Infrared Speckle Observations of Io: An Eruption in the Loki Region

Abstract. *Speckle observations of Jupiter's satellite Io at a wavelength of 5 micrometers during July 1984 resolved the disk and showed emission from a hot spot in the Loki region. The hot spot contributed a flux approximately equal to 60 percent of that from the disk. Images reconstructed by means of the Knox-Thompson algorithm showed the spot moving across the disk as the satellite rotated. It was located at 301° ± 6° west longitude, 10° ± 6° north latitude, and had a radiance of (2.96 ± 0.54) × 10^{22} ergs sec^{-1} cm^{-1} sr^{-1}/A where A is the area of the spot. For an assumed temperature of 400 K, the area of the source would be 11,400 square kilometers. An active "lava lake" similar to that seen by Voyager may be the source of the infrared emission.*

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The presence of volcanism on Jupiter's satellite Io makes it one of the most geologically interesting bodies in the solar system. Observations of this volcanism at present fall into two categories: the Voyager measurements, which have excellent spatial resolution but cover a limited time base; and the Earth-based infrared measurements, which now cover an interval of almost a decade but have only hemispheric spatial resolution.

Despite these limitations, it has been possible to gain some insight into the location and long-term stability of the volcanism. Johnson *et al.* (*1*) report from modeling of the 8-μm rotational lightcurve that much of the heat flow from Io comes from a source near 300° longitude, presumably the Loki volcanic region observed by Voyager. Direct imaging of the planet at thermal wavelengths would allow us to estimate the duration and interval between eruptions as well as the long-term pattern of volcanic activity. We now report observations that resolve the satellite in the infrared by means of speckle interferometry.

Speckle interferometry is a technique for achieving diffraction-limited resolution with large telescopes, despite the blurring caused by the atmosphere. By appropriate Fourier processing of short-exposure images, combined with measurements of known point sources, it is possible to recover the power spectrum of the true image out to a spatial frequency limit determined by the size of the telescope. The normalized square root of the power spectrum, termed the "visibility," can then be modeled to determine general properties of the image. For example, a uniform disk of diameter D has a visibility of 1 at a frequency of 0, but the visibility falls to 0 at a spatial frequency of approximately $1/D$; the visibility for a point source remains at 1. A uniform disk with a point source superposed gives approximately the linear combination of the two.

The details of infrared speckle interferometry (*2*) differ substantially from its visible wavelength counterpart. Because two-dimensional imaging detectors are not yet commonly available for the infrared, our observations were obtained by means of a single detector, with a long (6 arc seconds) but narrow (0.4 arc second) focal plane slit. The image was scanned across the slit at a rate of approximately 20 arc seconds per second, which is fast enough to "freeze" the seeing. This results in a one-dimensional measurement of the visibility. The slit orientation and scan direction could be changed; both east-west and north-south measurements were made.

Although visibility modeling is a useful way of interpreting the speckle data, true images (or, in this case, diffraction-limited slit scans) would be better. Several algorithms have been proposed to recover the phase information necessary for the Fourier inversion of the visibility (*3*, *4*). Such algorithms have met with limited success at visible wavelengths, but for various reasons the technique has better success in the infrared. In addition, the relatively simple image that Io is expected to present (an approximately uniform disk with, at most, a few bright points superposed) makes an ideal test case for these methods. This is particularly true since the image should change in a predictable way as the satellite rotates. We have investigated a variety of

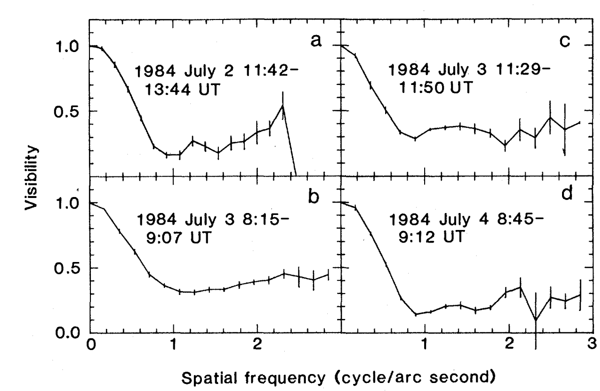

Fig. 1. Typical visibility curves for Io. (a and d) Data obtained on 2 July and 4 July, when the "inactive" side of Io faced Earth. They indicate a disk with a diameter of 1.2 arc seconds, with perhaps 15 percent of the flux coming from an unresolved hot spot. (b and c) Data obtained on 3 July, when the opposite hemisphere was visible. Approximately 35 percent of the flux is from an unresolved hot spot. The slight change between (b) and (c) is due to the rotation of the spot toward the limb. Because systematic errors may affect the highest spatial frequency sections, the contribution from the point source should be judged from the visibility where the curves first level off.

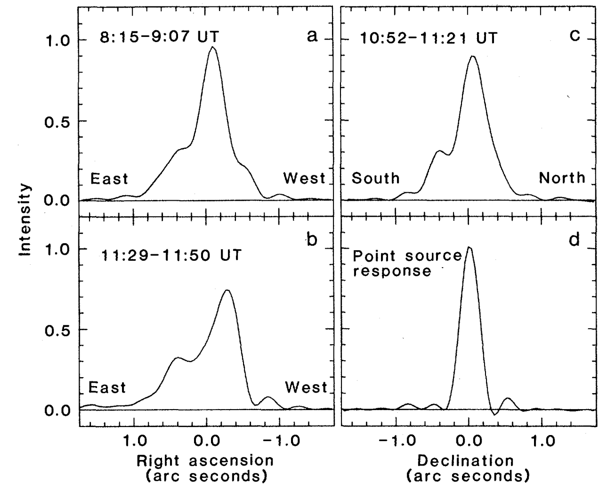

Fig. 2. "Images" reconstructed by means of the Knox-Thompson algorithm (*3*). (a and b) East-west scans, showing the movement of the hot spot. (c) North-south scans. (d) The reconstructed image of a star, which can be used to judge the effective resolution.

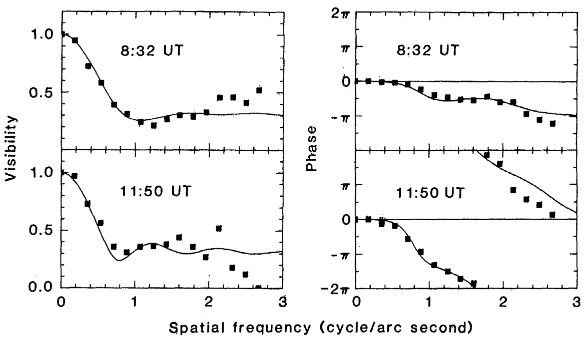

Fig. 3. Visibility and phase measurements (■) from individual observations; the solid lines are best-fit models. The upper set was obtained when the hot spot was near the center of the disk; the lower set was obtained when it was near the limb, causing the steep slope in phase.

algorithms. The results presented here were processed by the method of Knox and Thompson (*3*), which, at least for these data, gives the most consistent results.

The observations were made at the NASA Infrared Telescope Facility on Mauna Kea with a standard photometer and M (4.8 μm) filter. The data cover three consecutive nights: 2, 3, and 4 July 1984, during a time when photometry (*5*) indicated that a moderate thermal outburst of Io was near maximum. Because the rotation period of Io is 1.7 days, our observations provide fairly complete longitudinal coverage.

The visibility curves obtained on 2 and 4 July (Fig. 1, a and d) closely resembled those of uniform disks with a diameter of roughly 1 arc second. (The diameter of Io at the time of these observations was 1.19 arc seconds.) The visibility did not go exactly to 0 but instead leveled off between 0.10 and 0.20. Taken at face value, this would suggest that approximately 15 percent of the flux originated from an unresolved spot. This might be expected if 85 percent of the 5-μm flux was reflected sunlight and the rest came from a few volcanic regions on the surface.

This interpretation must be regarded with some suspicion. Various instrumental effects, such as telescope vibration and rapid "unfrozen" seeing, can produce spurious power at high spatial frequencies. Visibilities of 0.10 to 0.15 are typical. Therefore we must regard the value of 0.15 as only an upper limit to the unresolved hot spot flux from this hemisphere.

The situation was different on 3 July, when the opposite hemisphere faced Earth. The visibilities leveled out at 0.3 to 0.4 (Fig. 1, a and b). All the curves obtained on this night were similar; they indicated that approximately 35 percent of the total flux was from an unresolved source. Minor changes that were seen with time were what would be expected if a hot spot near the center of the disk at the beginning of the night were moving toward the limb. The visibility curves dropped more rapidly and perhaps to a slightly lower level.

Three average "images" or slit scans (Fig. 2) were produced from the individual reconstructions obtained on 3 July. They showed a bright unresolved source superposed on an underlying extended source roughly 1 arc second in diameter. The point source moved to the west (on the sky) with time (Fig. 2, a and b) as is expected from the rotation of Io. It was located slightly north of the equator (Fig. 2c).

To obtain an accurate position for the hot spot, we made least-squares fits of a model to the Io observations. The model consists of a uniform disk with a single superposed point source and has three parameters: the diameter of the disk, the brightness of the point source relative to the disk, and the location of the point source relative to the center of the disk. Each "observation" consists of 128 scans of Io, 128 scans of a nearby star, and appropriate system noise measurements. While observing, we alternated between such sets of Io and star scans to eliminate effects of variable seeing.

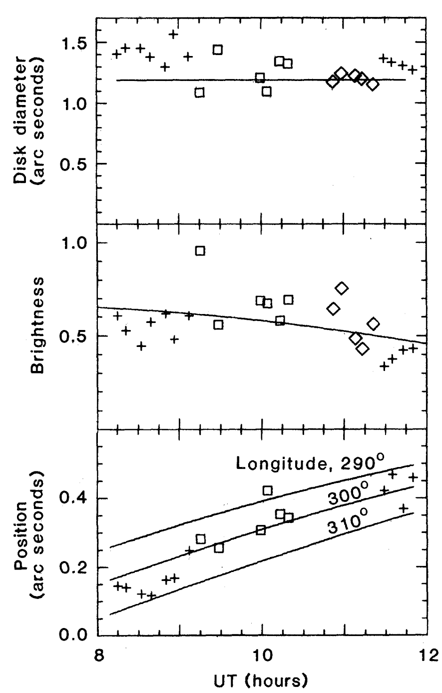

Fig. 4. Disk diameter, point source brightness, and point source position (measured west from the center of the disk). A line at the known 1.190–arc second diameter is shown, as is the expected variation in hot spot brightness for the adopted location and radiance. In the final plot, lines representing the apparent motion of points at 290°, 300°, and 310° west longitude are shown. (The latitude is assumed to be +10°.) Symbols: (+) east-to-west scans; (□) west-to-east scans; (◇) north-to-south scans.

We fit the model to the data in the Fourier domain rather than in reconstructed image space because this represents more directly the measured quantities. The abscissa (spatial frequency) is well defined, and the error in the ordinate (amplitude or phase) can be reasonably estimated. In contrast, in the reconstructed image, measurement error results in changes in both position and intensity that are hard to quantify. Amplitude and phase errors tend to increase at high spatial frequencies, so we weighted the data with a function that is 1 at a frequency of 0 and falls to 0 at a spatial frequency of 2.8 cycles per arc second. A similar function was used to apodize the visibilities before reconstructing the images.

For each individual observation (Fig. 3), the level of the visibility at high frequencies largely determines the brightness of the point source, and the slope of the phase curve determines its location. If the point source were centered, then the image would be symmetrical and the phase would be zero.

Modeling of the Io observations from 3 July (Fig. 4 and Table 1) showed that the hot spot brightness is relatively constant, that the apparent diameter is close to the known value for Io, and, most important, that the point source moves in roughly the way expected for a source on a rotating planet (*6*). The location that provided the best fit was 301.2° ± 1.3° west longitude, 10.2° ± 3.0° north latitude. Assuming that the spot is at this location and that the brightness varies as the cosine of the angle from the subearth point results in a predicted brightness of 0.685 ± 0.036 relative to the disk when it is at the subearth point. The errors are derived for the goodness of fit, assuming that the model is correct.

A comparison of the expected movement and brightness with that observed showed systematic residuals. In particular, the hot spot seems to move toward the limb slightly faster than expected, although the data could also be interpreted as showing a discontinuity in position near 9 hours universal time (UT).

This effect could be due to some undetected change in the scanning mechanism, but double stars measured before and after the Io observations showed no obvious difference. We suspect that the cause is the existence of other, weaker hot spots on the disk. For example, a hot spot near the western limb (230° to 250°) would increase the apparent east-west diameter, would shift the center of the modeled disk relative to the hot spot, and would increase the disk's relative brightness. The greater scatter in the east-west diameter, compared with that in the north-south, also suggests such an effect. However, because this is a new technique with perhaps unknown sources of error, we do not claim that the presence of such a hot spot is firmly required by the residuals.

Finally, the systematic effects mentioned above, which introduce spurious high-frequency power, resulted in an overestimate of the hot spot brightness. This spurious power adds in quadrature with the true power. Estimating that it would result in a visibility of 0.15 for a completely resolved disk, and subtracting the equivalent power, we obtained a corrected hot spot brightness of 0.67 when it is at the subearth point.

Measurements of the total brightness of Io, relative to the star λ Sgr, allowed us to estimate the hot spot flux. Adopting an M magnitude of 0.438 ± 0.005 for this star (*5*) and a zero magnitude flux of 170 ± 8 Jy (*7*), we obtained a hot spot flux of 5.78 Jy, which is equivalent to a radiance at Io's surface of 2.96×10^{22} ergs sec^{-1} cm^{-1} sr^{-1}/A, where A is the hot spot area.

In summary, after correcting for systematic effects and estimating the various sources of error, we adopt the following hot spot parameters: longitude, 301° ± 6°; latitude, 10° ± 6°; brightness, 0.67 ± 0.15 (relative to the disk); radiance, $(2.96 \pm 0.54) \times 10^{22}$ ergs sec^{-1} cm^{-1} sr^{-1}/A.

These data, when combined with the knowledge that an infrared outburst was occurring (*5*), indicate that an eruption was taking place in the Loki region. Loki Patera, the "lava lake" seen by Voyager, was located at (309°, +12°) (*8*). Two plumes issued from opposite ends of a dark feature slightly to the northeast: (305°, +19°) and (301°, +17°) (*9*). All these locations are slightly beyond the errors limits we have quoted for our measurements. The discrepancy is small enough that we cannot absolutely exclude them, but the polarization observations by Goguen and Sinton (*5*) also suggest a source slightly east of Loki Patera. (In this case, east is the direction on the planet, not on the plane of the sky.)

Table 1. North-south hot spot position on 3 July 1984.

Universal time (hours)	Location (arc seconds)	Longitude (degrees)
10:52	0.125	+13
10:58	0.176	18
11:08	0.044	5
11:13	0.007	2
11:21	0.122	13

We can derive an area for the hot spot from the radiance, but the result is highly dependent on the temperature assumed. For example, 400 K corresponds to 11,400 km^2, 600 K to 930 km^2, and 800 K to 260 km^2. For comparison, the overall area of Loki Patera was 50,000 km^2. In view of the large area required for any likely temperature, the source must be similar to a lava lake or flow rather than to the small vent of a plume. The position of the active part of the lava lake may have shifted. Voyager images (*10*) show evidence for several such shifts in the past, in the form of partly "solidified" or obscured sections extending to the northeast and southwest.

The recent development of techniques that allow observations of individual hot spots, such as the speckle observations described here, together with the work of Goguen and Sinton (*5*), should contribute toward a much improved understanding of volcanism on Io. Multiple wavelength observations will be particularly important because they will allow accurate estimates to be made of the hot spot temperatures and thus of the relative importance of silicate and sulfur volcanism.

References and Notes

1. T. V. Johnson *et al.*, *Science* **226**, 134 (1984).
2. H. M. Dyck and R. R. Howell, *Astron. J.* **87**, 400 (1982).
3. K. T. Knox and B. J. Thompson, *Astrophys. J.* **193**, L45 (1974).
4. J. R. Fienup and G. B. Feldkamp, *Proc. Soc. Photo-Opt. Instrum. Eng.* **243**, 95 (1980); J. G. Walker, *Appl. Opt.* **21**, 3132 (1982); J. C. Dainty, *Top. Appl. Phys.* **9**, 255 (1984).
5. J. D. Goguen and W. M. Sinton, *Science* **230**, 65 (1985).
6. One highly discrepant observation was obtained at 9:33 UT, indicating a disk diameter of 0.511 arc second, a brightness of 1.933, and a position of 0.467 arc second. This diameter is less than half the true value, the brightness is more than twice that of any other measurement, and the longitude is also inconsistent. We have deleted this point from the fits and the figures, but we do not understand the source of the error.
7. H. C. Campins *et al.*, *Astron. J.* **90**, 896 (1985). 1 Jansky = 10^{-26} W m^{-2} Hz^{-1}.
8. G. G. Schaber, in *Satellites of Jupiter*, D. M. Morrison, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 556–597; J. C. Pearl and W. M. Sinton, *ibid.*, pp. 724–755.
9. R. G. Strom and N. M. Schneider, *ibid.*, pp. 598–633.
10. The cover of the *Science* issue containing (*1*) is an excellent example.

11. We thank J. Goguen and W. Sinton for helpful discussions. This work was supported in part by NSF grant AST 82-08793 and NASA grant NASW3135. The Infrared Telescope Facility is operated by the University of Hawaii under contract from NASA.

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Characterization of Io's Volcanic Activity by Infrared Polarimetry

Abstract. *The thermal emission from Io's volcanic hot spots is linearly polarized. Infrared measurements at 4.76 micrometers show disk-integrated polarization as large as 1.6 percent. The degree and position angle of linear polarization vary with Io's rotation in a manner characteristic of emission from a small number of hot spots. A model incorporating three hot spots best fits the data. The largest of these hot spots lies to the northeast of Loki Patera, as mapped from Voyager, and the other spot on the trailing hemisphere is near Ra Patera. The hot spot on the leading hemisphere corresponds to no named feature on the Voyager maps. The value determined for the index of refraction of the emitting surface is a lower bound; it is similar to that of terrestrial basalts and is somewhat less than that of sulfur.*

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Io is the only body in the solar system, other than Earth, on which active volcanism has been observed directly. During the two Voyager encounters (March and July 1979), nine plumes were detected on Io above active vents on a young, craterless volcanic terrain; these features are indicative of vigorous, sustained eruptive activity (*1, 2*). Ground-based infrared (IR) photometry of the thermal emission from Io's hot spots has shown a stable, long-wavelength (8 to 20 μm) component (*3*) and a variable, short-wavelength (5 μm) component (*4*). Ground-based IR measurements do not resolve the disk and represent hemispheric averages. Disk-integrated measurements of the linear polarization of the thermal emission as Io rotates is a new technique that can be used to locate hot spots in both latitude and longitude, to measure the flux emitted from individual hot spots, and to estimate the index