THE ROLE OF LABORATORY IN ASTROPHYSICS: LABORATORY EXPERIMENTS ON ICES AND ASTROPHYSICAL APPLICATIONS

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Abstract: Laboratory experiments allow the scientific to simulate some of the conditions where the molecules of astrophysical interest are synthesized, and to study likely mechanisms that could have led to produce them. In a typical astrophysics laboratory many relevant physical properties (optical constants, density, absorbance, etc) can be studied along with their variations induced by temperature changes and UV or ion irradiation. In this work, we want to offer to the reader a general overview of the components of a typical astrophysics laboratory. In addition, we will present some results obtained after carrying out experiments on ion irradiation of ices. These experiments are carbon implantation in water ice and ion irradiation of methane. Finally, some astrophysical applications are shown to highlight the possibilities of this kind of experiments.

1 Introduction

During the last century observational astrophysics has moved from carrying out observations only in the visible region to span a much wider range of the electromagnetic spectrum (from gamma rays to radio). As a matter of fact, infrared (IR) observations have opened the possibility of studying molecules in gas or solid phase [1, 2]. The improvement in the resolution of the instruments and space observatories that avoid the problem of the strong absorption of H_2O and CO_2 present in our atmosphere, have made possible to identify some molecules in solid state phase such as H_2O, CO_2, CO and CH_4. Physical and spectroscopic properties of such molecules have been studied both by theoretical and experimental ways [3, 4, 5]. In fact, laboratory experiments using in-situ IR spectroscopy are a fundamental tool to understand the space chemistry. In a laboratory, it is possible to simulate adsorption-desorption processes, thermal annealing and UV or ion irradiation [6, 7, 8, 9]. Irradiation plays an important role in the chemical evolution of molecules whose formation reactions demand an energetic contribution [10, 11]. Depending on the scenario of interest a kind or another of radiation becomes relevant. In the inner part of molecular clouds, protected from the external UV field, ion irradiation is supposed to be the dominant mechanism. Our Solar System presents also scenarios where ion irradiation is dominant as the icy Galilean satellites immersed into the intense magnetosphere of Jupiter [12].

In the next sections we will show some results obtained after carrying out experiments on ion irradiation of ices. With this objective in mind, some experiments carried out in the "Laboratorio di Astrofisica Sperimentale di Catania (LASp)" Italy, will be discussed. In section 2 the experimental setup will be described. Ion irradiation experiments will be presented in section 3 showing that ion irradiation induces the modification of the physical and chemical properties of the ices. Finally, section 4 shows some astrophysical applications based in part on the experiments presented in section 3.

2 Experimental setup

The basic components of an astrophysics laboratory are a vacuum and low temperature system, an analysis technique, and for ion irradiation experiments, an ion gun. Figure 1 shows a block diagram of the experimental apparatus present in the LASp where all the experiments shown below have been carried out. The main component is a vacuum chamber (P $\sim 10^{-7}$ mbar). Inside the chamber is located a cold finger whose temperature ranges between 10 and 300 K. The working temperature is obtained from the balance of two factors. First of all, there is a closed-cycle He cryostat that is used to cool the substrate down to 10 K. Subsequently, a stationary temperature is kept by mean a resistor. The vacuum chamber has three windows. Two of them are made of KBr and are faced one to each other. This setup allows us to obtain the transmittance spectrum with a FTIR spectrometer Bruker Equinox-55, with a resolution of 1 cm^{-1}. The third window, perpendicular to the previous ones, let us to irradiate the sample. The surface where the ice is deposited onto, forms 45^o with both the ion and the infrared beams. In this way the sample can be analyzed before, during and after irradiation. Gases or mixtures of the molecules under study are prepared in a pre-chamber in a proportion estimated from their partial pressures. The gases come into the chamber through a needle valve that regulates the flow of the gas. The molecules accrete onto the substrate (usually a specular monocrystalline

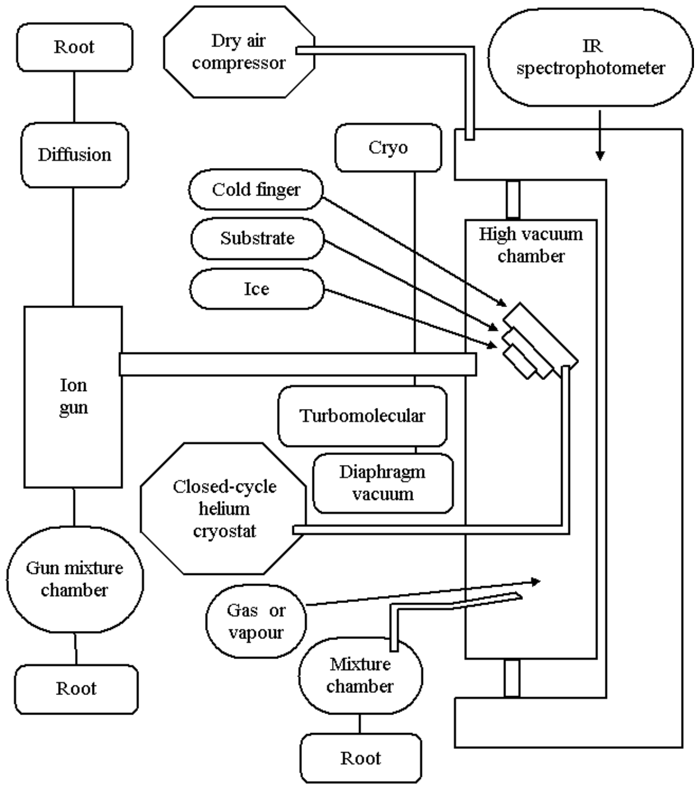

Figure 1: Block diagram of the experimental apparatus present at the Catania Laboratory of Astrophysics.

silicon wafer) put in thermal contact with the cold finger. The thickness of the sample is monitored by interferometry using an He-Ne laser beam. Since not all the molecules have the same sticking coefficient, the final composition of the ice is analyzed by the IR spectrometer. The ice can be irradiated during and/or after deposition, with an ion previously accelerated with a 30 kV potential. Deflection plates placed along the ions path let us irradiate the sample homogenously. The ion flux is controlled in order to avoid the macroscopic heating of the sample. The effect of the ion beam on the ice is monitored continuously with the spectrometer. It is also possible to carry out Temperature Programmed Desorption (TPD) experiments which let us study the sublimation temperature of the deposited and produced molecules. For further details on the experimental setup see [13, 14].

The experiments here described try to simulate the energetic processes suffered by the ices in different astrophysical scenarios. Depending on the scenario we are interested in, composition, thickness and temperature of the ices, and energy and kind of ion can vary vastly. Let's take as an example the ices present in the dense interstellar medium (ISM) and on the surface of the Jovian satellite Europa. In the first case the thickness of the ice is about tenths of microns while in Europa is more than nine orders of magnitude greater. As far as the ion flux is concerned, in the Jupiter satellite is around six orders of magnitude bigger than in the ISM. On the contrary, the energy of the most abundant ions in Europa is at least one order of magnitude smaller than those in the ISM. The experiments that better reproduce the dense ISM are called *thin film experiments* because the impinging ions have enough energy to pass throughout the sample. On the other hand, experiments that try to reproduce the situation found in a satellite surface or a comet are called *thick film experiments*. In this case, the ion has not enough energy to pass throughout the ice and is implanted into the target [15]. In this situation if the implanted ion is reactive (H^+, C^+, O^+, etc) the new molecules formed could contain the impinging ion [16].

3 Irradiation experiments

In this section some effects of ion irradiation of ices will be shown, in particular the chemical changes induced by ion irradiation.

3.1 Introduction

When a particular ion penetrates inside a material interacts with its atoms loosing energy as it travels through it. The interaction between the ion and the ice can be divided in two different types. The first one is electronic (excitations and ionizations) and the second one is nuclear (breaking of bonds and atomic displacements). These two mechanisms are also called inelastic and elastic respectively. For a detailed description of these processes we refer the reader to Johnson's book [17]. As said above, as the ion passes through the sample several processes are induced such as local increasing of temperature, formation of excited species and ions, etc. Local increasing of temperature is an important effect that must be taking into account when carrying out experiments of astrophysical interest. In space, the number of ions impinging on a surface usually is not enough to produce the macroscopic heating of the same. On the contrary, in laboratory one must be sure that the used ion flux is low enough to avoid heating up macroscopically the sample and therefore to produce some unwanted thermal processes.

The effects induced after ion irradiation of ices can be summarized as follows:

- Physical and chemical modifications of the target are produced including the formation of new species.
- In the case of an implantation experiment (*thick film*), if the used ion is reactive, the possibility exists that the new molecules formed contain the projectile.
- Material is eroded from the target (sputtering).

3.2 Implantation of $^{13}C^{+}$ in water ice

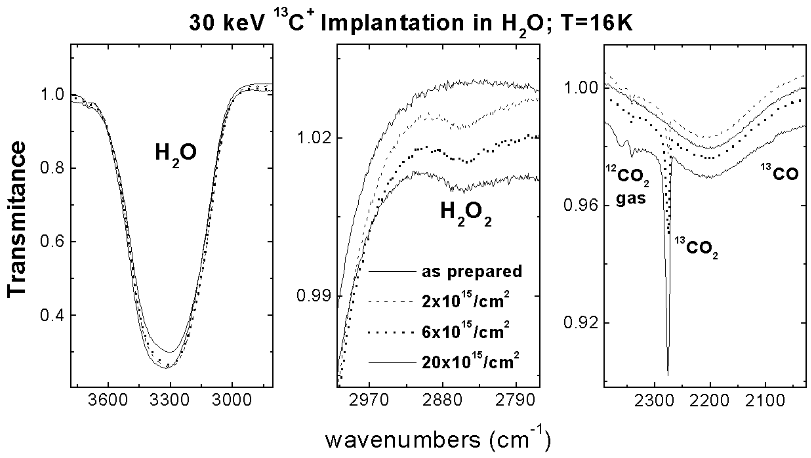

Figure 2: H_2O ice spectra as deposited and after implantation of 30 keV of $^{13}C^{+}$. From left to right, the three spectral regions correspond to H_2O, H_2O_2, and $^{13}CO_2$ and ^{13}CO bands respectively [10].

Figure 2 shows the results obtained after implantation of $^{13}C^{+}$ in water ice at a temperature of 16 K. In the figure are shown three different spectral regions. In the first one it is shown the 3.03 μm (3300 cm^{-1}) water ice band and how its area decreases as ion fluence increases. The decreasing in the water ice band intensity is due to two different effects. The first one is the water ice sputtering. The second one is that part of the radicals produced by ion irradiation can react to produce new molecules. The second region of the spectrum testifies for the appearance of a new species. In this particular case the feature centered at 3.50 μm (2850 cm^{-1}) is attributed to the hydrogen peroxide molecule. In this way we present a case where ion irradiation has produced a molecule originally not present in the sample. Finally, the third region shows that, after the implantation of 30 keV of $^{13}C^{+}$, $^{13}CO_2$ is detected. In this particular case, we have found a molecule originally not present that contains the projectile. As can be seen from the figure, we have also detected for the highest ion fluence ^{13}CO. Taking into account the band intensities and the integrated absorbances of both $^{13}CO_2$ and ^{13}CO, we have deduced that ^{13}CO has not been produced directly by ion implantation of $^{13}C^{+}$ but it comes from the destruction of $^{13}CO_2$. To conclude this section, we would like to point out that ion implantation into an ice not always produces species containing the impinging ion. As an example, oxygen implantation in frozen methane does not produce neither CO_2 nor CO [18].

3.3 Ion Irradiation of CH_4 ice

An important kind of compounds suggested to be present in different astrophysical scenarios are organic molecules. The study of the carbon chemistry has a particular interest because of its possible implication in the origin of life. In fact, the study of the formation of more complex organic compounds such as polymers from elemental molecules for instance CH_4 turns out to be very attractive [19].

Figure 3 shows the results obtained after irradiating with 60 keV of Ar^{++} ions on pure methane ice at 12 K [11]. The bottom part of the figure shows the spectrum of CH_4 deposited at 12 K in two different spectral regions. In the upper part of the figure the same spectral regions are shown after the CH_4 has been irradiated. In this experiment the thickness of the CH_4 ice is about 4 μm. The amount of energy deposited in average after irradiation (7 eV/16 amu), has been calculated in eV per 16 atomic mass units (eV/16amu). This is a convenient way of expressing the dose that allows to compare results obtained by different authors.

From figure 3 can be observed the appearance of many new IR bands after irradiation. These features mainly correspond to new synthesized organic molecules such as acetylene, ethene, ethane and propane. There are also some weak bands that we have not been able to assign to any particular species. These latter bands could be attributed to a carbonaceous residue of unknown composition. In the laboratory, it has been checked that this residue is refractory. In fact, when the temperature of the irradiated sample is increased up to room temperature all the ices sublimate and the only compound that remains onto the substrate is the residue. This stability at room temperature allows to analyze it with other techniques such as UV-Vis spectroscopy, Raman spectroscopy and photoluminescence. We have shown a general result that can be summarized as saying that ion irradiation of simple organic molecules produces

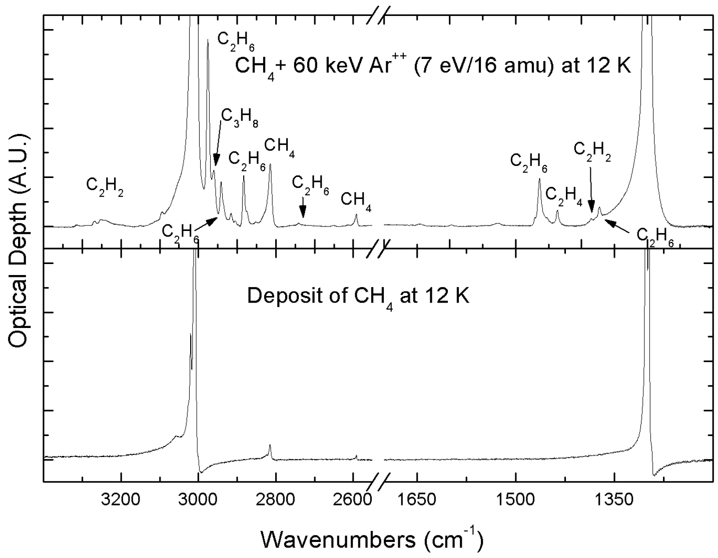

Figure 3: Spectra of methane ice as deposited at 12 K (bottom) and after irradiation with 60 keV Ar^{++} ions (top) in two different spectral regions.

a progressive carbonization (dehydrogenation) on the original ices.

There are some interesting experiments that can be carried out after irradiation of an ice with ions. By using TPD the sublimation dependence of an ice can be studied. It is known that ices sublimate at different temperatures depending on the matrix the molecule is embedded in. In the case the ice or mixture has been previously irradiated the variation of the sublimation temperature can be even greater.

4 Conclusions and astrophysical applications

The effects produced after ion irradiation of ices can be summarized as follows:

- Irradiation destroys sample molecules producing radicals that can then react to form new species.
- In the case a reactive ion is implanted into the ice, the possibility exists that it could form part of the new synthesized molecules.

- Ion irradiation of organic molecules produces a progressive dehydrogenation of the sample. After irradiation a residue is produced. This residue is stable at room temperature.

- Chemical and physical changes due to ion irradiation increase in some cases the sublimation temperature of the ices. These variations depend on the ice mixture, the used ion and on the irradiation dose.

To conclude we would like to give some examples of astrophysical scenarios where ion irradiation experiments have interest.

The first scenario is the Jupiter satellite Europa. NIMS data from the Galileo spacecraft have revealed a feature in the spectrum of Europa's surface that has been attributed to the molecule of H_2O_2. Recent experiments on ion irradiation of water ice have shown that hydrogen peroxide may be produced by radiolysis even if water ice is the only component found on the surface of satellite Europa [12]. The high efficiency for the production of hydrogen peroxide measured for $^{13}C^+$ and for other heavy ions, specially for oxygen, opens also the possibility of a patchy distribution on the surface of the satellite [12]. This result could be useful to support the suggested possibility of a radiation-driven ecosystem on Europa based on the availability of organic molecules and oxidants such as hydrogen peroxide [20].

There are several places in the Solar System such as Pluto and Triton where CH_4 ice is present [4] and suffers from ion irradiation. The chemistry induced by low energy ions on the uppermost layers of a surface is considered to be quite equivalent to that induced by more energetic cosmic ions at the end of their travel into thick solid bodies [15]. As an example, it has been evaluated that a fraction of 30 per cent of original ice can be altered at a depth of about 10 m within a cometary surface [15]. Pluto is in fact exposed to cosmic ions [21] and as a consequence its surface is altered to a depth of several meters during its total lifetime. On the other hand, low energy ions, which have higher fluxes, alter the outer surface layers of the planet in a much shorter timescale. On Triton the effects could be even more relevant because the satellite can also be bombarded by ions present in the magnetosphere of Neptune.

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