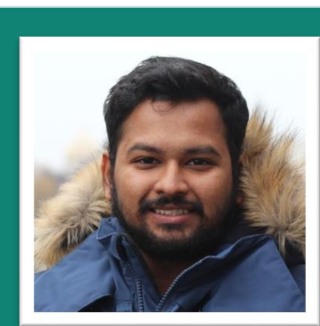
# Evolution and Dynamics of Tight Triple Systems

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## Abstract


Tight Triple Systems have stars in a hierarchical configuration with a third star orbiting the inner binary with a period of fewer than 1000 days. Such systems are subjected to various internal dynamical interactions and are important for understanding the formation and evolution of stars in multiple systems. Having a detached eclipsing binary (DEB) as one of its components allows us to obtain precise stellar and orbital parameters of these systems. A recent surge in such systems has been due to eclipse timing variation (ETV) studies using accurate photometry from space missions. We obtain accurate parameters of these systems using high-resolution radial velocity measurements coupled with precise space-based photometry. This will enable us to have a 3D geometrical picture as well as the metallicity, age, and evolutionary status of these systems.


## Introduction

Hierarchical triple systems have the third star at a greater distance compared to the inner binary separation. Such configuration can then be approximated as a two-star system with the inner binary pair being treated as a single entity. Most of these systems have long outer periods and therefore their dynamics can have timescales of decades or centuries. Meanwhile, a subset of these triples, called Tight Triple Systems (TTS) have an outer orbit period of fewer than 1000 days [1] and hence their dynamics can be observed in timescales of years.. Detached Eclipsing Binaries (DEB) are the source of most accurate stellar parameters (e.g, mass, radius, etc.). Accuracy of less than 1% can be attained by coupling high-precision photometry (e.g. from space telescopes and high-resolution spectroscopy [2]. The accuracy is robust and independent of different models and methods, even varying little due to different numerical implementation [3]. Therefore, TTS with DEB would serve as an ideal system to extract accurate stellar parameters. TTSs were once considered to be rare but with ETV analysis of photometric observations using space telescopes [4], more of these systems are being discovered.

Our study probes a sample of 20-25 TTS (Fig.1) which are spectroscopically SB2 or SB3 systems. The systems were extracted from literature, the spectra database of **CRÈME** project (P.I.: K.G. Hełminiak) and the photometric eclipse timing campaign, project **Solaris** (P.I.: M. Konacki).

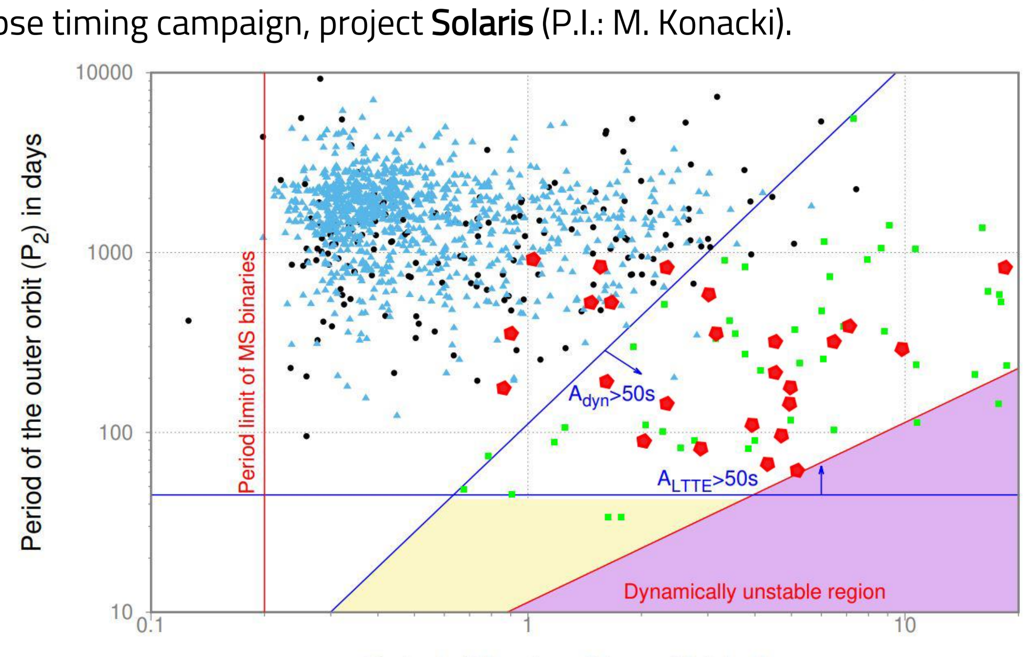


**Fig.1.** Distribution of triple star systems according to their inner orbit ($P_1$) and outer-orbit ($P_2$) periods taken from [12]. The light-blue triangles are the systems discovered from OGLE. Rest of the small markers are triples detected by Kepler and TESS. **Our targets are overplotted in big, red pentagons.** The shaded yellow area means that no LTTE can be detected, though dynamical effects may be significant and, therefore, certainly detectable. The purple region is a dynamically unstable region, in the sense of the stability criteria of [10].

## Methodology

### LIGHTCURVE MODELLING:

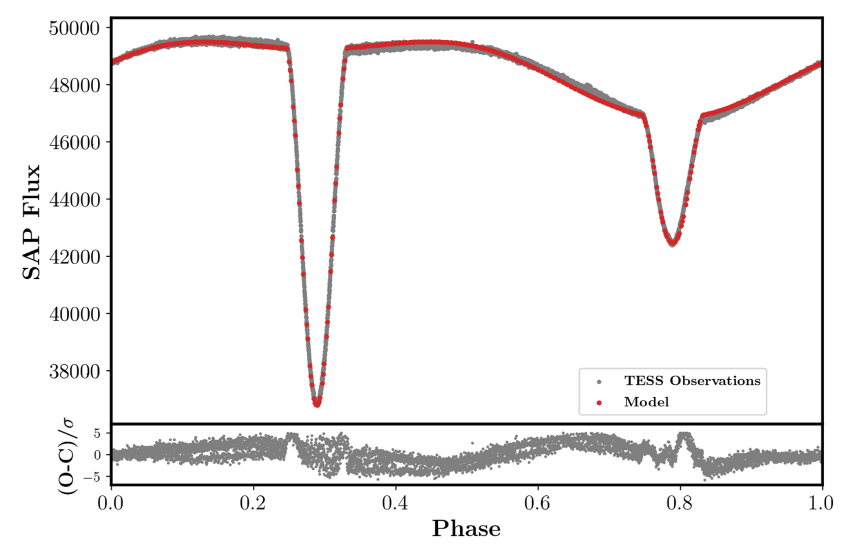


**Fig.2.** Phase-folded TESS light curve (grey) of BD+44 2258 with the best fit model (red) from PHOEBE2.3. For the accurate parameters of this system check https://doi.org/10.5281/zenodo.5123521 .

We have TESS and/or Kepler observations for our targets, available on the MAST archive. We use PHOEBE2.3 [5] eclipsing binary modelling code for modelling the light curves. PHOEBE2.3 has added advantages of modelling spots (Fig.2) on the stars. The errors on the parameters are calculated using MCMC sampling through the code.

### RADIAL VELOCITIES MODELLING:

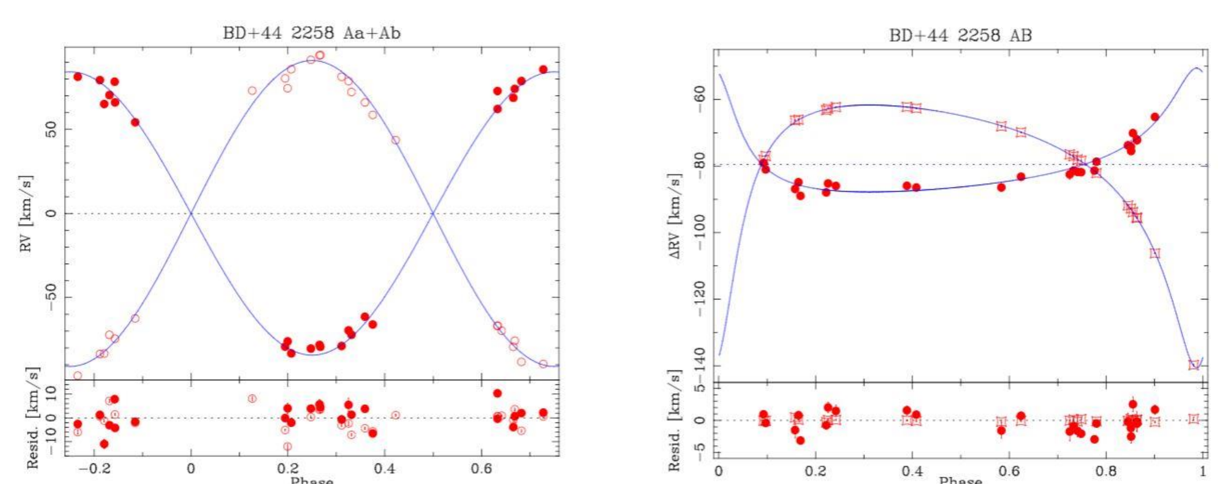


**Fig.3.** Phase-folded radial velocity curves for the SB3 system BD+44 2258.The inner-binary of the TTS (left). The centre-of-mass of the inner-binary vs the tertiary (right).

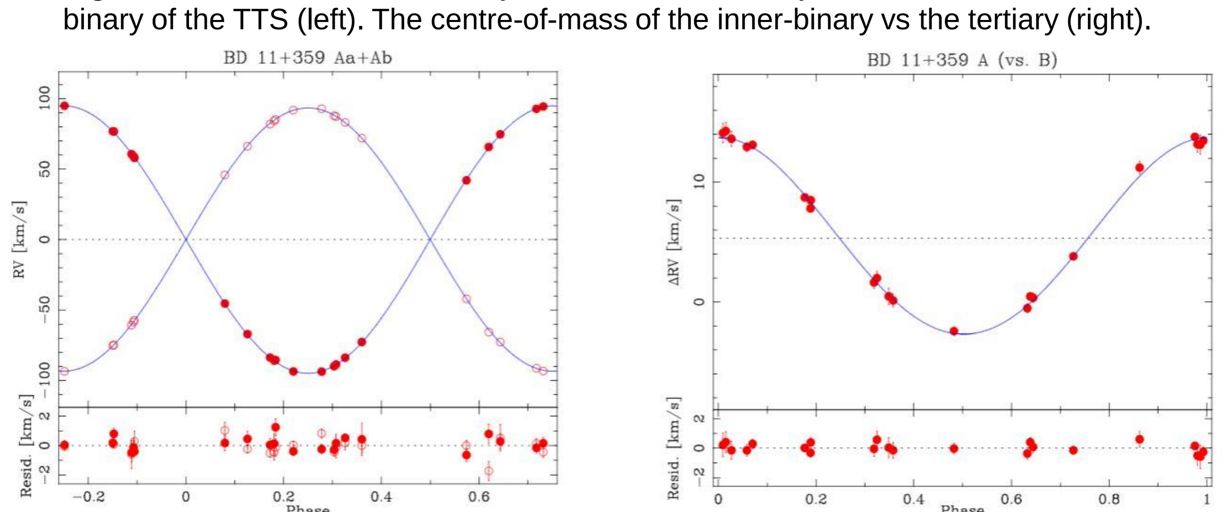


**Fig.4.** Phase-folded radial velocity curves for the SB2 system BD+11 359.The inner-binary of the TTS (left). The centre-of-mass of the inner-binary (right).

The radial velocities were extracted from spectra from the CRÈME project. We used the TODCOR algorithm [6] to extract radial velocities where we see two peaks in the cross-correlation map for SB2 systems and three peaks for SB3 systems. The obtained radial velocities are modelled with the V2FIT code [7]. The final masses of the inner-binary stars were calculated using inclinations from the light curve analysis. The centre-of-mass velocity of the inner-binary (Fig.,43: left) was then modelled (with the tertiary radial velocity if any; Fig.3,4: right). The total mass of the inner binary was used to get the mass estimate of the tertiary.

## Analysis

### CONSTRAINING AGE AND METALLICITY:

The measurements of mass and radius give us an opportunity to test evolutionary models of stars. Usually for TTS, we see no interactions between the stars themselves (unless their orbits are very dynamic). This would mean that all three stars in a TTS will evolve separately. Therefore we expect similar metallicity and age for the three stars in this "clean" system (Fig.5: left).

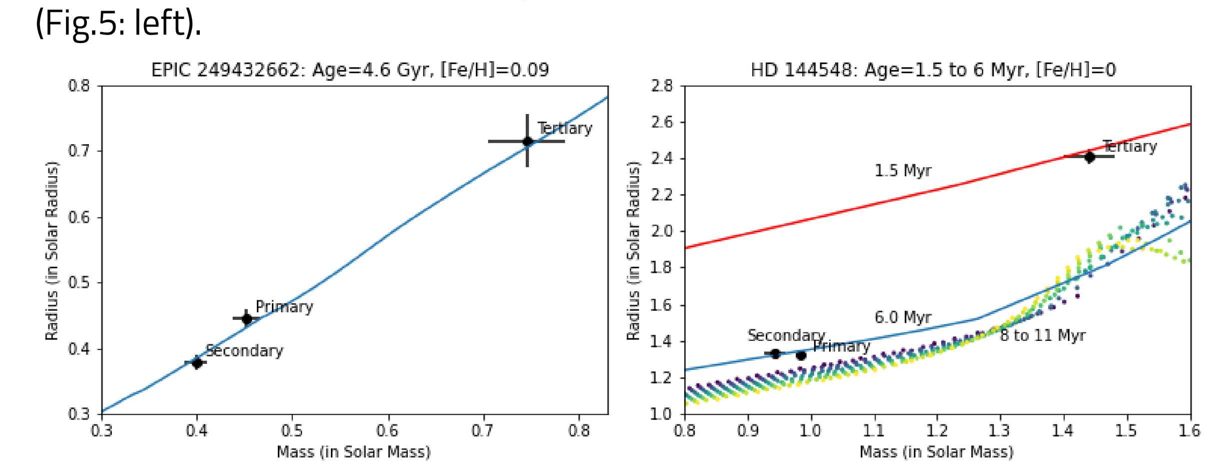


**Fig.5.** (Left) MESA isochrone in comparison to the parameters obtained for system EPIC 249432662 obtained by [8]. All the three stars are of the same age and hence form a "clean" system. (Right) Parameters of HD 144548 obtained by [9] against different MESA isochrones. The shaded space corresponds to isochrones of ages 8 to 11 Myr which is the current estimate of the age of the OB association in Upper Scorpius to which the system belongs.

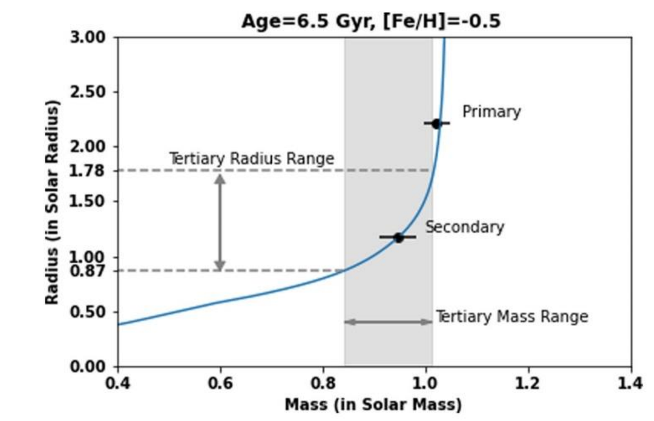


**Fig.6.** Estimate of radius of the tertiary by using masses from radial velocity modelling for BD+44 2258, assuming this to be a "clean" system.

The radius estimates for the tertiary are possible in triply eclipsing systems (Fig.5). But assuming a "clean" system, we can estimate a range for the radius of the tertiary (Fig. 6). But sometimes this "clean" system assumption fails and all the three stars do not follow the same isochrone (Fig.5: right). This calls for additional probe by independent estimates of metallicity and other relevant stellar parameters.

### CONSTRAINING DYNAMICS:

The stability of most of the hierarchical systems can be explained by the stability criteria of [10]. In TTS, higher-order dynamic terms are significant. Following the treatment in [11] we use the masses of the three stars and the

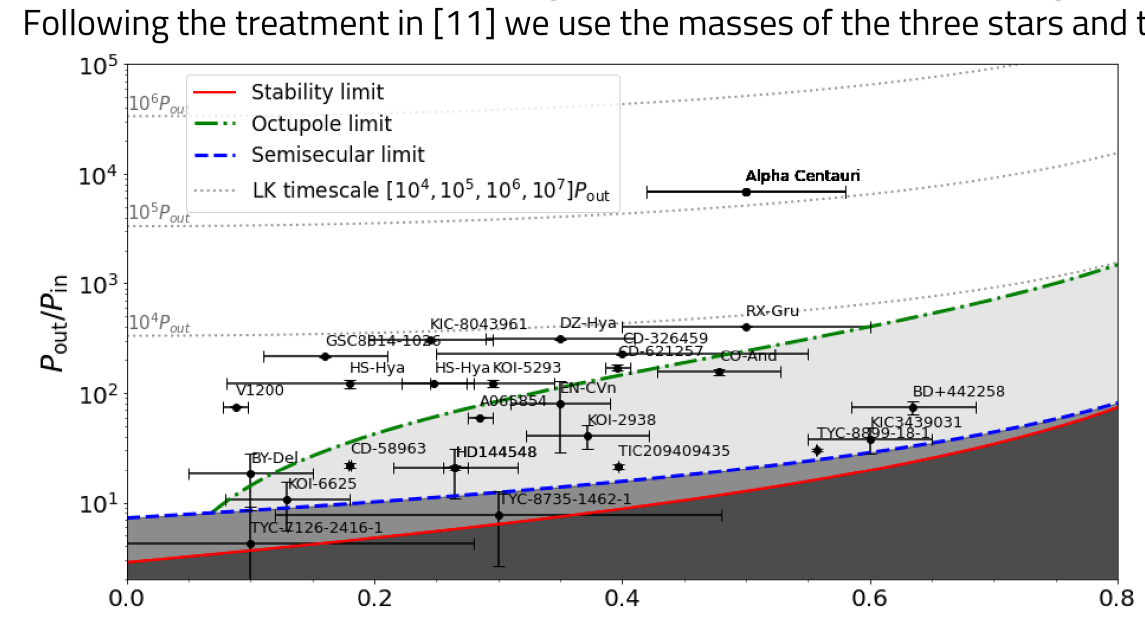


**Fig.6.** The visualisation of different dynamical regimes in a triple system, based on [11]. The regions correspond to a triple system with the primary, secondary, and tertiary masses as 1M,0.5M and 0.75M respectively. Our systems are over-plotted to this configuration and Alpha Centauri as a reference. The plot was generated using the interactive version of this plot at **https://bndr.it/wr64f**.

orbital parameters to predict the dynamical interactions that can occur in the triple systems. We found that most of the systems lie in the octuple regime where , the inner-binary has inclination flips. Three systems are seen to lie in the semi-secular region and are prone to stellar collisions. But the errors on the positions are too high to be conclusive and hence we plan for more observations to improve these estimates.

## Conclusion

Triple systems are now easier to probe with DEBs using high-precision photometry and high-resolution spectroscopy. The short timescales of different physical processes in TTSs gives us a great laboratory to test different theories of three-body dynamics and interactions. The accurate parameters of these systems enable us to test models of stellar evolutions of single as well as multiple star systems and are a good checkpoints for future models for multiple star evolution. The accurate mass distributions, orbital architectures provide a scope to test and improve various theories of multiple star formation. Most importantly, this preliminary study shows the need for more observations of such systems to improve the accuracy of the parameters for all the above cases.

## Future Work

1. We need multiple coverage of the outer-orbit period to improve the certainty of the detection and the accuracy of the stellar parameters obtained. Therefore, new spectra observations are planned for our targets.
2. The search for new targets is on-going and more is planned for the future with eclipse timing method using photometric observations from the **Solaris** project.
3. An independent estimate of metallicity, age and radius of the tertiary is planned using spectra disentangling procedures. This would give us atmospheric parameters too which could be used with the stellar parameters to better model the evolutionary tracks.
4. A check of multiple-star formation theories is planned using mass distributions and orbital architectures of all the systems in the sample.

## Acknowledgements


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