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Toward modeling Jupiter's 3D shape and gravity field

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Abstract

We present our preliminary results for the static tidal response of Jupiter and Saturn to the gravitational field perturbations raised by their satellites. Assuming a constant density interior, we find the fluid Love number k_2 of rotationally flattened planet models to be strongly enhanced compared to non-rotating planet models. Assuming a polytropic equation of state, this effect reduces by about a factor of two. We compare our predictions to recent measurements of k_2 based on Cassini data for Saturn and Juno data for Jupiter.

1. Introduction

The gas giant planets in the outer solar system, Jupiter and Saturn, are rapid rotators. They experience strong rotational flattening, which can be seen from their oblate shapes. Accordingly, also their gravity fields are non-spherical. Several gravitational moments have recently been accurately measured by the Cassini spacecraft at Saturn and the Juno spacecraft at Jupiter, respectively.

Deviations in shape and gravity field from perfect spherical symmetry allow us to look into the planetary deep interior, as the strength of deviation depends on internal mass density distribution. The latter in turn is influenced by composition (typically distinguished into hydrogen, helium, and heavy elements), composition distribution (e.g., the size of a core or the atmospheric metallicity), and the equations of state. For gas giant planets like Jupiter, the hydrogen equation of state matters most. Indeed, uncertainties in the behavior of hydrogen and helium under planetary interior conditions still lead to significant uncertainties in our understanding of internal structure and evolution. For instance, cool and dense Jupiter adiabats tend to predict sub-solar atmospheric metallicity, while warmer Jupiter adiabats yield heavy element-rich deep envelopes [4].

2. Tidal perturbation

Conventional Jupiter models assume symmetry of the mass density around the axis of rotation. This case applies to isolated fluid planets in hydrostatic equilibrium with spin axis perfectly aligned with the principal axis of inertia, and no winds. Jupiter and Saturn however are surrounded by satellites. The gravity field of a satellite can raise tides that break the symmetry. Moreover, zonal flows observed on Jupiter may also give rise to a longitudinal variation [1]. The longitudinal contribution can be expressed in terms of so-called tesseral moments C_{nm} and S_{nm}. Indeed, Juno measurements indicate non-zero moments C_{21} and S_{21}, while for the C_{22} and S_{22} components upper limits could already be inferred [1]. The uncertainty will decrease in the further course of the Juno mission as Juno is going to take a full 3D map of Jupiter's gravity field.

Assuming a single tide-raising perturber, the tesseral moments can be translated into the Love numbers k_{nm} according to [6]

$$k_{nm} = -\frac{3}{2}\,\frac{(n+m)!}{(n-m)!}\,\frac{C_{nm}}{P_n^m(0)q_{\rm tid}}\,(r_S/R)^{2-n} \quad , \quad (1)$$

where r_S is the planet–satellite distance, R is planet radius, and $q_{\rm tid}$ is the tidal forcing. For strong rotational forcing, the Love numbers k_{nm} are splitted and deviate from that of a spherical body.

Figure 1 shows current measured Love number k_{22} values of Jupiter from the Juno mission [1] and of Saturn including Cassini data [3] as well as theoretical predictions. Models that assume a spherical shape (e.g., [3], the yellow-black-dotted model by [6] for Saturn, and [5]), yield k_{22} values lower than the measured ones. In contrast, the yellow-black-dashed model [6] takes into account the rotational flattening in the tidal response calculation. This leads to $\sim 12\%$ stronger response; it clearly appears to be required to explain Jupiter's observed value.

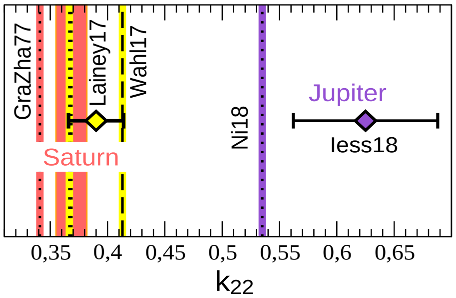

Figure 1: Static Love number k_{22} values of Jupiter (violet), Saturn (yellow, red) from Juno [1] and Cassini [3] observations (diamonds with error bars), and from planet models. Dotted lines: for spherical shape [3, 6, 5], dashed line: for rotationally flattened shape [6].

3. Preliminary results

Figure 2 shows preliminary results of this work for the tidal response of rotationally flattened Jupiter and Saturn assuming a simplified constant-density interior. The models were calculated following the method of [6]. For the Jupiter-Io and the Saturn-Tethys system we find, respectively, a strong 20% and 30% enhancement in the Love number k_{22} value due to the rotational flattening compared to the analytically known value for a spherical fluid planet, $k_2 = 1.5$. More centrally condensed models that are constrained by the low-order gravitational harmonics are expected to yield a less pronounced tidal response.

4. Outlook

Further work will address the influence of various effects on the static fluid Love number k_{nm} values of Jupiter. In particular, we will apply different physical equations of state, take into account mis-aligned rotation and principal axes, and a possible phase lag of the tidal bulge. The resulting predictions for an otherwise rigidly rotating Jupiter will help to disentangle the influence of winds, and thus provide and additional constraint on Jupiter's dynamic atmosphere.

As has been shown for Saturn [2, 6], different interior models which match the low-order gravitational harmonics yield extremely similar k_{22} values. Therefore, any offset between the measured and the predicted value will yield unique hints on missing physical effects in the tidal response calculation. Thanks to the current space-based Juno measurement of Jupiter's gravity field, this opens the opportunity of a new era of interior modeling.

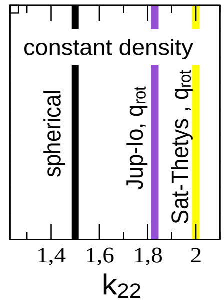

Figure 2: Same as Figure 1 but for constant density models and spherical shape (black), or Jupiter's and Saturn's rotational forcing.

Acknowledgements

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