Kraków 22.07.2024

Referral of the PhD dissertation by Ayush Moharana

Title: **Comprehensive study of low-mass Compact Hierarchical Triples -using Eclipsing Binaries.**

The thesis is in the form of a book manuscript, comprising two published articles, one already supplemented for publication and description of the study and analysis performed by the author. The author estimates his contribution to the published and submitted papers to be between 60% and 70%. The thesis begins with an introductory chapter (**Chapter 1**) on the creation and evolution of binary and multiple systems, focusing on compact hierarchical triples (CHT). The chapter is well-written and provides comprehensive knowledge on these systems in a single booklet, supplemented with extensive literature references.

Chapter 2 describes the broadening functions, radial velocities, and eclipse timing variations methods used in the author's work. The author implemented a broadening function method to re-investigate eclipsing binary spectra, demonstrating its advantage over the cross-correlation method. The author claims to have discovered eight new CHTs using eclipsing binaries. However, the actual number is difficult to ascertain due to conflicting statements: Figure 2.2's caption (pg. 20) indicates that triangles are discoveries (one can see 8 triagles), while the text mentions four new and two previously discovered systems (see the paragph below the figure). Ultimately, the author lists all results (six stars) on page 94, though careful reading is required to distinguish new discoveries from re-analyzed systems. In the included publication Moharana et al. (2024), the authors present their search results for CHTs in the Solaris (4 robotic 0.5m telescopes in the Southern hemisphere) survey's photometric data. The authors focused on finding *Light Travel Time Effect* signatures in the eclipsing binary observations of the CHT candidates, using both archived and new photometric and radial velocity spectral data. As a result, they identified one possible CHT candidate (out of seven analyzed systems).

Chapter 3 presents a general approach to light curve and radial velocity modeling, as well as stellar and orbital parameter retrieval. The codes used for modeling include PHOEBE2 and JKTEBOP for detached systems and REBOUND for N-body simulations. The section on spectral disentangling (3.2.1) is a thorough introduction to spectra separation of multiple body systems, enriched with a robust bibliography and links to relevant codes.

Chapter 4 is in the form of a publication (Moharana et al. 2023, MNRAS, 521, 1908). It details the discovery and photometric/spectroscopic analysis of a new triple-lined triple CHT system and the first spectroscopic estimates for a known one. The authors obtained stellar, orbital, and atmospheric parameters for all stars within the systems, estimated the age and evolutionary stages of the components, and used N-body simulations to study system stability. Despite minor issues (see below), the paper is well-prepared and includes useful links to the codes used.

Chapter 5 describes outer component orbital eccentricities and mass distributions. The chapter includes a publication in submission, presenting the discovery of three new CHTs and analysis of one known. The author uses TESS light curves, radial velocity modeling, and spectral analysis to derive orbital and stellar system component parameters. Using known and newly found CHTs he estimates dependencies of tertiary mass ratio to the inner binary mass and outer orbit eccentricity. The conclusion suggests metal-poor stars have no preferred mass ratio, while solar- and above-metallicity systems, as well as older systems, have mass ratios around 0.5. I found Figure C.1 not very useful due to overlapping points and the inclusion of many parameters to watch. However, it does allow other researchers in the field to compare details of their model grids and results.

Chapter 6 summarizes the thesis, concluding Mr. Moharana's work. The thesis ends with an appendix and it is written on 115 pages.

While the thesis is well-written and presents interesting results, it contains minor issues, including excessive acronyms and ambiguous descriptions. In general, using acronyms is acceptable and common, however, the author has introduced so many that it sometimes makes the work difficult to follow. The acronyms force the reader to go back and forth between pages to recall their meanings. Here is an excerpt from pg. 42: *„The presence of a third body around a DEB manifests itself in variations of the ν_{com}. We can treat these variations and the tertiary's RV measurements (if ST3) as a binary system itself, with its own COM velocity: γ. This gives us more constraints on the orbital parameters of the third body. If we have a ST2 we can constrain the period, eccentricity and periastron longitude."*

Some acronyms were introduced more than once. I suggest to use less of them in future works. Other minor issues encountered during reading the thesis were noted throughout the chapters. Below one can find a few examples (answers are not required). Note that some of these issues might be subjective.

Chapter 1:

pg. 16. Fig. 1.11, caption: *"M1 is the primary and most massive star in the inner binary, M2 is the secondary and least massive star in the inner binary,"* - if the primary is the most massive star, then the secondary is less massive, making it unnecessary to describe it as the "least massive star".

Chapter 2:

sect. 4.2, the authors wrote: *"The best-ftting LC models for all the targets are shown in Fig. 1."* However, to determine the number of targets, one needs to count them in the figure.

Fig. 8. A reference to a non-existing table 5. (Should be table A1.).

pg. 19. *"CRÉME contains around 7000 spectra of over 300 low-mass (primary star mass of 0.3-7 $M_\odot$)".* I would consider all masses bertween 2.25-9 solar masses to be medium.

pg. 20. Fig. 2.2. What do the blue arrows in the figure represent? What are the units of the periods? This should be explained in the figure caption.

Chapter 3:

pg. 38. Under Fig. 3.1 there is a description of t_1, ... , t_4 marked on x axis. I wonder, why the eclipse durations δ_1, δ_2 and depth of minima ϵ_1, ϵ_2 are omitted from the figure. The text only refers to the "depth of the eclipse (ϵ)" without specifying ϵ_1, ϵ_2.

pg. 40: Markov chain Monte Carlo (MCMC) or Monte Carlo (MC)" - acronyms already introduced on pg 25.

Chapter 4:

pg. 52 col. 1, middle: *„The accuracy is robust and **in**dependent of different models and methods, even varying slightly due to different numerical implementations"* – perhaps the authors ment „dependendt"?

pg. 54: *„we only model only Sector-41 for KIC65"* – „only" x 2

Appendix:
Are the wavelengths given in the appendix tables A.1-A.2 in vacuum or in air? This should be stated for clarity.

The analysis of archival and new observational data enabled the author to discover new CHT systems and re-analyze a few known ones. The thesis provides a detailed description of the methods used and the studies conducted, leading to interesting conclusions about the spectral and dynamical evolution of these systems, as well as the statistical properties of CHTs based on age and metal abundances. However, there are some issues in the presented work that I would like to see addressed:

Chapter 2, sect. 4: *"Then we cleaned the short-term trends using a window sized between 1/6 and 1/2 of the EB period, depending on the scale of variations in each target."* What was the reason for cleaning short-term variations from the light curve? How were these short-term trends introduced?

Chapter 3: What were the typical errors for log g, R, and M retrieved from the disentangled spectra, and how were they estimated? Is it possible to estimate how does the error change when adding stars into the system (therefore into the spectra)?

Chapter 4: pg. 53, sect. 3.2: *„We modified a single-order BF code, BF-RVPLOTTER,3 to calculate multi-order BF and also fit the function with multiple Gaussian or rotation functions."* Could the author elaborate on the implemented stellar rotation function? Is it the same as the rotational profile described by Gray (2005)?

Chapter 4: Was the effect of third-body light on the depth of minima taken into account when fitting binary models?

Chapter 5: Are there any estimates on a number of compact hierarchical tertiary systems which are close to or in the common envelope phase (similar to TIC387107961, section 4.2 of the submitted paper)? Can the author estimate the fate of such systems?

Chapter 5: According to the author, the preliminary estimates for tertiary mass distributions show peaks around 0.4 and 0.9 (Figure 5.2), while I see the distribution peaks at 0.4 and 0.8 (or between 0.7-0.9) - see: gray "all CHTs" and green GAIA in the figure. Could the author comment on this?

Summary:
The thesis focuses on the search and study of compact hierarchical triplets. The work presents a detailed analysis of the light curves, O-Cs, ETVs, radial velocity curves, spectral analysis and data reduction (both photometric and spectroscopic). Mr. Moharana leverages recent sky surveys and space photometric/astrometric and spectral observations to derive stellar parameters and estimate the dynamical evolution (via orbital configurations) of compact triples. The author's understanding and implementation of complex software for modeling CHT demonstrates a high level of individual work. Despite minor issues, the thesis is valuable and showcases Mr. Moharana as a promising scientist.

Therefore, **I consider the doctoral thesis of Mr. Ayush Moharan 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.**

dr hab. Jerzy Krzesinski, prof. UJ