Mem. S.A.It. Suppl. Vol. 20, 94

Memorie della
Supplementi

Sulfur and carbon bearing molecules on the Galilean moons

G.A. Baratta[1], D. Fulvio[2], M. Garozzo[1], Z. Kanuchova[1,3], M.E. Palumbo[1], F. Spinella[1] and G. Strazzulla[1]

[1] Istituto Nazionale di Astrofisica – Osservatorio Astrofisico di Catania, Via S.Sofia 78, I-95123 Catania, Italy
[2] University of Virginia, Laboratory for Atomic and Surface Physics, Charlottesville, USA
[3] Astronomical Institute of the Slovak Academy of Sciences, SK-059 60 Tatranska Lomnica, The Slovak Republic
e-mail: gianni@oact.inaf.it

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_2 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_3 and polymers, and O_3 but not H-S bonds. These results do not support the hypothesis that H implantation could result in the formation of H_2SO_3 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. 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_2O, CO_2, CO, CH_4 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

Send offprint requests to: G. Strazzulla 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, 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. 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 μm; 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).

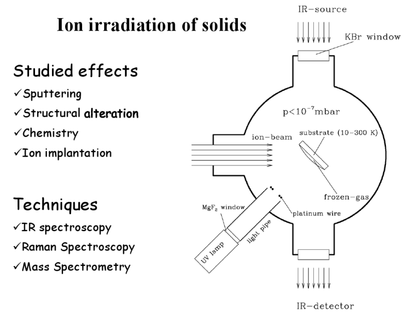

Fig. 1. A scheme of the vacuum chamber is shown along with the studied effects induced by the beam and the techniques we have used in our laboratory. Samples can be irradiated by ions or by UV photons. Spectra are obtained before, during and after irradiation.

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 (Energy, keV)	Target (T=16-80 K)	Major produced species	References
H (1.5, 30-100)	CO_2	CO, H_2CO_3, CO_3, O_3, O-H in poly-water	Brucato et al. 1997
H (30-100)	SO_2	SO_3, O_3, poly-SO_3, elemental sulfur	Garozzo et al. 2008
C (10, 30)	H_2O	H_2O_2, CO_2	Strazzulla et al. 2003
N (15, 30)	H_2O	H_2O_2	Strazzulla et al. 2003
N (15, 30)	H_2O+CH_4	C_2H_6, CO, CO_2, $OCNCO^-$, HCN	Strazzulla 1999
O (30)	CH_4	C_2H_6, C_2H_4	Palumbo 1997
O (30)	N_2+CH_4	C_2H_6, C_2H_4, HCN	Ottaviano et al. 2000
S (200)	H_2O	H_2SO_4 dissolved in H_2O	Strazzulla et al. 2007

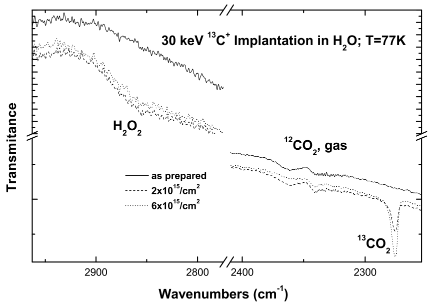

Fig. 2. Transmittance IR spectra of H_2O (77 K) ice before and after implantation of 30 keV $^{13}C^+$ ions at two different ion fluences.

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_2O (77 K) ice before and after implantation of 30 keV $^{13}C^+$ ions at two different fluences (ions cm^{-2}). We use isotopically labeled carbon to avoid the influence of gas phase CO_2 along the path of the IR beam. The appearance of bands testifies for the formation of H_2O_2, and $^{13}CO_2$. The formation of hydrogen peroxide is relevant because it has been detected on the surface of Europa (Carlson et al. 1999b), Ganimede 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 bombarded is responsible for the formation of H_2O_2 on the surfaces of the Jupiter's moons.

Strazzulla et al. (2003) measured the production yield of CO_2 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, Ganimede 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_2 (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_2SO_3) whose formation and stability is possible only under

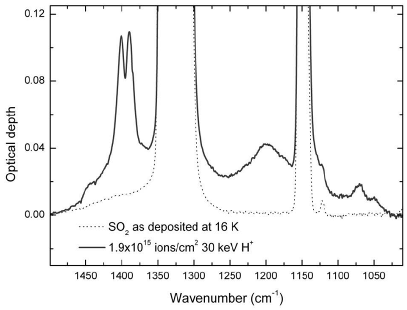

Fig. 3. IR spectra, in optical depth unit, of SO_2 ice (16 K) before and after implantation of 30 keV H^+ ions.

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 (Voegele et al. 2004) proposed that H^+ implantation in SO_2 ice can drive the formation of H_2SO_3. We have performed experiments of implantation of 30 keV H^+ in low T sulfur dioxide (Garozzo et al. 2008). The results (Fig. 3) indicate that H^+ implantation produces, in the IR spectrum, bands attributable to SO_3 (see the doublet at 1389-1400 cm^{-1} and the band at 1070 cm^{-1}), polymers (evidenced by the broad band at 1205 cm^{-1}), and O_3 (band at 1050 cm^{-1}) (Garozzo et al. 2008). The only molecules containing the projectile are O-H bonds and most probably H_2 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 relevant quantity of CO_2 can be formed by carbon ions implantation on Europa, Ganimede and Callisto, this is not the dominant formation mechanism. - Implantation of protons into sulfur dioxide produces mainly SO_3 and polymers, and O_3 but not H-S bonds. The results do not support the hypothesis that H implantation could result in the formation of H_2SO_3 on Io.

Acknowledgements. The research leading to these results has received funding from the [European Community's] Seventh Framework Programme [FP7/2007-2013] under grant agreement n [238258]. This work was also supported by Italian MIUR PRIN-2008.

References

Baratta, G.A. & Palumbo, M.E. 1998, JOSA 15, 3076
Brown, W.L. et al. 1978, Phys. Rev. Lett. 49, 1027
Brucato, J.R., Palumbo, M.E., & Strazzulla, G. 1997, Icarus 125, 135
Brunetto, R., & Strazzulla, G. 2005, Icarus, 179, 265
Carlson, R.W., Johnson, R.E., & Anderson, M.S. 1999a, Science 286, 97
Carlson, R.W. et al. 1999b, Science 283, 2062
Cooper, J.F. et al. 2001, Icarus 149,) 133
Garozzo, M. et al. 2008, PlSpSci 56, 1300
Gomis, O. et al. 2004, PlSpSci 52, 371
Hendrix, A.R., Barth, C.A., & Hord, C.W. 1999, JGR 104, 14.169
Hibbitts, C.A. et al. 2002, JGR 107, 5084
Lane, A.L., Nelson, R.M., & Matson, D.L., 1981, Nature 292, 38
Loeffler, M. J. et al. 2006, Icarus, 190, 265
McCord, T. B. et al. 1997, Science 278, 271
Moore, M. H., & Hudson, R. L., 2000, Icarus 145, 282
Moroz, L. et al. 2004, Icarus,170, 214
Sack, N. J. et al. 1992, Icarus 100, 534
Strazzulla, G. et al. 2003 Icarus 164, 163
Strazzulla, G. 1999 PlSpSci 47, 1371
Palumbo, M.E. 1997 AdvSpRes 20, 1637
Palumbo, M.E. et al. 2008 ApJ685, 1033 20, 1637
Ottaviano, L., Palumbo, M.E. & Strazzulla, G. 2000 Conf Proc. 68, SocItalFis, pp149

Strazzulla, G., Baratta, G.A. & Palumbo, M.E. 2001, Spectrochimica Acta A57, 825
Strazzulla, G. et al. 2003, Icarus 164, 163
Strazzulla, G. et al. 2005, Icarus, 174, 31
Strazzulla, G. et al. 2007, Icarus, 192, 623
Voegele, A.F. et al. 2004, Icarus 169, 242.