THE MESOSCALE MORPHOLOGIES OF ICE FILMS: POROUS AND BIOMORPHIC FORMS OF ICE UNDER ASTROPHYSICAL CONDITIONS

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ABSTRACT

We present the results of experiments in which we grow submicrometer- to millimeter-thick ice films at temperatures of 6–220 K at low pressures in situ in a cryo environmental scanning electron microscope. We find that ice films show pronounced morphologies at the mesoscale similar to those previously described in films of ceramics, semiconductors, and metals; materials with quite different material properties to ice. Our experiments are aimed at revealing the mesoscale morphologies of amorphous and crystalline ice with regard to astrophysical environments, as the conditions in which the ice films grow in our experiments are those under which exists most extraterrestrial ice. The porosity on the mesoscale of many of the morphologies is notable in this regard; a further intriguing finding is that these ice films can emulate biological forms.

Subject headings: comets: general — dust, extinction — instabilities — Kuiper Belt — molecular processes

1. INTRODUCTION

Dust grains in interstellar space are typically covered with an icy film formed at the very low temperature (3–90 K) of the interstellar medium (Tielens 2005); it has been estimated that most of the ice in the universe is to be found on these particles (Jenniskens et al. 1995). Larger icy bodies are supposed have formed through the accretion and reprocessing of this material (Ehrenfreund et al. 2003; van Dishoeck 2004); icy films are found in the interstellar medium, in the Oort cloud, in planetesimals, asteroids, comets, and Kuiper Belt objects, on the surfaces of icy planets and moons, and in planetary ring systems and atmospheres, and much astrophysics is presumed to take place on these icy surfaces. A fundamental question, on which hinge these astrophysical and astrochemical processes, is, in what forms—with what morphologies—may such ice films be deposited? An apparently unrelated area of science holds the key to answering this query. The deposition of films of ceramics, semiconductors, and metals is an extremely active field. Experimental results have been collated in an empirical structure zone model, which predicts the film morphology on the mesoscale depending on the substrate temperature and the gas pressure (Ohring 2001; Lakhakia & Messier 2005). To connect the two bodies of knowledge of film deposition and ice physics we undertook experiments in which we deposited films of ice at low pressure at 6–220 K. Our premise was to discover whether the structure zone model applies to ice, chemically very different to those materials from which it was derived. On one hand, our experiments were aimed at discovering the mesoscale morphologies of ice films with regard to bulk properties of astrophysical interest, such as porosity, which arise not only from the molecular scale but also from morphology at the mesoscale. On the other, this work furthers the understanding of the fundamental physics involved in the production of film morphologies, which as yet is only just beginning to be unravelled.

2. ICE FILMS

2.1. Molecular Structures

Although there are myriad forms of the solid phase of H₂O—ice—found on the Earth’s surface (Petrenko & Whitworth 1999) with very different morphologies and bulk properties, at the microscopic level they are all, from snowflakes to icebergs, composed of the same crystalline polymorph, hexagonal ice—ice Ih—which is the stable structure at the temperatures and pressures in our biosphere. Beyond these bounds, however, ice exhibits an extensive range of crystalline solid phases, or polymorphs, distinguished from one another by the arrangement of water molecules in the crystal lattice. The physical properties of the polymorph, such as density, conductivity, vapor pressure, and sublimation rate, are dictated by its crystalline structure. There exist at least 15 ice polymorphs (Johari & Andersson 2007). Most are thermodynamically stable under some range of pressure-temperature conditions and many of the high-pressure polymorphs may be found in nature within icy moons and planets (Cartwright 2007). However, at the lowest temperatures and pressures, water freezes not in a crystalline phase, but as amorphous ice (Loerting & Giovambattista 2006; Johari & Andersson 2007). In laboratory vapor-deposition experiments hexagonal crystalline ice (Ih) is formed above ~150 K, while between ~130–150 K there appears another crystalline phase; cubic ice (Ic). Below ~130 K, the ice produced by vapor deposition is amorphous; this ice is frequently termed amorphous solid water (ASW). ASW differs when deposited at lower and higher temperatures. At ~30 K, a higher density amorphous form is obtained, while at ~30–130 K a lower density amorphous form is deposited (Jenniskens & Blake 1994; Jenniskens et al. 1995). There is a great deal of debate as to whether different amorphous ice structures represent frozen versions of different liquid polymorphs of water with an associated phase transition (Loerting & Giovambattista 2006; Stanley et al. 2007). High-density amorphous ice constitutes the frost on interstellar dust grains, while the low-density form is present on comets and Kuiper Belt objects. Cubic and hexagonal crystalline ice is found at higher temperatures: on icy planets, moons and asteroids, in planetary atmospheres and ring systems, on comets that have undergone solar heating, and in the Kuiper Belt (Cartwright 2007).

The preceding summary has set out ice-film structure at the molecular scale. However, just as ice on the Earth’s surface is all ice Ih at the microscale, but has different mesoscale and macroscale morphologies from snowflakes to icebergs, beyond their molecular structure, films of ice may have different morphologies at the mesoscale with a concomitant impact on their bulk properties.
2.2. Mesoscale Morphologies

In another realm of science, for many years solid films of numerous different materials have been deposited onto substrates from the vapor phase (Ohring 2001; Lakhtakia & Messier 2005). The field is driven by a huge number of technological applications, but also has much scientific interest. One of the key differences between films and bulk materials is in their morphologies. While the very thinnest films of, say, less than 20 monolayers thickness, are epitaxial—that is, influenced by their substrate—this influence diminishes with film thickness, and it is found empirically with ceramics, semiconductors, and metals that once a growing film passes some hundred or so monolayers in thickness it begins to show characteristic morphologies independent of its substrate. From the 1960s on efforts have been made to construct an empirical classification of the morphology of a film depending on the conditions of its deposition. This has culminated in the structure zone model, which gives the distinct film morphologies obtained as a function of variables involved in the film deposition; in recent versions of the model, these variables are often the renormalized substrate temperature $T/T_M$, where $T_M$ is the melting point of the material being deposited, and $E/E_s$, where $E$ is the admolecule energy and $E_s$ is the sputtering threshold of the material being deposited: zone 1 (Fig. 2), porous morphology consisting of tapered columns separated by voids; zone T (Fig. 3), transition morphology with no long-range structure beyond the nanoscale; zone S (Fig. 4), sponge-like morphology characterized by a three-dimensional open network; zone M (Fig. 5), matchstick morphology consisting of parallel columns with domed tops; zone 2, columnar crystalline grain structure; and zone 3, recrystallized crystalline grain structure.

3. EXPERIMENTAL SETUP

In our experiments we used a FEI Quanta 200 environmental scanning electron microscope (ESEM) equipped with a liquid helium cold stage to grow ice films in situ at low pressures and temperatures of $6$–$220$ K. As well as a high-vacuum mode as in a conventional scanning electron microscope, an ESEM has further operating modes in which the chamber can function in the presence of water vapor and/or an auxiliary gas at pressures of up to $4000$ Pa, and observations can be made without the need to metal coat the sample. The combination of the ESEM with a liquid helium cold stage makes it possible to grow and image ice films in situ within the instrument. We began by evacuating the chamber in the high-vacuum mode of the microscope (target pressure $6 \times 10^{-4}$ Pa) and lowering the substrate to the working temperature. The microscope was set up so that the helium cold finger, together with a thermostat, was directly beneath the substrate on which we grew the ice film. As we discussed above, we were not expecting to find differences between the films grown on different substrates for the submicrometer to millimeter thick films that interested us. However, we employed several substrates (brass, carbon, copper, platinum, and titanium in flat samples that
were smooth at the micrometer resolution of the microscope and were thermally coupled as well as possible to the cold stage beneath them; we did not detect differences in film morphology between them. To grow an ice film we switched the microscope to low-vacuum mode, in which we could inject water vapor into the chamber for a given length of time and at a determined target pressure. We either used demineralized water alone, or else bubbled helium through the water prior to injection to provide an inert auxiliary gas in the chamber and to reduce the water vapor pressure. The ice film was then deposited on the substrate, which was the coldest point within the microscope. We switched again to high-vacuum mode to image the results.

After each experiment we heated the substrate to remove the ice film. As we took advantage of an existing ESEM setup for our experiments, rather than having to construct the experimental apparatus from scratch, which would have been prohibitively expensive, there were certain limitations around which we had to work. We did not have the means to measure the ice film thickness, except when the film peeled away from the substrate (see Fig. 3a), and the temperature measurement was at the base of the ice film, not at its surface. The microscope chamber walls were not thermally isolated from the room, so radiative heating of the sample altered the ice surface over a period of tens of minutes to an hour, even though the substrate was maintained at the programmed temperature.

The target pressure to which the ESEM controller was set would be the pressure present in the system if it were at equilibrium, but our experiments took place far from equilibrium; as soon as water vapor entered the experimental chamber it was sequestered by deposition on the substrate. The target pressure and injection time thus regulated the amount of water vapor allowed to enter the experimental chamber. After the entry of a controlled amount of vapor, the system was set back to high-vacuum mode. The pressure at the ice surface during injection is a dynamical variable dependent on the injection time and on the presence or absence of helium as an auxiliary gas, and the system tends to equilibrium at the vapor pressure of ice at the working temperature, given by the Clausius-Clapeyron equation: $p = ae^{-bT}$. For temperatures below around 150 K this implies that the pressure equilibrates to a value orders of magnitude lower than the high-vacuum mode target pressure $6 \times 10^{-4}$ Pa. We are not aware of any direct measurements of ice vapor pressure performed at these temperatures—it does not seem to be a trivial task—and values sometimes quoted in the literature are from formulations based on theoretical studies (the Clausius-Clapeyron equation with higher order corrections), with the numerical values of the terms ($a$ and $b$ in the Clausius-Clapeyron equation, etc.) determined by fitting at higher temperatures. In general, then, the surface pressures involved in these experiments vary enormously from extremely low pressures in the lowest temperature zones of the structure zone model, up to a few Pascals in the higher temperature zones. A summary of results is provided in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Figure</th>
<th>Zone</th>
<th>Morphology</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2......</td>
<td>1</td>
<td>Cauliflower</td>
<td>H$_2$O bubbled through with He injected with a target pressure of 10 Pa for 6 s, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a Ti substrate at 6 K</td>
</tr>
<tr>
<td>3......</td>
<td>T</td>
<td>Transition</td>
<td>H$_2$O injected with a target pressure of 133 Pa for 1 s, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a Cu substrate at 6 K</td>
</tr>
<tr>
<td>4......</td>
<td>S</td>
<td>Spongelike</td>
<td>Film deposited on a Cu substrate. (a) After 83 s of injection of H$_2$O with a target pressure of 10 Pa, then reset to target pressure $6 \times 10^{-4}$ Pa, with the substrate at 6 K. (b) Following a further 55 s of injection at target pressure of 10 Pa, during which the substrate temperature rose transiently to 80 K, followed by a reset to target pressure $6 \times 10^{-4}$ Pa</td>
</tr>
<tr>
<td>5......</td>
<td>M</td>
<td>Matchstick</td>
<td>H$_2$O bubbled through with He injected for 6 minutes with a target pressure of 133 Pa, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a Pt substrate at 6 K</td>
</tr>
<tr>
<td>6......</td>
<td>1/M</td>
<td>Intermediate (cauliflower/matchstick)</td>
<td>H$_2$O injected with a target pressure of 133 Pa for 13 minutes, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a brass substrate at 6 K</td>
</tr>
<tr>
<td>7......</td>
<td>2/3</td>
<td>Dendritic</td>
<td>H$_2$O injected with a target pressure of 10 Pa for 15 minutes, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a C substrate at 6 K.</td>
</tr>
</tbody>
</table>

#### 4. RESULTS

4.1. Lowest Temperature Zones

The region of lowest substrate temperature in the structure zone model is occupied by zone 1. Zone 1, or cauliflower morphology, has been found in other materials to consist of competing void-separated tapered columns whose diameters expand with the film depth according to a power law, so the film surface resembles a cauliflower, showing self-similarity over a range of scales. We produced an ice film of this morphology in the example in Figure 2 using water vapor accompanied by helium as an auxiliary gas in the chamber deposited on a substrate at 6 K. We injected water bubbled through with helium with a target pressure of 10 Pa for 6 s, then reset the microscope to target pressure $6 \times 10^{-4}$ Pa, and the film was deposited on a titanium substrate maintained at 6 K. We show in Figure 2 two images of cauliflower surface morphology from varying perspectives, an oblique view and a plan view; they are taken at different scales to illustrate the self-similarity.

By depositing the ice film at the same substrate temperature, but at a higher target pressure for a shorter time without an auxiliary gas, we obtained, in the example shown in Figure 3, zone T, or transition morphology, in which there is no long-range structure above the nanoscale. We injected water with a target pressure of 133 Pa for 1 s, then reset the microscope to target pressure $6 \times 10^{-4}$ Pa, and the film was deposited on a copper substrate at 6 K. The general view seen in Figure 3a shows the featureless surface characteristic of zone T; the film in this experiment had poor adhesion to the substrate and peeled away in places, enabling us to measure its depth as approximately 2 μm. Successively closer views in Figures 3b and 3c allow us to see the boundaries of the individual densely packed grains making up the surface, which were made visible as electronic charge accumulated on the grain boundaries of the poorly conducting ice surface during imaging.

In qualitative terms, the morphology of zone 1 is driven by a competitive process of growth of clusters at all scales, leading to
Fig. 2.—Zone 1, cauliflower morphology, film produced with water bubbled through with helium injected with a target pressure of 10 Pa for 6 s, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a titanium substrate at 6 K.

Fig. 3.—Zone T, transition morphology, film produced with water injected with a target pressure of 133 Pa for 1 s, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a copper substrate at 6 K.
Intermediate-Temperature Zones

We present an example of a morphology intermediate to zone 1 and zone T morphologies. As shown in Figure 4; following a further 55 s of injection at target pressure of 10 Pa, the film was deposited on a platinum substrate at 6 K, and the film was deposited on a brass substrate at 6 K. The columns display the domed tips characteristic of matchstick morphology, and also show interesting substructures; they are segmented both on the tip and along their length, giving them a biomimetic shape, like an icy worm. These large matchsticks may have been the morphology seen in experiments by Laufer et al. (1987), who described an ice film grown at somewhere between 20−100 K as looking like “a shaggy woolen carpet.”

The ice structures in zones S and M should appear in astrophysical contexts at low pressures and temperatures around the range 30−130 K typical of the Kuiper Belt and colder icy moons; they should thence typically be composed of low-density amorphous ice.

4.2. Intermediate-Temperature Zones

At substrate temperatures above those of the transition morphology of zone T, a spongelike morphology has been described for metallic films (Jankowski & Hayes 2003). We were able to reproduce this morphology, zone S, with an ice film, by injecting water vapor for a longer time than for zone T. The two images of the morphology we present in Figure 4 were taken at different stages during a long injection process. We used a copper substrate in this experiment. Figure 4a was after 83 s of injection of water with a target pressure of 10 Pa, then reset to target pressure 6 × 10^{-4} Pa, with the substrate at 6 K, and Figure 4b was following a further 55 s of injection at target pressure of 10 Pa, during which the substrate temperature rose transiently to 80 K, followed by a reset to target pressure 6 × 10^{-4} Pa.

As shown in Figure 4, this morphology is characterized by a three-dimensional open network of material like a sponge.

On the other hand at substrate temperatures above those corresponding to zone 1 cauliflower morphology, and for relatively high admolecule mobility there appears the final zone in the low-temperature region of the structure zone model: zone M, or matchstick morphology. In the examples of this morphology we reproduce in Figure 5 we see very large columns tens of micrometers in diameter resulting from ice deposition over several minutes using helium as an auxiliary gas in the chamber. We injected water bubbled through with helium for 6 minutes with a target pressure of 133 Pa, then reset the microscope to target pressure 6 × 10^{-4} Pa, and the film was deposited on a platinum substrate at 6 K. The columns display the domed tips characteristic of matchstick morphology, and also show interesting substructures; they are segmented both on the tip and along their length, giving them a biomimetic shape, like an icy worm. These large matchsticks may have been the morphology seen in experiments by Laufer et al. (1987), who described an ice film grown at somewhere between 20−100 K as looking like “a shaggy woolen carpet.”

The ice structures in zones S and M should appear in astrophysical contexts at low pressures and temperatures around the range 30−130 K typical of the Kuiper Belt and colder icy moons; they should thence typically be composed of low-density amorphous ice.
Although these forms are consistent with the tendency of ice to dendritic growth, seen, for example, in snowflakes (Libbrecht 2005) here the environment is significantly different. This fascinating palmlike morphology of branched whiskers is intermediate between dendritic growth and the whiskers of Figures 6c–6d. To obtain these structures we injected water with a target pressure of 10 Pa for 15 minutes, then reset the microscope to target pressure $6 \times 10^{-4}$ Pa, and the film was deposited on a carbon substrate at 6 K; the growing ice surface became progressively more thermally insulated from the substrate as the film depth increased and the morphology changed correspondingly. In our experiments the microscope chamber is evacuated but not thermally isolated from its surroundings, so the walls are at room temperature and radiate accordingly, and the film surface temperature reflects this. The temperature of the upper surface in this experiment can be estimated to be close to 200 K, taking into account the low thermal conductivity of the ice and the substrate and the radiation received. At this temperature there is high admolecule mobility, resulting in surface diffusion, both of molecules and of heat, and sublimation; this dynamic equilibrium of fluxes along and perpendicular to the surface is presumably the basic physics involved in producing this skeleton of palmlike structures formed by highly ordered branched whiskers.

These whisker-like and palmlike crystalline ice structures could be present under astrophysical environments in which the ice surface has been heated above 130 K, such as comets, Saturn’s rings, or the surfaces of some icy moons and planets.

5. DISCUSSION

As we have seen, structure zone model morphologies do appear in ice films. Can this knowledge contribute to understanding the fundamental physics of the structure zone model? And can such an understanding in turn allow us to comprehend better the astrophysics?

The two axes of the structure zone model commonly shown in work on ceramics, semiconductors, or metals are the renormalized substrate temperature and the ion energy, which is inversely proportional to the gas pressure in sputtering experiments used in that work (Messier et al. 2000; Lakhtakia & Messier 2005). On the other hand the deposition technique employed in these experiments is evaporation, involving thermal energies $(3/2kT < 1 \text{ eV})$ for the admolecules. However, the energy required to sputter a water molecule is $\sim 0.2 \text{ eV}$ (Bukowski et al. 2007) much lower than the $10-30 \text{ eV}$ sputtering threshold for ceramics, semiconductors or metals (Lakhtakia & Messier 2005). To generalize the structure zone model we may renormalize the scale of the second axis by the sputtering threshold, in the same way as the substrate temperature is renormalized by the melting point for the first axis. This we have done in Figure 1. It becomes apparent then that the physical basis for the two axes is admolecule mobility.
induced in one case by the temperature of the film itself, and in
the other by the impinging admolecules from the vapor. The lat-
ter mechanism is related in these experiments to the presence or
absence of helium as an auxiliary gas in the chamber that will
thermalize with the chamber walls. For sputtered films material
leaves the sputter source with relatively high energies (several
electron volts). As the gas pressure is increased more scattering
occurs and the arrival energy of the sputtered material decreases.
For evaporated films, on the other hand, the arrival energies are
low; if gas assist is added then the energy per admolecule in-
creases. That the different effects of the two sources for admo-
lecule mobility lead to more or less compact structures we can
comprehend by noting that, unlike thermal mobility, admolecule
movement induced by bombardment is highly directional. This
directionality is an avenue to explore in moving toward a phys-
ical understanding of the structure zone model as a consequence
of the competition between the spatially disordered deposition
of particles on the growing film surface and the ordering effect of
activated particle mobility processes.

The basic structure zone model is the result of normal depo-
sition, and of deposition when the vapor flux has a spread of an-
gles about the normal; this is our case, and is the most likely case
in a natural setting. When the vapor flux is collimated and its
angle is controlled, the columnar morphologies grow following
the incident beam, and so-called sculptured thin films can be pro-
duced (Lakhtakia & Messier 2005). In columnar morphologies,
the column spacing increases as the angle of beam and of the
growing columns is further from the normal. It is probable that
such sculptured thin films of ice were formed in experiments of
Kimmel and coworkers, in which beams of water vapor were de-
posited at a variety of growth angles on a surface at low tem-
perature, and the amorphous films grown at more oblique angles
were found to be more porous (Kimmel et al. 2001; Dohnálek
et al. 2003).

It has been noted in both experiments and simulations of film
deposition that there is an equivalence in terms of the mesoscale
morphology produced between the substrate temperature and
the deposition rate (Ohring 2001; P. A. Sánchez et al. 2008, in
preparation). This we can comprehend in molecular terms as a
competition between the timescale of the surface kinetics, and
the mean time between admolecule arrival at the surface. As long
as the latter is longer than the former—i.e., below a certain thresh-
old deposition rate—the deposition rate is not significant in terms
of morphology and alters only the timescale of the film growth. It
should be stressed that the field of solid film growth is largely
empirical, that experiments are generally undertaken on materials
with industrial applications in mind, and that although there are
complex simulations using molecular modeling techniques, there

![Fig. 6.](image-url)

(a) Morphology intermediate between zones 1 and M produced with water injected with a target pressure of 133 Pa for 13 minutes, then reset to target pressure $6 \times 10^{-4}$ Pa, deposited on a brass substrate at 6 K. (b, c, and d) Whiskers of ice form on top of this morphology during heating of the substrate as the temperature reaches 220 K.
is not yet a full understanding of the theoretical basis of why materials show these structures on the mesoscale; the latter question is being tackled in parallel with these experiments (Sánchez et al. 2008, in preparation).

Knowledge of the existence and morphologies of these mesoscale structures ought to aid understanding fundamental physical and chemical processes involving surfaces coated with icy films. In the very thinnest films epitaxial growth on the substrate is clearly determinant, as can be seen in work on very thin films of ice (Kondo et al. 2007). As the film thickness increases, the substrate ceases to play a role in the film morphology and the mesoscale morphologies of the structure zone model appear. Consistent with this development of mesoscale morphologies, ice-film experiments by Hornekaer et al. (2005) show increasing porosity as the film thickness increases. Icy mantles of nanometer thickness form on dust particles in interstellar clouds, through condensation from the gas phase or by reactions on the grain surfaces. As dense cores within interstellar clouds collapse, icy grains are incorporated in the coldest regions of the disk. Closer to the protostar, icy mantles are evaporated and reform as the disk cools. Over a few million years, the icy dust aggregates, forming small planetesimals, and subsequently planets and moons. The remaining planetesimals form the Oort Cloud and Kuiper Belt, asteroids and comets made up of regolith and ices. The bulk properties of these ice morphologies are important for understanding physical and chemical processes involving the surfaces of these bodies. On Earth, once such porous materials aggregate beyond the micrometer scale their weight compacts them. This will not occur in low-gravity environments, so the mesoscale porosity we have obtained in our experiments can only occur in thin films on Earth, but may be much more widespread as aggregates in lower gravity conditions. The agglomeration of particles during planetesimal formation should certainly be affected by the porosity of the icy film, which should aid aggregation and prevent fragmentation (Wang et al. 2005); the case of cometary dust aggregates is similar. Cometary ices are undoubtedly porous; our work imparts an understanding of how such porosity arises at the mesoscale and so provides a counterpoint to work on producing laboratory analogs of cometary ices (Colangeli et al. 2004) in which the effects of porosity are noted but the morphology is unknown. On the other hand, in the context of energetic processing of ice films, it has been suggested that, owing to cosmic ray bombardment, ice on interstellar grain mantles should be compact in structure, and it has been shown by infrared absorption spectroscopy that ice porosity decreases after ion irradiation (Palumbo 2005); in our terms this would correspond to the passage from zone 1 to zone T. A reconsideration in terms of the structure zone model morphologies of what is at present often
placed under the catch-all label of porosity is one of the basic proposals we wish to put forward.

Our experiments have been performed with water alone, while astrophysical ice is generally mixed with other volatile solids such as carbon monoxide, carbon dioxide, ammonia, methanol, and methane (Ehrenfreund et al. 2003; van Dishoeck 2004). We can view the effect of these impurities in terms of the structure zone model by noting that as they have different melting points and sputtering thresholds to water, we may expect them to alter the position of the deposited material on the structure zone model diagram. Depending on how far the position on the diagram changes, a structure zone boundary may be crossed, in which case the material could possess a different morphology to pure ice deposited at the same temperature and pressure.

An intriguing aspect of this work is the finding that ice on its own can form biomimetic structures under astrophysical conditions. Knowledge of this phenomenon is important for astrobiologists searching for life in similar extreme conditions in space, and is a timely reminder that biomorphic forms, especially at small scales, are not in themselves evidence of life.

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