EUROPA’S METALLIC CORE MAY HAVE TAKEN BILLIONS OF YEARS TO START FORMING *K.
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**Background:** While Europa is widely known as an icy satellite, the water-rich liquid/ice shell (hereafter referred to as “water shell”) consists of only ~6.2–9.2% of Europa’s total mass [1]. A new estimate of Europa’s normalized moment of inertia suggests an even lower thickness for the water-rich shell [2]. Most of Europa’s mass comes from the silicate mantle and metallic core [1, 3]. Current models of Europa’s interior evolution typically assume that Europa possessed its metallic core immediately or shortly after accretion [4, 5]. However, Europa is so small that heat from accretion is not nearly sufficient to cause rock-metal differentiation [6]. Whether Europa had enough radiogenic and/or tidal heat to form a metallic core early has yet to be studied in detail.

Here we investigate when Europa could start forming its metallic core by melting various Fe-FeS alloys. Rock-metal differentiation is also possible via melting silicates (generally, at higher temperatures), but we focus on metallic core formation where dense liquid metal sinks to the center of Europa. We treat Europa’s formation time, hydrated state of accreted silicates, tidal dissipation in the rock-metal interior, and metallic core composition as free parameters shown in Table 1. Consequently, this approach requires interpreting results from many simulations.

**Methods:** We conduct a series of one-dimensional thermal evolution models of Europa’s interior before rock-metal differentiation but after rock-ice segregation. Since the subsurface water ocean is in contact with the rocky seafloor [3, 7], we model only the evolution of the rock-metal interior and assume a fixed temperature boundary condition of 273 K at the seafloor. Figure 1 summarizes the results of thousands of simulations whose parameters vary according to Table 1.

We include both short- and long-lived radioactive isotopes [8]. We vary the abundance of short-lived species by varying the formation time of Europa between 3 – 5 Myr after calcium-aluminum-rich inclusions (CAIs) [9, 10]. The abundance of long-lived isotopes is not significantly affected by the uncertainty in Europa’s formation time.

We assume that Europa accreted some mixture of hydrous and anhydrous minerals. For the hydrated mineral assemblage, we use Prinn-Fegley 2 (PF2) rock as done in previous studies on small icy bodies [11, 12]. Antigorite makes up 53.5% of PF2 rock’s mass. At high temperatures, antigorite becomes unstable and produces enstatite, forsterite, water, and 3.77 kJ per kg of reactant [13]. We use “PF2D” to refer to PF2 rock where all antigorite has been dehydrated. Silicate dehydration releases water from the deep interior that supplies some portion of the water shell.

While it is often assumed that tidal heating in the silicate mantle is negligible [14], we treat this heating rate as another variable parameter. For simplicity, we treat total tidal dissipation as a constant throughout the mantle and vary it between zero and 10 mW/m² (equivalent top of mantle flux).

We approximate the composition of Europa’s metallic core to be an Fe-FeS alloy ranging from pure Fe to the eutectic. At 5 GPa, the Fe-FeS liquidus decreases from 1950 K to 1250 K with increasing sulfur content as shown in [15] (their Fig. 6). Metallic core formation via metal melting may begin once internal temperatures reach the appropriate liquidus. We assume that Europa accreted some mixture of hydrous and anhydrous minerals. For the hydrated mineral assemblage, we use Prinn-Fegley 2 (PF2) rock as done in previous studies on small icy bodies [11, 12]. Antigorite makes up 53.5% of PF2 rock’s mass.

**Table 1 The parameter space**

<table>
<thead>
<tr>
<th>Free parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europa’s formation time</td>
<td>3 – 5 Myr</td>
</tr>
<tr>
<td>Silicates initially hydrated</td>
<td>0 – 100 %</td>
</tr>
<tr>
<td>Total tidal dissipation</td>
<td>0, 3×10^6, 3×10^11 W</td>
</tr>
<tr>
<td>Fe-FeS core composition</td>
<td>0, 10, 25 wt% S</td>
</tr>
</tbody>
</table>

**Results and Discussion:**

1. *Europa’s metallic core may have taken billions of years to start forming.* Most simulations result in Europa starting its rock-metal differentiation a few Gyr after accretion. In cases with low sulfur content in the metal, there is insufficient heat to trigger metallic core formation at all. If we were to make the most generous assumptions within our parameter space to favor early core formation—late formation time, anhydrous start, 10 mW m⁻² tidal heat flux at the seafloor (equivalent to a total 3×10¹¹ W tidal dissipation in the silicates), and Fe-FeS eutectic core composition—then the metallic core formation would initiate ~0.5 Gyr after accretion.

2. *Fe-FeS core composition significantly affects when Europa can kickstart metallic core formation.* Sulfur abundances in the metal alone can shift metallic core formation times by billions of years if not inhibit core formation entirely. Other parameters have smaller effects. For example, two choices lead
to slightly earlier core formation times in our models: assuming 1) an earlier accretion time, or 2) that some of the silicates are initially anhydrous.

3. **Tidal heating is less important for sulfur-rich core compositions.** If we assume an anhydrous silicate start, 3 Myr formation after CAIs, and Fe-FeS eutectic core composition, changing tidal heat flux at the seafloor from 0 to 10 mW m⁻² expedites metallic core formation from a mere ~0.7 to 0.5 Gyr after accretion, respectively. However, tidal heating can enable the formation of sulfur-poor metallic cores or dominate other parameters if exceeding 3 × 10¹¹ W kg⁻¹ in the silicates by an order of magnitude.

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**References:**

**Fig. 1.** Timing of metallic core formation in Europa. Each plot summarizes the results of many simulations for different amounts of accreted hydrated silicates and formation time of Europa. The left, middle, and right columns represent 0, 10, and 25 wt% S in the Fe-rich core, respectively. The top, middle, and bottom rows represent 0, 3 × 10⁶, and 3 × 10¹¹ W in total tidal dissipation in the rock-metal interior. Colors and contour lines display the start time of metallic core formation. White spaces indicate scenarios where Europa never forms a metallic core.