A triple eclipsing system as a test case for close binary formation through Kozai cycles

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Abstract

Kozai cycles and tidal friction of a binary with a tertiary companion is one of the leading theories for the formation of close binary systems by tightening the orbit of the inner binary (Kozai 1962; Kiseleva et al. 1998). According to simulations, such systems should evolve into tight inner binaries with eccentric tertiary companions on wide orbits, and importantly predict the tertiary to have an orbital inclination misaligned relative to the plane of the inner binary, with an angle of misalignment that peaks strongly around 40 degrees (Fabrycky & Tremaine 2007). KIC 2835289 is a triple system comprising a ~0.9-day inner binary and a tertiary on a ~750 day orbit. The tertiary was identified through our eclipse timing variations and our finding of a tertiary eclipse event in the Kepler data (Conroy et al. 2014). Here we show, using photodynamical modeling of the system, that the tertiary in this system is on an eccentric orbit inclined ~40 degrees with respect to the inner binary, in superb agreement with theoretical prediction. KIC 2835289 is thus the first known triple system that directly attests to the key predictions of Kozai cycles and tidal friction as a mechanism to tighten binary star systems.

Data

Long cadence photometry for KIC 2835289 is available for the entirety of the Kepler mission (Q0-Q17), and short cadence data is available for Q17. This binary is an ellipsoidal variable - a binary star system that is in sufficiently close proximity that the stars' surfaces are distorted, resulting in phase-dependent light variations. The presence of two tertiary events constrains the inclination of the companion to be nearly 90 degrees.

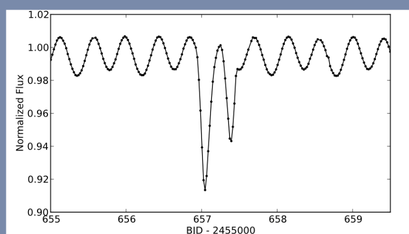
Additionally, eight triple-lined spectra were obtained at the Mayall 4-meter telescope at Kitt Peak National Observatory, providing full radial velocity phase coverage.

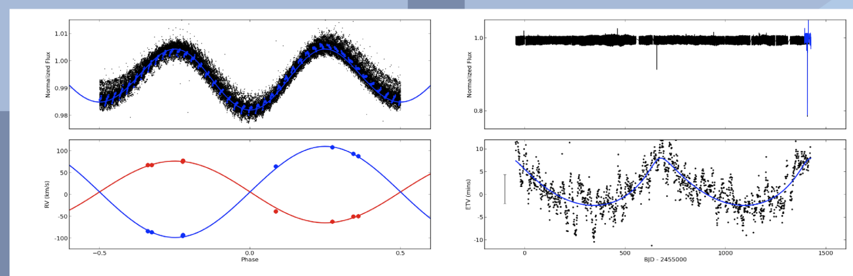
Eclipse Timings

Eclipse Timing Variations (ETVs) were determined by fitting a chain of four quadratic functions to the phased data and determining the time shift that minimizes the residuals to each individual eclipse (see Conroy et al. 2014 for details).

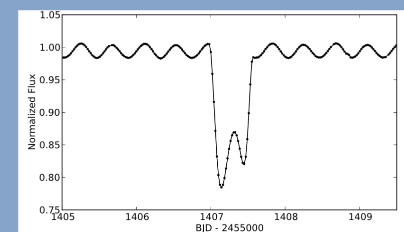
The ETVs were then modeled with an analytic function that depicts the Light Travel Time Effect (LTTE) due to the presence of a third body in a hierarchical orbit. This model results in an estimated period for the third body of 747.4 ± 23.7 days on an orbit with an eccentricity of ~0.6, consistent with the two available tertiary events which are separated by 750 days.

The location of the tertiary event with respect to the ETVs suggests that the third star eclipses the inner binary when it is near periastron.





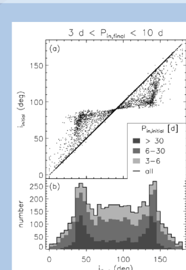
Long-cadence Kepler data from Q0-17 (upper-right). Eclipse Timings (lower-right) show that the tertiary eclipses occur near apastron and give an estimate for the period and eccentricity of the outer orbit (LTTE orbit shown in blue). SC data from Q17 (blue, upper-right) was phase-binned to average over the spot modulations (blue, upper left). This binned photometry along with the RVs (lower-left) were used to fit a PHOEBE model to the inner-binary.

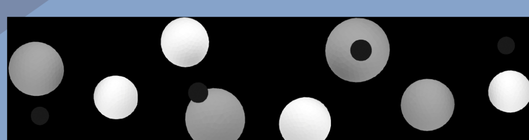


Kozai Cycles and Tidal Friction

Kozai cycles occur in a hierarchical three body system with any eccentricity in the outer orbit. Kozai found a critical initial mutual inclination, the angle between the binary's orbital plane and that of the wide tertiary about the binary, such that inner binaries in systems with mutual inclinations between 39.2 and 180-39.2 degrees cannot remain circular, and Kozai cycles will occur, causing oscillations in both the inner eccentricity and the mutual inclination (Kozai 1962, Fabrycky & Tremaine 2007). At some points during this cycle, the inner binary will be in a state of higher eccentricity, and tidal forces will increase during periastron, dampening the eccentricity cycles and tightening the orbit (Kiseleva et al. 1998). Eventually the inner binary tightens enough that tidal forces dominate and the eccentricity cycles cease, resulting in a close binary in a circular orbit with a wide, eccentric, and inclined companion.

Simulations for inner binaries with final periods between 3 and 10 days show that the final mutual inclinations for these systems peak around the same i=39.2 as Kozai found as the lower range to start Kozai cycles (Fabrycky & Tremaine 2007).





Inner-Binary Model

The inner-binary was modeled using PHOEBE (Prsa & Zwitter 2005). A monte-carlo approach was used to randomly sample the parameter space for the inclination, temperature ratio, primary and secondary potentials, third light, and a single spot.

Posteriors were then determined by binning the parameter values for models that fell below a cost function value that represented about 0.2% of all models sampled.

Using the orbital inclination of 49±6 for the inner-binary from the light curve modeling, together with the constraint from the tertiary eclipse events that its inclination is 90±1, we conclude that the mutual inclination between the third body and the inner binary is 51±8.

This model depicts a triple component that is clearly misaligned with respect to the inner binary, consistent with a scenario in which the inner binary was tightened through KCTF caused by the wide companion.