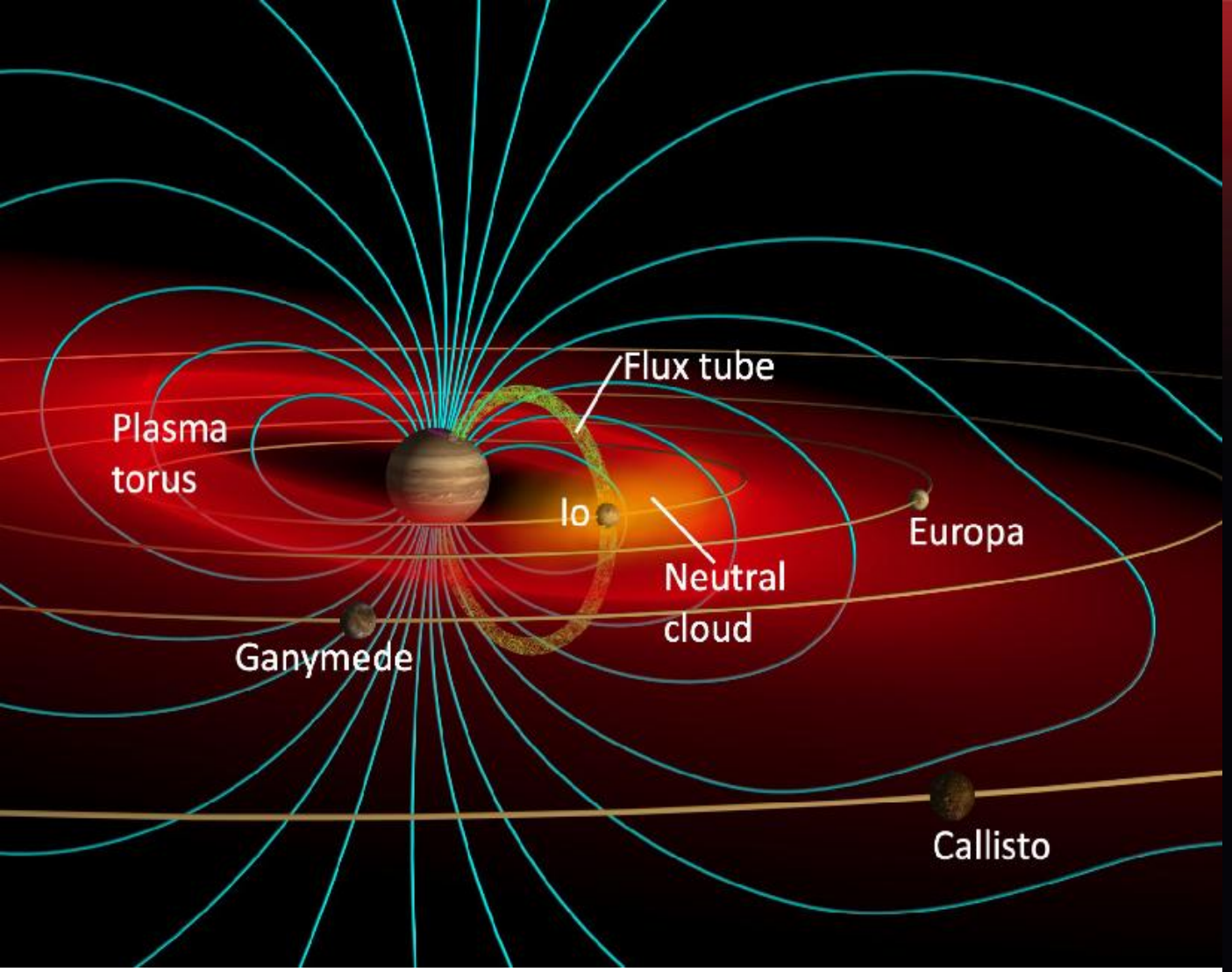


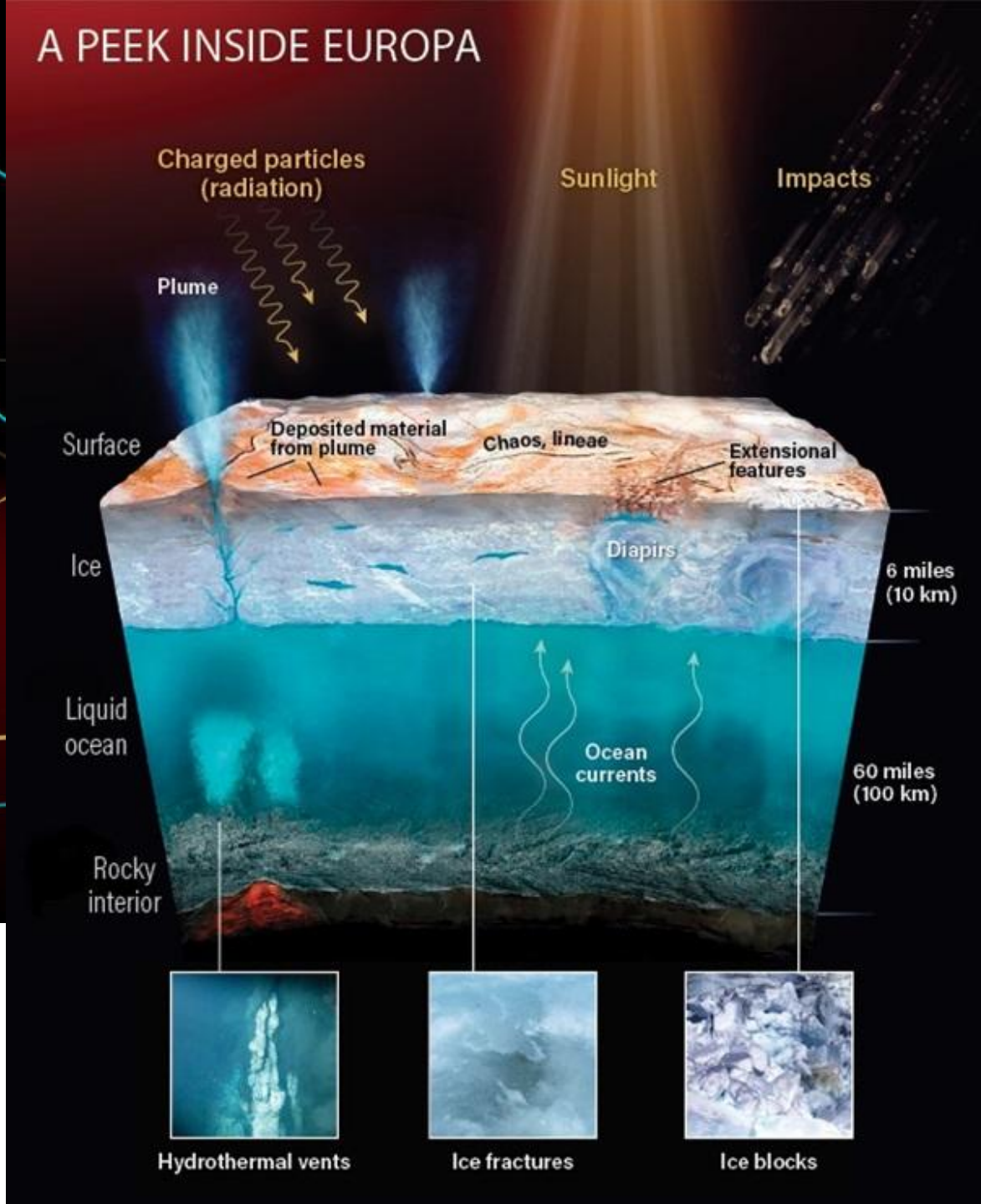
Radiation-Driven Sulphur Chemistry on the Surfaces of Jupiter's Galilean Moons

New Results from Laboratory Experiments

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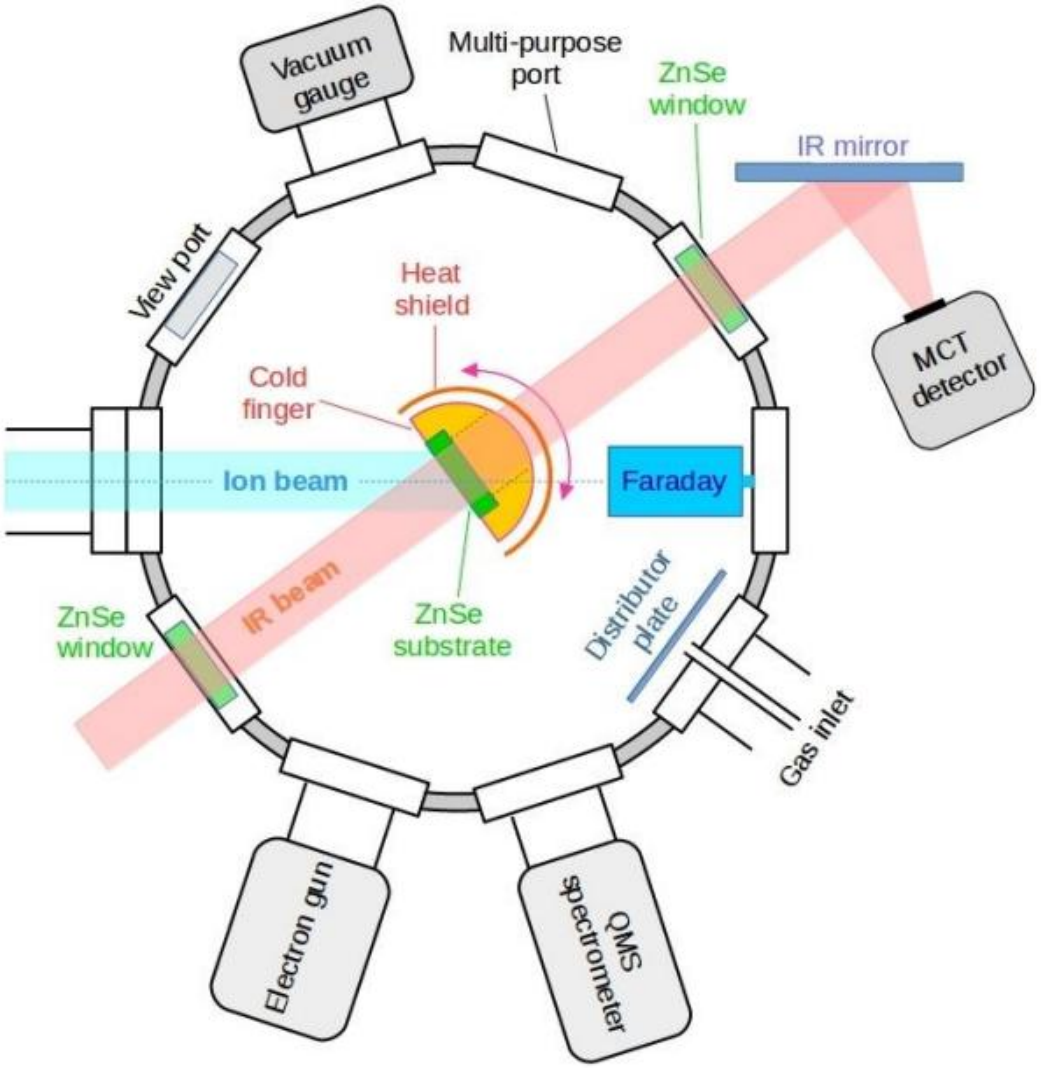
Europa's Radiolytic Sulfur Cycle

Image credit: NASA / SwRI

Laboratory Astrochemistry

- To simulate radiation chemistry on the surface of Europa, we need to:
  - *Simulate low pressures (UHV or better);*
  - *Simulate low temperatures (down to 10-20 K);*
  - *Simulate a radiation-rich environment;*
  - *Simulate the icy surface of Europa.*

- We achieve this using the ICA – one of five laboratory astrochemistry set-ups at HUN-REN ATOMKI.



Herczku et al. (2021), RSI, 92, 084501
Mifsud et al. (2021), EPJD, 75, 182
Rácz et al. (2024), RSI, 95, 095105

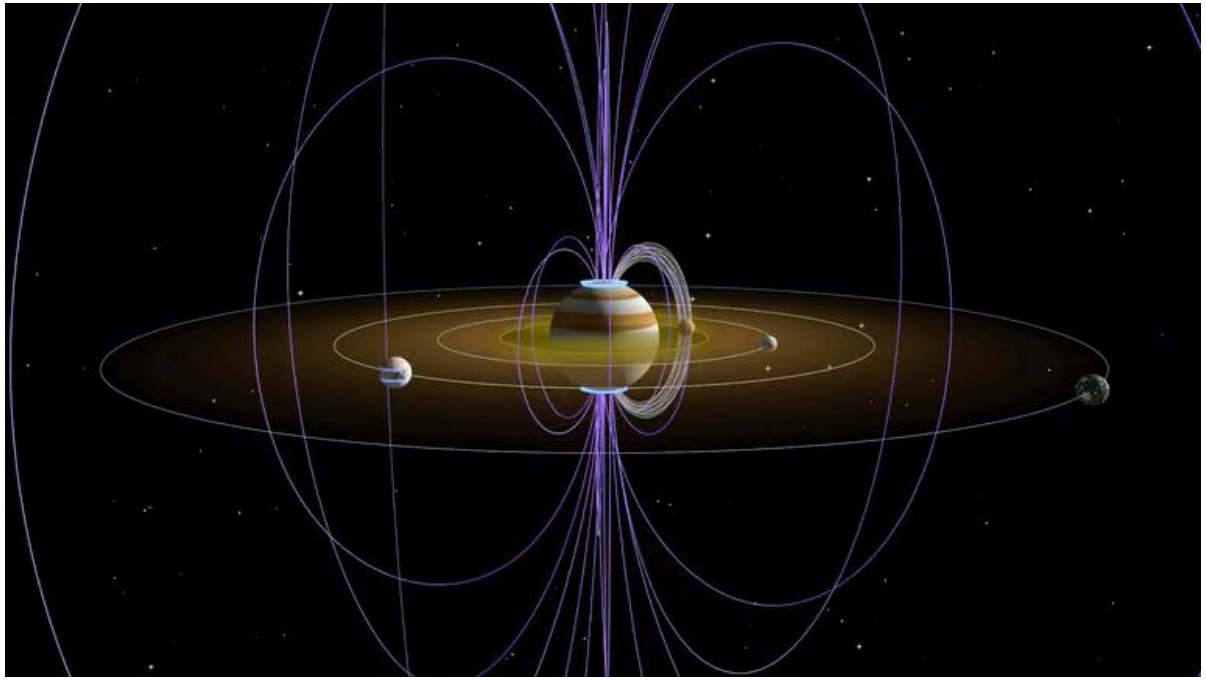
SO_2 on Europa

- Detected on the icy surface in 1981.
- Concentrated on the trailing hemisphere.
- Highly correlated to S^{n+} flux.

Logical Conclusion!

- Sulfur ions implant into Europa's surface and react to form SO_2.
- This should be a key step in the radiolytic sulfur cycle.

Image credit: ESA



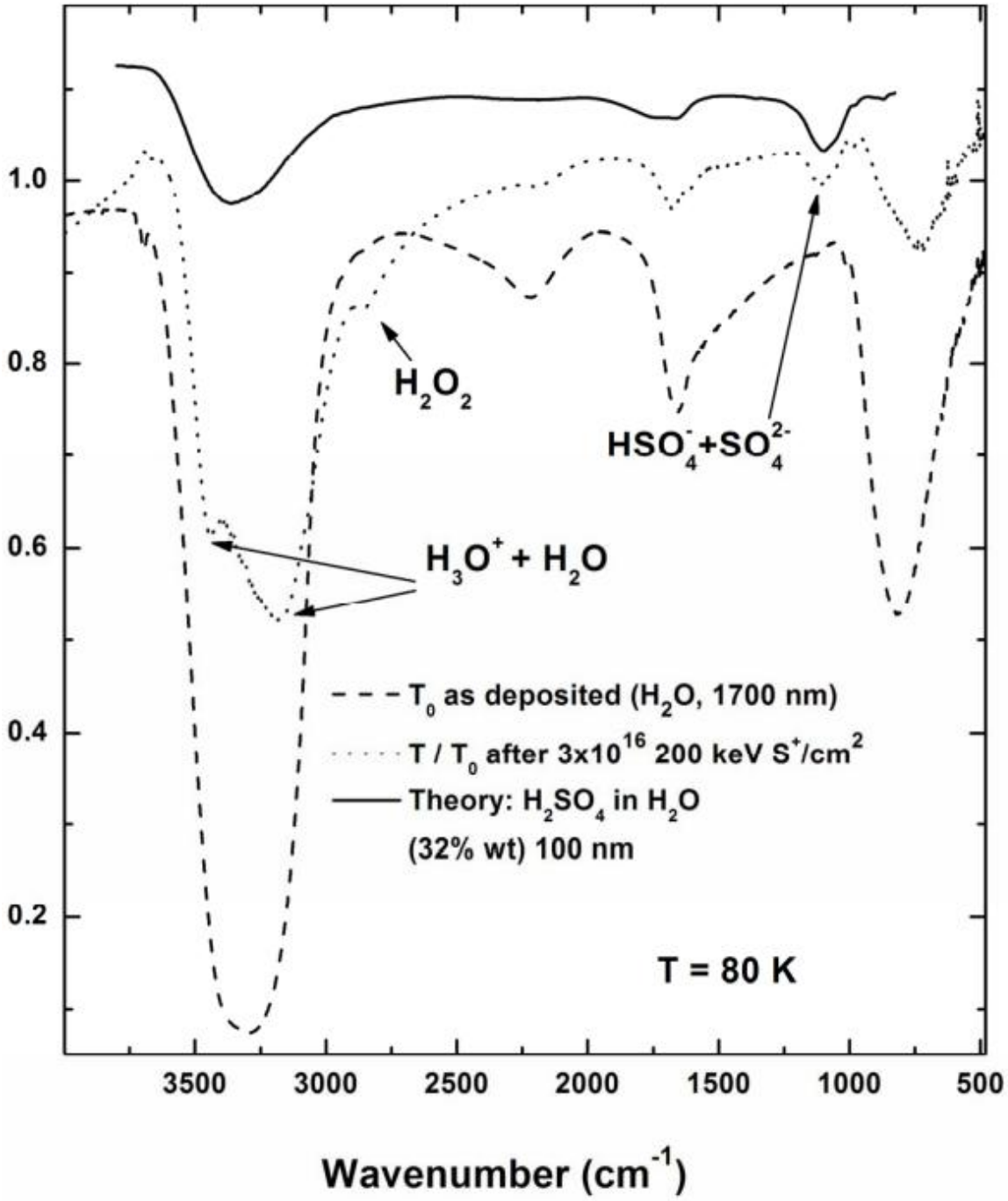
Lane et al. (1981), Nature, 292, 38
Hendrix et al. (2011), Icarus, 212, 736
Becker et al. (2022), PSJ, 3, 129

A Problem!

- There is no laboratory evidence for this process!
- Experiments show that when S^{n+} are implanted into H_2O ice, sulfuric acid hydrates are formed, not SO_2.

Next Step!

- What if the target is not H_2O ice, but a minor surface constituent (e.g., CO_2?)



Strazzulla et al. (2007), Icarus, 192, 623
Ding et al. (2013), Icarus, 226, 860
Strazzulla et al. (2023), Earth Moon Planets, 127, 2

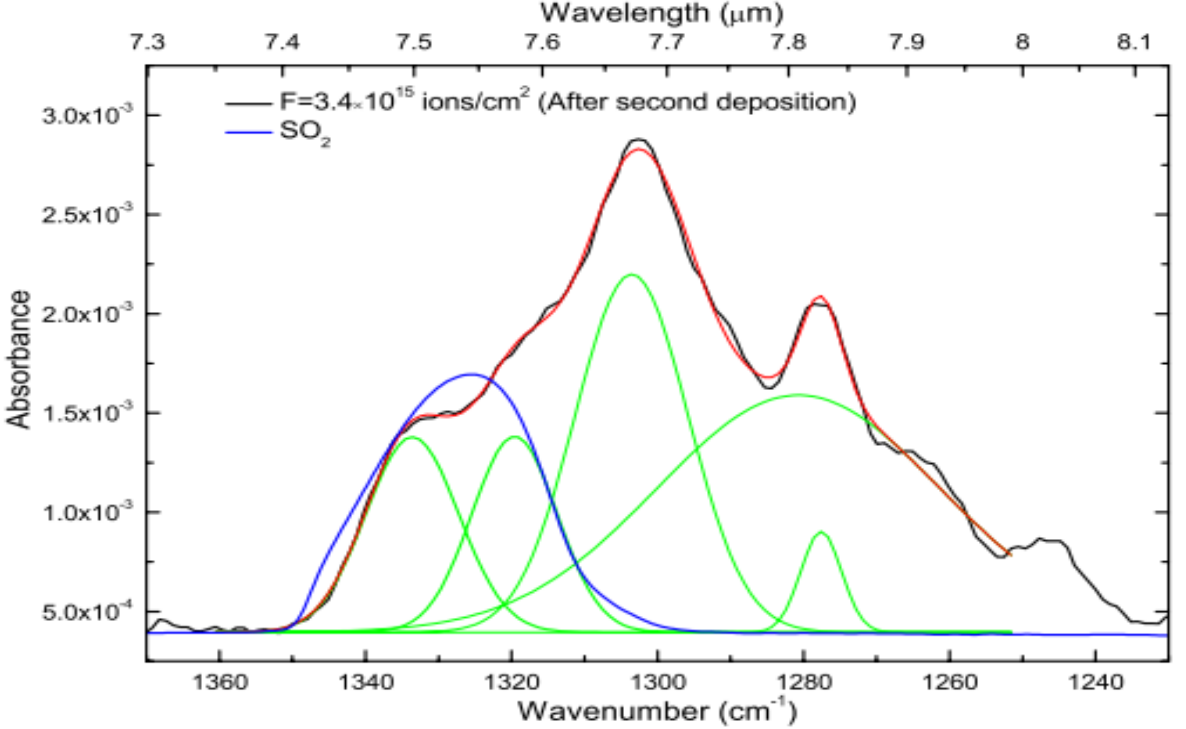
It Sort of Works!

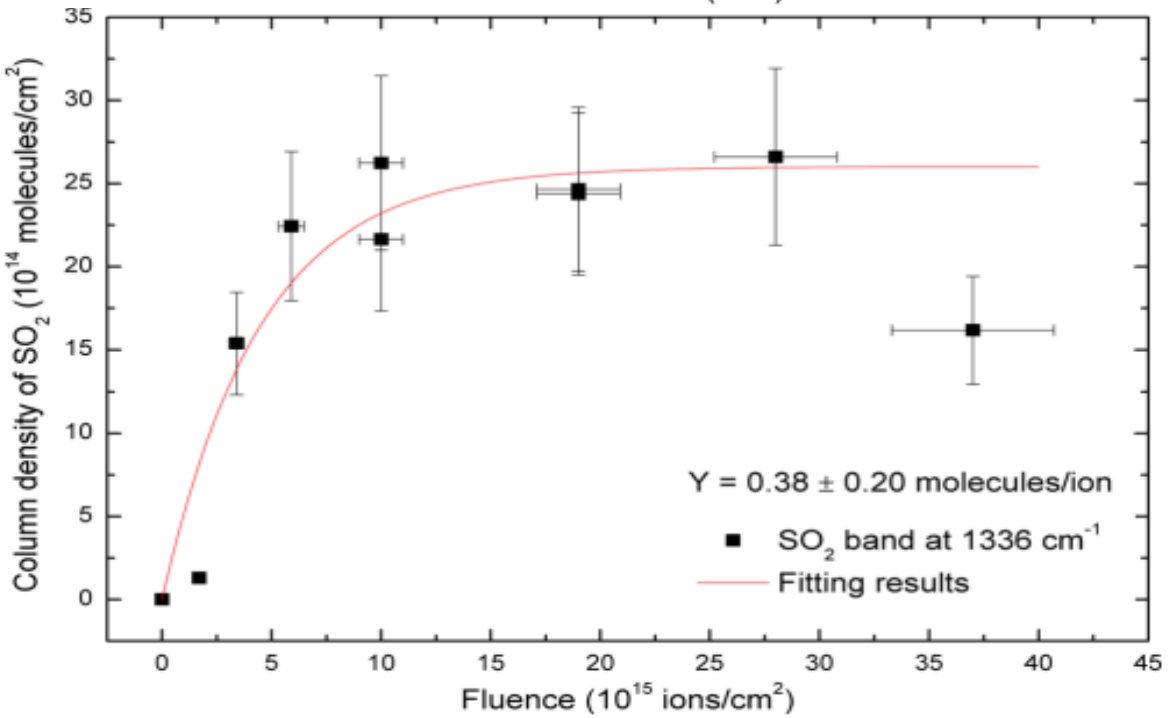
- Implanting 90 keV S^{9+} ions into H_2O ice at 15 K yields SO_2 at 0.38 molecules per ion.
- This is good, but too low a temperature for Europa.

Next Step!

- We should do experiments at different temperatures to test if this mechanism works on Europa.

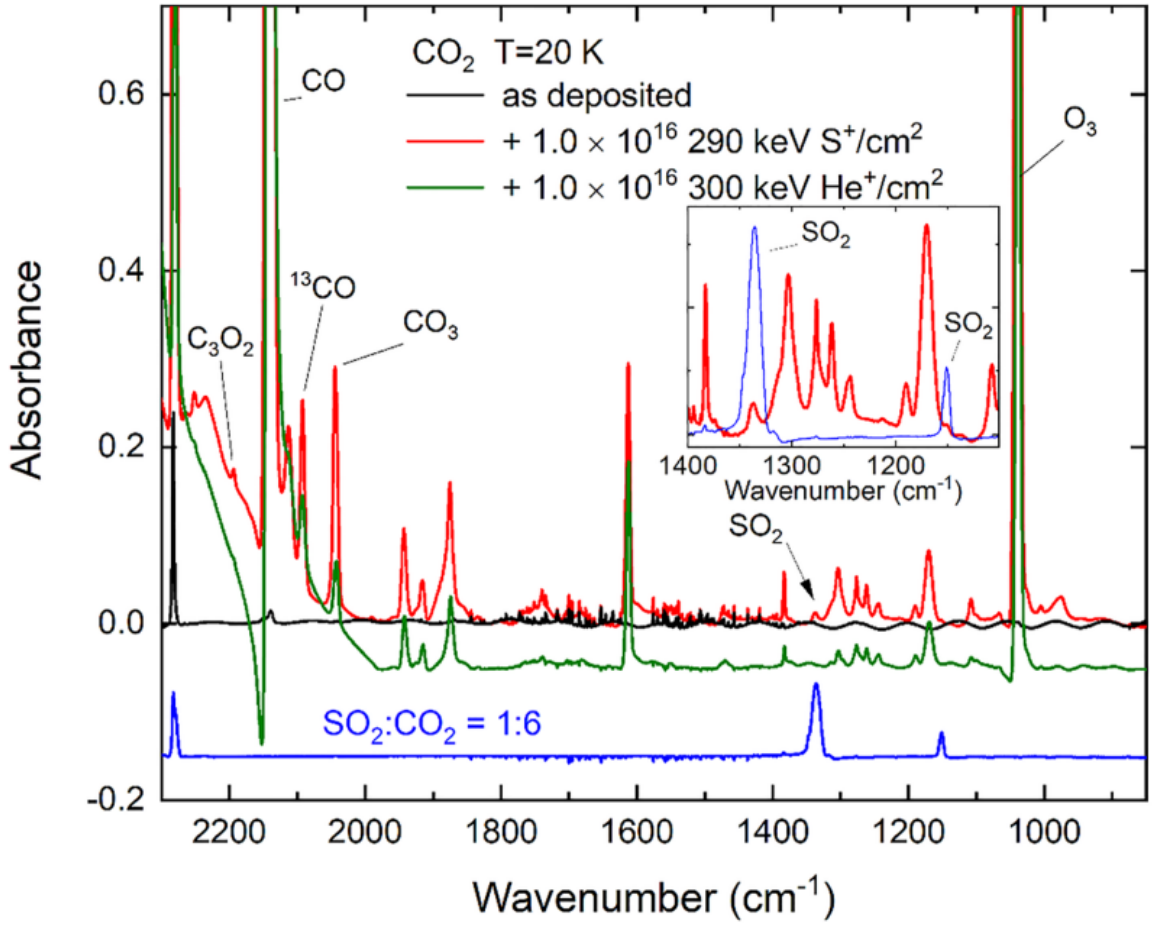
Lv et al. (2014), MNRAS, 438, 922
Mifsud et al. (2021), SSRv, 217, 14





It Works at Low Temperatures!

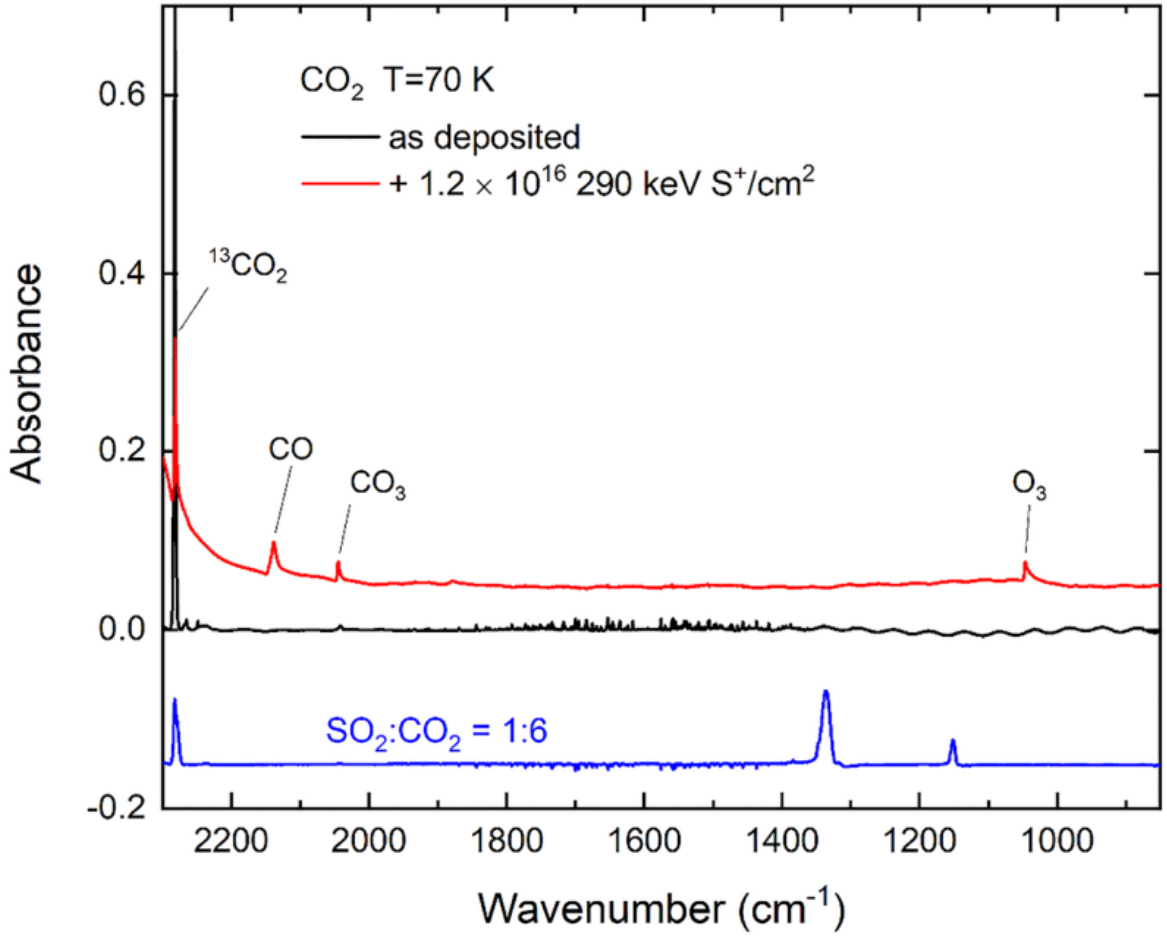
- Using ICA, 290 keV S^+ ions were implanted into CO_2 ice at 20 K.
- Several new IR bands appeared, including two small ones in the right position to be SO_2!
- A control experiment in which 300 keV He^+ ions were implanted produced all the bands ***except*** those two.
- SO_2 is confirmed to be formed in this experiment.



Mifsud et al. (2022), GRL, 49, e2022GL100698
Mifsud et al. (2024), Icarus, 411, 115926

But Not at Higher Ones!

- Repeating the experiment at 70 K gave drastically different results.
- Fewer new IR bands are observed, and none could be attributed to SO_2.
- Bands attributable to major products (e.g., CO, CO_3, O_3) are very muted compared to the 20 K experiment.
- This is due to the formation of O_2 which, at T > 40 K, undergoes sublimation that prevents the formation of oxygenated products.



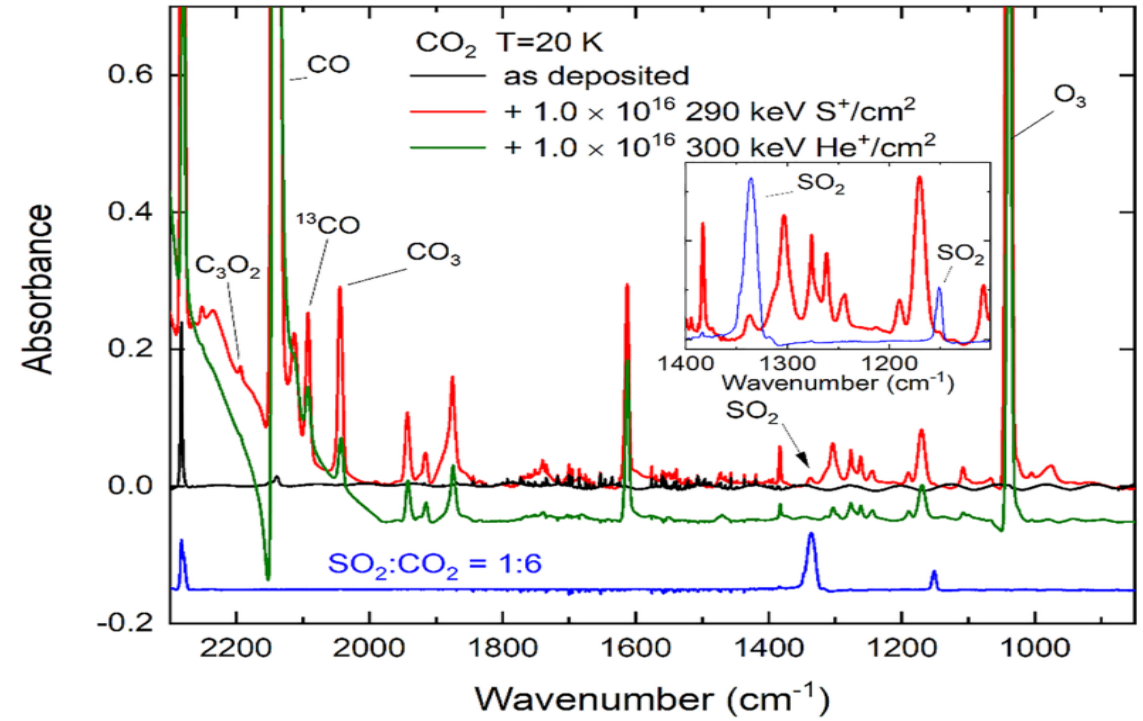
Mifsud et al. (2022), GRL, 49, e2022GL100698
Mifsud et al. (2024), Icarus, 411, 115926

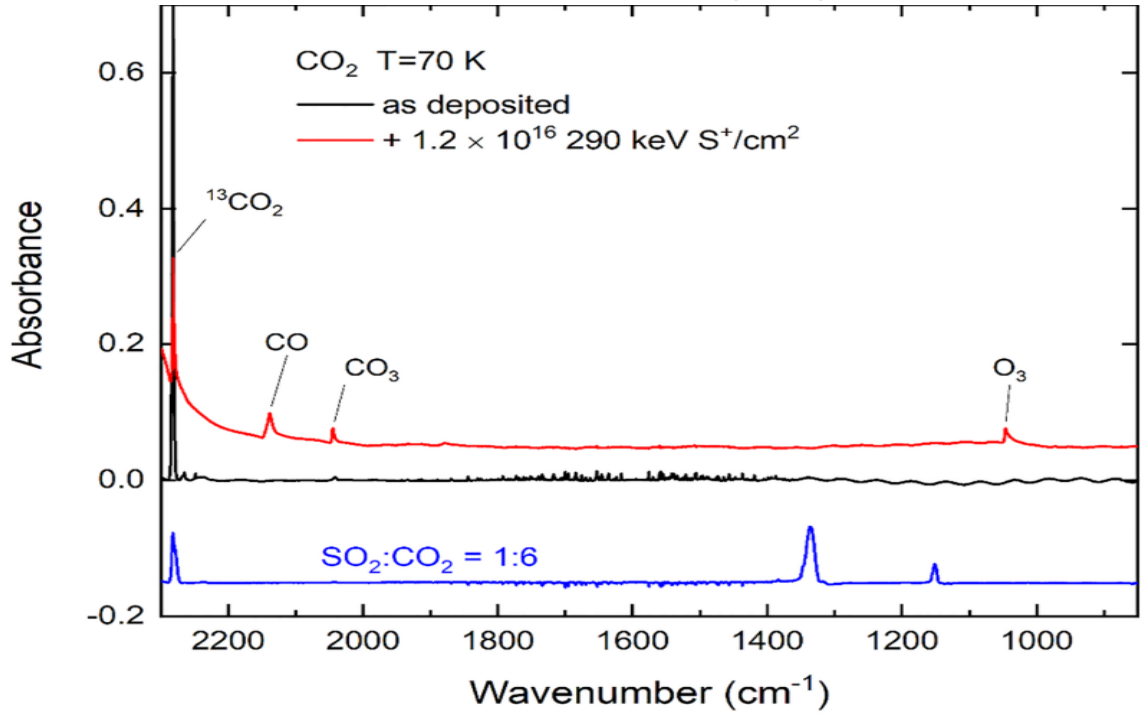
Where Does That Leave Us?

- There is no convincing laboratory evidence for the formation of SO_2 on Europa via sulfur ion implantation.

What Now?

- Should we test other sources of sulfur to explain the formation of SO_2?
- Can laboratory results reproduce observational data?





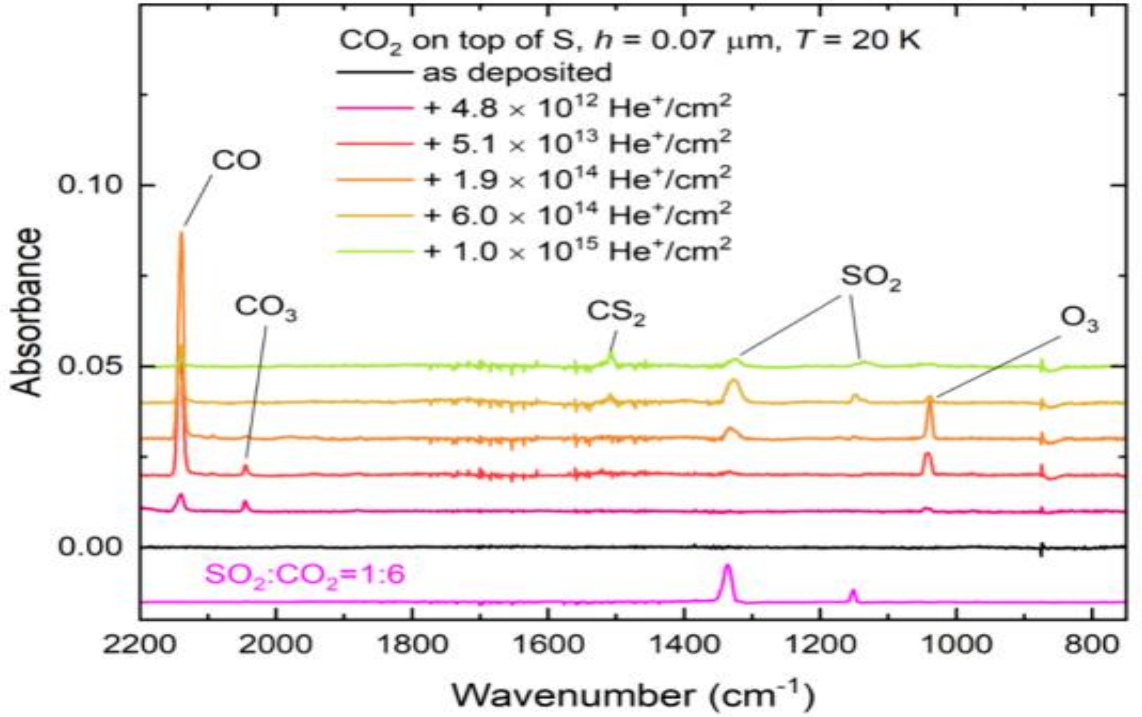
Mifsud et al. (2022), GRL, 49, e2022GL100698
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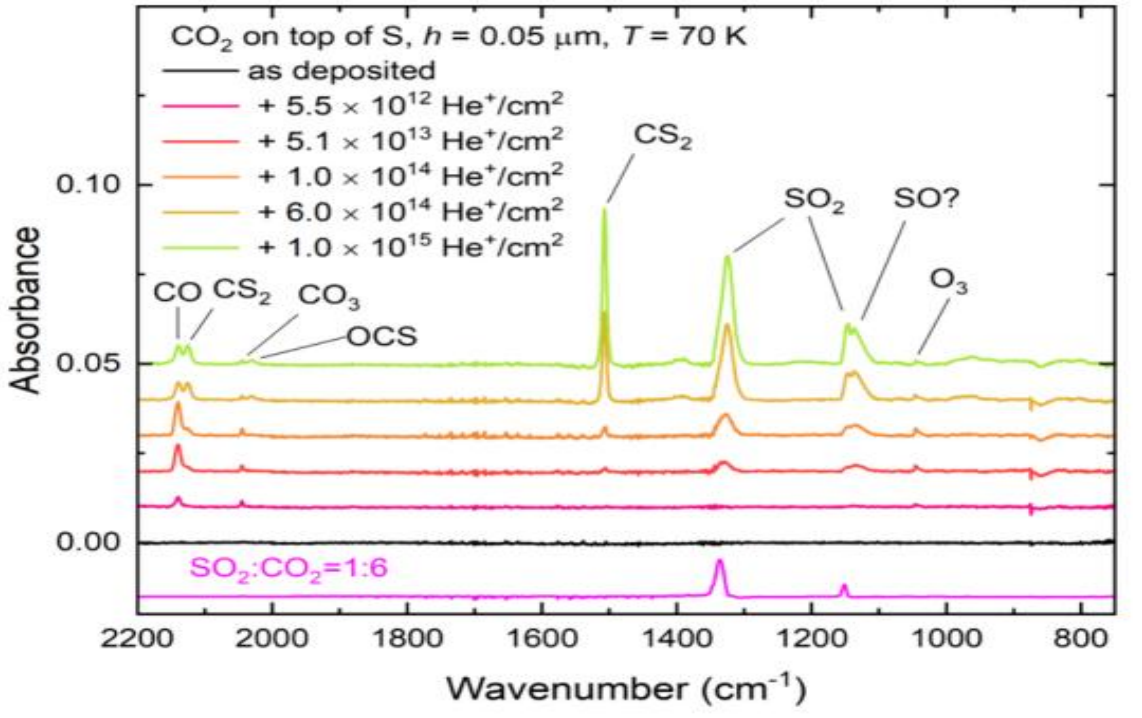
Irradiating H_2O and CO_2 Ices on S

- We irradiated H_2O and CO_2 ices on layers of allotropic sulfur at 20 and 70 K using 1 MeV He^+ ions.

CO_2 Results:

- At 20 K, oxygen-dominated chemistry leading to CO, CO_3, and O_3 is favoured.
- At 70 K, sulfur-dominated chemistry leading to SO_2, CS_2, and OCS is favoured.





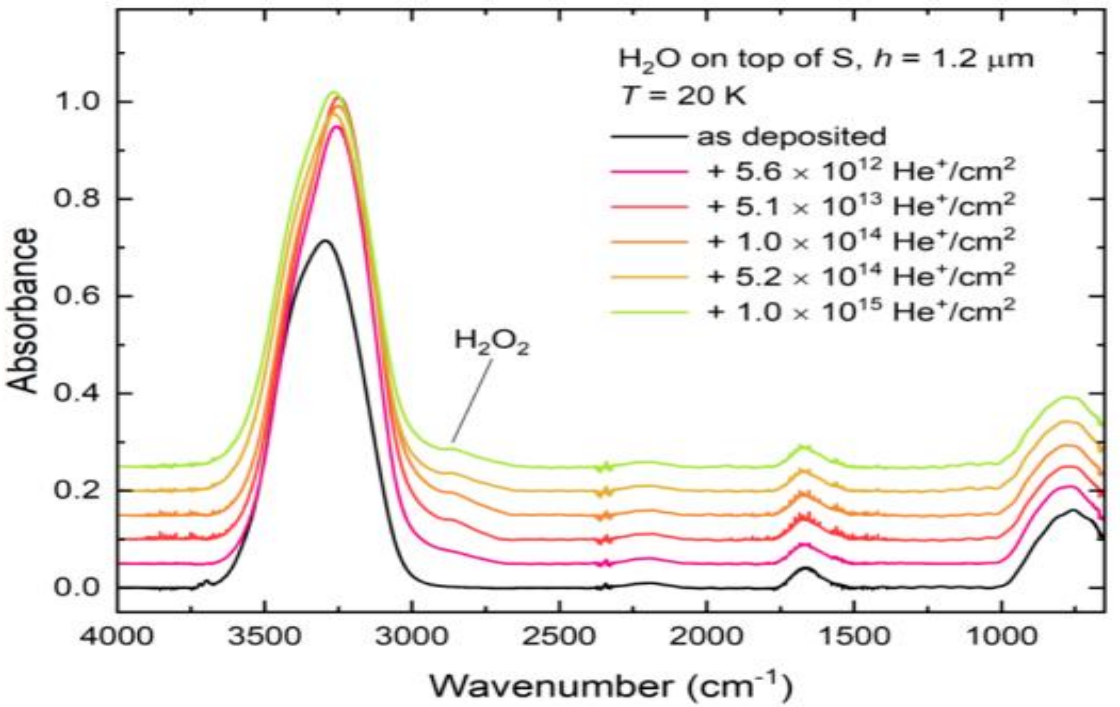
Mifsud et al. (2025), ACS Earth Space Chem, 9, 1227
Mifsud et al. (2026), PCCP, 28, 3642

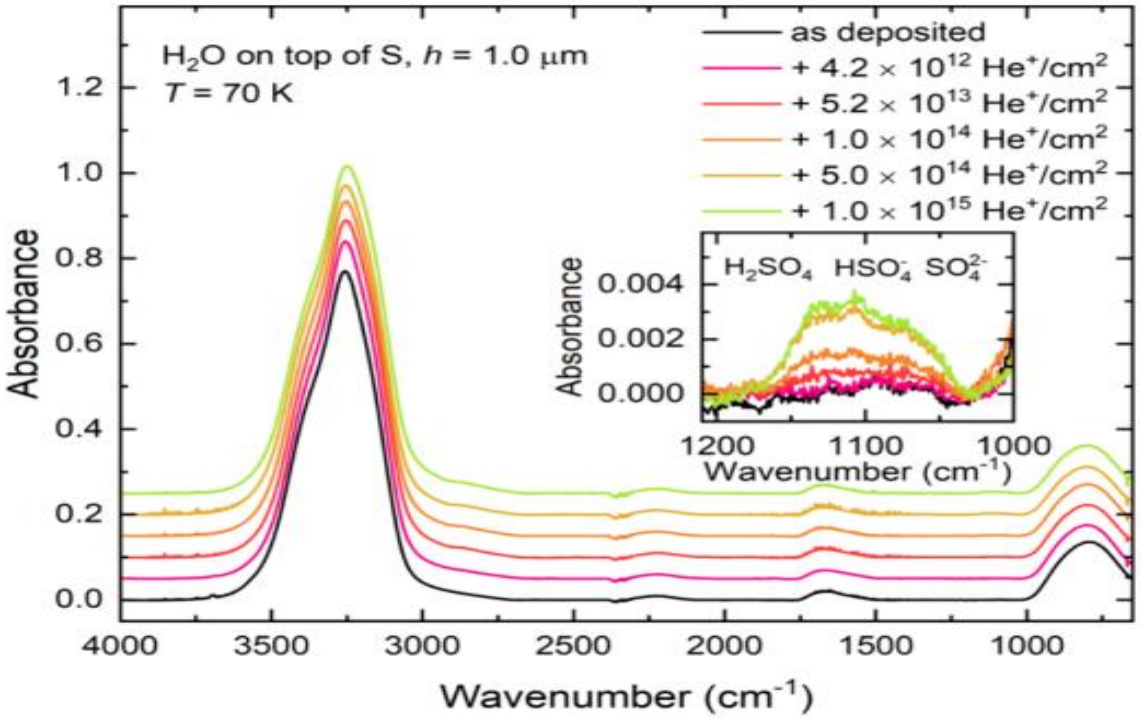
Irradiating H_2O and CO_2 Ices on S

- We irradiated H_2O and CO_2 ices on layers of allotropic sulfur at 20 and 70 K using 1 MeV He^+ ions.

H_2O Results:

- At 20 K, only H_2O_2 is detected as a radiolytic product.
- At 70 K, large quantities of sulfuric acid hydrates are detected as products.

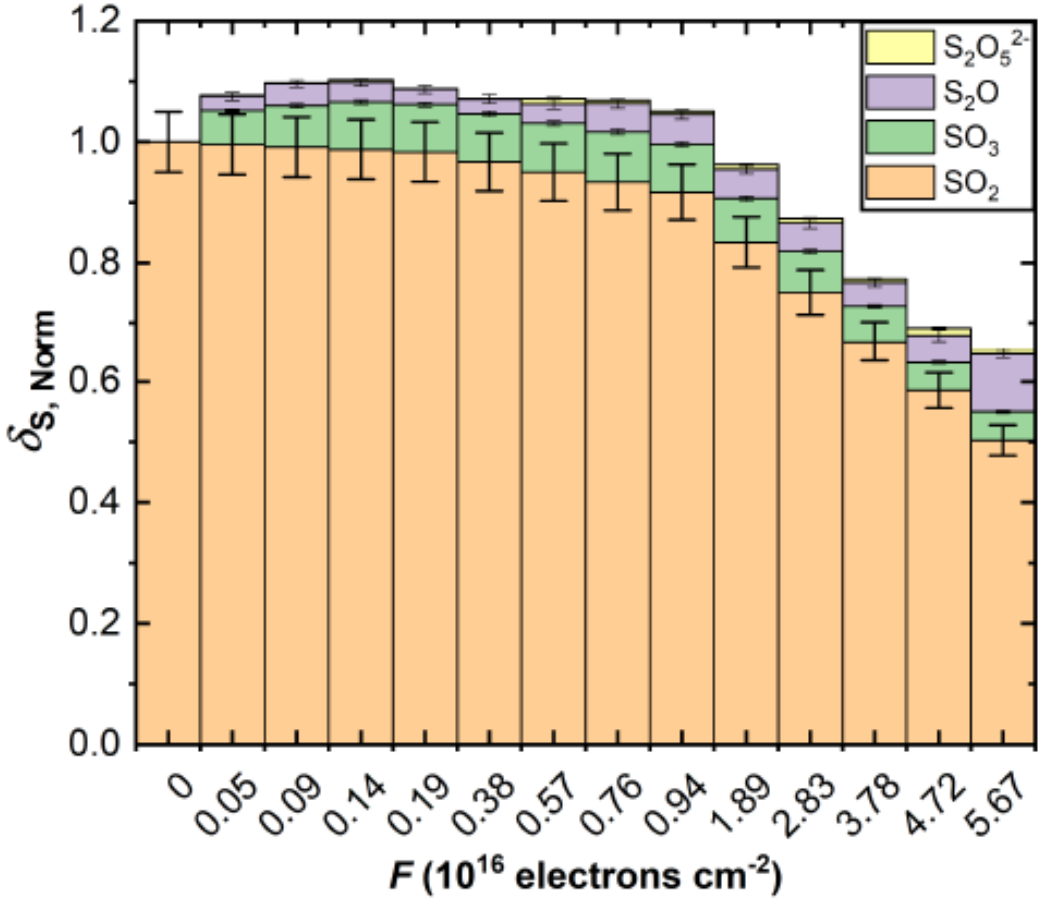




Mifsud et al. (2025), ACS Earth Space Chem, 9, 1227
Mifsud et al. (2026), PCCP, 28, 3642

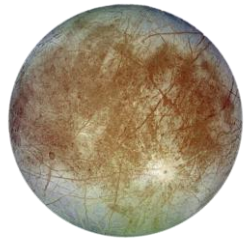
A Cyclical Relationship?

- Irradiation of SO_2 ice using 1.5 keV electrons revealed that a lot of the sulfur 'disappears' throughout irradiation.
- Sputtering of sulfur by electrons is a low-efficiency process.
- The sulfur must be converting to an IR-inactive molecule, the most likely candidate is S_8 (and other large sulfur allotropes).



Mifsud et al. (2022), Front Chem, 10, 1003163
Herath et al. (2026), Nature Commun, 16, 5571
Mifsud et al. (2026), ApJ, submitted

Summary



- There is no direct laboratory evidence for SO_2 formation on Europa as a result of S^{n+} implantation.
- The irradiation of ices in contact with allotropic sulfur could lead to SO_2 formation, but this does not explain the distribution of SO_2 on Europa.
- The irradiation of SO_2 could generate allotropic sulfur in a cyclical process.
- The chemical mechanism needs further refinement. Future avenues of research will include:
  - *Can SO_2 form as a result of the radiolytic decay of sulfuric acid hydrates?*
  - *Cold "cold" (< 1 keV) sulfur ions be solely responsible for the formation of SO_2 on Europa?*
  - *Do minerals play a role in the formation of SO_2 on Europa?*
  - *Is there a contribution of SO_2 that comes from endogenic sources, perhaps from the sub-surface ocean?*

Thank You for Your Attention!

Please reach out if you're interested in collaborating with us!

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