THE EVOLUTION OF A YOUNG OCEAN WITHIN MIMAS.

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Introduction: Mimas, a small icy moon of Saturn, is heavily cratered and devoid of the tectonic and eruptive activity observed on its neighboring moon, Enceladus, despite having a closer orbit and four times higher eccentricity that could raise significant tides [1,2]. One explanation for the dichotomy between the two moons is that Mimas is fully frozen, which vastly limits the global deformation that can result from tidal forces. However, observations of Mimas' librations point to a sub-surface ocean within Mimas [3-5], leading us to ask whether Mimas could be a stealth ocean world.

To address this question, we devised a series of hypothesis tests, including how an ocean-bearing Mimas could avoid tidally-driven fractures [6], whether an ice shell of the inferred thickness could remain thermally stable [7], and the ice shell thickness required to reproduce the shape of Mimas' largest crater, Herschel [8]. Taken together, these studies showed that an ocean within Mimas would have to be relatively young, with the ice shell thinning by 10s of km since the formation of Herschel (see full discussion in [9]).

Now, we address a critical issue – whether the coupled evolution of Mimas' ice shell thickness and eccentricity, which would be rapidly decaying if there were substantial tidal dissipation within Mimas, could generate a thinning ice shell and growing ocean. We then consider the geologic implications of an emerging ocean and compare them to observations of Mimas' geology. We find that there is a viable pathway by which Mimas can have an ocean today while satisfying all of the geologic constraints [10].

Methods: We used existing numerical models [7,11] to 1) assess the tidal heating associated with an ocean-bearing Mimas at the initiation of an ocean and 2) self-consistently track changes in ice shell thickness, tidal dissipation, and eccentricity through time. Because dissipation will act to reduce the eccentricity, we test initial eccentricity values between 2 and 3 times the present-day value of 0.0196. We assume an Andrade rheology for the ice, a conductive thermal profile applied to a 50-layer ice shell, and assume an initial ice shell thickness of 70 km with a 1.6 km ocean underneath. We consider an evolution to be plausible if it can reproduce the current eccentricity of Mimas while the ice shell is between 24 and 31 km. This range matches the libration measurements [3], although somewhat thicker shells could be compatible with the librations if the ice shell is porous [3].

There are several unknowns regarding Mimas' interior, including the radius and density of the core and the density of the ice shell, such that Mimas' hydrosphere could be thicker than we have assumed, with a correspondingly smaller core. However, the values we assume provide a reasonable starting point to determine whether a thinning ice shell is viable.

We use these results to determine whether the ice shell could be thinning even as the eccentricity decays, and to obtain estimates of the stress and heat flows that would be applied to the surface as a result of the ocean. We compute tidal stresses, track stress from cooling and thickening of an ice shell, and model relaxation of craters due to tidal heating to determine whether the evolutions we simulate are compatible with the limited tectonic activity and crater relaxation thus far identified on Mimas [1].

Results: Across a wide range of parameters, we find a similar evolution of eccentricity and ice shell thickness, which is illustrated in Figure 1. Upon initiation of an ocean (upper left), the tidal heating generated within Mimas significantly exceeds the amount of heat that can be conducted out of it, and the ice shell begins to melt, which is consistent with our previous results at present-day conditions [7]. As the ice shell thins, tidal dissipation acts to circularize Mimas' orbit, reducing tidal heating and allowing thicker ice shells to achieve thermal equilibrium (Point A). Eventually, the thinning ice shell and the decreasing eccentricity balance, and the ice shell is in temporary thermal equilibrium (Point B). Then, continued eccentricity decay from the on-going tidal dissipation reduces the available tidal heating such that the ice shell begins thickening (Point C). Without a mean motion resonance to force Mimas' eccentricity, the orbit will continue to circularize as the ocean freezes out.

For an eccentricity at the onset of melting between 2 and 3 times the present value (~0.05-0.06), we find that the ice shell can thin to within the inferred range from the libration measurements. The evolution from the onset of melting to the present-day conditions takes 10-14 Myr. The extent of tidal dissipation we assume in Mimas' core affects which initial eccentricity provides the best results. However, the range of plausible starting eccentricities allows for solutions with both highly and minimally dissipative cores.

Discussion: Our results show that an ocean that emerged within Mimas ~10 Ma could evolve to match the present-day ocean/shell thickness, at the present-day eccentricity, while remaining in a state of thinning over the age of Mimas' surface. This history for Mimas requires a recent eccentricity-pumping event such that the eccentricity was 2-3 times the present-day value at the onset of melting. Establishing the mechanism for this event is outside the scope of our work, but we note that even higher past eccentricities have been proposed for Mimas [14][15], suggesting that our implied starting conditions are plausible.

Tidal stresses associated with this evolution remain well under the lab-based tensile failure strength of ice (1-3 MPa, [12]). Similar tidal stress magnitudes are produced on Europa and Enceladus [6], which have extensive tectonic activity. If stress from ice shell thickening contributes to failure on those moons (e.g., [11]), a thinning ice shell on Mimas may be the limiting factor in forming analogous fractures.

In contrast, due to Mimas' low gravity, we find that even minimal thickening of an ice shell creates fractures that transit the entire shell, with sufficient ocean pressure to drive surface eruptions of ocean material. The lack of such features on Mimas further supports the idea that Mimas' ice shell is presently thinning or stable (e.g., Point A or B in Figure 1). Assuming Mimas has an ocean today, we predict that it will transition to a state of shell thickening within the next ~10 Myr, leading to an era of tectonic and eruptive activity, similar to that observed at Enceladus today.

The presence of an ocean leads to elevated heat flows that may alter crater topography. Using the finite element modeling software, Tekton (as in [13]), we exposed a 26 km diameter crater to heat flows corresponding to the peak heating in our co-evolution models. After 2 Gyr of constant heat flow, we found that the resulting depth change (~10 m) was well below the detection limit given the current imaging data at Mimas. Hence, an ocean within Mimas is consistent with the lack of crater relaxation thus far identified.

Conclusion: By tracking the co-evolution of Mimas' eccentricity and ice shell thickness, and addressing the implications of this evolution on Mimas' geology, we have identified the key characteristics of an ocean that can remain consistent with observational constraints. In particular, the ocean needs to be relatively young (of order 10 Myr), and the onset of melting had to occur when Mimas' eccentricity was 2-3 times the present-day value. While we cannot confirm an ocean based on these results, we have shown that Mimas could be a stealth ocean world. We also find that, in the absence of a mean motion resonance to preserve its eccentricity, Mimas will likely enter a phase of ice shell thickening and ocean freezing over the next ~10 Myr, with a high potential for eruption activity akin to that observed at Enceladus.

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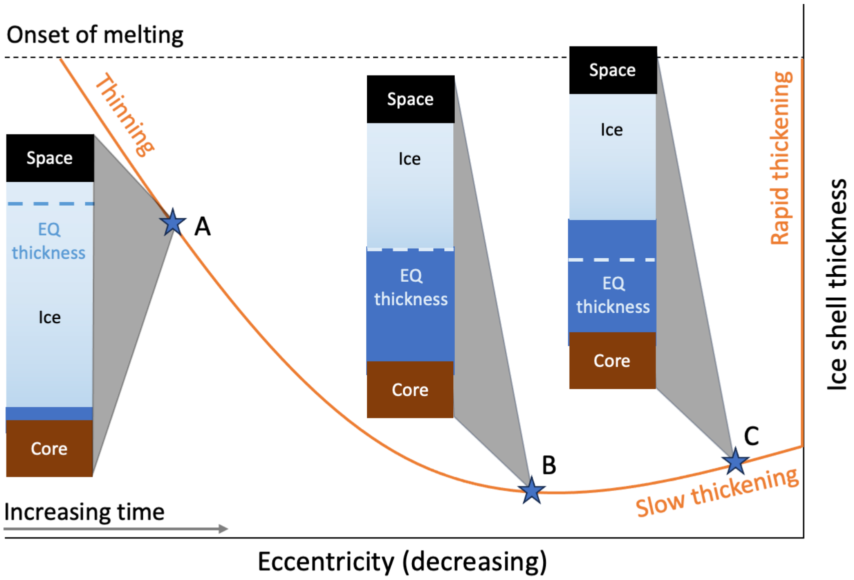

Figure 1: An illustrated evolution of Mimas' ice shell thickness (y-axis) and eccentricity decay (inverted x-axis) over time, in which the ice shell thins from the onset of melting, chasing the thickness associated with thermal equilibrium. Because tidal dissipation reduces Mimas' orbital eccentricity, the thickness associated with thermal equilibrium will steadily increase as the eccentricity decreases. Mimas' geology requires that its ice shell is currently thinning or stable (e.g., Point A or B, here). In future, an ocean-bearing Mimas will transition to ice shell thickening (Point C), which can easily produce tensile fractures and eruptions. The evolution depicted here is observed across all of our models.