Io’s Active Volcanoes During The New Horizons Era: Insights From LORRI And MVIC

General comment- for drafts like this, it’s better to put the figures and captions in line with the text rather than as text boxes, because Word wreaks havoc with the placement when edits are made. Only place them nicely once the text has stabilized…]

# Introduction:

Io is the most volcanically active body in the solar system, with more than 100 active volcanoes at any time. Data from spacecraft (Voyager and Galileo) and ground-based telescopes (such as IRTF) have been used to study Io’s volcanoes and how their activity changes with time. More recently, the New Horizons spacecraft flew by the Jupiter system on its way to Pluto. Its closest approach to Io occurred on February 28th, 2007 at a range of 2.24 million km. For more than 3 days, the spacecraft was within 3.5 million km, close enough to obtain high quality observations covering all longitudes of Io.

The Long-Range Reconnaissance Imager (LORRI), a high-resolution black and white camera, obtained 190 images, including many4 of an eclipsed Io. These images covered about 60% of the surface (missing longitudes 30 to 170 W). The Multicolor Visible Imaging Camera (MVIC), a four-color (visible to near infrared) camera, obtained 17 sets of images. Spencer et al. (2007) searched these data for plumes and surface changes, and found a new bright hotspot at 22 N 245 W that they designated “East Girru”, due to its location east of the Girru hotspot. Here, we present a complete view of hotspots in all LORRI and MVIC data.

With a wide-band filter covering approximately 400 to 900 nm, LORRI data are more useful than MVIC data for detecting high-temperature eruptions, changes in brightness with time, and, due to the higher spatial resolution, precisely locating emission sources. Many of the images captured a partially daylit disk that could be used to fit Io’s limb and, thus, determine locations of any hotspots with great accuracy (within 50 km in most cases).

# Image processing

Figure 1 shows the bandpasses of the LORRI and MVIC instruments. Morgan et al. (2005) give LORRI’s responsivity in units of (DN/s/pixel)/(W/cm2/str). We use this to calculate the isophotal wavelength (defined as the wavelength at which the monochromatic flux is the same as the total flux through the filter) for a 1200 K blackbody. We then can translate all LORRI images into W/cm2/str at this wavelength. When we total all emission from each hotspot, we account for the area of the field of view and the result is power output in W/nm/str.

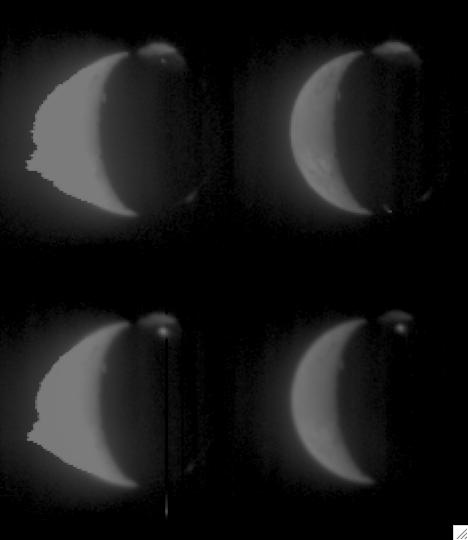
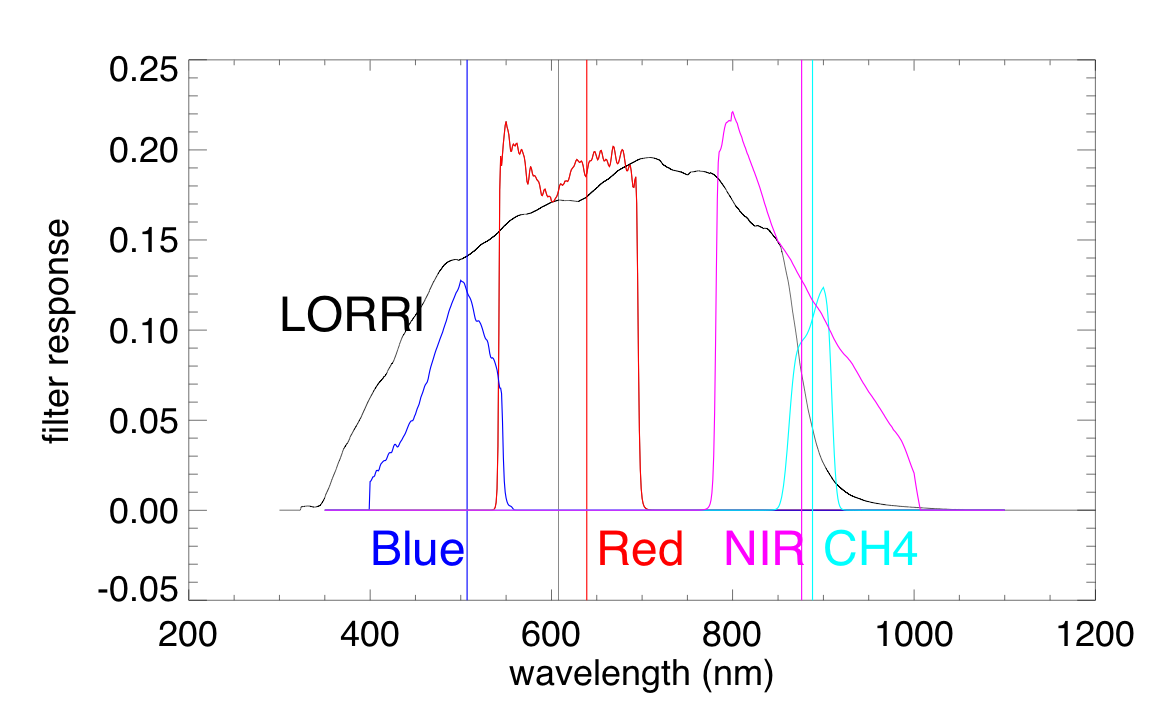
The MVIC camera obtains 4 images sequentially in four different filters (figure 2). The total spectral response for each filter is shown in figure 1. These preliminary curves include the filter response, mirror transmissivities, and CCD quantum efficiency for the camera (reference?, JOHN – I got these from the files you sent and the document by Jessica Lovering). To use the multicolor data to determine color temperatures, for each filter we calculated the isophotal wavelength (defined as the wavelength at which the monochromatic flux is the same as the mean flux through the filter [an equation would be useful here- what exactly do you mean by “mean flux”?] for a 1200 K blackbody (vertical lines in figure 1). The band passes of the near infrared (NIR) and methane (CH4) filters are too similar to yield meaningful color temperatures.

Figure : Response function for each filter in MVIC and LORRI. Vertical lines indicate the effective wavelength for a 1200 K blackbody corresponding to each filter. [Y axis is total throughput, not just filter response, right? (LORRI has no filter)]

Figure : MVIC observation of Io showing Tvashtar hotspot and plume in the upper right of each image. The upper left images is in the red filter, upper right in blue, lower left in NIR, and lower right in methane [more readable if you put the filter labels in the image].

For each hotspot, we calculated the total thermal emission measured by adding up the signal from nearby pixels and subtracting the nearby background level, yielding a total data number and uncertainty which we converted to physical units using the isophotal wavelength [note this is only valid if the temperature really is 1200 K…]. For hotspots observed in multiple MVIC filters in the sequential images, we calculated color temperatures [strictly, this needs to be iterative if the resulting color temperature is not 1200 K]. We also attempted fitting blackbody curves to a combination of the MVIC and LORRI brightnesses calculated in W/nm/str, but had difficulty obtaining good fits to the data. We next calculated the filter response in DN for each filter given a specific blackbody, and varied the temperature and area of the blackbody to obtain the measured DN values within the uncertainties. Due to the large uncertainties and similarity of filters (particularly NIR, CH4, and LORRI), we were unable to satisfactorily constrain either of these parameters [do you mean no filter comparisions gave useful constraints, or that a few combinations, like NIR/CH4, didn’t work? If some worked, this seems like a more reliable method than using a single isophotal wavelength].

All of the MVIC images (figure 2) and many of the LORRI images were obtained with part of the Io’s disk illuminated- the hot spots were only seen on the unilluminated portion of the disk . Due to the short exposures of these images, only the brightest hotspots can be observed in these images, but the presence of Io’s illuminated limb allows us to determine the location of these hotspots precisely, particularly in the higher spatial resolution LORRI data. We use the SPICE system from NASA’s Navigation and Ancillary Information Facility (NAIF) to determine the orientation and limb shape of Io at the time each of the LORRI observations was obtained, assuming a triaxial ellipsoid shape for Io. We fit this outline of Io to the limb observed in the images. For each hotspot, we found the centroid of the brightness and computed its location on Io in latitude and longitude, obtaining accuracies of 50 km or better in most cases.

iecl04pretty.epsOnce we determined the location of the bright spots measurable in the partial daytime images, we used those to refine the locations of other hot spots seen in the eclipse images. Of course, the uncertainty in location is larger for the eclipse images than for the partial daytime images [do you mean before or after bootstrapping from the sunlit hot spot locations? If after, why “of course”?]. Two eclipses were observed by LORRI, on February 27th and March 1st 2007. We examined individual images to determine temporal variations and combined all observations from each eclipse to significantly increase the signal to noise and identify many more hotspots [careful what you call a “hot spot”- the fainter sources may not actually be “hot spots”. Use a more generic term]. Of course, we could not observe the temporal variability of those fainter spots [again, explain “of course”- it’s because we have to average all the images to get useful SNR on the fainter spots].

## Temporal variations

Figure : Total image from co-adding most 4x4 binned images from the March 1st eclipse, but avoiding images contaminated by scattered light from Jupiter. Dashed line indicated the SPICE-derived position of the limb and terminator [registered to what? The limb emission? E. Girru?]. Red plus signs indicated emission sources. Note that all emission sources appear to be point sources at this resolution, with the obvious exception of Kurdalagon in the lower right.

During the February eclipse, 23 images were obtained at irregular intervals over an hour and a half. Three volcanoes were observed in these images: Reiden, Pele, and E. Girru. None of the three demonstrated substantial variations during that time (Figure?).

During the March eclipse, two sets of images were obtained. The first set took 39 images approximately every second. The same 3 hotspots were observed in these images as in the previous eclipse. About 5 minutes later (after 9:35), a second set of 27 images were obtained approximately every 8 seconds [this info should be in a table, along with the other images used in the study]. This set was binned on-chip by 4 by 4 pixels to increase signal to noise. Four additional hotspots were detected in these observations: Isum, Marduk, shortplot.epsMulungu, and an unnamed hotspot at 28 N, 192 W [say something about the distinction between “hot spots” and the other emission sources in Fig. 3]. In addition, a bright area centered on Kurdalagon was also measured. The Kurdalagon emission feature differed from the others in that it was measurably extended as opposed to a point source (Figure 3). Of the seven hotspots observed during eclipse at short time-scales, none exhibited measureable variations over seconds, minutes, or an hour time-scale (figure 4) [fig 4 only shows second-timescale variations]. This was the first time Io’s volcanoes could be observed on such short time scales and demonstrates that the volcanoes are remarkably stable [no- reference Jani Radebaugh’s measurements of Pele’s brightness in the Cassini eclipse images]. This indicates the thermal emission is dominated by an emplacement process that does not vary greatly on short timescales, which favors lava flows as opposed to more energetic phenomena like lava fountains. With the exception of “East Girru”, there were also no detectable changes over the several days of observations [demonstrate this].

Figure : Brightness of three volcanoes at short time scales obtained during the March 1st eclipse.

### Long time-scale changes

The Galileo Solid State Imager (SSI) obtained eclipse images in an open filter with a nearly identical wavelength range to LORRI, enabling comparisons on a decade time scale by comparing images obtained by Galileo from 1995-2003 to the New Horizons observations from 2007. SSI observed 44 emission sources over 14 eclipses covering the entire globe (Lopes et al., 2007) [are there no visible wavelength flux measurements of the Galileo ISS eclipse sources? If not, say so- it explains why the following discussion does not compare fluxes]. Of those, Pele was observed most often, followed by Pillan, Kanehekili, Amarani, Acala, Loki, Marduk, Ruwa, and Zal. We consider these persistent high-temperature sources. All except Ruwa were also observed by Galileo as having emission at near-infrared [right? “thermal” is ambiguous in this context, where thermal emission can be seen at visible wavelengths] wavelengths. We located 54 total hotspots [again, careful with “hotspots”] in the LORRI images which covered only 60% of the surface (missing longitudes 30 to 170 W). Thus, LORRI detected twice as many emission sources as SSI. Of the 9 persistent high-temperature sources, Kanehekili, Amarani and Zal are located in the region not well covered by New Horizons. Of the remainder, Pele and Marduk were observed by New Horizons in multiple images and Pillan and Ruwa were fainter and observed only in co-added eclipse images. Acala and Loki were not detected, which may indicate that high-temperature volcanism has ceased at these locations [I checked, and did not after all see Loki in the LORRI eclipse image (though it’s visible, faintly, to LEISA in the near-IR- you might mention that, citing the Spencer 2007 paper)]. Dazhbog and Llew were observed by LORRI but not Galileo SSI, but were confirmed hotspots from other Galileo instruments, indicating that something new (perhaps a new high-temperature eruption) is occurring at these locations.

mapnewspots.epsOf the 54 emission sources observed by New Horizons, 40 had not been previously observed by SSI, 31 had not been previously observed as hot by any instrument, and 13 were clearly extended sources (figure 5). Many of these sources were located in large areas that are bright in eclipse near the Jupiter-facing and anti-Jupiter points (figure 6) [reference previous Galileo and Cassini observations of bright emission at these locations (Geissler et al. 1999, 2004]. Most of them are near identified paterae, but not necessarily dark paterae. Galileo also observed areas on the limb that were bright in eclipse (figure 6) and suggested they were due to the interaction of the atmosphere with the Io torus (Geissler et al., 2004). Because of the concentration of many of these emission sources in regions of enhanced atmospheric emission, the fact that many are extended, and do not correlate with thermal emission seen by LEISA (Spencer et al. 2007), we agree with Spencer et al. (2007) that many of these faint sources are probably non-thermal in origin.

Figure : Location of emission sources identified by LORRI that were not found by SSI.

## ieclipse03.jpgTvashtar

prettylorriplot.epsA major eruption at Tvashtar was observed by the Galileo spacecraft (Millazzo et al., 2005). In November 1999, it included active fire fountains and lava flows. Galileo NIMS measured a color temperature of 1060 +- 60 K while SSI inferred a temperature of 1300-1400 K. The fire fountains were located in the middle patera [this statement doesn’t make sense without context- how many paterae are there? To be clear, give a lat/long or, better, show on an map] and had a size of 25 km2. In February 2000, thermal emission from an active lava flow was observed in the western patera. SSI measured a color temperature of 1300 K over 6.3 km2 and a brightness temperature of 1220 K – 1240 K over an area of 0.1 km2 from parts of this active flow [correct?].

Figure : At Right: Co-added LORRI image from the February eclipse. Left: two eclipse images from Galileo SSI (from McEwen et al., 1998). All show a background glow near the limb of Io.

Tvashtar was by far the brightest hotspot observed by New Horizons. The hot spot was observed 3 times by LORRI, always on the night side of partially-sunlit images. In these observations, taken over 2 days, the emission angle varied between 68 and 78 degrees. The variation in power output with emission angle matches cosine dependence, indicating that the emission was from horizontal surfaces such as surface flows as opposed to fire fountains (figure 7) (or, less likely, that temporal variability over the two days coincidentally mimicked a cosine variation with emission angle). The location of the emission is closer to the location of the eruption observed by the Gailileo spacecraft in November 1999 [closer than to what? Again, it’s important to show an image or map]. Although we were unable to determine a blackbody fit to all the data simultaneously, we determined the color temperature of Tvashtar based on the ratio of observed MVIC brightnesses in different filters These brightnesses are nearly simultaneous and yielded temperatures of 1160 +/- 60 K for the Red/NIR ratio and 1200 +/- 100 K for the Red/CH4 ratio. Using 1200 K as the temperature, a flow size of 40 km2 best matches the absolute fluxes, a larger size than the 25 km2 observed by Galileo.

Figure : Measured brightnesses of the Tvashtar hotspot as a function of emission angle. The variation matches that expected from a surface flow.

## “East Girru”

East Girru was not previously observed as a thermal source from Voyager, Galileo, or from the ground. It was the second brightest source observed by New Horizons (again, we should give numbers , in a table) and was detected by both LORRI and MVIC, though MVIC detected East Girru only in the overlapping near infrared and methane filters, preventing determination of a color temperature. Over the course of the 6 days of LORRI data, a decrease in brightness of more than a factor of 4 was detected. Smaller decreases were detected in two MVIC filters (near infrared and methane) over 3 days. [Need details, in a figure]

The location of E. Girru was well determined using LORRI images that included part of Io’s disk in sunlight,. The emission is located approximately 200 km to the east of the previously detected Girru hotspot (reference). Galileo images show no low albedo region near this new emission region and New Horizons images, while lower spatial resolution, show no surface changes. The highest resolution obtained was on February 27 at 15 mapgirrulorri.epskm/pixel. Reducing the resolution of the USGS Galileo black and white mosaic to the same resolution shows that no changes occurred in this region (figure 8) [need to include the Galileo image in Fig. 8]. Nearly all thermal emission regions on Io are correlated with a low albedo feature (e.g. McEwen et al., 1998), yet there is no conspicuous dark feature at East Girru. The eruption source could be very small, below the spatial resolution of the best image, or the eruption could be very recent, perhaps just beginning in February 2007. However, new eruptions are often accompanied by plumes and no plume was observed by NH at this location. (Spencer et al., 2007)

Figure : Highest resolution LORRI image of E. Girru region with location of observed hotspots superimposed. The location of Girru is shown for comparison. Note that there is no low-albedo feature near the detected hotspots [reword- there is a modest low albedo feature nearby]. [compare to Galileo image- lack of changes is important]

## Pele

Figure : Single image from the February eclipse. Note the double hotspot at Pele in the lower left. [Inset with enlargement of Pele to make double nature more obvious?]

Pele is one of the most persistent sources of thermal emission on Io, especially in the shorter wavelengths. High-temperature components within Pele have been calculated at 1100-1700 K (Radebaugh et al., 2004) from Galileo SSI and NIMS. A very high-spatial resolution Galileo nighttime observation of Pele’s thermal emission is shown in red/yellow pseudocolor in figure 10. The color temperature in each pixel ranges from 1270 K to 1605 K (Radebaugh et al., 2004). Cassini obtained observations on the timescale of minutes and found that the total intensity varied little on that time scale and that any variation could be explained by mappele.epsthe change in emission angle, similar to our LORRI observations [which LORRI observations are you referring to here? Fig 4? You’ve only discussed Tvashtar changes with emission angle so far] (Radebaugh, et al., 2004). Since only LORRI observed Pele, we were unable to determine its temperature.

Figure : Position of Pele hotspot determined from LORRI images overlaid on Galileo images (from Howell and Lopes, 2011). The dated locations in blue are from co-added eclipse images while the lower two locations are from the double hotspot. While we are confident of the relative positions of these locations, their absolute position relative to the Galileo images may shift up to the red arrows.

[you said in the previous sentence that MVIC didn’t observe it] Pele was observed by LORRI during both eclipses. During the March 1 eclipse, the spatial resolution was high enough (give number) to reveal Pele as a double hotspot (figure 9). The two thermal emissions regions were of roughly equal brightness and separated by about 40 km [right? give the actual separation, not an upper limit] (figure 10). High spatial resolution Galileo SSI images revealed a complicated pattern of thermal emission, with multiple sources over approximately 80 km [looks like <80 km in Fig 10…] (Howell and Lopes, 2011). Observations by SSI and NIMS showed that while the pattern changed on the time-scale of months, there was always a single dominant bright area. The New Horizons observation therefore shows a different configuration of emission from Pele than was ever seen by Galileo, though with a similar overall extent].

## Conclusions

The New Horizons observations of Io’s volcanoes allowed us to determine changes on several new time scales. At the short end, which Galileo was unable to obtain, none of the seven volcanoes observed showed substantial changes on the order of seconds, minutes, or hours. Furthermore, only E. Girru demonstrated variation over days.

Many changes were observed between the Galileo SSI and NH LORRI observations a decade later. Many volcanoes stopped exhibiting high temperature emission while others began such emissions. E. Girru was a brand new emission source, interpreted as a volcano. However, the lack of both a plume and a low-albedo feature at the location of the thermal emission is surprising. Most of the observations of new emission at a location are likely due to non-thermal activity. [needs work, but you knew that]

[Need table of detected hot spots and their locations, fluxes, and temperatures where known. Also a table of observations]

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