Vulcanism on Io with Aperture Masking Interferometry on *Webb*'s NIRISS

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Vulcanism on Jupiter's innermost Galilean moon, Io, presents a solar system science opportunity for the Aperture Masking Interferometry (AMI) mode of the Near Infrared Imager and Slitless Spectrograph (NIRISS) on *Webb*. Precise determinations of the positions of unresolved volcanic eruptions will be possible. NIRISS' F380M, F430M, F480M or F277W filters are well matched to emission from Io's lavas, which have temperatures of 500 K–2000 K. Accurate, high-cadence photometry of the eruptions in some or all filters will provide uniquely powerful insights into short-term variability, eruption temperatures and active areas, and long-term trends in activity for individual calderas on Io. These data could also provide new measurements of the global distribution of vulcanism on Io, improving constraints on the depth and location of tidal heating in the interior.

AMI is enabled by a seven-hole non-redundant pupil mask (NRM). The mask generates an interferogram in the image plane, turning the full aperture of the telescope into an interferometric array with an angular resolution of 0.5 λ/D, rather than full aperture resolution of 1.22 λ/D. We explore this capability by creating simulated observations of volcanic features on Io as observed with the NRM and F430M filter.

When Io is observable with *Webb* it will be at distances between 4.6 and 5.3 AU, and its 3642 km diameter will typically span 16 NIRISS pixels with pixel scale of approximately 65 mas. It can be placed at four different dither positions on the 80 × 80 pixel fast readout subarray designated for the AMI mode. The dithers are separated by 36 detector pixels (about 2.36''), to mitigate against persistence and other detector and calibration noise sources (Greenbaum et al. 2015). This strategy also reduces the effect of flat-field errors (which we include in our simulations) and bad pixels.

We have simulated NIRISS AMI data for Io, including the effects of read noise, Poisson noise, dark current, sky background, and dither-position uncertainties (predicted to be 15 mas[1] 1-sigma radial) and jitter (7 mas 1-sigma radial). The dithers are randomly located within a pixel because of these placement errors, which may help mitigate against the effects of inter-pixel capacitance (re-distribution of signal due to capacitive coupling between pixels).

We create a count-rate image of the disk of Io including the contributions from reflected sunlight (IR albedo assumed to be 0.5) and from volcanoes calculated for assumed temperatures and radii. Loki, the largest volcanic feature on Io, is assumed to have a near-IR emitting area 20 km in radius with a temperature of 500K. Our so-called "Big event" has a radius of 4 km with a temperature of 1700 K, and our "Typical event" is only 1 km in radius, with a temperature of 1000 K.

Our simulated images are oversampled by a factor of 11 relative to the NIRISS pixels scale; even so, the volcanoes only occupy a fraction of the pixel, so we treat them as point sources. With NRM and F430M we estimate the count rate of Io disk to be 25,000 photons/sec/pixel, the count rate of Loki to be 5.4×10^5 photons/second, the count rate from bright events 2.8×10^6 photons/second and the count rate from typical event as 4×10^4 photons/second. We convolve the count rate images with NIRISS PSF created with *Webb* PSF simulation tool WebbPSF (Perrin et al. 2014) and introduce the noise and other effects mentioned above. For observations with Loki being the only active volcanic feature, the exposure time at each of the four dither positions is set to 29.5 seconds. Observations involving bright events are much shorter, with an exposure time set to 8 sec at each of the four dithers.

The FITS file containing the exposure at each dither position is made up of slices, one for each integration, and each such integration is made up of multiple non-destructive frames. In practice each non-destructive frame samples the signal every 75 milliseconds in the 80 × 80 AMI subarray, and the count rate can be accurately measured even for sources that would saturate in less than one second.

Figure 1 illustrates the results of our data modeling for a case with four active eruptions on Io. The NRM produces a PSF that has a sharp peak and an extended structure made up of coherent fringe patterns overlaid across one another. When convolved with the model input image, both Io's sunlit disk and emission from vulcanic sources is visible. Emission from the eruptive centers is more readily apparent in disk-subtracted images, as shown in the bottom panels of the figure, including emission from

[1] milli-arcsecond

the fainter sources. Note that the simulated data (panel *d*) shown here is for a single AMI integration of 0.45 seconds and for our simulations each exposure is made up of 18 such integrations. Multiple exposures from the dithered AMI observation would be co-added in practice, significantly improving the SNR of the data beyond what is shown here.

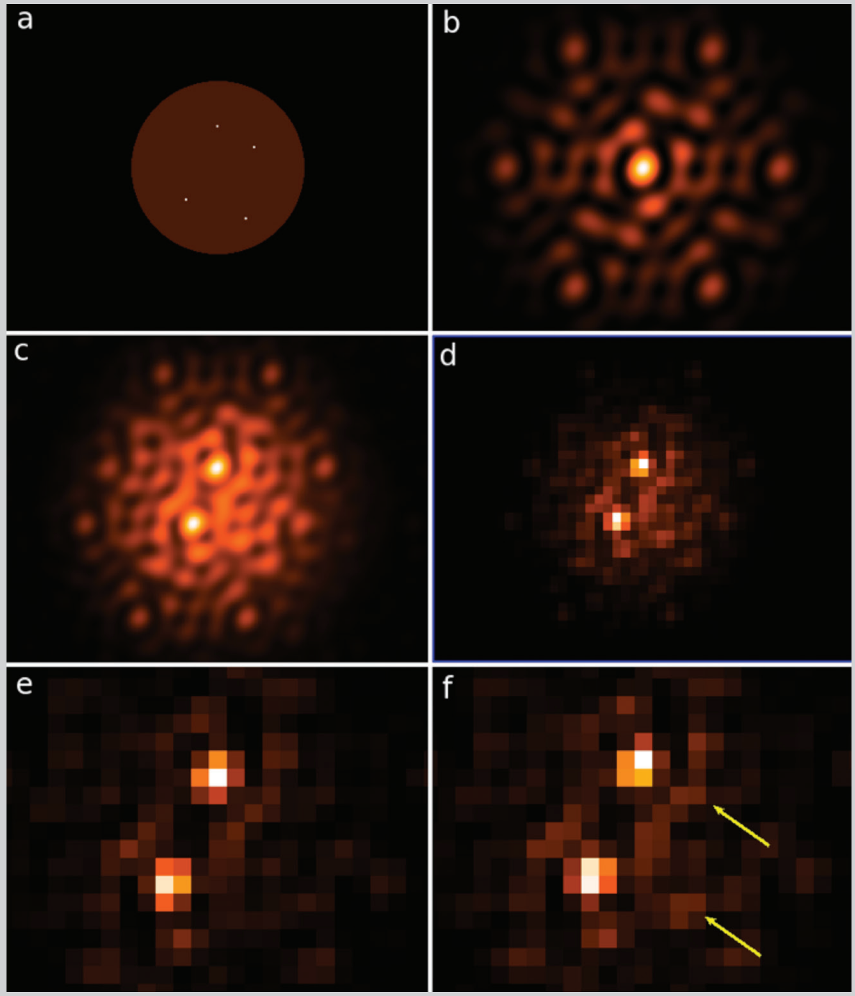

Figure 1: Panel *a* shows count rate image of Io with Loki, two bright events and one typical event that is used as an input image, Panel *b* is the NRM PSF of a point source created using WebbPSF for F430M filter. Panel *c* shows the convolution of input image with NRM PSF and Panel *d* is the simulated data (one integration). Panels *e* and *f* are the difference images obtained by subtracting simulated Io image without volcanoes from simulated Io image with volcanoes. To pinpoint the location of two fainter volcanoes, we first simulated the data with two bright events (Panel *e*) and then with two bright and two fainter events (Panel *f*). A comparison of Panels *e* and *f* reveals the location of two fainter volcanoes that are indicated by arrows in Panel *f*. The dimensions of Panels *a*, *b* and *c* are in 11× oversampled pixels and are displayed with linear stretch. Panels *d*, *e* and *f* are binned to the NIRISS pixel scale and are displayed using a squared stretch.

To explore the ability of NIRISS AMI to resolve closely spaced eruptions, we simulated a bright event and Loki at separations of 88 mas and 177 mas respectively from each other. The results are equally encouraging to those shown above. Even closely spaced eruptions appear to be resolvable in the raw model images where the disk of Io has been subtracted. Using deconvolution or other more advanced techniques, it should be possible to retrieve much clearer images reflecting a wealth of detail across the disk of Io. While SO_2 frost, with an absorption at about 4.1 µm, is also of interest, NIRISS lacks an appropriate filter for mapping that species. Nevertheless, NIRISS has the potential to acquire remarkable and unique data constraining volcanism on Io.

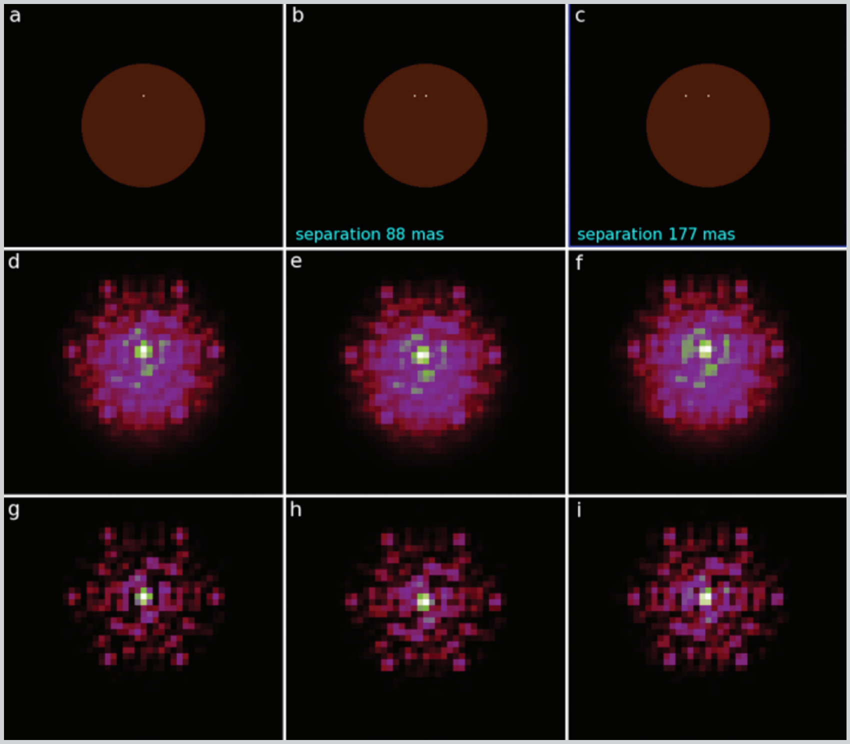

Figure 2: Panels *a*, *b*, and *c* show input model count-rate images with one bright event (Panel *a*), a bright event and Loki separated by 88 mas (Panel *b*), and a bright event and Loki separated by 177 mas (Panel *c*). Panels *d*, *e*, and *f* show one integration of the simulated data based on the models in *a*, *b*, and *c*, respectively. Panels *g*, *h*, and *i* are the difference images obtained by subtracting a simulated Io image without volcanoes from the images in *d*, *e,* and *f*, respectively. The images in Panels *a*, *b*, and *c* are in 11× oversampled pixels and are displayed using a linear stretch; Panels *d* to *i* are binned to the NIRISS pixel scale and are displayed using a squared stretch. Subtle differences between *h* and *g*, and between *i* and *g,* suggest that deconvolution methods should allow the retrieval of fluxes and locations for even closely spaced eruptions from AMI observations of Io.

Conclusions

Our initial efforts at modeling AMI observations of Io volcanism are very promising. The volcanic emission from even fairly typical eruptions is visible in the raw simulated images for exposures of only a few 10s of seconds. Scattered light from Jupiter may be an issue for such observations, but can be mitigated directly by choosing appropriate filters. We hope to explore this application of AMI further by modeling scattered light gradients across the scene, and applying deconvolution to retrieve images that reflect more clearly the ~65 mas spatial resolution that should be achievable from the data.

References

Greenbaum, A. Z., Pueyo, L., Sivaramakrishnan, A., & Lacour, S. 2015, ApJ, 798, 68
Perrin, M., et al. 2014, Proc. of SPIE, Vol. 9143, 91433X-1