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Close, hierarchical triple star systems in the era of sky survey space telescopes

PhD thesis statements

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1. Scientific background

When it comes to stars, it is not uncommon for them to form binary or multiple star systems. In contrast to our Sun, which is a single star, when we examine our cosmic environment, approximately half of the stars with similar mass to our Sun are part of binary systems (Raghavan et al., 2010). In the case of binary star systems, the stars within them are gravitationally bound and orbit around a common center of mass. The motion of these systems can be described based on the principles of celestial mechanics, allowing us to determine physical properties of the stars that would not be possible or would be much less accurate in the case of single stars. Systems containing more than two stars can be even more interesting and useful for determining parameters. As soon as more than two stars are present in a system, it is important to consider that, over long periods, they cannot orbit in arbitrary paths but can only arrange themselves in hierarchical configurations. The essence of a hierarchical configuration is that if we select three stars in the system, one of them will always orbit much farther from the other two stars. If this condition were not met, the system would disintegrate due to dynamical perturbations in a short period of time. Systems containing more stars are rarer in our Galaxy, so the most common representatives of multiple systems are hierarchical triple star systems. Only one configuration is possible in these systems: two close stars orbit each other within the system forming a binary (referred to as the inner orbit), while a third component is located much farther away. The center of mass of the inner binary and the third component orbits around the total center of mass of the system, which is referred to as the outer orbit. In systems with a high number of stars, various configurations are possible. The evolution of hierarchical triple star systems can follow a very unique path due to the perturbing influence of the third component. During their evolution, hierarchical triple systems can become unstable and one of the stars may leave the system. This can explain some of the stars in our Milky Way that have a high proper motion, as they can be ejected rapidly from such systems due to dynamical effects (Toonen et al., 2022). In other cases, this can lead to stellar collisions, creating "blue stragglers". In rare cases, it can even trigger collisions of white dwarfs, leading to the formation of Type Ia supernovae.

One of the dynamical perturbation effects that play a role in creating close inner binaries is the KCTF-mechanism (Kozai Cycles with Tidal Friction), caused by the third component (Kiseleva et al., 1998). The essence of the mechanism is that when the mutual inclination value (the difference between the inclinations of the outer and inner orbits) reaches around 90 degrees, the eccentricity of the inner binary can increase significantly due to dynamical perturbation, causing the sizes of the inner orbits of the components to decrease significantly due to tidal friction. This process continues until the tidal forces prevent the mechanism from further reducing the size of the inner orbit. This phenomenon provides an opportunity for binary stars to become close not only at their formation but also at a later stage of their lives. Later, these systems can evolve into "blue stragglers" or contain compact objects (such as white dwarf or neutron star pairs). If the outer orbit's period is less than 1000 days, we can consider the system as a close hierarchical triple star system. In such systems, strong and observable dynamical effects are expected, providing a better understanding of these unique objects.

A rare subtype of hierarchical triple star systems is represented by those systems in which both the inner binary and the third component exhibit eclipses. The first such objects were discovered by two independent research groups in the same year, 2011: Carter et al. found the KOI-126 system, while Derekas et al. found the HD 181068 system. Both of these systems were discovered using data from the *Kepler* space telescope. The *Kepler* and later the *TESS* space telescopes are particularly suitable for identifying triply eclipsing hierarchical triple star systems. Thanks to these telescopes, we have access to ultraprecise photometric measurements with a high temporal resolution. Since eclipses of the third component occur relatively rarely, continuous long-term observations are necessary to detect these eclipses multiple times, thereby confirming the existence of the third component. The *Kepler* space telescope originally observed only a small portion of the sky, but it did so continuously for four years without significant interruptions. The *TESS* space telescope can observe the entire sky but typically observes each sky sector for only about a month before returning to the same area after about a year. Near the ecliptic poles, where the observing sectors overlap, even better temporal coverage of light curves is available. Most triple eclipsing hierarchical triple star systems have been discovered through the study of light curves measured by these two telescopes.

Despite their importance, we know relatively little about close hierarchical triple star systems; currently, there are a total of 394 systems. Tokovinin et al. (2018) compiled a catalog of multiple star systems (Multiple Star Catalog, MSC), which includes 201 such systems. After examining the data from the OGLE (Optical Gravitational Lensing Experiment; Udalski et al., 1992) survey in 2019, Hajdu et al. discovered 177 close hierarchical triple star systems, and in 2022, an additional 16 such systems were found by them. There are fewer than 50 triple eclipsing hierarchical triple star systems known in the literature. Therefore, research on these systems is currently at the forefront of astronomy, as a better understanding of these objects can benefit other branches of astronomy.

The latest sky survey space telescopes provide new opportunities for discovering such systems. The *Gaia* space telescope, launched in the winter of 2013, was designed to perform ultraprecise astrometry and parallax measurements on nearby stars, accurately determining the positions and distances of stars. In the third data release in 2022, it was examined for the first time whether the stars in the catalog could be members of binary systems. The *Gaia* Non-Single Star (NSS) catalog contains the orbital solutions of binary systems detected through astrometric, spectroscopic, and/or eclipsing methods.

2. Research methods

The orbital solutions of binary stars detected by *Gaia* have provided an opportunity to identify new triple systems. In the case of astrometric detection, the *Gaia* collaboration (Halbwachs et al., 2022) applied strong constraints to ensure data accuracy. Binary stars that *Gaia* intermittently observed as either separated or merged were excluded from further analysis, so only unresolved stars are included in the astrometric solutions. This means that hierarchical triple star systems can be found in the NSS catalog if *Gaia* detected the outer orbit of the hierarchical triple and determined its parameters. To search for these stars, I selected more than 1 million eclipsing binary stars from available catalogs and then searched for their *Gaia* NSS solutions. In cases where such a solution existed, I compared the orbital period value from *Gaia* NSS solutions to the period given in the eclipsing binary catalog. If the *Gaia* NSS solution's period was at least five times longer than the period of the eclipsing binary, I assumed that the NSS solution belongs to a more distant third component in the system. Using this approach, new hierarchical triple star systems could be discovered within *Gaia*'s data. Some of these triple star system candidates detected in this way were also observed by the *TESS* space telescope, allowing for independent confirmation from another source and verification through different methods. The production of light curves was performed by my advisor, Dr. Tibor Mitnyan, using the FITSH software package (Pál, 2012). After determining the eclipsing minimum times in the light curves from the *TESS* space telescope, I focused on examining Eclipse Timing Variations (ETVs). Changes in the period between eclipses can indicate the presence of a third component in the system. These changes can be apparent[1] or real. The Rømer effect, typically referred to as the Light Travel Time Effect (LTTE) in the field of triple systems, occurs when the eclipsing (inner) binary in the triple system orbits around the common center of mass, sometimes approaching and sometimes receding from the observer. As a result, the eclipses observable from Earth occur either earlier or later in time, respectively. For the systems I examined, the analytical formula of Irwin (1952) was sufficient to model the ETVs.

During a detailed examination of the *TESS* light curves, I found four previously unknown triply eclipsing hierarchical triple star systems. The complex photodynamical analysis of these systems was performed using the "LightcurveFactory" software package devel-

[1] caused by the finite speed of light and known as the Rømer effect

oped by my advisor, Dr. Tamás Borkovits (Borkovits et al., 2020a, 2022). This program is capable of conducting complex photodynamical analyses of triply eclipsing hierarchical triple star systems using the system's light curves and data from other sources. Within the program, it can be set whether the motion of stars in the hierarchical triple system is numerically integrated or if the program describes the inner and outer orbits with two Keplerian orbits when dynamical perturbations are negligible. The numerical calculations are based on a built-in seventh-order Runge-Kutta-Nyström integrator. The program searches for the parameter space and errors using a Markov Chain Monte Carlo (MCMC) algorithm, which explores the entire parameter space and can be used for error estimation as well. With the help of this software package, almost all of the system's most important stellar and orbital parameters can be determined. During my work, I numerically integrated the orbits, allowing me to investigate the dynamical perturbations in these systems as well.

3. Results

1. Using a completely new method not applied in the literature before, I identified previously unknown close hierarchical triple star systems. (Czavalinga et al., 2023a)

1.a. For objects found in multiple catalogs containing eclipsing binary stars, I searched for *Gaia* NSS solutions where the orbital period of the eclipsing binary was at least five times longer than the orbital period derived from *Gaia* NSS solutions. I assumed that the *Gaia* NSS catalog could contain hierarchical triple systems in which *Gaia* had determined parameters related to the outer orbit.

1.b. I identified a total of 403 close hierarchical triple star system candidate, of which 27 were previously known systems. The remaining 376 systems represent new discoveries, with 100 systems having purely spectroscopic solutions, 267 having astrometric solutions, and 31 stars having a combination of both in the *Gaia* NSS catalog.

1.c. I analyzed the distributions of the outer periods and eccentricities of the candidates and found that the distribution of outer eccentricities is similar to those of systems discovered by the *Kepler* and OGLE missions in the literature.

1.d. Through the analysis of Eclipse Timing Variations (ETVs) in the light curves from the *TESS* space telescope, I found nonlinear changes in 218 systems, confirming the presence of a third component. This significantly increased the number of known close hierarchical triple star systems.

1.e. Using the *Gaia* NSS database and *TESS* light curves, I discovered four previously unknown triply eclipsing hierarchical triple star systems.

I provided an assessment of the reliability of parameters for binary stars found in the *Gaia* NSS database for 22 hierarchical triple systems, using parameters derived from Light Travel Time Effect (LTTE) analysis. (Czavalinga et al., 2023a)

2.a. I performed LTTE analysis for 22 previously unknown hierarchical triple star systems and determined their outer periods, eccentricities, and their projected semi-major axes. This allowed me to evaluate the reliability of *Gaia* NSS parameters against parameters derived from the LTTE analysis, which had not been done with this type of independent method in the literature.

2.b. I found that the period is the most reliable parameter among the studied systems, as the period values from both methods showed very good agreement for all 22 hierarchical triple star systems.

2.c. Although eccentricities had larger uncertainties, they still showed good agreement within the error margins, making them relatively reliable as well.

2.d. In the case of the projected semi-major axes and periastron arguments derived from *Gaia* NSS catalog, I observed significant discrepancies, concluding that these parameters cannot be directly compared to similar parameters from the LTTE analysis due to methodological differences.

I conducted complex photodynamical analysis of the four triply eclipsing hierarchical triple star systems I discovered, using measurements from the *TESS* space telescope and archival ground-based sky surveys. (Czavalinga et al., 2023b)

3.a. I calculated the main orbital elements and stellar parameters for the systems TIC 14839347, TIC 66893949, TIC 88206187, and TIC 298714297, and determined the extent of dynamical perturbations caused by the third components.

3.b. In the case of TIC 14839347, I found that the secondary component could have filled its Roche lobe and transferred mass to the primary component. Due to the likelihood of past mass transfer, I could not use stellar evolutionary tracks in modeling, so I iteratively determined the main system parameters. I demonstrated that previous mass transfer is suggested by the fact that the third component has evolved off the main sequence while the primary, of similar mass, has not, implying that the primary may have been less massive initially. The mutual inclination differs from zero, suggesting that over time, dynamical effects can change the depth of eclipses.

3.c. I found that all three components in the system have masses similar to the Sun. The outer eccentricity was calculated to be 0.402, the highest among the studied systems. The mutual inclination is small, indicating limited dynamical perturbations.

3.d. The complex photodynamical analysis of the TIC 88206187 system revealed that the third component is a red giant, and it could eventually fill its Roche lobe and transfer mass to the inner binary. I found that significant tidal forces may be present in the system.

3.e. The analysis of the TIC 298714297 system, combined with parallax measurements from the *Gaia* space telescope, showed it to be one of the closest triply eclipsing hierarchical triple star systems. It contains K and F type stars with masses smaller than the Sun. Examination of the light curve indicated that the inner binary exhibits spot activity and flares. My analysis suggests that these features may originate from the primary component, indicating magnetic activity.

3.f. By comparing the parameters derived from photodynamical analysis with those from *Gaia* NSS solutions, I confirmed that photodynamical parameters are significantly more accurate. This allowed me to assess the expected accuracy of *Gaia* NSS parameters. I confirmed that the *Gaia* NSS inclinations and outer periods for these four systems were correct within the error margins. However, larger discrepancies were observed for eccentricities.

4. References

Borkovits, T., Mitnyan, T., Rappaport, S., et al., 2022, MNRAS, 510, 1

Borkovits, T., Rappaport, S., Hajdu, T., et al., 2020, MNRAS, 493, 4

Carter, J., Fabrycky, D., Ragozzine, D., et al., 2011, Science, 331, 6017

Derekas, A., Kiss, L., Borkovits, T., et al., 2011, Science, 332, 6026

Hajdu, T., Borkovits, T., Forgács-Dajka, E., et al., 2019, MNRAS, 485, 2

Hajdu, T., Borkovits, T., Forgács-Dajka, E., et al., 2022, MNRAS, 509, 1

Halbwachs, J., Pourbaix, D., Arenou, F., et al., 2023, A&A, 674, A9

Irwin, J., 1952, ApJ, 116, 211

Kiseleva, L., Eggleton, P., Mikkola, S., 1998, MNRAS, 300, 1

Pál, A., 2012, MNRAS, 421, 3

Raghavan, D., McAlister, H., Henry, T., et al., 2010, ApJS, 190, 1

Tokovinin, A., 2018, ApJS, 235, 1

Toonen, S., Boekholt, T., Portegies Zwart, S., 2022, A&A, 661, A61

5. Publications

Publications associated with the thesis

Refereed papers:

- Czavalinga, D. R., Mitnyan, T., Rappaport, S., Borkovits, T., Gagliano, R., Omohundro, M., Kristiansen, M., Pál, A.,: *New compact hierarchical triple system candidates identified using Gaia DR3*, 2023, Astronomy & Astrophysics, 670, A75

- Czavalinga, D. R., Borkovits, T., Mitnyan, T., Rappaport, S., Pál, A.,: Four New Compact *Triply Eclipsing Triples found with Gaia and TESS*, 2023, Monthly Notices of the Royal Astronomical Society, accepted

Other matters related to the topic of the thesis

Refereed papers:

- Rappaport, S., Borkovits, T., Gagliano, R., Jacobs, T., Tokovinin, A., Mitnyan, T., Komžík, R., Kostov, V., Powell, B., Torres, G., Terentev, I., Omohundro, M., Pribulla, T., Vanderburg, A., Kristiansen, M., Latham, D., Schwengeler, H., LaCourse, D., Bíró, I., Csányi, I., Czavalinga, D. R., Garai, Z., Pál, A., Rodriguez, J., Stevens, D.,: *A study of nine compact triply eclipsing triples*, 2023, Monthly Notices of the Royal Astronomical Society, 521, 1

- Borkovits, T., Mitnyan, T., Rappaport, S., Pribulla, T., Powell, B., Kostov, V., Bíró, I., Csányi, I., Garai, Z., Gary, B., Kaye, T., Komžík, R., Terentev, I., Omohundro, M., Gagliano, R., Jacobs, T., Kristiansen, M., LaCourse, D., Schwengeler, H., Czavalinga, D. R., Seli, B., Huang, C., Pál, A., Vanderburg, A., Rodriguez, J., Stevens, D.,: *Triply eclipsing triple stars in the northern TESS fields: TICs 193993801, 388459317, and 52041148*, 2022, Monthly Notices of the Royal Astronomical Society, 510, 1

- Korth, J., Moharana, A., Pešta, M., Czavalinga, D. R., Conroy, K.,: *Consequences of parameterization choice on eclipsing binary light curve solutions*, 2021, Contributions of the Astronomical Observatory Skalnate Pleso, 51, 1

Conference talks:

- Czavalinga D. R.: *Photometric examination of NGC2281 open cluster* – KOLOS 2017, 7-9 December 2017, Stakcin, Slovakia

- Czavalinga D. R.: *The effect of unresolved binaries in the colour-magnitude diagram of open clusters*, International meeting on variable stars research – KOLOS 2019, 5-7 December 2019, Stakcin, Slovakia

- Czavalinga D. R.: *Newly identified compact hierarchical triple system candidates using Gaia DR3* - APRIM2023, Asia-Pacific Regional IAU Meeting 2023, 7-11 August 2023, Koriyama, Japan