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THE PLUMES OF IO:

A DETECTION OF SOLID SULFUR DIOXIDE PARTICLES

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ABSTRACT

Spectra of Io obtained during eclipse show a narrow deep absorption feature at 4.071 μm, the wavelength of the $\nu_1 + \nu_3$ band of solid SO_2. The 4-μm radiation comes from volcanic hot spots at a temperature too high for the existence of solid SO_2. We conclude that the spectral feature results from SO_2 particles suspended in plumes above the hot spots. The derived abundance of approximately 8×10^{-4} gm/cm^2 may imply an SO_2 solid-to-gas ratio of roughly one for the Loki plume, which would in turn suggest that it is driven by the SO_2 rather than by sulfur.

INTRODUCTION

Io appears to be the most volcanically active body in the solar system. The first recognition of that activity came through the Voyager 1 images in 1979. In light of that discovery, it has been possible to interpret several phenomena observed telescopically from Earth as due to the volcanoes, and to use those phencmena to monitor the volcanism. In particular, a significant fraction of the flux in the 4 to 10 µm region has been found to come from the thermal hot spots on Io's surface (1,2).

The eclipses that occur as Io traverses the shadow of Jupiter provide an opportunity to measure the hot spot emission in the absence of reflected sunlight. Observations at such times imply that typically one-third of the total out-of-eclipse flux at 4.8 µm comes from the hot spots, decreasing to one-tenth at 3.8 µm. Because of the limited observing time available during eclipse, studies of the hot spot flux have until now been made only with broad spectral bandpasses. However, the recent development of multidetector cooled-grating spectrometers has made more sophisticated measurements possible.

OBSERVATIONS

We report here "high" resolution ($\lambda/\Delta\lambda \approx 500$) observations of Io obtained during the eclipse of 2 August 1983 using the new 7-detector cooled-grating spectrometer (3) at the United Kingdom Infrared Telescope on Mauna Kea. Eight indepandent spectra were obtained over an interval of 14 minutes, beginning when the satellite was 10 arcseconds from the limb of Jupiter and ending 11 minutes before it left the shadow. They result from the seven channels obtained at a single setting of the grating. To remove instrumental and atmospheric effects, the spectra were divided by that of the nearby star α Librae. An out-of-eclipse spectrum was obtained on 30 June, using ϕ Ophiuchi as a standard.

Figure 1a shows the average of all of the eclipse spectra. Because of guiding errors introduced while the satellite was invisible on the television monitor, the absolute signal level fluctuated. However, the 7 data points were measured simultaneously, so the shapes of the spectra were not affected. In order to estimate the errors, we first normalized each of the 8 separate observations by the total flux, then found the standard deviation of the mean for the normalized spectra.

DISCUSSION

A feature is present at 4.071 ± 0.005 µm, the wavelength of the $\nu_1 + \nu_3$ band of solid SO_2 (4,5). This band also appears in Io reflection spectra (Figure 2), but is then saturated and extends from approximately 4.0 to 4.1 µm. In reflection it arises predominantly from SO_2 frost found on the surface; however, this cannot be the source of the band seen in eclipse. At such times the radiation comes from surface hot spots at a temperature of several hundred degrees Kelvin, and solid SO_2 cannot exist at these temperatures. Its melting point is 198°K, and even at somewhat lower temperatures it would quickly sublimate. SO_2 gas cannot produce the feature; in that phase the $\nu_1 + \nu_3$ band is centered at 4.00 µm.

We propose that the solid SO_2 which produces the observed band in eclipse must be present as small particles in volcanic plumes above the hot spots. We can find no other mechanism that allows it to be in the line of sight to the hot spots but isolated thermally from them.

Such solid SO_2 in the plumes has been suggested by three earlier observations. The most direct was the Voyager 1 IRIS observation of the plume at Loki (6). It observed the 7.4-µm ν_3 fundamental of SO_2 gas in the line of sight to the hot spot. A feature on the long wavelength side of the band could not be fit well by gas alone; the IRIS team and later Slobodkin et al. (7) suggested that it could be due to solid SO_2. In addition to the infrared observations, Voyager visual images of the scattered light from the plumes were interpreted as implying the existence of a considerable amount of submicron size particles (8). Finally, the spectral characteristics of parts of Io's surface suggest that SO_2 is deposited by the plumes.

Although the central point in Figure 1a is only 1.7 standard deviations below the apparent continuum, other evidence convinces us that the feature is real and suggests that it may be variable. The central channel produced the lowest signal on four of the eight individual spectra obtained. Even individually, these four suggest the presence of the band. However, three others show no evidence of the band. Excess noise, which was present in the middle spectrometer channel, could explain some of this, but does not seem large enough to account for it entirely. In Figure 1b we have plotted the average of the first six of the eight spectra obtained; the band appears to be significantly deeper. If real, the variability could be due to nonuniformities in the plumes. The Voyager images show such nonuniformities, and the time of flight for the particles is a few tens of minutes.

Additional evidence for the reality of the feature comes from the post-eclipse spectrum shown in Figure 2. Out-of-eclipse spectra should show sunlight reflected from the surface, with hot spot emission superposed on it. The details of the pure reflection spectrum are uncertain, since they depend upon the radiative transfer in the frost structure. However, the simplest interpretation of the data would attribute a smooth, broad band from 4.0 to 4.1 µm due to reflection, with a dip at 4.07 µm due to plume absorption of the hot spot component. This dip appears to be roughly equal in magnitude to that seen in eclipse.

We can draw three immediate conclusions from the presence and the depth of the 4.07-μm band: (1) Plumes are still erupting 4 years after they were observed by Voyager 2; (2) these plumes contain significant amounts of solid SO_2; and (3) the thermal radiation must come from at most a few hot spots, which are associated with plumes. If it came from many small hot spots distributed over the surface, then most of these would not lie under plumes, and the absorption band would be much weaker.

ABUNDANCE and IMPLICATIONS

The equivalent widths of the absorption bands in Figures 1a and 1b are $(4.4 \pm 2.0) \times 10^{-3}$ and $(6.0 \pm 2.0) \times 10^{-3}$ μm, respectively. These are derived by assuming that the average of the outer four points of the spectra represented the continuum, and the middle three points, the band. When compared with laboratory transmission spectra (9), these values imply pathlengths through SO_2 of $(3.2 \pm 1.8) \times 10^{-4}$ and $(4.8 \pm 2.8) \times 10^{-4}$ cm. Assuming a density of 2 gm/cm^3 results in abundances along the line of sight of 6.4×10^{-4} and 9.6×10^{-4} gm/cm^2. We adopt a value of 8×10^{-4} gm/cm^2 as a best estimate of the abundance of solid SO_2, and believe the error to be less than 50%. This abundance is the average for the hot spots, weighted by their infrared brightness. For example, all of the hot spots could be associated with plumes that have a $\nu_1 + \nu_3$ band depth of one half. On the other hand, a relatively thick plume could exist over a single hot spot contributing half of the flux, while the rest of the energy came from spots not covered by plumes. However, in this latter case the single plume could not be too much thicker than our estimate, or the band would saturate and broaden beyond that seen in our spectra.

There is some evidence that most of the thermal flux we saw came from a single hot spot; if this is true, then the abundance we quote applies primarily to the plume associated with it. Johnson et al. (2) have recently measured Io's rotational light curve at 8-10 μm, concluding that most of the body's emission originates from just two hot spots--one at the Loki volcanic center ($\approx 310^{\circ}$ W longitude, 13° N lattitude) and a weaker one in the opposite hemisphere. The sub-earth longitude during our observations was 15°, so the Loki center would have been visible, 24° from the limb. During both Voyager encounters the Loki complex had a large hot spot and an active plume. Although the shorter wavelength radiation we observe may not come from exactly the same surfaces as the longer wavelengths, we assume that they are nearby.

Our particle abundance falls in the middle of the range estimated from Voyager images of the Loki plume as seen above the planet's limb. Although such results are highly sensitive to assumed particle size, Collins (8) suggested that 10^{-4} to 10^{-1} gm/cm^2 of small particles were present.

Because the Voyager 1 IRIS experiment obtained a gas abundance for the Loki region, we can compare the relative amounts of solid and gas in the plume. The value of 0.2 cm atm of SO_2 gas which they measured is equivalent to 5×10^{-4} gm/cm^2. The similarity to our value of 8×10^{-4} gm/cm^2 indicates that roughly equal amounts of SO_2 gas and solid are present.

The principal uncertainty in the solid-to-gas ratio results from the differences in time and viewing geometry between the gas and solid observations. The Voyager measurements were made four years before ours. Although the plume apparently shows short-term variations, the roughly similar appearance in the two Voyager encounters and the constancy of the Earth-based eclipse radiometry, suggest that the activity continues at the same average level. This provides some reason for believing that the IRIS gas abundance is still a reasonable estimate. The path length effects due to different viewing geometry through the plume are difficult to evaluate, since this would require knowledge of the plume density as a function of height and distance from the thermal source. For the present we regard the solid-to-gas ratio as uncertain by a factor of 10. During future eclipses it may be possible to observe both the 4.07-μm frost band and the 4.00-μm gas band, thereby allowing a much better comparsion. The low absorption coefficient for the gas will, however, make this observation difficult.

Approximately equal amounts of gas and solid are predicted by models in which the plumes are driven by SO_2 (10). Although the alternate model, in which the plumes are driven by elemental sulfur, might have equal amounts of gaseous and solid sulfur, we expect that the higher temperatures would not allow condensation of a significant fraction of any SO_2 that might be present. Since detailed thermodynamic models of the plumes have only been generated for single gas systems, this last assertion needs to be checked. Nevertheless, at the time of our observation, the plume appears to have been SO_2 driven.

We intend to obtain observations at a variety of sub-earth longitudes during the next year. The longitude at eclipse varies from 340° to 20° during an apparition of Jupiter. At 340°, Loki would be much closer to the center of the disk, and measurements there could help check both the effect of viewing geometry upon abundance, and the identification of Loki as the primary source. The other hemisphere of Io is never seen in eclipse, but because there may be a change in plume character with longitude (11), observations of it are also important. If, as mentioned above, the dip at 4.07 μm in the out-of-eclipse spectra is due to plume absorption of the added hot spot emission, then this feature proves the presence of SO_2 in plumes at these longitudes. A detection of rapid variability would confirm this.

In conclusion, the discovery of an absorption band of solid SO_2 in spectra of Io's hot spots provides important clues regarding the nature of the volcanic processes. The spectra we present demonstrate that at least one plume is still active some four years after the Voyager 2 fly-by, and confirm the existence of significant amounts of solid SO_2 in it. They show that the hot spot emission comes from at most a few sources (perhaps just one) which must be located near plumes. The suggested solid-to-gas ratio in the Loki plume implies that it is SO_2 driven. Future observations may provide more accurate solid-to-gas ratios for this plume and perhaps for those in the opposite hemisphere. Eclipse observations provide a way to monitor the long-term stability of the plume activity in the Loki hemisphere. This work was supported by NASA grant NGL 12-001-057.

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FIGURE CAPTIONS

FIG. 1 a) The average of 8 spectra taken while Io was in eclipse. The error bars are the standard deviation of mean, computed after the individual spectra have been normalized to the same total flux . The solid line is the band expected for 6.4×10^{-4} gm/cm^2 of solid SO_2. b) The same as 1a except that only the first 6 spectra have been averaged. The solid line is the band expected for 9.6×10^{-4} gm/cm^2 of SO_2. Variations seen in the individual spectra suggest that the feature is variable on a time scale of a few minutes.

FIG. 2 The lower squares are the eclipse spectrum from figure 1b, while the upper ones are spectrum obtained immediately after the satellite emerged from Jupiter's shadow. The line is a spectrum obtained approximately one month earlier, viewing the other hemisphere. The presence of the dip at 4.07 μm in the reflection spectra may result from the superposition of a sharp band to due plume absorption of hot spot emission on top of the broad, smooth band in the light reflected from surface. The sharp bands at 4.11 and 4.14 μm are the ^{34}S and ^{18}O isotopic bands due to the surface SO_2 frost.

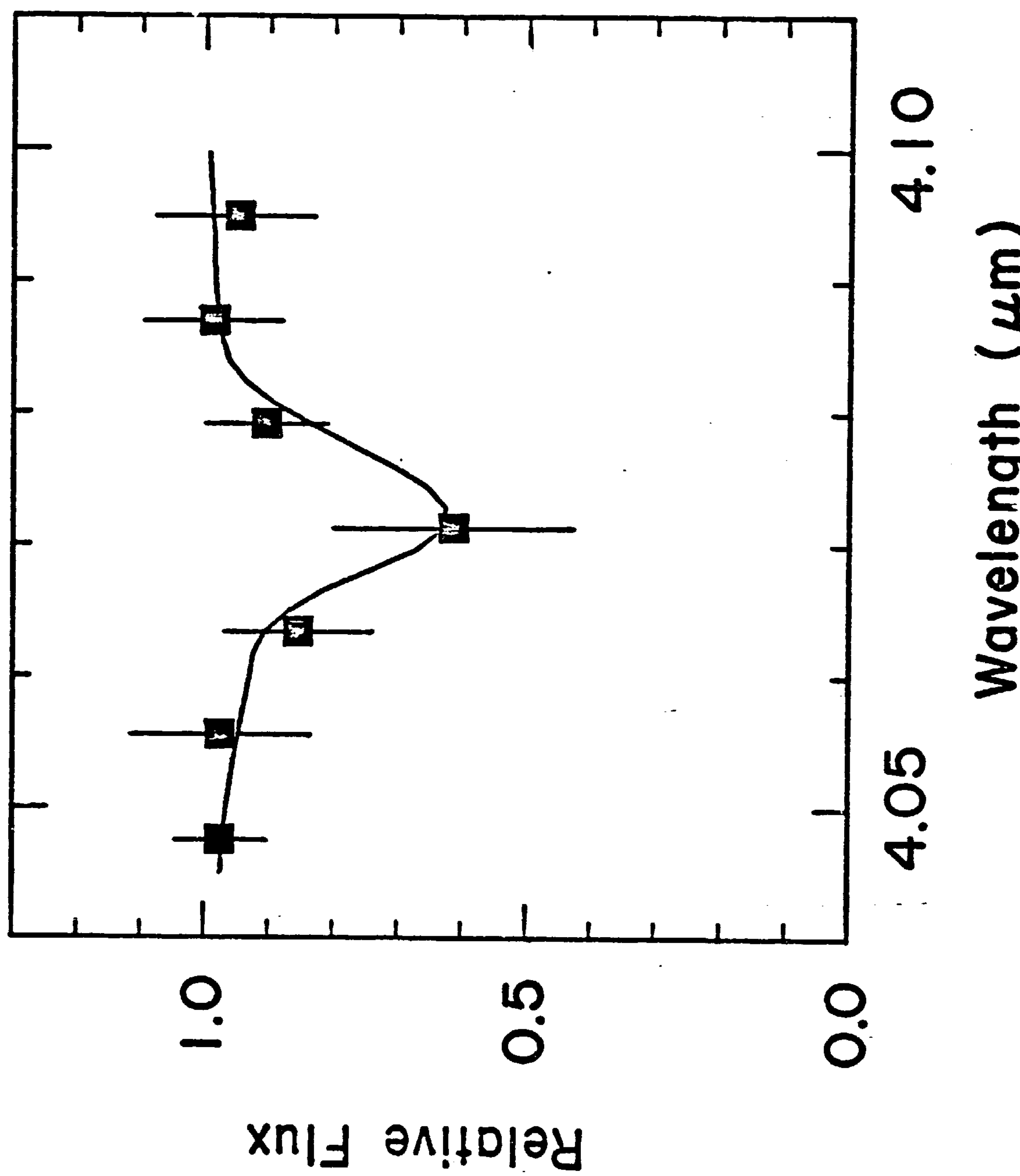

Fig. 1a

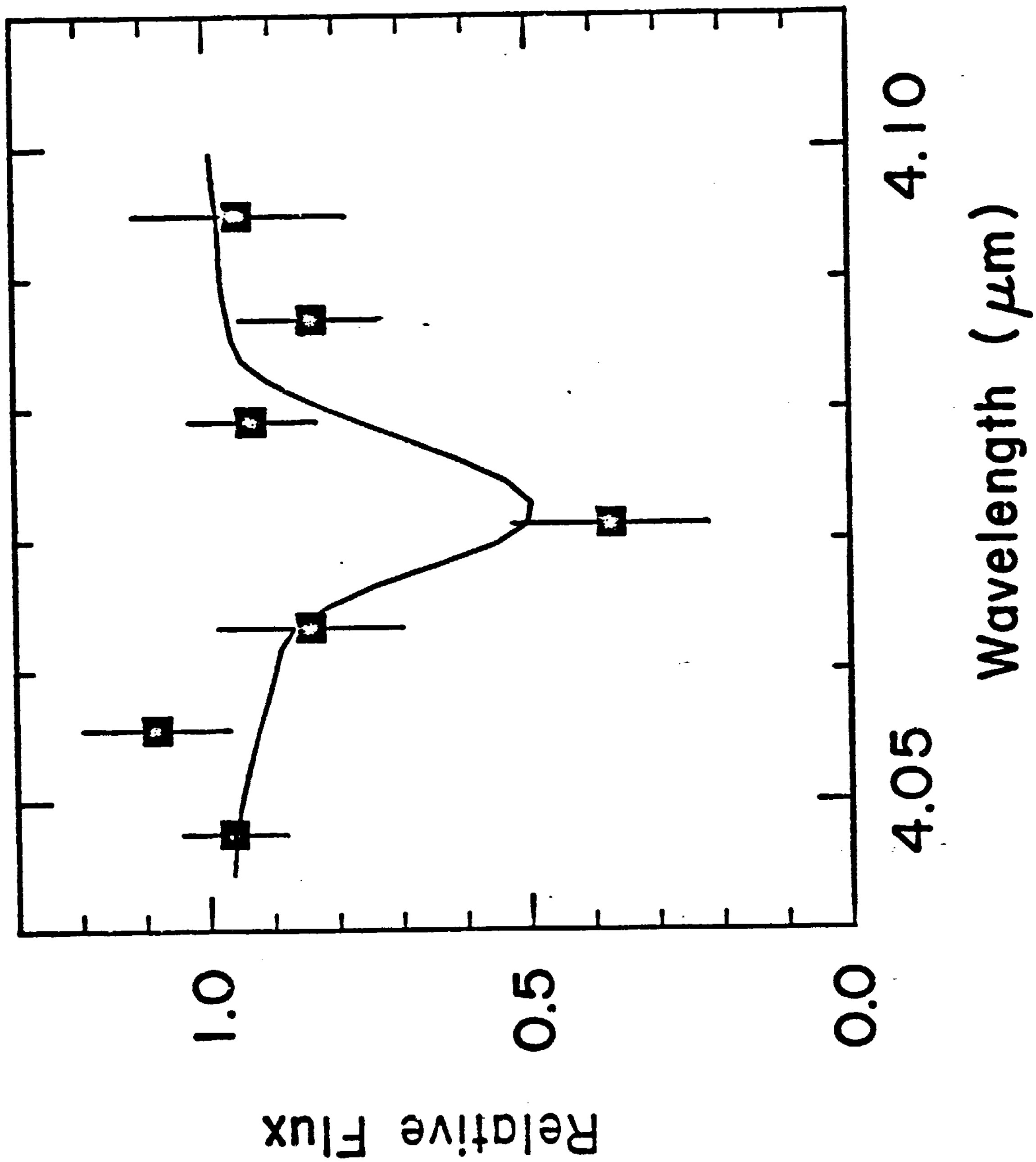

Fig. 1b

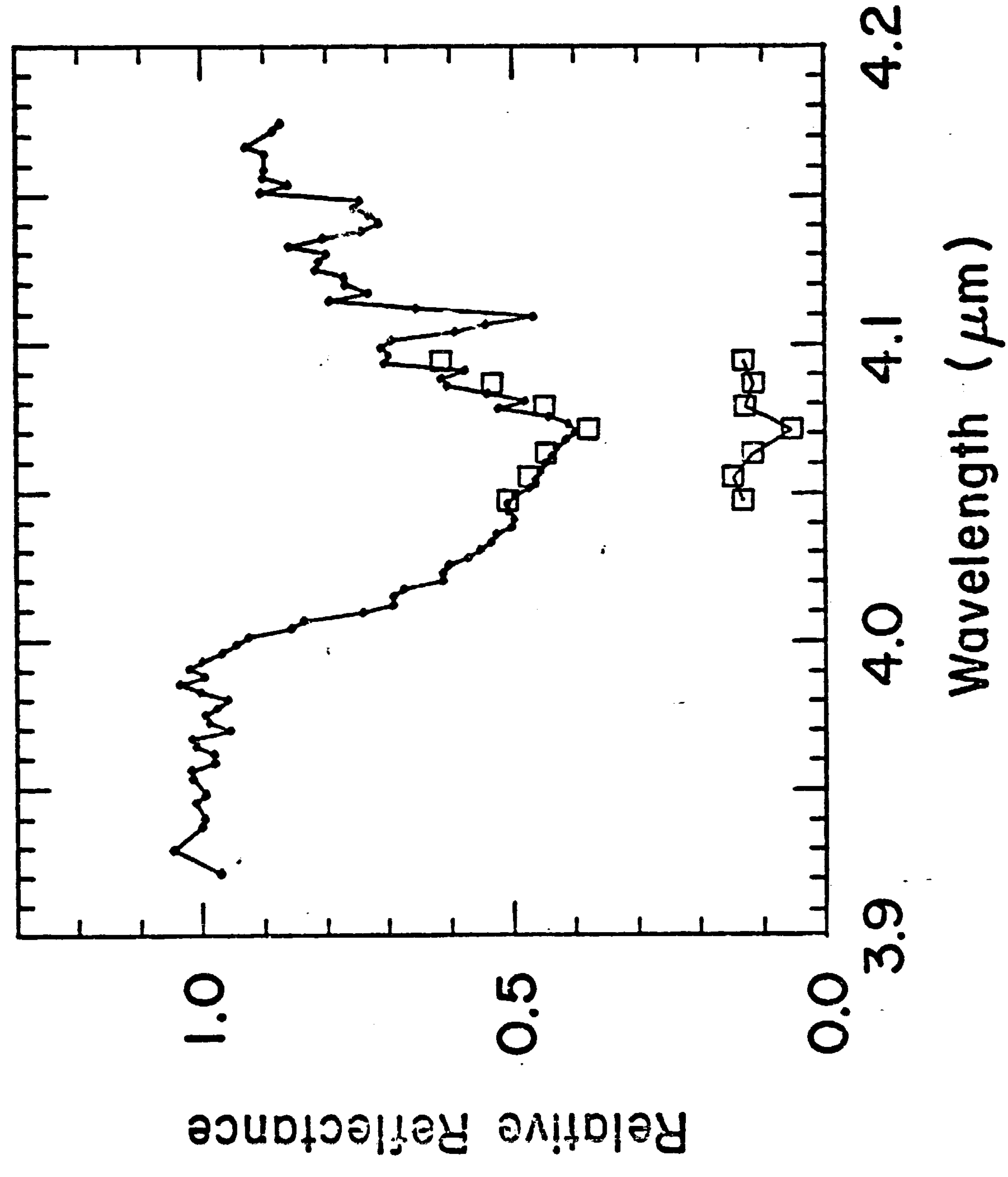

Fig. 2