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OBSERVATIONAL STUDIES OF CLOSE BINARY STARS

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Abstract. The Stellar Physics Group at Astronomical Observatory of Belgrade conducts observational studies at the forefront of binary star research with the aim to improve understanding and modeling of complex physical processes within close, interacting binaries on both ends of the stellar mass scale. On the intermediate to high mass end, we study double-periodic variables – close binaries featuring accretion disks, gas streams and various circumbinary structures, characterized by two strongly correlated photometric periodicities; on the low mass end, we study W UMa contact binaries as well as semi-detached and detached binaries in pre- and post-common-envelope stages of evolution. In this review, I will showcase some of our recent results and publications, and present our plans to enter the scene of automated processing of massive data sets using machine learning and advanced model optimization methods.

1. INTRODUCTION

The Stellar Physics Group at Astronomical Observatory of Belgrade is a government-funded research unit, or project, coordinating the work of several smaller groups in different areas of stellar physics. These areas include the observational studies of close binary stars, the theory and numerical methods related to the problem of radiation transfer and spectral synthesis (recently including transfer of polarized radiation), and the studies of stellar rotation and stellar oscillations in single and binary stars. This review will focus on the observational studies of close binary stars.

In this section, I will enumerate some reasons why studying binary stars is still interesting, challenging, and necessary to support other fields of astrophysics. Next, I will describe the typical process of characterization of an individual binary star. Within our group, this is done using software tools that we develop and maintain ourselves. These will be the subject of the Section 2.

In Sections 3 and 4, I will turn to the two subjects that our group has recently been focused on: the double-periodic variables – close binaries in the stage of active mass transfer through an accretion disk, with many poorly understood observational characteristics; and contact binaries of the W UMa type.

Dealing with both these topics, we witnessed the need to develop procedures for automated processing of massive data sets. I will conclude the review by describing our first steps in that direction, related to applications of machine learning and advanced model optimization techniques in automated analysis of binary star observations from ongoing and future space- and ground-base surveys.

1. 1. WHY ARE WE STILL INTERESTED IN BINARY STARS?

The fraction of stars with one or more companions is above 50% for solar type stars, and above 80% for O and B type stars (see ee.g. Duchêne & Kraus, 2013). Stellar multiplicity is obviously an omnipresent outcome of star formation. Knowledge of the frequency and main properties of binary and multiple stars, and the dependence of these properties on the environment, are powerful tools to probe the process of star formation.

Binary stars remain the most reliable source of precisely determined stellar masses and radii (Stassun & Torres, 2016). With the instrumental and analytical advances made during the past decades – like the advent of space telescopes and all-sky surveys, as well as advances in automated analysis – the census of binary and multiple stars has increased (and keeps increasing) by orders of magnitude. Our ability to reliably estimate the orbital and stellar parameters of this growing sample and construct distributions of these parameters is key for many population synthesis studies (see e.g. Abate et al. 2015, Anderson et al. 2016).

Those same instrumental and analytical advances showed us that there are still new discoveries to be made within this old and well-established field. Previously unknown phenomena, such as heartbeat stars (Barclay et al. 2012) and double-periodic variables (Mennickent, 2017) have been discovered in the past few decades thanks to ultra-precise space-based photometry and long-term survey data.

1. 2. SOLVING INDIVIDUAL BINARIES

The contribution of our group to the studies of binary stars is in analyzing, or as it's customary to say, "solving" individual objects.

The first step in this process is to gather observational data. We work first and foremost with multicolor CCD photometric observations, or light curves, folded in phases according to the orbital period (see Figure 1). For a complete characterization of most binary stars, it is also necessary to observe them spectroscopically and construct radial velocity curves. Radial velocity curves can be fitted with a simple Keplerian two-body model to determine with good precision the mass ratio, eccentricity and maximum separation of the stars, all of which are key for measuring the masses and sizes of the components in Solar units.

With mass ratio and orbital separation fixed, we typically proceed to construct a detailed mathematical model of the system. By fitting the synthetic light curves calculated from the model to the observations, we can determine the other important orbital and stellar parameters of the system, such as the orbital inclination, temperatures of the stars, their masses and sizes. A more detailed look at the model follows in the next section.

In the three decades since the founder of our group, dr Gojko Djurašević, started to work in the field of binary stars, we have published the results of analysis for more than 85 individual binary stars in more than 50 research papers. And most of this work was done using software tools that we develop and maintain ourselves.

2. OUR MODELING SOFTWARE

The binary system modeling software that we use the most in day to day research was created by dr Gojko Djurasevic in the nineties (Djurašević, 1992a; Djurašević et

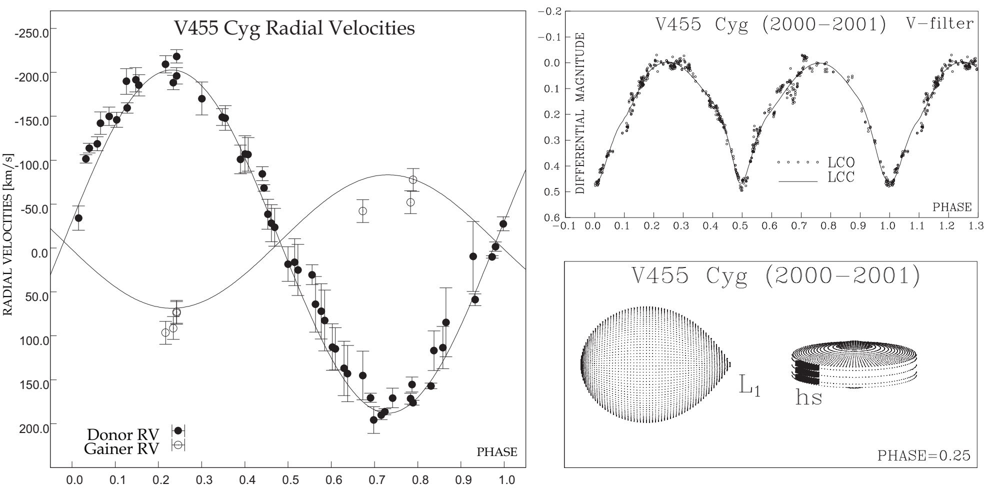

Figure 1: Radial velocities (left), light curve (top right) and geometric configuration (bottom right) of V455 Cyg, a massive, close binary with a geometrically and optically thick accretion disk that completely obscures the gainer. Points indicate observations, and solid lines represent the model. From Djurašević et al. (2012).

al. 1998). It is based on the Roche model, promoted in studies of binary stars by Kopal (1959). Initially the software was not principally different from the popular Willson-Devinney code (Wilson & Devinney, 1971). However, it has been in constant development since its inception, and presently has several unique capabilities, among which the ability to model accretion disks around one of the system components has proven to be the most sought-after feature in various collaborations. Another important feature of this software is its speed in solving the direct problem (constructing synthetic observables such as light curves based on given parameters) and the inverse problem (estimating parameter values by optimizing the fit of the synthetic observables to actual observations). Created during an era when every numerical operation was precious, this software is remarkably well optimized and executes in milliseconds on modern desktop computers.

Recently we made an effort to modernize the model and re-implement it as a new software tool called *Infinity* (Latković & Cséki, 2014). While based on the same principles as the original model, *Infinity* differs from it in several key points. It allows simultaneous fitting of light and radial-velocity curves, modeling of eccentric systems and modeling non-radial stellar oscillations on the components. These and other generalizations and improvements came at the cost of speed, however, and the original software remains our go-to modeling tool in most applications.

Some other directions in which we would like to expand the capabilities of our modeling are: modeling of various additional system components, such as the gas stream feeding into the accretion disk or falling directly onto the gainer; modeling of circumbinary structures, such as disks of escaped or infalling material. We would also like to add synthetic spectra and polarized light curves to the outputs of the model. These improvements require the combined expertise of the whole Stellar Physics Group and will be a part of our planned proposal for the next round of government funding.

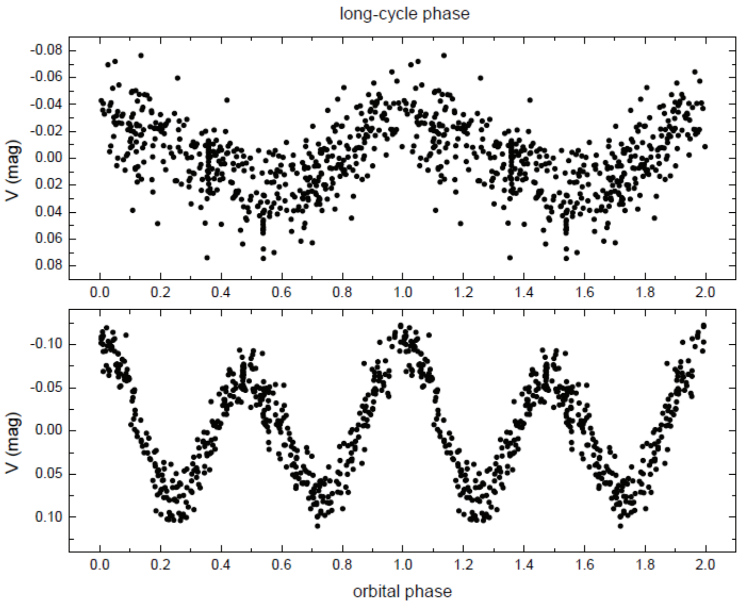

Figure 2: Disentangled ASAS light curves of the double-periodic variable HD 170582 folded with the long period (top) and the orbital period (bottom). From Mennickent et al. (2015).

Now I move on to the overview of two research topics that most of our recent work has been focused on: double-periodic variables, and contact binaries of W UMa type.

3. DOUBLE-PERIODIC VARIABLES

Double-periodic variables (DPV) are a recently discovered group of interacting binaries whose identifying characteristic is the existence of two photometric periodicities. The shorter periodicity, of the order of days, is due to the orbital motion of the two stars and in most cases it's easily recognizable from the eclipses or the ellipsoidal variation.

The longer periodicity, of the order of hundreds of days, is roughly 33 times longer than the orbital period for all discovered double-periodic variables and its origin has not yet been definitively established. Figure 2 shows the disentangled light curves of the double-periodic variable HD 170582 folded according to the orbital and long period.

Since their discovery it has gradually become clear that double-periodic variables are semidetached Algol type binaries of intermediate to high mass and low mass ratio; all the individually analyzed cases have proven to be in a phase of active mass transfer through an optically and geometrically thick accretion disk around the more massive star. Additional system components, such as the gas stream, a hot spot where the gas stream meets the accretion disk, winds or jets from the hot spot, have been detected in some of the well-studied systems. Our binary system model was crucial in establishing these properties of DPVs (Mennickent et al. 2012; Garrido et al. 2013; Mennickent et al. 2015; Garrido et al. 2016).

About 200 double-periodic variables have been detected in the Magellanic Clouds and of about 20 in our Galaxy. The number of known Algol type semidetached binaries is about 400, which suggests that the DPV phenomenon is a relatively long-lasting stage in the lifetime of a close binary. Yet there remains much about them that remains unexplained, such as the constancy of orbital period despite the active mass transfer, absence of chromospheric emission related to magnetic activity expected from the donor, and finally, the long cycle itself (Mennickent, 2017).

Several hypotheses have been explored in the attempts to explain the long cycle, and specifically, its enigmatic linear dependence on the orbital cycle. The latest, and the most promising, is that the long cycle is related to the magnetic activity of the donor star. Internal magnetic field can affect the structure and the shape of a star, and cause cyclic changes of the orbital period through spin-orbit coupling. This phenomenon is known as the Applegate mechanism (Applegate, 1992) and has been detected in many close binaries. In the case of double-periodic variables, the variation in the shape of the donor, specifically the increase in oblateness due to the Applegate mechanism, is suspected to cause periodic phases of enhanced mass transfer, which would lead to cycles of brightening and attenuation of the accretion disk and the hot spot, and create the long cycle (Schleicher & Mennickent, 2017). Although this theory awaits confirmation from studies of magnetic fields in double-periodic variables, the initial comparison of predicted and observed ratio of long orbital period from the orbital period looks satisfactory.

4. CONTACT BINARIES OF W UMA TYPE

W UMa stars are low mass, low temperature, short period contact binaries in one of the most extreme and least understood stages of binary evolution. Components of a close binary system may come in contact when the more massive (and thus more quickly evolving) star fills its Roche lobe during its normal post main sequence expansion, and deposits a large amount of material on its companion, which then in turn fills its own Roche lobe, so that a common envelope is formed. This stage binary of evolution follows the mass transfer phase such as we have with double-periodic variables (Yakut & Eggleton, 2005; Eggleton, 2006).

Light curves of W UMa stars are distinguished by continuous changes in brightness resulting from ellipsoidal variation, minima of nearly equal depths, and maxima that are not always symmetric due to the presence of dark spots that arise from magnetic activity typical for late type stars (see Figure 3). Many of these systems have variable orbital periods, either due to the action of the Applegate mechanism, or to the whole system being a component of a wider binary.

Among other properties that make W UMa stars attractive subjects for photometric studies, such as the short orbital period which means it is possible to observe the entire light curve in only a few nights, and the existence of a period-luminosity relation that makes them a useful distance indicator (Rucinski, 2004), possibly the most interesting is that their mass ratios can be inferred even in the absence of complementary spectroscopic data (Terrell & Wilson, 2005). This is a trivial consequence of the Roche geometry: in a contact system, both components are bounded by the same equipotential surface of the combined gravitational and rotational potential, and its shape is a function of the mass ratio.

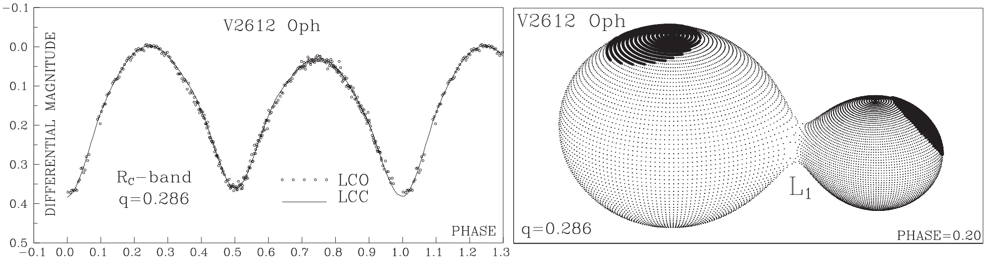

Figure 3: Light curve (left), and the geometrical configuration (right) of the spotted W UMa contact binary V2612 Oph. Points indicate observations, and solid lines represent the model. From Çalışkan et al. (2014).

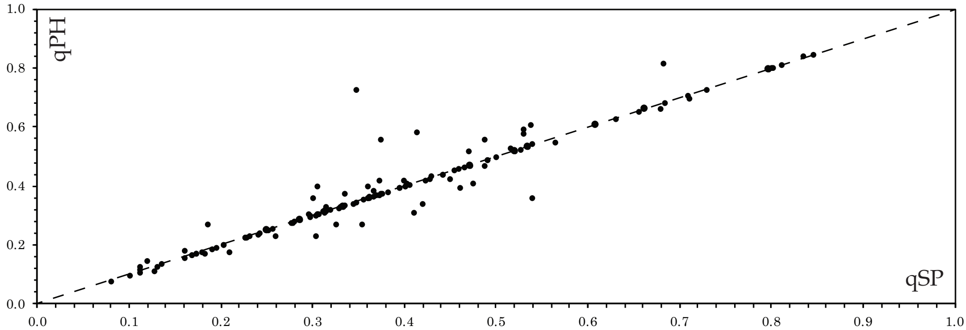

Figure 4: Relation of spectroscopically (qSP) and photometrically (qPH) determined mass ratios for a sample of around 100 well-studied W UMa stars. The dashed line indicates equality. The sample is discussed in Djurašević et al. (2016).

In terms of observables, the mass ratio of contact binaries can be estimated from the ratio of radii, which are measurable from the light curves. Mass ratios determined this way are most reliable for systems exhibiting total eclipses, but can be estimated regardless of inclination as long as the eclipses are present. Figure 4 shows a sample of about 100 well-studied W UMa stars with mass ratios determined both from spectroscopy and from photometry. Apart from several outliers, the photometric estimates typically do not deviate far from the spectroscopic measurements. The importance of this lies in the possibility to reliably characterize a contact binary from photometry only, a trait that earns contact binaries a special status in the context of amassing of unprocessed photometric data.

5. LOOKING FORWARD: AUTOMATED ANALYSIS

The volume of data already at the disposal of the binary star community is constantly increasing thanks to ongoing and future space missions and sky surveys. It has become obvious even before the advent of Kepler space telescope that studying individual objects "by hand" cannot keep up with the data accumulation rate.

And the community has been working out automated approaches. In their seminal work, the Kepler eclipsing binaries team used machine learning to automatically classify and derive basic parameters for the 3000 binaries in Kepler catalogue by fitting the light curves with parametrized chained polynomials (Prša et al. 2011). However, much of the work to make that result possible, such as fine-tuning the ephemerides, was still done by hand; and all the additions to the catalogue, from later quarters of the Kepler main mission and from the K2 mission, were also partly processed by hand (Kirk et al. 2016). A more recent example of successful automation is the work of Lee (2015a; 2015b), who used a simplified but fast-to-compute physical binary system model for automated light curve analysis of more than 3000 detached binaries identified in several surveys.

5. 1. AUTOMATED LIGHT CURVE ANALYSIS OF W UMA STARS

We plan to do something similar with W UMa stars identified in various light curve repositories. Where variability classification and a reliable orbital period are already provided, we can use our binary system model for automatic analysis.

Together with colleagues from the Mathematical Institute of the Serbian Academy of Sciences, we are developing a heuristic model optimization scheme that will be fast enough to process thousands of light curves, and at the same time robust enough to provide the most likely model parameters. Software tools for modeling binary stars solve the inverse probelm by minimizing the sum of squared residuals between the observations and model outputs; traditionally, this is done using the "greedy" optimization algorithms such as the gradient descent, implemented as part of the Willson-Devinney code (Wilson & Devinney, 1971), or the Marquardt-Levenberg method, implemented as part of our own modeling software (Djurašević, 1992b), that quickly converge to the closest local minimum which might not be the only or the best solution, and parameter correlations leading to degenerate solutions abound. Heuristics are one way to deal with this in the absence of a human operator who may use experience and intuition (for better or for worse) to choose between different models that fit the observations equally well. Coupled with a heuristic optimization method, our model can deliver the principal parameters of contact binaries, which can then be converted to absolute parameters (stellar masses and radii in solar units) using empirical calibrations, based on light curves alone. We hope to use these results to expand the existing sample of solved W UMa binaries by an order of magnitude.

5. 2. APPLICATIONS FOR MACHINE LEARNING

Machine learning techniques can be applied to tackle huge light curve repositories, such as WASP, where variability classification and periods are not provided. Automated period determination could also be applied in relation to a previous topic, namely for detection of double-periodic variables, since many of the ongoing surveys collect long-cadence, long-term data well suited for discovering cyclic phenomena with periods of the order of years.

Were only just embarking on this multidisciplinary research adventure and it is hard to predict how much time and effort it will take to get to first results, but we are excited and looking forward to the challenges ahead.

6. CONCLUSION

The Stellar Physics group at the Astronomical Observatory of Belgrade has a long tradition and a great deal of experience in observational studies of close binary stars. We have our own modeling tools that can handle a wide diversity of objects and complex phenomena. Recently, our work has mainly been focused on double-periodic variables and W UMa contact binaries, but now we are considering automated classification, period determination and modeling in order to keep up with the accumulation of observational data from ongoing and future space- and ground-based surveys.

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