Icy Bodies of the Solar System
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Heavy ion irradiation of astrophysical ice analogs

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Abstract. Icy grain mantles consist of small molecules containing hydrogen, carbon, oxygen and nitrogen atoms (e.g. H_2O, CO, CO_2, NH_3). Such ices, present in different astrophysical environments (giant planets satellites, comets, dense clouds, and protoplanetary disks), are subjected to irradiation of different energetic particles: UV radiation, ion bombardment (solar and stellar wind as well as galactic cosmic rays), and secondary electrons due to cosmic ray ionization of H_2. The interaction of these particles with astrophysical ice analogs has been the object of research over the last decades. However, there is a lack of information on the effects induced by the heavy ion component of cosmic rays in the electronic energy loss regime. The aim of the present work is to simulate of the astrophysical environment where ice mantles are exposed to the heavy ion cosmic ray irradiation.

Sample ice films at 13 K were irradiated by nickel ions with energies in the 1-10 MeV/u range and analyzed by means of FTIR spectrometry. Nickel ions were used because their energy deposition is similar to that deposited by iron ions, which are particularly abundant cosmic rays amongst the heaviest ones.

In this work the effects caused by nickel ions on condensed gases are studied (destruction and production of molecules as well as associated cross sections, sputtering yields) and compared with respective values for light ions and UV photons.

Keywords. astrochemistry, methods: laboratory

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1. Introduction

Astrophysical ices are exposed to many types of irradiation either with high and low energy; they are: energetic particles from galactic cosmic rays and stellar or solar wind (in the case of the solar system), UV radiation and the particles accelerated by the giant planets magnetosphere (Gerakines *et al.* 2001; Dartois 2005; Pilling *et al.* 2009). The irradiation produces a number of effects whose knowledge is relevant to understanding the evolution of these objects. One can distinguish two major effects: (i) sputtering (the material is eroded at the surface) and (ii) physical-chemical modifications in the bulk, including the formation of different molecules.

Most of the experiments on laboratory ices have been done with protons and helium ions using infrared spectroscopy as a tool to follow and describe the evolution. Some experiments using heavy ions beams (mostly Oxygen and Argon) were performed at low energy and using mass spectrometry or RBS to analyze the ices. In the current work, the ices were irradiated by heavy ions in the electronic energy loss regime and analyzed with IR spectroscopy.

Nickel is one of the solar wind and cosmic rays components. Recently, its abundance in the solar wind was measured Karrer *et al.*(2007). As thestopping powers of Ni and Fe are close one to the other, the physical and chemistry processes induced by them are similar.

The objectives of this work are: (i) to understand the mechanisms of swift heavy ion interactions with molecular solids (ices); (ii) to identify the new species formed; (iii) to determine the destruction and formation cross sections for molecules; (iv) to determine the sputtering yields induced by heavy ions.

2. Experimental procedure

The experiments were performed in the CIMAP-GANIL laboratory situated at Caen, France, where beams in a wide range of ions (up to lead) and energies (up to GeV) are available. To simulate the astrophysical environment, the ices were formed inside a vacuum chamber by the condensation of gases on a cold substrate. The experimental device used, called CASIMIR, allows to regulate the sample temperature and measure the infrared spectra. The cryostat works by closed-cycle of helium gas. The ices were prepared by gas condensation onto a CsI substrate at 13 K. The CsI is a small disk with 13 mm diameter and 2 mm thick. It is positioned at the extremity of the cryostat. To reduce the effects of thermal radiation, a shield was installed around the substrate. Its temperature is maintained at 70 K. The ensemble is positioned inside the spectroscopy cuve. More details about the experimental procedure can be found in Seperuelo Duarte *et al.* (2009).

3. Results

Figure 1 presents the IR spectrum of CO ice before and after heavy ion irradiation. Many infrared bands were identified by means of their wavenumber positions (Trottier *et al.* 2004; Jamieson *et al.* 2006; Palumbo *et al.* 2008).

The decrease of the ice column density is related to the formation of other species and to sputtering induced by heavy ions. To analyze theseeffects, the data were fitted by an equation taking into account both the destruction cross section and the sputtering mechanism (Seperuelo Duarte *et al.* 2009)

$$N = N_0 \exp(-\sigma_d F) - Y/\sigma_d (1 - \exp(-\sigma_d F)) \tag{3.1}$$

where N_0 is the initial column density, σ_d – the destruction cross section, and Y – the sputtering yield. Table 1 presents the cross sections and a sputtering yields measured for the ices studied in the current experiment. In the case of water ice and ammonia, a condensation from the residual gas prevented the measure of the sputtering yield.

4. Conclusions

Ice films were irradiated by MeV Ni ions. The new species produced in the samples are essentially the same as those found after proton, photon, and electron irradiation.

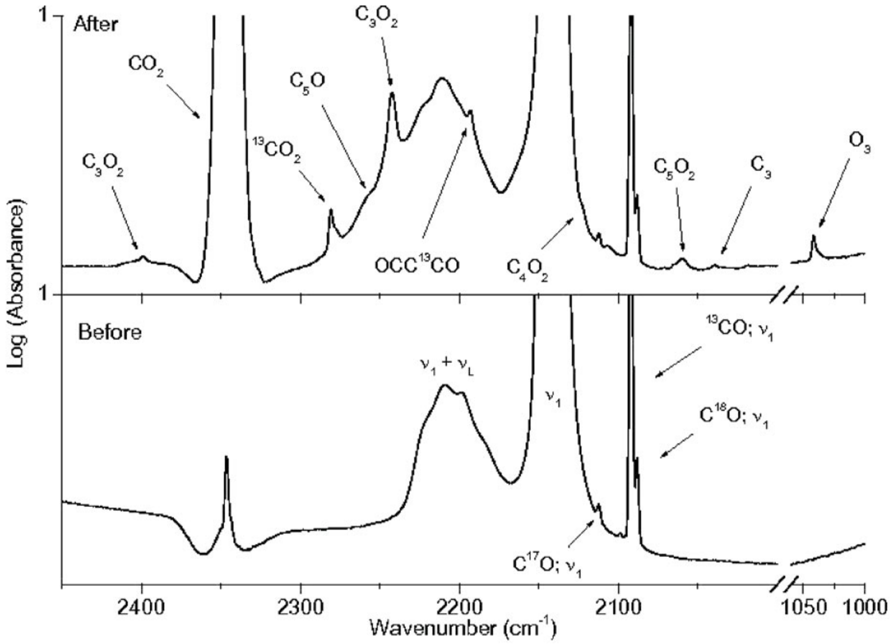

Figure 1. Infrared spectrum of CO ice before and after 46 MeV $^{58}Ni^{11+}$ irradiation with fluence of 1.0×10^{12} cm^{-2}. Many infrared bands were identified by means of their wavenumber positions.

Table 1. Destruction cross section and sputtering yield values of ices studied in this work.

Species	σ_d (10^{-13}cm^2)	Y (10^4 molecules/impact)
H_2O	1.1	-
CO	1.4	9
CO_2	1.7	4
*NH_3	1.4	-

Notes: *Value measured in a mixture of H_2O:CO:NH_3 (1:0.4:0.6).

Destruction and formation cross sections, as well as sputtering yields were determined. The measured sputtering yields scale with the squared electronic stopping power values, extending for higher S_e the results of Brown *et al.* (1984). Desorption induced by heavy ion sputtering is proposed to be one of the dominant processes leading to the presence of gas phase CO molecules for grains deep inside dense clouds and protoplanetary disks.

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