THERMAL AND TIDAL EVOLUTION OF URANUS WITH A GROWING FROZEN CORE. L. Stixrude[1], S. Baroni[2,3], and F. Grasselli[2,4], [1]Dept. of Earth, Planetary, and Space Sciences, University of California, Los Angeles, Los Angeles, CA 90095, USA. lstixrude@epss.ucla.edu, [2]SISSA-Scuola Internazionale di Studi Avanzati, Trieste, Italy, [3]CNR-IOM DEMOCRITOS@SISSA, Trieste, Italy, [4]COSMO-Laboratory of Computational Science and Modelling, IMX, Ecole Polytechnique Federale de Lausanne, 1015 Lausanne, Switzerland.

Introduction: The origin of the very low luminosity of Uranus is unknown [1,2], as is the source of the internal tidal dissipation required by the orbits of the Uranian moons [3,4]. Models of the interior of Uranus often assume that it is inviscid throughout, but recent experiments show that this assumption may not be justified; most of the interior of Uranus lies below the freezing temperature of H_2O [5]. The high viscosity of the solid phase provides a means of trapping heat in the deep interior while also providing a source of tidal dissipation. We find [6] that the presence of a growing frozen core explains the anomalously low heat flow of Uranus. Our thermal evolution model also predicts time-varying tidal dissipation that matches the requirements of the orbits of Miranda, Ariel, and Umbriel.

Approach: We construct a thermal evolution model that includes the effects of a frozen core, including the thermal boundary layer that develops at its surface, trapping heat at depth, and show that this effect can explain the low luminosity of Uranus today. We base our model on key material properties determined from ab initio molecular dynamics simulations of the solid (superionic) phase of H_2O, which we show has a high viscosity dominated by the oxygen sub-lattice. We compute the tidal response of Uranus throughout its thermal evolution and from this the evolution of the orbits of its moons.

Results: Our thermal evolution model predicts a cooling time of 4.5 Gyr, explaining the low luminosity of Uranus. We find that the frozen core nucleates at 0.8 Gyr and grows to occupy two-thirds of the planet today. The presence of the frozen core significantly lowers the tidal Love number k_2 as compared with a completely fluid interior.

The tidal response varies with time as the frozen core grows, producing evolution of the orbits of the Uranian moons that explains observations, including formation of the moons well outside the Roche limit, resonance encounters that explain the anomalously large inclination of Miranda, and avoidance of a Ariel:Umbriel 2:1 resonance, in which these moons would have been trapped had they ever encountered it, contrary to observations. We predict an Ariel-Umbriel 5:3 resonance 0.9 Gyr ago that may explain surface features on Miranda associated with significant tidal heating [4].

Conclusions: It is often assumed that the interior of Uranus is entirely fluid. However, no current observations require this to be the case. Moreover, an entirely fluid interior is at odds with experimental observations that the freezing temperature of H_2O is much higher than plausible interior temperatures. The size of the frozen core is dictated by phase equilibria, rather than compositional layering, so that the frozen portion of the planet grows with time.

The presence of a growing frozen core explains the low luminosity of Uranus and its tidal dissipation self-consistently. The frozen core traps heat at depth because of the high viscosity of the solid phase, which also provides the source of dissipation. The growing frozen core model makes predictions that can be tested against future missions, including the tidal Love number of Uranus and the present-day rate of recession of the Uranian moons.

Acknowledgments: This project supported by the National Science Foundation under grant EAR-1853388 (LS), the EU through the MaX Centre for Excellence for Supercomputing Applications (SB) and the Swiss National Science Foundation (FG).

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