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## **Evidence of SO<sub>2</sub> on Io from UV observations**

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**Gaseous SO<sub>2</sub> was discovered on Io, the innermost galilean satellite of Jupiter, by the IRIS IR Michelson interferometer<sup>1</sup> on board Voyager 1 in March 1979. This SO<sub>2</sub> is likely to be associated with eruptions of the seven active volcanoes discovered at the same time by the Voyager cameras<sup>2</sup>. The UV spectrum of the solar light reflected by the surface of Io should be modified by the transmission  $\bar{S}(\lambda)$  of a SO<sub>2</sub> atmosphere and by the reflectivity  $r(\lambda)$  of the surface. Both gaseous SO<sub>2</sub> and solid<sup>3</sup> SO<sub>2</sub> present a deep absorption band around 290 nm. We have examined a published spectrum of Io taken in 1978 by the IUE Earth-orbiting telescope<sup>4</sup>, and found an absorption dip centred around 290 nm in the albedo curve. We attribute this dip to gaseous SO<sub>2</sub>, with a possible contribution of solid SO<sub>2</sub>. However, the absorption dip is smaller than if the gaseous SO<sub>2</sub> quantity measured by Voyager 1 in the IR were uniform. It can be better represented by an SO<sub>2</sub> frost controlled gaseous atmosphere and a temperature distribution of Io's surface compatible with observations.**

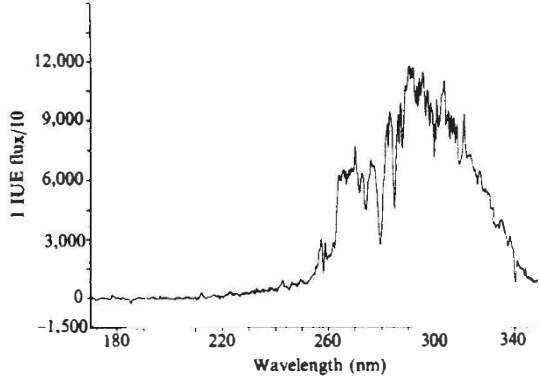


Fig. 1 The UV spectrum of Io as measured in 1978 with the orbital telescope IUE<sup>4</sup>.

The surface of Io, even when covered with SO<sub>2</sub> frost, probably does not have the same UV optical characteristics as pure SO<sub>2</sub> frost obtained in the laboratory, as other materials are certainly present at the surface. To conduct a quantitative analysis, we have considered successively two extreme cases: either the surface reflectivity of Io does not show the absorption dip of pure SO<sub>2</sub> frost (which does not exclude its presence) or it reproduces it exactly (and therefore indicates its presence).

The average surface temperature of Io on the dayside is =127 K, but some 'hot spots' exist where the temperature is probably as high as 290 K (ref. 5). This high temperature, which yields a high surface IR radiance, allowed the identification of an SO<sub>2</sub> absorption feature at 1,350 cm<sup>-1</sup>. The vertical column density  $N$  is estimated to be 0.2 cm atm (ref. 1) which corresponds to a surface pressure of  $1.0 \times 10^{-4}$  mbar. This value is close to the vapour pressure of SO<sub>2</sub> frost at  $T = 129$  K ( $1.4 \times 10^{-4}$  mbar). The similarity of these numbers led to suggestions that gaseous SO<sub>2</sub> content in Io's atmosphere is controlled by SO<sub>2</sub> frost. This idea is also supported by the recent identification of absorption due to SO<sub>2</sub> frosts in ground-based IR reflection spectra<sup>6,7</sup>.

The geometric albedo of Io has been measured down to 320 nm from ground-based observations<sup>8</sup> and is displayed in Fig. 2. Further in the UV, the spectrum of Io in Fig. 1 has been measured with IUE<sup>4</sup>, as was the spectrum of Mars. We derive the geometric albedo  $G(\text{Io})$  below 320 nm from these data by using the relation:

$$\frac{G(\text{Io})}{G(\text{Mars})} = C \frac{\text{Spectrum}(\text{Io})}{\text{Spectrum}(\text{Mars})}$$

where  $C$  is a constant of proportionality which depends on the IUE observing conditions. The geometric albedo of Mars is obtained from measurements by OAO 2 (ref. 9), which is rather flat in this region (from 0.051 at 240 nm to 0.040 at 330 nm). The value of  $C$  was found to be 0.5 by matching the IUE albedo and the ground-based albedo at 330 nm.  $G(\text{Io})$  is displayed in Fig. 2 and shows a pronounced dip, centred near 290 nm, reminiscent of the absorption coefficient  $K_{\lambda}$  of gaseous SO<sub>2</sub> also shown in Fig. 2. The vertical optical column density of 0.2 cm atm represents a vertical optical thickness  $\tau_{\nu}(\lambda) = k_{\lambda}N$  of  $6 \times 10^{-3}$  at 340 nm and 3.5 at 280 nm. As only the integrated albedo on the surface is available, we computed the averaged transmission  $\bar{S}(\lambda)$  of various SO<sub>2</sub> atmosphere models, assuming that the temperature of SO<sub>2</sub> frost controlled the gaseous SO<sub>2</sub>. The vapour pressure  $\rho$  of gaseous SO<sub>2</sub> over frost is a function of surface temperature  $T$  (ref. 10)

$$\log_{10} \rho (\mu \text{ bar}) = -1,843.04/T + 13.7164$$

and the vertical column density is  $N(\text{cm atm}) = 1.96 \rho(\mu \text{ bar})$ . Given a temperature distribution  $T(\theta)$  as a function of solar zenith angle  $\theta$ , the transmission  $S_{\lambda}(\theta)$  of the atmosphere to reflected sunlight at 0° phase angle is  $S_{\lambda}(\theta) =$

$\exp[-2k_{\lambda}N(\theta)/\cos \theta]$ . If  $r(\lambda)$  is the normal reflectivity of Io's surface in the absence of atmospheric absorption, the geometric albedo at 0° phase angle is:

$$G(\lambda) = r(\lambda) \int_0^{\pi/2} \cos^{n+1} \theta S_{\lambda}(\theta) d(\cos \theta) = r(\lambda) \bar{S}(\lambda)$$

which defines the equivalent transmission  $\bar{S}(\lambda)$ .  $n$  is an index representing the limb darkening effect. However, we present here results only for  $n=0$ , as the dependence on  $\theta$  is strongly dominated by the function  $T(\theta)$ . We have computed the equivalent transmission  $\bar{S}(\lambda)$  for various temperature distributions  $T(\theta)$  and have compared it with the measurement  $G(\lambda)$  of Fig. 2. We take first a model for  $r(\lambda)$  below 340 nm, with no SO<sub>2</sub> frost absorption dip, as a linear extrapolation of the trend observed above 340 nm. At 240 nm, where SO<sub>2</sub> absorption coefficient is small, this model (dashed line on Fig. 2) coincides with the measured  $G(\lambda)$ .

First we considered uniform temperature distribution. With a temperature  $T = 127.2$  K giving  $N = 0.2$  cm atm, we find  $\bar{S}(340 \text{ nm}) = 1$  (negligible absorption) and  $\bar{S}(280 \text{ nm}) = 2 \times 10^{-4}$  (total absorption). As  $r(\lambda)$  must be  $< 1$ , it implies that the albedo should be effectively zero at 280 nm. In fact, the non-zero albedo measured at 280 nm implies either a very low uniform value of  $N$  ( $\approx 0.014$  cm atm corresponding to  $T = 117.4$  K) or a non-uniform distribution of the temperature and SO<sub>2</sub> column density.

We then considered models of the form

$$T(\theta) = T_s - \Delta T(1 - \cos^m \theta)$$

where  $T_s$  is the temperature at the sub-solar point,  $T_s - \Delta T$  the temperature at the terminator, and  $m$  a parameter describing how fast  $T(\theta)$  decreases from  $T_s$  to  $T_s - \Delta T$ . For each value of  $T_s$  and  $m$ , a value of  $\Delta T$  can be found which satisfies the observational constraint  $\bar{S}(\lambda) \approx 0.50$  at 290 nm. The value of  $m = 1/4$ , which provides a good empirical representation on

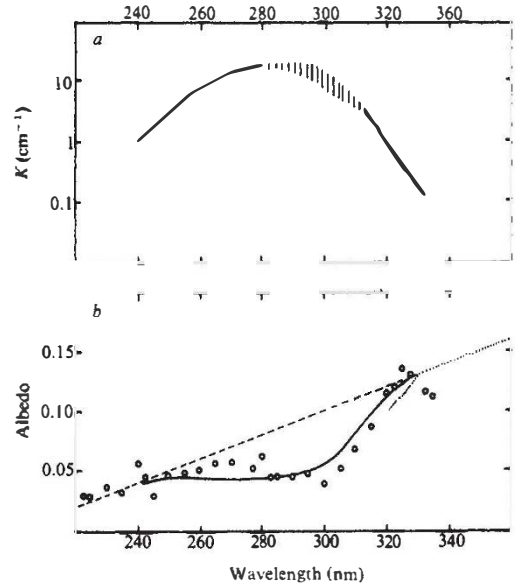


Fig. 2 a, The absorption coefficient  $K$ , of gaseous SO<sub>2</sub> as a function of wavelength<sup>10</sup>. There is a pronounced band structure between 280 and 320 nm which is represented schematically only. b, Geometric albedo of Io as a function of wavelength. Dotted line, ground-based measurements<sup>8</sup>. The linear extrapolation of ground-based measurements below 330 nm (dashed line) represents surface reflectivity variations  $r(\lambda)$ , if the SO<sub>2</sub> frost signature is ignored.  $\circ$ , The measurements derived from spectrum of Fig. 1, spectrum of Mars and the known albedo of Mars. The solid line is the result of a computation of the transmission of a saturated SO<sub>2</sub> atmosphere (averaged over the disk of Io) above SO<sub>2</sub> frost, containing 0.2 cm atm at the sub-solar point, and a temperature variation compatible with IR measurements.

Mercury's temperature profile, would imply small values of  $T_s$  and large values of  $\Delta T$ :  $T_s = 123$  K and  $\Delta T = 60$  K, which do not fit the IRIS data of  $T_s = 127$ – $130$  K, and  $T = 110$  K at the evening terminator (ref. 1 and J. Pearl, personal communication). For  $m = 1$ , a good fit of  $G(\lambda)$  is obtained with  $T_s = 127$  K (corresponding to  $N = 0.19$  cm atm) and  $\Delta T = 34$  K and is represented in Fig. 2. This is quite reasonable, as we expect the morning terminator to be colder than the evening terminator. We, therefore, conclude that there was, at the time of IUE observations, a quantity of gaseous  $\text{SO}_2$  comparable to the quantity detected by Voyager 1, if the temperature distribution was represented by  $T = T_s - \Delta T(1 - \cos \theta)$ , and if the surface reflectivity  $r(\lambda)$  behaves as assumed, without any UV  $\text{SO}_2$  frost signature.

Now we consider the other extreme case where the surface of Io has a reflectivity  $r(\lambda)$  reproducing exactly the UV  $\text{SO}_2$  frost signature. Indeed, it has been suggested<sup>3</sup> that the decrease of geometric albedo from 330 to 320 nm (ground observations) may be due to  $\text{SO}_2$  frost. A laboratory reflectivity spectrum of pure  $\text{SO}_2$  frost at 130 K was recently obtained<sup>12</sup>, showing a decrease of a factor of 28 between 325 and 275 nm. Such a decrease is clearly absent from IUE observations, which would mean in this case that only a fraction  $A_f \approx 0.24$  of the planet is covered with  $\text{SO}_2$  frost, the rest being covered with a background material with a reflectivity  $\alpha_B = 0.064$ . This is obtained

by fitting IUE observations at 275 and 325 nm with a combination of background material, pure  $\text{SO}_2$  frost and gaseous  $\text{SO}_2$  over this  $\text{SO}_2$  frost. In such a case, the absorption due to gaseous  $\text{SO}_2$  at 275 nm would be  $\sim 12\%$ , averaged on the whole disk.

The UV spectrum of Io shows evidence of the UV  $\text{SO}_2$  band centred at 280 nm. To what extent this band has a contribution of  $\text{SO}_2$  frost or is only due to gaseous  $\text{SO}_2$  is still an open question. It could be solved by resolving the spectral structure of the gaseous  $\text{SO}_2$  between 280 and 310 nm, absent from the pure  $\text{SO}_2$  frost spectrum. However, our model of the temperature-controlled  $\text{SO}_2$  atmosphere has shown that the variations of  $\bar{S}(\lambda)$  are much smaller than the variations of the gaseous  $\text{SO}_2$  absorption coefficient  $k_\lambda$ , requiring, therefore, accurate measurements. The monitoring of the geometric albedo spectrum, from ground observations, but more conveniently from IUE, would provide a record of changes in the atmospheric  $\text{SO}_2$  content. This  $\text{SO}_2$  content is a result of volcanic activity, extent of  $\text{SO}_2$  frost deposit, temperature profile, and escape to the ionised torus discovered by Voyager 1 at the orbit of Io<sup>13</sup>. It would be of particular interest to observe the rise and decay times associated with a large surge of activity.

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