



# Sulfur and carbon bearing molecules on the Galilean moons

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**Abstract.** The surfaces of the Jupiter's Galilean moons are dominated by frozen sulfur dioxide (Io) or water ice (Europa, Ganimede and Callisto) and exhibit traces of other carbon and/or sulfur bearing molecular species. Being dipped in the Jovian magnetosphere those surfaces are continuously modified by irradiation of magnetospheric ions. The study of the induced effects is based on laboratory simulations. Here we review some of the results of experiments performed by our group, namely implantation of reactive ions in ices. In particular we present results relative to carbon implantation in water ice and of proton in frozen sulfur dioxide. We find that a relevant quantity of CO<sub>2</sub> can be formed by carbon ions implantation on Europa, Ganimede and Callisto, but this is not the dominant formation mechanism. Implantation of protons into sulfur dioxide produces mainly SO<sub>3</sub> and polymers, and O<sub>3</sub> but not H-S bonds. These results do not support the hypothesis that H implantation could result in the formation of H<sub>2</sub>SO<sub>3</sub> on Io.

**Key words.** Galilean moons – methods: laboratory – techniques: spectroscopic

## 1. Introduction

The surfaces of airless bodies in the Solar System are continuously altered by micrometeoroids bombardment and irradiation by solar wind, flares and cosmic particles. Major effects of this process - space weathering - are sputtering, structural and chemical alterations and ion implantation. As a whole the chemical composition and the color of an irradiated surface are changed. Experiments have been conducted on several different kind of materials.

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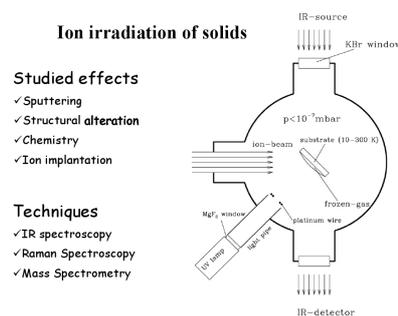
Here we limit ourself to give some examples of results obtained in our laboratory in Catania (Italy). Refractory solids that have been studied include red bitumens (asphaltite and kerite) (Moroz et al. 2004), and different kinds of silicates (Brunetto and Strazzulla 2005, Brunetto et al. 2006, Strazzulla et al. 2005). In addition to single ices (H<sub>2</sub>O, CO<sub>2</sub>, CO, CH<sub>4</sub> etc.), investigated icy mixtures belongs roughly to three major categories: CO rich mixtures (e.g. Palumbo et al 2008) that lead to the formation of carbon chains, hydrocarbon rich mixtures (e.g., Brunetto et al. 2005) that produce

refractory organic residues, and mixtures rich in S-bearing species that lead to the formation of sulfurous residues.

Here we are interested to the surfaces of the Jupiter's Galilean moons that are dominated by frozen sulfur dioxide (Io) or water ice (Europa, Ganymede and Callisto) and exhibit traces of other carbon and/or sulfur bearing molecular species. Being dipped in the Jovian magnetosphere those surfaces are continuously modified by irradiation of magnetospheric ions. Here we review some of the results of experiments performed by implantation of reactive ( $H^+$ ,  $C^+$ ,  $N^+$ ,  $O^+$ ,  $S^+$ ) ions in ices, the ion irradiation induced synthesis of molecules at the interface between two different ices (or mixtures) or at the interface of water ice and carbonaceous or sulfurous solid materials. The results, discussed in the light of some questions concerning the surfaces of the Galilean moons, contribute to understand whether minor molecular species ( $CO_2$ ,  $SO_2$ ,  $H_2SO_4$  etc) observed on those objects are endogenic i.e. native from the satellite or are produced by exogenic processes, such as ion implantation.

## 2. Experiments

The experimental apparatus is schematically shown in Fig. 1 along with the studied effects induced by the beam and the techniques we have used in our laboratory. The high vacuum ( $P < 10^{-7}$  mbar) chamber used in most of our past experiment has been recently upgraded to ultra-high vacuum ( $P < 10^{-9}$  mbar). It is faced to an IR spectrometer (1-25  $\mu m$ ; 10000 - 400  $cm^{-1}$ ). The spectra here shown have a resolution of 1  $cm^{-1}$ . Icy films are prepared by vapor deposition on IR-transparent substrata (KBr or silicon) at low temperature (15-150 K). Ions are obtained from a 200 kV ion implanter (Danfysik). The ion beam is swept to obtain uniform irradiation on an area of about 3  $cm^2$  i.e. much larger than the area sounded by the IR beam and ion currents are low enough (10-100's nano amperes) to avoid a significant heating of the sample (Strazzulla et al. 2001). An He-Ne laser can be used to monitor the thickness (micrometers) of the ice film during accretion (Baratta & Palumbo 1998).



**Fig. 1.** A scheme of the vacuum chamber is shown along with the studied effects induced by the beam and the techniques we have used in our laboratory. Samples can be irradiated by ions or by UV photons. Spectra are obtained before, during and after irradiation.

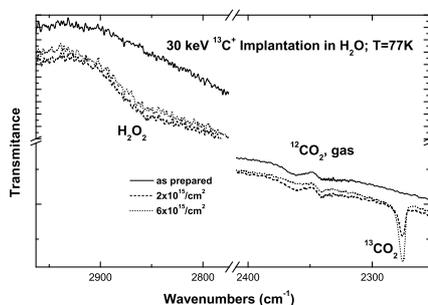
In addition the thickness of the deposited ices (molecules  $cm^{-2}$ ) is obtained by the integrated band area (in  $cm^{-1}$  and in an optical depth scale) of the bands in the IR spectra and by knowing the band strength of that band ( $cm$  molecule $^{-1}$ ).

## 3. Results

Deposited icy films may have a thickness greater or smaller than the penetration depth of the incoming ions. We refer to implantation experiments when the film is thicker than the ion penetration depth. In this case the ion travels through the target, deposits its energy and remains implanted in the target. When a reactive ion ( $H^+$ ,  $C^+$ ,  $N^+$ ,  $O^+$ ,  $S^+$ ) is implanted in ice has a chance to form new species containing the projectile with a maximum yield of one molecule per incoming ion. Since about 15 years we conducted experiments, listed in Table 1, that have the aim to investigate the implantation of reactive ions in many ices of planetary relevance (McCord et al 1997, Carlson et al. 1999a, Hibbits et al. 2002, Lane et al. 1981, Sack et al 1992). Icy Galilean satellites orbit within Jupiter's giant magnetosphere and their surfaces are subjected to intense bombardment by protons and ions such as  $H^+$ ,  $S^{n+}$  and  $O^{n+}$ , and by energetic electrons (Cooper et al. 2001). This motivated experiments of implantation in

**Table 1.** List of implantation experiments conducted in our laboratory.

| Ion<br>(Energy, keV) | Target<br>(T=16-80 K)            | Major produced<br>species   | References             |
|----------------------|----------------------------------|---|------------------------|
| H (1.5, 30-100)      | CO <sub>2</sub>                  | CO, H <sub>2</sub> CO <sub>3</sub> , CO <sub>3</sub> , O <sub>3</sub> , O-H in poly-water | Brucato et al. 1997    |
| H (30-100)           | SO <sub>2</sub>                  | SO <sub>3</sub> , O <sub>3</sub> , poly-SO <sub>3</sub> , elemental sulfur                | Garozzo et al. 2008    |
| C (10, 30)           | H <sub>2</sub> O                 | H <sub>2</sub> O <sub>2</sub> , CO <sub>2</sub>   | Strazzulla et al. 2003 |
| N (15, 30)           | H <sub>2</sub> O                 | H <sub>2</sub> O <sub>2</sub>   | Strazzulla et al. 2003 |
| N (15, 30)           | H <sub>2</sub> O+CH <sub>4</sub> | C <sub>2</sub> H <sub>6</sub> , CO, CO <sub>2</sub> , OCNCO <sup>-</sup> , HCN            | Strazzulla 1999        |
| O (30)               | CH <sub>4</sub>                  | C <sub>2</sub> H <sub>6</sub> , C <sub>2</sub> H <sub>4</sub>                             | Palumbo 1997           |
| O (30)               | N <sub>2</sub> +CH <sub>4</sub>  | C <sub>2</sub> H <sub>6</sub> , C <sub>2</sub> H <sub>4</sub> , HCN                       | Ottaviano et al. 2000  |
| S (200)              | H <sub>2</sub> O                 | H <sub>2</sub> SO <sub>4</sub> dissolved in H <sub>2</sub> O                              | Strazzulla et al. 2007 |

**Fig. 2.** Transmittance IR spectra of H<sub>2</sub>O (77 K) ice before and after implantation of 30 keV <sup>13</sup>C<sup>+</sup> ions at two different ion fluences.

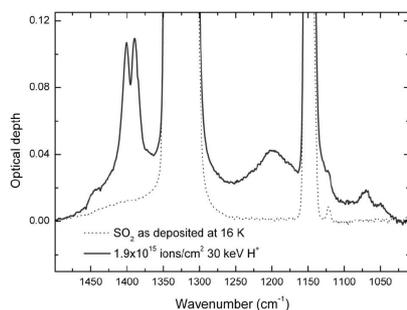
some ices such as water, carbon dioxide and sulfur dioxide. Here we discuss some of the results obtained so far.

1. We have investigated (Strazzulla et al. 2003) the formation of carbon dioxide after implantation of C ions in water ice. Fig. 2 shows the transmittance IR spectra of H<sub>2</sub>O (77 K) ice before and after implantation of 30 keV <sup>13</sup>C<sup>+</sup> ions at two different fluences (ions cm<sup>-2</sup>). We use isotopically labeled carbon to avoid the influence of gas phase CO<sub>2</sub> along the path of the IR beam. The appearance of bands testifies for the formation of H<sub>2</sub>O<sub>2</sub>, and <sup>13</sup>CO<sub>2</sub>. The formation of hydrogen peroxide is relevant because it has been detected on the surface of Europa (Carlson et al. 1999b), Ganymede and

Callisto (Hendrix et al. 1999). Different groups have studied the formation of hydrogen peroxide by ion bombardment of water ice (Moore and Hudson 2000, Gomis et al. 2004, Loeffler et al. 2006). All of the results support the hypothesis that magnetospheric ion bombardment is responsible for the formation of H<sub>2</sub>O<sub>2</sub> on the surfaces of the Jupiter's moons.

Strazzulla et al. (2003) measured the production yield of CO<sub>2</sub> to be 0.42 and, by estimating the flux of magnetospheric C-ions from the space measurements (Cooper et al. 2001) they conclude that a relevant quantity of carbon dioxide can be formed by carbon implantation on Europa, Ganymede and Callisto but this is not the dominant formation mechanism. It is however possible that the dissociation of water molecules due to ion irradiation (not only carbon implantation) in the presence of C-bearing species induces the formation of sufficient amount of CO<sub>2</sub> (McCord et al. 1997). An additional hypothesis suggests the formation of carbon dioxide at the interface between water ice and solid carbon-bearing refractory materials (Gomis & Strazzulla 2005).

2. Io is a very peculiar object having an intense volcanic activity that causes a continuous deposition of sulphur-rich material having a variety of colors. The surface is dominated by frozen sulphur dioxide. One open question is the presence of sulfurous acid (H<sub>2</sub>SO<sub>3</sub>) whose formation and stability is possible only under



**Fig. 3.** IR spectra, in optical depth unit, of SO<sub>2</sub> ice (16 K) before and after implantation of 30 keV H<sup>+</sup> ions.

opportune conditions, as e.g. it must stay in a low temperature environment. In fact its half-life is 1 day at 300 K and almost 3 billion years at 100 K. Some authors (Voegelé et al. 2004) proposed that H<sup>+</sup> implantation in SO<sub>2</sub> ice can drive the formation of H<sub>2</sub>SO<sub>3</sub>. We have performed experiments of implantation of 30 keV H<sup>+</sup> in low T sulfur dioxide (Garozzo et al. 2008). The results (Fig. 3) indicate that H<sup>+</sup> implantation produces, in the IR spectrum, bands attributable to SO<sub>3</sub> (see the doublet at 1389-1400 cm<sup>-1</sup> and the band at 1070 cm<sup>-1</sup>), polymers (evidenced by the broad band at 1205 cm<sup>-1</sup>), and O<sub>3</sub> (band at 1050 cm<sup>-1</sup>) (Garozzo et al. 2008). The only molecules containing the projectile are O-H bonds and most probably H<sub>2</sub> molecules that are not easily noticeable with IR-spectroscopy.

#### 4. Conclusion

Since the pioneer work on water ice sputtering (Brown et al, 1978) a large number of experiments have been and are performed in many laboratories in the world with the aim to investigate on the physico-chemical effects induced by fast ions irradiating astrophysical relevant materials.

In this paper we have discussed the finding of two experiments performed by our group, namely implantation of reactive carbon ions in water ice and of protons in sulfur dioxide. The main results indicate that: - Although a rele-

vant quantity of CO<sub>2</sub> can be formed by carbon ions implantation on Europa, Ganymede and Callisto, this is not the dominant formation mechanism. - Implantation of protons into sulfur dioxide produces mainly SO<sub>3</sub> and polymers, and O<sub>3</sub> but not H-S bonds. The results do not support the hypothesis that H implantation could result in the formation of H<sub>2</sub>SO<sub>3</sub> on Io.

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