AN INVESTIGATION OF THE FORMATION OF LAKE STARS AS AN ANALOG FOR EUROPA'S MANANNÁN CRATER SPIDER FEATURE

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Introduction: Europa's surface hosts many features proposed to originate from brine sources within its icy crust [8]. An intriguing possible example is the asterisk-shaped `spider' at the center of Manannán crater, identified by the Galileo mission [1] (Fig. 1a). The feature has been proposed to consist of a network of fractures, and [2] suggest formation by impact-induced cryovolcanic plume activity. However, due to limited spatial resolution of the Galileo Solid State Imager in this area (20-100 m/pixel), topographic data from DTMs cannot ascertain whether the feature does consist of fractures.

Additionally, [2] invoke the geyser process hypothesized to form spider features on Mars (Fig. 1b), citing radial fractures as evidence for a rigid surface subject to pressure from below. However, Martian spiders are not ice fractures; they are negative topography troughs that are likely eroded into loose regolith via the solid-state greenhouse effect [10]. In this process, sunlight penetrates translucent ice, causing basal sublimation. Confined gas scours the surface and is explosively released via a vent. This mechanism is one example of a gradient-driven growth process recognized to form dendritic, fractal `finger-like' patterns in nature. These include Saffmann-Taylor fingers in Hele-Shaw cells, river channels and even `lake stars' on frozen lakes (Fig. 1c) [7].

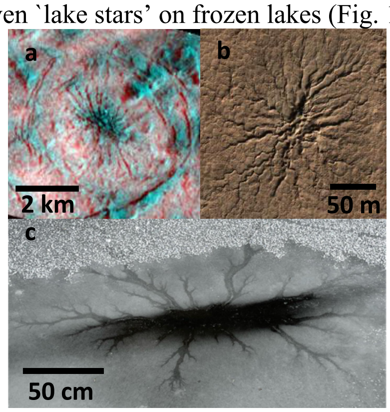

Figure 1: (a) Manannán spider. (b) Example of a spider on Mars. (c) Lake star from our field tests in Breckenridge, CO.

We present a new formation hypothesis for Manannán's spider. We suggest that the feature may originate from a process similar to that forming lake stars on Earth, where its `arms' are not fractures but instead are low-albedo ice surrounded by frozen impact slurry. We describe laboratory experiments to investigate the formation of this pattern in Europa granular ice simulant, and we present initial calculations to describe the hypothesized process for Europa.

Lake Stars on Earth: Lake stars are striking patterns that develop on the surface of ice-covered lakes in winter. They form when a lake surface freezes and snowfall covers the thin ice, sometimes developing into slush. Either due to the weight of the snow, or a protrusion such as a stick, the ice cracks and water wells through the snow or slush [3]. As it melts the snow, this relatively warm water creates dark regions. Locations with faster flow rates melt preferentially, leading to an instability that results in `fingers' [3, 7]. Eventually the water which has flowed through the system freezes, preserving this `star-like' pattern encased within the ice.

Lake Star Formation Hypothesis for Manannán's Spider: Following impact, a transient localized atmosphere developed above the impact site, and a brine pool formed locally beneath the surface (Fig. 2a,b). During cooling, impact slurry covered an ice layer above the brine pool. Eventually, the ice cracked (Fig. 2c), allowing liquid water to rush to the surface and spread through the slurry. As temperatures and pressures were elevated at this time [6], and also via the presence of salts [5], water could remain in a liquid state transiently.

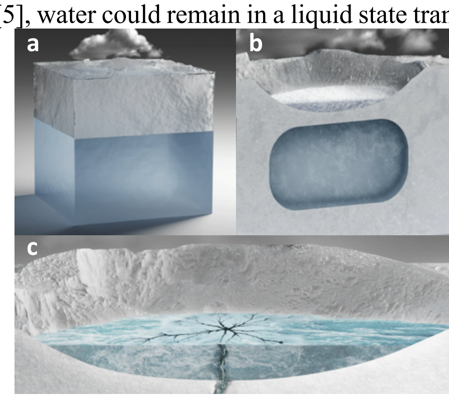

Figure 2: Illustration of `lake star' hypothesis for Europa. Artist credit: Wax Visuals.

Partial vaporization upon the liquid brine surfacing also increased local pressure [11]. In a similar manner to lake stars (though under different pressure and temperature regimes), water flowed through and melted the slush to form a `spider-like' pattern, which was preserved as it froze. The spider has a low relative albedo because of its higher salt concentration, which we suggest darkened over time due to radiation exposure [12].

Laboratory Experiments of Lake Star Formation Under Simulated Post-Impact Conditions: We performed experiments where liquid water was flowed through Europa granular ice simulant of discrete grain size ranges to investigate whether lake star patterns developed. Experiments by [7] with coarser ice grains of less-constrained size indicate first order `fingers' develop under restricted temperature regimes.

We aim to further explore the parameter space governing pattern development. As a first step, the experiments were performed under Earth pressure. We will repeat this procedure under simulated post-impact transient atmosphere pressures of ~$1.3x10^{-3}$ Pa and for different `pool' sizes, salt content and granular ice expanses. Similar pressures were previously used for Ceres and Vesta impact experiments, showing that liquid brines can exist transiently when agitated for ~ 1 hour [5].

The experiments were performed under the hotter-than-average temperatures expected on the surface of an icy impact crater shortly after formation [4, 5]. For each trial, a 25 x 35 x 4.5 cm container was cooled using a liquid nitrogen glovebox from -30-0°C and granular ice of grain size ranges from ~20μm to ~300μm, ~ 0.5 cm thick was spread on its base and cooled to ambient temperature. This was to simulate a thin, frozen ice layer in contact with slush. A wash-bottle of outlet diameter 1 mm was placed at the surface. Water was flowed through the center of the granular ice at a constant rate until a lake star pattern appeared, or did not and the water reached the edge of the simulant. The volume of water used and the duration of each experiment were noted.

For an initial estimate of the influence of temperature on pattern development, we explored four temperature regimes: (i) 0°C ambient temperature, a 0°C granular ice layer and room temperature (~22°C) water, (ii) 0°C ambient temperature, a 0°C granular ice layer and ~4°C water, (iii) 0°C ambient temperature, a 0°C granular ice layer and 0.5°C water and (iv) -30°C ambient temperature, a -80°C granular ice layer and room temperature (~22°C) water. Experiments were repeated for salty granular ice (3.7 wt% $MgSO_4$, average particle diameter = 286 μm, σ = 120 μm).

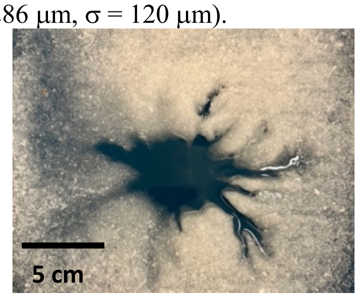

Figure 3: Example of a `lake star' pattern in the laboratory.

Results: In each case, a melt `pool' of water similar to those observed when lake stars grow on frozen lakes, formed almost instantaneously. As the flow continued, the pool spread through the ice, and first order arms began to develop after ~6 seconds. After ~9 seconds, second order bifurcations developed on the arms, markedly similar in pattern (though much smaller in scale) to lake stars. `Arms' developed in all cases, but were less distinct for salty simulant. For the ambient room temperature case, the dendritic arms developed into more branched features than for other cases.

Constraints on the source reservoir: Prior studies demonstrated a transient atmosphere could subsist for a few months [4] after a meteoritic impact on bodies of the outer solar system. As the formation of spider features may require a transient atmosphere to allow for liquid water to flow through the post-impact slushy ice, we use this time-scale as an upper limit of the time available for a source reservoir to trigger an eruption and thus infer properties of the reservoir. Using the freezing-induced eruption simulation from [9], we obtained the results in Fig. 4 demonstrating that lens-shaped reservoirs up to 3 km in radius could be the source of the eruption that formed the Manannán spider. Depending on the reservoir depth, up to 0.1 km^3 of material could have been erupted to form the spider feature. Possible timing of spider formation in conjunction with residency time-scales of the transient atmosphere for Europa conditions will be further explored, as this will be limited by Jupiter's harsh radiation environment. If Manannán's spider formed by the proposed process, it and potentially other smaller features on icy worlds have the potential to reveal surface properties after impact, as well as the subsurface cryovolcanic processes that may form them.

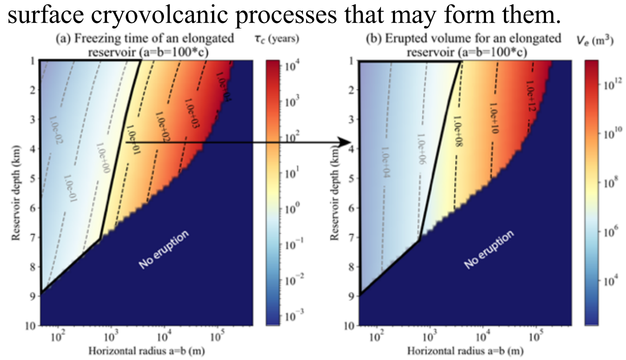

Figure 4: Potential freezing times and erupted volume of water that may have formed a lake star on Europa

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