EXPLORING THE PARAMETER SPACE OF EUROPA'S OCEAN SALINITY THROUGH TIME

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Introduction: Europa's ocean depth, thickness, and composition have changed through time. They have evolved with the geodynamics of its rocky interior and likely metallic core, and in step with the loss of water and hydrogen to space and accretion of water and other chemical species from comets, dust, and Io's volcanism. The available constraints of likely starting materials and present geophysical properties provide a large parameter space of possibilities. That parameter space can be reduced by applying geochemistry and thermodynamics. We are combining internal structure models with detailed calculations of ocean composition. Recent advances in high-pressure aqueous chemistry and water-rock interactions allow us to compute the equilibrium conditions and pH throughout Europa's interior. Here, we develop radial structure and composition models for Europa, using self-consistent thermodynamics of all components, developed using the PlanetProfile software [1].

Europa's Starting Materials Based on Its Water Budget: Consistent with gravitational constraints on Europa's density structure [2] the amount of water in the 80-170 km thick H_2O upper layer may be compared with the amounts of water included in possible chondritic building blocks for Europa [3]. Model Europas are constructed from different chondrite compositions [4]. Europa is assumed to have a metallic core with all of the iron from Fe(m) and FeS contained in the respective chondrites. Silicate densities are adjusted after accounting for H_2O, Fe, and FeS (1,000; 8,000; and 5,150 kg m^{-3}). CV and CM chondrites contain amounts of water within 5% of Europa's mass, a discrepancy less than the ~6% of water, by mass, implied by gravity measurements. Discrepancies in this range can be accounted for by sputtering, and sequestration in the rocky interior; or addition from comets, icy planetesimals, or CI chondrites.

Europa's Starting Materials Based on Jupiter's Formation: Recently, Desch et al. [5] argued that Jupiter's formation would have caused a local pressure maximum in the gas disc just beyond proto-Jupiter's position at 3 AU. This region is where Ca-rich Al inclusions (CAIs) would have accumulated, and also the likely main feeding zone for the formation of Jupiter's moons. This further supports to idea that CM and CV chondrites were main starting materials for Europa and the other Galilean moons. The fact that these materials appear to be aqueously altered is not relevant to the present discussions. It is assumed that their bulk compositions are primordial, and any alteration prior to incorporating into Europa was erased by heating during accretion or subsequent evolution [6].

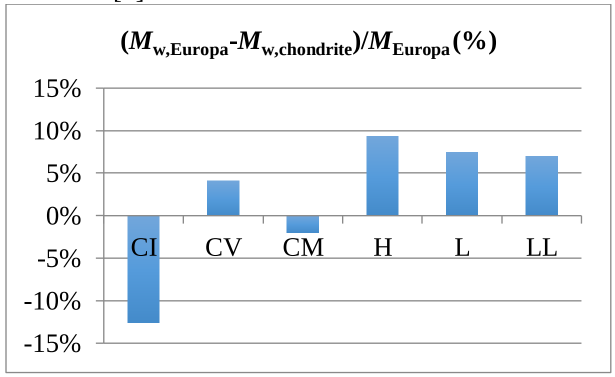

Fig. 1. Missing water in Europa's ocean, relative to chondritic meteorites, as a percent of total mass, assuming all water from the parent body ends up in Europa's ocean, and no more.

Self-consistent Europas From Chondritic Inputs: We incorporated bulk silicate compositions of chondrites into the PlanetProfile radial structure model [1] using the Perple_X software [7]. This allows us to calculate the stable mineral assemblage, including variation of material properties with P and T, and to account for ocean salinity. Model calculations for CI, CM, and CV chondrites are shown in Table 1. A subeutectic (i.e., low-sulfur) Fe-FeS core is assumed, containing 25 wt% FeS (7.3 wt% S). Excess masses (or deficits) of H_2O and S are noted as a percent of Europa's total mass.

Specifying core S greater than 20 wt% in the CV model of Europa exceeds the available chondritic abundance. We note that higher amounts are unlikely for Europa as has been previously suggested [3], because the Fe-FeS eutectic at Europa core pressures in the range 5-6 GPa is lower than the 26% value at 0.1 MPa [8]; for comparison, Earth's core S content is less than 1 wt% [9]. If such high (>20 wt%) S abundances occur in Europa's core, a CV composition would imply little endogenous sulfur in the ocean.

Ocean Composition: We use our PlanetProfile results to calculate Europa's bulk ocean chemistry, based on bulk silicate Earth models [3]. Extractions into Earth's upper continental crust [10] and ocean [11] are scaled to Europa as shown in Figure 2, assuming a 100 km-deep ocean. The present results reproduce those of Zolotov and Shock [3], and demonstrate that the scaling to Earth predicts much lower concentrations than the 35 g kg^{-1} (as $Na+Cl+SO_4+Mg+Ca+K+Br$) in Earth's mean ocean composition [12]. We note recent work that strongly argues chondritic abundances of chloride Cl are 6-9x lower than the (previously measured) standard values used here [13]. Future refinements will expand the list of dissolved oceanic elements to include Fe, Si, and N; and to compute the their molecular distribution (speciation).

	CI	CM	CV
SiO_2	48.27	38.38	37.06
Al_2O_3	3.62	2.87	3.51
FeO	9.85	29.33	29.25
MgO	33.76	26.34	26.79
CaO	2.89	2.50	2.86
Na_2O	1.62	0.57	0.53
D_{ice} (km)	*31*	*31*	*31*
D_{ocean} (km)	*122*	*121*	*122*
R_{rock} (km)	*1408±15*	*1409±15*	*1408±15*
R_{core} (km)	*397±141*	*410±130*	*397±141*
ΔH_2O (wt %)	*7.1*	*0.6*	*-9.5*
ΔS (wt%)	*3.0*	*2.1*	*2.2*

Table 1. Composition and structure of Europa based on chondritic inputs [4; in wt%, normalized to the total], assuming a relatively thick ice shell and a seawater salinity identical to Earth's.

Ocean Composition Through Time: The radial structure models described here can be used to explore how Europa's ocean composition may have evolved through time, by considering different depths and temperatures of water rock interaction as radiogenic heating decreases, and with varying amounts of tidal heating [14]. Coupled to these is the changing pH of the ocean due to changing fluxes of reductants and bases from the seafloor, and oxidants and acids from the ice [15,16]. Because different mineral dissolution reactions exhibit different pH dependences, we can expect potentially dramatic changes in the major element composition of the ocean. Understanding this rich parameter space provides key context for future exploration by the Europa Clipper mission concept.

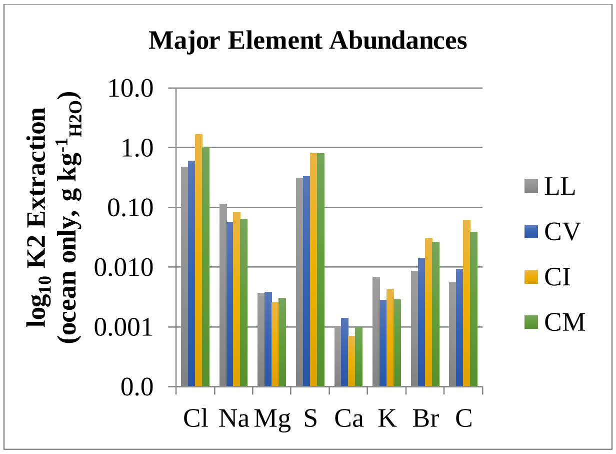

Figure 2. Bulk silicate Earth extraction into the ocean for different chondritic inputs. Charge balance and oxidation state would require precipitation of some of the materials even at these low abundances [3].

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