

PRESERVATION OF DEEP OCEANS IN THE URANIAN MOONS, PREDICTED COMPOSITIONS, AND PHYSICAL CHARACTERISTICS. J. Castillo-Rogez¹, B. P. Weiss^{1,2}, C. B. Beddingfield^{3,4}, J. B. Biersteker², R. J. Cartwright³, A. Goode², M. Melwani Daswani¹, M. Neveu^{5,6}. ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA (Julie.C.Castillo@jpl.nasa.gov), ²Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, ³SETI Institute, Mountain View, CA, USA, ⁴NASA Ames Research Center, Mountain View, CA, USA, ⁵University of Maryland, College Park, MD, USA, ⁶NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Summary: As the only native ice giant satellite system, the five large moons of Uranus are important targets for future spacecraft missions. To inform the exploration of these moons, we model their internal evolution, present-day physical structures, and geochemical and geophysical signatures that may be measured by spacecraft. We predict that if the moons preserved liquid until present, it is likely in the form of residual oceans less than 50 km thick in Ariel, Umbriel, Titania, and Oberon. The preservation of liquid strongly depends on material properties and, potentially, on dynamical circumstances that are presently unknown. Miranda is unlikely to host liquid at present unless it experienced tidal heating a few tens of million years ago. We find that since the thin residual layers may be hypersaline, their induced magnetic fields could be detectable by future spacecraft-based magnetometers.

Methodology: The approach is based on proven thermal modeling combined with the tracking of porosity [1]. The code also tracks the fates of accreted volatiles upon differentiation and subsequent freezing of the hydrosphere with the Geochemist's Workbench and FREZCHEM software. We use a reference CI elemental composition with the addition of a few percent of carbon ices and ammonia, as described in [2]. The rock composition and physical properties are derived from the PERPLEX software [3]. We track the impact of thermal metamorphism on the composition of the rock and the nature of fluids released to the ocean over time. That information is then used to derive estimates for the degree-two gravity fields of the moons and the induced magnetic field that may be generated in their oceans [4].

Results: Tidal heating in the Uranian moons is mainly significant for only Miranda and Ariel, when they crossed mean motion resonances. This is suggested by the high heat flow derived from relatively recent geological features (<~100 My in the case of Miranda and <~1 Gy in the case of Ariel) [5]. Even accounting for tidal heating, the moon interiors freeze on timescales of a few tens of My (Miranda) to hundreds of My. Primordial porosity preserved in the outer part of the outer shell and low-eutectic-temperature compounds like ammonia and chlorides,

can increase the volume of residual liquid preserved until present [6]. However, a large fraction of accreted ammonia is expected to be converted into ammonium [2] so that the antifreeze role of the compounds is greatly diminished. Clathrate hydrates, water cages surrounding gas molecules that have been invoked to decrease the thermal conductivity of icy shells [e.g., 7] are unlikely to form in the moons because carbon-bearing ices are primarily used in the production of carbonates [2]. The most important process contributing to the preservation of a deep liquid layer until present is thermal metamorphism. Around 1-1.5 Gy after formation, heated rock releases the equivalent of several tens km of water and other volatiles (e.g., CO₂) from the decarboxylation of carbonates.

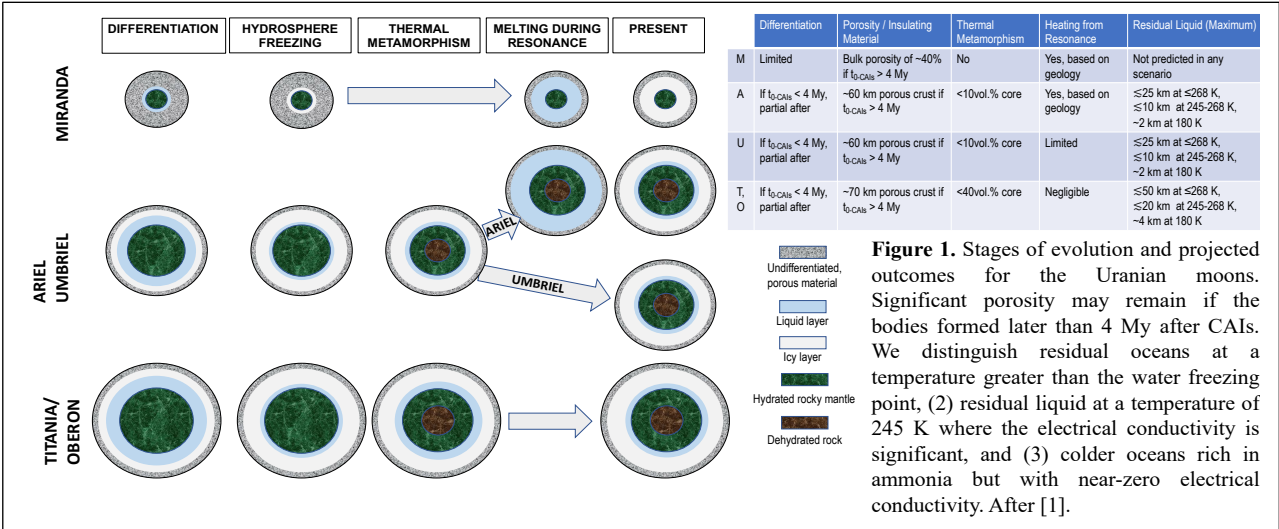
Altogether, we predict that the largest moons, Titania and Oberon (>1500 km diameter, ~1.6 g/cm³) should host deep oceans up to 50 km thick. Ariel and Umbriel, of intermediate size (~1200 km, ~1.5 g/cm³) should preserve less than ~30 km thick oceans (Figure 1). These estimates have much uncertainty because stochastic processes like basin-forming impacts, can accelerate heat loss. A larger contribution of cometary material can also decrease the relative fraction of radioisotopes. On the other hand, tidal heating could have contributed to extensive melting of the hydrosphere, at least in Ariel. Hence, these ocean estimates should be taken as a baseline against which future observations can be compared.

In absence of tidal heating, Miranda, the smallest and least dense of the major Uranian moons (<500 km diameter, ~1.2 g/cm³) is unlikely to have been globally melted at any point in its evolution and host liquid at present. On the other hand, the high heat flow derived from geological landforms [8] requires enhanced heating via resonance crossings as suggested by dynamical studies [e.g., 9]. Even so, tidal dissipation associated with an orbital resonance would have to occur very recently, less than tens of Ma, for Miranda's hydrosphere to still be partially liquid. A future mission could set timing constraints on the dynamical evolution of the Uranian system.

Residual liquid layers in the Uranian moons are likely very concentrated in ammonium, ammonia, and chlorides. The relative concentrations [NH₃]:[NH₄]

and $[HCO_3]:[CO_3]$ depend on the extent of freezing (Figure 2). The potential detection of NH_3 at the surface of Ariel [10] is consistent with the predicted

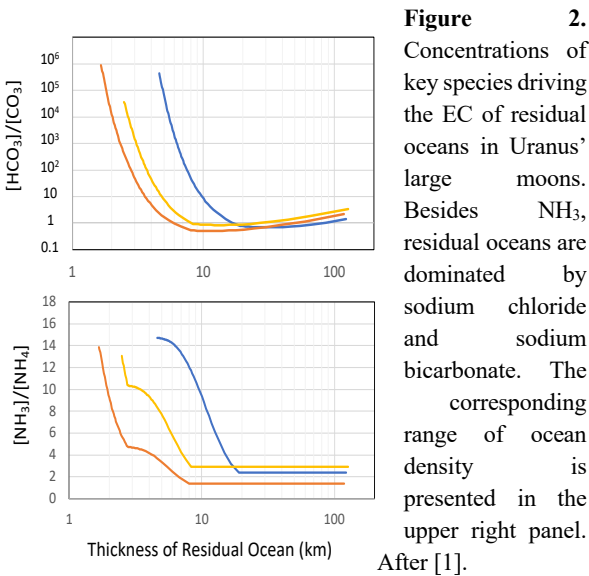
ocean composition for that moon. The full range of outcomes can be found in [1]



Future Observations: The predicted interior structures and compositions can serve as a basis to formulate future gravity and magnetic field investigations in the context of the Uranus Orbiter and Probe mission, the first priority of Origins, Worlds, and Life decadal survey for Flagship-class missions [11]. The search for induced field measurements indicative of conducting oceans can confirm or discard assumptions on porosity, metamorphism, tidal heating, and ocean composition. A major limitation on ocean detection by induction is that if the ocean is primarily dominated by ammonia then then that layer would likely have a low electrical conductivity (<0.01 S/m) due to the negative dependence of that property on temperature. In the case of Miranda, gravity measurements can test if the moon has preserved a highly porous shell or underwent global melting and differentiation. The compositional models can help frame requirements for future optical remote sensing and mass spectroscopy. The porosity and temperature profile models from this study can inform geological modeling, for example crater morphology [e.g., 12].

Altogether, the geochemical and geophysical exploration of the Uranian moons could return critical constraints on the workings of ocean worlds and the dynamical evolution of the Uranian system.

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