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Photometric and spectroscopic study of contact binaries and analysis of the triple system TIC 278825952

PhD thesis statements

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Scientific background

In our nearby cosmic environment, at least half of the stars belong to binary or multiple systems. Due to different effects between the components (e.g. orbital revolution around the mass center, periodic eclipsing events in case of appropriate inclination, dynamical interactions), there are several observational constraints that allow the determination of the main physical parameters of these systems (e.g. mass, radius, effective temperature, etc.) that can not or only be determined by limitations in case of single stars. Nevertheless, these parameters are essential in order to fine-tune star formation and stellar evolution theories, and the theoretical models of physical processes occurring on and between these stars. Thus, studying binary and multiple stellar systems still belongs to the most fundamental areas of astronomy.

Systems that show periodic brightness variations because of eclipses between the components during their orbital revolution around their mass center play a crucial role in these analyses. Combining photometric and spectroscopic observations, the eclipses allow the determination of all of the physical and orbital parameters of the components with high precision.

Contact binaries are the most special subtype of eclipsing binaries, and the main part of my research focused on these systems. There are still no complete theories regarding the formation and evolution of contact binaries, that could explain all observable properties of these systems. According to the most accepted model (Lucy 1968), contact binaries basically consist of two main sequence stars with F, G, K spectral type that are filling their Roche lobes and making physical contact with each other. Moreover, they have a common convective envelope that allows energy and mass transfer between them causing a thermal equilibrium state. This geometrical configuration means that the shape of the stars become distorted due to the strong tidal forces and their rotation synchronized with the orbital revolution with a period shorter than 1 day. Their light curves have a nearly sinusoidal shape, but there could be differences between the maximum or minimum values during a full orbital phase. Based on the light-curve minima, contact binaries can be divided into two sub-groups: in case of A-type systems, during the primary minimum the primary component is the one that is eclipsed, while for the W-types, it is the secondary (Binnendijk 1965, 1970). The most probable explanation for the existence of these subtypes is the photospheric (magnetic) activity of the components (Mullan 1975).

Magnetic activity is a property of stars that we do not fully understand even in the case of our Sun; however, it is one of the most important processes that can be observed in most contact binaries. Its study can give information about the inner structure and mechanisms of stars similar to the Sun; moreover, it can bring us closer in the understanding of formation and evolution of contact binaries. The photospheric activity ((in a form of stellar spots)) is mostly detectable through its distorting effects on the light curves and spectral lines of these objects, while the chromospheric activity can be observed mostly through the emission excess in the spectral lines formed by multiply ionized elements in the outer layers of the stellar atmospheres. There is only a few studies in the literature about the possible links between different types of activity (and, especially, the role of the chromospheric activity in case of contact binaries). In their study on VW Cephei, Kaszás et al. (1998) found that the photospheric and chromospheric activity of the system mainly originates from the primary component and there is a possible connection between them. Rucinski (1985), based on the emission excess of 15 contact binaries measured in low resolution ultraviolet spectra, found that the level of chromospheric activity correlates with several physical parameters of these systems like the orbital period, the B–V color index, and the logarithm of the inverse Rossby number. Barden (1985) made similar observations concerning the level of chromospheric activity detected in the optical regime based on the emission excess measured in the Hα line of a much smaller sample of four objects. The main motivation of the first part of my research was to confirm the suggestions of Kaszás et al. (1998) based on own photometric and spectroscopic observations. The other part of my work was to extend the study of Barden (1985) focusing on the correlations between the level of the chromospheric activity detected in the optical regime and the physical parameters of contact binaries based on own spectroscopic measurements.

In the last part of my research, I performed the complex analysis of TIC 278825952, a cataloged but previously unstudied eclipsing binary. The motivation behind this study was that the *TESS* space telescope obtained an almost 1-year-long, ultraprecise photometric data set about it. During its analysis, I found such extra eclipsing events that are caused by a third star in the system revolving on a much wider orbit. To date, we only know a handful of this kind of triply eclipsing hierarchical triple systems, because, in order to discover them, the stars have to revolve almost in the same orbital planes. On the other hand, we also need sufficient observational data with appropriate length, temporal resolution, and precision. Nevertheless, these systems play an important role in astrophysics because of the possibility of precise stellar parameter determination and the analysis of possible dynamical interactions between the components. Thus, they serve as a natural laboratory for star formation and stellar evolution theories.

Research methods

For the reduction of photometric and spectroscopic data of contact binaries, I used the appropriate routines of the `IRAF`[1] and the `iSpec` (Blanco-Cuaresma et al. 2014, Blanco-

[1] http://iraf.noao.edu

Cuaresma 2019) software packages. I applied the cross-correlation technique for measuring the radial velocities of the components on the reduced spectra; this is based on shifting the observed spectra along a radial velocity standard spectrum and determining the degree of this shift where these spectra match the best. This way we get a cross-correlation function (CCF) with peaks that belong to the components detected in the system. I fit these peaks with the sum of the necessary number of Gaussians and identified the radial velocities of the components by the location of maxima of the fitted Gaussians. In order to refine the different physical parameters of the systems, I modeled the radial velocity curves using the 1.0 version of the `PHOEBE` code (Prsa & Zwitter 2005).

In the case of VW Cephei, beside the radial velocity curve, multi-color light curves were also observed, hence, for this object, I simultaneously fitted these with `PHOEBE` models. The latest similar study in the literature on the system was performed by Kaszás et al. (1998). While the method of deriving the radial velocities is the same for the two study, there are several important differences: the signal-to-noise ratio of the spectra obtained by Kaszás et al. (1998) is 2-3 times higher than my spectra, nevertheless, the spectral resolving power of the spectrograph I used is better and I could also use significantly longer ($\sim$7 times) useful wavelength range than them. In order to fit the light curves well, I had to assume two cold spots on the surface of the primary component.

After that, I fit the observed spectra of all objects with synthetic spectra. In order to produce synthetic spectra, I assumed that the composite spectrum of the components can be described with one rotationally broadened spectrum with well-chosen effective temperature because of the near thermal equilibrium. I calculated theoretical rotational broadening functions for every observed orbital phases with the `WUMA4` program (Rucinski 1973) and then convolved them with `ATLAS9` (Kurucz 1993) and `MARCS.GES` (Gustafsson et al. 2008) model atmospheres using different temperatures beside solar surface gravity and metallicity values. In several sytems, spectral lines of a third component appeared in the observed spectra; in these cases, I added an additional model atmosphere broadened with a Gaussian with with an FWHM of of the transmission function of the spectrograph to the model of the contact components assuming a reasonable flux ratio. I fitted these synthetic spectra to the regions outside of the Hα line of the observed spectra. Finally, I subtracted the best-fit synthetic spectra from the observed ones and I measured the equivalent width of the residual Hα profile on the residual spectra that I identified as the level of the chromospheric activity. This way, I could analyze the phase-dependent variations of the chromospheric activity for all the 13 systems and plot the equivalent widths (EWs) in the function of orbital phase. In the end, I averaged the EWs in case of every object and searched possible correlations between the mean chromospheric activity level and the physical parameters of the systems.

In the case of TIC 278825952, after downloading the calibrated Full-Frame Images (FFI) obtained by *TESS* from the MAST portal[2], I applied convolution-based image subtraction photometry using the *fitess* server operated by András Pál with his automatic image reduction pipeline based on the `FITSH` program (Pál 2012). I supplemented the resulting *TESS* light curve with archive, ground-based observational data thanks to P. F. L. Maxted and determined the eclipse timing variations of the inner binary from these light curves. Moreover, I collected cataloged passband magnitudes of different sky surveys in order to produce the spectral energy distribution (SED) of the system. After that, I simultaneously fitted the light curves, the eclipse timing variations and the SED with the `LIGHTCURVEFACTORY` program (Borkovits et al. 2013, 2019, 2020a,b). In the lack of radial velocity curves, I determined the mass of the components during each iterations with the use of theoretical `PARSEC` isochrones (Bressan et al. 2012). As the result of this comprehensive analysis, I determined all important physical parameters of the system (first time in the literature) anddrew conclusions on the formation and evolution of the system.

Results

1. I performed a complex physical analysis of VW Cephei based on own photometric and spectroscopic observations. (Mitnyan et al. 2018)

1.a. After the data reduction, I refined the physical parameters of the system modeling the light and radial velocity curves simultaneously. My newly determined parameters are mostly consistent with the results of the latest similar study of Kaszás et al. (1998). The mass ratio derived from my models (q=0,302±0,007) is slightly lower than the one found in the previous study (q=0,35±0,01), nevertheless, the results from the new observations are believed to be more reliable. In the best-fit models, cold spots appear on the surface of the opposite sides of the primary component, which is consistent with the model of Holzwarth & Schüssler (2003) based on theoretical considerations.

1.b. I measured the EWs of the residual Hα profile after fitting and subtracting synthetic models from the observed spectra. I plotted the measured EWs versus orbital phase, thus I could analyze the phase-dependent variations of the chromospheric activity. Based on this plot, I showed that chromospheric activity has maxima in those orbital phases where the spots in the light curve models point directly towards us. This is also well-illustrated on the residual after subtracting spotless model light curves from the observed light curves that has a fully consistent variation with EWs. Thus, I showed that there is a correlation between the phase-dependent variations of the photospheric and

[2] https://mast.stsci.edu

chromospheric activity.

1.c. To date, there is only one contact binary for which the flip-flop phenomenon had been directly detected (HH UMa, Wang et al. 2015). Based on the spot configuration in my light curve models combined with the seasonal light curves of VW Cephei, I proposed that VW Cephei might also show the signs of the flip-flop phenomenon. At the same time, it should be noted that the length of the available data is too short compared to the timescale of this effect, hence, in order to confirm this hypothesis, additional (long-term and regular) observations are needed.

2. I studied the chromospheric activity measured in the hydrogen Balmer-alpha line in the case of 12 additional contact binaries based on new spectroscopic observations. (Mitnyan et al. 2020a)

2.a. In the case of 10 objects, I detected the occurrence and short-term variations of the chromospheric activity for the first time, while for the remaining two systems (SW Lac, HX Uma), I confirmed the previous observations regarding their activity.

2.b. According to my results, these systems can be divided into three separate groups by the temporal variations of their EWs: i) the EWs do not change significantly during the orbital revolution; ii) the EWs show maximum in a specific orbital phase; iii) the EWs show maxima in two different orbital phases.

2.c. Based on the correlation between photospheric and chromospheric activity observed in the case of VW Cephei, I suggested that the other systems may have a similar behavior, hence, different spot configurations could explain the existence of these three groups. In the order written above: i) no significant spot activity, or the spots are distributed equally on the surfaces of the binary components; ii) there is a dominant spot (or a spot group) in a specific orbital phase; iii) there are dominant spots (or spot groups) in two different orbital phases on the surface of the active component.

3. I studied the connection between the chromospheric activity measured in the optical regime and the physical parameters of contact binaries on the largest sample to date. (Mitnyan et al. 2020a)

3.a. There are 9 objects out of 13 in my sample that follow the same correlations found by Rucinski (1985) and Barden (1985) in the UV and in the optical regime, respectively, regarding the B–V color index, the orbital period and the logarithm of the inverse Rossby number. Nevertheless, there are 4 (A-type) outlier objects that show unexpectedly large equivalent widths and do not follow these correlations. These systems all have similar properties: relatively long orbital period (slower rotation) and small B–V color index (higher effective temperature). According to earlier studies, strong magnetic activity is unusual in such hotter and slowly-rotating stars, thus I suggested that, for these outlier objects, the chromospheric activity may only be partly responsible for the observed emission excess in the Hα line.

3.b. For the 9 objects mentioned above, there is some kind of a correlation, in the case of the following parameters: B–V color index, orbital period, logarithm of the inverse Rossby number and temperature difference of the components. This is consistent with the preliminary results found by Rucinski (1985) and Barden (1985, studying only 4 objects). I also analyzed the connection of the chromospheric activity with respect to some other physical parameters (mass ratio, fill-out factor, inclination), but, for these, I had not found such correlations.

3.c. In the case of the 9 objects mentioned in 3.a., both A- and W-type contact binaries show the same correlations for all physical parameters. Comparison between these two large subtypes of contact binaries in this aspect have not been published earlier in the literature.

4. I performed the complex physical modeling of the eclipsing system, TIC 278825952, based on a nearly 1-year-long ultraprecise photometric data set obtained by the *TESS* space telescope, on archive ground-based optical light curves, and on data collected from different catalogs. (Mitnyan et al. 2020b)

4.a. Based on extra eclipses seen on the *TESS* light curve, and the eclipse timing variations determined from the *TESS* and ground-based observations, I showed that while this system previously was cataloged as an eclipsing binary, in fact, it is a triply eclipsing triple system.

4.b. I simultaneously modeled the *TESS* and ground-based light curves, the eclipse timing variations derived from them, and SED of the system. As a result, I determined the astrophysical and orbital parameters of all three components in the system. In the lack of radial velocity data, I derived the mass of the components from theoretical stellar isochrones.

4.c. The mutual inclination of the inner and outer orbit shows that the system is flat, moreover, both orbits are circular. While, for the tighter inner orbit, this is not unusual for a system at such an age, for the outer orbit, this is not expected based on earlier observations. There is only one such object known in the literature (HD 181068, Borkovits et al. 2013); nevertheless, in this system, a red giant with larger mass and radius than that of the inner components was found in the outer orbit, which can be a good explanation for the circularization of the outer orbit because of the stronger tidal forces, or ongoing mass transfer, or mass loss. However, in the case of TIC 278825952, I did not find any similar physical processes that could be responsible for the circularization of the outer orbit, thus I suggested that it represents its primordial configuration.

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Publications

Publications associated with the thesis

Refereed papers:

- **Mitnyan T.**, Bódi A., Szalai T., Vinkó J., Szatmáry K., Borkovits T., Bíró I. B., Hegedüs T., Vida K., Pál A.: *The contact binary VW Cephei revisited: surface activity and period variation*, 2018, Astronomy and Astrophysics, 612, A91
- **Mitnyan T.**, Szalai T., Bódi A., Kriskovics L., Vida K., Cseh B., Hanyecz O., Ordasi A., Pál A., Vinkó J.: *Chromospheric activity in bright contact binary stars*, 2020, Astronomy and Astrophysics, 635, A89
- **Mitnyan T.**, Borkovits T., Rappaport S. A., Pál A., Maxted P. F. L.: *TIC 278825952: a triply eclipsing hierarchical triple system with the most intrinsically circular outer orbit*, 2020, Monthly Notices of the Royal Astronomical Society, accepted

Other matters related to the topic of the thesis

Refereed papers:

- Borkovits, T., Rappaport, S. A., Hajdu, T., Maxted, P. F. L., Pál, A., Forgács-Dajka, E., Klagyivik, P., **Mitnyan, T.**: *TICs 167692429 and 220397947: the first compact hierarchical triple stars discovered with TESS*, 2020, MNRAS, 493, 5005
- Borkovits, T., Rappaport, S. A., Tan, T. G., Gagliano, R., Jacobs, T., Huang, X., **Mitnyan, T.**, Hambsch, F. -J., Kaye, T., Maxted, P. F. L., Pál, A., Schmitt, A. R.: *The compact triply eclipsing triple star TIC 209409435 discovered with TESS*, 2020, MNRAS, 496, 4624

Conference talks:

- **Mitnyan, T.**: *The contact binary VW Cephei revisited: surface activity and period variation*, International meeting on variable stars research – KOLOS 2017, 7-9 December 2017, Stakcin, Slovakia
- **Mitnyan, T.**: *Correlations between chromospheric activity and physical parameters of contact binary stars*, International meeting on variable stars research – KOLOS 2018, 6-8 December 2018, Stakcin, Slovakia
- **Mitnyan, T.**: *Correlations between chromospheric activity and physical parameters of contact binary stars*, Joint Conference of the Sub-Regional European Astronomical Committee and the Bulgarian Astronomical Society, 4-8 June 2019., Sofia, Bulgaria

- **Mitnyan, T.**: *Chromospheric activity of some bright contact binary stars*, Universe of binaries, binaries in the Universe, 7-11 September 2019, Telc, Czech Republic

- **Mitnyan, T.**: *Chromospheric activity of some bright contact binary stars*, International meeting on variable stars research – KOLOS 2019, 5-7 December 2019, Stakcin, Slovakia

Seminar talk:

- **Mitnyan, T.**: *Correlations between chromospheric activity and physical parameters of contact binary stars*, 15 January 2018, Bulgarian Academy of Science, Sofia, Bulgaria

Conference poster:

- **Mitnyan, T.**, Borkovits, T.: *Complex photodynamical analysis of the close hierarchical triple systems KIC 6525196 and KIC 8043961*, The Impact of Binaries on Stellar Evolution, 3-7 June 2017, Garching bei München, Germany