Reports

Io: Longitudinal Distribution of Sulfur Dioxide Frost

Abstract. *Twenty spectra of Io (0.26 to 0.33 micrometer), acquired with the International Ultraviolet Explorer spacecraft, have been studied. There is a strong ultraviolet absorption shortward of 0.33 micrometer that is consistent with earlier ground-based spectrophotometry; its strength is strongly dependent on Io's rotational phase angle at the time of observation. This spectral feature and its variation are interpreted as indicative of a longitudinal variation in the distribution of sulfur dioxide frost on Io. The frost is most abundant at orbital longitudes 72° to 137° and least abundant at longitudes 250° to 323°. Variations in spectral reflectivity between 0.4 and 0.5 micrometer, reported in earlier ground-based spectral studies, correlate inversely with variations in reflectivity between 0.26 and 0.33 micrometer. It is concluded that this is because the Io surface component with the highest visible reflectivity (sulfur dioxide frost) has the lowest ultraviolet reflectivity. At least one other component is present and may be sulfur allotropes or alkali sulfides. This model is consistent with ground-based ultraviolet, visible, and infrared spectrophotometry. Comparison with Voyager color photographs indicates that the sulfur dioxide frost is in greatest concentration in the "white" areas on Io and the other sulfurous components are in greatest concentration in the "red" areas.*

Frozen SO_2 has been identified on Io by three separate and independent studies on the basis of the close match between Io's infrared spectrum at ~ 4.0 μm from ground-based telescope observations and laboratory spectra of the frost (*1-3*). Nash *et al.* (*4*) recently measured the laboratory spectrum of SO_2 frost in the visible and ultraviolet range and found, by comparing it with Io's full-disk spectrum, that SO_2 frost covers less than about 20 percent of Io's projected surface area. Here we map the distribution of SO_2 frost, including optically thick frost and adsorbate, on Io's surface.

Nelson and Hapke (*5*) proposed allotropic forms of sulfur (S_x) as candidate materials for Io's surface on the basis of the close agreement between Io's ultraviolet and visible reflection spectrum and laboratory spectra of the various sulfur allotropes (*6*). Later, when Voyager images became available, Sagan (*7*) further developed this model by suggesting that molten sulfur flows, rapidly quenched on Io's cold surface, could explain the satellite's vivid and variegated coloration. This is supported by photometric data on individual pixels (*8*).

Here we present 20 new spectra of Io that we obtained with the International Ultraviolet Explorer (IUE) spacecraft. We interpret these spectra in terms of a two-component model for Io's surface in which one component is SO_2 frost and the other is some combination of sulfur-bearing materials, for example, sulfur allotropes. However, we do not imply that only these two components are present on Io's surface; in fact, alkali sulfides have also been shown to match Io's reflection spectrum in the same spectral regions as sulfur allotropes (*2, 9*). Furthermore, the presence of alkali metal compounds is required to provide a source for Io's sodium and potassium clouds (*10*). Our intent is to demonstrate that the SO_2 frost can be spatially distinguished from other sulfurous components. Existing ground-based observations between 0.32 and 5.0 μm are consistent with this interpretation.

Figure 1a shows the laboratory reflection spectrum from 0.26 to 0.65 μm of a typical sulfur allotrope (S_x) and SO_2 frost. Figure 1b shows the laboratory spectrum of the frost from 1.0 to 4.5 μm. Sulfur allotropes are known not to have bands in the 4-μm region. The allotrope was produced by rapidly quenching, in liquid nitrogen, liquid sulfur that had been heated to 128°C in an oxygen-free environment.

Inspection of these laboratory spectra shows that mixtures having high fractional ratios of S_x to SO_2 frost would be expected to have weak absorption shortward of 0.33 μm, a high reflectivity change between 0.4 and 0.5 μm, and a weak infrared band at 4.08 μm. Conversely, mixtures having high fractional ratios of SO_2 frost to S_x would have strong absorption shortward of 0.33 μm, a low reflectivity change between 0.4 and 0.5 μm, and a strong 4.08-μm band.

Because Io is in synchronous rotation about Jupiter, observations made at any given orbital (rotational) phase angle θ always refer to the same Ionian hemisphere as seen by an Earth-based observer. Thus, a comparison of spectra taken at different orbital phase angles shows the variation in longitudinal distribution of differing spectral domains on Io's surface.

Our 20 spectra of Io in the range 0.26 to 0.33 μm, taken over a wide range of rotational phase angles, show significant variation in absolute ultraviolet flux from Io as a function of orbital phase. We compared the absolute signal intensity at 0.29 μm of two spectra taken 10 hours apart at different orbital phases and found that the ultraviolet flux at orbital longitude 314° is ~ 30 percent greater

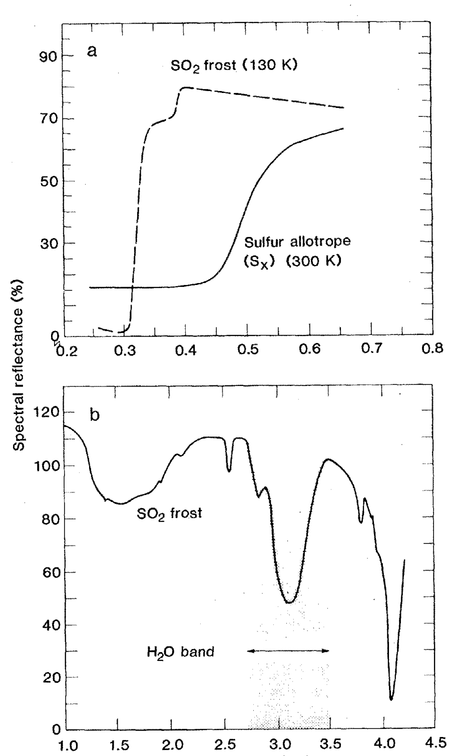


Fig. 1. (a) Spectral reflectance of SO_2 frost (*4*) and allotropic sulfur. The allotrope was made by rapidly quenching liquid sulfur that had been heated to 128°C in an oxygen-free environment. (b) Infrared spectrum of SO_2 frost (*1*).

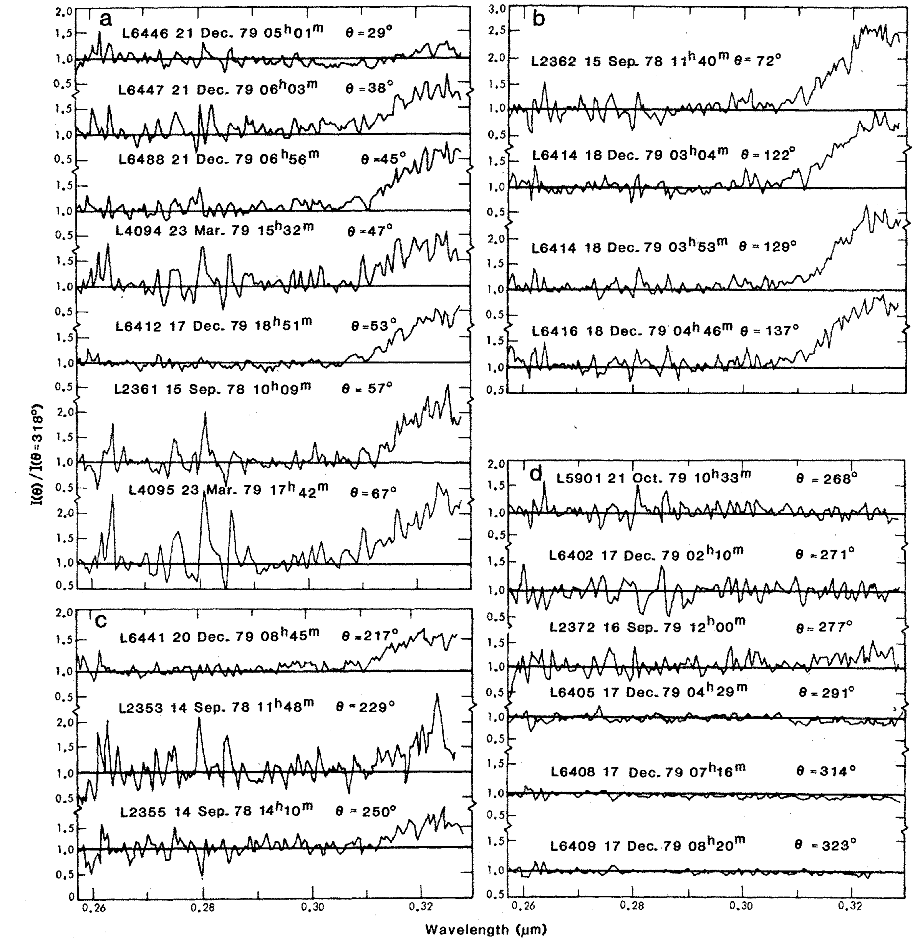
than that at 53°. Assuming the existence of two spectroscopically active components, we conclude from this that the hemisphere centered at longitude 53° has a greater abundance of the more strongly ultraviolet-absorbing material than the hemisphere centered at longitude 314°. In general, the ultraviolet absorption in all our spectra is weakest at rotational phase angles near 314°.

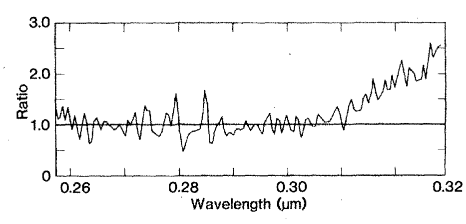
To illustrate the orbital longitude variation, we converted our ultraviolet IUE data to ratio spectra. The spectra at all rotational phase angles were divided by the sum of the two flattest spectra at 314° and 323°, where the absorption is weakest. The resulting ratio spectra best show the variation of the absorption as a function of rotational phase angle. The unsmoothed ratio spectra, normalized to unity at 0.27 μm, are shown in Fig. 2, a to d. Of particular interest is the spectral upturn between 0.305 and 0.325 μm. The sharp spikes in some of the spectra are probably random noise or unresolved Fraunhofer lines and are not compositionally diagnostic.

We note that the ultraviolet absorption increases steadily between longitudes 29° and 72°, remains consistently strong from 72° to 137°, diminishes in strength from 137° to 250°, and is virtually nonexistent from 250° to 323°. Therefore the abundance of ultraviolet-absorbing material on Io is greatest at longitudes between 72° and 137°. In terms of our hypothesis, this would imply that over this longitude range Io's surface has the greatest fractional abundance of SO_2 frost.

We caution that because these are ratio spectra and not absolute spectra, only relative abundances of SO_2 frost can be discerned; that is, we do not conclude that SO_2 frost is absent at longitudes 250° to 323°, only that it is relatively less abundant. To demonstrate this point, we took the ratio of the sum of two Io spectra at 314° and 323° to an average Callisto spectrum, with the result shown in Fig. 3. Because it is known from infrared spectra (*11*) that Callisto has no band at 4.08 μm, and hence no SO_2 frost, the presence of the 0.33-μm absorption feature in the ratio spectrum means that SO_2 frost is present on Io even at longitudes 314° and 323°; however, it is least abundant there.

Figure 4a shows the spectrum of Io between 0.32 and 0.67 μm at rotational phase 32° from ground-based spectrophotometry (*5*). Figure 4b shows the ratio of ground-based spectra taken at other rotational phase angles to the spectrum at 32°. These ratio spectra have been normalized to unity at 0.45 μm. We





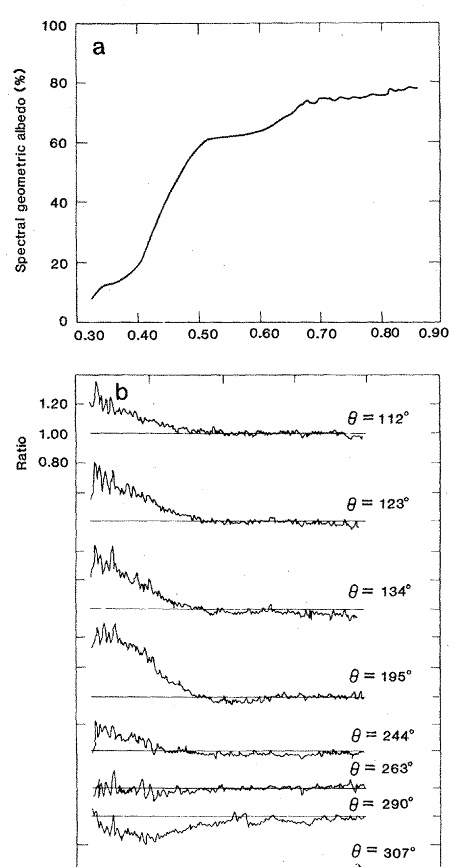


Fig. 2 (top). (a) Spectra of Io (0.26 to 0.33 μm; orbital longitudes, $29° \leq \theta \leq 67°$) that have been divided by an average of two spectra at orbital longitudes 314° and 323°. The ratio spectra have been normalized to unity at 0.27 μm. The strength of the 0.32-μm absorption increases, indicating an increase in SO_2 frost concentration with increasing longitude. (b) Same as (a), except at $72° \leq \theta \leq 137°$. Note the constant strength of the SO_2 frost absorption. (c) Same as (a), except at $217° \leq \theta \leq 250°$. Note the decrease in strength of the SO_2 frost absorption. (d) Same as (a), except at $268° < \theta < 323°$. This longitude on Io is relatively least abundant in SO_2 frost coverage. Fig. 3 (bottom left). Average Io spectrum at orbital longitude 318° divided by a typical Callisto spectrum. Note that even at longitudes where SO_2 frost is least abundant on Io, the frost is nevertheless present. Fig. 4 (bottom right). (a) Spectral geometric albedo (0.32 to 0.87 μm) of Io at orbital longitude 32° (*5*). (b) Ratio of spectra of Io (0.32 to 0.67 μm) at other rotational phase angles to the spectrum in (a). The ratio spectra have been normalized to unity at 0.56 μm (*5*). The 0.32-μm absorption is strongest at longitudes $123° < \theta < 195°$. This is consistent with the IUE spectra shown in Fig. 3.

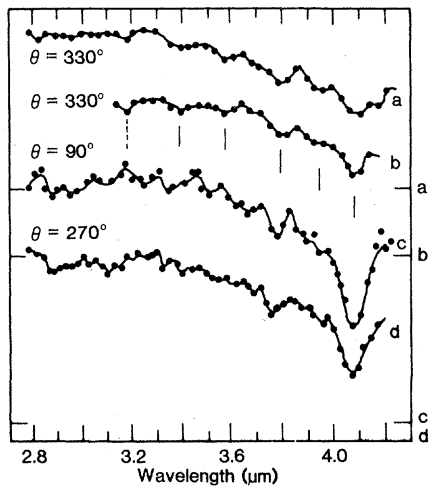


Fig. 5. Infrared spectra of Io (2.8 to 4.2 μm) from Cruikshank, Jones, and Pilcher (*12*). Note that the 4.08-μm SO_2 frost band is strongest at longitude 90°, where the 0.33-μm edge is strongest.

note that at orbital longitudes 290° and 307°, Io has a reflectance change at 0.4 to 0.5 μm that is greater than the change at 32°. Furthermore, at orbital longitudes $112° < \theta < 244°$, Io is relatively more reflecting shortward of 0.5 μm (that is, has a smaller reflectivity change at 0.4 to 0.5 μm relative to 32°). The variation in reflectivity shortward of 0.33 μm in the ground-based spectra is not inconsistent with the variation detected by IUE. We conclude that the relatively stronger reflectivity change between 0.4 and 0.5 μm at longitudes $290° < \theta < 307°$ is consistent with a greater fractional abundance of S_x relative to SO_2 in that area because S_x has a strong absorption between 0.4 and 0.5 μm. This interpretation derives further support from the IUE data, which show that the 0.33-μm reflectivity change (which we interpret as being due to variations in the longitudinal distribution of SO_2 frost) varies in the opposite sense of the 0.4- to 0.5-μm reflectivity change.

Figure 5 shows the ground-based infrared spectrum of Io at four orbital phase angles from Cruikshank *et al.* (*12*). The 4.08-μm band (due to SO_2 frost) is weakest at orbital phase 330° and strongest at orbital phase 90°. These data are also consistent with our hypothesis that the greatest fractional abundance of SO_2 frost is at longitudes greater than 29° and less than 250° and that the least abundance of SO_2 frost is at longitudes around 314°.

We conclude from all these data sets that the greatest fractional abundance of SO_2 frost is at approximate longitudes $72° < \theta < 137°$ and that those longitudes are least abundant in S_x. Also, longitudes $250° < \theta < 323°$ are least abundant in SO_2 and most abundant in S_x. Comparison with the Voyager color relief map in (*13*) shows that the longitudes where our spectrophotometric analysis finds SO_2 frost to be in greatest abundance are those where Io has the greatest coverage of "white" material. Furthermore, the longitudes where our analysis finds Io to be least abundant in SO_2 frost and most abundant in S_x are those where there is substantially less white material and a greater preponderance of "red" material. We therefore conclude that the white material on Io is associated with a greater fractional abundance of SO_2 frost, and the red material with a greater fractional abundance of other sulfurous materials.

Since volcanic activity on Io is known to be variable (*13*) and SO_2 frost deposits may originate from condensed volcanic emissions, it would not be surprising to find a major temporal as well as spatial variation in SO_2 frost coverage. We do not believe that most of the variation we see could be attributed to temporal changes because, to first order, inspection of the times of the spectral observations in Fig. 2, a to d, shows that the data have been repeatable as a function of orbital phase over a 15-month baseline. However, close scrutiny of the spectra (for example, L6412, L2361, L4095, and L2362) shows that the possibility of time variability cannot be completely ruled out. Because of the distinct longitudinal variation we document, the detection of any temporal variation will need synoptic observation with very careful longitudinal control.

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1979J2: The Discovery of a Previously Unknown Jovian Satellite

Abstract. *During a detailed examination of imaging data taken by the Voyager 1 spacecraft within 4.5 hours of its closest approach to Jupiter, a shadow-like image was observed on the bright disk of the planet in two consecutive wide-angle frames. Analysis of the motion of the image on the Jovian disk proved that it was not an atmospheric feature, showed that it could not have been a shadow of any satellite known at the time, and allowed prediction of its reappearance in other Voyager 1 frames. The satellite subsequently has been observed in transit in both Voyager 1 and Voyager 2 frames; its period is 16 hours 11 minutes 21.25 seconds ± 0.5 second and its semimajor axis is 3.1054 Jupiter radii (Jupiter radius = 7.14 × 10^4 kilometers). The profile observed when the satellite is in transit is roughly circular with a diameter of 80 kilometers. It appears to have an albedo of ~ 0.05, similar to Amalthea's.*

Detailed examination of a wide-angle image of part of Jupiter's equatorial region (frame FDS 16383.50) taken by the Voyager 1 spacecraft 4 hours 28 minutes before its closest approach to Jupiter revealed a dark area 10 picture elements (pixels; 1 pixel $\cong 7 \times 10^{-5}$ rad) in diameter that looked like a shadow (Fig. 1). The same dark area was also observed in the next wide-angle frame (FDS 16383.54), taken 192 seconds later (Fig. 2), but approximately 70 wide-angle pixels from its previous position relative to nearby atmospheric features.