Quantifying Oxidant Delivery to Europa’s Ocean via Basal Melt.

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Introduction: Jupiter’s ocean moon, Europa, is considered a primary target for habitability and life detection missions [1] due to the likely presence of a liquid water ocean[2][3] beneath its geologically young outer ice shell[4][5][6]. Liquid water within the ocean acts as a necessary solvent for life. The water remains liquid in part due to tidal dissipation within Europa’s interior and this dissipation, through heat and displacement, has likely been variable over the history of the satellite [7][8][9]. However, life also requires energy, which can be achieved through redox gradients in the environment [10]. Such a gradient can be achieved if oxidized compounds from the highly irradiated surface[11][12] can be transported through the ice shell and enter an ocean that has been reduced by hydrothermal fluids[13][14]. We consider the possibility that basal melt at the ice-ocean interface is likely a continuous process, ongoing on local scales in some regions even during times of ice shell growth, capable of delivering oxidants into Europa’s ocean, and we estimate the delivery rate under variable thermal states.

Delivery of oxidants into Europa’s ocean has been previously explored through a variety of methods [14][15][16] and is an area of debate, especially in regard to the rate and efficiency at which oxidants are transported through the ice shell. We examine the problem using a box model to examine delivery in a two-part method: transport from the surface into the ice shell and transport via melt at the base of the ice shell. By constraining the rate both into and out of the ice shell, we also obtain an estimate of the amount of oxidants within the ice shell at any point over probable thermal settings. This allows us to be agnostic about the explicit transport processes within the ice shell, while still providing constraints on ocean delivery. We also do not assume that all oxidants are efficiently transported into the ocean.

Transport into the shell: Our method of defining rates of oxidant transport into the ocean is based on surface age constraints similar to that of Hand, 2007. It is estimated that the oxygenated surface layer is centimeters to meters thick [14][16]. Using this we can calculate both a maximum and minimum volume of the oxygenated surface layer by solving for the outer spherical shell of thickness ranging from 5cm to 10m. The minimum rate at which this oxygenated layer is entirely replaced is the oxygenated volume divided by the surface age of Europa, τ, with a minimum estimate of 30 million years and an upper estimate of 90 million

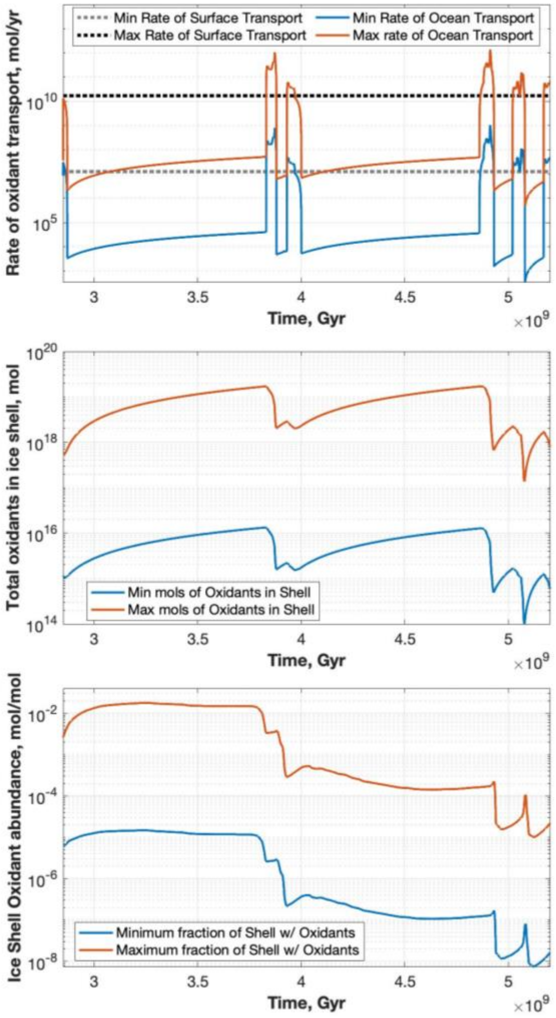

Figure 1: (top) The rate of oxidant transport into the ice shell is faster than the rate that oxidants are released into the ocean via melt. The rate of transport into the ice shell is likely to be variable as well, though rates of surface overturning are not well constrained. Once in the shell (**middle**) it is assumed that oxidants become well-mixed within the ice shell due to a combination of geological processes, including convection. These intra-shell oxidants represent a dynamic, potential reservoir that may act as a source for redox potential within the ice shell for putative biology. The large amount of oxidants within the ice shell may have geophysical implications on ice shell structure, depending on their abundance and stability within the shell. For larger, thicker ice shells, the abundance of oxidants in the ice shell (**bottom**) will be lower than that of a thin shell for the same total amount of oxidants.

years [6]. Within this outer, oxidized layer we assume a set of species abundances based on observational data [14].

Table 1: maximum and minimum estimates of oxidized species abundance, $A_{i,1}$, within Europa's upper surface layer in units of mol/ mol H_2O

	H_2O_2	O_2	SO_4	CO_2	SO_2
Maximum	0.0013	0.046	0.1	0.00123	0.017
Minimum	0.0013	0.012	0.1	0.00036	0.001

The oxidants are accumulated within the ice shell at a total rate of 1E8 mol/yr - 4E10 mol/yr, consistent with previous studies.

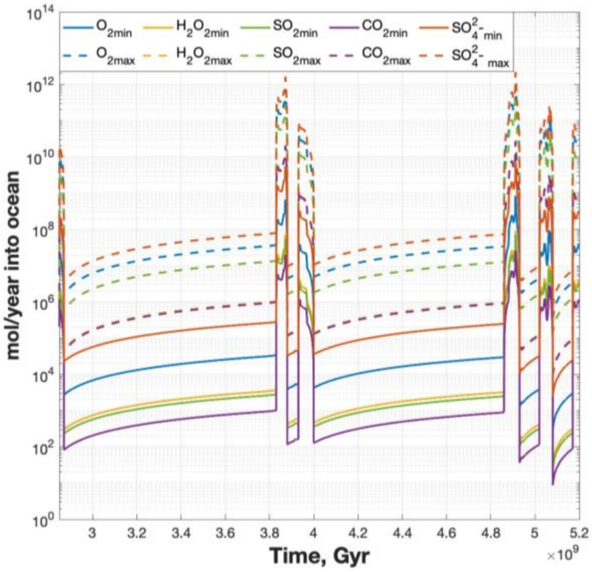

Figure 2: Minimum and maximum rates of delivery of various oxidizing species into Europa's ocean. The differences in minimum and maximum rates is defined by teh thickness of the oxidized layer at Europa's surface, the rate of delivery into the ice shell, and the initial surface abundance of the species.

Transport out of the shell: Basal melt is a continuously occurring process on Earth ice sheets that is critical for nutrient transport to the deep shelf environments. Recent work has suggested that the Europan ice shell may have continual basal melt (Green et al, 2021) due to the large discrepancy between low and high latitude equilibrium thicknesses and the lack of observational evidence for such shell thickness variation. They hypothesize that as lateral displacement of ice from the thicker equatorial regions reaches the thinner polar regions, the ice will extend beyond its equilibria thickness inducing melting at the poles. The study suggests that continuous melting may be occurring at the Europan poles, even during periods of net freezing. This is supported by studies of Antarctic ice sheets on Earth that demonstrate some amount of basal ice melt, even during net ice growth (Depoorter et al., 2013; Jacobs et al., 1992). We can therefore reasonably infer that basal melt is likely to be an important and continual mechanism of oceanward transport in Europa.

As oxidants accumulate in the shell at the rate specified in the section above, the abundance of oxidants within the shell, $A_{i,2}$, is recorded and used to determine the ratio of oxidants within the melt.

Total melt is calculated through change in ice shell thickness. During periods of net shell melting, the surface area of the base of the ice shell times the thickness change in the shell dictates the volume of melt created. An additional term is included to capture additional melt that would be cancelled out by localized freezing. During periods of net freezing, a fraction of the ice shell base is assumed to be melting and is inversely proportional to the heat flux at the base of the ice shell.

Results: We present a novel quantification of oxidant delivery that demonstrates that continuous delivery of oxidants into Europa's ocean is possible, even during periods of extreme ice shell thickening. These results further indicate that oxidant delivery may vary with Europa's thermal-orbital evolution, leading to oscillatory rates of oxidant transport. This has large implications for the satellite's ocean chemistry and any putative biology that may relyon oxidant transport. In particular, these results show that for most of Europa's history oxidant delivery may be as low as 10^3 – 10^5 mol/yr, far lower than most estimates of hydrogen production due to water-rock reaction at Europa which are on the order of 10^8 – 10^12 mol/year [13], implying a lreduced ocean for most of Europa's history.

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