

IS MIMAS A STEALTH OCEAN WORLD? A. R. Rhoden¹, M. E. Walker², C. A. Denton³, and S. N. Ferguson¹¹Southwest Research Institute, Boulder, CO, alyssa@boulder.swri.edu, ²Planetary Science Institute, Tucson, AZ,³Purdue University, Dept. of Earth, Atmospheric, and Planetary Science, West Lafayette, IN.

Introduction: Europa and Enceladus are confirmed ocean worlds whose young surfaces are riddled with fractures, display evidence of flows and/or eruptions, and maintain their relatively thin ice shells through tidal heating caused by their eccentric orbits. Curiously, despite having a more eccentric orbit than either Europa or Enceladus, Mimas' surface is heavily cratered with sparse tectonic features, no evidence of cryovolcanic processes, and minimal crater relaxation that suggests limited heat flow.

If Mimas remained frozen throughout its lifetime, its cold interior would be minimally deformable by tides, which could explain the lack of geologic activity in the presence of high eccentricity [1,2]. And yet, *Cassini* measured a large libration at Mimas that requires that the moon is differentiated [3], and the phase of the libration is best explained if Mimas has a subsurface ocean today [4,5].

Before we can accept the possibility that Mimas is, indeed, an ocean world, there are several outstanding questions that must be addressed. 1) Could Mimas retain not only an ocean, but also a relatively thick ice shell, when it occupies such a close-in, eccentric orbit? 2) If Mimas has an ocean, why doesn't it have fractures like those observed on Europa and Enceladus? 3) How did the ice shell withstand the Herschel-forming impact and preserve craters against relaxation? 4) What are the pathways from Mimas' formation to a present-day ocean? Here, we report the results of our tidal heating analysis [6], which addresses the first of these open questions and the implications for the remaining questions.

Using the most plausible parameters, we find that Mimas can maintain an ocean under a 24-29 km thick ice shell, consistent with the constraints from its libration, although we cannot rule out a frozen Mimas with this analysis. If Mimas does have an ocean today, its ice shell must have been warming and thinning over the surface age to be compatible with all of the observations. We will discuss the implications of these findings on Mimas' formation and the potential for spacecraft measurements to definitively determine whether Mimas does, indeed, have an ocean today.

Methods: As described in [6], we calculated tidal heating and tracked heat transport in Mimas' ice shell due to Mimas' eccentricity and measured physical libration. We assumed a 50-layer conductive ice shell, computed the depth-dependent tidal heating, and then averaged the heat generation over lat-lon space to

collapse the solution to one dimension, for use in our 1D heat transport model [6].

We tested both Maxwell and Andrade rheologies. Andrade is thought to provide a more accurate description of ice rheology, although Maxwell has been more widely used in past tidal heating studies [e.g., 7]. In our canonical case, we assumed a melting point viscosity of $1\text{E}13\text{ Pa}\cdot\text{s}$, a melting point temperature of 273 K, and a surface temperature of 80 K, which is within the range of temperatures derived from *Cassini* measurements [8,9].

Past work has used higher viscosity values for the ice shell because, in those cases, the entire ductile portion of the ice shell was being characterized by only one set of parameter values [e.g., 10]. Setting the viscosity of that layer to the melting point viscosity (MPV) would artificially enhance dissipation in the entire volume of ductile ice. Here, we have separated the shell into 50 layers, so we fully capture the change in heating with depth that results from the viscosity-dependence of tidal dissipation, and thus, we assign the deepest layer the MPV.

The amount of heat entering the ice shell from below (i.e., basal heating) is unknown, but the ice shell thickness is tightly constrained by the libration measurements. We, thus, specify an ice shell thickness and then determine the basal heating required to maintain that thickness. In some cases, the ice shell generates too much tidal heating to avoid melting regardless of how little basal heating we apply.

Results & Discussion: In Figure 1, we show the basal heat flux required to maintain each ice shell thickness (blue dots) and the associated surface heat flux (orange dots), for thicknesses between 1 km and the maximum of 29 km. Thicker ice shells produce too much heat to remain stable against melting. To achieve thicknesses compatible with the librations (green shaded region), very low basal heat fluxes are required to avoid further melting the ice shell. With Mimas' relatively low rock fraction, it is plausible that heating from the silicate interior is limited [1].

The plot in Figure 1 uses our canonical parameters, including an Andrade rheology. Using a Maxwell rheology causes more melting, reducing the *thickest* stable ice shell to only 6 km. In contrast, increasing the MPV or lowering the surface temperature can produce thicker stable shells. *Cassini* data shows that Mimas' surface temperature varies [8,9], which may influence the local ice shell thickness. A 3D model of tidal heating

and heat transport is needed to capture lateral flow and potential local variations in ice shell thickness and surface heat flow.

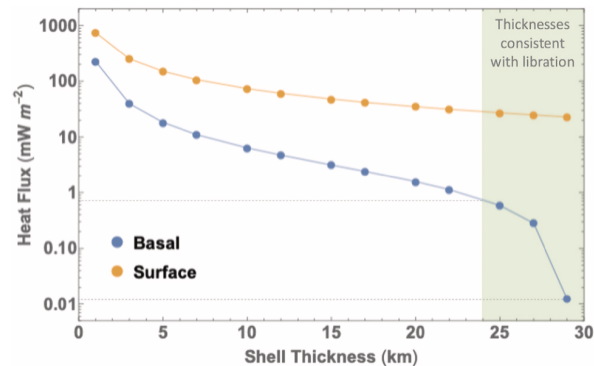


Figure 1: Conditions for stable ice shell thicknesses for Mimas using the canonical parameters and present-day orbital elements. The green shaded region denotes the thicknesses implied by Mimas' librations [3], which require very low basal heat flow (blue dots) and produce moderate surface heat flows (orange dots).

It is important to note that the surface heat flux is strongly tied to the ice shell thickness because, for a particular thickness to remain stable, there is a specific amount of heat that must be transported out of the shell. In Mimas' present orbit, the surface heat flux would be 21 to 26 mW/m² for ice shells between 24 and 29 km (Figure 1). In comparison, a thinner, 20 km shell would have an increased heat flow of 32 mW/m², while an ocean-free Mimas would result in only 6 mW/m². Hence, heat flow measurements may be a powerful diagnostic tool for detecting oceans and constraining ice shell thicknesses of tidally-heating moons.

It is important to consider the implications of a present-day ocean and sub-30 km ice shell on Mimas' formation and evolution. Past work has shown that tidal stresses, assuming that interior structure, would be comparable to stresses on Europa and Enceladus [11], which suggests an additional source of stress contributes to failure on those moons. Cooling stresses from a freezing ocean are often invoked [12-14], but the lower gravity on Mimas should make it even easier to crack the shell and reach the ocean with cooling stresses than on these other moons. Hence, we conclude that Mimas' ocean, if it exists, cannot be freezing today or in the recent past.

Preliminary iSALE-2D modeling of the Herschel-forming impact shows that the ice shell could not have withstood the impact at its present-day thickness, reinforcing the idea that Mimas' ocean is warming and expanding rather than freezing and thinning. Determining how Mimas could come to be in such a

state is the next major challenge in our understanding of Mimas.

Conclusions: We find that tidal heating in Mimas could easily produce an ice shell consistent with the libration constraints, even when we account for the extra tidal heating caused by libration. Adopting an Andrade rheology is critical to meeting these constraints. We also find that surface heat flow is a sensitive function of ice shell thickness, perhaps providing a pathway to identify ocean worlds solely from spacecraft measurements. We still lack a clear formation pathway for Mimas to have a present-day ocean, and we cannot rule out a frozen Mimas from this analysis. Rather, we need to continue exploring issues of basin formation, crater relaxation, and alternative evolution pathways for Mimas to determine whether it can be an ocean world today.

If Mimas is not an ocean world, it is most likely a ring-born moon [e.g., 15], as that model can produce a differentiated Mimas that would not have circularized its orbit [16]. However, if spacecraft measurements confirm an ocean within Mimas, it would reveal a new class of "stealth" ocean worlds in which the surface does not betray the existence of the ocean. Given the numerous icy moons in the outer solar system, it is possible that there are far more ocean worlds than we previously recognized, making Mimas a critical target for assessing the habitability of the outer solar system.

Acknowledgments: This work was supported by NASA's SSW program, grant 80NSSC19K0557, and benefitted from discussions with M. Bland, R. Rufu, M. Siegler, B. Noyelles, and the Ocean Worlds Collaborative.

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