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Subject
Review of PhD Dissertation

Dear colleague,

With great interest I have read the PhD Dissertation of Ayush Moharana titled "Comprehensive study of low-mass Compact Hierarchical Triples using Eclipsing Binaries" under the supervision of Dr. hab. K.G. Hełminiak at the Nicolaus Copernicus Astronomical Center of the Polish Academy of Science. Moharana has conducted innovative, independent research into the demographics of compact hierarchical triples. While several hundreds of compact hierarchical triples are known, only a few tens have been completely characterised, leaving many questions unanswered. Moharana has applied an impressive amount of numerical techniques and mastered an impressive number of software packages to maximise the power of compact hierarchical triples and understand their characteristics. I recommend the doctoral thesis to be admitted to a public defense, for reasons I will detail below.

<u>Chapter 1: Twinkle, twinkle multiple stars: Stellar multiplicity at a glance</u>
Chapter 1 provides a one of the best overviews on compact hierarchical triples that I have come across so far - and one I will recommend to read to anyone interested in the topic. In places compact triples in context through a historical perspective on stellar multiplicity in observational astronomy. It reviews improvement through the years due to spectroscopic as well as photometric surveys, and ground-based as well as space based telescopes. Besides observational astronomy, it also discusses theoretical points of view, in particular regarding the formation and evolution of compact hierarchical triples.

Remarks:
- page 2/3: Moe & Di Stefano 2017 is credited for revealing the dependence of the multiplicity on spectral type (and therefore mass), however this was already brought forward by Raghavan 2010 mentioned earlier.
- Page 5: note that even in a detached binary, the stars may not interact with each other physically, but they may affect each other's evolution through tidal affect and rotation. Hence not all stars in detached eclipsing binaries truly evolve as single stars.
- Page 14: 'Roche lobe in an eccentric binary is significantly smaller than that of a circular binary" Ref missing: Sepinsky et al. ~2007

<u>Chapter 2: Three in one: Search for Compact Hierarchical Triples</u>
Subsection 2.1-2.3.1: Developments in observational astronomy have opened up several ways of detecting triples. Moharana discusses in detail the three of these techniques, which are all used in the subsequent paper. These techniques include broadening functions, radial velocity measurements, and eclipse timing variations.

Remarks:

- While the techniques of radial velocity measurements and eclipse timing variations are explained clearly, the explanation of the broadening functions is hard to follow. It is mentioned that one spectrum suffices to detect a compact hierarchical triple with spectroscopy, as the velocity of the stars in such a compact orbit is of the same order - for a non-expert on the method it is not clear why the similarities between the velocities help. Next, three conditions are supplied, but are these conditions to have similar velocities? Conditions to detect a compact triple with spectroscopy? To only need one spectrum? During the public defense, I would like to ask the candidate to explain the method of detecting triples with broadening function to me.

The published paper: Chapter 2 also includes the 2023 paper published in MNRAS titled "Solaris photometric survey: Search for circumbinary companions using eclipse timing variations:. It presents the initial results from the Solaris photometric survey, which uses four 0.5-m robotic telescopes in the Southern hemisphere to look for circumbinary companions. It presents the method of light-curve extraction, detrending, and eclipse binary modelling using observations from the Solaris network. Using these light curves, they extract precise eclipse timings for seven EBs, and find a signals of a companion in the target GSC 08814–01026.

Remarks:
- page 24: "For this paper, we filtered targets with at least 16 000 frames of observations, spread across a minimum of 30 nights. We further narrowed down this sample to seven targets based on the quantity and quality of the eclipses in the final LC." Can the candidate explain why this set-up was chosen (16000 frames, 30 nights)? And what was deemed sufficient quantity and quality?
- Page 25: "A tertiary around a binary system can produce three classes of perturbation (Brown 1936). They are (i) short-period perturbations of the order of the inner orbital period (P_1), (ii) long-period perturbations of the order of the outer orbital period (P_2), and (iii) apse-node perturbations of order (P_2^2/P_1)". Can the candidate explain the origin of these perturbations? Which types of systems are you sensitive to? What bias does this introduce?
- Page: 27: Table 3 presents the final seven eclipsing binaries that are studied in detail. Can the candidate summarise the selection effects / observational biases on this samples? Is it a coincidence that the inner periods are all roughly 1d?
- Page 30: Su Ind. the mass ratio is deemed to be significantly lower than 1 (q=0.966±0.018) while the radii are nearly equal? How is this possible taking into account what you know about stellar evolution? What does significantly mean? Assuming a three sigma error e.g?
- Page 30 : 'Algol-type' please define. Different researchers may use this term in different ways.
- General question: What can you say about the detection rate or fraction of detectable triples in eclipsing binaries? Taking into account selection effects?

<u>Chapter 3: Everything in the Arsenal: Extraction of absolute parameters</u>

Chapter 3 provides an overview of the different methods of measuring stellar, orbital and atmospheric parameters in a compact hierarchical triple. These include light curve modelling, radial velocity measurements, spectral disentangling and spectral analysis.The software packages PHOEBE2, JKTEBOP, V2FIT, REBOUND, REBOUNDX, FD3, DSAA, and iSPEC.

Remarks:
- Page 37: "A combination of LC and RV modelling of a SB2 EB can give quite precise and accurate masses and radii of two stars." - Would be great to quantify this statement. In addition, can we trust the radius measurements of stars of these stars? Do tides affect these stars?
- Page 38: "The Roche model is one of the most accurate models of binary star geometry. The Roche model (named after its formulator, E.A. Roche) assumes that both the stars are point objects surrounded by massless envelopes, the periods of free non-radial oscillations are negligible, and the stars rotate as a rigid body." - accurate… I'd say the Roche model, in particular Roche lobes is an oversimplified picture. What assumptions should we worry about most?
- General question: Have you checked if there are any systematic differences between the parameters found by PHOEBE2 & JKTEBOP?

- Page 42: iAB is not defined in the thesis. Can the candidate explain the difference between iM, iA & iAB.
- Page 42: "Simplifying the calculations from Gronchi & Tommei (2007)" - Best mention how you've simplified them, otherwise it's unclear for the reader and possibly unreproducible.
- Page 43: "To further constrain this range, we rule out the unrealistic i_m by looking at average i_A variations in the numerical integration of orbital parameters and comparing with the i_A from the observations. " - Can you quantify this? For reproducability
- Page 44: "For a single isolated star, it is easy (relatively) to extract basic atmospheric parameters **from a spectrum**, as one can use **a** single-epoch, medium-resolution spectra**->spectrum**. The problem with the extraction of spectra for **unresolved?** binary stars increases three-fold. " ->true for all stars?
- Page 46: "The final disentangling product undergoes a lot of processes from its original state in a composite spectrum. Therefore, if a large chunk of spectra undergoes spd, it is likely that the line depths deviate (even though on small scales) from their true depths for certain lines (usually broad lines). Therefore, a better approach for spectral analysis would be to analyse a lot of spectral lines simultaneously to obtain atmospheric parameters from disentangled spectra. While grid fitting seems to be the first approach for this, the density of the grid limits the errors on the obtained parameters. A better approach would be to do a grid fitting with χ^2 minimisation, but with finer grids being calculated at each instance of minimisation check. This is one of the reasons why we use iSpec (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019) for our spectroscopic analysis. " I don't understand what is ment
- Page 47: "For the eclipsing systems, we kept the log g fixed as the values that we obtain from LC and RV modelling as the spectroscopic log g matched well but had lower precision. We kept the log g free for the tertiary spectra." -> I don't understand what is ment

Chapter 4: Written in the stars: Parameters to evolution and dynamics

In this paper, Moharana uses independent observational techniques (radial velocity measurements, broadening functions, spectral disentangling, spectroscopic analysis) to estimate the orbital, stellar, and atmospheric parameters of two triple-lined compact hierarchical triples. I've compiled a list of numerical methods used: TODCOR with synthetic spectra from ATLAS9, V2FIT, BF-RVPLOTTER, FDBINARY, PHOEBE2, iSPEC, Rebound, reboundx.

Remarks:
- Page 54: why are spots the most likely explanation for the distorted Broadening Functions? How do you know it is not a numerical artifact?
- Page 54: Info from the RV & BF methods are used as input for the spectral disentangling - but what if these values are wrong because the spectra are entangled?
- Page 55: how to errors propogate into the spectral analysis? What do you consider as the error on your radius & mass measurements?
- Page 59: Are the adopted tidal parameters appropriate for your stars?
- Page 60: different alphas for stars in the same system. What does that mean?
- Page 60: BD+44 component B is lower in mass but further evolved than component Aa. What does that imply?
- General question: How robust are the measured parameters? And would this change your outlook on the future evolution of the system?

Chapter 5: Three in a crowd: Distributions of CHT parameters

Chapter 5 is to be submitted to A&A. Moharana again uses an impressive set of methods, displaying an impressive gained skill set with a large variety of numerical codes (& probably programming languages) to determine the stellar, orbital and atmospheric parameters of four more compact hierarchical triples. Furthermore Moharana creates a sample of compact triples with these four systems, the prior two systems studied, supplemented by sources from the literature and aims to draw conclusions on a population level.

Remarks:
- Page 70: also mentioned elsewhere: “A special class of triple **stars,i.e.**, compact hierarchical triples (CHTs) have seen increased incidence rates which is surprising as they were considered rare before (Tokovinin 2004).” Are CHTs really more common or are you simply very efficient in finding them?
- Page 75: if you draw the conclusion that the stars are coeval, should the metallicity not be the same then as well?
- Page 82: (figure 5.2 on page 68). Why do the ogle and gaia samples find such different eccentricities? There must be strong selection effects here. What are they?
    - Given the strong selection effects, can you convince me that the metallicity dependence is real, and not just a consequence of the selection effects?
- figure 5.1, page 68: eccentricities peak ~0.2. Are there any selection effects as play here?

Summing up, I consider the doctoral thesis of Ayush Moharana to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation be admitted to a public defense.

Sincerely yours,

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