DELAYED TIMING OF METAL-SILICATE DIFFERENTIATION IN EUROPA.

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Introduction: Europa is arguably the best place to search for alien life given its relative accessibility, subsurface water ocean, and Earth-like pressure and temperature conditions at the seafloor [1, 2]. The habitability of its subsurface ocean substantially increases if volcanism and hydrothermal vents exist at the rock-water interface [3]. In addition, solar radiation can interact with Europa's tenuous atmosphere to produce oxidants and hydrocarbons [1, 4] that are eventually deposited into the subsurface ocean via ice shell resurfacing processes. The NASA *Galileo* mission failed to detect an intrinsic magnetic field at Europa [5], but it is possible that an ancient Europan dynamo could have existed and reduced the amount of products from solar wind irradiation [6]. Studies on Europa's habitability would benefit from knowing if and when submarine volcanoes, hydrothermal vent systems, and a geodynamo have existed. However, core formation and its subsequent existence is crucial for understanding Europa's full thermal and magnetic history, so it must be preceded by a description of Europa's early structural evolution.

Mass and moment of inertia (MoI) measurements from the Galileo mission imply the presence of a metallic core, silicate mantle, and water-rich ocean/ice shell in Europa [7]. The size of each layer is dependent on the metallic core composition which may contain anywhere between zero to Fe-FeS eutectic amounts of sulfur [8]. Unlike terrestrial planets, Europa would not have warmed enough during formation to differentiate an iron core. Later radiogenic heating could raise Europa's interior temperatures to initiate metal-silicate differentiation at the bulk silicate or appropriate Fe-FeS melting point. Studies typically assume that Europa differentiated immediately into a silicate mantle and metallic core. However, we argue that Europa's metallic core formation may not have begun for billions of years after calcium-aluminum-rich inclusions (CAIs).

Methods:

Two-layer conduction model. We developed a one-dimensional radial model of Europa's interior assuming that thermal conduction alone transports heat. Both short- and long-lived radioactive isotopes are used [9]. Europa is represented by a 2-layer model: rock-metal interior (r = 1455 km, c_p = 1000 J kg^{-1} K^{-1}, ρ = 3500 kg/m^3) and water-rich ocean/ice shell (thickness = 106 km, c_p = 1930 J kg^{-1} K^{-1}, ρ = 950 kg/m^3), with an initial temperature of 100 K throughout the body. The surface temperature is fixed at 100 K.

Generally, the thermal evolution of Europa's silicate interior is independent of ocean thickness so long as an ocean is present. That is, the heat flux out of the silicates is entirely dependent on the temperature and thermal conductivity of the seafloor. Any difference between the heat flow into and out of the ocean will change the ocean thickness via melting or freezing.

Formation time and radionuclides. Europa's formation time dictates the magnitude of heating from short-lived radioactive isotopes, which include ^{26}Al, ^{60}Fe, and ^{53}Mn. In Figure 1, we present simulations with start times of 3 and 5 Myr after CAIs. Contributions from short-lived isotopes are insignificant if Europa formed 5 Myr after CAIs, thus resulting in a cooler thermal history and late core formation.

Geologically significant temperatures. Figure 1 includes four vertical lines: the approximate start (550 K) and end (900 K) of silicate dehydration, the melting point of the FeS eutectic at 5 GPa (1250 K), and the pressure-dependent melting point of anhydrous silicates [10]. Arrival at any one of these lines should start a process that consumes latent heat, thus delaying the further warming of the interior.

Tidal heating. The Laplace resonances of the Io-Europa-Ganymede system make tidal heating a significant factor in Europa's thermal history. However, most of this heat is dissipated in the water liquid-ice shell, and the amount of tidal heating in the silicate mantle is expected to be relatively low [11]. In Figure 1a and 1b, we do not include any tidal heating, which will yield the same thermal profiles had we assumed all tidal heating is concentrated into the ice shell. Hereafter, we will refer to tidal heating as "insignificant" if it does not play a role in rock-metal core evolution. In Figure 1c, we consider 5 Myr after CAIs and include enough tidal heating for silicate melting to occur at the same time as that of 3 Myr and no tidal heating.

Preliminary Results:

1) Formation time of Europa plays a significant role in metallic core formation initiation. A 3 Myr formation time results in 6, 820, and 2200 Myr to arrive at silicate dehydration initiation, FeS eutectic melting, and bulk silicate melting. On the other hand, a 5 Myr formation time results in 385 and 1800 Myr for the first two aforementioned processes, and insufficient heat is generated to melt anhydrous silicates. This finding treats tidal heating as insignificant in the silicates.

2) Large amounts of tidal heating in the rock-metal interior are needed to expedite core formation. If Europa dissipates 2.8 x 10^{11} W of tidal heat throughout the entire body for a formation time of 5 Myr after CAIs, Europa will melt bulk silicates around 2200 Myr. This is the same as 3 Myr formation time after CAIs with no tidal heating in the rock-metal core (see Figures 1a and 1c). Tidal dissipation of 2.8 x 10^{11} is far in excess of what has been predicted for the rock-metal interior in dissipation models [11].

3) An ancient Europan dynamo is less likely given late core formation (see Figure 1b). If tidal heating is insignificant and formation starts 5 Myr after CAIs, Europa's peak temperature would be insufficient to melt pure Fe. This scenario is an extreme case since the core should contain sulfur, but it is not incompatible with NASA *Galileo's* failure to observe a present-day dynamo. A dynamo is less likely for sulfur-poor cores.

4) Core formation could have started 2200 Myr or later (see Figure 1b). Around this time, an initially dehydrated rock-metal core would melt its silicates. Fe and heavy materials would start sinking towards Europa's center if there is enough melt, assuming that FeS alloys have yet to melt.

Future work: Adding realistic complexities to our models should increase the accuracy of our predictions. First, an investigation of the rock-metal hydration state is warranted. High-pressure ice phases do not exist in Europa, so there exists a rock-water interface [12]. This leads to hydration and dehydration reactions that can only delay core formation. Second, our study would benefit from laboratory experiments of ice and silicate viscoelastic behavior at the forcing periods relevant to Europa. This would confirm that tidal heating in the silicate mantle is negligible.

Beyond constraining our model results, we have yet to model the core formation process itself, which will affect the subsequent thermal and magnetic evolution. The melting of metal and silicates consumes latent heat and delays the warming of the interior, so our model outputs are most useful for pre-core formation time periods. Once a metallic core has formed, we can describe core-mantle boundary temperatures and heat flux out of the core, thus determining if and when core convection existed to generate an ancient dynamo.

References: [1] Vance et al. (2016) *Geophys. Res. Lett. 43*, 4871—4879. [2] Vance et al. (2018) *J. Geophys. Res. Planets*, *123*, 180—205. [3] Dombard & Sessa (2019) *Icarus*, *325*, 31—38. [4] Cooper et al. (2001) *Icarus*, *149(1)*, 133-159. [5] Kivelson et al. (2000) *Science*, *289(5483)*, 1340—1343. [6] Johnson (2004) *The Astro. J.*, *609(2)*, L99—L102. [7] Anderson, et al. (1998) *Science*, *281*, 2019—2022. [8] Sohl et al. (2002) *Icarus*, *157*, 104-119. [9] Bierson et al. (2018) *Icarus*, *309*, 207—219. [10] Katz et al. (2003) *G3*, Vol. 4(9). [11] Sotin et al. (2009) *Europa*, 85—117. [12] Kuskov & Kronrod (2005) *Icarus*, *177*, 550—569.

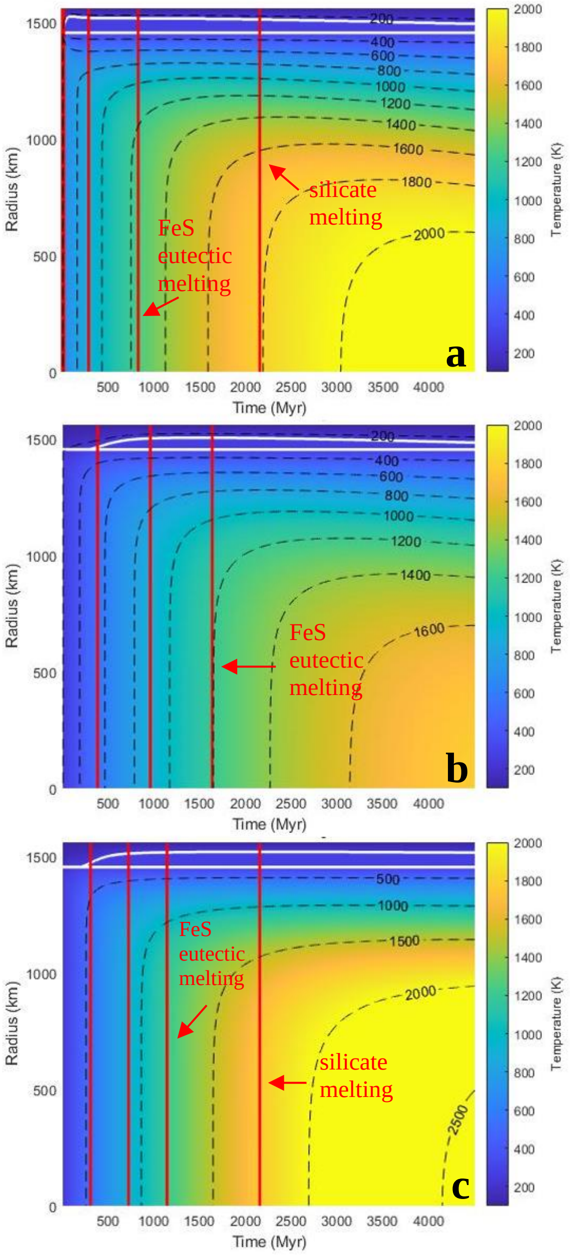

Figure 1) Thermal evolution models of Europa. The white lines are the top and bottom of the subsurface water ocean. The red lines are the approximate start (550 K) and end (900 K) time of silicate dehydration, melting of eutectic FeS at 5 MPa (1250 K), and pressure-dependent melting of anhydrous silicates. Dashed lines represent temperature contours. Panels (a) and (b) represent have formation times of 3 and 5 Myr, respectively, with no tidal heating implemented. Panel (b) never warms enough to melt anhydrous silicates. Panel (c) represents a formation time of 5 Myr after CAIs and includes tidal heating of 280 GW distributed throughout the entire body, which results in the same timing for silicate melting in Panel (a).