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Thermodynamically Governed Interior Models of Uranus and Neptune

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Abstract

Uranus and Neptune are often modeled as consisting of several discontinuous, compositionally homogeneous layers: a hydrogen-rich outer shell ("gas"), an underlying water-dominated layer ("ice"), and sometimes a separate core of refractory components ("rock"). However, these discrete compositional layers would not be stable if the major constituents of adjacent layers were mutually soluble. Extrapolation of the known H_2-H_2O critical curve, which has been experimentally derived to 3 GPa [1], suggests water and hydrogen are immiscible in the deep interiors of Uranus and Neptune (Figure 1), including at radii of $r/R_{total} \sim 0.7$ where it is generally understood that a transition from a hydrogen-rich shell to a denser, water-rich region should occur in order to satisfy these planets' gravity fields. This thermodynamic evidence (as well as the presence of dynamos in these planets, indicating the absence of convection-inhibiting compositional gradients) is consistent with a scenario in which the water- and hydrogen-dominated regions are comprised of coexisting phases separated by a compositional discontinuity (Figure 2). According to this thermodynamically governed framework, the compositions of the adjacent layers should be governed by the H_2-H_2O coexistence curve, expected to be roughly symmetrical at relevant multi-GPa pressures. Applying this constraint, we find that, to satisfy its mean density and measured gravitational field, Neptune likely must contain a mol fraction $\chi_{H_2O} > 0.1$ relative to hydrogen in the outer shell (Figure 3). In contrast, Uranus models require a much smaller water fraction in their outer shells, $\chi_{H_2O} \lesssim 0.01$, to satisfy the gravity field. The consequences for the heat output of these planets will be discussed.

Acknowledgements

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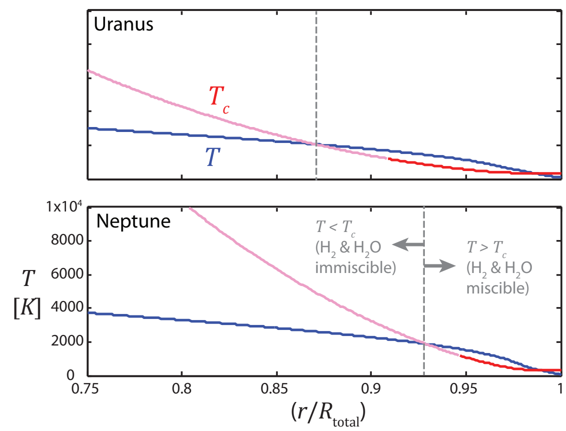

Figure 1: Comparison of the experimentally derived critical temperature T_c (red) [1], with the extrapolated curve (pink) beyond 3 GPa, versus the adiabatic temperature profile (blue) in the outermost, hydrogen-dominant layer in models of Uranus and Neptune, for a variety of distances r from the center. A region of hydrogen-water immiscibility (i.e. $T < T_c$) is predicted in the deeper regions of this layer, indicating that a discontinuity at a phase transition is plausible in the interiors of these planets.

References

[1] Bali, E., Audétat, A., and Keppler, H.: Water and hydrogen are immiscible in Earth's mantle, Nature, 495, 220-222, 2013.

[2] Jacobson, R. A.: The orbits of the Neptunian satellites and the orientation of the pole of Neptune, *AJ*, 137, 2009.

[3] Jacobson, R. A.: The orbits of the Uranian satellites and rings, the gravity field of the Uranian system, and the orientation of the pole of Uranus, *AJ*, 148, 76, 2014.

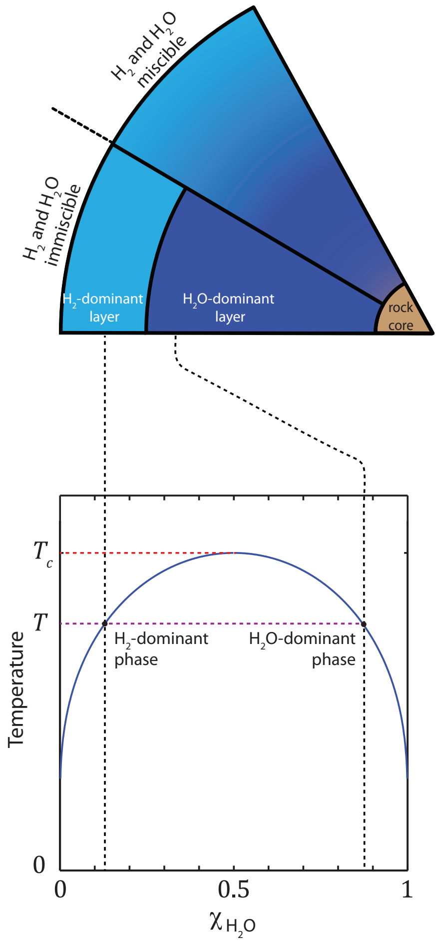

Figure 2: Schematic diagram illustrating the constraint imposed in this work—that the compositions of the assumed H_2-dominant and H_2O-dominant layers should correspond to the coexisting phase compositions as governed by the H_2-H_2O coexistence curve (bottom). A compositional discontinuity inside the planet (top) is thermodynamically favorable only if immiscibility of major constituents is implicated.

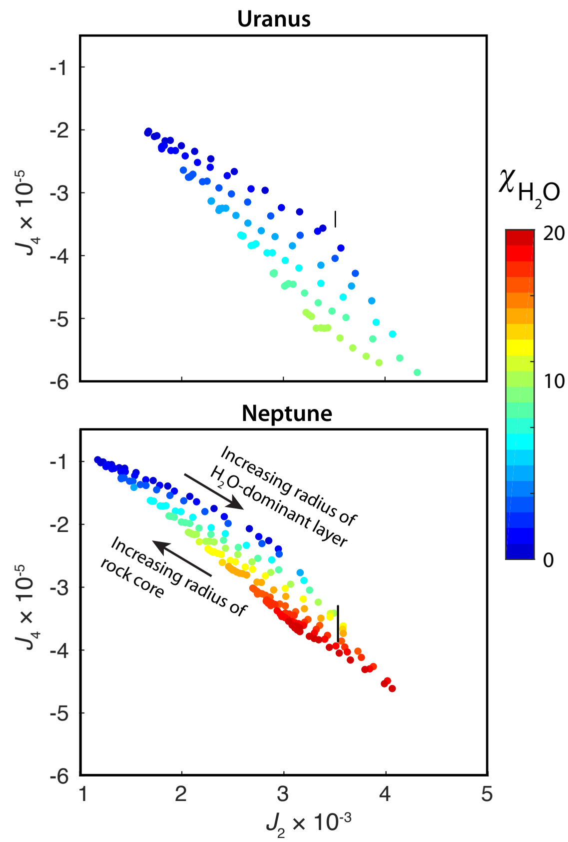

Figure 3: Gravitational harmonics for derived three-layer models following the constraints described in Figure 2. Gravitational harmonics J_2 and J_4 for Uranus and Neptune [2, 3] are shown as black boxes (the boxes resemble line segments due to sufficiently tight constraints on J_2). Colors represent the mol fraction χ_{H_2O} of water relative to hydrogen in the outer, hydrogen-dominant shell. For each composition chosen for this outer layer, the composition of the deeper (water-dominant) layer was selected in accordance with the rationale described in Figure 2.