Magnetospheric Ion Implantation in the Icy Moons of Giant Planets

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NWO visitor (May-July 2012)
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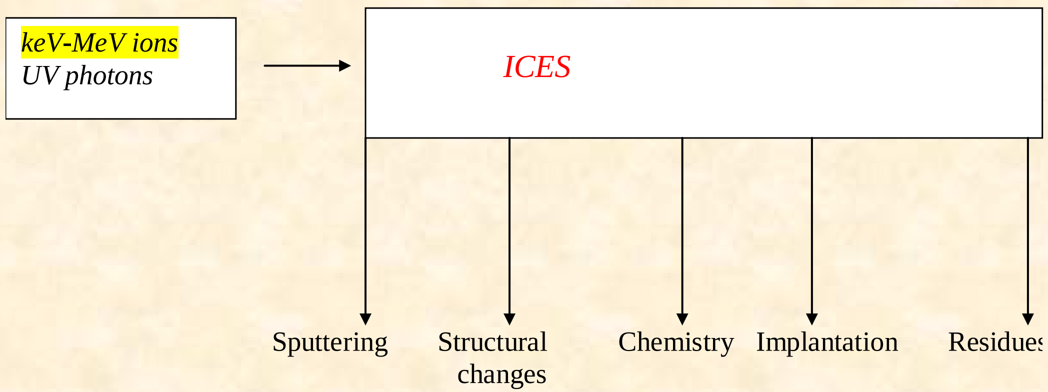
CoI at CIMAP-GANIL, Caen, (France) :
P.Boduch, J.J. Ding, T. Langlinay, X.Y. Lv,
H. Rothard

The experimental work in Catania has been performed by the LASP Team and coworkers (G.A. Baratta, R. Brunetto, D. Fulvio, M. Garozzo, O. Gomis, S. Ioppolo, Z. Kanuchova, G. Leto, P. Modica, L. Moroz, M.E. Palumbo, F. Spinella, G. Strazzulla, et al.).

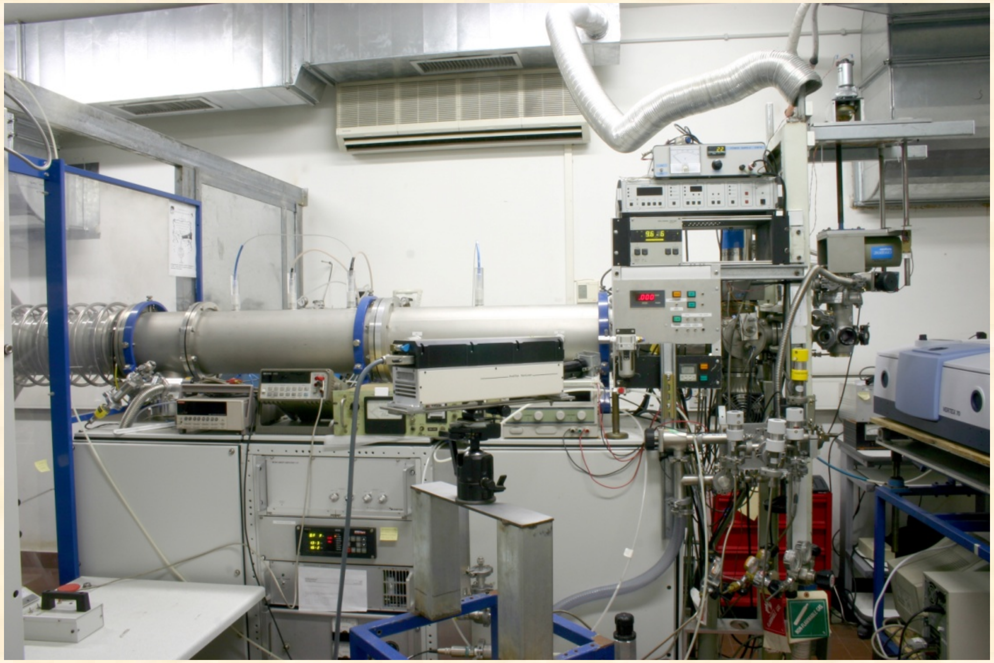
Experimental study of the effects induced by fast ions on solids of astrophysical interest have been performed in several laboratories in the world

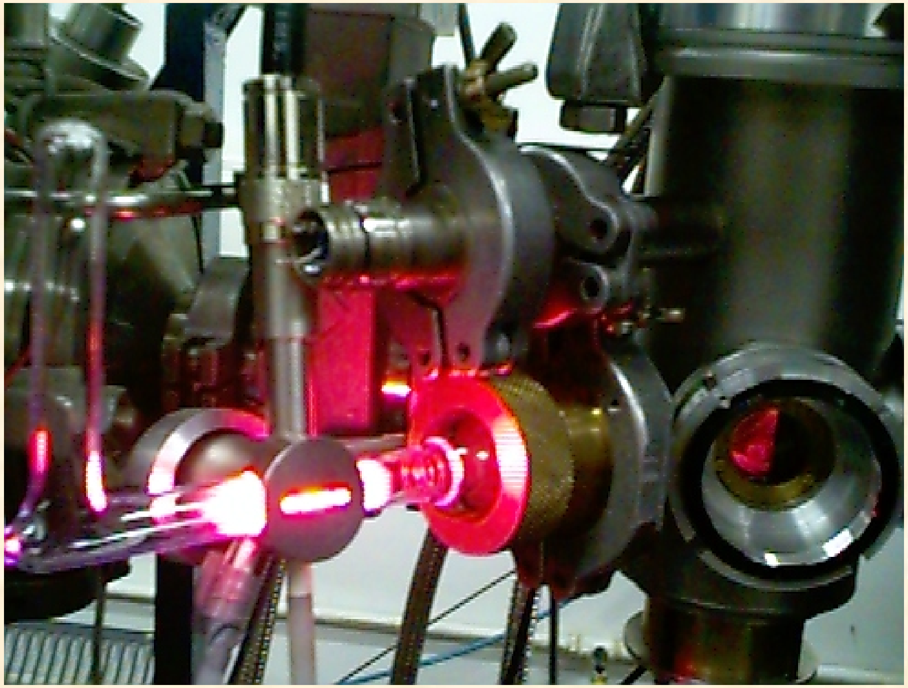


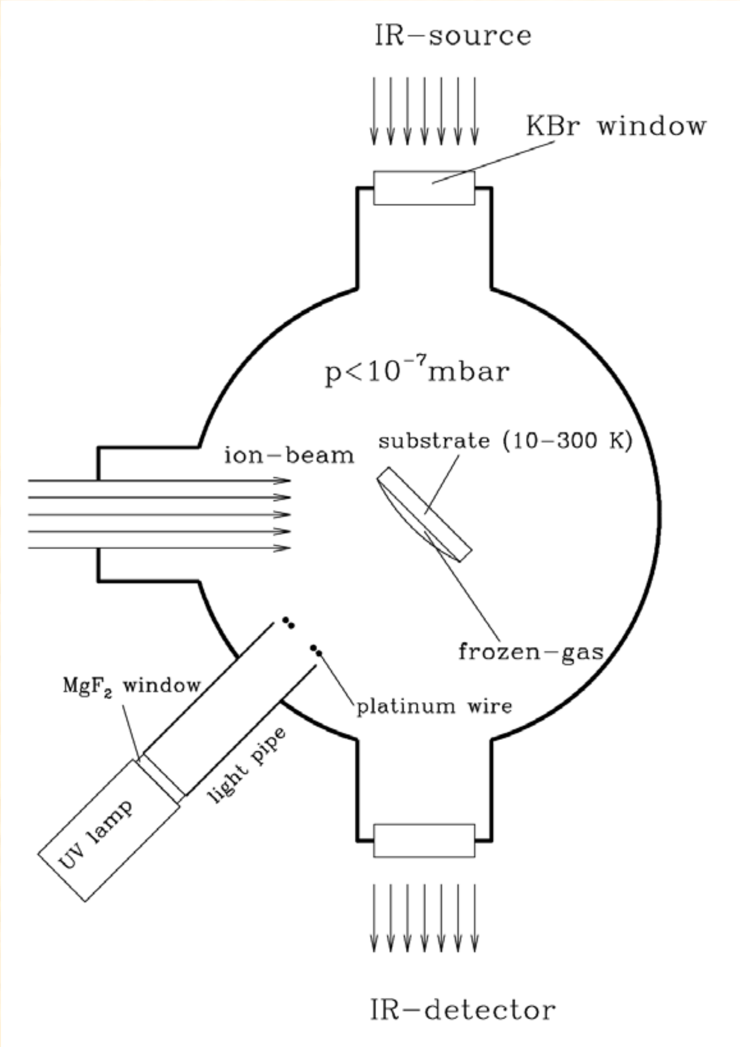
Techniques of analysis :

- IR Spectroscopy
- Raman Spectroscopy
- Mass Spectrometry

In “situ” PROCESSING







Solid Materials in Space

	SILICATES	CARBONS	ICES
WHAT:	olivines	PAHs	H_2O
	piroxenes	graphite	CO_2
		Amorphous carbons	CO
			NH_3
			CH_4
			OCS

WHERE:

- Interstellar medium (ISM)
- Circumstellar regions
- Interplanetary medium
- Planets and satellites
- Minor objects (asteroids, comets, TNOs)

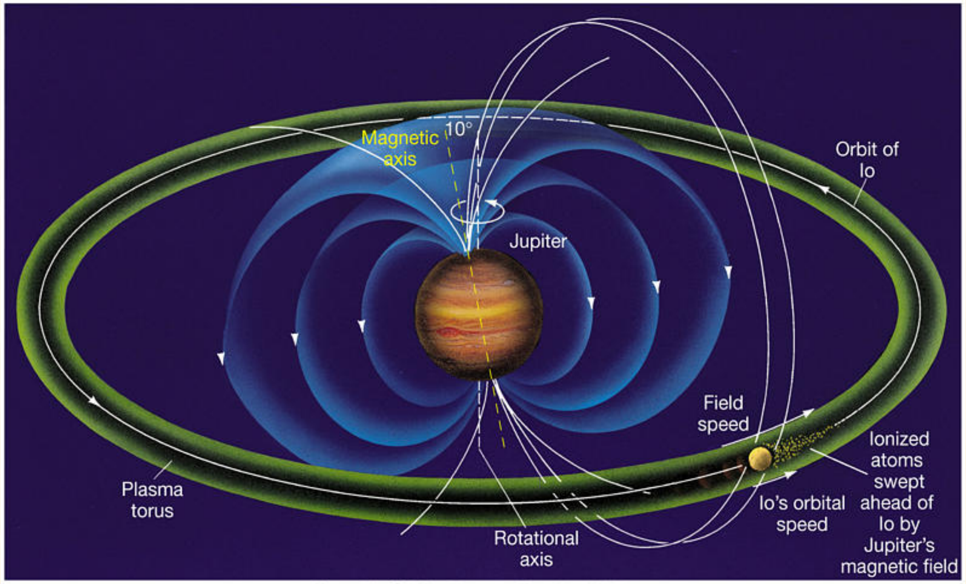
The Jovian magnetosphere

Jupiter's moons are dipped into the magnetosphere and their surfaces are continuously bombarded by energetic ions (mainly H^+, S^{n+} and O^{n+}) accelerated by Jupiter's magnetic field:

Mean Energy Flux (keV cm^{-2} s^{-1})

Io	**1 x 10^9**
Europa	**6 x 10^{10}**
Ganymede	**5 x 10^9**
Callisto	**2 x 10^8**

Cooper et al., 2001, Icarus 149, 133



✓ Effects → Sputtering

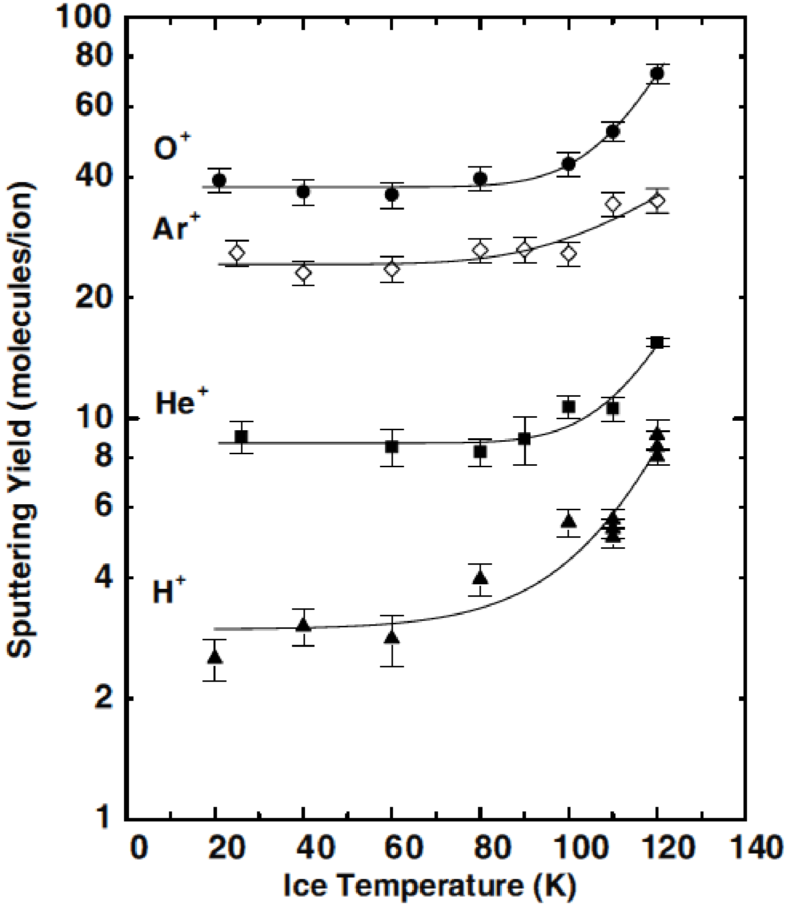


Fig. 2. Sputtering yield of ice for 30 keV ions at normal incidence versus temperature.

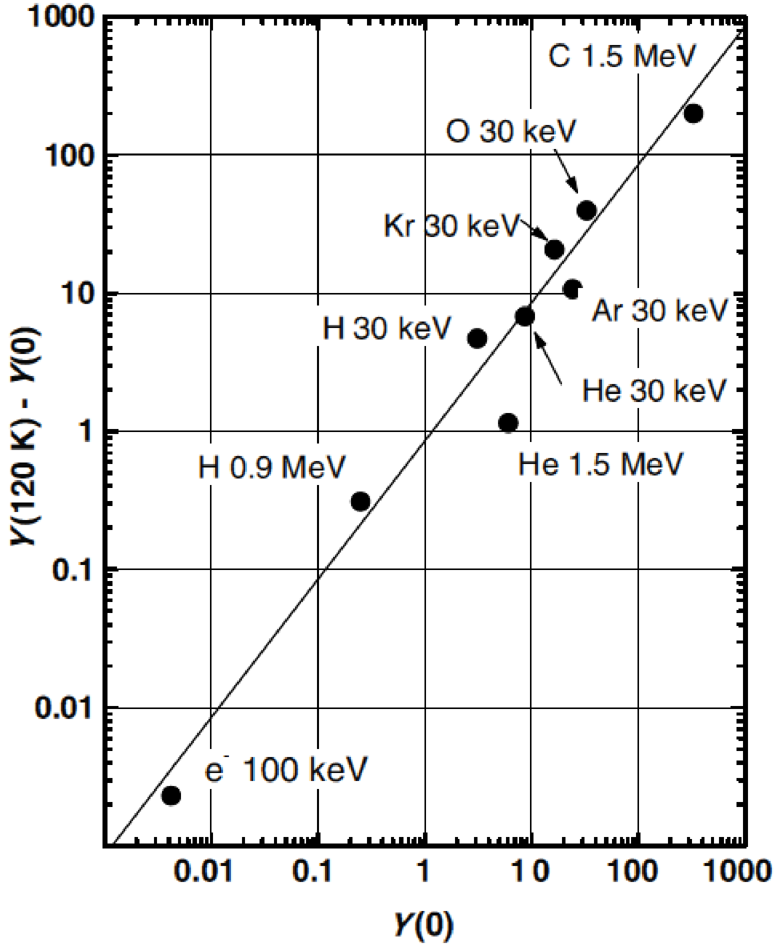


Fig. 3. The difference in the sputtering yield at 120 K and at <90 K: $Y(120)–Y(0)$, versus $Y(0)$. Data for 30 keV H, He, O and Ar ions: this work; 30 keV Kr [21]. Electron data from [45]. MeV data from [8]. The line is a linear fit, $Y(120\ \mathrm{K}) = 0.85Y(0)$.

H_2O ice

Measurements of sputtering yield allow e.g.:

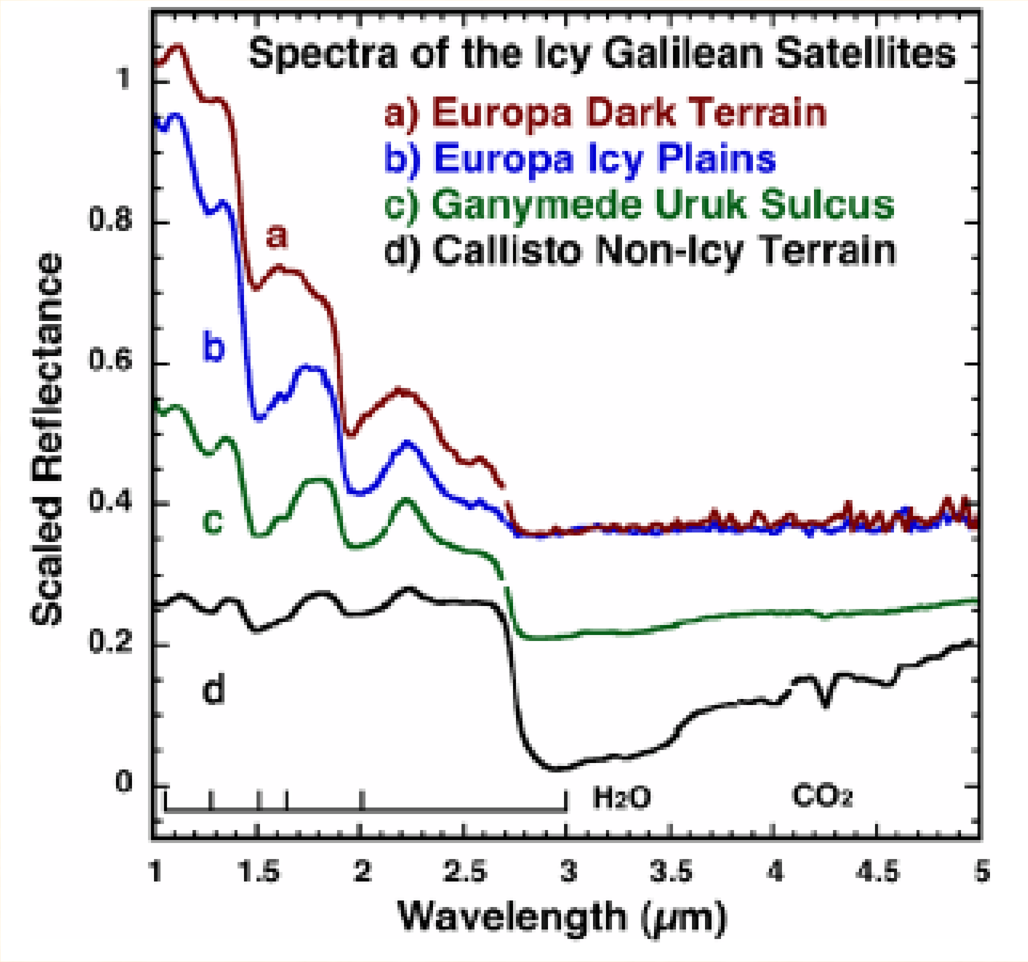
-To calculate the lifetimes for the destruction of icy grains
(e.g. Baragiola RSLTS 362, Issue 1814, 29, 2004)

-To predict the column density of O_2 in the atmosphere of Europa
(e.g. Johnson et al., GeoResLett 25, 3257, 1998)

And (hopefully) will allow:

-To explain the presence of ionised and neutral species in the environments of the Jovian Moons (JUICE!!)

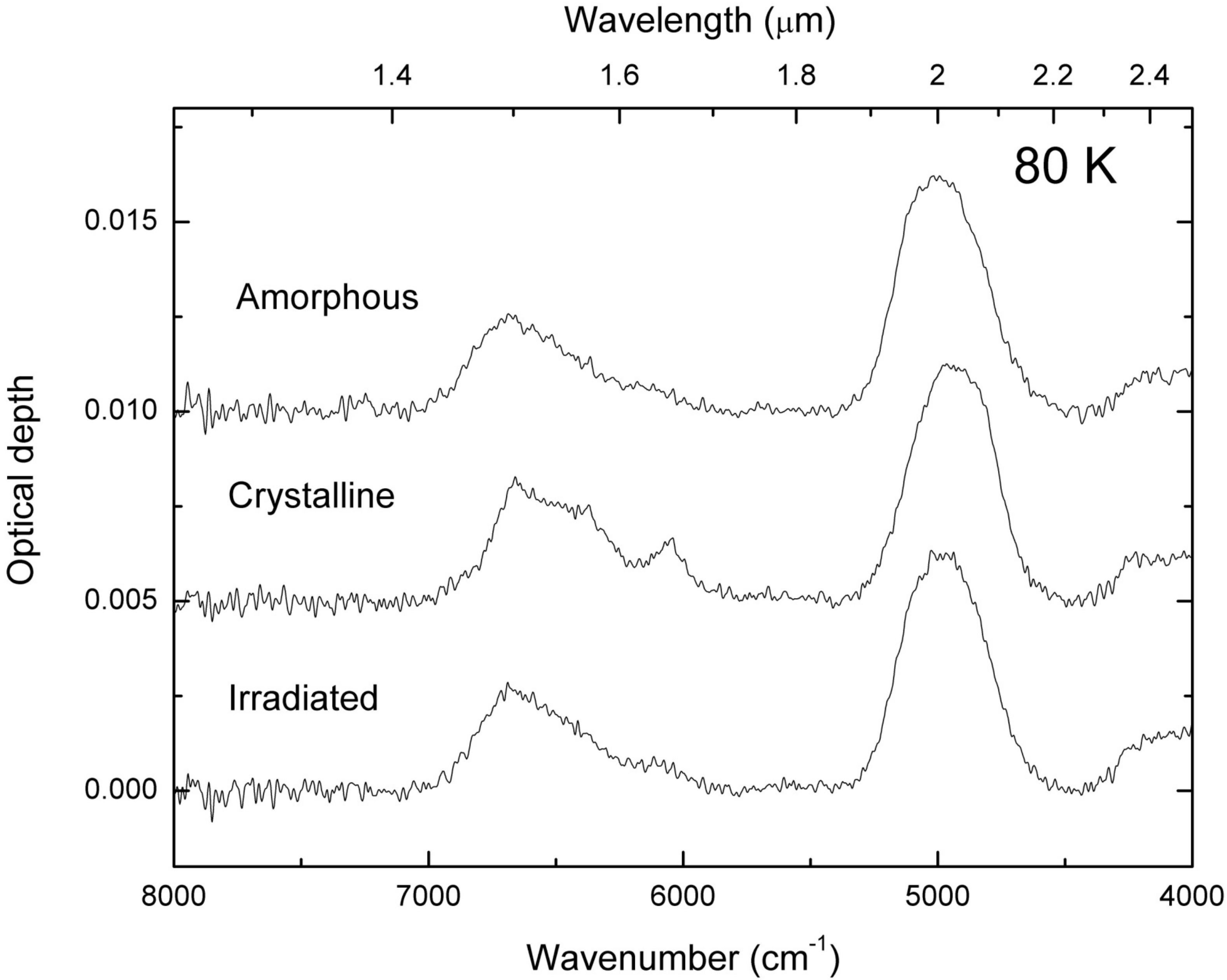
✓ Effects → Structure of the ice



Galileo NIMS :

primary H_2O absorption at ~1.0, ~1.25, ~1.5, ~2.0 and ~3.0 µm are .

The 1.65-µm crystalline water ice feature is apparent on all three satellites, but is faint in the Europa dark terrain spectra, which also exhibit strongly asymmetric absorption feature shapes at 1.5 and 2.0 µm representative of bound water such as hydrated salts and sulfuric acid hydrate.



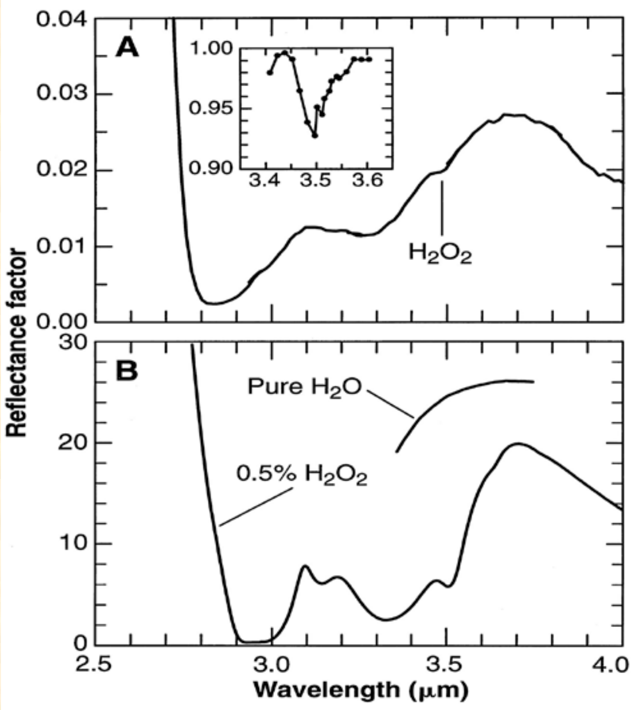
Wavelength (μm)
1.4
1.6
1.8
2
2.2
2.4
80 K
Amorphous
Crystalline
Irradiated
Optical depth
0.015
0.010
0.005
0.000
8000
7000
6000
5000
4000
Wavenumber (cm-1)

✓ Effects → Chemical

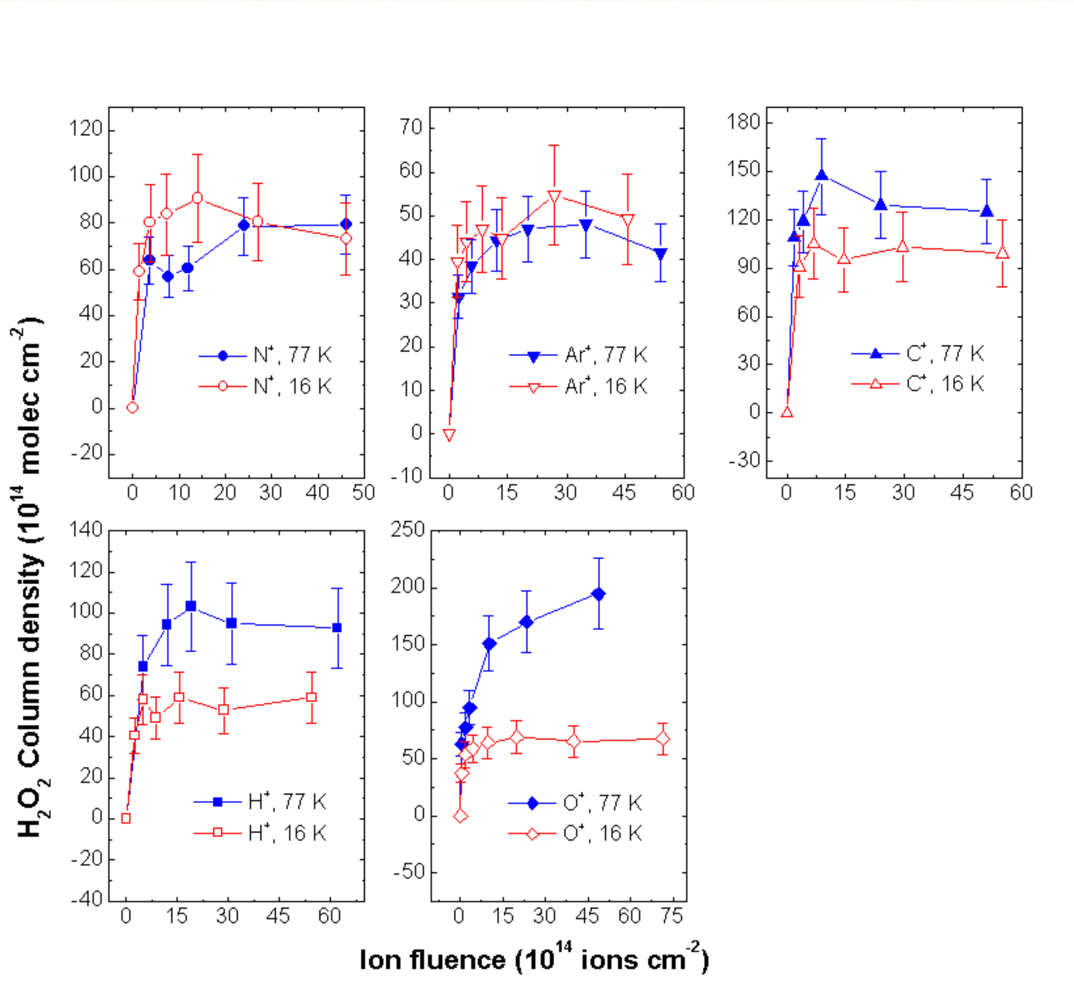
Hydrogen peroxide in the Solar System
Previous Work

Carlson *et al.* (1999) observations

- H_2O_2 found on the surface of Europa by Galileo NIMS spectra
- Radiolysis is supposed to be the dominant formation mechanism



H_2O_2 production as a function of temperature



Ion	Range (A)
H^+	7800
C^+	1800
N^+	1500
O^+	1350
Ar^+	700

Ion penetration depth

The ion energy is 30 keV

H_2O_2 production is greater or, at most, equal at 77 K than at 16 K:

- Radical mobility
- Diffusion velocity
- Incoming H and O may form H_2O_2 molecules

O. Gomis, M. A. Satorre, G. Strazzulla, G. Leto
Hydrogen peroxide formation by ion implantation in water ice and its relevance to the Galilean satellites.
PlSpSci 52, 371 (2004)
G. Strazzulla, G. Leto, O. Gomis, M. A. Satorre
Implantation of carbon and nitrogen ions in water ice.
Icarus 164, 163 (2003)
O. Gomis, G. Leto, **G. Strazzulla**
Hydrogen peroxide production by ion irradiation of thin water ice films.
A & A 420, 405 (2004)

- Ion irradiation is the primary candidate to explain the presence of H_2O_2 on the Galilean moons

- On Europa, H_2O_2 could be concentrated in patches

- The results support the possibility of a radiation-driven ecosystem on Europa

✓ Effects → Ion Implantation

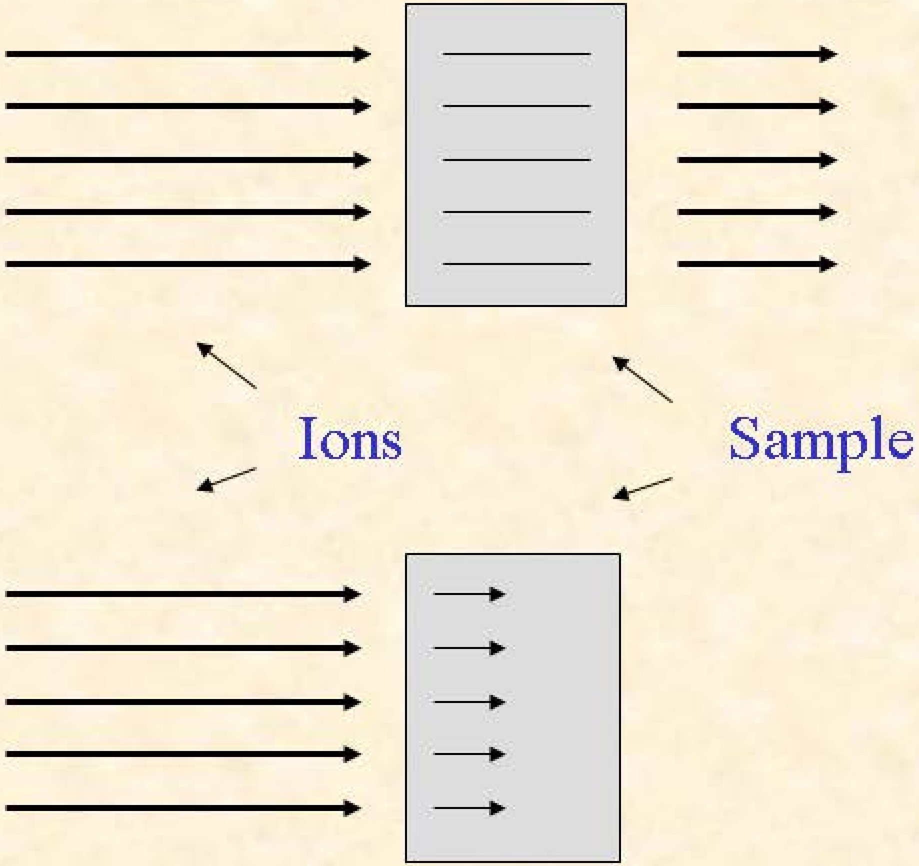
Two kinds of experiments

❖ Thin film
(beam passes through)

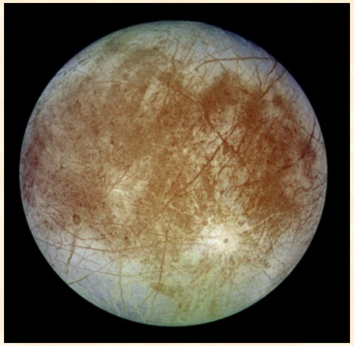
InterStellarMedium

❖ Thick film
(ion implantation)

Solar System



ION (E in keV)	**TARGET T= 16-150 K**	**MAJOR PRODUCED SPECIES (In bold those containing the projectile)**	**REFERENCES**
H (1.5, 30-100)	CO_2	CO, **H_2CO_3**, CO_3, O_3 **O-H in poly-water**	Brucato, Palumbo, Strazzulla. Icarus 125, 135, 1997
	SO_2	SO_3, polySO_3, O_3 , elemental S	Garozzo, et al PlSpSci 56, 1300, 2008
C^{n+} (10, 30) n=1-3	H_2O	H_2O_2, **CO_2**	Strazzulla, et al. Icarus 164, 163, 2003 Lv et al 2012 (submitted)
N (15, 30)	H_2O	H_2O_2	Strazzulla, et al. Icarus 164, 163, 2003
	$H_2O + CH_4$	C_2H_6, CO, CO_2, **OCN^-, HCN**	Strazzulla, PlSpSci 47, 1371, 1999
O (30)	CH_4	C_2H_6, C_2H_4	Palumbo AdvSpRes 20, 1637, 1997
	$N_2 + CH_4$	C_2H_6, C_2H_4, HCN	Ottaviano, Palumbo, Strazzulla, Conf Proc. SIF 68, 149 , 2000
S^{n+} (35-200) n= 1-11	H_2O	H_2O_2 **H_2SO_4** dissolved in H_2O	Strazzulla et al. Icarus, 192, 623, 2007 Ding et al. in preparation



Europa

Near IR observations made by the NASA *Galileo* spacecraft showed that:

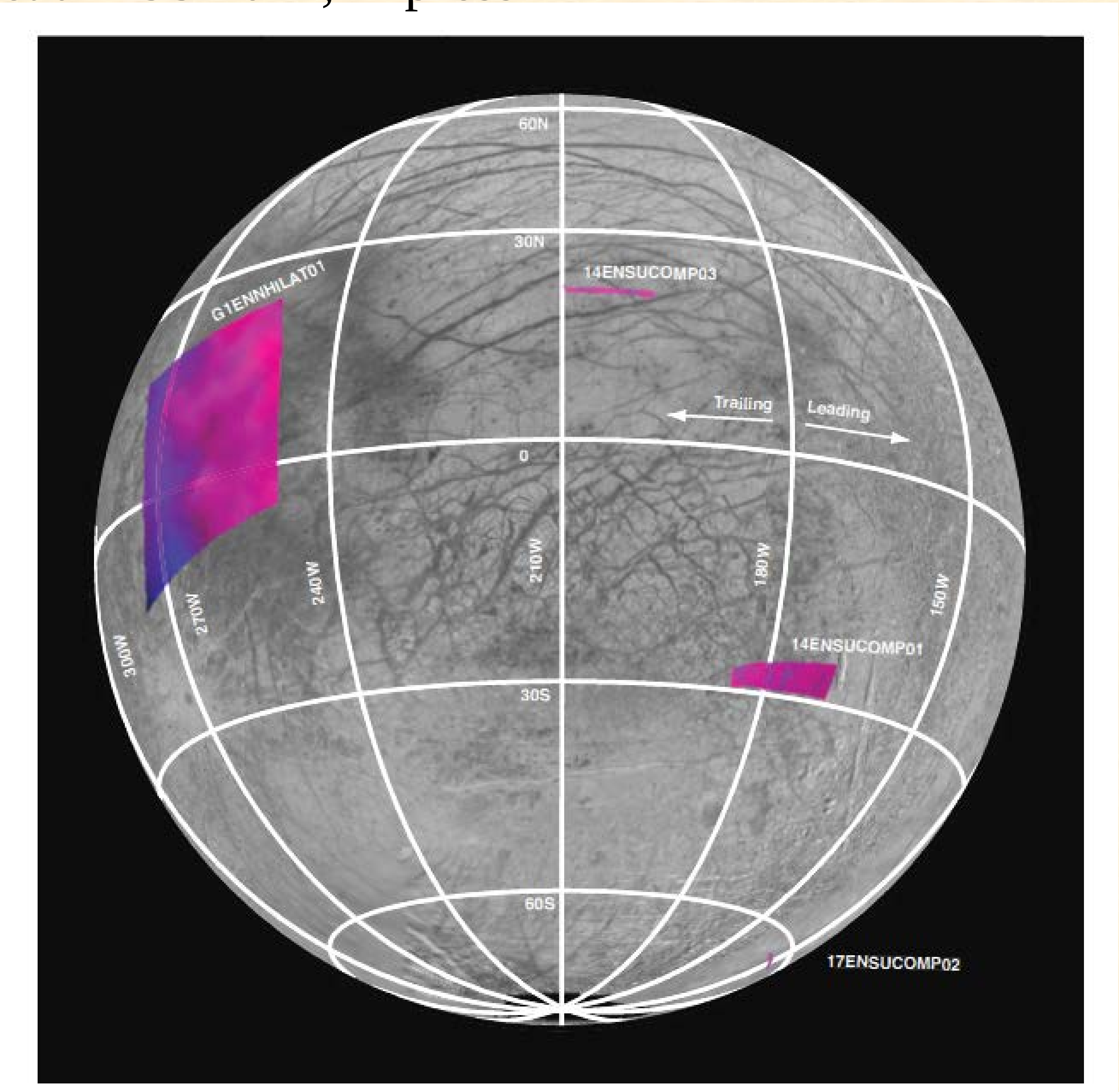
- On Io **SO_2** ice is dominant
- On Europa, Callisto and Ganymede **H_2O ice** is dominant
- On Europa significant quantities of **magnesium and sodium sulfate and carbonate hydrates**
- Other absorption features and their prime candidates are:
- **3.4 μm** (~2940 cm^{-1}) C-H
- **3.5** " (~2857 cm^{-1}) H_2O_2
- **3.88** " (~2580 cm^{-1}) S-H, H_2CO_3
- **4.05** " (~2470 cm^{-1}) SO_2
- **4.25** " (~2350 cm^{-1}) CO_2
- **4.57** " (~2190 cm^{-1}) CN

Ganymede

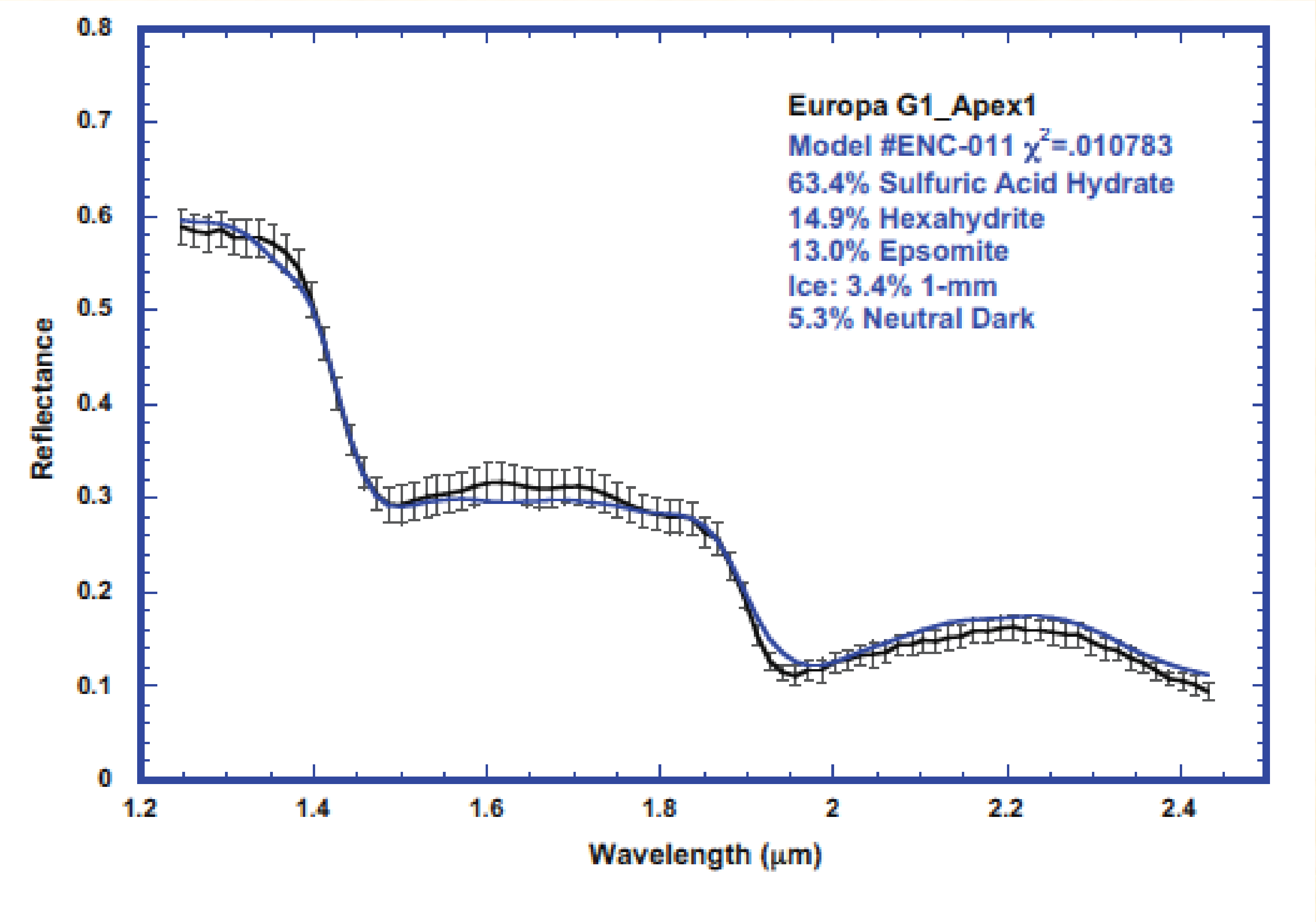
Callisto

A still open question is to understand if those species are **native** from the satellites or are **synthesized** by exogenic processes such as ion implantation.

Dalton et al PSS 2012, in press

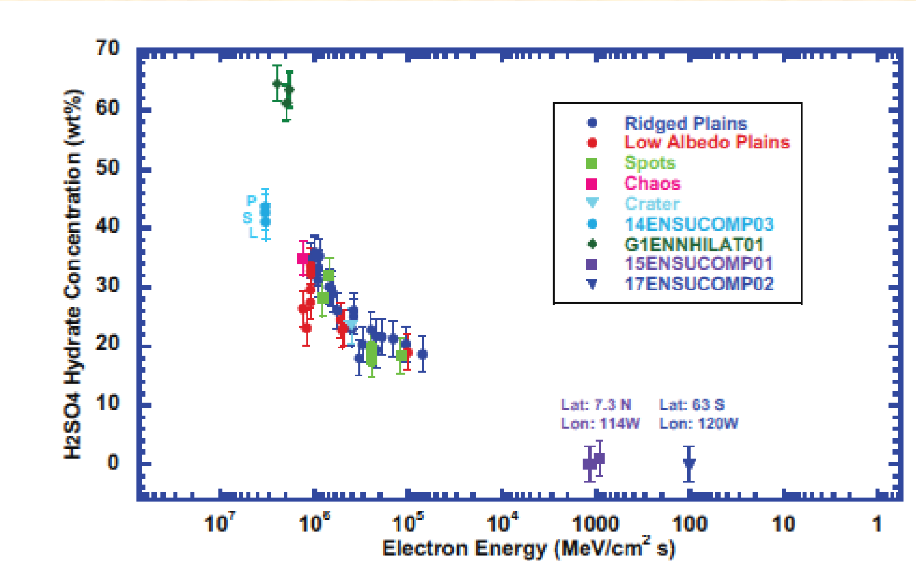


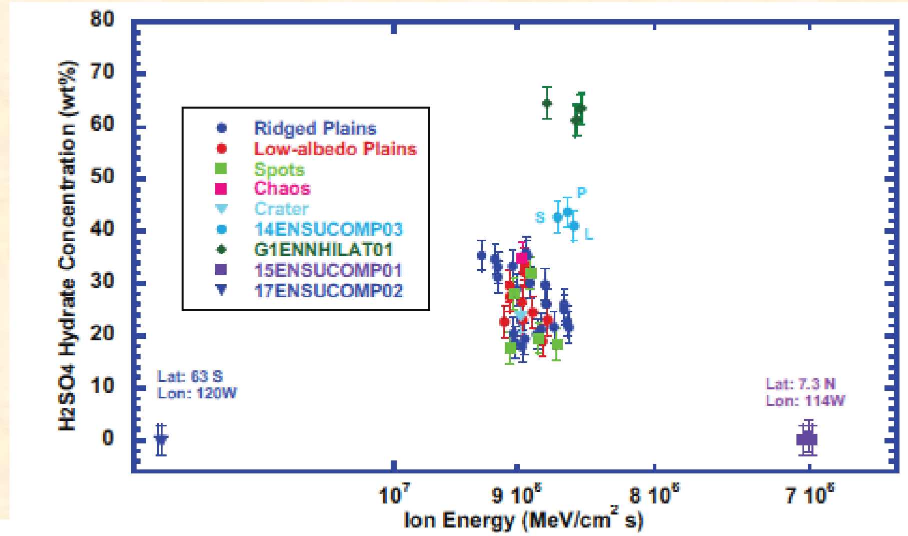
Dalton et al PSS 2012, in press

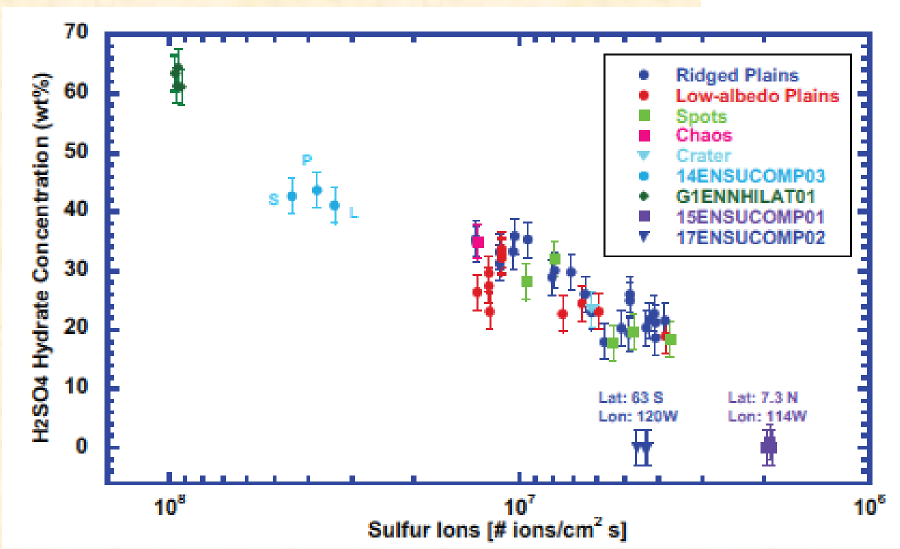


Sulfuric acid (H_2SO_4) Hydrate
Hexahydrite: $MgSO_4 \cdot 6(H_2O)$
Epsomite: $MgSO_4 \cdot 7(H_2O)$

Dalton et al PSS 2012, in press







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Icarus 192 (2007) 623–628
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Hydrate sulfuric acid after sulfur implantation in water ice

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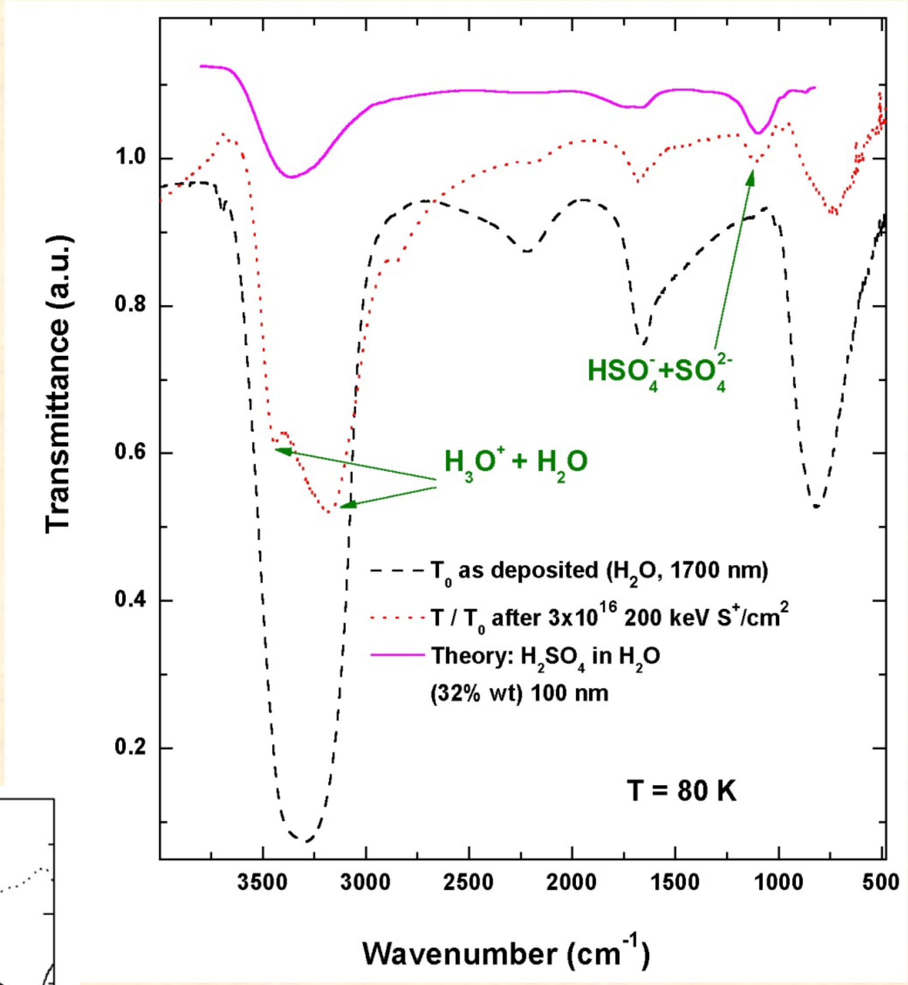
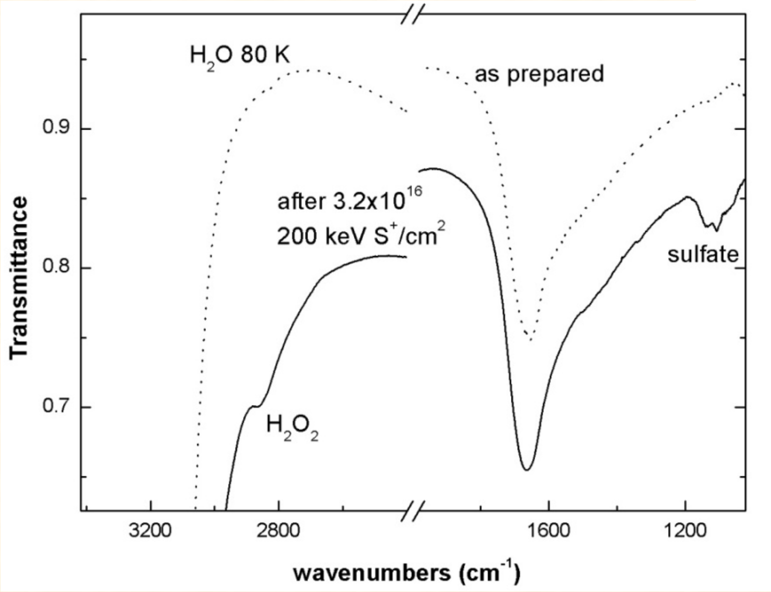
Available online 8 September 2007

We demonstrate that S-implantation efficiently forms hydrated sulfuric acid whose observed abundance is explained as caused by an exogenic process.





EPSC Abstracts
Vol. 7 EPSC2012-25 2012
European Planetary Science Congress 2012

Implantation of S^{n+} ions on the Galilean moons

J.J. Ding (1), P. Boduch (1), A. Domaracka (1), T. Langlinay (1), X.Y. Lv (1), M.E. Palumbo (2), H. Rothard (1) and **G. Strazzulla** (2)

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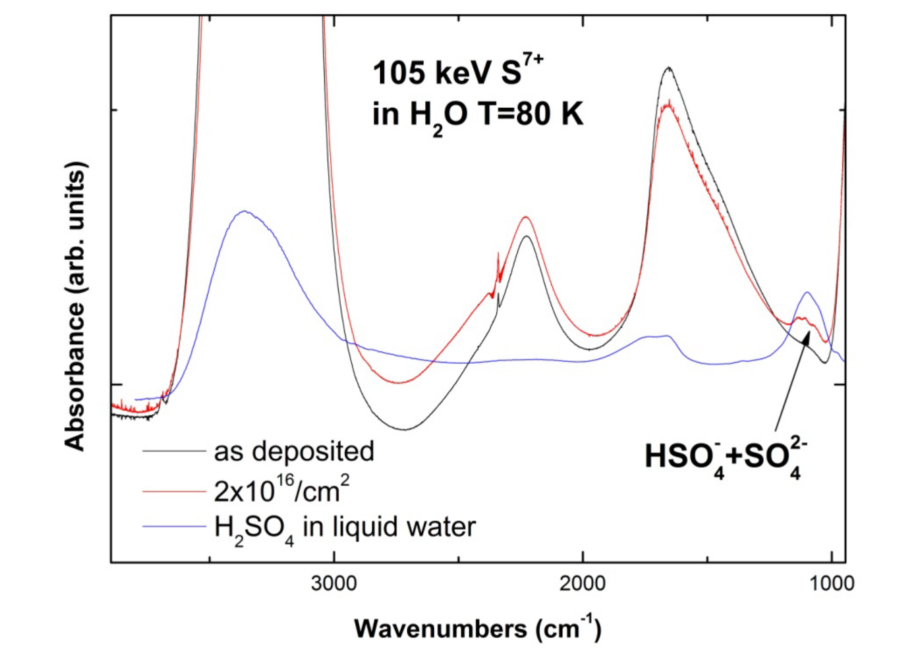
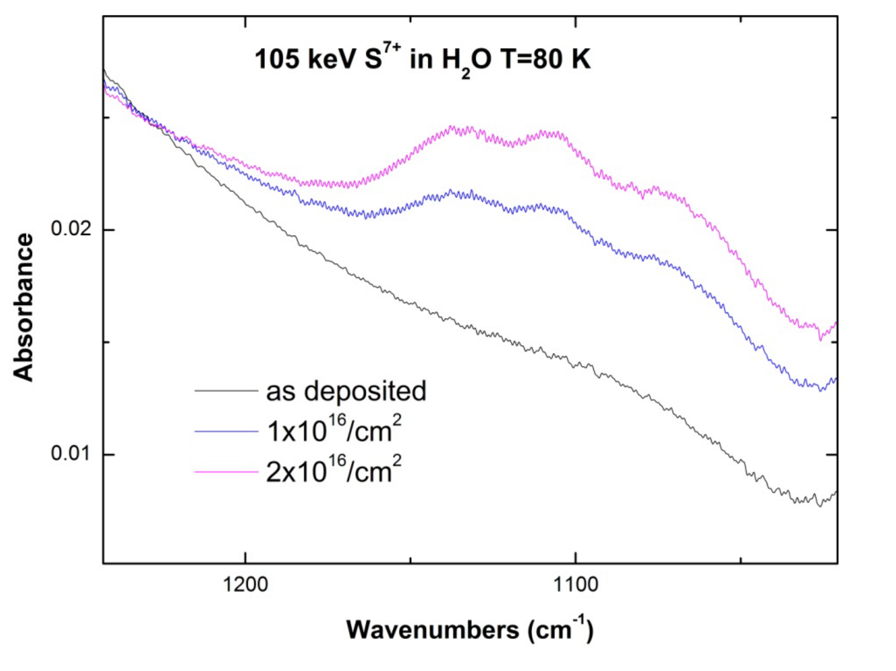
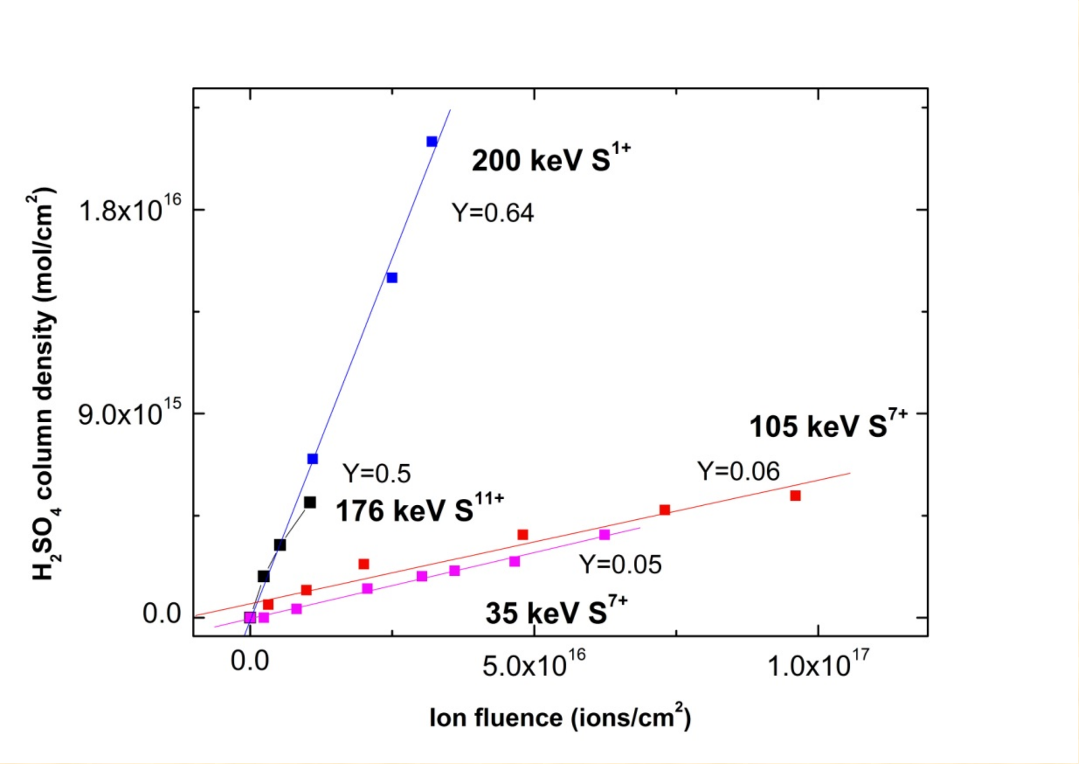
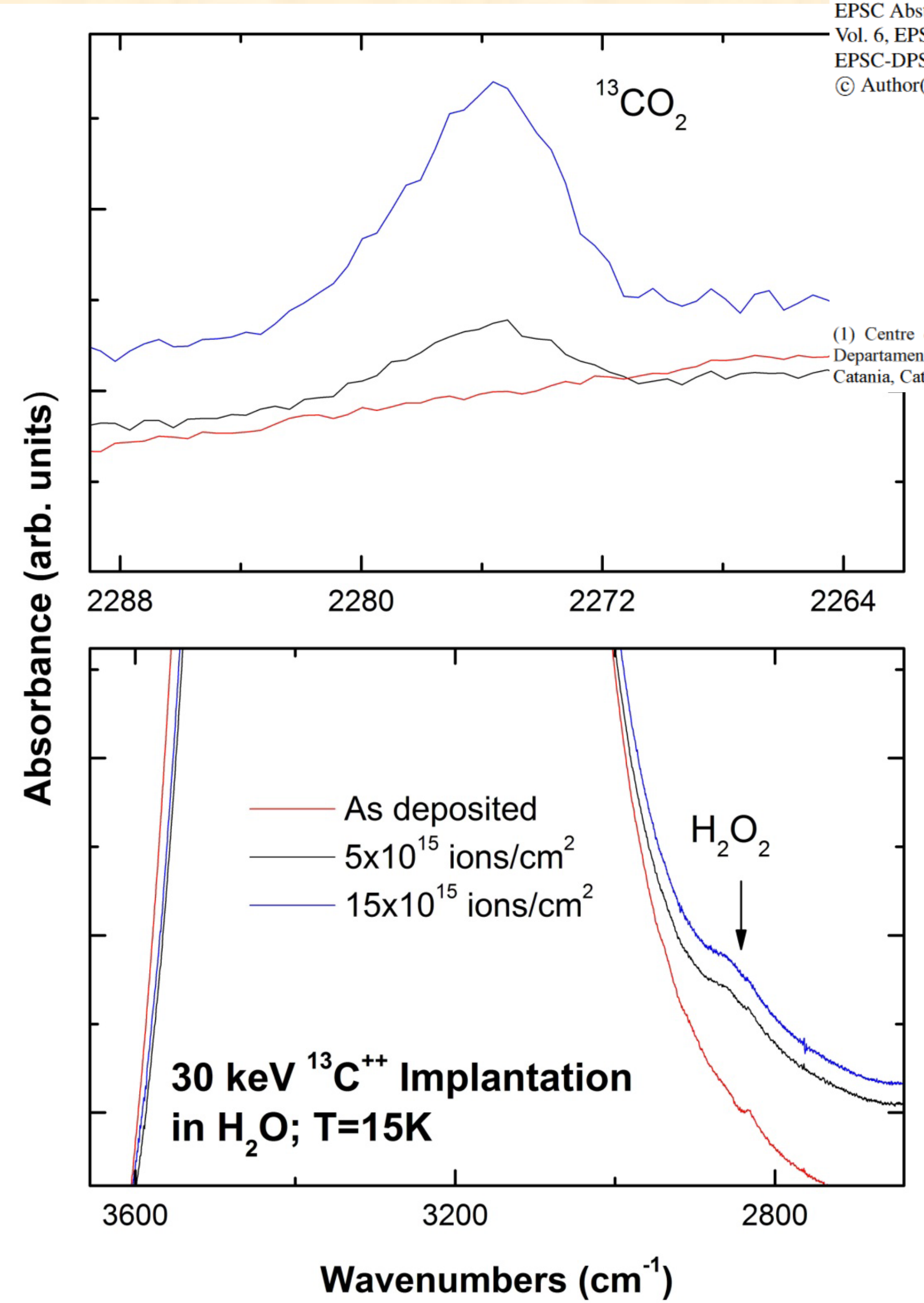




Ding et al. 2012
In preparation





EPSC Abstracts
Vol. 6, EPSC-DPS2011-299-1, 2011
EPSC-DPS Joint Meeting 2011

Implantation of C^{n+} ions on the Galilean moons

X.Y. Lv (1), P. Boduch (1), V. Bordalo (2), A. Domaracka (1), T. Langlinay (1), M.E. Palumbo (3), S. Pilling (4), H. Rothard (1) and **G. Strazzulla** (3)

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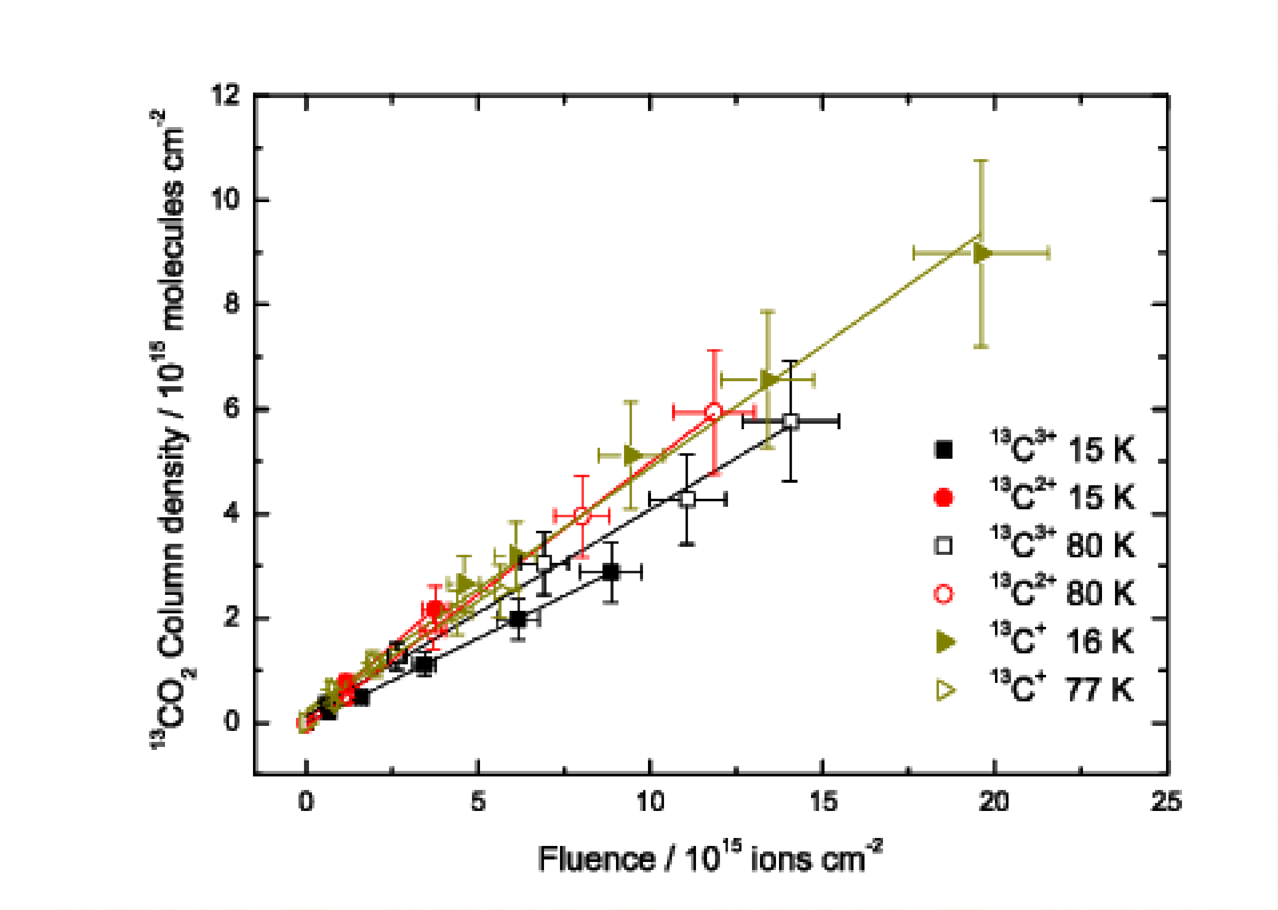
Lv et al. 2012 submitted

Experiments are conducted at the GANIL Laboratories (Caen, France)

Available ION Beams: Multi Charged; E from a few keV to hundreds MeV

Lv et al. 2012
submitted



Application to icy satellites

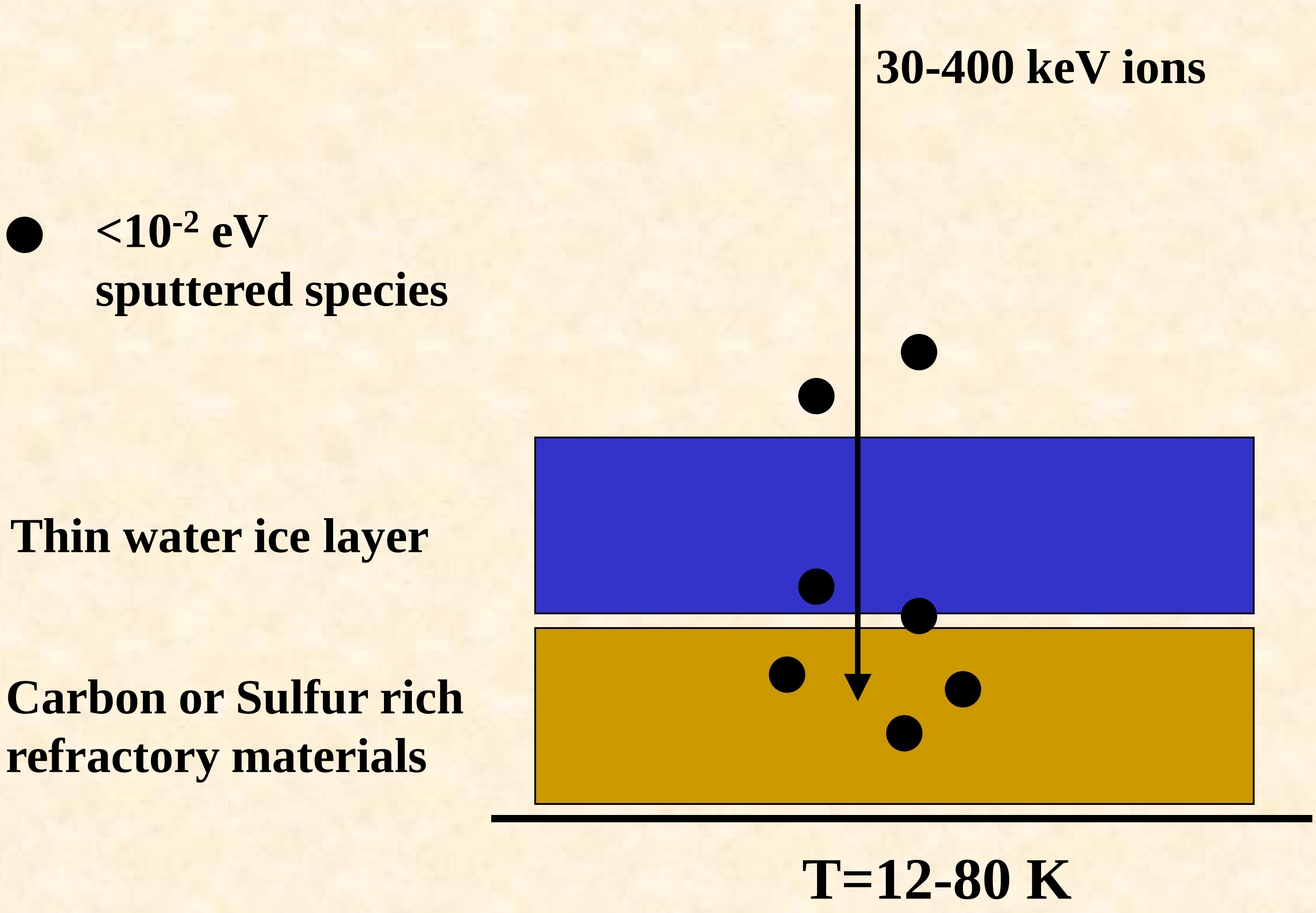
- Although a relevant quantity of CO_2 can be formed, this is not the dominant formation mechanism provided that the fluxes of C ions are correct.
(In particular we would expect more CO_2 at the polar region of Ganymede than at the equator but observations indicate this is not the case)

- Sulfur implantation is the primary mechanism to explain the presence of hydrated sulfuric acid

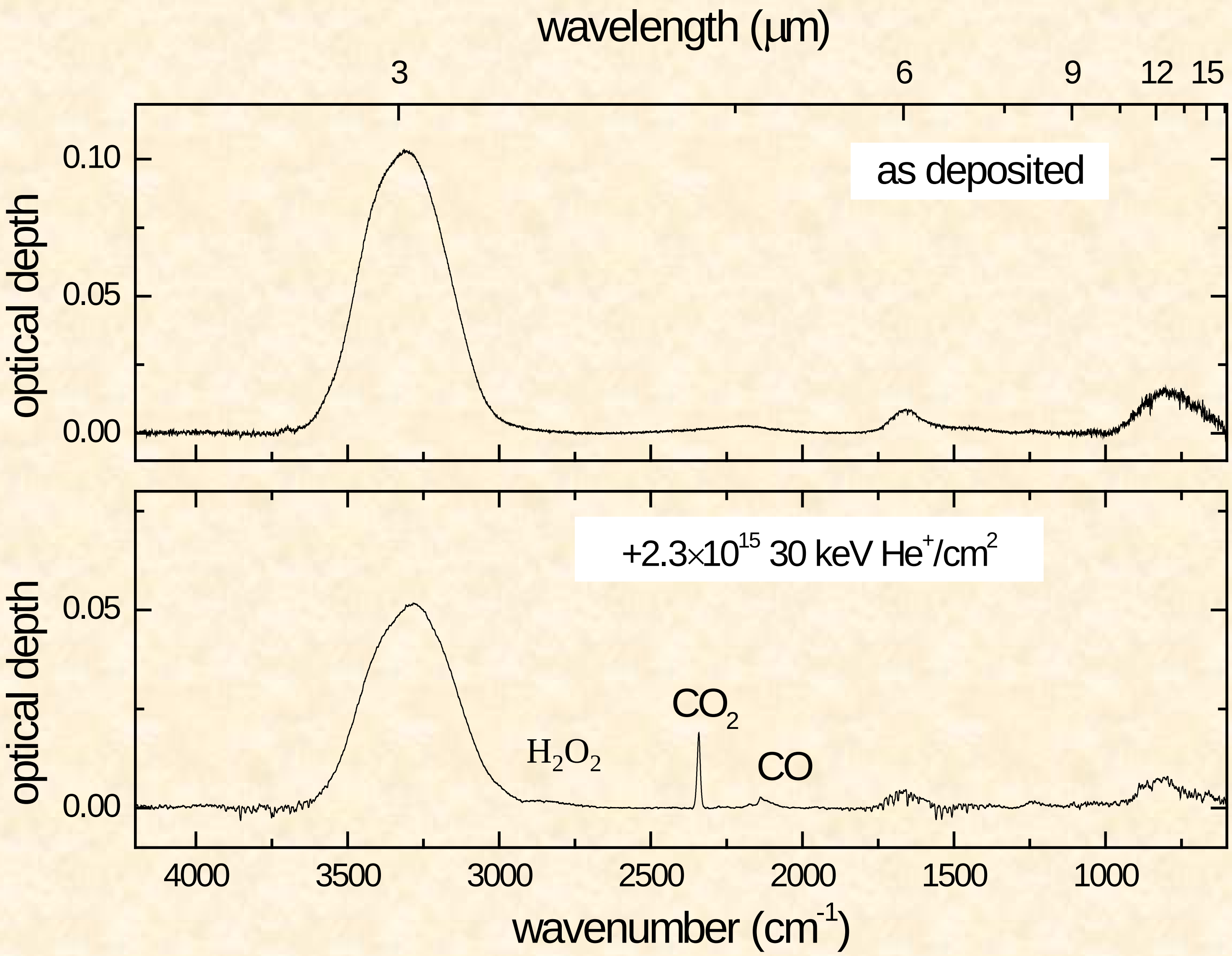
Satellite	S-ions $cm^{-2}\ s^{-1}$	C-ions $cm^{-2}\ s^{-1}$	Time (years) to produce $3x10^{17}$ CO_2 mol cm^{-2}	Time (years) to produce $2x10^{17}$ SO_2 mol cm^{-2}	Time (years) to produce $3x10^{19}$ H_2SO_4 mol cm^{-2}
Europa global	0.2-1.4 $x10^8$	0.4-2.8 $x10^7$	0.8-5.7 $x10^3$	0.2-1.2$x10^4$	1.0-7.3$x10^4$
Ganymede polar	3.2$x10^6$	1.6$x10^6$	1.5$x10^4$	1.5$x10^4$	1.5$x10^4$
Ganymede equator	5.8$x10^4$	2.9$x10^4$	8.2$x10^5$	8.2$x10^5$	8.2$x10^5$
Callisto global	3.6$x10^5$	3.6$x10^5$	6.6$x10^4$	6.6$x10^4$	6.6$x10^4$

- ✓ **Effects at the interface solid/ice → mixing**

Water ice on C or S-rich substrates



H_2O on amorphous carbon at 12 K



Mennella, Palumbo, Baratta 2004, ApJ 615, 1073

The carbon cycle: initiated by ion processing at the interface s between C-bearing solids and water ice!!

Time necessary to produce the amount of CO_2 molecules of the order of those detected on the surfaces of the Galilean satellites (3×10^{17} molecules cm^{-2}) for three different surface depths. The times have been obtained from Fig. 20.5 of Johnson et al. (2004) with the assumptions on the amount of available carbonaceous surface area done in the text.

Satellite	Time (years) to produce 3×10^{17} CO_2 molecules cm^{-2}		
Europa global	5×10^1	3×10^2	2×10^3
Ganymede polar	3×10^2	4×10^3	4×10^4
Ganymede equator	2×10^4	2×10^5	5×10^6
Callisto global	6×10^3	1×10^5	2×10^6
Surface depth (μm)	10	100	1000

Gomis & Strazzulla, Icarus 177 (2005) 570–576

We need Juce!

What next?

Some of the (many) open questions:

-Where SO_2 comes from?

-What produces the UV dark material and its distribution on the surfaces?

-Optical constants of relevant materials

-Inter-relations between sulfur and carbon cycles

-………………………………