Compaction of Porous Solar System Ices by Ion Irradiation: Laboratory Studies U. Raut[1], M. Famá[1], M.J. Loeffler[1] and R.A. Baragiola[1]. [1] Laboratory of Atomic and Surface Physics, University of Virginia, Charlottesville, VA 22904.

Introduction: The surface of objects in various astrophysical environments, such as cold satellites, rings, comets, and TNOs [1] is likely coated with ice formed from accretion of water molecules in vapor phase. For example, water molecules in the sputtered flux or in the ejecta produced by micrometeorite impacts can return to the surface of satellites in gravitationally bound trajectories. The water vapor observed in plumes as seen on Enceladus can coat the surface of grains in the rings of Saturn. Laboratory measurements show that ice grown by accretion from the gas phase is porous with pore dimensions from the sub-nm scale to the mesoscopic scale [2-4]. Porosity determines important properties of ice such as its gas adsorption capacity, thermal conductivity and behavior under stress.

Astrophysical ices exist in radiation environments where they are continually bombarded by energetic photons and ions. The energy deposited by these particles can affect the porosity and, in fact laboratory studies have demonstrated that ion irradiation can compact porous ice films [5, 6]. For instance, we previously observed that irradiation with 100 keV Ar^+ ions to a fluence of ~ 10^{14} ions/cm^2 was sufficient to fully compact an ice film with 26% initial porosity [6]. Though the details of physical processes by which compaction occurs in our ice films are not fully understood, we posit that the energy deposited by the ions causes molecular motion that alters the ice structure to decrease the internal surface energy of the porous film. The compaction process should therefore depend on the energy deposited by the ion per unit path length or stopping power (dE/dx). In this study, we irradiated porous ice films using different ions at different energies. By varying the type and energy of the projectiles we were able to study the dependence of compaction on the stopping power. We analyze the results with theoretical models that have been used to describe amorphization and damage created by fast ions in solid targets. We intend to use these models to extrapolate our results to solar system and interstellar conditions to estimate compaction timescales for porous ice subjected to ion irradiation, including cosmic rays.

Experimental Details: Thin ice films were deposited at 30 K from a collimated vapor source at 45° incidence onto the polished surface of a gold-coated quartz crystal microbalance. The incidence angle was chosen to produce wholly microporous films with significant porosity [4]. The microbalance measures the areal mass of the films, which is converted to column density in molecules/cm^2 by dividing by the molecular mass. Ices were irradiated at 20° incidence with different ions at different energies produced from a 300 kV mass-analyzed ion accelerator. Reflectance spectra in the 200-800 nm wavelength range were collected at near-normal incidence using an Ocean Optics CCD spectrometer. The interference fringes in the reflectance spectra were fit using Fresnel equations to obtain the index of refraction and the film thickness *d*, which together with the areal mass of the microbalance, gives the average film density ρ . We derive the average film porosity, $1 - \rho / \rho_c$, using ρ_c = 0.94 g/cm^3 for compact ice.

Preliminary Results: Figure 1 shows the change in porosity of ice films when irradiated with different projectiles at different energies. In all cases, the porosity of the ice films reduces from ~ 0.26 (± 0.02) to 0 (± 0.01) as a result of irradiation. Different projectiles show different fluence dependence of compaction. For instance, 80 keV protons need nearly ten times more fluence to compact the ice film than 150 keV Ar^{++}.

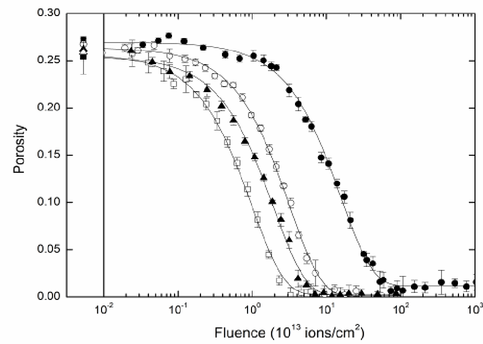

Figure 1 - Fluence dependence of compaction for ice films deposited at 40 K at 45° incidence for different projectiles at different energies. Symbols: 80 keV H^+ (●), 320 keV He^{++} (○), 150 keV Ne^+ (▲), and 150 keV Ar^{++} (□). The lines are fits to data of the form $\Phi(F) = y_o + \Phi_o \exp(-\sigma_c F)$. The data points shown in the left partition of the plot are the initial porosities of the unirradiated films.

The porosity (Φ) decays exponentially with ion fluence (F) suggesting that the rate of compaction of porous ices due to ion bombardment is proportional to the fraction of voids or pores present in the ice during irradiation. The data is fit with $\Phi(F) = y_o + \Phi_o \exp(- \sigma_c F)$, where y_o is the residual porosity after compaction, Φ_o is the film porosity of the unirradiated ice, and σ_c is the "compaction cross section". We assume that ice compacts in a small cylindrical region around the ion's path (the track), whose radius r_c is given by $(\sigma_c / \pi)^{1/2}$.

Models: There are two theoretical models that predict the how the damage track size, caused by ions traversing through the solid, is related to the the electronic stopping power of the ions: (i) *the modified lattice potential* model [7] where secondary electrons ejected by the ion modify the effective intermolecular lattice potential and transfer sufficient energy to produce motion of nuclei and molecules in the solid in some restricted region around the path of the ion, and (ii) the *thermal spike* model [8] which assumes that the solid is melted in a high-temperature region formed around the track. Both models predict that the track radius is proportional to the square root of the electronic stopping power of the projectile and have been successfully tested in experimental studies of amorphization and radiation damage of solids like quartz and YIG.

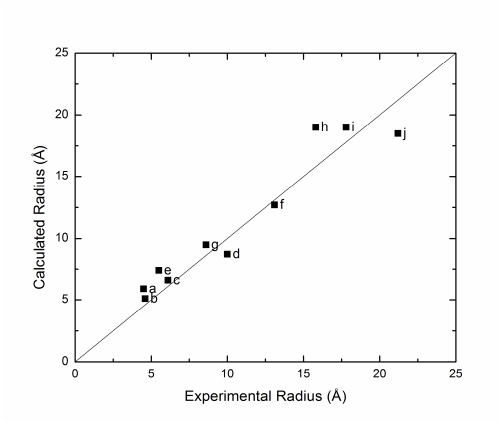

Figure 2 – The calculated radii vs. experimental radii (r_c). The experimental values obtained from fits similar to those shown in Figure 1 for (a) 80 keV H^+, (b) 220 keV H^+, (c) 80 keV He^+, (d) 320 keV He^{++}, (e) 120 keV He^+, (f) 150 keV Ne^+, (g) 400 keV Ne^{++}, (h) 150 keV Ar^+, (i) 150 keV Ar^{++} and (j) 300 keV Ar^{++}. The calculated radii are deduced from the empirical equation discussed in the text.

In Figure 2, we plot the values of calculated radii obtained by using the empirical equation,

$$r\ (\text{calculated}) = \alpha\ (\sqrt{S_e} + \sqrt{S_n})$$

vs. the experimental radii, r_c. Here S_e and S_n are the mean electronic and nuclear stopping power of the different ions in water ice respectively. The coefficient $\alpha \approx 2\ (\text{Å}^3/\text{eV})^{1/2}$. In our experiments, the fast light ions such as H^+ and He^+ lose their energy in the ice films mostly through electronic excitations. Their nuclear stopping power is negligible compared to their electronic counterpart. The compaction radius for these fast light ions is proportional to the square root of the electronic stopping power, in agreement with the models. However, for low velocity projectiles like Ar ions, the nuclear stopping power is not negligible, and therefore should contribute to the compaction. For these ions, both electronic and elastic processes induce compaction. We assume that the radius produced from the elastic collisions has a square root dependence on the nuclear stopping power and add its contribution to that obtained for electronic processes.

Further work is in progress to refine this model. Our goal is to estimate timescale for compaction of astrophysical ices, provided we have information regarding radiation environment (particle, energy, flux) that irradiate these ices.

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