

SOLAR WIND AND COSMIC RAY IRRADIATION OF GRAINS AND ICES -  
APPLICATION TO EROSION AND SYNTHESIS OF ORGANIC COMPOUNDS IN THE SOLAR SYSTEM.  
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Introduction. The solar wind irradiation of the lunar surface modifies the physical, chemical and isotopic properties of the micron-sized grains at the very top of the regolith. In particular, it is responsible for their very high erosion rate as well as the presence of organic compounds within the amorphous layer surrounding the grains (1). We have studied, through in-situ infrared spectroscopy, the carbon chemistry of  $\text{SiO}_2$  implanted with mixtures of keV H + He + C ions (2). In this paper, we present the experiments performed with  $\text{H}_2\text{O}$  ice implanted by keV ions, intended to simulate the irradiation of comets, ring grains and satellites of outer planets, either by the primitive solar particles or by contemporary solar wind or solar cosmic rays nuclei.

Experimental Procedure. Thin films of  $\text{H}_2\text{O}$  ice are made onto a KBr substrate maintained at liquid nitrogen temperature within a vacuum chamber, by the condensation of Milli-Q processed water at a speed of  $\sim 0.5 \mu\text{m h}^{-1}$ . The thicknesses of the films are measured by the absorption bands that appear in the  $4300\text{--}400 \text{ cm}^{-1}$  infrared spectrum. The spectra are obtained with a Nicolet MXS Fourier Transform Spectrometer, coupled with a LeCroy 3500 computer. This system is on line with an ion implanter.

The erosion rates are measured by in situ observation of the decrease of the  $\text{H}_2\text{O}$  ice absorption bands. In the  $4300\text{--}400 \text{ cm}^{-1}$  range, the ice presents a number of spectral features, centered at  $3260 \text{ cm}^{-1}$ ,  $830 \text{ cm}^{-1}$ ,  $1620 \text{ cm}^{-1}$  and  $2250 \text{ cm}^{-1}$ , in decreasing order of intensity. The stronger one saturates for film thicknesses around  $1 \mu\text{m}$ . Due to the mean projected range of the implanted ions with energies in the keV region, which do not exceed a few thousands Å, we have chosen to work on films with thicknesses around  $5000 \text{ Å}$ . Consequently, none of the absorption features is saturated and computation of the thicknesses is made with the first two bands. Oscillator strengths are taken from literature. However, our procedure includes an absolute calibration through a Rutherford backscattering experiment, performed on a film condensed onto a Be substrate.

The possibility of storing repetitive spectra allows the detection of synthesized molecules, down to levels smaller than  $10^{14} \text{ molecules cm}^{-2}$ . We have implanted D, He,  $^{12}\text{C}$ ,  $^{13}\text{C}$ ,  $^{15}\text{N}$ , with fluences up to  $10^{17} \text{ cm}^{-2}$  and energies in the keV/amu range.

Sputtering rates. The model proposed below for the formation of organic matter by irradiation requires that the erosion of the irradiated icy grains proceeds at a rate low enough to allow an efficient doping by reactive species. We thus measured the sputtering yields of the grains implanted by H, He and particles with higher masses, for energies of a few keV/amu. Moreover, we measured the yields as a function of the fluxes and fluences, in order to estimate values relevant to the actual astrophysical situations. For H and He irradiations, the rates obtained decrease continuously with fluxes. We have not been able to measure the rates for fluxes lower than  $\sim 1 \mu\text{A.cm}^{-2}$ . Consequently, the erosion rate obtained at  $\sim 1 \mu\text{A.cm}^{-2}$  represents very likely an upper limit of the actual rate, which corresponds to fluxes orders of magnitude lower than that simulated. For that value, the rates are respectively  $0.6 \pm 0.15 \text{ H}_2\text{O}$  molecule per incident proton and  $\sim 4$  for He irradiation.

Considering the elemental ratios in the solar wind, our experimental data lead to a total erosion yield slightly smaller than unity.

Molecular synthesis. After  $^{12}\text{C}$  and  $^{13}\text{C}$  implantations, the most intense lines that appear are those of  $^{12}\text{CO}_2$  and  $^{13}\text{CO}_2$ , at  $2340$  and  $2275\text{ cm}^{-1}$  respectively (figure). As in the case of C implantation into silicates (2), the bands corresponding to implanted species are different from those of gaseous ones: instead of the usual P-R double structure due to vibration-rotation transitions, we observe single bands for implanted species; moreover, these bands are slightly shifted towards smaller wavenumbers in comparison with the center of the gaseous double structure. However, in contrast with the implantation within  $\text{SiO}_2$ ,  $\text{CO}_2$  remains the dominant C compounds at high fluences, instead of being partly transformed into CO.

It is interesting to note that hydrocarbides are not the dominant species upon the implantation of C into  $\text{H}_2\text{O}$ . Thus, the observations of CO and  $\text{CO}_2$  in cometary tails, in large excesses as compared with molecules or radicals containing C-H bondings, would be consistent with an irradiation origin for the carbon chemistry in comets. Our experiments would also indicate that the primary molecules are  $\text{CO}_2$ , CO resulting from their partial photodissociation within the coma.

Discussion. We propose a model for the formation of organic matter within icy solar system bodies, in agreement with our experimental results of erosion rates. The organic molecules, frozen-in within the icy mantles of the grains present in the protosolar nebula, would originate from their primitive irradiation. Such an irradiation would have taken place during an early stage of the proto-sun, when both the low energy (solar wind) and high energy (cosmic ray) particles were by orders of magnitude more intense.

- (1) Bibring J-P. and Rocard F. (1982), Ion implantation phenomena in space, *Rad. Effects*, **65**, 159-165
- (2) Rocard F. and Bibring J-P. (1982), Molecule formation by implantation in insulators, *Phys. Rev. Lett.*, **48**, 25, 1763-1766

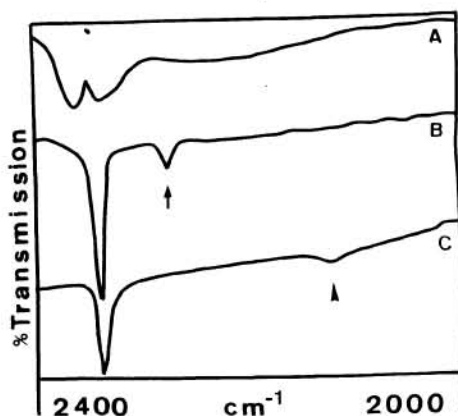


Fig. :  $2400 - 2000\text{ cm}^{-1}$  infrared spectra of: (A) unirradiated  $\text{H}_2\text{O}$  ice. It exhibits the usual double structure centered at  $2349\text{ cm}^{-1}$ , corresponding to residual atmospheric  $\text{CO}_2$  within the spectrometer. (B) same film, after implantation of  $3.5 \cdot 10^{16}\text{ cm}^{-2}$   $^{12}\text{C} + ^{13}\text{C}$  40 keV ions. The two bands which appear at  $2340$  and  $2275\text{ cm}^{-1}$ , correspond to  $^{12}\text{CO}_2$  and  $^{13}\text{CO}_2$  (arrow) respectively. (C)  $\text{SiO}_2$  film implanted with  $5 \cdot 10^{16}\text{ cm}^{-2}$   $^{12}\text{C}$  40 keV ions. The irradiation leads to the synthesis of  $^{12}\text{CO}_2$  and  $^{12}\text{CO}$  (arrow), centered at  $2341$  and  $2130\text{ cm}^{-1}$  respectively.