Coupled Tidal and Thermal Evolution of Known Transiting Planets

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Abstract

An extrasolar giant planet evolution model that couples the orbital-tidal and thermal evolution is presented, and it is tested against 41 of the known transiting planets. For each observed planet, the model is run through the estimated age of the system over a grid of initial orbital parameters and heavy-element core mass. Each grid is searched for runs with final semimajor axis eccentricity and transit radius consistent with the observed values. For most systems, we find that including the orbital evolution and concurrent tidal heating in the planet's thermal evolution gives a radius and orbital elements that are consistent with observed values. For some planets, previous models that did not include tidal evolution gave radii in agreement with observations. For many of these cases, tidal heating is insufficient to affect the planet's radius, and agreement between model and observation is retained. For other planets, previous models that did not include tidal heating gave radii that were smaller than the observed radii. For many of these cases, tidal heating is sufficient to inflate the planet's radius, and the observed radius can be explained if time-varying tidal heating is included. However, for other planets, the observed radii are larger than predicted by previous modeling, and we find that even tidal heating may not be sufficient to account for these inflated radii.

Background and Model Description

Recent transit observations of hot Jupiter exoplanets have found a few suprisingly large planets against the expectations of simple planet cooling models. Some possible explinations for this range in planet radii have arisen: tidal heating and orbital evolution, variation in core size, variations in the planet's metallicity, convection inhibiting double diffusive layering, and giant impacts. This work focuses on testing if the tidal evolution model is sufficient to explain the especially large radius planets.

Apart from previous models, this work self-consistently couples the planet's thermal evolution and tidal evolution. The thermal evolution is dependent on the orbital evolution because the incident flux from the star varies over its evolution and tidal energy can be deposited into the interior of the planet. The tidal evolution is very sensitive to the planet's radius, which is determined by its thermal evolution. The thermal evolution model is composed of a solid rock/ice core, convective envelope and flux-dependent model atmosphere described in detail by [4]. The orbital evolution model has been recently described by [5]. Also, apart from previous work, our model includes the coupled tidal evolution of semimajor axis (a) and orbital eccentricity (e). As a planet's semimajor axis and eccentricity evolves, dissipation of tidal energy within the planet results in time-varying tidal heating, which may inflate the planet's radius. We consider a range of planetary core sizes, initial semimajor axes, and eccentricities. We model the evolution of semimajor axes, eccentricity and planetary radii forward in time to determine which set of core sizes and initial orbital elements give agreement with the observed radii and current orbtial elements.

Example cases for TrES-1, WASP-10 and HD 209458 have been plotted in Figures (1), (2), and (3) respectively. TrES-1, in Figure (1), is a generic case where the planet's orbit has been circularized and tidal heating is not important. In this case the model easily explain the observed radius with a core between 10 and 30 M_E. WASP-10, in Figure (2), is a case where the planet has a non zero eccentricity and inflated planet. To be consistent with the observed orbital parameters, either the initial eccentricity was required to be fairly large, which would be possible under the planet-planet scattering migration model [6], [2], [3] or an eccentricity driving mechanism is required. HD 209458, in Figure (3), remains to be difficult to explain with tidal heating since it is observed to have zero eccentricity.

The possible radius values that would also be consistent with the observed semimajor axis, eccentricity, and age has also been found for 41 of the known transiting systems as shown in Figure (4). These systems are in order of increasing incident flux. In all of these runs, $Q_p = 10^5$ and $Q_s = 10^5$. Notice that for most systems, this model is able to explain the observed radius of the planet, while there remain systems for which the model is not able to explain the radius.

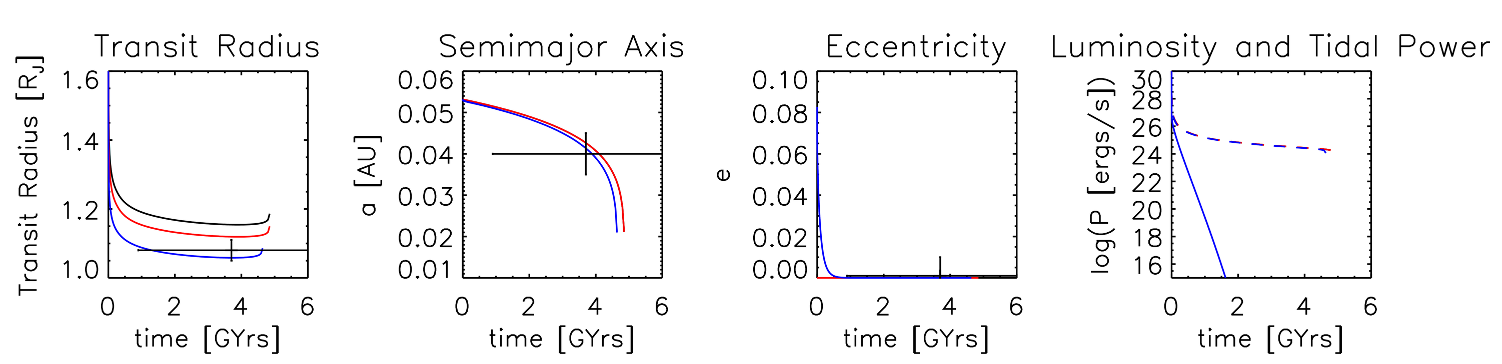

FIGURE 1: **TrES-1 orbital and thermal evolution**. $Q_p = 10^5$, $Q_s = 10^5$. Possible tidal/thermal evolution tracks for the planet around the star TrES-1. Black: no core. Red: 10 M_E core. Blue: 30 M_E core. This is a 0.76 M_J planet orbiting a 0.89 $M_\cdot$ star. First panel: transit radius in optical evolution. Second panel: semimajor axis evolution. Third panel: eccentricity evolution. Fourth panel: Tidal power injected into the planet (solid) and planet luminosity emitted (dashed). Observed semimajor axis, eccentricity and observed radius are plotted in their respective subfigures. These evolution tracks were selected to have orbital parameters that agree with the observed values within the possible age interval. **In this case tidal effects cause the planet to undergo significant orbital evolution, however the injected tidal power is always significantly smaller than the planet's luminosity.**

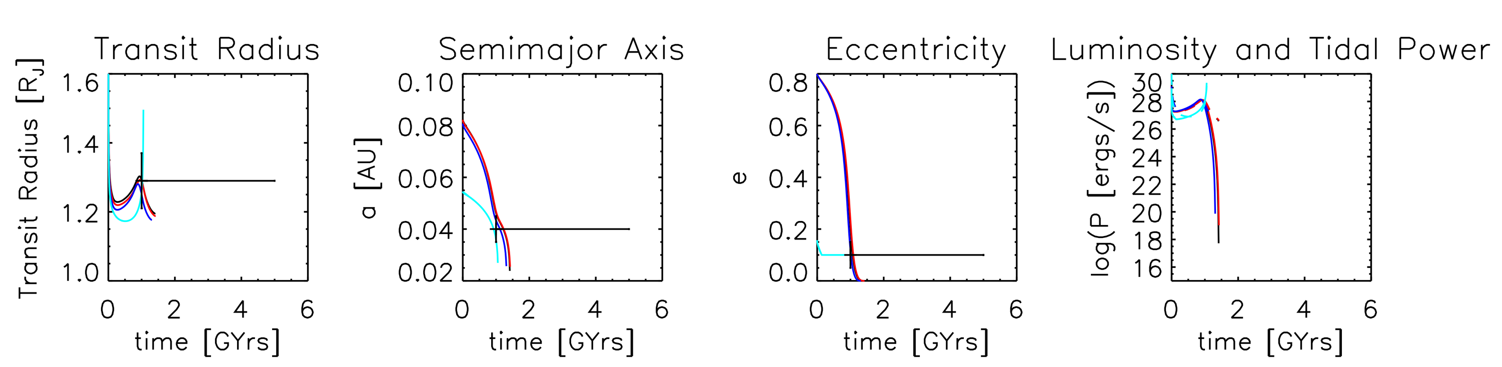

FIGURE 2: **WASP-10 orbital and thermal evolution**. $Q_p = 10^5$, $Q_s = 10^5$. Possible tidal/thermal evolution tracks for the planet around the star WASP-10. This is a 3.06 M_J planet orbiting a 0.71 $M_\odot$ star. Black: no core. Red: 10 M_E core. Blue: 30 M_E core. Light Blue: 30 M_E core with minimum eccentricity equal to the observed value, 0.1. **In this case, tidal heating is sufficient to account for the inflated radius, if the planet began with a large initial eccentricity or some interaction acts to maintain a non-zero current eccentricity.** In the first case, there is a surge of tidal power that inflates the radius as the eccentricity is damped Such a high initial eccentricity may be possible with a planet-planet scattering mechanism [6], [2], [3].

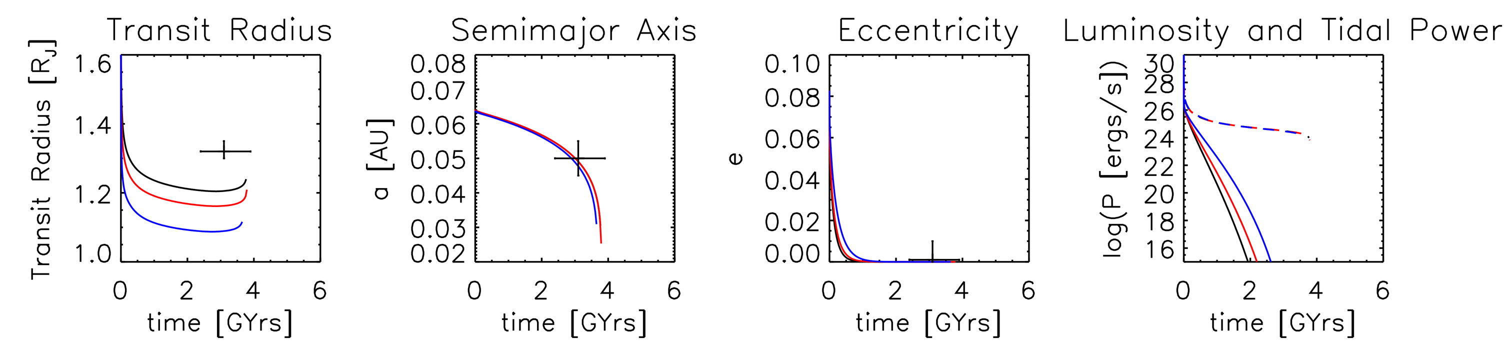

FIGURE 3: **HD 209458 orbital and thermal evolution**. $Q_p = 10^5$, $Q_s = 10^5$. This is a 0.657 M_J planet orbiting a 1.101 $M_\odot$ star. The planet has a radius of 1.32 R_J and an observed eccentricity of zero. Black: no core. Red: 10 M_E core. Blue: 30 M_E core. These runs were selected from a grid over initial semimajor axis and eccentricity such that the model orbital parameters agree with the observed orbital parameters during the system's possible age interval. The observed transit radius, semimajor axis and eccentricity are plotted. In the lower right panel, the dashed lines are the planet's intrinsic luminosity, while the solid lines are the planet's tidal heating. **Using this model, no evolution history has been found that explains the planet's observed radius. This suggests that some other mechanism may be responsible for the large-radius value HD 209458.** One possible mechanism is double diffusive layering which may significantly inhibit convection [1].

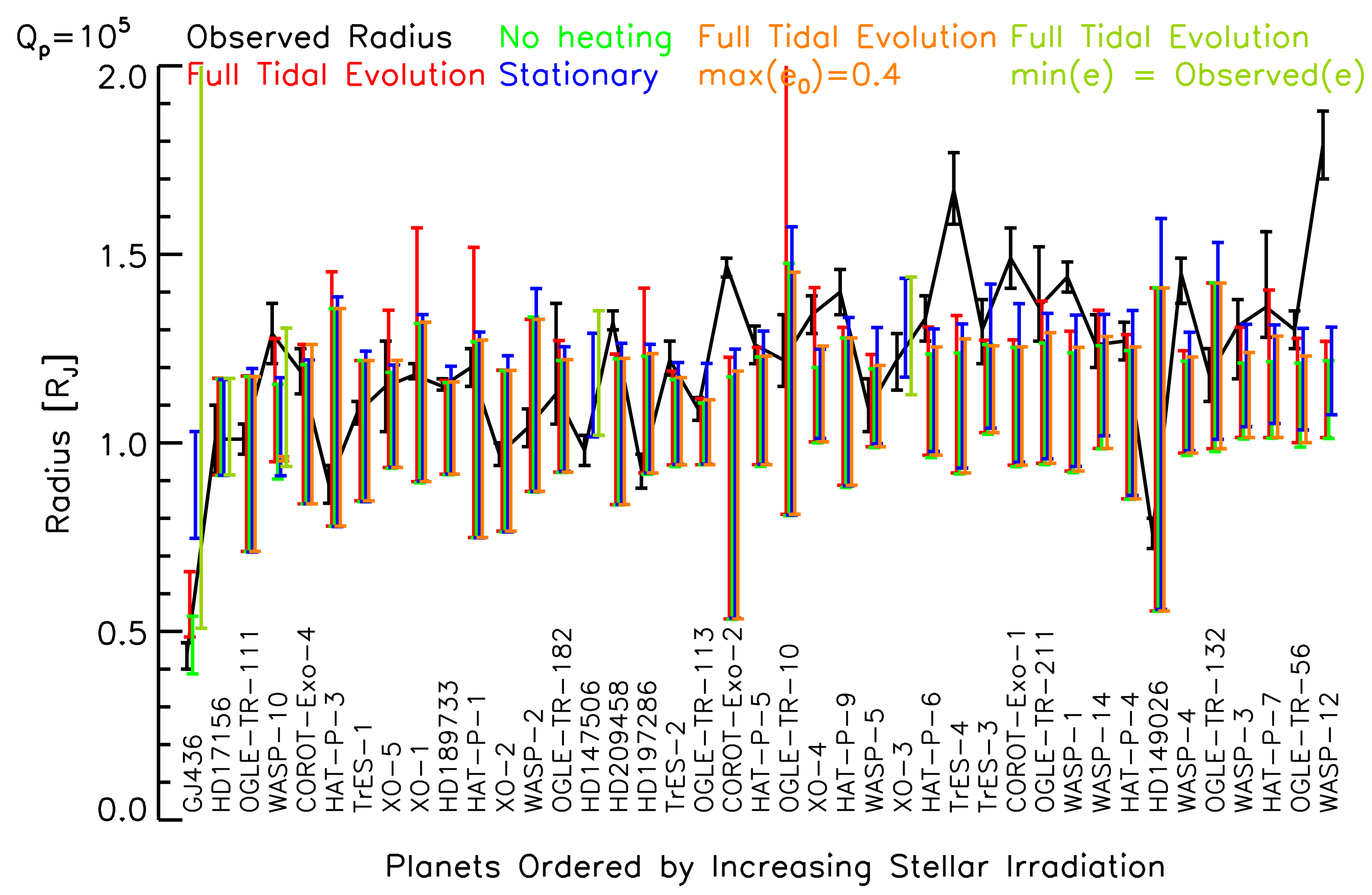

FIGURE 4: **Range of possible planet radius values** that would be consistent with the observed parameters. The observed radius is shown in black. The range of possible radius values under the full tidal evolution model is plotted in red with no constraint on the initial eccentricity. The radius range for a model with orbital evolution, but without the tidal heating into the interior of the planet is plotted in green. The radius range for a model without any tidal effects is plotted in blue. The radius range for the full tidal evolution model with a maximum initial eccentricity of 0.4 is plotted in orange. In cases where a nonzero eccentricity has been observed, the radius range with an eccentricity floor equal to the observed value is shown in yellow. As expected, there are cases where tidal heating is able to greatly enlarge the planet's radius compared to the model without tidal effects. There are also cases where the insolating effect of the incident flux results in the non-tidal model having larger radius values than the tidal model. This is possible because tidal evolution allows the planet to emit a higher luminosity early in its lifetime at larger semimajor axis. **This tidal-thermal model is able to explain the radius of the majority of planets. There remain a few planets with observed radii that are larger than achieved by this model.**

Conclusions

- This tidal-thermal evolution model can explain the majority of transit observations
- Some systems with nonzero eccentricity can only be explained if a) they originally had a very high eccentricity or b) an eccentricity driving mechanism is at work.
- In other cases, this model can't explain the planet's inflated radius.

References

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