Tidal Response and Shape of Hot Jupiter

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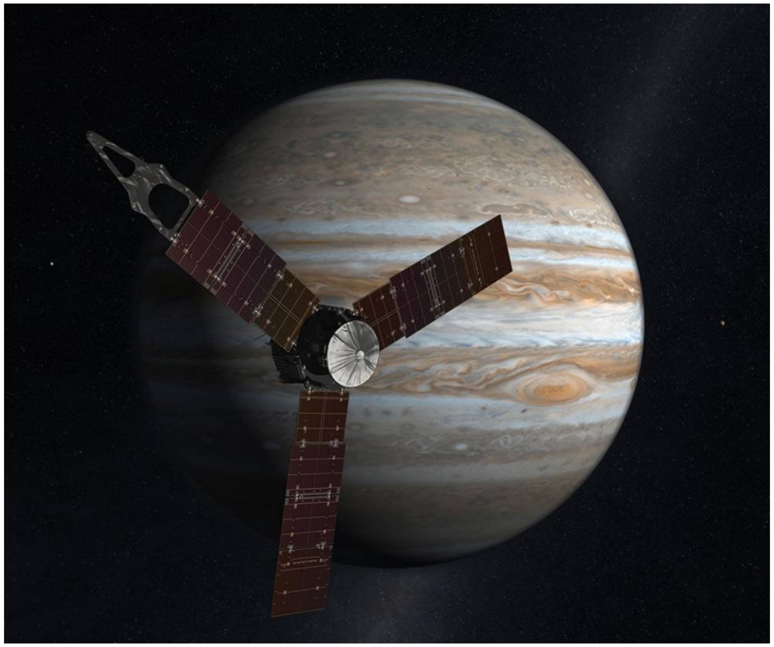
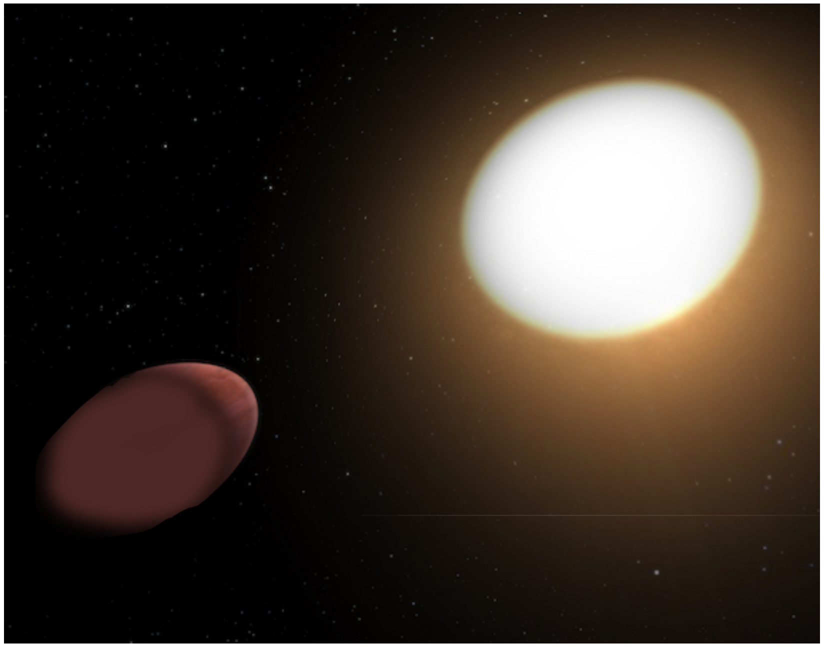
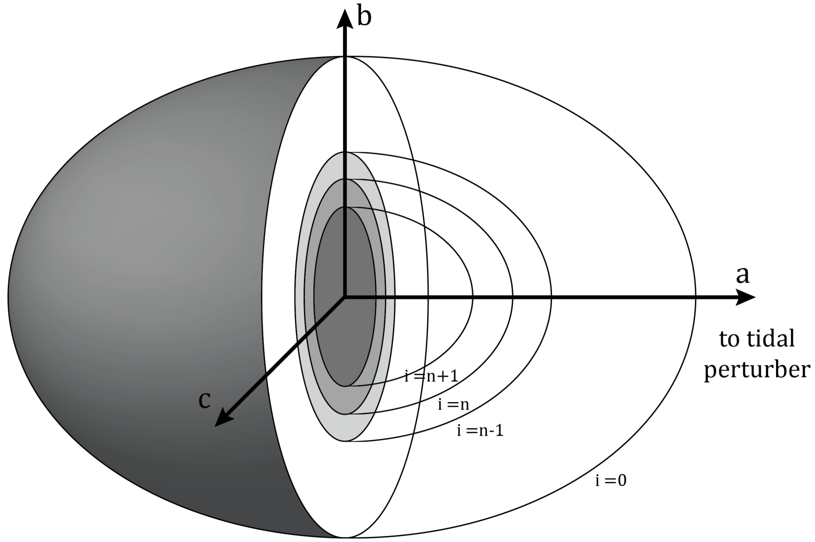
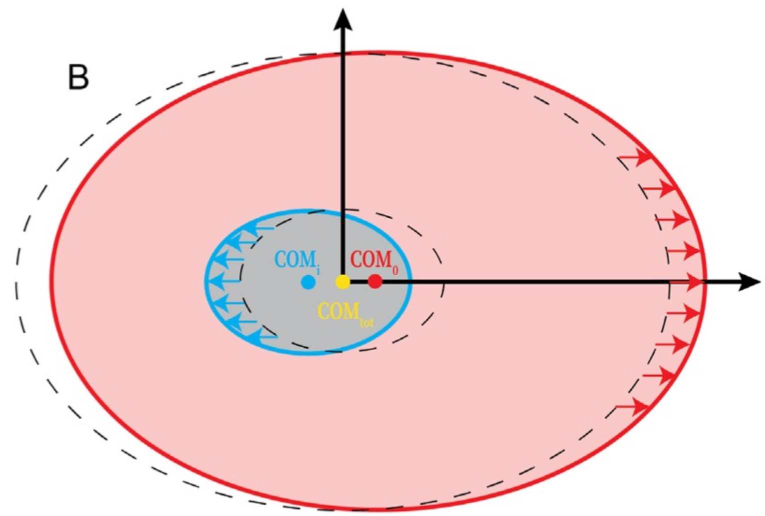
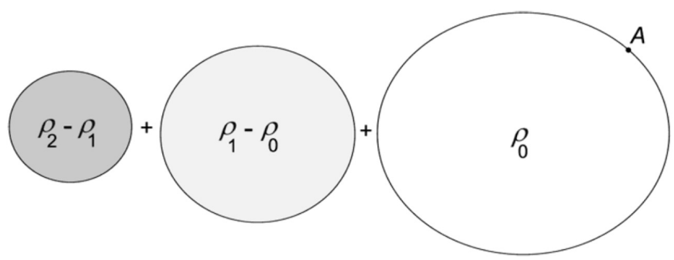




Concentric Maclaurin Spheroid (CMS) theory for rotating bodies







Concentric Maclaurin Spheroid Method, Hubbard, ApJ (2013)

Accelerated CMS method Militzer et al, ApJ (2019)

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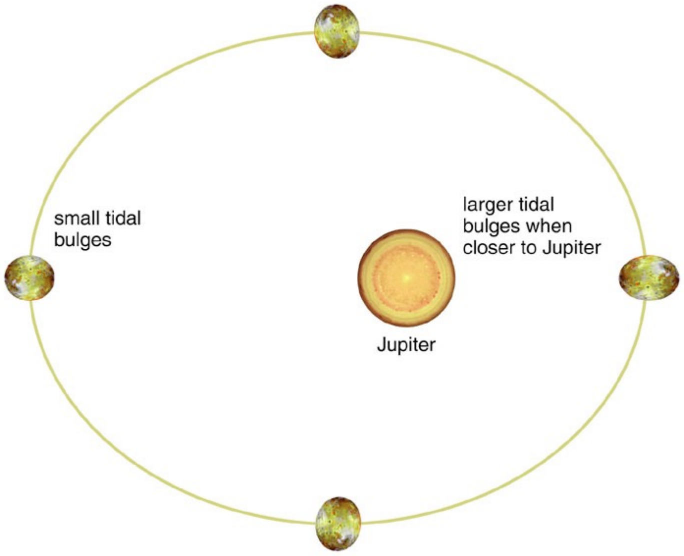
Abstract

We study the response of hot Jupiters to a static tidal perturbation using the concentric MacLaurin spheroid method. For strongly irradiated planets, we first performed radiative transfer calculations to relate the planet's equilibrium temperature, $T_{\rm eq}$, to its interior entropy. We then determined the gravity harmonics, shape, moment of inertia, and static Love numbers for a range of two-layer interior models that assume a rocky core plus a homogeneous and isentropic envelope composed of hydrogen, helium, and heavier elements. We identify general trends and then study HAT-P-13b, the WASP planets 4b, 12b, 18b, 103b, and 121b, and Kepler-75b and CoRot-3b. We compute the Love numbers, k_{nm}, and transit radius correction, ΔR, which we compare with predictions in the literature. We find that the Love number, k_{22}, of tidally locked giant planets cannot exceed a value of 0.6, and that the high $T_{\rm eq}$ consistent with strongly irradiated hot Jupiters tends to further lower k_{22}. While most tidally locked planets are well described by a linear regime response of $k_{22} = 3J_2/q_0$ (where q_0 is the rotation parameter of the gravitational potential), for extreme cases such as WASP-12b, WASP-103b, and WASP-121b, nonlinear effects can account for over 10% of the predicted k_{22}. The k_{22} values larger than 0.6, as they have been reported for planets WASP-4b and HAT-P13B, cannot result from a static tidal response without extremely rapid rotation and thus are inconsistent with their expected tidally locked state.

Two types of tidal interactions of giant planets

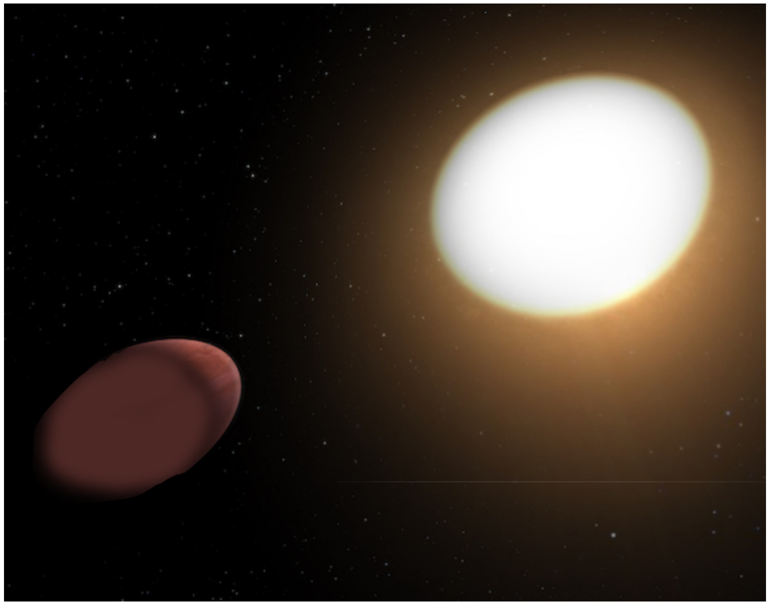
Planet interacts with orbiting satellites that may introduce dynamic tidal effects.

- Static tidal calculation k_{22}=0.590 (Wahl 2020)
- Juno mission k_{22}=0.565 ± 0.006
- Idini (2021): Coriolis acceleration $\Delta k_{22} = -4\%$



Exoplanet is tidally locked to host star which acts as tidal perturber. Rotation is thus slow.

- Planet changes shape. Apparent radius reduced by up to 4%.
- Planet's gravity field changes. (other planets)



Definition of tidal perturbation. Love number k_{22}

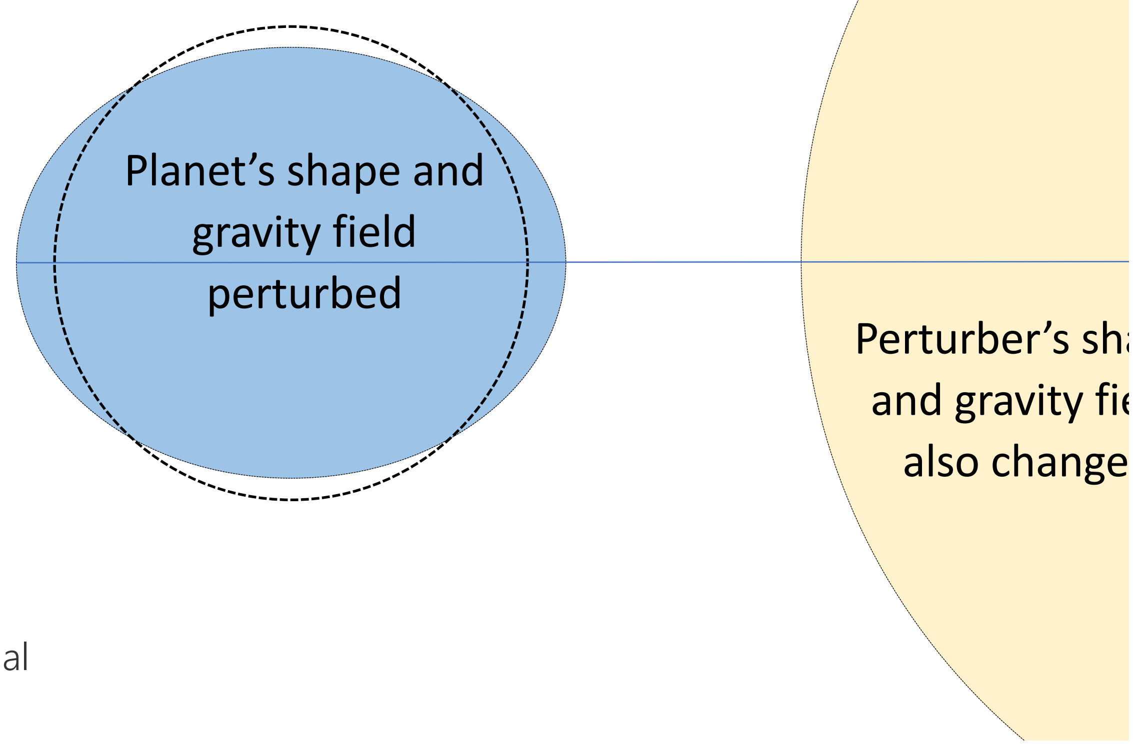
Perturbation of gravity

$$k_{22} = -\frac{16}{9}\frac{C_{22}}{q_{tide}} \longrightarrow 3\frac{J_2}{q_{rot}}$$

Shape Love number:
h = 1 + k_{22}

$$q_{tide} = -3\frac{M_{pert}}{M_{planet}}\frac{R_{planet}^3}{R_{orbit}^3}$$

$$q_{rot} = \frac{\omega^2 R_{planet}^3}{GM_{planet}}$$

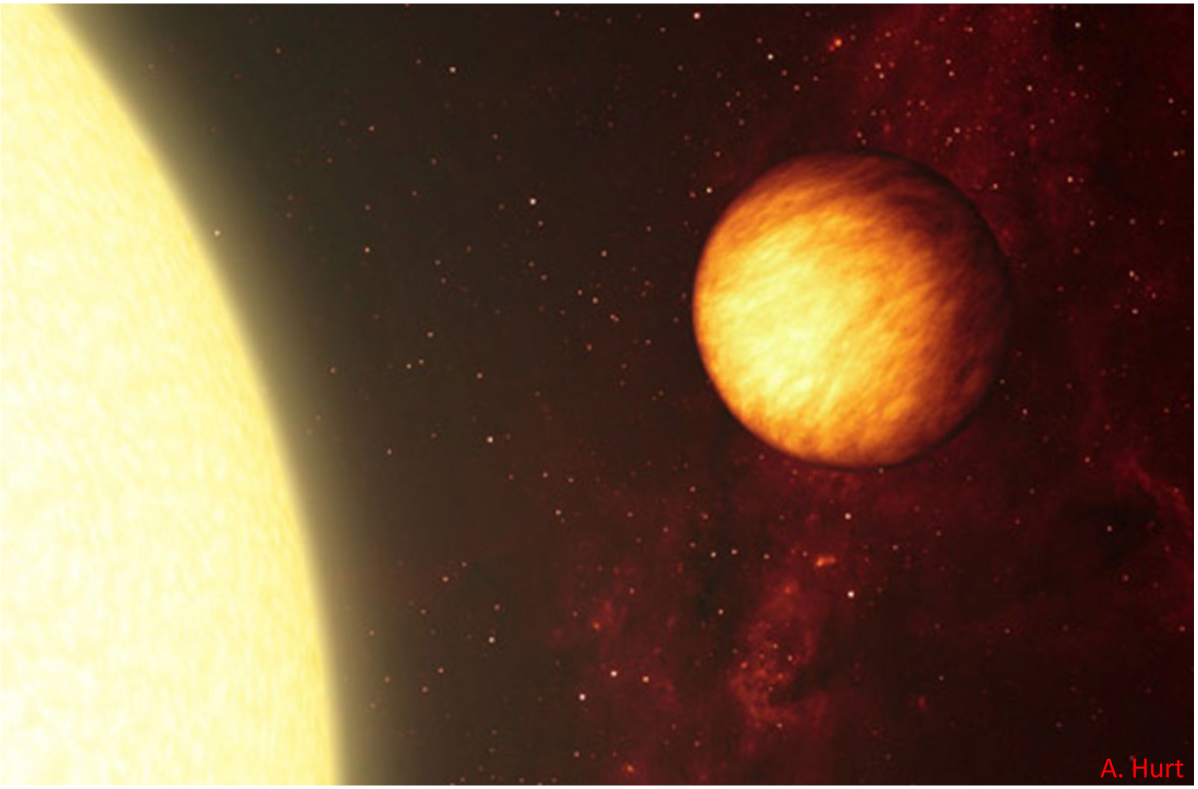


Static tides: Infinite time to establish hydrostatic equilibrium. Tidally locked case. Potential theory applies. Often a very good approximation. E.g Jupiter

Dynamic tides: Orbital frequency and rotation frequency differ. Perturber supplies energy. Tidal heating strong if orbits eccentric.

Interior Models of Strongly Irradiated Giant Exoplanets Constructed with CMS Method

- We first performed radiative transfer calculations to relate the planet's equilibrium temperature, T_{eq}, to its interior entropy. (Thorngren & Fortney, 2018, AJ, 155, 214)
- Planets tidally locked to host star. Rotation is thus slow.



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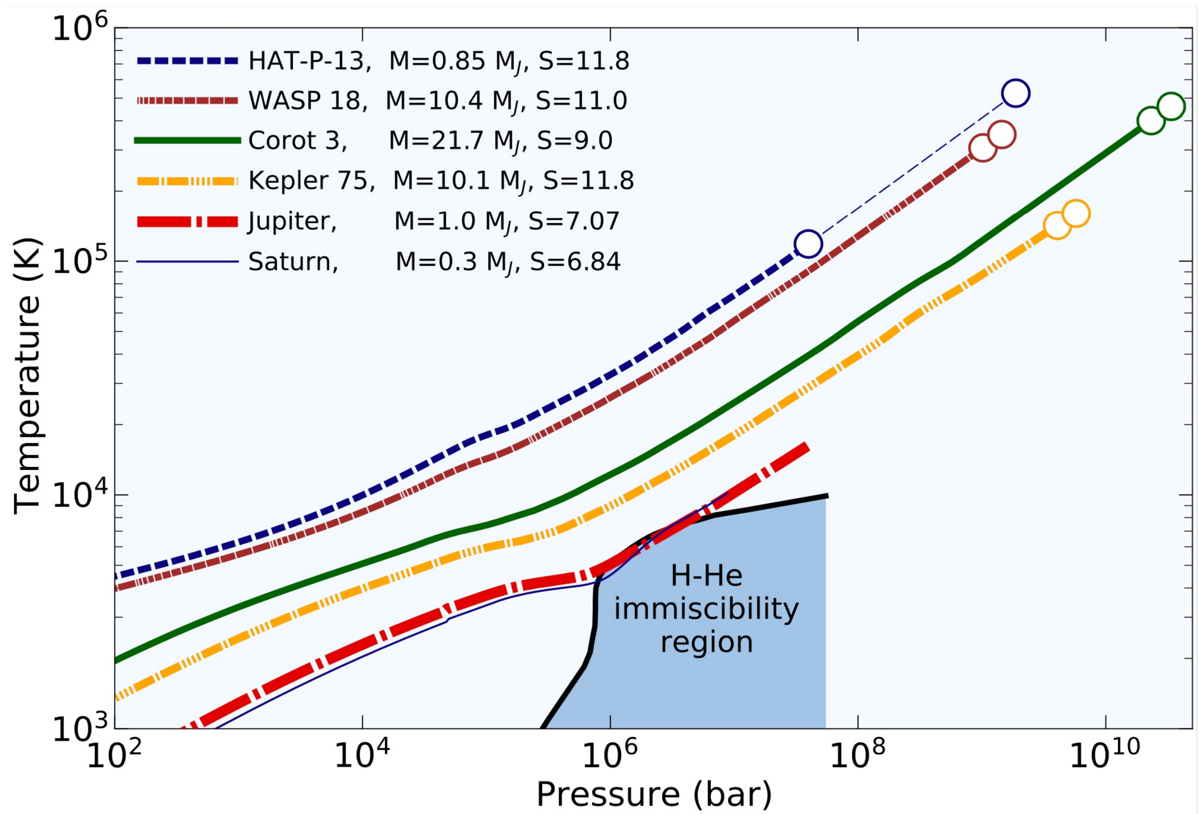
- Planets tidally locked to host star. Rotation is thus slow.
- Constructed Interior models with homogenous envelopes with CMS.
- Match mass and radius under two assumptions
    - a) No core, all Z in envelope
    - b) Maximal core, no Z in envelope



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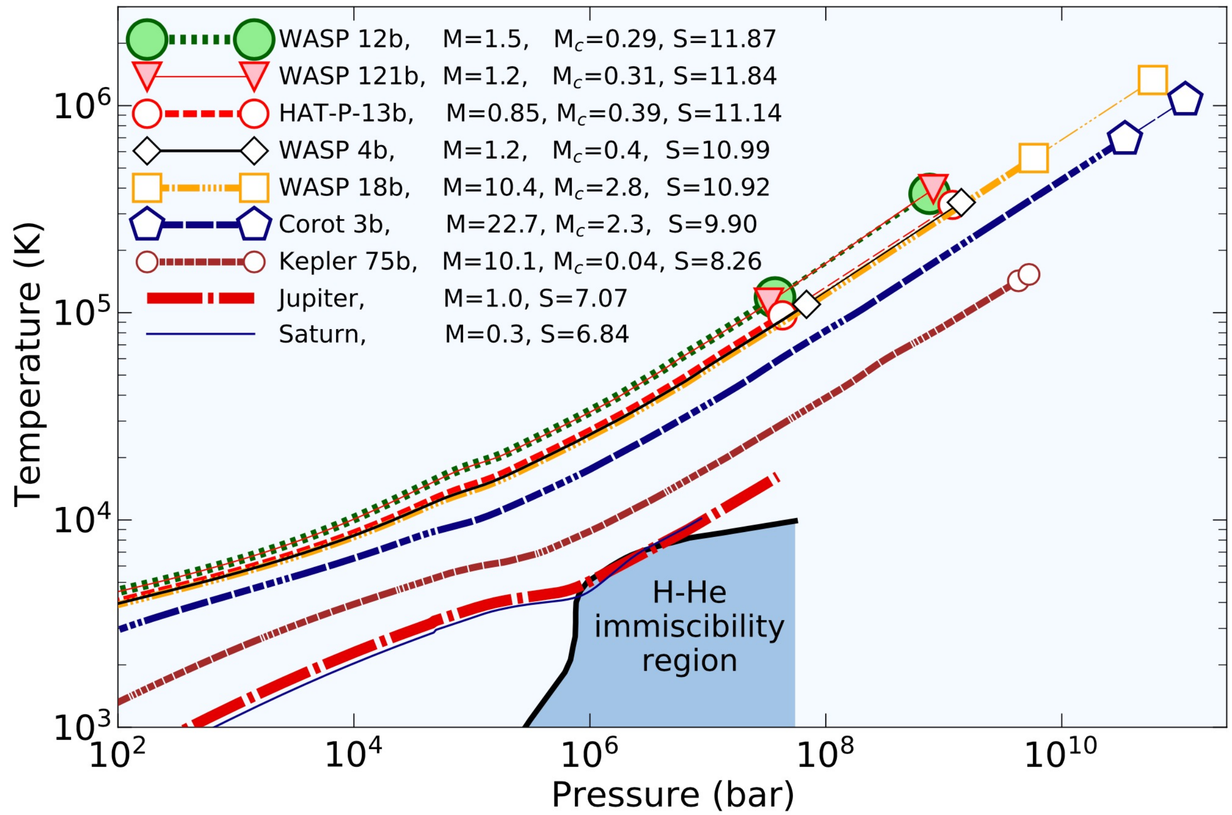
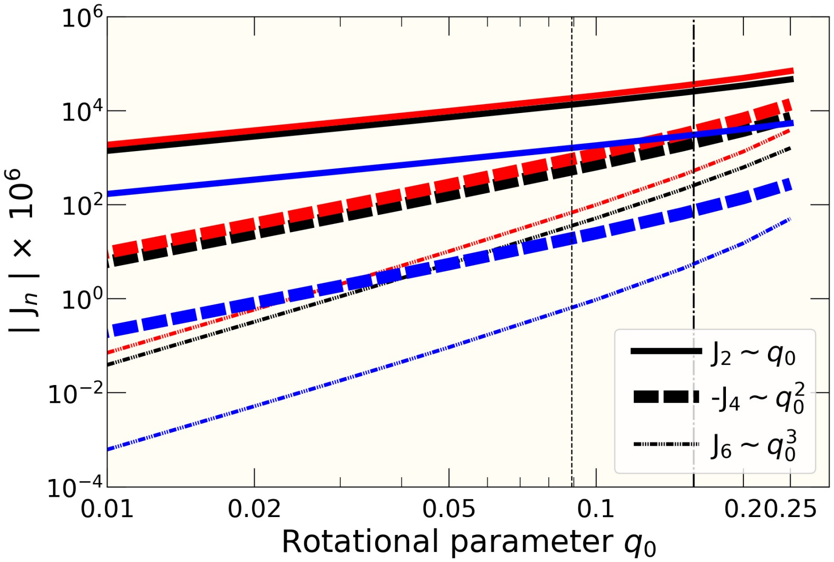
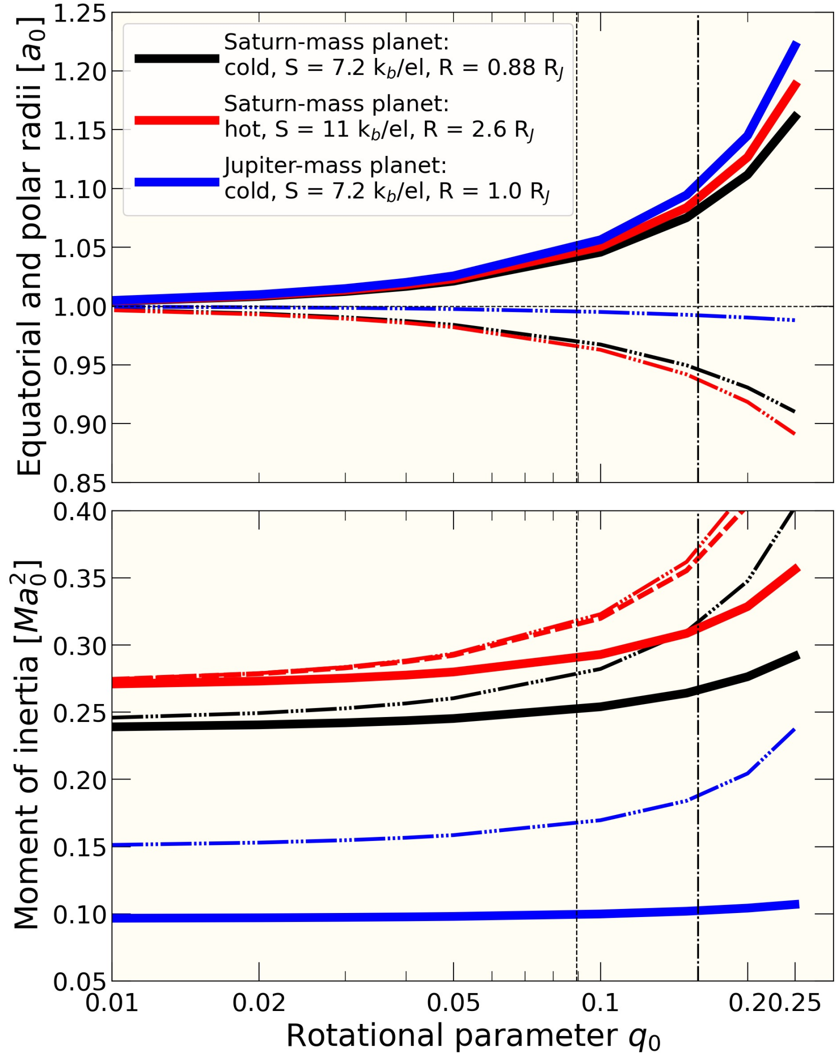
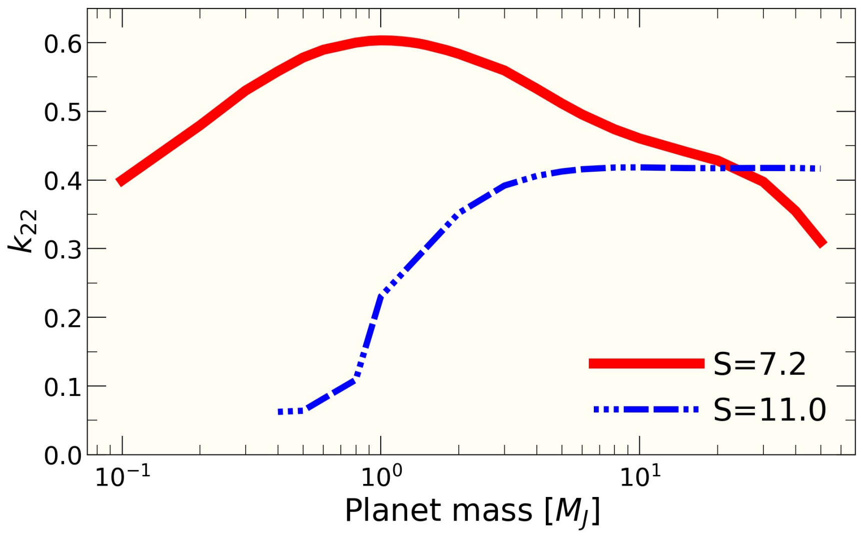
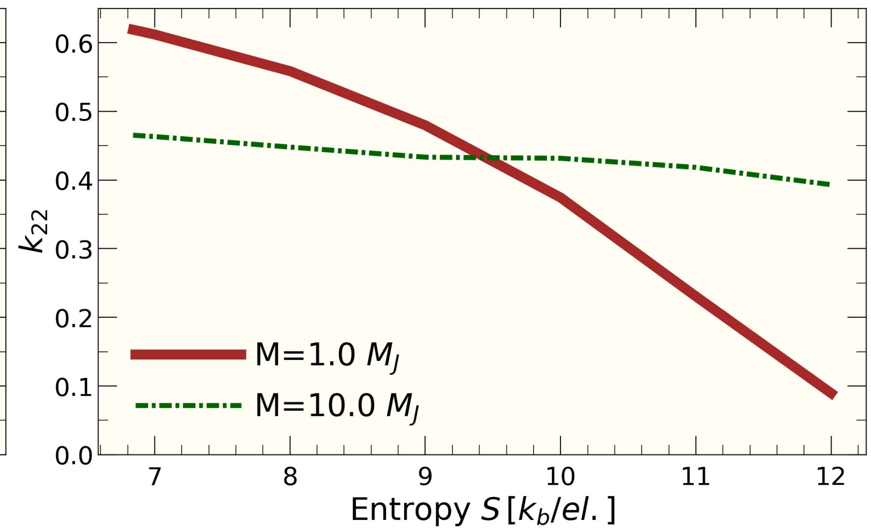




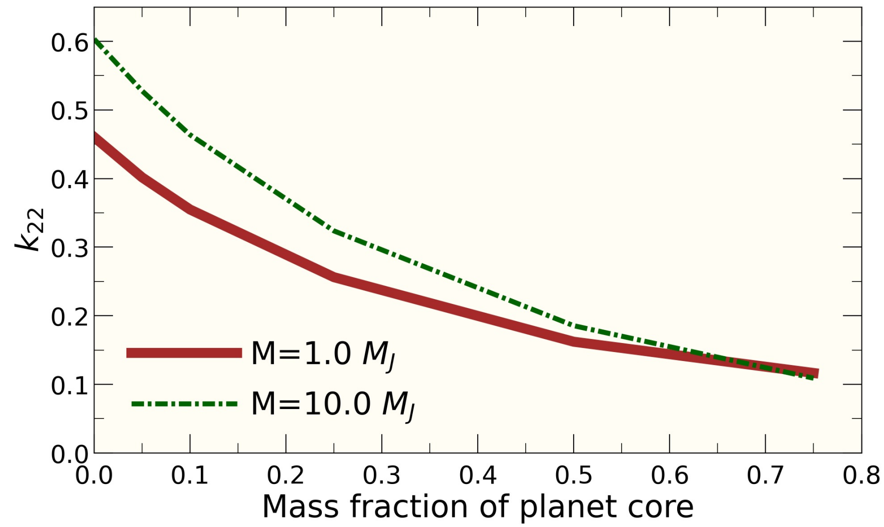


- Slowly rotating regime: $J_n \sim q_{rot}^{n/2}$
- Darwin-Radau does not work for giant planets



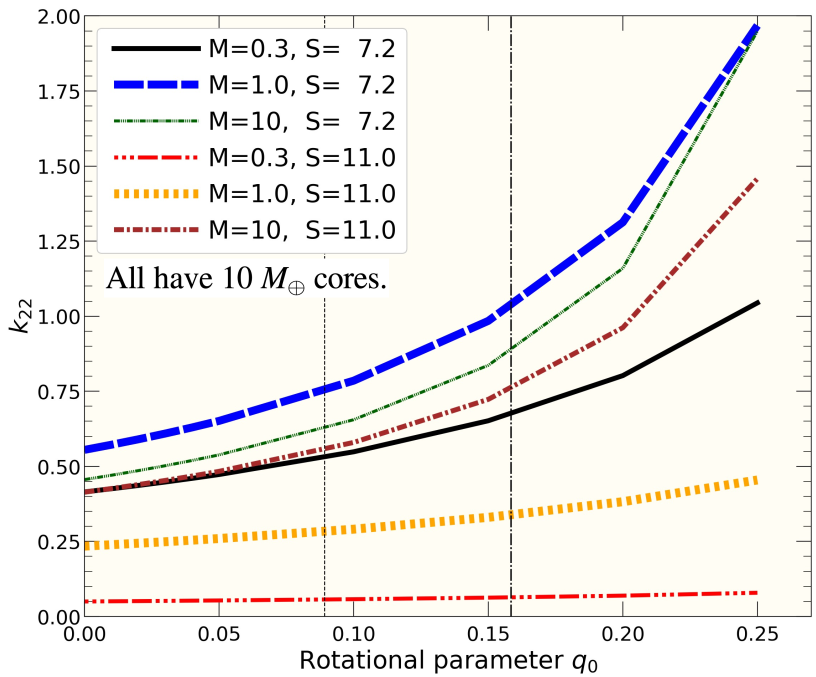


- k_{22} is sensitive to planet mass and entropy
- Only if both are kept fixed, a simple correlation between k_{22} and core mass fraction emerges that has been cited as a way to infer the core mass of exoplanets (Batygin 2006, Ragozzine & Wolf 2009)

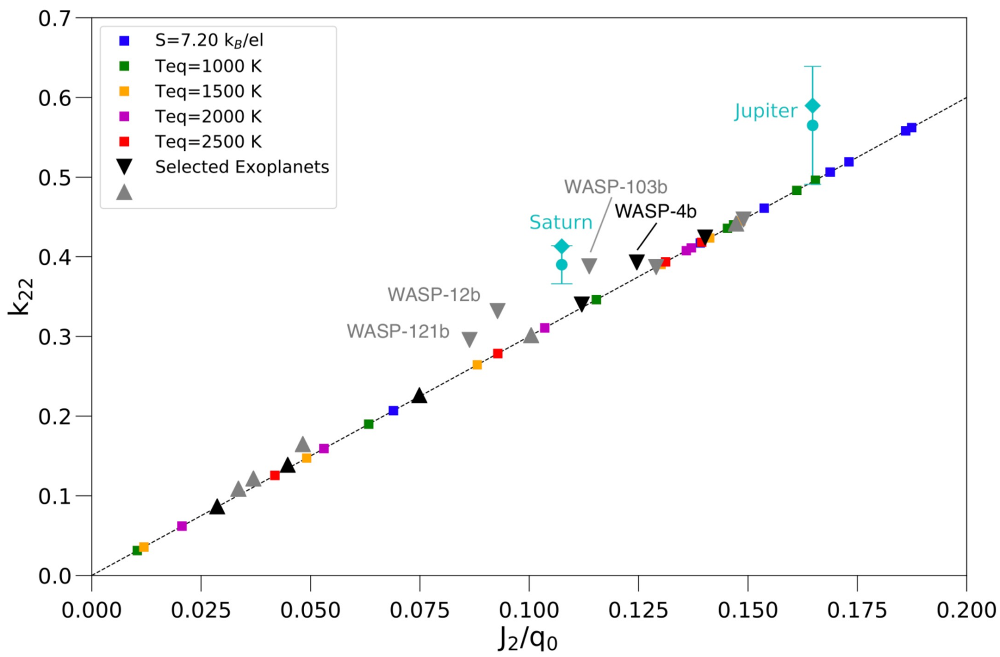


A) Nonlinear Regime of Rapid Rotation
B) Linear Regime of Slow Rotation

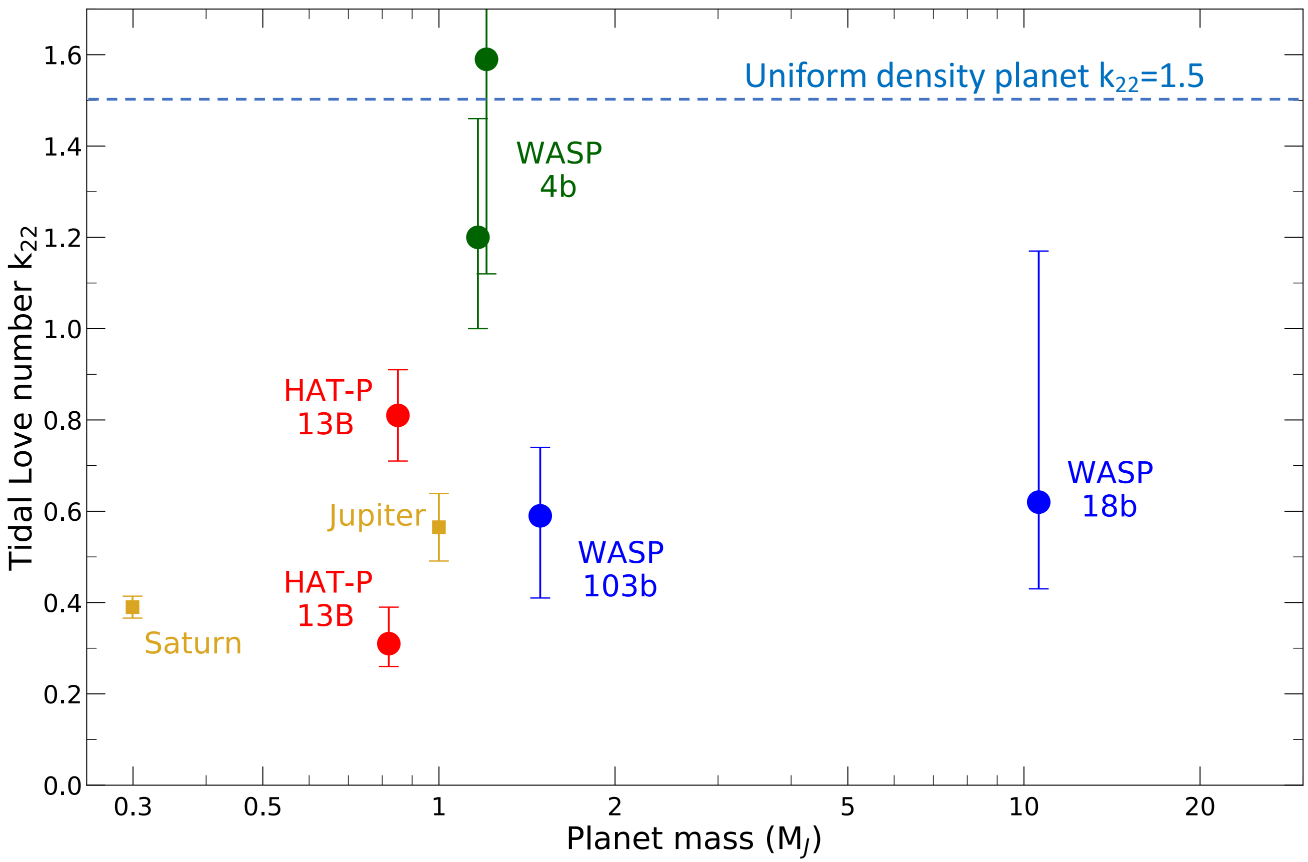
- Regime of rapid rotation: k_{22} varies nonlinearly.



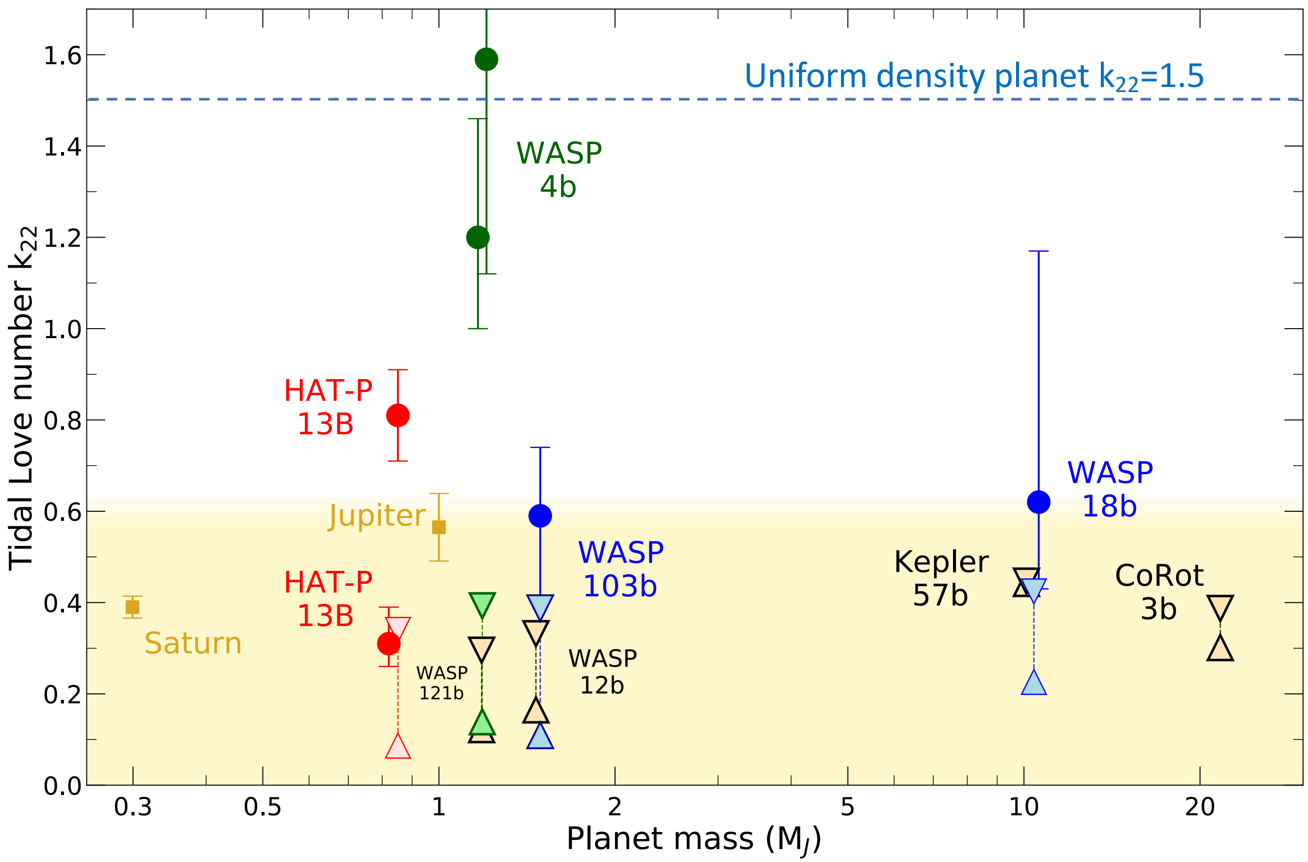
- Linear regime of slow rotation: $k_{22} \sim J_2 \,/\, q_{rot}$



Observations predict a large range of k_{22} values



Interior models predict $k_{22} \leq 0.6$. So all observations with large k_{22} cannot be matched.



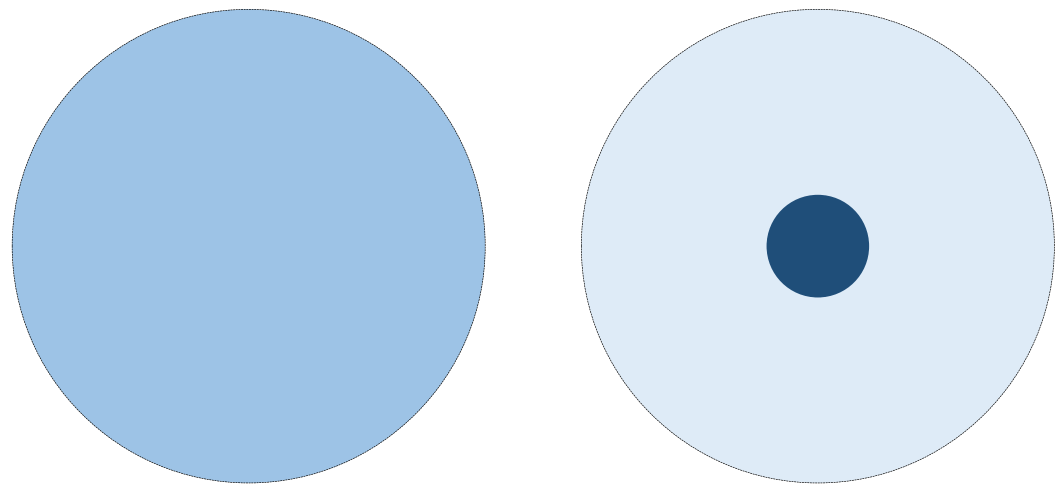
Why does k_{22} depend on core mass fraction?

Definition

$$k_{22} = -\frac{16}{9}\frac{C_{22}}{q_{tide}} \longrightarrow 3\frac{J_2}{q_{rot}}$$

$$q_{tide} = -3\frac{M_{pert}}{M_{planet}}\frac{R_{planet}^3}{R_{orbit}^3}$$

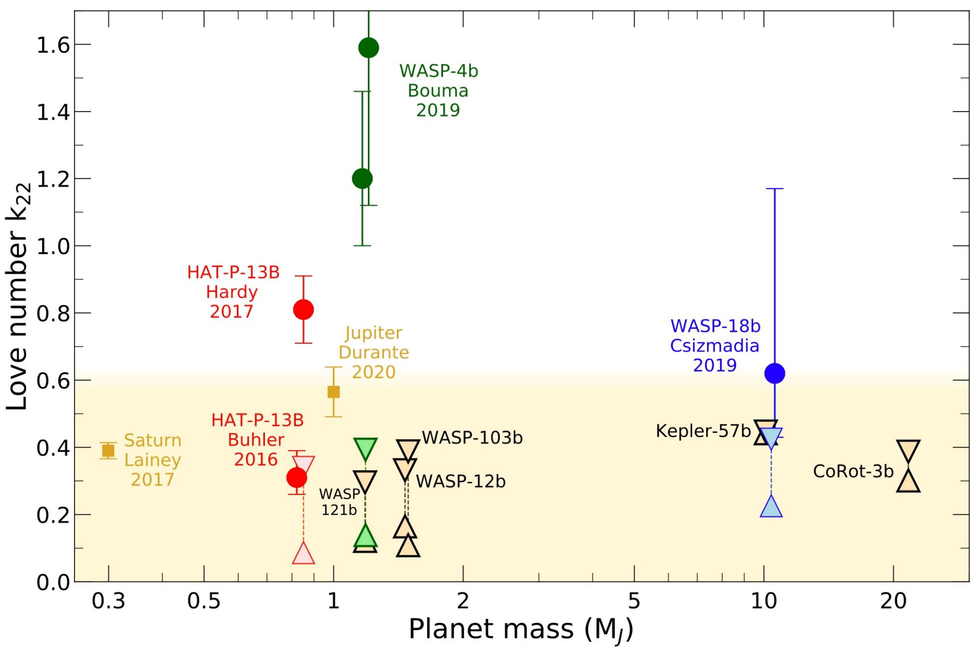
$$q_{rot} = \frac{\omega^2 R_{planet}^3}{GM_{planet}}$$



Uniform density planet
k_{22}=1.5

Concentrate mass in core
$k_{22} = 1.5 \times r_{core}^5$

Conclusion



- All existing measurements/predictions with k_{22}>0.6 are unrealistic. Density changes too much throughout a giant planet's interior.
- Observations need to be reinterpreted. Bouma (2020) attributes TTV to an unseen companion of WASP-4B.
- k_{22} is affected by planet mass, core mass, and interior entropy.
- Tides change a planet's shape. The apparent radius is smaller than that of an unperturbed planet by up to 4%.