S^+ Implantation into Condensed CO_2: Relevance for Europa

D.V. Mifsud[1,2], Z. Kaňuchová[3], P. Herczku[2], Z. Juhász[2], S.T.S. Kovács[2], B. Sulik[2], K.K. Rahul[2], R. Rácz[2], I. Rajta[2], I. Vajda[2], S. Biri[2], P.A. Hailey[1], A. Traspas Muiña[4], S. Ioppolo[4], R.W. McCullough[5], and N.J. Mason[1]

[1]Univeristy of Kent, Canterbury, United Kingdom; [2]Institute for Nuclear Research (Atomki), Debrecen, Hungary; [3]Slovak Academy of Sciences, Tatranská Lomnica, Slovakia, [4]Queen Mary University of London, London, United Kingdom, [5]Queen's University Belfast, Belfast, United Kingdom

Abstract

- The implantation of energetic S^+ ions into pure CO_2 ices was tested as a formation route for SO_2.
- At 20 K, mid-infrared spectral signatures of SO_2 were clearly observed as a result of ion implantation.
- At 70 K, no evidence was found for the formation of SO_2.
- S^+ ion implantation is likely not the source of SO_2 on the surfaces of Europa and the other icy Galilean moons.

SO_2 on Europa: An Uncertain Sulfur Source

- SO_2 on Europa is predominantly found on the trailing hemisphere arranged in a 'bulls-eye' pattern. This is indicative of a magnetospheric sulfur source.[1]
- Laboratory studies have failed to detect SO_2 after sulfur ion implantation into H_2O ices, which dominate the surface of Europa. Instead, H_2SO_4 is formed.[2]
- Implantations into other Europan surface materials, such as CO_2 ice, have been largely inconclusive and were performed at 20 K: a temperature which is too low to simulate Europa.[3,4]
- We have therefore performed high fluence (~10^{16} ions cm^{-2}) 290 keV S^+ ion implantations into condensed CO_2 at 20 and 70 K to resolve this issue.

Experimental Methodology

- Experiments were performed using the Ice Chamber for Astrophysics-Astrochemistry (ICA) set-up in Debrecen, Hungary.[5,6]
- The chamber base pressure is ~10^{-9} mbar.
- A thick (~3 μm) CO_2 ice was prepared *via* background deposition at 20 and 70 K.
- 290 keV S^+ ions (current: 120 nA) were implanted into the ice until a fluence of ~10^{16} ions cm^{-2} was achieved.
- Fresh ice layers were continually deposited to compensate for sputtered material.
- Physico-chemical changes in the ice were monitored *in situ* using FT-IR transmission absorption spectroscopy (range: 4000-650 cm^{-1}; resolution = 1 cm^{-1}).

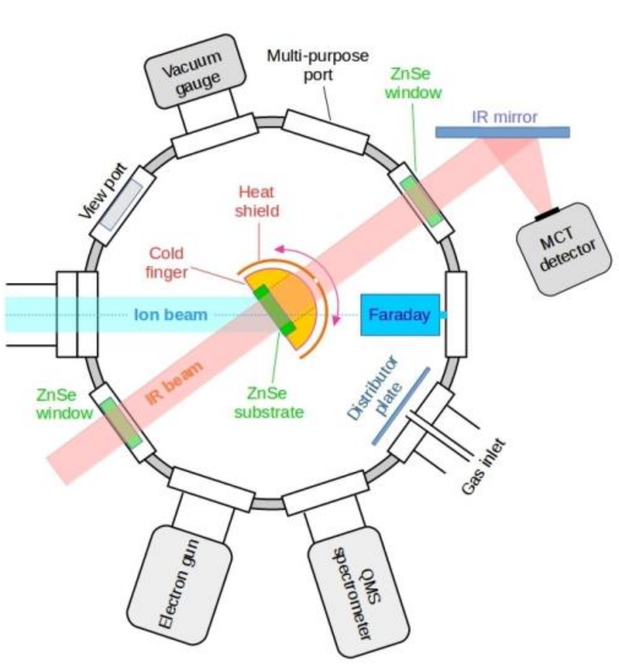
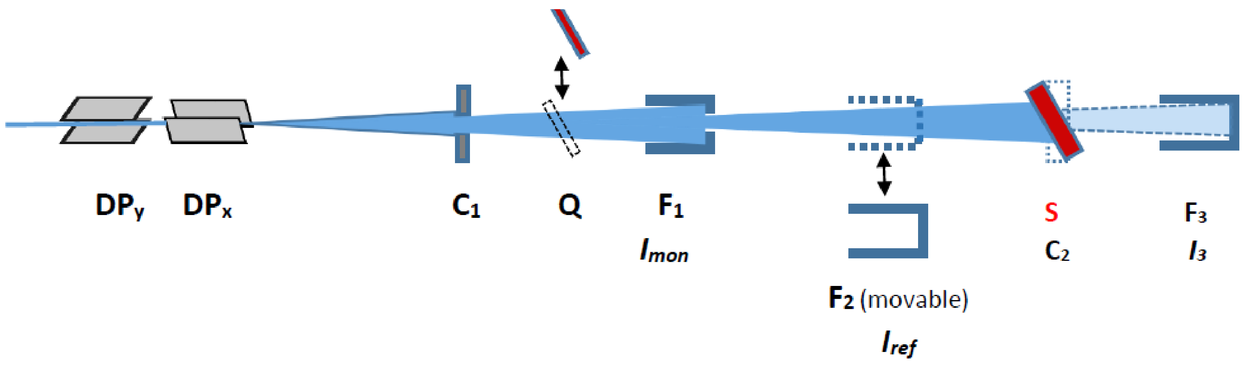


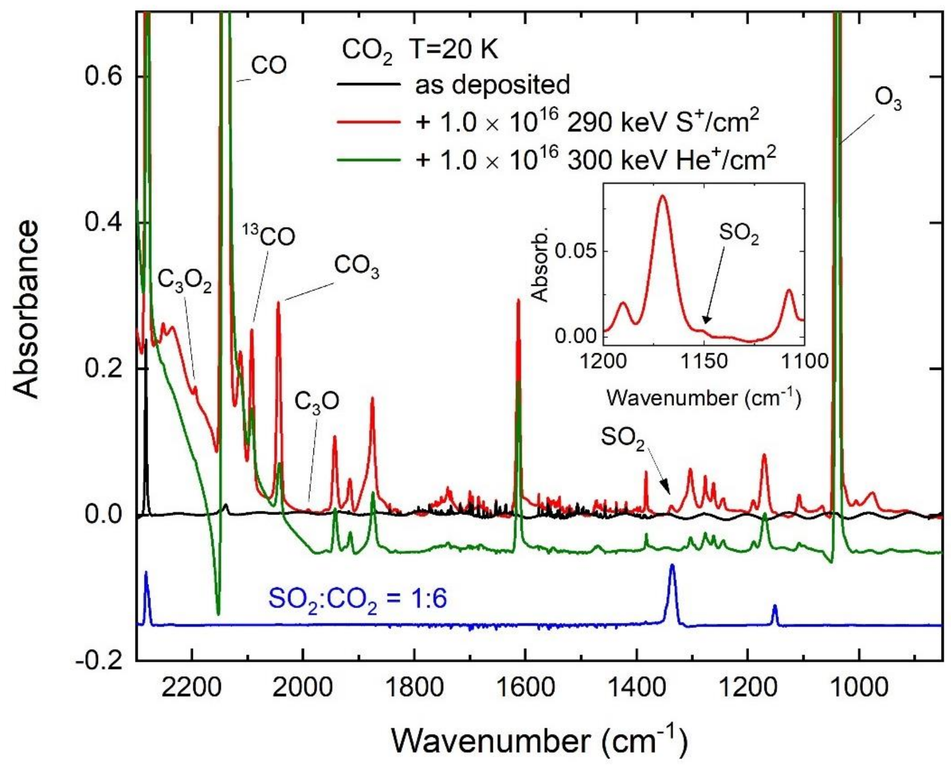
Fig. 1: The ICA set-up. *Left*: Top-view schematic of chamber. *Above*: Sample holder and ZnSe deposition substrates. *Below*: Ion beam guiding and monitoring system.

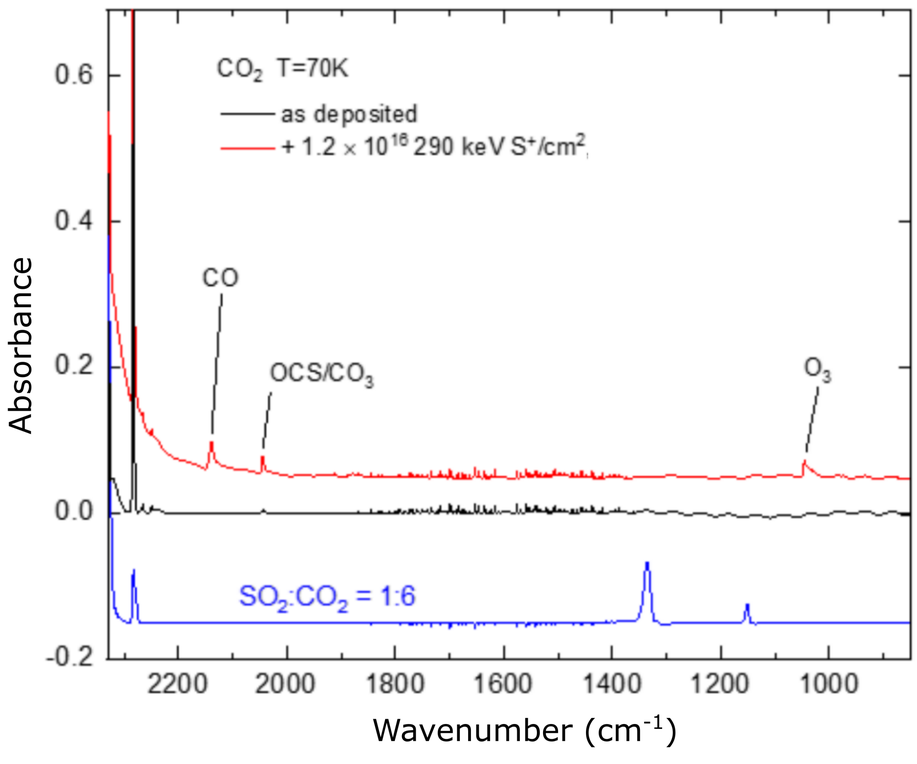
Precautionary Experiments

- Spectra of unirradiated CO_2:SO_2 ice mixtures were collected to determine the positions of the SO_2 absorption bands.
- Since the region in which SO_2 ice presents absorption bands also hosts several other absorption bands, 300 keV He^+ ions were also implanted into CO_2 ice.
- In this case, all bands associated with the irradiative processing of the ice will still be present, except those that incorporate sulfur.



Results, Interpretation, and Conclusion





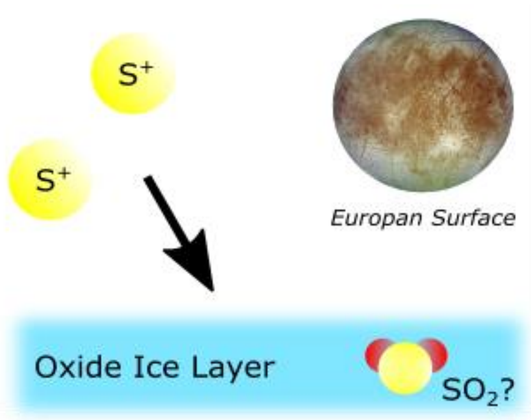


Fig. 2 *(above)*: Graphical representation of the process simulated in this study.

***Fig. 3 (left)*:** FT-IR spectra after S^+ ion implantation into CO_2 ice at 20 (left) and 70 K (right).

At 20 K:

- Both the symmetric and asymmetric SO_2 stretching bands were detected after S^+ ion implantation into CO_2 at 20 K.
- The formation rate was calculated to be (0.48 ± 0.01) SO_2 molecules per ion.

At 70 K:

- No SO_2 bands were detected after implantation at 70 K, a temperature more relevant to the surface of Europa.
- Oxygen atom combination to yield O_2 is more efficient at higher temperatures.
- At 70 K, O_2 efficiently sublimates from the ice into the gas phase, leaving fewer oxygen atoms available for SO_2 formation.
- S^+ ion implantation is likely not an efficient mechanism to account for the SO_2 observed on Europa and the other Galilean satellites.
- Endogenic sources of sulfur should be considered instead (e.g., irradiation of hydrated H_2SO_4 surface ices).[7]

References and Acknowledgements

1. T.M. Becker *et al.* (2022). *Planet. Sci. J.* **3**, 129.
2. J.J. Ding *et al.* (2013). *Icarus* **226**, 860.
3. X.-Y. Lv *et al.* (2014). *Mon. Not. R. Astron. Soc.* **438**, 922.
4. P. Boduch *et al.* (2016). *Icarus* **277**, 424.
5. P. Herczku *et al.* (2021). *Rev. Sci. Instrum.* **92**, 084501.
6. D.V. Mifsud *et al.* (2021). *Eur. Phys. J. D: Atom. Mol. Opt. Plasma Phys.* **75**, 182.
7. D.V. Mifsud *et al.* (2021). *Space Sci. Rev.* **217**, 14.
8. A manuscript based on the results presented here is currently being prepared for submission.

We acknowledge funding from the Europlanet 2024 RI, funded by the EU Horizon 2020 Research Innovation Programme under grant agreement No. 871149. The ICA was built using funding from the Royal Society through grants UF130409, RGF/EA/180306, and URF/R/191018. D.V. Mifsud acknowledges receipt of a University of Kent Vice-Chancellor's Research Scholarship. Z. Kaňuchová is supported by VEGA – the Slovak Grant Agency for Science (grant No. 2/0059/22) and the Slovak Research and Development Agency (contract No. APVV-19-0072). S. Ioppolo acknowledges the Royal Society for financial support.