SPECTRAL REFLECTANCE OF SODIUM SULFIDE: A COLORANT ON IO?
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The vivid colors of the surface of Io have been ascribed to allotropes of sulfur in sulfur flows (1,2,3), once-molten basalt/sulfur mixtures (4), sulfur polyoxides (5), or some as yet unidentified material or contaminant (6). Sulfides of the alkali metals sodium and potassium are potential minor (- few percent) but important constituents since they provide a source for the Na and K atoms observed in Io's extended exosphere (7) and are compatible in a high sulfur environment. Published spectral reflectances (0.3-1 \( \mu \)m) of Na\(_2\)S and K\(_2\)S are consistent with the large drop in reflectance in the ultraviolet that is observed for Io (8) but the presence of strong water bands in the infrared (1-5 \( \mu \)m) have hampered close comparisons between the reflectances of Io and these extremely hydroscopic materials.

We have measured the spectral reflectance of Na\(_2\)S by dehydrating commercially available Na\(_2\)S\(\cdot9H_2O\) according to published methods (9) which involve initial drying in vacuum for several weeks and subsequent heating in a hydrogen atmosphere. The spectral reflectance of powdered Na\(_2\)S at various stages of drying is shown in Fig. 1. Strong water absorptions are apparent in the fully hydrated sample as well as two weak absorptions at about 0.4 and 0.6 \( \mu \)m. When the excess water is removed in a vacuum dessicator the water bands diminish in strength and the 0.4 \( \mu \)m absorption feature appears stronger, in agreement with previously published results (8). When the bound water is totally removed the 0.4 \( \mu \)m feature weakens considerably and a prominent absorption appears centered at 0.56 \( \mu \)m. Although this feature was noticed in the proton bombardment of Na\(_2\)S (8), it is not due to NaHS or to H\(_2\)S or SO\(_2\) which are removed by the heat treatment in our sample. This feature is tentatively ascribed to Na\(_2\)S. In Fig. 2 we compare the normalized spectral reflectances (0.3-2.4 \( \mu \)m) of the trailing side of Io and the dehydrated Na\(_2\)S. The match between the 0.56 absorption of Na\(_2\)S and the 0.56 absorption on Io is remarkable. Sodium sulfide provides a better match to the 0.56 micron feature than the "boiled" sulfur hypothesis (4).

We have also investigated the spectral reflectances of sulfur-sodium sulfide mixtures. In Fig. 3 we compare the spectral properties of Io with two materials: a dense (> 1.803), "highly reddened" material formed when equal amounts of sulfur and Na\(_2\)S are heated in vacuum to 444°C and an "orangish" material formed when Na\(_2\)S is added as a contaminant (~ 10%) to the hot sulfur. This procedure of mixing and heating is reported to produce sodium polysulfides (Na\(_2\)S\(_x\), \( x > 1 \)) (9). The reddish material is presumed but not known to contain a significant proportion of the sodium polysulfides whereas the orangish material is presumed to contain lesser amounts. As can be seen in Fig. 3 the 0.56 \( \mu \)m signature of Na\(_2\)S is still visible in the yellowish material but masked in the darker, reddish material. The strong broad absorption in the visible region (0.3-0.7 \( \mu \)m) in these mixtures may be caused by the polysulfides themselves or it may be produced by the formation of strongly absorbing "color centers" in sulfur crystals caused by the sodium contaminant.

We conclude that Na\(_2\)S is a strong candidate for a surface contaminant on Io based upon the falloff in reflectivity at \( \lambda < 0.4 \) \( \mu \)m, the prominent absorption at 0.56 \( \mu \)m and the lack of absorption features between 1 and 2.5 \( \mu \)m, all of which are consistent with the general spectral reflectance of Io. Na\(_2\)S and polysulfides of sodium mixed with sulfur are important candidates as colorants of individual areas on Io which removes the requirement for sulfur allotrope formation by quenching of sulfur flows. The role of potassium sulfide remains to be investigated but based on the similarities of published spectral reflectance properties (8,9) of hydrated Na\(_2\)S and K\(_2\)S, the dehydrated sulfides of K (and mixtures with sulfur) are strong candidates, also.

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Spectral Reflectance of Sodium Sulfide

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Fig. 1. The hemispherical spectral reflectance (0.3-2.4 μm) of Na₂S in various states of dehydration measured on a Cary 14 spectrophotometer relative to a halon standard. Curve A is fully hydrated, commercially available Na₂S·9H₂O; curve B is Na₂S·9H₂O dried in vacuum over H₂SO₄ for several weeks; curve C is Na₂S dehydrated at 500°C in a stream of hydrogen gas (9).

Fig. 2. The normalized (at λ = 0.54 μm) spectral reflectance of the trailing side of Io (8) compared with dehydrated Na₂S. The geometric albedo of Io at 0.54 μm is p = 0.6. The reflectivity of Na₂S is r = 0.84.

Fig. 3. The smoothed spectral reflectance of the trailing side of Io (D) compared with the spectral reflectance of various sulfur and sodium polysulfide mixtures. Curve A is the reddish polysulfide formed when equal amounts of Na₂S and S are heated to 444°C; curve B, ~10% Na₂S in the mixture before heating; curve C, ~5% Na₂S in the mixture before heating.