Coupled Orbital and Thermal Evolution of Transiting Planet TrES-4

N. Miller[1], J. Fortney[1] and B. Jackson[2]

[1]Department of Astronomy and Astrophysics, University of California, Santa Cruz
[2] Lunar and Planetary Laboratory, University of Arizona

ABSTRACT

The hot Jupiter planet TrES-4 currently has a radius of 1.75 Jupiter radii, making it the largest known transiting planet. Explaining this large radius represents a theoretical challenge. Our goal is to find a self-consistent orbital and thermal evolution history of this planet that is consistent with the observed semimajor axis, eccentricity and radius. We have performed the first calculations of TrES-4's thermal evolution that incorporate the planet's tidal and orbital evolution. Tidal evolution of the planet's orbit deposits energy into the planet's interior resulting in an enlarged radius. Some previous calculations of hot Jupiter tidal evolution have ignored the change in radius of the planet, which we explicitly include here. We also investigate the future evolution of the planet and find that it may end with the planet tidally evolving into the Roche lobe of the host star and being destroyed. Our study provides constraints on the past evolution of the planet and on the present orbital and tidal parameters that can explain its current radius.

TEXT

There has been an surge of research in the area of planetary science recently due to observational advances that have allowed us to detect and parameterize planetary systems; more than 250 systems have been detected by the radial velocity method and more than 40 systems are transits. In a transiting system, it is possible to also estimate the size of the planets which allows us to further understand the structure and evolution history of these planets.

A gas planet's interior structure can be described by a simple model of three components: a solid core of order a few earth masses, a convective envelope and a radiative atmosphere. The existence of a core is motivated by the favored core accretion formation scenario. Because the core is high density, large cores are an attractive explination for the transiting systems with smaller than expected radii. The convective envelope makes up the primary component of the mass, volume and internal energy of the planet. The atmosphere controls the planet net luminosity; its structure is a function of the incident flux and spectrum from the parent star, the composition, the temperature at the outer convective region and the surface gravity of the planet. The energy flow rate through the atmosphere then determines the rate that the planet radius shinks.

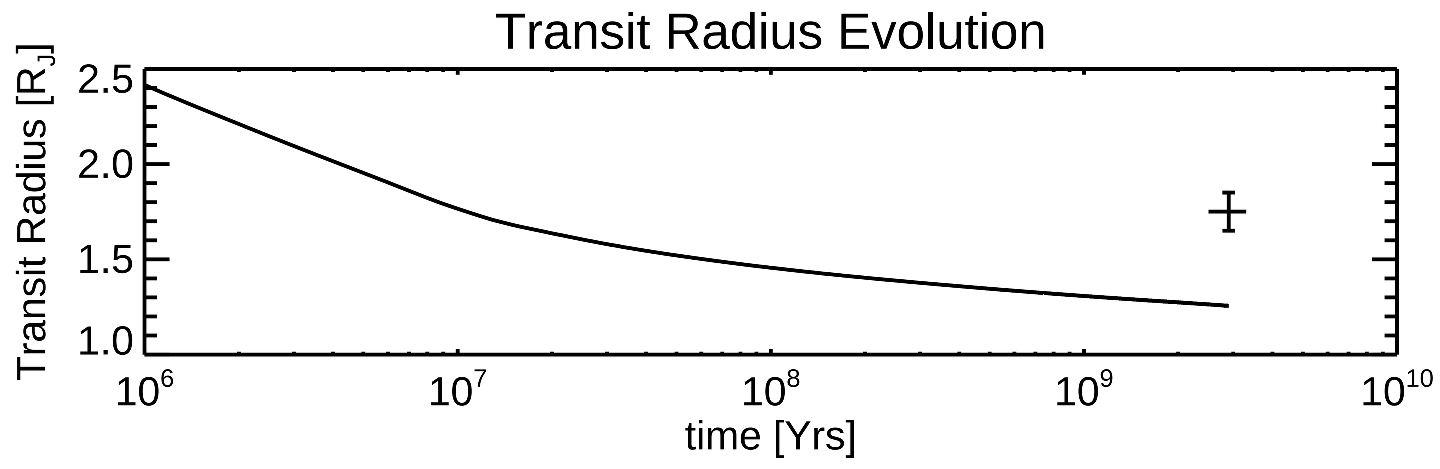
Unexpectedly, the transiting system TrES-4 has been observed to have a transiting radius of 1.75 Jupiter Radii (R_J) and semimajor axis of Torres et al. (2008), but is orbiting around a system that is 2.9 billion years old. Also, the eccentricity has been observed by (H. Knutson, personal communication) to be very small. The large-radius is puzzling because under the simple model described above, the planet would have cooled and shrunk in radius to a significantly smaller size even if it was placed at its current semimajor axis at the time of formation. See Figure 1 where the "transit" radius (the radius that would be observed including the effect of the atmosphere height) has been calculated as a function of time. Notice that the current observed radius at the present time is significantly larger than the model value. Therefore some mechanism such as tidal heating is necessary to explain this and other large-radius systems.

This work investigates whether tidal heating is a viable mechanism to explain this large-radius observation. A coupled orbital tidal and thermal evolution model has been built and applied to the TrES-4 system. This model uses the planet thermal evolution model described by Fortney et al. (2007) and orbital tidal evolution model described by Jackson et al. (2008). Note that the Jackson et al. (2008) orbital tidal evolution model takes into account the coupled evolution in both semimajor axis (a) and eccentricity (e). In Figure 2 a grid of runs over initial orbital parameters is computed for characteristic values of model tidal parameters Q_p and Q_s, for which there are weak constraints Jackson et al. (2008). Although it is possible to have a current transit radius of order 1.75 R_J, in every run that this occurs the current model eccentricity is significantly larger than the observed value by (H. Knutson, personal communication). Since the observed eccentricity has been found by transit timing it is possible that the estimated eccentricity is too small due to a projection effect.

However, it appears that using reasonable initial conditions and a large range of model Q parameters, an evolution history that results in the current observed parameters can not be found. Also, the model predicts that an input power of 6×10^{27} ergs / s is required to maintain the current radius. With the current observed eccentricity, this would require the $Q_p \sim 10^3$ which is significantly smaller than the value expected for Jupiter of $\sim 10^5$ described by Jackson et al. (2008). **Therefore, it appears that tidal heating may not be a sufficient mechanism to explain the observed radius of TrES-4.** This model is currently being used to study other transit systems to determine how widespread this result is.

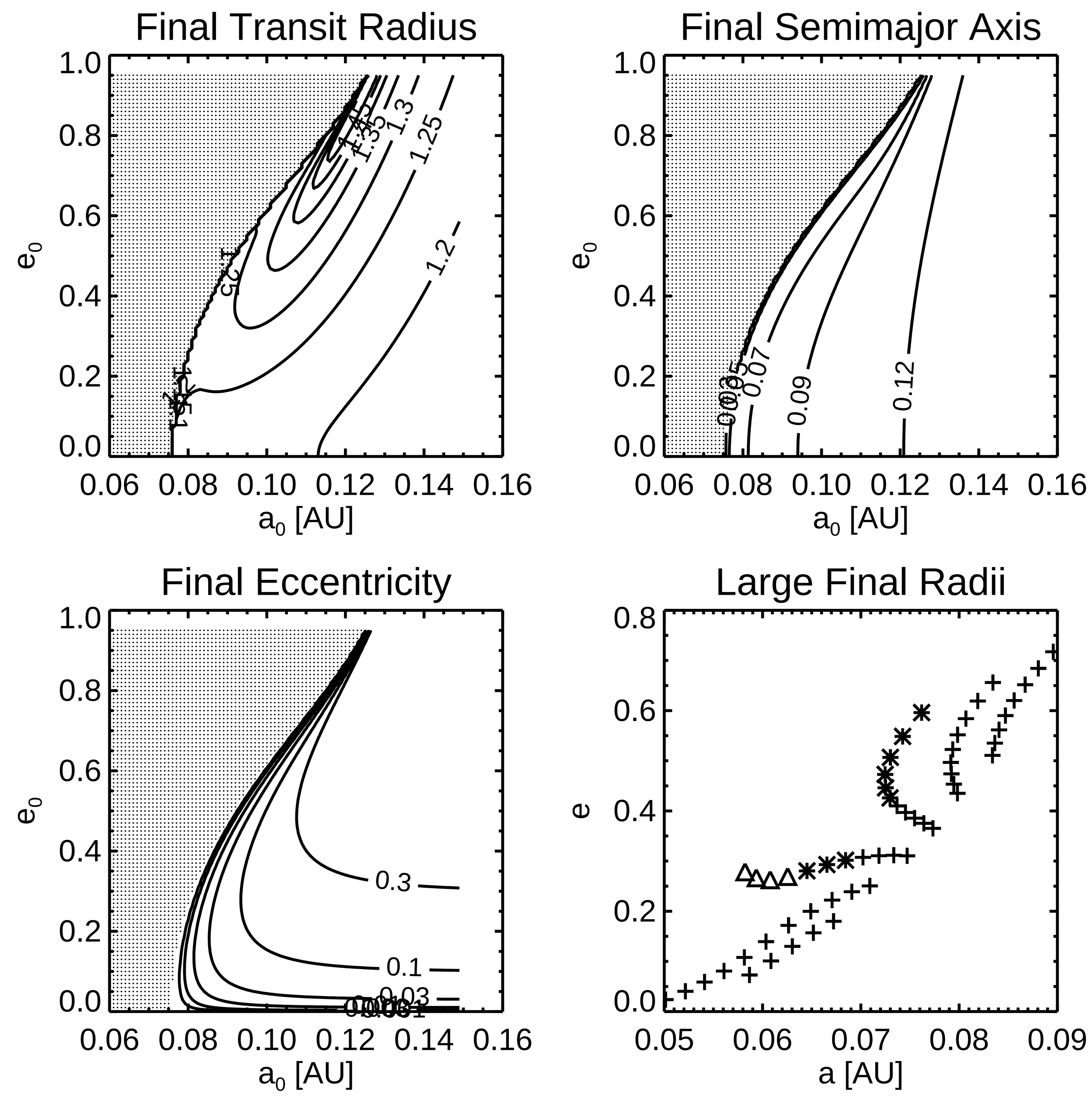
The model has been used to calculate the future evolution of the system TrES-4 using the current observed parameters of the system. This calculation is depicted in Figure 3. The model predicts that the planet will fall into the Roche Lobe of the star within the next billion years at most and decrease in radius in the next $10^{7.5}$ years despite the expected tidal heating.

FIGURE 1



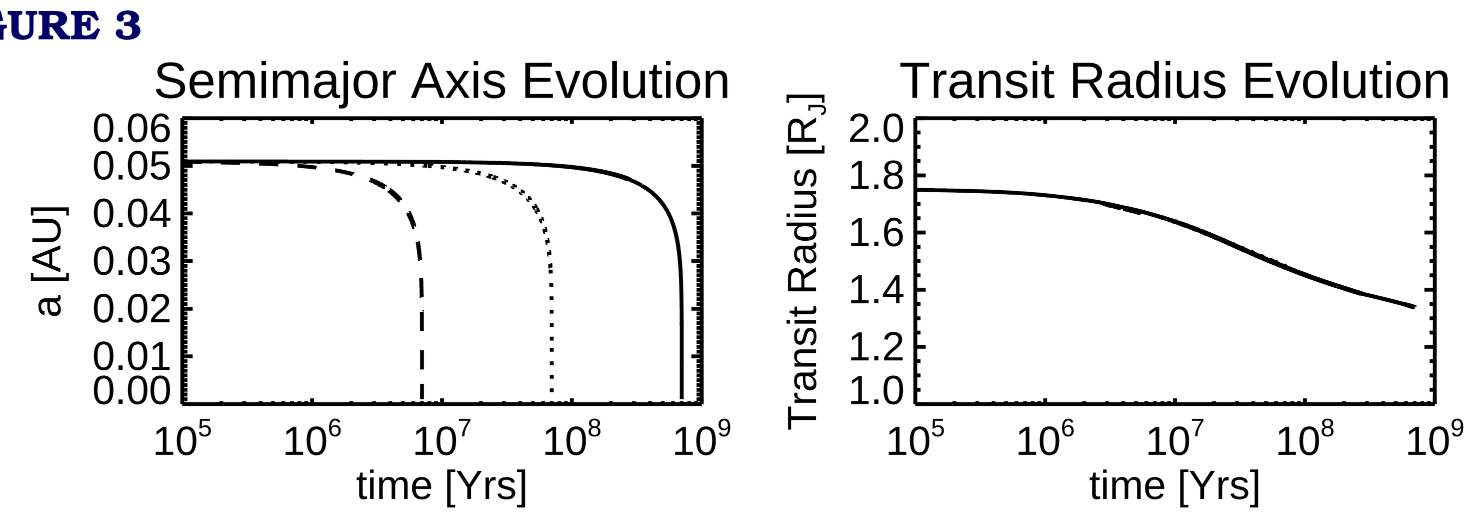
Transit radius history without tidal evolution maintaining the semimajor axis at 0.05 AU from formation. The observed radius is marked using the value from Torres et al. (2008). This calculation demonstrates that some physical mechanism, possibly tidal heating, is necessary to inflate this planet to its current radius.

FIGURE 2



Grid of thermal and orbital planet evolution calculations with $Q_s = 10^{5.5}$ and $Q_p = 10^{5.5}$ over a range of initial planet orbital parameters (a_0 initial semimajor axis and e_0 initial eccentricity). Upper left: contour plot of final transit radius as a function of initial orbital parameters. Upper right: contour plot of final semimajor axis as a function of initial orbital parameters. Lower left: contour plot of final eccentricity as a function of initial orbital parameters. Lower right: current semimajor axis and eccentricity of runs with 1.5 R_J < R < 1.6 R_J crosses, 1.6 R_J < R < 1.7 R_J stars and R > 1.7 R_J triangles. Notice that the runs that have transit radius consistent with the observed transit radius have current eccentricity that is significantly larger than the small observed value by (H. Knutson, personal communication). Hatched region of parameter space results in the planet falling into the star's Roche Lobe in a shorter period than the age of the system.

FIGURE 3



Future evolution of TrES-4 including model tidal heating for various values of Q_s (solid 10^6, dotted 10^5, and dashed 10^4). The planet evolution models are given initial parameters equal to the observed. The initial semimajor axis is 0.05092 AU and initial transit radius of 1.75 R_J from Torres (2008). The initial eccentricity is set to the small estimate by (H. Knutson, personal communication). Notice that from these initial conditions, we predict that in about $10^{7.5}$ years, the planet will have shrunk from its current radius and that in between 10^7 to 10^9 years the planet will fall into the Roche Lobe of the star.

References

Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, ApJ, 659, 1661

Jackson, B., Greenberg, R., & Barnes, R. 2008, ApJ, 681, 1631

Torres, G., Winn, J. N., & Holman, M. J. 2008, ApJ, 677, 1324