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Core-ocean-ice exchange processes in Europa, Ganymede and Callisto

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Magnetic data gathered by the Galileo spacecraft [1, 2] along with the observations of time-varying auroral emissions [3] provide evidences for deep salty water oceans within Jupiter's moons, Europa, Ganymede and Callisto. However, the composition and the depth of these internal oceans remain very poorly constrained. Identifications of magnesium-bearing and sodium-bearing salts at the surface of Europa [4] provides some indications about the possible oceanic composition. For Ganymede and Callisto, unfortunately, no compositional clues exist yet. The thickness of the outer ice shell is also unconstrained. Based on thermal evolution models, Europa's ice shell thickness is estimated between 10 to 40 km, while Ganymede and Callisto may have an ice shell as thick as 100 km. Due to their large volume of H_2O compared to Europa, Ganymede and Callisto are expected to have a high-pressure ice mantle separating the ocean base from the rock core. However, the thickness of this high-pressure mantle remains unconstrained. Future geophysical and compositional measurements by the NASA Europa Clipper mission [6] and the ESA JUpiter ICy moon Explorer (JUICE) mission [5] will provide crucial constraints on the hydrosphere structure, the ocean composition and the deep interior structure of these bodies [7].

In preparation of the future measurements, we model the possible present-day internal structure of these three icy ocean worlds and the exchange processes between their internal layers. A first step is to develop structural models consistent with available experimental and geophysical constraints. In order to predict accurately the density profile and the ice-ocean interfaces, we use a thermodynamical representation based on local basis functions [8]. Different oceanic compositions are considered in order to test their influence on the hydrosphere structure and the potential signature of oceanic composition in the future geophysical measurements. For the moment, only the global shape and the degree-two component of the static gravity field are known, with significant uncertainties. Future measurements will give access to both gravity and topography data at much higher degree together with time variations due to tides. First estimates based on NaCl and $MgSO_4$ oceanic compositions [7] indicate that tidal fluctuations are sensitive to the oceanic composition in addition to ice shell thickness. Similar to the approach developed for the interpretation of Cassini data at Titan [9, 10], the joint interpretation of gravimetric and altimetric data may provide constraints on ice shell thickness variations, providing indirect informations on the thermal state of the ice shell and on heat flux anomalies at the ocean-ice interface. New models of ice shell dynamics including composite rheology are developed in order to better characterize the thermal structure of the outer ice shell and the efficiency of heat transfer from the ocean to the surface.

The present-day structure and composition of the ice-covered ocean worlds results from a complex interplay between heat production and transfer, water-rock interactions, and melting/crystallization processes. Since their formation, each moon has followed a unique evolutionary path, characterized by various degree of rock-water-ice interactions. For Ganymede and Callisto, massive water-rock interactions may have occurred during their differentiation stage, while on Europa direct contact between the ocean and the rock core promotes efficient water-rock interactions all along its history. However, using 2D and 3D numerical simulations of thermal convection in the high-pressure ice mantle [11, 12], we show that efficient transport of volatiles and salts from the rock core to the ocean may have also occurred in Ganymede, at least in the past, and possibly in Callisto. The ocean crystallization/melting varies as a function of time depending on the heat production mostly due to radiogenic and tidal heating and on the efficiency of heat release to space. Tidal heating, which is a main driver of Europa's evolution, is likely negligible at present on Ganymede, but could have played a role in the past. Based on models, the present-day tidal dissipation at present in Europa is expected to be larger than the radiogenic heating and may have been even larger in the past depending on its orbital evolution, which is intimately linked to Io and Ganymede through the Laplace resonance. Therefore, understanding the evolution of these icy ocean worlds requires a simultaneous description of their evolution and their tidal interactions. A detailed model incorporating these various processes and their coupling is under development. The ultimate goal is to provide a theoretical framework to interpret the future data and to assess their implications in terms of thermal history and habitability of these icy ocean worlds.

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