Abstract

Astronomical bodies without atmospheres are subject to irradiation with energetic photons and particles. The resulting surface alterations are evident in the optical reflectance spectra discernible through remote optical sensing from Earth. Here I review the most important processes initiated by electronic excitations and ionizations by ions. These include electronic desorption or sputtering, chemical reactions, and charge transfer. It is argued that dissociative electron attachment and Auger initiated desorption play a role in desorption of ice mantles on grains in dense interstellar molecular clouds. The paper describes the essentials of laboratory simulations and points out to opportunities for atomic collision physicists to contribute to important astrophysical and planetary problems, including the evolution of galactic matter and the possible extraterrestrial genesis of life.

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1. The problem of mass balance in dense interstellar clouds

Let us start by addressing the balance of molecules in the gas and the dust grains in dark molecular clouds (MCs), one of the central unsolved problems in astrophysics [1]. The problem consists in the following. Due to the low temperature of MCs (10–15 K) and high condensation coefficients, all gaseous species, with the exception of H_2 and He would be depleted by condensation on grains, in times of ~10^5 years for typical gas densities [2]. However, no desorption mechanism of those proposed so far can convincingly maintain the gas population observed, during typical MC lifetimes of millions of years. The lack of understanding is such that desorption rates have been taken as adjustable parameters when modeling MCs [3,4]. In the following, I discuss the desorption mechanisms that have been considered so far and, in the face of their insufficiency,
propose additional mechanisms that may help solve the problem.

1.1. Photodesorption by stellar Lyman-\(\alpha\) photons

We have shown that this mechanism is effective in limiting water ice mantles on grains in low-density diffuse clouds [5,6]. Its importance in denser molecular clouds is uncertain; although Lyman-\(\alpha\) photons do not significantly penetrate dense clouds, they will affect grains if they circulate between the inside and outside of the cloud, or if the cloud is lumpy. Hard ultraviolet photons, which may also be produced in collisions of cosmic rays with gas phase H\(_2\) [7–9], can desorb ice mantles of grains inside the cloud by electronic excitations. However, this UV flux appears to be very low from recent estimates [2,10].

1.2. Desorption by cosmic rays

These energetic particles can desorb by spot heating (a misnomer) or by whole grain heating and sublimation. Spot heating refers to the prompt, non-thermal desorption of molecules around the track of the particle and thus is independent of grain size [11,12]. The estimated lifetime of condensed volatiles due to this mechanism is 4 MY [13]. Thermal desorption induced by cosmic rays is delayed and results from the temperature increase of the whole grain due to the deposited energy [11,14]. But again here the desorption rate is too low, with an estimate mean time to remove volatiles of 8 MY for a 0.25 \(\mu\)m grain [11]. Moreover, recent more accurate molecular dynamics calculations [15] yield desorption rates of volatiles by cosmic ray that are an order of magnitude smaller than the earlier values given above, and thus even longer lifetimes.

1.3. Explosive desorption in exothermic reactions during spike heating of photolyzed ice

This proposed mechanism [11,16–19] requires the buildup of concentrations of a few percent of radical species by photolysis with background UV light [20,21] and, in addition, some heating process that activates chemical reactions involving the stored radicals. This needed heating could be achieved by grain–grain collisions (an original proposal later abandoned) or by a passing cosmic ray. This proposal is based on few experiments on specific gas mixtures (H\(_2\)O, CO, NH\(_3\), and CH\(_4\)) and many assumptions, several of which have been questioned [2]. The time to obtain >1% radical concentration is large if one considers that a fluence of a few \(10^{18}\) photons/cm\(^2\) were needed in the experiments of d’Hendecourt et al. [16] to reach radical concentrations at the percent level required for explosion of the ice when heated. The time to achieve this dose in a MC, with the normally assumed background UV photon flux of \(4 \times 10^3\)/cm\(^2\)/s driven by cosmic rays [7] is again very large, of the order of 30 MY. However, the fluence dependence was not studied, and it is likely that lower fluences (and therefore times) may suffice to build the required radical concentration. For instance, saturation of CO\(_2\) synthesis in CO occurs at a fluence of \(\sim 4 \times 10^{17}\) Lyman-\(\alpha\)/cm\(^2\) [22], and similar fluences also apply for CO production from CO\(_2\) [23]. The explosive desorption mechanism is likely highly selective; for instance, we have seen desorption spikes when heating photolyzed carbon dioxide [23], but not photolyzed water ice.

1.4. Desorption resulting from reactions involving incident free radicals

Impinging radical atoms, like H, O, C, N, produced by UV photons and cosmic rays in gas-phase dissociation collisions [19], can initiate exothermic reactions that result in desorption. This mechanism has been proposed for the formation of H\(_2\) by recombination of incoming H (by far the most abundant radical), making the assumption that at least 1% of the \(\sim 4.5\) eV released in H-H recombination on a grain surface goes into desorption of a molecule in an adjacent site [2,24]. However, no experimental evidence supports this model and it is likely that the probability of the process was overestimated. From what is known of molecular dynamics simulations in the solid state, the H\(_2\) molecule would cool fast by multiphonon relaxation involving a large number of atoms in the grain.
1.5. Desorption by dissociative electron attachment

Electrons from gas-phase ionization in the MC by passing cosmic rays will degrade in energy very slowly once they fall below \( \sim 10 \text{ eV} \) (so-called sub-excitation electrons) and join other low energy electrons from photoionization of gas molecules and photoelectron emission from grains. These slow electrons may collide with grains and be trapped, and in fact this is one of the processes often mentioned when discussing possible dust charging. Electrons of a few eV interact most efficiently with molecular ices through the process of dissociative electron attachment (DEA), symbolized by \( \text{AB} + e^- \rightarrow \text{AB}^- \rightarrow \text{A}^- + \text{B}. \) That is, an electron (\( e^- \)) attaches to a molecule \( \text{AB} \) to produce a transient excited anion \( \text{AB}^- \) in a repulsive potential, which then dissociates into the molecular fragments \( \text{A}^- \) and \( \text{B} \). Since DEA has not been considered before for IS grains, I discuss it further here.

A competitive channel to DEA in the gas phase is the decay of the repulsive state back to the ground state by emitting the electron (autodetachment), with the only effect remaining being vibrational excitation in the final state of \( \text{AB} \) and a lower energy electron. When the molecule dissociates, the excess kinetic energy gained by the fragments can result in direct desorption. If DEA occurs in the bulk, the energized fragment will collide with adjacent molecules and start a collision cascade, such as in the case of sputtering. If this collision cascade is close to the surface – as is the case for thin ice mantles – the result can be desorption of a surface molecule, most likely uncharged.

Dissociative electron attachment appears to occur in the most common ices that are relevant in astrophysics, including CO, O\(_2\) [25], and amorphous H\(_2\)O ice [27]. With cross sections of the order of \( \sigma \sim 10^{-17} \text{ cm}^2 \) [28], the probability of a DEA event will be unity in a typical 100-monolayer ice mantle impacted by these low energy electrons.

1.6. Auger desorption by neutralization of slow ions

In this mechanism, also not considered before for desorption of interstellar ices, an ion captures a valence electron from a condensed molecule, with the energy released in exciting another valence electron (an Auger process). Energetically, it is favored that the two final holes remain in different molecules. The Coulomb repulsion energy between the two ions, acting before the holes can drift away, can transform into kinetic energy and result in desorption. For this process to occur, the recombination energy of the incoming ion must exceed the energy of the two holes in the lattice. Such a condition will exist for He\(^+\) impacting most condensed gases, and for H\(^+\) on some ices with sufficiently small band gap. Less abundant multiply charged ions can also be expected to produce Auger desorption, with a higher probability per ion impact.

2. Radiation synthesis of complex molecules

Ice-coated interstellar grains are thought to be the matter from which comets form during the gravitational collapse of a part of a dense molecular cloud – the presolar nebula – into the proto-planetary disk. This is suggested by the content of volatiles gases in comets [29–34]. Interstellar grains, including their ice mantles are processed by gas-surface reactions, radiation (ultraviolet photons and fast ions) [35–40] which result in the synthesis of complex molecules, including prebiotic species [41], that may have had a role in the formation of life on Earth. Such molecules are identified on interstellar ice mantles from the analysis of absorption bands in infrared spectra, most notably lately from the Infrared Space Observatory (ISO) [42], based on laboratory simulations that include the essential aspects of the problem. These simulations have normally involved the growth of interstellar ice mantle analogs (thin films of pure ices or ice mixtures), irradiation with UV photons or energetic particles and characterization by infrared spectroscopy. Comparison of the infrared spectra of the processed ice samples and astronomical spectra
then serve to identify the physical state of particular ices and obtain abundances which serve to test hypotheses and constrain models [32,41,43–46].

A specific question in this area is the observed abundance of condensed carbon dioxide, which is greater than expected from the known concentration in the gas phase. Carbon dioxide can be synthesized by radiolysis of solid carbon monoxide, but recent measurements using Lyman-\(\alpha\) photons and 200 keV protons suggest that radiolysis is insufficient to produce the observed CO\(_2\)/CO abundance ratios in interstellar ices [22]. It is possible that an additional process, found in our laboratory, can account for the discrepancy. This is the synthesis of CO\(_2\) when carbon grains coated with water ice are irradiated by 100 keV ions [47].

Another mechanism for molecular synthesis can occur on grain surfaces by impinging radical atoms created in dissociation collisions by cosmic rays and UV photons [19]. Reactions between radical atoms and surfaces will occur except at low temperatures in cases where there is an activation barrier; thus their study is important to provide input to models of gas–grain chemistry [48]. There have been interesting experimental studies of reactions involving radicals on analogs of astrophysical surfaces [49–53]; few of those are quantitative. In a significant study Vidali and co-workers [54] searched for the reaction O (thermal) + CO (ice) \(\rightarrow\) CO\(_2\). They detected no CO\(_2\) formation at 5 K, consistent with the existence of a predicted activation barrier [55]. However, they observed the release of CO\(_2\) when heating a frozen CO + O ice to 160 K indicating that the reaction occurred while heating.

3. Radiation processing of solar system ices

The tenuous atmospheres around the icy satellites in the outer solar system allow solar ultraviolet photons and energetic charged particles from the solar wind and planetary magnetospheres to impact on the icy surfaces, causing sputtering and radiolysis. The sputtered species may escape the gravitational pull or may contribute to the formation of an atmosphere, adding to any existing contribution of sublimation [56–58] or meteorite impact ejection. The incoming radiation also generates radiation products in the atmosphere that in turn interact with the surface through solid-state chemical processes. Therefore, the state of the surface of the icy bodies is determined by a competition of radiation damage and erosion due to energetic particles, photons, meteorite impact, and sublimation, by thermal diffusion, by interactions with the atmosphere, and by a variety of radiation enhanced chemical processes. These include formation of radicals, synthesis of new molecules, creation of optically active centers, phase transitions, release of trapped gases, and surface roughening [56,59–62]. Disentangling the interrelated phenomena requires laboratory studies of individual processes and their mutual effects, to expand our knowledge and constrain parameters in theoretical models.

There have been several experiments that show the presence of trapped radicals in radiolyzed or photolyzed condensed gases. Here we summarize the results for water ice, the most fundamental of those substances. Dissociation in the solid state often leads to immediate reformation of the molecules, since the dissociation fragments suffer collisions with surrounding molecules and cannot escape. The consequence of this phenomenon, called the cage effect, is a substantially smaller yield of radiation products in solids as compared to the gas phase [63]. The early stages of radiation chemistry studies used gamma ray irradiation and electron spin resonance analysis, showing formation and trapping of isolated H, O and OH radicals at low temperatures. Such radicals become mobile at \(\sim\)100 to 120 K, and react to form stable molecular products such as H\(_2\)O\(_2\), O\(_2\), and HO\(_2\). Energetic ions, on the other hand, can produce a high density of radicals in their track, which can recombine immediately. This causes a higher yield of molecular products as compared with the case of gamma rays or fast electrons.

Of the molecular products, O\(_2\) is particularly important because solid oxygen was detected on Ganymede, a satellite of Jupiter. This finding has been very perplexing, because at the reported high diurnal temperatures in Ganymede the vapor
pressure of O₂ would exceed the atmospheric pressure by several orders of magnitude. The interpretation of the astronomical observations has been controversial. Our experiments show that the quantity of O₂ generated by radiolysis in water is orders of magnitude smaller than assumed [64–66] but suggest that atmospheric oxygen can condense on cold patches of the surface during the night and evaporate slowly during the day.

Whenever O₂ is present in a radiation experiment, the synthesis of ozone is expected. Several experiments were performed in ozone synthesis in condensed gases to understand observations by the Hubble space telescope of ozone on several icy satellites. We quantified the ozone column density by measuring the depth of the Hartley band in reflectance spectroscopy, during irradiation with 100 keV protons, finding that these ions are two orders of magnitude more efficient in producing ozone that previously thought [67] We could synthesize ozone not only with ices containing O₂, but also irradiating CO₂ and H₂O₂. No ozone was found irradiating pure water ice, within the detection sensitivity of our optical and mass spectrometer techniques. Ozone was also detected by mass spectrometry during thermal desorption of the irradiated ices. An interesting finding has been that that ozone formation doubles the sputtering yield of solid O₂ [68].

In our experiments of photodesorption of water ice using Lyman-α radiation [5,6] and 100 keV protons [69], we observed that evaporation of the photolyzed ice released not only water, as expected, but also HO₂ and H₂O₂ molecules. The hydrogen peroxide molecule is important because it was identified in the Galilean satellite Europa through the absorption of solar infrared and ultraviolet light [70]. This observation led to new studies where H₂O₂ synthesis was detected using infrared spectroscopy of ice during irradiated with protons and heavy ions [71–73]. All these results not only explain the presence of H₂O₂ in the Galilean satellites but also lead to the prediction of even larger concentrations of this molecule in colder icy satellites (such as those around Saturn, currently being explored by the Cassini probe), and in the ice mantles of interstellar grains.

4. The prospects of extraterrestrial life

Finding extraterrestrial life would have profound implications for humanity, and it is therefore natural that the possibility drives strong scientific curiosity. Potential habitats for life in our solar system beyond Earth include the icy Galilean satellites, especially Europa, which is covered with water ice and which, according to several pieces of evidence, may have a warmer subsurface ocean, hundreds of kilometers below an icy crust. The exciting possibility that such an ocean might contain life brings the question of the source of energy required for life, at the depths below the surface where photosynthesis is not possible. Chyba [74] has proposed that energy may be provided by the relatively intense flux of energetic charged particles that strike Europa’s surface [58] (∼10¹² keV/cm² s). Such radiation could liberate oxygen from oxygen-bearing species like water, carbon dioxide, and sulfur dioxide, which are known to exist in the surface ice. This oxygen and other radiolytic oxidants like hydrogen peroxide or ozone, would in turn release energy in reactions with hydrocarbon compounds. Since the penetration of radiation is limited to depths of typically microns and at most a few centimeters, a mechanism is required to transport the energy kilometers deep to reach the ocean, where it could fuel bacterial life. Such transport mechanism could be sporadic surface cracking and melting of the surface ice, created by tidal stresses, tectonic activity or meteorite impact. Ample evidence of surface cracking is contained in high quality images obtained by the Galileo spacecraft. Indirect evidence of a salty ocean comes from the observation that the infrared reflectance spectra of Europa is very similar to that of hydrated salts [75] and from the magnetic response of the satellite to Jupiter’s magnetic field.

Thus, the subject of radical storage in ice as a biological fuel merits investigation in the laboratory. Although this phenomenon is fully expected from existing knowledge of radiation biology and chemistry, there are two critical pieces of information that are lacking for application to planetary ices. The first is the quantification of the amount of species trapped, especially for the case of light
and heavy ions in the 10–200 keV energy range, typical of Europa’s magnetosphere (except for photolysis below 40 K [17,16,76] and the case of H$_2$O$_2$ formation, mentioned above, there is little published data for ice between 70 and 130 K, typical of Europa). The second piece missing is a body of quantitative data on reactions of trapped radicals and energy release in ice, particularly in conditions of temperature excursions. The complexity of the problem has been reviewed recently [77].

5. Charge transfer between ions and grains

The ion/neutral ratio in molecular clouds is known through high resolution spectroscopy with radio telescopes. The relative ionic abundances of different species in various environments suggest that neutralization in ion-grain collisions is important in the overall charge balance. Resonant neutralization by a valence band electron is likely for protons, O$^+$ and N$^+$, and Auger neutralization for He$^+$ incident on grains coated with molecular ices. Ions of lower ionization potential may not be able to neutralize on grains. It is also possible that some electronegative atoms, like O and C may capture electrons from some surfaces to become negative ions, if their velocity is high enough. Grains can also charge positively by electron emission when hit by a hard ultraviolet photon or a cosmic ray, and they can charge negatively by capturing sub-excitation electrons. In the latter case, they will present a larger cross section for incoming positive ions than the geometrical value. The nature of each type of charge on the grain surface and the mobility of the charge across the grain have not been ascertained yet. Analysis of charging is still in its infancy; the literature is divided in the applications to the interstellar medium [78,79] and planetary plasmas [80] but a unified treatment of the mechanisms should be possible.

6. Notes on laboratory simulations

Since one purpose of this article is to stimulate experimental research on atomic collisions of importance to astrophysics, it is pertinent to give information on experimental techniques which are used to study electronic processes in laboratory analogues of interstellar and solar-system ices. Our experimental arrangement has been described in several publications [6,64,81]. Standard ultrahigh vacuum conditions ($\sim$10$^{-10}$ Torr) are used to simulate the space environment and to prevent condensation of unwanted gases on the samples.

Ice films with thickness from sub-monolayers to several mm can be grown by condensing high purity gases or gas mixtures on a quartz crystal microbalance (QCM) cooled to the desired temperature using closed-cycle He refrigerators or liquid He. In the QCM technique, changes in the mass of thin deposits cause a change in the resonant frequency of the quartz crystal, driven at its natural frequency. The stability of the microbalance is equivalent to a mass change rate per unit area of $5 \times 10^{11}$ H$_2$O mol/cm$^2$ s, or about 0.0005 monolayers/s. Different pure and mixed gases are directed onto the target through a uniform gas doser, consisting in a 25 mm diameter array of microcapillaries, $\sim$50 $\mu$m diameter, and 500 $\mu$m long). The porosity of the condensed gas, which might affect the stability of trapped species, can be varied over a wide range by changing the angle of incidence of the molecules onto the surface [82]. When using gas mixtures, the composition of the gases in the manifold is adjusted to take into account the mass-dependent conductance of the gas doser, and the actual composition of the films is measured by a mass spectrometer (residual gas analyzer or RGA) during thermal desorption. A technique we often use is isotopic labeling (i.e. water with $^{18}$O, carbon monoxide with $^{13}$C) to reduce or eliminate interference from residual gases in the mass spectrometer or infrared measurements.

The RGA is also used to monitor the composition of the desorbed flux during irradiation. The instrument is calibrated using sublimation fluxes from ices deposited on the QCM, which can measure the mass loss absolutely. It is convenient to install the RGA in a separately pumped ultrahigh vacuum chamber, with a cryogenic shield around the ion source, to reduce interference by background gas. The RGA is also useful to determine which molecules were synthesized in the ices while
warming them up. It is important to note that the information in this case is not just what happens during irradiation, but may also include the effect of reactions during warming up the ice.

Condensed gas samples can be characterized using standard surface analysis techniques. For instance we have shown the usefulness of electron energy loss spectroscopy (EELS) in monitoring trapped radicals during irradiation [73], in conditions where X-ray photoelectron and Auger spectroscopies give little information. EELS is closely related to optical absorption spectra but the information depth is limited, thus it is most useful to study surface processes. Optical techniques give integral information of composition inside thin films. For this purpose we measure optical reflectance using an ultraviolet-visible spectrometer (0.1–0.8 μm) and a Fourier Transform infrared spectrometer (FTIR) over a wide range (0.5–20 μm) that allows identification of molecules by their light absorption at particular vibrational frequencies. We obtain the density of the ice films by measuring the index of refraction over a range of wavelengths [82]. Since the QCM measures the column (mass) density of the films, we have the ability to determine absolute optical constants, for instance the infrared absorbance of a species of interest, using the FTIR.

Different techniques are needed to study analogues of non-icy extraterrestrial materials, such as silicates. An example is given in our work on the formation of metallic iron in the mineral olivine under simulated irradiation by the solar wind [83]. Perhaps unexpectedly, experiments on mineral samples are often harder than those with condensed gases. There are several reasons for this. In most cases, these natural samples have multiple components and are inhomogeneous, leading to questions of reproducibility. Sample preparation is not straightforward, since there is the need to avoid contamination from exposure to the atmosphere. We prefer to prepare samples by fracture done just before the experiments. Removal of contaminants by sputtering is undesirable, since it often produces changes in the sample composition. Annealing of ion beam damage by heating is often undesirable since heating may cause compositional changes and alter the crystallinity of the sample. Preparation by fracture is not without problems, since materials tend to fracture along planes of reduced bonding, and this may imply a concentration of impurities larger than average. Fracture also produces rough surfaces, with the possibility that protrusions shadow depressions during irradiation and/or analysis.

Since all the surfaces of interest are electrical insulators, an important concern is electrostatic charging during irradiation. For thin ice films, this is not an issue, since hole conductivity is sufficient to drain most of the charge deposited by the ion beam and carried away by secondary electrons. The situation is different when studying mineral samples, such as natural rocks, which cannot be easily prepared with small thickness. In addition, since these natural surfaces are compositionally complex, holes produced by irradiation have low mobility or tend to trap efficiently, leading to a high concentration of charges on the surface and in the bulk. The electric field due to this charge distribution can produce large surface potentials, even on mm thick samples, that can deflect energetic ion beams. We have observed the total reflection of a 40 keV Ga⁺ focused ion beam from an olivine sample a few mm thick. For meaningful results, charging must be eliminated as much as possible. The standard method for charge compensation is to spray the samples with electrons from a “flood gun”, consisting of a thermoionic emitter (heated W filament) biased at a small negative voltage (<1 V) with respect to ground. When the sample charges positive as a result of ion bombardment, it attracts electrons from the flood gun until the charge is cancelled. This procedure does not work for electron irradiation, where the surfaces may charge negatively (for energies below a few tens of eV and above a few keV). In this case, it is possible to neutralize the charge with low energy ions from a specialized ion source. Another solution to the charging problem that works for some, but not all applications, consists in pressing a grounded, highly transparent metal mesh, with small openings, against the sample surface. This decreases the leakage distance for the surface charges and eventually limits, through field emission, the maximum surface potential that can build up during irradiations.
6.1. How accurate are laboratory simulations?

The basic need is that the selection of material and irradiation energies match the astronomical situation to be simulated. Only for the Moon and interplanetary dust we have actual samples that we can use. In other cases we must infer what the surface materials are from the interpretation of their optical reflectance and our knowledge of likely surface processes, both of which are uncertain. In addition, a central question is to know what variables are important for the simulation since laboratory time scales are necessarily orders of magnitude shorter than those relevant in most astronomical problems. In order to accelerate simulations, particle and photon fluxes are used that are much larger than those in space. For instance, one hour of irradiation in the laboratory may correspond from thousands to millions of years in space. The first consideration is always to ensure that fluxes are below those that produce significant heating in the samples. This is tested by varying the irradiation flux, in some of our experiments over several orders of magnitude, and verifying linear behavior. Although flux effects may exist (they are known, for instance, in radiation assisted diffusion in some materials) in practice we have not found them under our experimental conditions were significant heating is avoided. Similarly, films of condensed gases are always deposited at rates low enough that the effects of the release of condensation energy is negligible, as determined by the independence of results on deposition rate.

7. Outlook

Having presented a succinct description of the astronomical scenario and some unique laboratory issues, I end up by pointing to some topics that need to be researched, with the goal of motivating new experiments. In the area of interstellar processes, there is the need to measure desorption cross sections in a wide variety of condensed gas solids, mainly for Lyman-α radiation and heavy ions simulating cosmic rays. In such experiments, it would be very useful to determine what species are synthesized, and how their population is affected by thermal excursions, looking specifically for explosive desorption. Another area in need of quantitative experiments is the investigation of the outcome of reactions of thermal ions, radical atoms, and electrons with condensed gases, silicates and carbon grains.

Two main goals can be identified for such experiments. One is the solution of the problem of balance of molecules between the gas and solid phases, enunciated at the beginning of this paper. The other is to understand the limits in the generation of complex organic molecules that, carried by comets, could have triggered life on Earth. These limits appear because radiation can both make complex molecules from simple ones, and destroy complex molecules. In fact, life as we know it, cannot exist in the presence of large amounts of radiation. In this context, it would be interesting to know the conditions necessary for a particular microorganism to survive space travel.

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References