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# Sulfur-bearing molecules on the Galilean moons: an experimental approach

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## Abstract

Some sulfur-bearing molecules (e.g., sulfur dioxide, $SO_2$ or sulfuric acid, $H_2SO_4$) have been detected on the surfaces of the moons of Jupiter, while the presence of hydrogen sulfide ($H_2S$) or sulfurous acid ($H_2SO_3$) has been suggested.
A still open question is to understand if those molecules have been synthesized by exogenic processes such as ion implantation on the surface of the satellites of ions coming from the Io torus. Here we present experimental results obtained by implantation of fast ions ($S^+$ and $H^+$) into thick films of water and $SO_2$ ices at 80 K. Water ice is in fact the most abundant species on the surfaces of Europa, Ganymede and Callisto, while $SO_2$ frost is the major constituent of the surface of Io.
Our results show that implantation of $S^+$ ions into water ice produces hydrated sulfuric acid with high efficiency providing an important contribution to the sulfur cycle on the surface of Europa and other Jovian satellites; implantation of $H^+$ into $SO_2$ ice produces $SO_3$ and polymers, but not H-S bonds.

## 1. Introduction

IR observations made by *Galileo*, the spacecraft sent by NASA to study the planet Jupiter and its moons, confirmed that on the surface of Europa, Callisto and Ganymede water ice is the dominant species. Features due to sulfur-bearing minor species such as $SO_2$ and $H_2SO_4$ have also been detected.
The formation mechanism of those molecules is a still open question. A possible way is via exogenic processes such as implantation of sulfur ions coming from the Jovian magnetosphere.
Io's surface contains large quantities of frost $SO_2$ and colorful sulfur allotropes, both originating in plumes and flows from the tidally driven volcanoes. Voegele et al. [7], suggested the presence of sulfurous acid ($H_2SO_3$) possibly formed by implantation of protons, taking cue from the reported synthesis of carbonic acid ($H_2CO_3$) by $H^+$ implantation on pure $CO_2$ ice [1]. $H_2SO_3$ and $H_2CO_3$, in fact, show several common characteristics.
To attempt to answer those questions we have carried out experiments in which reactive ions, namely $S^+$ and $H^+$, were respectively implanted into a thick film (i.e., thicker than the penetration depth of the ions) of water ice and $SO_2$ ice, in order to study the formation of new molecules that contains the projectile ions.

## 2. Experimental apparatus

Experiments were performed at a temperature of 80 K, appropriate for the Galilean moons. For details on the experimental apparatus the reader is referred to Strazzulla et al. [5].

## 3. Results

In Fig. 1 the IR spectrum of frozen water before and after implantation with 200 keV $S^+$ ions is shown together with the calculated synthetic spectra of hydrate sulfuric acid.
The newly formed broad band centered at about 1100 $cm^{-1}$ is due to $HSO_4^-$ and $SO_4^{2-}$, the products of the dissociation of sulfuric acid in water. The same band is easily produced after irradiation of water-$SO_2$ [Moore et al., ref. 4].
Strazzulla et al. [6] estimated the production yield of equivalent sulfuric acid molecules formed per impinging S ion that is Y = 0.65±0.1.
No $SO_2$ bands clearly appear in the spectra of frozen water after S implantation. However an upper limit to the production yield of sulfur dioxide of $Y \leq 0.025$ molecules/implanted ion has been estimated; $H_2S$ has not been detected [6].
In Fig. 2 the IR spectrum of pure $SO_2$ at 80 K is shown before and after implantation of 50 keV $H^+$.

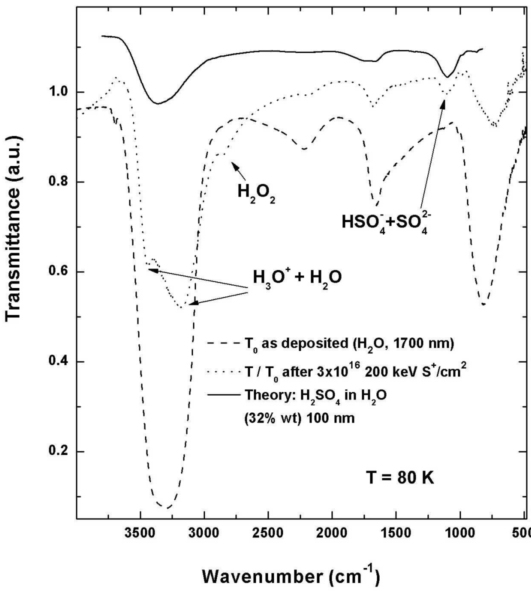


Figure 1: Spectrum of water ice as deposited at 80 K and after implantation of 200 keV $S^+$ ions compared with the synthetic spectrum of sulfuric acid hydrate.

No bands attributable to $H_2SO_3$, $H_2SO_4$ or $H_2S$ have been detected after irradiation, the new features have been attributed to $SO_3$ and its polymers [3]. This testifies to the efficiency of the oxidation of $SO_2$ to form $SO_3$ and the ability of $SO_3$ to form polymer chains. In addition implanted $H^+$ ions form O-H bonds.

# 4. Application to icy satellites

Carlson et al. [2] evaluated the amount of S-bearing species possibly present in the Europa surface layers: $SO_2$ (about $2\times10^{17}$/cm$^2$) and hydrated sulfuric acid $H_2SO_4$ (about $3\times10^{19}$/cm$^2$).
By using the measured fluxes of S ions and the formation yields, the time necessary to produce the inferred amount of $SO_2$ and $H_2SO_4$ can be evaluated.
We demonstrate that the observed quantity of $H_2SO_4$ can be formed by implantation of sulfur on time scales of the order of $10^4$ years that renders S-implantation a very relevant formation mechanism.
More difficult it is to say if the observed $SO_2$ is quantitatively justified by S implantation, in fact we have been able to find only an upper limit to its production yield.
As said, experiments of H implantation in sulfur dioxide are relevant to Io. The energy flux on Io surface is mainly due to $H^+$, $S^{n+}$, $O^{n+}$ with energies of tens keV. If we suppose that all energy is due to

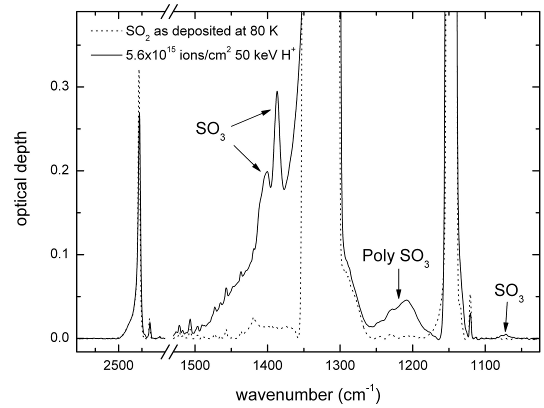


Figure 2: IR spectra of $SO_2$ ice as deposited at 80K and after 50 keV $H^+$ implantation.

50 keV $H^+$, the total fluence used in our experiment (Fig. 2) correspond to about 10 years at Io.
This time interval is short and although the resurfacing effects, due to the high level of volcanic activity on Io, are significant we predict that $SO_3$ and its polymers are produced and should be searched for. On the other hand $H_2SO_3$ or other H-S-bearing molecules cannot be produced in relevant quantities by proton implantation on the satellite surface.

# Acknowledgements


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