

A Close-Up Look at Io from Galileo's Near-Infrared Mapping Spectrometer

Rosaly Lopes-Gautier,^{1*} S. Douté,² W. D. Smythe,¹ L. W. Kamp,¹
R. W. Carlson,¹ A. G. Davies,¹ F. E. Leader,² A. S. McEwen,⁴
P. E. Geissler,⁴ S. W. Kieffer,³ L. Keszthelyi,⁴ E. Barbini,¹
R. Mehlman,² M. Segura,¹ J. Shirley,¹ L. A. Soderblom⁵

Infrared spectral images of Jupiter's volcanic moon Io, acquired during the October and November 1999 and February 2000 flybys of the Galileo spacecraft, were used to study the thermal structure and sulfur dioxide distribution of active volcanoes. Loki Patera, the solar system's most powerful known volcano, exhibits large expanses of dark, cooling lava on its caldera floor. Prometheus, the site of long-lived plume activity, has two major areas of thermal emission, which support ideas of plume migration. Sulfur dioxide deposits were mapped at local scales and show a more complex relationship to surface colors than previously thought, indicating the presence of other sulfur compounds.

A major objective of the Galileo mission was to investigate Io's volcanoes and their surface modification processes using high spatial resolution spectral images. Observations were obtained during three flybys of Io in October (orbit I24) and November (orbit I25) of 1999 and February (I27) of 2000 using the near-infrared mapping spectrometer (NIMS). It was known previously that Io's surface is dotted with active volcanoes (hot spots) (1) and covered by SO₂ frost and other compounds (2–4). Some hot spots exhibit plumes that may inject gaseous SO₂ into the atmosphere (5), subsequently condensing as frost on the surface.

NIMS obtained 17 observations during I24, four observations during I25, and 10 observations during I27, most with spatial resolutions from 0.5 to 25 km/NIMS pixel. These were obtained at 14 fixed infrared (IR) wavelengths (in the range from 1.0 to 4.7 μm) instead of the planned 360, because the instrument's spectral scanning capability malfunctioned. This anomalous operation provided greater sampling density (24 samples instead of 1) at each wavelength, increasing the signal-to-noise ratio. The reduced number of wavelengths is suitable for temperature determination and SO₂ mapping, but our search for yet unknown surface compounds was compromised.

The NIMS spectral range includes reflected sunlight and thermal emission components (Web fig. 1) (6). A pixel showing volcanic activity may contain lavas at different temperatures (7), but here we use a single-temperature Planck function to estimate the brightness temperature T_B and the color temperature T_C , with a correction for reflected sunlight in daytime observations (8). T_B is a measure of the average emitted thermal energy within a given wavelength interval and pixel area. T_C uses the shape and amplitude of the Planck function to determine a temperature and its corresponding emitting area within the pixel. T_C estimates tend to be dominated by cooler materials that typically cover larger areas and thus emit greater power (in the wavelength range used) than hotter materials having much smaller areas.

For SO₂ mapping, the reduced number of wavelengths precluded the full-spectrum modeling used previously (3). We used the 4.1-μm spectral channel, which lies within the strong SO₂ $\nu_1 + \nu_3$ absorption band (Web fig. 1) (6), as a qualitative SO₂ indicator. Specifically, we form the relative band depth from the absorption depth at 4.1 μm relative to measurements at a nonabsorbing wavelength (3.0 μm) (9). The relative band depth depends on the SO₂ abundance, the mean grain size, and the presence of other materials and their mixing mode (spatially segregated or intimately mixed at the scale of photon path lengths). Here, we assume spatially segregated mixing. Sulfur dioxide absorbs strongly at 4.1 μm [absorption coefficient ~11 cm⁻¹ (10)], so nonzero reflectance at that wavelength indicates the presence of other, nonabsorbing material. The assumption of spatially segregated mixing (11) with spectrally neutral material gives upper bounds to

current heat-flow estimates are really lower limits, because they do not include heat conducted through the crust, which cannot be detected by current remote-sensing techniques.

References and Notes

1. E. E. Russell *et al.*, *Space Sci. Rev.* **60**, 531 (1992).
2. The close Io flybys were I24 on 11 October 1999, I25 on 26 November 1999, and I27 on 22 February 2000.
3. Brightness temperature is the temperature of a blackbody emitting the same radiance at the wavelength of interest, and is an approximation to the kinetic temperature for most solid surfaces, which exhibit near-blackbody behavior. Color temperature is the temperature of a blackbody emitting the same brightness ratio at a pair of wavelengths. Calibration accuracy can be judged by comparing the brightness temperature, T_B , of Loki Patera at the two independently calibrated wavelengths, 17 and 21 μm, for which we have resolved data. The closeness of the wavelengths, and the smoothness of Loki's spectrum from Voyager IRIS at these wavelengths (16), lead us to expect that T_B at the two wavelengths will differ by no more than 2 or 3 K. We obtain T_B of 244 K at 17 μm and 239 K at 21 μm for a representative region of the caldera, and thus conservatively estimate a 10-K temperature uncertainty at these temperatures. An additional check on calibration comes from simultaneous NIMS and PPR observations of another region of Loki Patera, for which PPR gives a 17-μm T_B of 247 K and NIMS gives a 4.4-μm T_B of 273 K, consistent with a two-temperature blackbody fit to NIMS and PPR data (see text). Observations of the on-board calibration target give an estimated T_B uncertainty of 5 K at the 125-K temperature of the target. Nighttime T_B in the wide-open filter on the Jupiter-facing hemisphere also includes a contribution from sunlight reflected from Jupiter; scaling from observations of Europa in the same filter (25), we estimate this contribution to be <2 K.
4. G. J. Veeder, D. L. Matson, T. V. Johnson, D. L. Blaney, J. D. Goguen, *J. Geophys. Res.* **99**, 17095 (1994).
5. J. R. Spencer, B. E. Clark, L. M. Woodney, W. M. Sinton, D. Toomey, *Icarus* **107**, 195 (1994).
6. J. R. Spencer *et al.*, *Geophys. Res. Lett.* **24**, 2451 (1997).
7. J. D. Goguen *et al.*, *Icarus* **76**, 465 (1988).
8. J. D. Goguen *et al.*, *Bull. Am. Astron. Soc.* **29**, 978 (1998).
9. R. Howell and A. J. Grocholski, *Lunar Planet. Sci. XXXI*, 1974 (2000) [CD-ROM].
10. J. R. Spencer, J. A. Stansberry, J. A. Rathbun, unpublished data.
11. R. Lopes-Gautier *et al.*, *Science* **288**, 1201 (2000).
12. A. S. McEwen *et al.*, *Icarus* **135**, 181 (1998).
13. B. MacIntosh *et al.*, in preparation.
14. Supplemental Web material is available at Science Online at www.sciencemag.org/feature/data/1050309.shl.
15. R. R. Howell, personal communication.
16. ———, *Icarus* **127**, 394 (1997).
17. A. S. McEwen *et al.*, *Science* **288**, 1193 (2000).
18. J. R. Spencer, K. L. Jessup, M. A. McGrath, G. E. Ballester, R. V. Yelle, *Science* **288**, 1208 (2000).
19. O. L. Hansen, *Icarus* **18**, 237 (1973).
20. A. S. McEwen *et al.*, *Science* **281**, 87 (1998).
21. R. Lopes-Gautier *et al.*, *Icarus* **140**, 243 (1999).
22. A. G. Davies *et al.*, *Geophys. Res. Lett.* **24**, 2447 (1997).
23. A. S. McEwen, N. R. Isbell, J. C. Pearl, *Lunar Planet. Sci. XXXIII*, 881 (1992) [CD-ROM].
24. M. Segatz, T. Spohn, M. N. Ross, G. Schubert, *Icarus* **75**, 187 (1988).
25. J. R. Spencer, L. K. Tamppari, T. Z. Martin, L. D. Travis, *Science* **284**, 1514 (1999).
26. We acknowledge the great efforts of the Galileo spacecraft team in making the Io encounters a success. R. Howell and R. Lopes provided valuable information and advice. Funded by the Galileo project and NASA grant NAG5 6794.

¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. ²IGPP, University of California, Los Angeles, CA 90095, USA. ³S. W. Kieffer Science Consulting Inc., 6 Queen Street, Suite 206, Post Office Box 520, Bolton, ON L7E 5T4 Canada. ⁴Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. ⁵U.S. Geological Survey, Flagstaff, AZ 86001, USA.

*To whom correspondence should be addressed. E-mail: rlopes@lively.jpl.nasa.gov

10 March 2000; accepted 19 April 2000

the SO₂ abundance. The depth of sampling at 4.1- μ m wavelength is limited to about 1 mm, so we cannot distinguish between thick frost deposits and thin layers, which can be transparent in the visible and at nonabsorbing IR wavelengths.

Loki Patera. NIMS imaged Loki Patera on Io's nightside, targeting a light-colored, island-like feature in the caldera (Fig. 1). This feature has not changed significantly in appearance, at scales of several km, since 1979. It is cut by a dark-colored, linear feature about 3.5 km wide that may be a crack exposing dark lava, or a valley flooded by lava. Additional NIMS data on and beyond the caldera floor, having lower spatial sampling density, were obtained as the spacecraft's scan platform moved to the next target. Temperature maps (Fig. 1) show that the island and the light terrain outside the caldera exhibit low thermal emission (no T_C fits to these data were attempted), while the dark floor of the caldera and the crack have higher thermal output. The dark caldera floor is quite uniform in brightness temperature (273 ± 6 K), with 70% of the pixels having median T_B values of 273 ± 2 K. Median T_B values for the crack material are lower (215 ± 10 K). However, median T_C values for the material in the crack are higher (350 ± 55 K) than those for floor (305 ± 44 K). This indicates that the area of the hot crack is smaller than the size of the NIMS pixel with most of the contribution for the T_B map arising from the cooler material. The

areas corresponding to the T_C values can be obtained. For a pixel on the crack at the median T_C , the area is 0.0065 km² (0.28% of the pixel area that could be represented as a linear feature 4.3 m wide by the length of the pixel, 1.5 km). For a pixel on the floor, the area is 0.655 km² (28.5% of the pixel area).

The caldera floor's temperature distribution shows that it is uniform in terms of energy output (similar T_B values) but at a scale below the size of individual pixels (T_C values) the lavas show a more complex structure. This is consistent with a field of overlapping, cooling lava flows, or with the cooling, nonuniform surface of a lava lake. Observations by Galileo's photopolarimeter radiometer (12), taken at longer wavelengths, also show little variation in temperature on the eastern caldera floor, but show higher temperatures near the southwestern edge of the caldera and extending to the west of the island, regions not observed by NIMS. This is near the site of an eruption that begun in early September 1999 (12). The lavas observed by NIMS on the caldera floor were probably emplaced during an earlier eruption. If the lava were erupted at 1475 K (typical for basaltic lavas) and were at least 5 m thick, the time under Io conditions for the lava to cool down to the median T_C for the caldera floor (305 K) would be about 127 days (13). However, the lava would only need about 39 days to cool down to the median T_C for the crack (350 K), so it is possible that the lavas

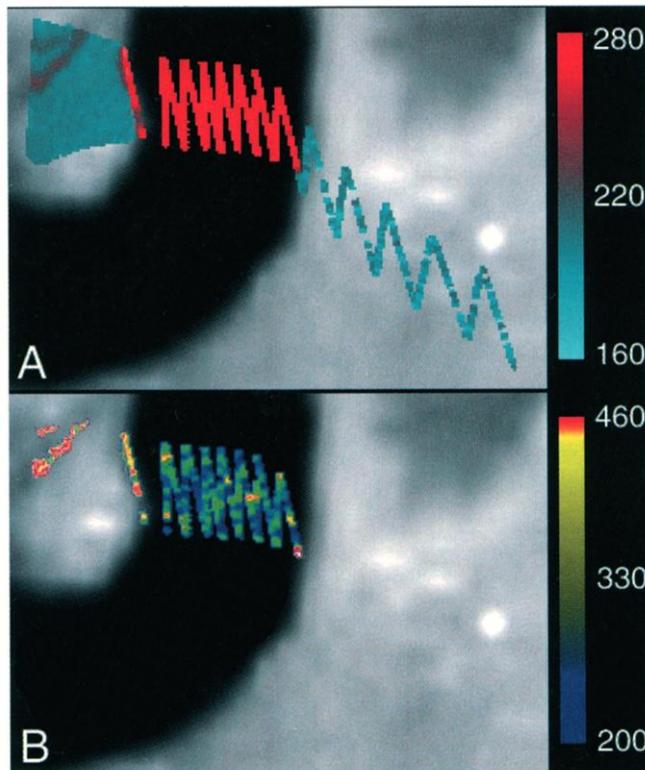
in the crack were emplaced during the earlier phase of the September 1999 eruption.

Tvashtar Catena. This chain of calderas were observed by NIMS and Galileo's solid state imaging (SSI) experiment in I25, and almost simultaneously from the ground. The ground-based (14) and SSI observations (15) were interpreted as images of a fire fountain erupting hot lavas. The observation by NIMS covers the eastern part of the active caldera, and the pixels at most wavelengths are saturated. The hottest pixel for which a temperature could be derived, which is cooler than the hottest pixel observed, yielded $T_C = 1060 \pm 60$ K (area = 0.003 km²). This estimate can mask small areas having high temperatures and is a lower limit that, although well within the range of basaltic lava temperatures, does not exclude ultramafic compositions such as those observed at Pillan Patera (16). Data just returned from the third Io flyby (I27) show that activity had fallen to a lower level by February 2000. NIMS pixels from the same locations as in I25 do not show saturation and yield temperatures between 500 and 600 K.

Prometheus. Prometheus is the site of a persistent plume discovered by Voyager in 1979 (5). Observations by SSI during Galileo's first orbit in 1996 showed that the Prometheus plume site had moved about 80 km west since 1979 (17), but the size and appearance of the displaced plume had not changed. Observations by SSI in I24 showed a caldera just to the north of the Voyager plume site (15), and a long lava flow between the Voyager and Galileo plume sites. The NIMS observation of the same region (Fig. 2) showed two main hot spots, though thermal emission can be detected along the flow. The eastern hot spot is near the location of the 1979 plume, while the western hot spot is at the location of the current plume. The eastern hot spot is hotter but smaller in area (median $T_C = 550 \pm 120$ K, area = 0.01 km²) than the western hot spot (median $T_C = 450 \pm 70$ K, area = 0.04 km²). Values obtained for a pixel between the two hot spots yielded $T_C = 408 \pm 40$ K. This temperature distribution is consistent with that of a lava flow being erupted from the eastern hot spot, which cools and becomes crusted over as it moves away from the vent. Hot lava can flow through tubes and break out at the distal edge of the flow, spreading out over the surface, with hot material spreading over a larger area than at the vent. The vent associated with the eastern hot spot did not move. Instead, the plume moved to the western hot spot, even though the eastern hot spot remained active. This could arise from an interaction between hot lava and the underlying SO₂ snowfield (18).

The deposition of material from the

Fig. 1. NIMS observation over Loki Patera obtained during the I24 flyby, superimposed on a SSI image. (A) Brightness temperature map shows that the temperatures for the lavas on the caldera floor are fairly uniform and hotter (red) than those for materials on the "island" and on the outside of the caldera. (B) Color temperature map shows higher temperatures (reds and yellows) in the "crack" or valley that runs through the light-colored "island" in the center of the caldera. The small hot areas in the "crack" appear cool in brightness temperature because of their small size relative to the pixel. NIMS spatial resolution ranges from 1.3 to 2.1 km/pixel (22), and the SSI image is 162 km across.



Prometheus plume was mapped from a NIMS observation at spatial resolution of 20 to 25 km/NIMS pixel (Fig. 3). Thermal emission and SO₂ absorption can be seen at 4.1 μm (Fig. 3B). The SO₂ relative depth map (Fig. 3C) has been translated into a SO₂ distribution map (Fig. 3D), using the linear correlation between the relative depth and the SO₂ frost coverage (11). A striking feature (Fig. 3D) is the SO₂ deposition ring that circles the vent. When compared with the low-phase visible image (Fig. 3A), the SO₂ deposition ring appears larger than its visible white counterpart. This suggests that Prometheus emits several different compounds (such as S₈) in the gas phase, that condense with a deposition distance from the vent inversely related to volatility. Before the flybys, it was thought that areas that were bright and white at low phase angles corresponded to regions rich in coarse-grained SO₂ (2, 4). Our observation suggests that some other white material may be present.

Faint hot spots and vents. Several hot spots other than Prometheus are visible in this image (Fig. 3B). Camaxtli and Culann Patera had been detected before (1, 17) but, at this higher spatial resolution, their complex structures are revealed. Culann Patera appears to have two separate hot spots within the same volcanic complex, while the Camaxtli Patera hot spot has two neighboring, small hot spots that may be independent volcanic centers. Six other relatively small and faint hot spots, which could not be seen in the global-scale observations, were detected (19). Brightness temperatures for the faint hot spots are ~220 K, and >270 K for the brighter hot spots that had been detected at low spatial resolution. One of the faint, previously undetected hot spots coincides with the feature Chaac Patera, a distinct green region in visible images (4). This hot spot became active sometime between the two flybys. NIMS data from I24 showed no thermal emission from Chaac Patera, but an observation at comparable spatial resolution in I25 showed that it had become active and that a region to the northwest of this hot spot had become darker at the shorter NIMS wavelengths. Dark materials on Io correlate with volcanic activity, as noted in previous studies (20), including those from NIMS and SSI images at low spatial resolution (1, 4). Comparison of parts A and B in Fig. 3 illustrates this correlation well, as areas of low-albedo deposits in Fig. 3A coincide with areas of enhanced thermal emission which appear bright in Fig. 3B.

Culann Patera and Tohil Patera. The hot spot Culann (Fig. 4) and the Tohil region, where no hot spot has so far been detected, show distinct red deposits. The SO₂ relative depth maps superimposed on SSI images

show locally enhanced concentrations of SO₂ that coincide with deposits having a pinkish-white to red appearance at visible wavelengths. Red deposits may be short-chain S allotropes (21) and are generally associated with hot spots (1, 4). This intimate associa-

tion of compounds having different volatility requires a particular emission or deposition mechanism that prevents their spatial segregation. A higher S₂/SO₂ ratio than that at Prometheus, for example, can lead to a dense atmospheric population of radiatively cooled

Fig. 2. Color temperature map (A) made from NIMS data obtained during the I24 flyby, at a spatial resolution of 5.5 to 8.5 km/pixel (22). The SSI image (B), taken in July 1999, is 142 km across. Two major hot spots are seen in (A): the eastern hot spot (right side of panel), which has higher temperatures, is located near the site of the Voyager-era plume. The western hot spot coincides with the location of the currently active plume. The brightest red in (A) is approximately 820 K.

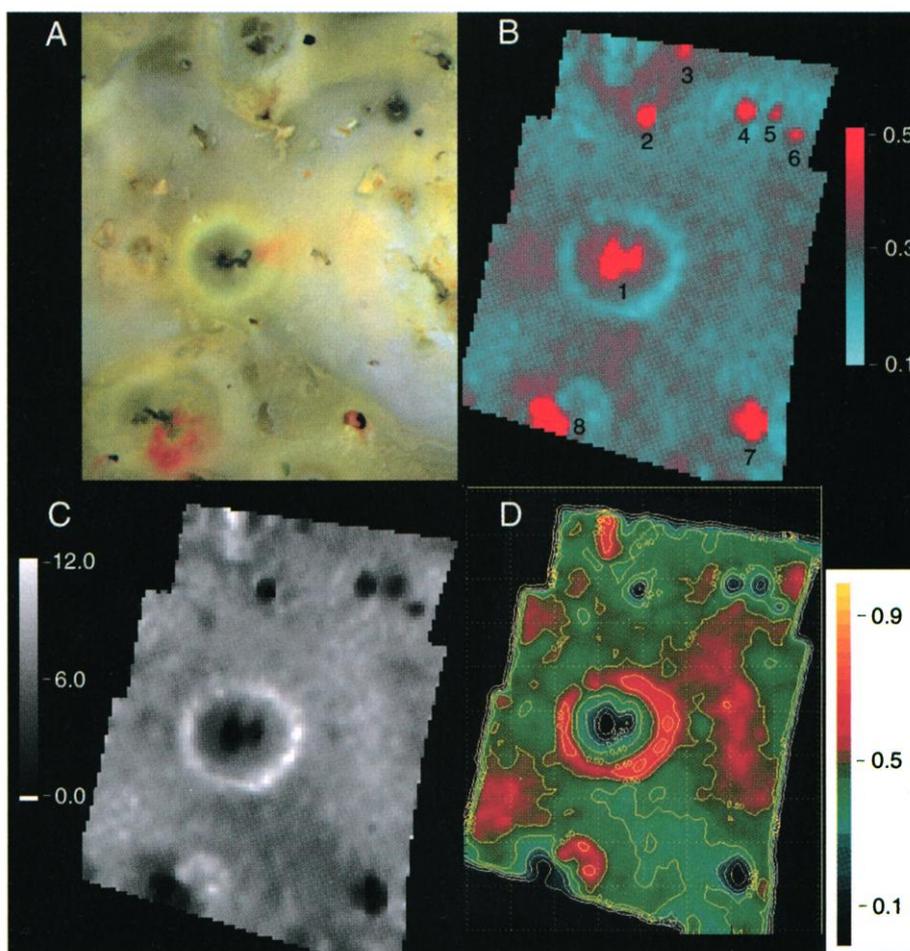
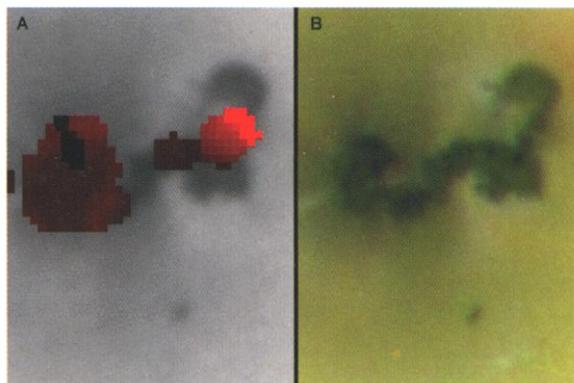
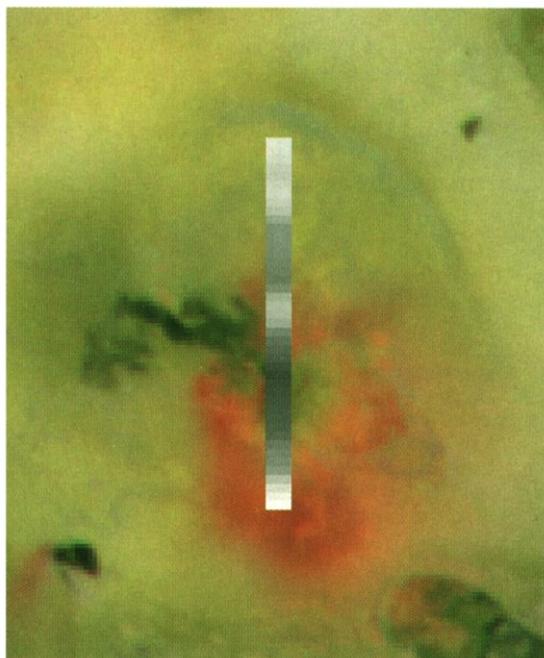


Fig. 3. Prometheus region imaged by SSI in July 1999 (A) and by NIMS at 4.1 μm during the I24 flyby (B). The NIMS observation is at spatial resolution of 22 to 25 km/pixel (22). Hot spots appear red in (B), whereas SO₂ appears blue. Hot spots are labeled 1 (Prometheus), 5 (Camaxtli), 7 (Tupan), and 8 (Culann). Hot spots 2, 3, 4, and 6 were not previously known. The color scale in (B) represents radiance in units of bidirectional reflectance (solar irradiance/π). The SO₂ deposition ring around Prometheus is clearly seen in the center of (B) and in (C), the relative band-depth map (9). A qualitative SO₂ distribution map is shown in (D). The color scale gives the fractional area covered by SO₂ frost and varies from 0 (very dark blue) to 1 (yellow). The area shown in each panel is ~1300 km across.

Fig. 4. NIMS obtained data over Cullann Patera during the I25 flyby. A SO₂ relative band depth map (9) is shown over an SSI image acquired in July 1999. NIMS data show enhanced concentrations of SO₂ coinciding with deposits that are pink to red in visible wavelengths. Spatial resolution is 11 km/pixel (22), and the SSI image is 340 km across. The color scale is the same as in Fig. 3C.



S₂ solid nuclei on which SO₂ condenses. Alternatively, boiling liquid SO₂ with short-chain S or other coloring agents dissolved in it may reach the surface from below and freeze before complete sublimation. The diffuse appearance of the red deposits may arise from the entrainment of liquid droplets with escaping gases.

References and Notes

1. R. Lopes-Gautier *et al.*, *Icarus* **140**, 243 (1999).
2. R. W. Carlson *et al.*, *Geophys. Res. Lett.* **24**, 2479 (1997).
3. S. Douté *et al.*, in preparation.
4. P. E. Geissler *et al.*, *Icarus* **140**, 265 (1999).
5. R. G. Strom and N. M. Schneider, in *Satellites of Jupiter*, D. Morrison, Ed. (Univ. of Arizona Press, Tucson, AZ, 1982), pp. 598–633, and references therein.
6. Web fig. 1 is available at www.sciencemag.org/feature/data/1049493.shl
7. A. G. Davies *et al.*, *Lunar Planet. Sci.* **XXX** (1999) [CD-ROM].
8. The brightness temperature, T_b , is defined as $B(\lambda, T_b) = I(\lambda)$, where B is the Planck function, λ is the wavelength, and I is the corrected radiance. The corrected radiance is defined as $I(\lambda) = I_o(\lambda) - A * F(\lambda)$, where $I_o(\lambda)$ is the observed radiance, $F(\lambda)$ is incident solar flux at that wavelength, and A is an albedo estimate derived from the 1- to 2- μ m region. For nightside observations, $I = I_o$. The color temperature, T_c , is defined as $B(\lambda_1, T_c)/B(\lambda_2, T_c) = I(\lambda_1)/I(\lambda_2)$. We used two pairs of (λ_1, λ_2) : (4.1, 4.4 μ m) and (4.4, 4.7 μ m). The reported T_c is the average between the two values. In dayside observations, T_b and, in particular, T_c , are sensitive to the albedo used to correct the observed radiances, both in absolute value and its spectral slope (due to the SO₂ absorption at 4.1 μ m). Therefore, calculations are made using a range of albedos, typically 60 to 80% of the value obtained at short wavelengths. The results are then averaged. Results displaying a high sensitivity to this variation (typically when $T_b < 200$ K) are omitted, as are those in which the error between the two estimates of T_c exceeds 20% of the mean. T_c is only calculated for pixels in which T_b exceeds a threshold (usually 210 to 250 K, depending on the noise level), to avoid errors due to the SO₂ absorption, since this absorption disappears at hot spots. Correct albedo values should yield $I(\lambda) =$

0 for the cold areas of Io. Small residual uncertainties in the NIMS calibration can sometimes yield a spurious $T_b \sim 180$ K for these areas, but pixels where $T_b < 200$ K were not used in this analysis.

9. The relative band depth is defined as the ratio $[A(3.0)/A(4.1)]$, where $A(\lambda)$ is the measured albedo (reflectance)

- at wavelength λ . This ratio was not obtained for pixels in which thermal emission could be detected.
10. B. Schmitt *et al.*, *Icarus* **111**, 79 (1994); B. Schmitt *et al.*, in *Solar System Ices*, B. Schmitt, C. De Bergh, M. Festou, Eds. (Kluwer Academic, Dordrecht, Netherlands, 1998), pp. 199–240.
11. We have checked and quantitatively calibrated this simple approach (segregated mixing and linear combination of computed radiances) by comparing the relative band depth map of a global observation taken in I24 with the SO₂ distribution maps of S. Douté *et al.* (3), which modeled 408-wavelength NIMS spectra.
12. J. R. Spencer *et al.*, *Science* **288**, 1208 (2000).
13. Times calculated using the model of A. G. Davies [*Icarus* **124**, 45 (1996)]. These temperatures and cooling rates assume that the surface heat loss is buffered by the release of latent heat from a still-molten flow interior.
14. R. Howell *et al.*, *Lunar Planet. Sci.* **XXXI** (2000) [CD-ROM].
15. A. S. McEwen *et al.*, *Science* **288**, 1193 (2000).
16. A. S. McEwen *et al.*, *Science* **281**, 87 (1998).
17. A. S. McEwen *et al.*, *Icarus* **135**, 181 (1998).
18. S. W. Kieffer *et al.*, *Science* **288**, 1204 (2000).
19. Previously undetected hot spots detected by NIMS during I24 and I25 are located at (+21, 146W, near Surya), (+14, 150 W), (+20, 149W), (+12, 158W, near Chaac), (-5, 132W, the dark feature Seth), and (+9, 133W)
20. J. C. Pearl and W. M. Sinton, in (5), pp. 724–755.
21. J. R. Spencer *et al.*, *Icarus* **127**, 221 (1997).
22. The pixel size in NIMS-processed images is 0.5 \times the instrument's spatial resolution.
23. Portions of this work were performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

15 February 2000; accepted 18 April 2000

Prometheus: Io's Wandering Plume

Susan W. Kieffer^{1*}, Rosaly Lopes-Gautier,² Alfred McEwen,³ William Smythe,² Laszlo Keszthelyi,³ Robert Carlson²

Unlike any volcanic behavior ever observed on Earth, the plume from Prometheus on Io has wandered 75 to 95 kilometers west over the last 20 years since it was first discovered by Voyager and more recently observed by Galileo. Despite the source motion, the geometric and optical properties of the plume have remained constant. We propose that this can be explained by vaporization of a sulfur dioxide and/or sulfur "snowfield" over which a lava flow is moving. Eruption of a boundary-layer slurry through a rootless conduit with sonic conditions at the intake of the melted snow can account for the constancy of plume properties.

Of the many remarkable phenomena on Io, one of the most intriguing is the wandering of some of the large plumes, the so-called "Prometheus-type plumes" (1–3). A new dark feature, interpreted to be a lava flow, connects the Voyager-era and Galileo-era plume sources. During the past 4 years, the

lava has apparently been building up on top of itself rather than advancing farther west, because a large lava delta is the most pronounced feature on the west end, and the position of the plume within this area has not changed, nor have its geometric and optical properties. Material around, and presumably under, the lava flow consists of bright plains, which are interpreted to be a snowfield (4) of SO₂ and/or S. Such a steady, continuous discharge of material over such a long period of time is unlike that ever seen at terrestrial volcanoes.

It had been assumed by most researchers that the gas required to drive the plumes on Io

¹S. W. Kieffer Science Consulting, Inc., 6 Queen Street, Suite 206, Post Office Box 520, Bolton, ON L7E 5T4, Canada. ²Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. ³Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

*To whom correspondence should be addressed. E-mail: skieffer@geyser.com