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Evidence of SO₂ on Io from UV observations

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Gaseous SO₂ was discovered on Io, the innermost galilean satellite of Jupiter, by the IRIS IR Michelson interferometer¹ on board Voyager 1 in March 1979. This SO₂ is likely to be associated with eruptions of the seven active volcanoes discovered at the same time by the Voyager cameras². The UV spectrum of the solar light reflected by the surface of Io should be modified by the transmission $\tilde{S}(\lambda)$ of a SO₂ atmosphere and by the reflectivity $r(\lambda)$ of the surface. Both gaseous SO₂ and solid³ SO₂ present a deep absorption band around 290 nm. We have examined a published spectrum of Io taken in 1978 by the IUE Earth-orbiting telescope⁴, and found an absorption dip centred around 290 nm in the albedo curve. We attribute this dip to gaseous SO₂, with a possible contribution of solid SO₂. However, the absorption dip is smaller than if the gaseous SO₂ quantity measured by Voyager 1 in the IR were uniform. It can be better represented by an SO₂ frost controlled gaseous atmosphere and a temperature distribution of Io's surface compatible with observations.

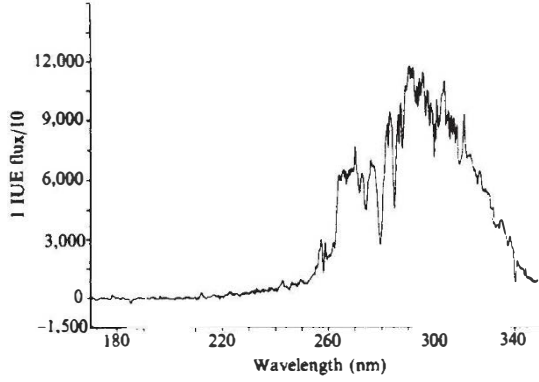


Fig. 1 The UV spectrum of Io as measured in 1978 with the orbital telescope IUE⁴.

The surface of Io, even when covered with SO₂ frost, probably does not have the same UV optical characteristics as pure SO₂ 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 SO₂ 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 SO₂ absorption feature at $1,350 \text{ cm}^{-1}$. The vertical column density N is estimated to be 0.2 cm atm (ref. 1) which corresponds to a surface pressure of $1.0 \times 10^{-4} \text{ mbar}$. This value is close to the vapour pressure of SO₂ frost at $T = 129 \text{ K}$ ($1.4 \times 10^{-4} \text{ mbar}$). The similarity of these numbers led to suggestions that gaseous SO₂ content in Io's atmosphere is controlled by SO₂ frost. This idea is also supported by the recent identification of absorption due to SO₂ frosts in ground-based IR reflection spectra^{6,7}.

The geometric albedo of Io has been measured down to 320 nm from ground-based observations⁸ and is displayed in Fig. 2. Further in the UV, the spectrum of Io in Fig. 1 has been measured with IUE⁴, 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_λ of gaseous SO₂ 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 6×10^{-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 SO₂ atmosphere models, assuming that the temperature of SO₂ frost controlled the gaseous SO₂. The vapour pressure p of gaseous SO₂ over frost is a function of surface temperature T (ref. 10)

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

and the vertical column density is $N(\text{cm atm}) = 1.96 p(\mu \text{ bar})$. Given a temperature distribution $T(\theta)$ as a function of solar zenith angle θ , 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 θ 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 SO₂ frost absorption dip, as a linear extrapolation of the trend observed above 340 nm. At 240 nm, where SO₂ 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 $T = 127.2 \text{ K}$ giving $N = 0.2 \text{ cm atm}$, 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 ($\approx 0.014 \text{ cm atm}$ corresponding to $T = 117.4 \text{ K}$) or a non-uniform distribution of the temperature and SO₂ 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 ΔT 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

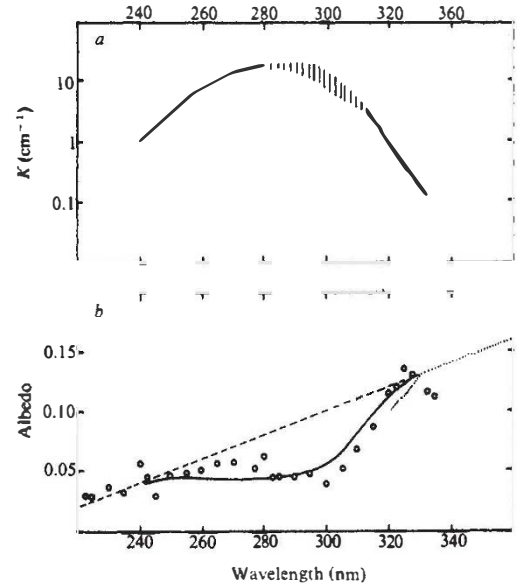


Fig. 2 *a*, The absorption coefficient K , of gaseous SO₂ as a function of wavelength¹⁰. There is a pronounced band structure between 280 and 320 nm which is represented schematically only. *b*, Geometric albedo of Io as a function of wavelength. Dotted line, ground-based measurements⁸. The linear extrapolation of ground-based measurements below 330 nm (dashed line) represents surface reflectivity variations $r(\lambda)$, if the SO₂ 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 SO₂ atmosphere (averaged over the disk of Io) above SO₂ 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 ΔT : $T_s = 123$ 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 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 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 SO_2 frost signature. Indeed, it has been suggested³ that the decrease of geometric albedo from 330 to 320 nm (ground observations) may be due to SO_2 frost. A laboratory reflectivity spectrum of pure SO_2 frost at 130 K was recently obtained¹², 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 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 SO_2 frost and gaseous SO_2 over this SO_2 frost. In such a case, the absorption due to gaseous SO_2 at 275 nm would be $\sim 12\%$, averaged on the whole disk.

The UV spectrum of Io shows evidence of the UV SO_2 band centred at 280 nm. To what extent this band has a contribution of SO_2 frost or is only due to gaseous SO_2 is still an open question. It could be solved by resolving the spectral structure of the gaseous SO_2 between 280 and 310 nm, absent from the pure SO_2 frost spectrum. However, our model of the temperature-controlled SO_2 atmosphere has shown that the variations of $\bar{S}(\lambda)$ are much smaller than the variations of the gaseous SO_2 absorption coefficient k_λ , 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 SO_2 content. This SO_2 content is a result of volcanic activity, extent of SO_2 frost deposit, temperature profile, and escape to the ionised torus discovered by Voyager 1 at the orbit of Io¹³. It would be of particular interest to observe the rise and decay times associated with a large surge of activity.

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