puted theories of the origin of the extensive stratiform copper ores of the Zambian Copperbelt. These theories call for introduction of large amounts of copper into sediments from some kind of solution either during or subsequent to sedimentation.

The burrows discussed here are in well-mineralized sediments that contain roughly 1 percent copper in the oxidized zone and higher values in the sulfide zone down dip. The question of when this mineralization occurred is crucial to understanding the processes of ore formation. Because copper at more than trace concentrations in ionic, and to a lesser degree in complexed, form is lethal to most or all organisms, its introduction during or immediately after sedimentation would be negated by evidence of active, contemporaneous burrowing of the enclosing sediments. As the burrows appear not to be contemporaneous with sedimentation, however, the timing of introduction of the copper-bearing solutions is not constrained by their presence.

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28 March 1980; revised 21 August 1980

Io: Ground-Based Observations of Hot Spots

Abstract. *Observations of Io in eclipse demonstrate conclusively that Io emits substantial amounts of radiation at 4.8 and 3.8 micrometers and a measurable amount at 2.2 micrometers. Color temperatures derived from the observations fit blackbody emission at 560 K. The required source area to yield the observed 4.8-micrometer flux is approximately 5×10^{-5} of the disk of Io and is most likely comprised of small hot spots in the vicinity of the volcanoes.*

The existence of warm regions on Io discovered by the Voyager infrared spectroscopy and radiometry (IRIS) instruments (*1*) and the occasional 5-μm outbursts (*2*) call into question the assumption (*3*) that all of Io's normal flux between 2 and 5 μm is reflected sunlight. A test of this assumption has been carried out by performing *K*, *L*, and *M* (2.2, 3.8, and 4.8 μm) photometry of Io as it is eclipsed by Jupiter.

To see if this is really a test, we first consider what might be the expected flux from known sources when Io is eclipsed. The temperature of 135 K or less inferred for the surface outside eclipse from measurements at wavelengths beyond 10 μm (*4*) would add only 0.02 percent to the reflected sunlight at *M* wavelengths and even less in the *L* and *K* bands. Another source of residual flux from an eclipsed satellite is sunlight that is incident on the satellite after being refracted in the upper atmosphere of Jupiter. This effect, called the refractive tail, has been studied (*5*) at wavelengths as long as 1.05 μm for Ganymede, for which an eclipse proceeds more slowly than it does for Io. Computations (*6*) of the refractive tail at 1.05 μm yield a dimming of 7.5 magnitudes (1000 times) 16 minutes after immersion for Ganymede and 10 minutes after immersion for Io. Observations indicate additional dimming of several magnitudes due to aerosol scattering and molecular absorption. Although both these dimming effects are wavelength-dependent, the reflected sunlight component should nearly vanish in the *K*, *L*, and *M* bands when Io is eclipsed.

Table 1. Photometry of three eclipses in the *K*, *L*, and *M* bands.

Bands	Date (1979) and time (U.T.)* 15 December 15:58	22 December 17:51†	24 December 12:20
Preimmersion magnitude			
K	3.96	3.89	3.67
L	3.98	3.92	3.65
M	3.87	3.62	3.42
Postimmersion magnitude			
K	10.61	10.61	10.54
L	6.28	6.42	6.24
M	4.85	4.90	4.54
Reflectance			
p_K	0.70	0.72	0.87
p_L	0.62	0.62	0.79
p_M	0.77	0.93	1.10
p_K (corrected)	0.70	0.72	0.87
p_L (corrected)	0.54	0.56	0.72
p_M (corrected)	0.50	0.64	0.71

*Time at midpoint of immersion. †See (*14*).

Our first observations of an eclipse of Io at *K*, *L*, and *M* wavelengths were made on 15 December 1979 simultaneously with the 3-m Infrared Telescope Facility (IRTF) and the 3.8-m United Kingdom Infrared Telescope (UKIRT) at Mauna Kea, Hawaii. Before and after immersion, both telescopes independently cycled through the *K*, *L*, and *M* filters, but during the rapid immersion phase UKIRT observed in *K* and IRTF observed in *M*. The observations (Fig. 1) show that the decreases in flux were only 6.5, 2.3, and 1.0 magnitudes (factors of 400, 8, and 2.5) at *K*, *L*, and *M*, respectively, and that there was no further decrease from immediately after immersion until the end of observing nearly 30 minutes later. The constancy of the flux while Io was in eclipse disagrees with calculations for a refractive tail, but is exactly what would be expected from hot spots on the surface of Io.

The sensitivity of the photometric equipment was such that we could easily find Io and maximize the infrared signal long after the satellite had disappeared visually. We made tests for light scattered from Jupiter by moving away from Io in several directions and then returning to it. The fluxes measured by the two telescopes, before and after eclipse, agree within 10 percent at all wavelengths. Subsequently, two of us (W.M.S. and A.T.T.) made additional observations of eclipses with the 2.2-m telescope of the University of Hawaii. The results from three eclipses are shown in Table 1.

From the flux that remains after entrance into eclipse, we conclude that Io has sources of emission other than the thermal radiation at 135 K characteristic of most of its surface. From the residual fluxes in the *K* and *L* and in the *L* and *M* bands, we determined a color temperature for this emission. Using Wien's approximation, which differs from the Planck formula by less than 1 percent for

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Table 2. Temperatures and areas derived from eclipse fluxes.

Temperature and area	Date (1979)		
	15 December	22 December	24 December
T_{K-L} (K)	574 ± 29	590 ± 29	577 ± 29
T_{L-M} (K)	523 ± 77	493 ± 69	442 ± 57
T_{K-M} (K)	563 ± 23	567 ± 23	543 ± 22
Area (km^2)	587	517	895
Fraction of Io's disk	5.5×10^{-5}	4.9×10^{-5}	8.4×10^{-5}

all temperatures of interest in this problem, we formed the ratio of the fluxes $B_{\lambda_1}/B_{\lambda_2}$ at wavelengths λ_1 and λ_2. The resulting equation is readily solved for the temperature

$$T = \frac{C_2(1/\lambda_2 - 1/\lambda_1)}{\ln(B_{\lambda_1}/B_{\lambda_2}) - 5\ln(\lambda_2/\lambda_1)} \quad (1)$$

where C_2 is the second radiation constant and is 14,387 μm K. The effective wavelengths were computed from

$$\lambda = \frac{\int_0^\infty \lambda F(\lambda)\, d\lambda}{\int_0^\infty F(\lambda)\, d\lambda} \quad (2)$$

and the measured filter transmissions $F(\lambda)$. The effective wavelengths are 2.21, 3.85, and 4.76 μm.

The postimmersion magnitudes in Table 1 were used with the zero-magnitude flux calibrations, 3.8×10^{-14}, 5.5×10^{-15}, and 2.0×10^{-15} W cm^{-2} μm^{-1} for the *K*, *L*, and *M* bands, respectively, to obtain the flux ratios. The resulting temperatures are given in Table 2 with error estimates that were calculated from an error analysis of Eq. 1 and estimated uncertainties of 20 percent in the flux ratios and 2 percent in the effective wavelengths. This flux ratio error is larger than would normally be encountered because it includes possible errors in centering the eclipsed satellite.

Within the very large error for the *L-M* temperature, the data appear to be consistent with blackbody emission. Table 2 shows a trend toward lower temperatures for the longer wavelength *L-M* measurements than for the shorter-wavelength *K-L* determination. Although this effect is only marginally indicated by the data presented here, it is in agreement with the presence of lower temperature spots (~ 300 K) such as those found in the Voyager data (*1*). The lower temperature spots produce significant flux in the 4.8-μm band and affect primarily the *L-M*-derived temperatures (*7*). Finally, we derived temperatures from the *K-M* colors, as these give the most precise determination. With these temperatures we derived the area of a blackbody emitter required to yield the flux observed in the *M* band and the fraction of Io's projected surface area (last two rows of Table 2). We do not know whether this hot area represents only one spot or many smaller spots together.

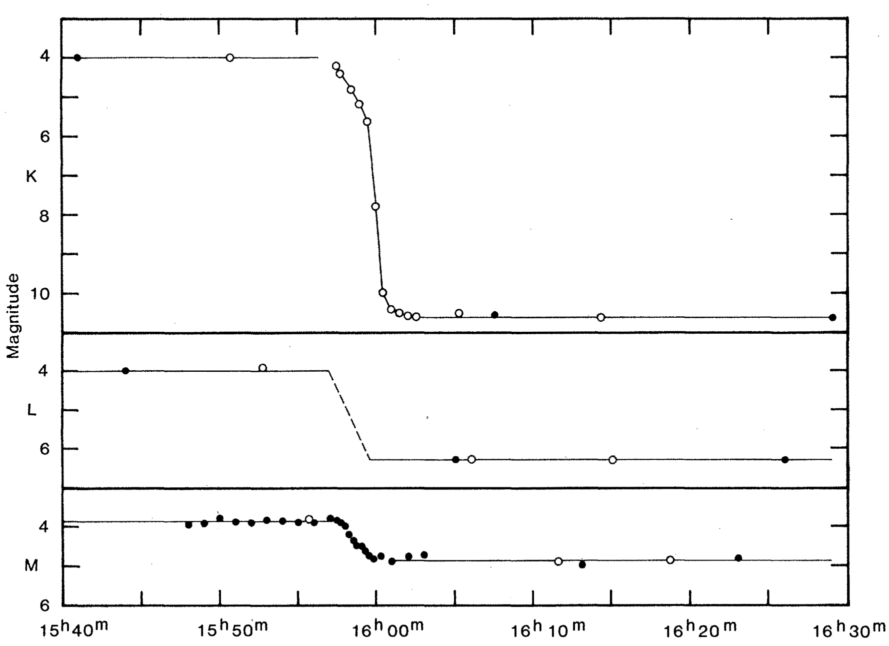

Fig. 1. Measurements of the brightness of Io during the eclipse of 15 December 1979 (*U.T.*). Observations at IRTF are indicated by closed circles and observations at UKIRT by open circles. The dashed portion of the *L* curve was unobserved.

Additional observations of Io when it was not in eclipse were made as part of a University of Hawaii monitoring program. The brightness of Io in the *M* band before the times of the eclipses is of interest here. The apparent reflectance of Io in the direction of the earth is determined from

$$2.5 \log p = M_\odot - m + 5 \log (r\Delta/R) \quad (3)$$

where $M_\odot$ is the magnitude of the sun, *m* is the magnitude of the satellite, *r* and Δ are the distances of the satellite from the sun and the earth, and *R* is the radius of the satellite; *r*, Δ, and *R* are in astronomical units. Usual values of *p* for Io are 0.7 to 1.0 in the *M* and *K* bands and 0.6 to 0.7 in the *L* band (*8*). At the time of an outburst the apparent reflectance in the *M* band, p_M, has increased to 2 or more (*2*). When the value of *p* is enhanced by emission it has lost its association with reflectance, but it is still useful for determining whether an outburst is occurring. The values of *p* immediately before the eclipse at Io's orbital phase angle (*9*), $\phi = 339°$, are given in Table 1. The values shown for 13 and 22 December are close to normal and demonstrate that an outburst was not occurring. The values for 24 December are slightly above normal, but the elevation in *M* is not comparable to those in previously observed outbursts.

It is clear that a significant part of the measured flux in the *L* and *M* bands is not reflected solar radiation. From the eclipse measurements, the apparent reflectance determined just before eclipse can be corrected for emitted energy. The corrected values are listed in Table 1 and apply to the hemisphere centered approximately on west longitude 339°. We have made measurements of the opposite hemisphere, for which eclipses cannot be observed; the reflectances are similar to those in Table 1 and we presume that they are also affected by emission from hot spots.

Detection of 500 K hot spots by the Voyager probes was not reported (*1*). However, Voyager 1 data that were analyzed only recently showed a hot spot 3 to 5 km in diameter with a temperature of 650 to 700 K in the region of plume P1 (*10*). Analysis of much of the Voyager data has not been completed because time-consuming special treatment is required. In nearly one-third of a hemisphere where the analysis has been completed, no large area having $T \sim 500$ K has been found.

It appears most reasonable to assume

at this time that there are many small hot spots rather than one or two large spots. Two possible geological interpretations of the hot spots are presented. (i) They are the vents of the active volcanoes (*11*) (this is supported by the Voyager 1 observation of the small spot in the region of P1). (ii) They are cracks caused by convection in the crust of the numerous black calderas seen on Io (*12*). Such cracks are frequently seen glowing red in the lava lakes that sometimes fill terrestrial calderas. However, if the surface of the black calderas is quenched amorphous sulfur, as has been suggested (*13*), it may not form cracks.

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7. The effect of the hot spots on the spectrum of Io is discussed by D. L. Matson, G. A. Ransford, and T. V. Johnson (in preparation) and W. M. Sinton (in preparation).
8. Most of the data from our monitoring program fall into these ranges. Earlier data [for instance, O. L. Hansen, in (*3*)] also fall into this range when reduced with the solar magnitudes from H. Johnson [*Commun. Lunar Planet. Lab.* **3**, 73 (1965)] that we used in our reductions.
9. The orbital phase angle is the angle along Io's orbit from superior geocentric conjunction with Jupiter. Since Io has a nearly circular orbit and keeps the same face toward Jupiter, the angle is also nearly the west longitude of the central meridian.
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14. This eclipse occurred in full daylight. By using a Quantex TV and digital image processing system and deep red filter, we could readily see Io at visual magnitude 5.6 before the eclipse. A single-frame background image obtained with Io slightly displaced was stored in the system memory. A running weighted average of 32 TV frames with this background subtracted was then displayed with greatly enhanced contrast.
15. W.M.S. was Visiting Astronomer at the Infrared Telescope Facility, which is operated by the University of Hawaii under contract from the National Aeronautics and Space Administration. E.E.B. and C.J. were visiting astronomers at the United Kingdom Infrared Telescope facility. T.J.L. is the astronomer-in-charge of the UKIRT, which is operated by the Royal Observatory, Edinburgh, on behalf of the Science Research Council. We are grateful to J. Pearl of NASA/Goddard Space Flight Center for discussions about the existence of high-temperature spots. This research was supported in part by NASA grant NGL 12-001-057.

14 March 1980; revised 24 June 1980

Internal Winds in Water Lilies: An Adaptation for Life in Anaerobic Sediments

Abstract. *The network of internal gas spaces in the yellow water lily constitutes a pressurized flow-through system which forces oxygen to the roots and rhizome buried in the anaerobic sediment. By the purely physical processes of thermal transpiration and hygrometric pressure, several liters of air per day enter the young, newly emerged leaves of* Nuphar luteum *against a small pressure gradient. This air moves en masse down the petioles of the young leaves (at rates up to 50 centimeters per minute) to the rhizome, forcing a simultaneous flow of gas (rich in carbon dioxide) from the rhizome up the petioles of the older emergent leaves to the atmosphere. The ventilation system has important physiological and ecological consequences.*

Plant roots growing in flooded soils must withstand long periods of anaerobiosis and the presence of soluble phytotoxins. The capacity of higher plants to survive these conditions is largely dependent on the rate of oxygen supply to the buried tissue, since oxygen supports root respiration and contributes to the detoxification of the rhizosphere (*1*). This transport of oxygen is generally achieved within the plant through an extensive system of gas spaces or lacunae.

Until now, models of gas transport in plants have held that the gas phase in the lacunae is essentially stationary, and that the individual gases simply diffuse along concentration gradients (*1, 2*). In his widely cited study, Laing (*3*) described the gas dynamics in the lacunae of the yellow water lily as the product of diffusion in a static gas phase along concentration gradients generated by plant photosynthesis and respiration. My research has shown that the gases in the lacunae are not static: they flow en masse at linear rates up to 50 cm/min.

Nuphar luteum, the yellow water lily, grows in lakes by means of a horizontal creeping rhizome that usually lies buried in the sediment. During summer growth new leaves continually develop and rise to the lake surface, supported by petioles up to 2 m long. I measured gas flows in the petioles of young emergent leaves by injecting a small volume (usually 0.1 ml, standard temperature and pressure) of ethane gas tracer into the upper end of the petiole. The tracer passed quickly down the petiole past the sampling point at the lower end (Fig. 1). This technique showed that gas flowed in the opposite direction in the petioles of older emergent leaves.

This pattern of bulk flow from the young leaves toward the older leaves was confirmed by another tracer experiment. All the leaves on an isolated shoot apex were enclosed in gas-impermeable Saran bags and an ethane tracer was injected into the upper portion of the petiole of the youngest emergent leaf. Results of a typical experiment are shown in Table 1, where more than 60 percent of the tracer had left the plant within several hours. None of the tracer escaped through the youngest leaf; most escaped through the oldest.

The flows originate in the lacunae of the youngest emergent leaves where gas pressures slightly greater than ambient were measured by a manometer. The pressures were highest during midday (up to 0.002 atm above ambient), and declined to ambient at night. The rate of gas flow down the petioles of these leaves was a linear function of the observed pressure gradient, in accordance with Darcy's law for flow through porous media (*4*).

The capacity of the young emergent leaves to draw air from the atmosphere into their lacunae against a pressure gradient was confirmed by inverting a 4-liter beaker over an influx leaf. With a healthy undamaged leaf exposed to sunlight inside the beaker, the water level in the beaker rose as much as 2 cm above the lake surface. This means that the leaf tended to draw a vacuum in the process of "pumping" air into its lacunae. There was no measurable selectivity by the pump for any particular component of the atmosphere. Except for the higher water vapor (humidity) in the gas of the midrib of these influx leaves, there was no measurable difference between the

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