ON THE SURVIVAL OF AMORPHOUS WATER ICE WITHIN ICY BODIES DURING COLLISIONAL EVENTS IN THE EARLY SOLAR SYSTEM. J. K. Stecklof1,2, G. Sarid1 1Planetary Science Institute, 1700 East Fort Lowell, Suite 106, Tucson, AZ 85719-2395, USA 2University of Texas at Austin, Dept. of Aerospace Engineering and Engineering Mechanics, W.R. Woolrich Laboratories, C0600, 201 east 24th Street, Austin, TX 78712-1221 USA 3Florida Space Institute, 12354 Research Parkway, Partnership 1 Building, Suite 214, Orlando, FL 32826-0650, USA

Introduction: Amorphous water ice (AWI) is a solid phase of water ice that forms in the conditions of the solar nebula and proto-planetary disk[1]. Models suggest that AWI later adsorbed onto silicate grain surfaces as complete icy grains or included in into mixed silicate grains, and then accreted together to form the original population of cometary bodies in the outer solar system[2]. Following formation, Nice-style instabilities triggered massive dynamical evolution that scattered these icy planetesimals into the Oort Cloud and Scattered Disk, the two reservoirs of comets in our solar system[3,4]. The resulting dynamical excitation led to collisional evolution of this icy planetesimals population[5]. Hypervelocity impacts can produce significant shock heating, which changes the temperature-dependent crystallization rate of AWI [6], reducing the amount of AWI present in the icy planetesimal.

Understanding the survival/destruction of AWI is important to understanding the mechanisms driving cometary activity. AWI can trap volatiles species during its formation, and later release them upon crystallization [7]. Thus, if AWI is present in comets, its crystallization may contribute to volatile production rates [8]. Although two tentative, weak spectroscopic detections of AWI have been reported [9,10], AWI has never been conclusively detected on an icy body’s surface in the present Solar System [11]. This begs the question: has amorphous water ice even survived collisional evolution in the early Solar System?

Methods: To explore the effects of this early collisional evolution on the crystallization of amorphous water ice, we use the iSALE impact shock physics hydrocode to simulate impacts between icy planetesimals, and feed the results through a script to compute the fraction of AWI that crystallizes. iSALE expands upon the SALE shock-physics hydrocode [12] to include an elastic-plastic constitutive model for impacts into solid bodies, material fragmentation models, multiple materials and their equations of state [13,14], and modified strength models [15]. More recently, the creation of porosity through dilatancy [16] and porous compaction of materials [17,18] have been incorporated into iSALE.

We simulate a 1 km pure AWI impactor striking a 100 km (the expected size of a primordial planetesimals [19] AWI target at 2 km/s (fig 1). 2 km/s is a typical, if slightly below average, impact speed between icy planetesimals during the Nice-style instability [5]. Both bodies have a uniform initial temperature of 100 K. We neglect porosity in both target and impactor, which biases our results toward higher shock temperatures, and thus higher crystallization rates of AWI. Although iSALE does not have an equation of state for amorphous water ice, similar physical properties between AWI and amorphous water ice (e.g., similar densities of 940 kg/m3 and 920 kg/m3, respectively) allow us to use a crystalline water ice equation of state to substitute for AWI, to allow for reasonably accurate computation of the shock pressures, temperatures, and crater morphology. We use tracers in iSALE to track the pressures and temperatures experienced by material throughout the target body during the impact process.

Impact-induced AWI crystallization. We compute the rate of AWI crystallization using the Gibbs Free Energy approach of Kouchi et al. [6], which computes the fraction of AWI that crystallizes in a given amount of time \( (\theta(t)) \) as:

\[
\theta(t) = 1 - e^{-\frac{t}{\tau}}
\]

\[
\tau = \frac{1}{2m_w} \left( \frac{k T}{\sigma} \right) \left( \frac{1}{\Omega} \right) \left( \frac{3k T}{2m_w} \right) \left( \frac{m_w + 4m_p}{3m_w} \right) \left( 
\frac{T_m}{T_f}
\right)^{3/2}
\]

where \( \tau \) is the crystallization timescale, \( \alpha \) is a geometrical factor that depends on the morphology of crystal growth, \( \Omega \) is the effective volume of a water molecule, \( \sigma \) is the interfacial tension (i.e., surface tension), \( D_n \) is an empirically derived reference diffusion constant, \( E_a \) is the activation energy of self-diffusion, \( L \) is the enthalpy (latent heat) of crystallization per molecule at 0 K, and \( T_m \) is the freezing point temperature, where solid and liquid co-exist [6]. By differentiating equation 1 and integrating over time at the crystallization timescale (\( \tau \)) changes in response to changing material temperature (fig. 2), we can compute...
the fraction of AWI that crystallizes in a given parcel of material.

Figure 2: Thermodynamic conditions for AWI initially located 2 km below the surface, and 1 km from the axis of collision (near the edge of the transient crater). The passage of the impact shock wave (the peak shock pressure and temperature), is clearly an irreversible process that raises material temperature. Closer to the impact site, these shock pressure and temperatures increase dramatically.

**Exothermicity of AWI Crystallization.** Whereas the crystallization of pure AWI releases 1.7 kJ/mol of energy, impure AWI with ~2% CO or CO₂ impurities releases no heat upon crystallization [20]. Furthermore, impurities in excess of ~2% make AWI crystallization endothermic [20]. Given that comets typically release ~2-10% CO₂ relative to water [21], it is most likely the case that AWI crystallization in comet nuclei is not a source of heat. Thus, this computation treats the crystallization of AWI as neither exothermic nor endothermic. Moreover, the kinetic energy of the 2 km/s impactor (36 kJ/mol) dominates any energy that would be absorbed by AWI, but errs our results on crystallizing more AWI than would be expected when the endothermicity of impure AWI-crystallization is accounted for.

**Results and Discussion:** We find that collisions of small icy planetesimals into larger primordial planetesimals during Nice-style instabilities rapidly crystallizes any AWI present at the impact site. However, the magnitude of the shock heating within the target body rapidly decays with distance from the impact site, resulting in little to no crystallization of AWI outside of the transient crater, preserving AWI within the body. Most of the crystalline water ice produced from the impact is ejected from the crater, coating the surface of the body in crystalline water ice as the ejecta falls back onto the surface. This results in a unique structure in which a body that contains AWI would nevertheless appear to be crystalline at its surface. This is consistent with AWI having never been conclusively detected on the surface of any solar system body [11]. This result is not likely to hold for impacts between similarly sized objects, since the objects are themselves comparable to the size of the transient crater. Nevertheless, smaller planetesimals numerically dominate the larger icy planetesimals in this population, these results are representative of most collisions between icy planetesimals.

If this general structure is preserved over time, later evolution of cometary bodies may be able to shed this crystalline mantle. Mass wasting events [22,23] and rotational disruption [24-26] would all expose relatively pristine interior materials to the surface, where any AWI could be detected. Thus, the lack of direct detection of AWI may suggest that: (1) any AWI present is rapidly crystallized and therefore not seen, (2) rotational disruption in the Centaur region [26] causes all AWI to rapidly crystallize, producing a nearly AWI-free comet nucleus by the time it enters the Jupiter Family of Comets, (3) any AWI has receded deeper into the interiors of comet nuclei, where AWI cannot be detected [27,28], and/or (4) catastrophic collisions and/or other evolutionary processes crystallize the object’s remaining AWI.


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