LEARNING A PLANET’S DEEP INTERIOR SECRETS FROM ITS EXTERNAL GRAVITY FIELD: A NEW APPROACH FOR EMPIRICAL PLANET MODELING. N. Movshovitz\textsuperscript{1}, J. J. Fortney\textsuperscript{1}, C. Mankovich\textsuperscript{1}, D. Thorngren\textsuperscript{1}, and R. Helled\textsuperscript{2} \textsuperscript{1}University of California, Santa Cruz, \textsuperscript{2}University of Zurich, Switzerland.

Introduction: One piece of information that is available for many solar system bodies, but is as yet outside the realm of possibility for exoplanets, is an approximate description of their gravity fields. This requires a visit by spacecraft; an orbiter is best but even a single fly by will provide valuable data. Gravity data is so valuable because it is one of very few ways we have of probing the deep interior of a planet, in principle through to the center. If our solar system giant planets are used as proxies for understanding giant exoplanets, it is essential to understand the interior structure of these planets in as much detail as possible, as well as limits to our ability to interpret these interior structures.

But gravity data is not only hard won but also difficult to interpret. There are two problems. The first is that connecting the interior structure to the gravity data is a forward-modeling task: an interior model is created first, and then its gravity is computed and compared with the observed field. Inevitably, this introduces model specific assumptions that will limit, often quite severely, the robustness of the results. Many published studies of Jupiter and Saturn interiors for example are based on models with three compositionally homogeneous layers and an adiabatic thermal profile. These are good models, but they are only a subset of possible interior structures.

The second problem is that the gravity field is a non-unique feature of the interior mass distribution. In other words, a continuum of interior structures are consistent with a measured gravity field, particularly given the finite precision to which the gravity is known.

How can we best remove this degeneracy and narrow down the range of possible planetary structures implied by a measured gravity field? Can we at the same time satisfy a competing preference for generality? Here we present preliminary findings from a theoretical attempt to answer this question, focusing on Saturn and on the solar system’s ice giants, Neptune and Uranus.

We use Saturn to demonstrate how empirical models, interior density profiles created without reference to an assumed composition and thermal state, allow exploration of a much wider range of possible interior structures, using the gravity data obtained during Cassini’s Grand Finale orbits [1].

We then use toy models of Uranus and Neptune constructed in a Markov-Chain Monte Carlo process that ensures we explore all structures, and only such structures, that are consistent with an arbitrarily precisely given gravity. By varying that precision level we can determine how much our knowledge of a planet can improve with improved gravity data.

Composition agnostic models of Saturn’s interior: Traditionally, studies of Saturn’s interior begin by assuming some realistic but necessarily simple structure defined by a small number of physical variables, and then proceed to tune these parameters to match the model to Saturn’s observed properties, namely its mass, equatorial radius, and gravitational potential field represented by the coefficients of its expansion in Legendre functions. A common model is one of the planet comprising three layers, an upper envelope, a lower envelope, and a core, with homogeneous composition and adiabatic thermal gradient inside each layer. It’s a potentially physically sound model, and allows derivation of tight constraints on things like the heavy element abundance in the planet, but the host of a priori ad hoc assumptions that go into the model limit the strength of such inferences.

Here we present constraints on Saturn’s interior derived by setting the planet’s gravity field as a likelihood function driving a Markov-chain Monte Carlo sampling of the space of so called empirical models. These are models where the interior density profile is explicitly varied, rather then derive from an assumed composition, thermal state, and material equations of state as in traditional models. Constraints on interior structure derived in this way framework are necessarily less informative, but are also less biased and more general.

Figure 1 below shows a sample from the posterior distribution of these empirical models, obtained by MCMC. We find that the outer half of Saturn’s radius is relatively well constrained and the density suggests a significant metal enrichment, in line with atmospheric abundances from remote sensing [2]. As expected, the inner half of the planet’s radius is less well-constrained by gravity, but we generally find solutions that include a significant density enhancement, which can be interpreted as a core, although this core is often lower in density and larger in radial extent than typically found by standard models. This is consistent with a dilute core and/or composition gradients [3-4].

Limitations of gravity as interior probe: Whenever model we use for the interior structure, a comparison with gravity data yields a range of solutions, rather than a single answer. There are two reasons.
gravity data, like all observational data, is of finite precision. Second, the external gravity field is an integrated quantity. Even when measured with extreme precision it may not uniquely define the density structure.

Gravitational potential coefficients are available for Uranus and Neptune, but with much larger error bars than those for Saturn and Jupiter. We can only set very loose constraints on their interior density based on these. Instead we derive increasingly narrower distributions of interior models by using the sampling of empirical models approach, as for Saturn, but with very simple models and by artificially increasing the assumed precision of the known gravity field. We thus determine the accuracy required of hypothetical future measurements, such as from a 2030s/2040s space mission to visit one or both of the ice giants.


Figure 1. Visualization of the posterior probability distribution of Saturn interior density profiles. Top: The thick black line is the sample-median of density on each level surface. The dark gray shaded region includes values between the 16th and 84th percentiles of the sample and the light gray shaded region includes all values between the 2nd and 98th percentiles. Bottom: Several hundred profiles covering the sampled range. By nature of the MCMC algorithm regions of the figure where lines are closer together correspond to high likelihood areas of parameter space. For comparison, three profiles derived by physical models with a pure H2O core [5] are overlaid.