by colored squares in Figure 1. All of the surface brightness measurements for one of the apertures are shown as small black dots. The right panel of Figure 2 shows an 11-day moving median (blue histogram), which smooths the effects of variable weather. As discussed in more detail in Section 5, the enhancement bears the mark of modulation in brightness of a centrally peaked source because the more centrally concentrated apertures have larger modulations as a function of time. The extrapolation of the 20 $R_J < r < 25 R_J$ aperture, shown in Figure 2 (right, orange line), suggests that the enhancement started no later than 2018 early January. The scatter in the data suggests that the enhancement could have begun as early as 2017 mid-December. The emission peaked in brightness in March and remained bright until 2018 June, making this 1.8 times longer than the events observed by Brown & Bouchez (1997) and Yoneda et al. (2015) and comparable in length to that observed by the Galileo Dust Detector in 2000 (Krüger et al. 2003). The intensity of the enhancement is discussed in more detail in Section 5.

5. Discussion

As discussed in Sections 2–3, IoIO does not see to the edge of the Jovian sodium nebula. Furthermore, to maximize observing time on the plasma torus, sodium sky background observations away from Jupiter were not systematically recorded. Thus, we must take some care in our analyses to ensure that we are detecting modulation in the Jovian sodium nebula and not some other source.

The first factor we consider that could possibly contribute to the long-term modulation seen in Figure 2 is improper subtraction of the continuum light recorded in our on-band images. This is particularly concerning given the systematic change in OFFSCALE noted in Section 3. We rule out this concern in several ways. First, the change in OFFSCALE occurred more abruptly in April compared to the decline seen in Figure 2. Second, we reversed the sense of the long-term change in OFFSCALE and re-processed images in March and June, and found that the March aperture surface brightness values were still higher than those in June. Perhaps most convincingly, we create plots like Figure 2 using our on-band and off-band images separately. These plots show more scatter than Figure 2, but the on-band plot already shows the trend seen in Figure 2. The off-band plot shows no long-term trend. These observations confirm that our background subtraction is reasonable and that the modulation seen in Figure 2 comes from line emission, and not continuum emission, in the on-band filter bandpass.

Next we consider the response of IoIO to the primary source of sodium emission other than the Jovian sodium nebula: the Earth’s mesospheric sodium layer. This layer is formed from the ablation of meteors. Its thickness has seasonal dependence in the same sense as the modulation seen in Figure 2 (e.g., Dunker et al. 2015, their Figure 4), which is why it is of concern for our analyses. Mesospheric sodium also has a diurnal variation because it is excited by photochemical processes local to the layer (e.g., Kirchhoff et al. 1979). In contrast to this, the Jovian sodium nebula has negligible nightly modulation over the $\sim 3.5 \times 10^9$ km region covered by the IoIO FOV. Thus, by considering our data on a night-by-night basis, we can probe the response of IoIO to a uniform field-filling source without interference from the nebula. The black dots in Figure 2 (left panel) show that the extent of the nightly modulations for the $r < 15 R_J$ aperture fall within the 40–200 $R_J$ range seen at other locations. Larger excursions, such as the last two nights in the 2017 observing season, recorded as the monsoon season started, are due to passing clouds. Nightly variations in emission in all of the apertures are highly correlated with correlation coefficients tending to one, as expected for variation in a uniform, field-filling source. Thus, we simultaneously confirm with the IoIO data themselves the design criterion that IoIO’s detection efficiency is flat as a function of position (Section 2) and that seasonal modulation of a field-filling source would result in equal responses in all the apertures. We show in the next paragraph how this is not what is seen in Figure 2 (left panel).

To demonstrate that IoIO detected modulation in the brightness of the Jovian sodium nebula, we point out that the curve for each aperture in Figure 2 (left panel) has a unique shape. Relative to their respective baselines, the more centrally concentrated apertures have larger absolute amplitudes. This is the signature of modulation in the brightness of a centrally peaked source. The baseline values for our inner ($r < 7.5 R_J$), middle ($r < 15 R_J$), and outer ($20 R_J < r < 25 R_J$) apertures are $1030 \pm 30 R_J$, $370 \pm 25 R_J$, and $80 \pm 15 R_J$, respectively. The peak amplitudes of the middle and inner apertures are factors of $\sim 1.5$ and $\sim 2.2$ higher than the outer aperture, respectively. After removal of their respective baselines and scaling, the curves from the three apertures are in good agreement. Were we seeing seasonal modulation in the telluric sodium layer, the amplitudes would all have the same values in the same way that the nightly modulations do. This is our most convincing evidence that we are detecting modulation in the Jovian sodium nebula.

Although we have ruled out mesospheric emission as the cause of the long-term modulation seen in Figure 2 (left panel), we cannot rule out its contribution as a relatively stable background. In fact, we expect it. As discussed above, we did not record systematic sky background measurements, so this is not something that we can estimate independently. Instead, we compare the measured surface brightness in our outer aperture during the nebula’s quiescent state to the surface brightness of inner aperture used by Yoneda et al. (2009) during similarly quiet conditions. Both of these apertures correspond to $r \sim 25 R_J$. As quoted above, the baseline in our outer aperture is $80 \pm 15 R_J$. The mesosphere-subtracted value quoted by Yoneda et al. (2009) is $20 R_J - 30 R_J$. This suggests that $50 R_J - 60 R_J$ of our emission is mesospheric, which is comparable to baseline values measured by this team at other locations. Subtracting this from our $r \sim 25 R_J$ aperture results in Figure 2 (right panel), which shows that the peak amplitude of the modulation observed in the Jovian sodium nebula at $r \sim 25 R_J$ is $155 \pm 25 R_J$ or a factor of $\sim 2$ larger than the $70 - 80 R_J$ peak in the event measured by Yoneda et al. (2009). The peak amplitude in the 2015 January to 2015 April enhancement reported by Yoneda et al. (2015) was a factor of $\sim 1.5$ larger than the Yoneda et al. (2009) enhancement. Thus, the 2018 enhancement detected by IoIO was a factor of $\sim 1.3$ brighter.
Yoneda et al. than the 2015 January to 2015 April enhancement reported by Yoneda et al. (2015).

6. Conclusion

We have detected a large and long-lasting enhancement in the Jovian sodium nebula. The extrapolation of the data shown in Figure 2 (right) suggests that the enhancement started no later than 2018 early January. The scatter in the data suggests the enhancement could have begun as early as 2017 mid-December. The calculations detailed in Section 5 suggests the event was $\sim 30\%$ brighter than the primary enhancement reported by Yoneda et al. (2015). The nebula remained bright until 2018 June, making this 1.8 times longer than the events observed by Brown & Bouchez (1997) and Yoneda et al. (2015) and comparable in length to that observed by the Galileo Dust Detector in 2000 (Krüger et al. 2003). Infrared observations recorded at NASA’s IRTF by our team and at the W. M. Keck Observatory by K. de Kleer & I. de Pater as a continuation of the monitoring program discussed in de Kleer & de Pater (2016) achieved full longitudinal coverage of Io, but detected no IR-bright eruptions that lasted for over a month in the 2017 December to 2018 January timeframe. A new eruption near Susanoo/Mulunungu paterae ($20^\circ N$ 218$^\circ W$) was observed to begin sometime between January 2 and 12 (K. de Kleer & I. de Pater, 2018 personal communication). This event was 20 GW $\mu m^{-1} \text{sr}^{-1}$ at brightest detected $L_p$ (3.78 $\mu m$) and would therefore be classified as a faint eruption in the taxonomic scheme of de Kleer & de Pater (2016). The proximity in time between this eruption and the onset of the sodium nebula enhancement is suggestive but not conclusive evidence of a relationship. A more convincing case was made by de Kleer & de Pater (2016) that the two sodium nebula enhancements seen by Yoneda et al. (2015) were associated with two eruptions in the “mini-outburst” class at Kradulagon Patera, as both eruptions were contemporaneous with the onset of the nebula enhancements. However, as noted by de Kleer et al. (2016), during the three-year study of de Kleer & de Pater (2016), not all of the detected sodium nebula enhancements had identifiable IR counterparts. Along the same lines, the two Kradulagon Patera outbursts were a factor of $\sim 3$ brighter than the eruption near Susanoo/Mulunungu paterae, yet the two enhancements found by Yoneda et al. (2015) were not of equivalent size nor were they larger than the enhancement reported here, as one would expect if IR brightness was correlated with the amount of gas released. The picture that emerges is that IR activity on Io is simply not predictive of sodium nebula enhancement. This observation is strengthened by the fact that all of the associations between IR eruptions and sodium nebula enhancements have been made posteriori. This highlights the importance of synoptic observations of the Jovian sodium nebula for monitoring the supply of material to Jupiter’s magnetosphere—material that drives a host of magnetospheric phenomena.

With our detection of such a long-lasting event during the first half of the 2018 Jovian opposition, other observations may be placed in context. This is particularly important for observations conducted by Juno, large-aperture observatories, and HST, which themselves do not have synoptic coverage comparable to IoIO and were therefore not able to independently detect this event. For instance, our team regularly conducts observations of the IPT with the ARC 3.5 m telescope at Apache Point Observatory (Schmidt et al. 2018). In May 2018, these were seen to be the brightest yet recorded by this facility. Preliminary reduction of our IoIO [S II] images also shows evidence that the overall brightness of the IPT follows a similar envelope to that observed by Brown & Bouchez (1997) during the volcanic event they saw (Section 1). EUV observations of the IPT by Hisaki over this time period should be brighter than normal and show chemical and periodicity changes similar to those seen by Steffl et al. (2008) and Kimura et al. (2018) after volcanic events. We predict the neutral oxygen cloud around Jupiter, detectable with the Hisaki satellite (Koga et al. 2018a, 2018b), will show higher values than found previously. Finally, higher than average auroral activity on Jupiter should be detected by in situ measurements from the Juno/Jovian Auroral Distributions Experiment (JADE) instrument; in the UV by Juno/UVS; in the infrared by Juno/Jovian Infrared Auroral Mapper (JIRAM) and ground-based infrared telescopes; and in the radio by Juno/WAVES and ground-based radio telescopes such as the Nançay Decametric Array (e.g., Radioti et al. 2013; Kimura et al. 2015; Kita et al. 2016; Gladstone et al. 2017; Kurth et al. 2017; Marques et al. 2017; McComas et al. 2017).

Although we cannot provide independent measurement of the geological and atmospheric processes responsible for the production and release of gas detected from Io, we can use the shape of the 11-day running median in Figure 2 (right panel) to provide an estimate of the time evolution of the gas release, which, upon further study, may provide clues to its origin. Electron impact ionization is the primary loss mechanism of sodium within the IoIO FOV and is of order 10–20 days (e.g., Wilson et al. 2002, their Figure 3), which is short compared to the $\sim$180 day enhancement in the nebula. Thus, the shape of the 11-day running median is primarily determined by the physical processes responsible for gas release from Io.

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