Charging and Discharging of Amorphous Solid Water Ice: The effects of Cracking and Implications for E-ring Grain Surface Potential. C. Bu[1], C. Dukes[1] and R. A. Baragiola[†], [1]University of Virginia, Laboratory for Astrophysics and Surface Physics, Charlottesville, VA 22904 [caixiabu@virginia.edu, cdukes@virginia.edu], [†]Deceased.

Introduction: Water-ice is ubiquitous on many planetary satellites, rings, and dust grains in the solar system. Within Saturn's E ring, resident ice and dust grains (0.3–3 μm) are coated by water-vapor co-released with ice grains from geyser-like eruptions from south polar region of Enceladus [1]. These water-coated particles are subsequently processed by Saturn's inner magnetospheric plasma (dominated by the cold electrons and ions; $T_e \approx 0.5$–8 eV, $T_i < 100$ eV) [2], which changes the charge characteristics (and composition) of the grains and alters the electric fields within the E-ring. The grain surface potentials can affect the flux of incoming charged particles; however, published models [3] for the charging of the E-ring grains rarely discussed the effects of the surface potential resulting from water-ice coatings [4]. In this study we performed a series of laboratory experiments to investigate the surface potential of water ice coatings using amorphous solid water (ASW) films as laboratory analogues, providing ground-truth data for new studies of the charging of E-ring grains.

Experiments: Experiments were performed in an ultra-high vacuum system (base pressure: ~2×10^{-10} Torr). ASW films were deposited by directing collimated vapor beams onto a liquid-helium cooled, gold-coated quartz crystal microbalance (QCM). The column density (in units of monolayers, ML, 1 ML = 1×10^{15} molecules/cm^2) of the film was measured by the QCM, and the thickness (in units of μm) was measured using a UV-visible interferometry. The density (ρ) of the ice film was calculated from the ratio of the column density to the thickness. Surface potential (V_s, in units of volt, V) of the film was measured using a Kelvin probe. Surface microstructures of the film, cracks larger than a few microns, were imaged using an optical microscope.

During growth, the deposition rate was controlled at 0.7 ML/s. The surface potential was monitored as a function of the thickness, and the deposition was stopped when the film cracked. Films with different porosities (defined as $\Phi = 1 - \rho/\rho_c$, $\rho_c = 0.94$ g/cm^3) were prepared by changing the deposition temperature or the incidence angle of the vapor beam [5]. After the growth, the cracked films were warmed from the deposition temperature to 200 K at a rate of 4.8 K/min, while measuring the surface potential to study the effects of thermal cycling. To simulate the positive charging of ice-coated grains in the E-ring, the cracked films were charged electrostatically with 500 eV He^+ at normal incidence for 270 seconds to a fluence of $(0.9 \pm 0.1) \times 10^{12}$/(cm^2 s) prior to warming,.

Results: *During Growth.* The magnitude of the native negative surface potential ($|V_s|$) of an ASW film increases linearly with thickness for films of less than 0.5 μm [5]. Extending the experimental thickness to a few microns, the $|V_s|$ decreases abruptly above a critical thickness (Fig. 1(a)), compared the corresponding extrapolated value using the straight-line fit (open circles in Fig. 1(a)). At this critical thickness, cracks appear in telescopic images of the films (Fig. 1(b)).

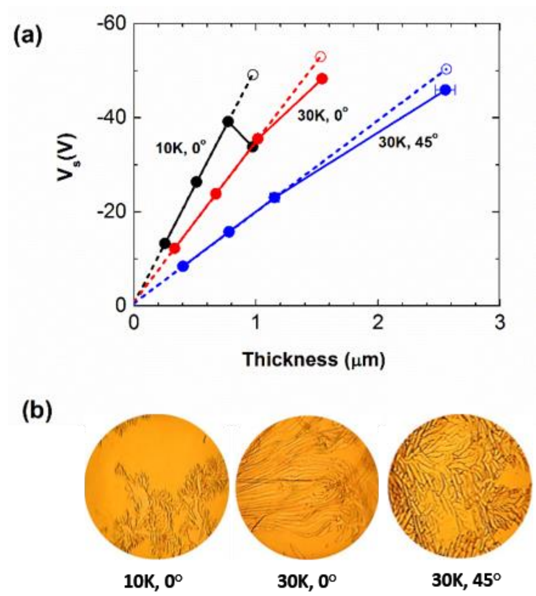

Fig. 1 (a) During growth, the surface potential of (V_s) of an ASW film (solid dots connected with solid lines) builds up, following a linear function of the thickness (dashed lines) until the thickness exceeds a critical value (L_c). The temperatures and angles next to the curves are the corresponding deposition temperature and incidence angles of the vapor flux, respectively. The X- and Y-error bars are smaller than the size of the data points if not seen. (b) Telescopic images of the films suggest that the films crack at a critical thickness L_c.

Effects of Thermal Warming. The thick, cracked films were warmed and the surface potential monitored; V_s as a function of the temperature is shown in Fig. 2(a). To understand the effect of adding additional charges to a negatively polarized ice film surface, the cracked films were electrostatically charged by depositing low energy He^+, resulting in an overall positive surface potentials (V_+). Thermal evolution of the V_+ is shown in Fig. 2(b) for films initially grown at varied temperature and porosity. For all cracked films, significant voltages ($|V_s|$ or V_+ is ~10 V) remain at temperatures as high as ~120 K, compared to almost zero in the thin, transparent films (without cracks) reported in earlier studies [4].

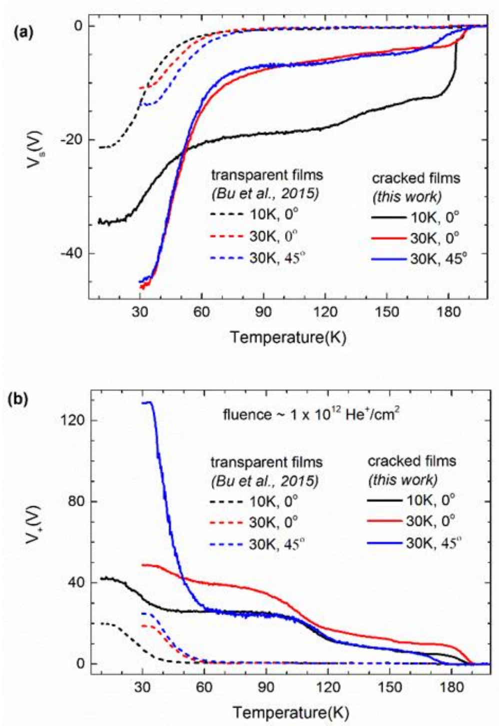

Fig. 2 Thermal-induced evolution of the ASW surface potentials for transparent (dashed lines) [4] and cracked films (solid lines) without and with deposited charges, (a) and (b), respectively. We observe that the cracked films have significant voltages at high temperatures.

Discussion: These results must be applied to models of the interactions between a planetary plasma and embedded icy grains and/or icy planetary surfaces. As a case study, we consider the build-up of voltages resulting from the deposition of cryo-volcanic water vapor onto a surface, such as the regolith of Enceladus or Saturn's E-ring grains. Our measurements here show that water ice films with thickness of a few microns, the size range of the E-ring grains, crack spontenously during growth. Though the magnitude of the negative surface potentials of the cracked films was reduced due to the cracking, the remaining values (|Vs| > ~40 V as shown in Fig. 1(a)) are sufficient to affect the flux of the cold electrons or ions reaching the grain surfaces. In contrast to thin (< 0.5 µm, no cracks) ASW films, significant surface voltages, resulting either from growth or deposited of charges, could remain in films even after thermal cycling. As shown in Fig. 2, the cracked films retain a potential of ~ 10 V even with temperature increasing from 30 K to ~120 K. Thus, our measurements here suggest the effects of the surface potentials of the ice water must be considered in modeling studies of the charging processes of the water-coated grains in Saturn's E ring

Conclusions: We found that laboratory-prepared ASW films cracked when the thickness exceeds a critical value, less than ~3 µm at temperatures below 30 K. For thick, cracked films subjected to thermal warming, a significant fraction of the original surface potentialis retained at high temperatures, up to ~10 V at ~120 K; this is in contrast to thin, transparent films which discharge almost completely with warming [4]. These results suggest that the effects of surface potentials resulting from the growth of water ice at low temperatures shoud be considered in studies of interactions between the planetary plasma and the embedded icy grains and/or ice-covered planetary surfaces.

References: [1] R. H. Brown, et al. (2006) Science 311, 1425-1428. [1] J. H. Waite Jr., et al. (2006) Science, 311, 1419-1422. [2] J. E. Wahlund et al. (2009) Planet. Space Sci. 57, 1795-1806. [3] S. Jurac, et al. (1995) J. Geophys. Res 100, 14821-14831. [4] (C. Bu et al. (2015) JCP 142, 134702; [5] U. Raut, et al. (2007) JCP 127, 204713 .