Thermal-Compositional Evolution of Europa's Interior and Ocean Since Accretion

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Abstract

Europa's compositional evolution is not well constrained. Observations only provide approximations of the current interior structure of Europa. However, dynamic models [Hussmann & Spohn 2004] resolve the magnitude of interior heating produced by tidal interaction over time. We couple the heat production to thermodynamic and chemical equilibrium models Perple_X [Connolly 2005], Rcrust [Mayne+ 2016] and CHIM-XPT [Reed 1998] to compute compositional changes of the interior and ocean. Assuming that Europa's interior is not molten now, a Fe core could have accommodated up to 24 wt % S during accretion, assuming chondritic accretion material. However, a metal-silicate segregated magma ocean was needed to allow such high S content in the core. More likely, accretion proceeded with low impact rates that allowed heat dissipation. Based on this and experimental metal-silicate partition behavior, Europa's core contains ˜1 wt % S. Two mantle melting events were calculated corresponding to putative events in Europa's thermal-orbital evolution: a first event that melted up to 30 vol % of the volatile-rich silicate shell, at pressures of 2.5 – 1.2 GPa [?]4 Ga ago, and a possible melting event ˜1.3 Ga ago resulting from increased dissipation as the mantle's rigidity increased [Hussmann & Spohn 2004]. Melt intrusive to extrusive ratios (I/E) for Europa are unknown, but eruption to the ocean-rock interface would have been hindered by high stress needed to cause fracture propagation and melt migration at depth [Byrne+ 2018]. Assuming I/E = 10, <7 wt % melt would have erupted (Fig 1). Even if lava erupted during the first event, limited heat transfer from, and dehydration of, the mantle may not have prevented the second event from occurring. Considering Europa's volcanism enables us to predict the minerals likely to have influenced the ocean's composition and the mineralogy of concurrent water-rock activity. Erupted lava reacting with the ocean results in water-to-rock ratio dependent proportions of sulfides, saponite, chlorite and carbonates. We will describe implications for the ocean's composition and habitability. A part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Thermal-compositional evolution of Europa's interior and ocean since accretion: Did Europa's solid tides prevent the thermodynamic death of its ocean?

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Aqueous environments in chemical disequilibrium are candidate locations for the emergence and existence of life. Europa's ocean could be one such location in the Solar System, but questions remain about the persistence of disequilibrium there. However, water-rock interactions may have been promoted by tidal interaction between Jupiter and its moons. How the composition of Europa's interior and ocean has responded to orbital evolution remains unconstrained. Here we test whether the "thermodynamic death" of Europa's seafloor and ocean could be avoided by sustained element flux between them enabled by orbital evolution.

Problem

High pressures at the seafloor (150 – 200 MPa; Vance et al., 2018) may seriously restrict fracture formation at the water-rock interface, the flow of water, and hydrothermal venting (Vance et al., 2007; Byrne et al., 2018) required for element fluxes favorable for life (e.g. McCollom 1999). As a result, chemical equilibrium between the ocean and the rocky interior could have been attained billions of years ago (Gaidos et al., 1999).

A solution?

Orbital evolution and periods of eccentricity equilibration due to resonance locking (Fuller et al., 2016) may have caused temperature spikes, resulting in metamorphic reactions, silicate melting, and deformation that consequently controlled the pumping of water and dissolved ions through, and out of, the silicate interior.

Objectives

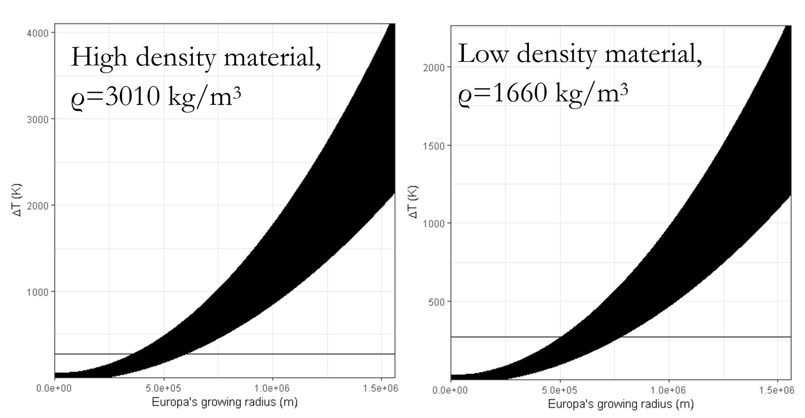
1) Resolve the interior structure of Europa since its accretion by coupling a tidal-orbital evolution model to interior structure models.

2) Determine the composition of the silicate interior and reactions throughout Europa's evolution, including silicate partial melt production and the loss and retention of volatile and redox-sensitive elements. This would be done by using our coupled model and petrological models based on experimental phase relations and Gibbs free energy minimization.

3) Determine the volume of silicate melt extruded to the water – rock interface, and the heat loss and crystallization timescales. This would inform about the sequestration and loss of volatiles from the interior in time.

How much water did Europa accrete?

High temperatures caused melting and vaporization at the surface during accretion...



Increasing temperature calculated at the surface of Europa during accretion. (Material properties from Opeil et al. (2012). Upper and lower bounds are found using chondrite heat capacities.)

As Europa accreted, temperature at the surface would have reached the melting point of silicate rocks:

$$\Delta T = \int_0^{M_{Europa}} \int_0^{R_{Europa}} \frac{GM}{RC_p}\, dM\, dR$$

(modified from Stevenson et al., 1986)

Where ΔT is the temperature increase at the surface of the growing body, with respect to the accretion disk, M and R are the mass and radius of the growing body, G is the gravitational constant, and Cp is the heat capacity of the accreting material.

Different meteoritic building blocks of Europa contain different amounts of water:
CI chondrites (~11 %) > CM chondrites (~10 %) > Europa (~8 %) > L chondrites (~1 %) > > H chondrites (~0.3 %) > CV chondrites (~0.2 %) (Lodders and Fegley, 1998)

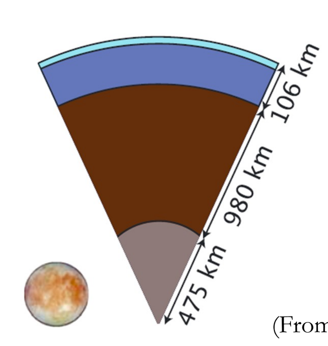
Could the water originally accreted water have been retained? Or was the ocean delivered by meteorites after accretion?

Let's consider Europa's current energy flux ≈ 1012 kJ/s (e.g., Canup and Ward, 2009)
If Europa has been in the same Laplace resonance over the past 4.5 Ga (Peale and Lee, 2002):
(1012 kJ/s × 4.5 Ga)/(Mass Europa ≈ 4.8 × 10^{22} kg) ≈ 3 × 10^6 kJ/kg

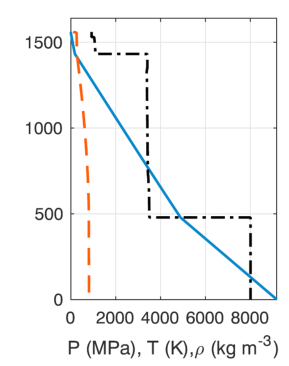
3 × 10^6 kJ/kg >> 2 × 10^3 kJ/kg (the latent heat required to vaporize water (Datt, 2014))
and 3 × 10^6 kJ/kg >> 1.2 × 10^3 kJ/kg (the gravitational binding energy of Europa (Barr and Canup, 2008))

...So a lot of that initially accreted water may have been driven off from Europa!

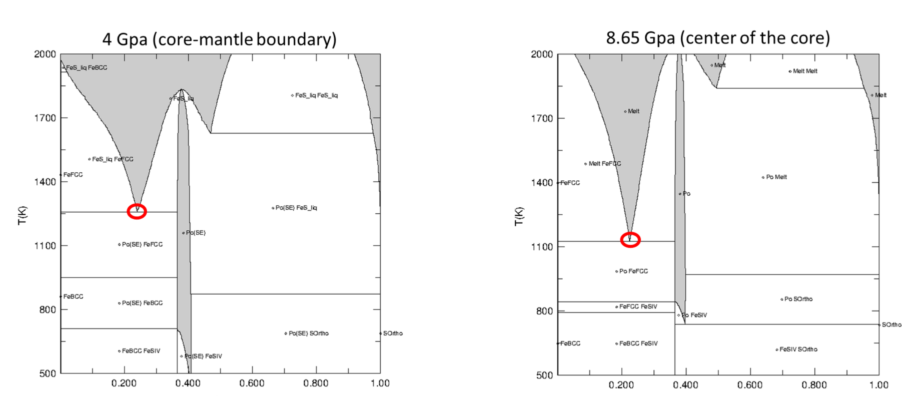
Interior structure and composition of Europa



(From Vance et al., 2018.)



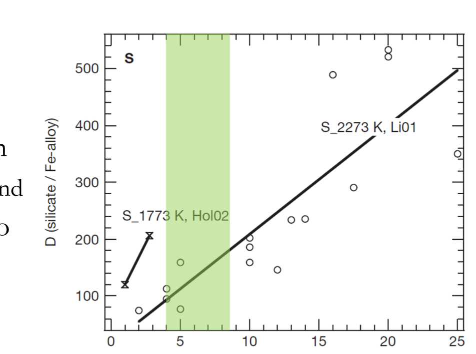
PlanetProfile (Vance et al., 2018) was used to determine the spherical shell model of Europa's interior, based on *Galileo* constraints (MoI, radius, density), and thermodynamics (ice, ocean and interior compositions and densities).



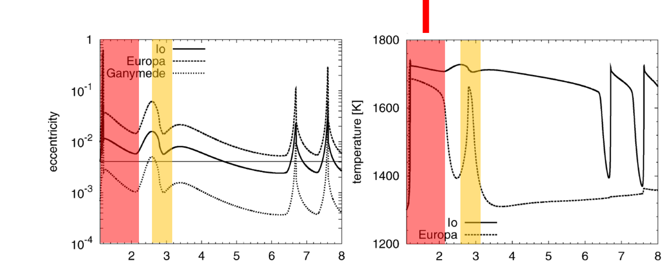
Phase relations in the Fe-S system. At conditions relevant to Europa's Fe ± S core, up to 24 wt. % sulfur could be present at the eutectic point (red circle). Calculated with *Perple_X* (Connolly 2005; 2009) using the thermodynamics of Saxena and Eriksson (2015) and Europa pressure constraints from Vance et al. (2018). FeFCC = face-centered cubic iron, FeBCC = body-centered cubic iron, Po = pyrrhotite, SOrtho = orthorhombic S, "liq" = melt phase.

Fe is subtracted from the bulk chondritic composition to form the mass required by the Fe ± S core. The amount of sulfur partitioned into Fe is ≈ 24 wt. % at the eutectic in the conditions relevant for Europa's. However, experimental silicate-alloy segregation shows that only ~1 wt. % sulfur could partition into Europa's core during planetary differentiation (e.g. Li and Fei, 2014).

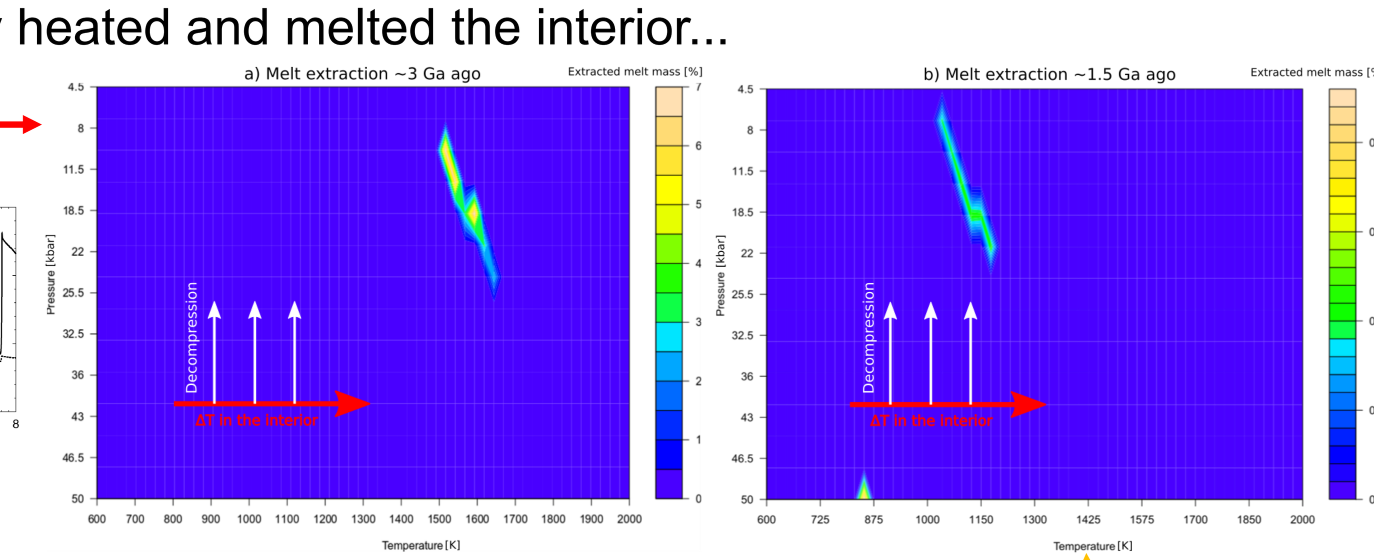
Sulfur partitioning behavior between silicate and Fe-alloy as a function of pressure and temperature, from experimental work (Figure from Li and Fei, 2014). The green field highlights the pressure conditions relevant to Europa's core. Only about 1 wt. % sulfur would partition from the chondritic composition into the Fe-alloy under these conditions.



Returning to low eccentricity heated and melted the interior...



Eccentricity of Europa and resulting temperature in the silicate interior (Figures from Hussmann and Spohn, 2004).



Silicate melt erupted from the mantle to the seafloor at different times in Europa's history from homogeneous heating of the interior and decompression at all depths.

Calculated with *Perple_X* (Connolly 2005, 2009) and *Rcrust* (Mayne et al., 2016), assuming a CI chondrite Europa, and intrusive to extrusive ratio = 10.

Partial melts erupted at the seafloor bring oxidants, methane and sulfide into the ocean, which may be used by biology.

Erupted melt compositions (weight %)	H_2	C	Mg	Si	S_2	Fe	O_2	Total	Vented fluids
Initial bulk composition (CI chondrite - Fe core with 1 wt.% S)	2.29	3.90	10.97	12.03	6.03	12.30	52.48	100	-
First melt (~3 Ga ago)	1.47	0	19.05	20.22	0	9.33	49.92	100	-
First melt + magmatic fluid	6.73	13.28	12.95	13.74	13.03	6.34	33.93	100	CH_4>H_2S>H_2
Second melt (~1.5 Ga ago)	0.88	0	2.54	13.35	0	46.15	37.08	100	-
Second melt + magmatic fluid	13.14	22.05	0.47	2.45	4.74	8.46	48.69	100	H_2O>CH_4>H_2S

Conclusions and future work

If tidal dissipation occurred in the silicate interior of Europa, the resulting heat provided a way to mobilize elements from the deep interior into the ocean, in the form of silicate ± metal melt and H_2O-CH_4-H_2S-H_2 fluids.

In the near term, we will use different starting bulk compositions for Europa, implement carbon and sulfur solubility in the silicate melt, and determine the speciation of the magmatic and metamorphic fluids from source. We will also implement a geodynamic model to constrain the volumes of melt and fluids that were able to erupt at the seafloor throughout Europa's orbital history. Finally, we are also working on the chemical interactions that occur when silicate melt is quenched in a deep ocean.

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References: Vance S. D. et al. (2018) *J. Geophys. Res. Planets* **123**, 180–205. Vance S. D. 2007 et al. (2007) *Astrobiology* **7**, 987–1008. Byrne P. K. et al. (2018) In *Ocean Worlds*, LPI Contributions p. 6030. McCollom T. M. (1999) *J. Geophys. Res. Planets* **104**, *30729—30742*. Gaidos E. J. et al. (1999) *Science* **284**, 1631. Fuller J. et al. (2016) *Mon. Not. R. Astron. Soc.* **458**, 3867—3879. Lodders and Fegley (1998) *The planetary scientist's companion*, Oxford University Press, New York. Canup R. M. and Ward W. R. (2009) In *Europa*, University of Arizona Press with Lunar and Planetary Science Institute, Tucson, AZ, pp. 59—83. Peale S. J. and Lee M. H. (2002) *Science* **298**, 593. Barr A. C. and Canup R. M. (2008) *Icarus* **198**, 163—177. Datt P. (2011) In *Encyclopedia of Snow, Ice and Glaciers*, Springer Netherlands, Dordrecht p. 703. Stevenson D. et al. (1986) In *Satellites*, Space Science series, University of Arizona Press, pp. 39—89. Opeil C. P. et al. (2012) *Meteorit. Planet. Sci.* **47**, 319—329. Hussmann H. and Spohn T. (2004) *Icarus* **171**, 391—410. Connolly J. A. D. (2005) *Earth. Planet. Sci. Lett.* **236**, 524—541. Mayne M. J. et al. (2016) *J. Metamorph. Geol.* **34**, 663—682. Saxena, S., & Eriksson, G. (2015). Thermodynamics of Fe–S at ultra-high pressure. *Calphad*, **51**, 202–205. Li, J., & Fei, Y. (2014). 3.15 - Experimental Constraints on Core Composition. In H. D. Holland & K. K. Turekian (Eds.), *Treatise on Geochemistry* (Second Edition) (pp. 527–557). Oxford: Elsevier.

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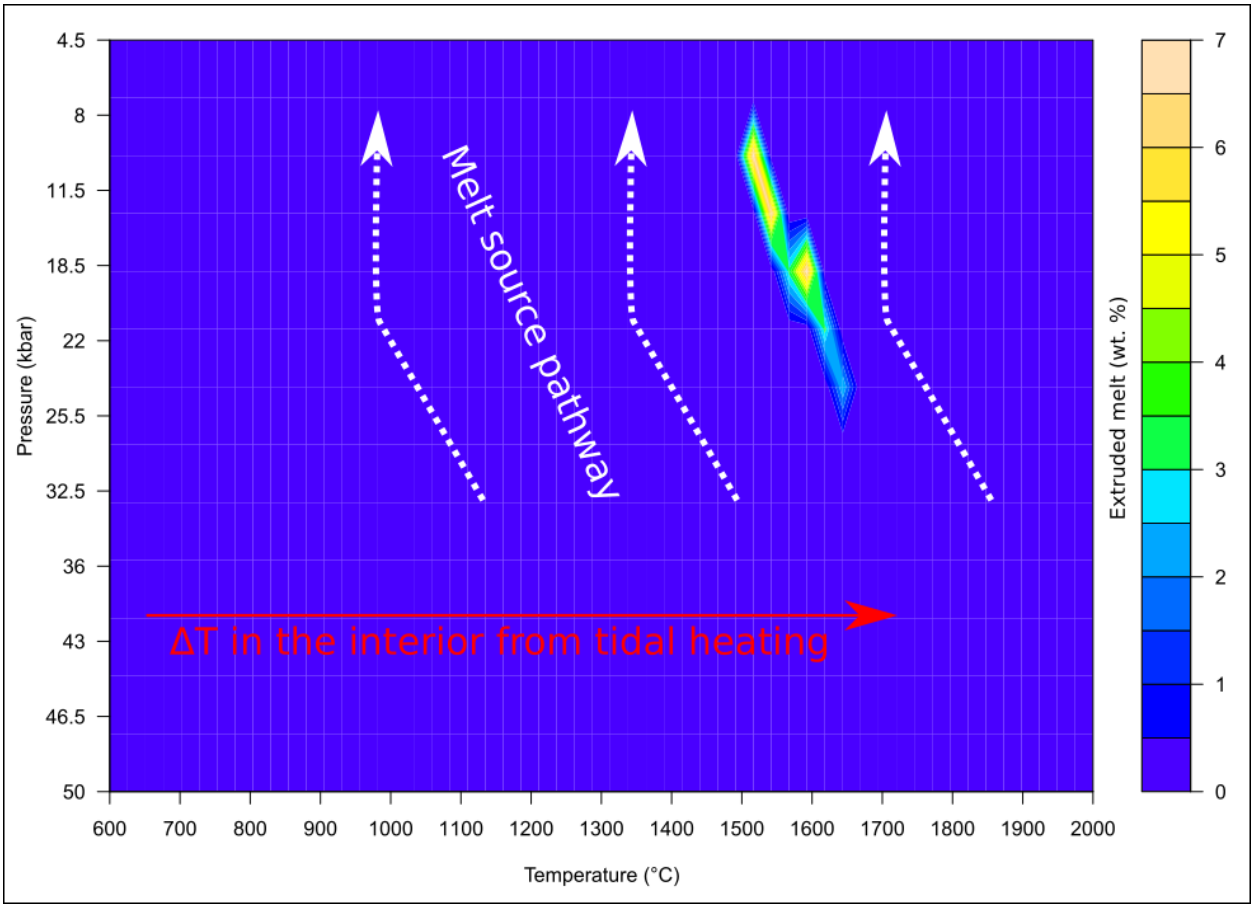

Melt source pathway
ΔT in the interior from tidal heating
Pressure (kbar)
4.5
8
11.5
18.5
22
25.5
32.5
36
43
46.5
50
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Temperature (°C)
Extruded melt (wt. %)
7
6
5
4
3
2
1
0