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Walter Van Hamme & Petr Zasche

# UNIVERSE OF BINARIES, BINARIES IN THE UNIVERSE

September 7 – 11, 2019, Telč, Czech Republic

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# PREFACE

The recent discovery of planets in binary star systems has raised considerable interest in how such systems form and evolve. Satellites such as Kepler and TESS are providing observational data of unprecedented precision and time-wise coverage, uninterrupted by the diurnal cycle. They have opened new avenues for exploration and discovery. So we are grateful to our Czech colleagues for having organized a conference devoted to some of the latest developments in binary star research. Entitled "A Universe of Binaries – Binaries in the Universe," the conference was held at the University Centre of Masaryk University from the 7th to the 11th of September, 2019. The picturesque town of Telč, nestled in the hills of the Czech Vysočina region, roughly halfway between Prague and Vienna, provided a perfect backdrop.

The meeting was structured around a broad range of topics, each anchored by one or more forty-minute invited oral presentations. One of the themes highlighted the important role citizen-astronomers are playing in binary and variable star astronomy and the indispensable organizations that facilitate such collaborations. Examples are the American Association for Variable Star Observers (AAVSO) in the U.S. (Kafka) and Chungbuk National University in Korea (Kim). There is a long history of amateur astronomers providing photometric data on variable stars and eclipse timings, but we now also see amateur spectroscopy making inroads into binary star astronomy as demonstrated by activities of the Astronomical Ring for Amateur Spectroscopy (ARAS) in France (Teyssier). Space missions like Kepler, Kepler2, and TESS, originally designed with the discovery of exoplanets in mind, have resulted in a treasure trove of binary data and more is to come from future missions like CHEOPS and PLATO (Csizmadia). The binary star community can anticipate a deluge of eclipsing binary data in Gaia Data Release 3 (Pourbaix). Detection of planets around binary stars has spawned research into the formation of binary systems and planets (Moe) and planetary systems in binaries (Triaud, Orosz, Martin). Many binary systems are members of hierarchical multiples, creating interesting interactions (Tokovinin, Brož). Pulsating stars in binaries (Murphy, Mkrtichian) and the presence of discs have inspired modeling program developers (Prsă, Wilson) to expand underlying physical models. Massive binary star evolution (Renzo), binaries with composite spectra (Griffin), and cataclysmic variables (Sion) all added fascinating topics for discussion.

I thank the invited speakers (names above in parentheses) for framing the conference, and all other participants who were given the opportunity to present oral or poster contributions. Manuscripts were reviewed and edited by members of the Scientific Organizing Committee. All manuscripts submitted before the deadline are printed in this volume.

I am pleased to acknowledge all who have contributed to the success of the conference. First I thank the sponsoring institutions: Masaryk University in Brno, Charles University in Prague, the Astronomical Institute of the Academy

of Sciences of the Czech Republic in Ondřejov, and the Astronomical Institute of the Slovak Academy of Sciences at Tatransá Lomnica, Slovakia. I am grateful to my fellow SOC members for valuable suggestions on invited speakers, assistance with putting together the scientific program and help with managing the manuscript review process. SOC members included Tamasz Borkovits (Hungary), Kyle Conroy (USA), Ed Guinan (USA), Stella Kafka (USA), Chung-Uk Lee (Korea), David Mkrtichian (Thailand), Theo Pribulla (Slovakia), John Southworth (UK), Andrei Tokovinin (Chile), Silvia Toonen (The Netherlands), Guillermo Torres (USA), Chris Tout (UK), and Bob Wilson (USA). It was a privilege to serve as SOC chair. Special thanks go to the Local Organizing Committee (Jan Janík, Richard Komžík, Ernst Paunzen, Marek Skarka, Pavel Suchan, Gabriel Szász, Petr Zasche) and the tireless LOC chair, Miloslav Zejda, for conceiving the conference and managing all of its logistical aspects. And not least, we thank all participants for making this conference memorable and scientifically rewarding. Participation by so many young researchers and graduate students bodes well for the future of the field.

Walter Van Hamme, SOC Chair — Miami, January 2020

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# Professional-amateur programs at Chungbuk National University

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**Abstract.** Efforts at the Chungbuk National University, Korea, to encourage amateur astronomers to participate in astronomical observation are presented. The Chungbuk National University Observatory opened the Jincheon station with 1.0-m and 0.6-m optical telescopes for research and education. The observatory is equipped with a fully automated observation and control system. Since its opening in 2008, the observatory has developed amateur astronomer programs and provided training in astronomical observation. The observatory also aims at stimulating other observatories in Korea to engage in reserach and education. We summarize our programs and future plans regarding professional-amateur collaborations in Korea.

**Key words:** small telescopes – professional-amateur programs

## 1. Introduction

Small telescopes are recognized as useful observational tools, even in the current era of large professional telescopes. Many astronomers are using small telescopes to monitor variable or transient objects because of ease of installation of small instruments and lack of heavy competition for telescope time. Even though in Korea there are many small telescopes at universities, research institutes, astronomical observatories, and science high schools, these telescopes often remain underutilized.

The professional-amateur program can be understood as encouraging amateur astronomers to participate in astronomical observing. Amateur astronomers are in need of proper training to conduct observations, therefore educators are essential for the success of the program. Small telescopes at observatories can be used as training facilities for this purpose.

Chungbuk National University (CBNU) has a department of astronomy and space science where many astronomical educators are trained to help amateurs using small telescopes, and a university observatory (CBNUO) providing the technical support for various astronomical observations. Before explaining what is done at CBNU, the current status of small telescopes in Korea will be introduced. We will then discuss projects that can be done using small telescopes and will close by discussing the future of small telescopes in Korea.

## 2. Current status of small telescopes in Korea

The locations of facilities with small telescopes in Korea are shown in Fig. 1. Small telescopes are located in 12 education and science research institutes, 6 science museums, 28 astronomical observatories, 7 private observatories, and 8 universities. The Korean government funded the construction of many astronomical observatories since 2005 with the goal of increasing science literacy in Korea. Among these telescopes, there are 17 refractors and 40 reflectors. Reflectors with diameters larger than 50 cm are most common in the Korean observatories, and we must note that few of these telescopes are being used for research purposes.

About 5000 amateur astronomers are enrolled in the Korea Amateur Astronomer Society (KAAS), and 30% of its members are school teachers. However, most of them are more interested in astrophotography than photometry or spectroscopy. Because there are many amateur astronomers who have a small telescope with a diameter larger than 40 cm diameter, there is the potential of their engagement in scientific projects.

## 3. Projects at CBNU

The Department of Astronomy and Space Science at Chungbuk National University (CBNU) recognized this situation and began to teach students how to encourage amateur astronomers to participate in making astronomical observations. The department introduced graduate courses for public astronomy in 2005, and now over 80 students with bachelor's, master's or Ph.D. degrees are working in astronomical observatories, science museums, and private astronomical institutes. The training of educators for public astronomy is being carried in connection with the University Observatory (CBNUO), which plays the role of technical supporter for other observatories as well as conducting active observations.

In the graduate program of public astronomy, 11 students have graduated with a Master's degree and one with a Ph.D. so far, while 19 students are enrolled in the Master's program, 6 students in the doctoral program, and one student in the integration program. Over 80 students who graduated in our department are active at various astronomical observatories, science museums, and private astronomical institutes.

CBNUO installed a 1-m Ritchey-Chrétien telescope in the Jincheon station of the university observatory in 2008. We began to observe variable stars with this telescope. One 0.6-m wide-field telescope has also been available since 2009


**Figure 1.** Distribution of small telescopes in Korea.

and is now used as the main telescope for scientific observations. CBNUO developed a fully automated robotic observation program and control system for its 1-m, 0.6-m and 0.4-m telescopes for scientific observations.

As an example, the current status of the 0.6-m telescope is shown in Fig. 2. Between 2010 and 2018, observations were made on a total of 700 days, on average 5 hours per day and 100 days per year. A total of 141 objects were observed in the last 10 years. The maximum number of observing nights, 110, was for the magnetic cataclysmic variable DO Dra, and the maximum number of individual observations (11,361) was for the eclipsing binary DY Lyn. Eclipsing binaries are analyzed by Professor Chun-Hwey Kim (see, for example, Kim et al., 2014). Today about 20 refereed papers concerning binaries have been published. Other objects such as exoplanets, asteroids, and satellites, are also observed. Hinse et al. (2015) and Wang et al. (2019) are papers that include exoplanet data obtained with CBNUO telescopes.

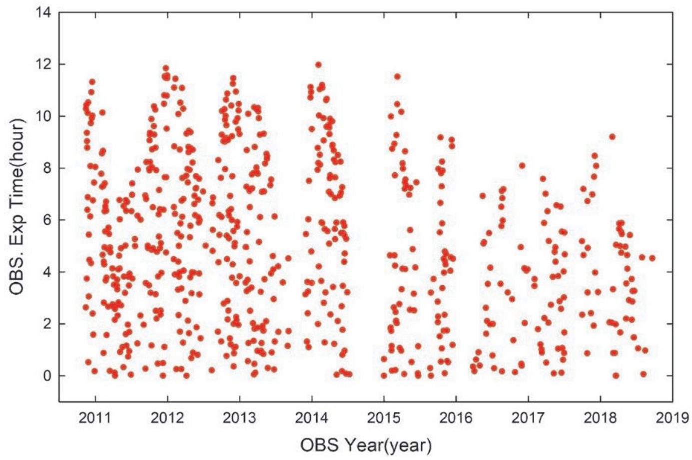


**Figure 2.** Observation status of the 0.6-m telescope of CBNUO.

CBNUO is also providing the know-how to other astronomical observatories related to the development of control and observational systems, as well as telescope maintenance. We are proud to have carried out 17 technical service projects for other astronomical observatories over the past 10 years. Yoon et al. (2012, 2013) are papers showing our efforts for setting up automatic observation. In order to encourage teachers to observe variable stars, we helped construct a 50-cm telescope with a remote observation system at Gyeonggi Science High School in 2015, and we encouraged one of the teachers to observe variable stars. Many students are now being trained to observe variable stars with this telescope. However, it needs to be mentioned that it is very hard to convince high school teachers to observe variable stars. As amateur astronomers, most teachers are more interested in photography.

## 4. CBNU future plans

As described in the previous section, CBNUO accumulated the know-how about fully automatic observational systems as well as educating students who will later work in public astronomy, and to encourage amateur astronomers to carry out scientific observations. CBNU has taken proper measures to connect amateur astronomers with scientific data taking. Many alumni of our department who are now working in public astronomy are facilitating doing this.

Fortunately, the optical and IR astronomy division of the Korean Astronomical Society (KAS) is preparing a small telescope network project that will encourage amateur astronomers to participate in astronomical observations. Telescopes between 40 cm and 1 m diameter will be networked for common use in research and education. This small telescope network project, planned for 2020, will be competing for various research projects that either require a rapid response or require long-term, steady monitoring. Examples are observations of exoplanet transits, active white dwarf binary systems, solar system small bodies, supernovae, and Active Galactic Nuclei.

CBNU focuses on producing experts who will encourage amateur astronomers to participate in astronomical observing, and on providing efficient technical support for observing with small telescopes. The small telescope network brings small telescopes in full operation and offers astronomers competitive observational resources in several astronomical regions. Amateur astronomers will be encouraged to engage in international cooperation.

## 5. Concluding remarks

Small telescopes are very useful for researching interesting celestial objects, even in the era of big telescopes. CBNU is making efforts with CBNUO to help astronomical institutes develop fully automatic observational systems and maintain their telescopes, as well as to educate students to become experts to teach general astronomy and scientific observation. Such efforts will also provide amateur astronomers to take part in the scientific enterprise.

The interest of amateur astronomers in scientific observations will be amplified by the planned networking of small telescopes in Korea and assistance with the maintenance of small telescopes. Through their training at CBNU, students become experts and crucial assets in establishing professional-amateur programs in astronomy.

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# The importance of studying active giant stars in eclipsing binaries – and the role of citizen scientists in finding them

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**Abstract.** Red giant stars with deep convection zones and rapid rotation maintain a strong surface magnetic field which may alter their observable astrophysical parameters. The resulting lower surface temperature due to spots makes the inferred masses and ages from evolutionary tracks uncertain. Eclipsing binaries having an active giant component can help in finding the stellar mass independently.

However, until the recent space missions it was nearly impossible to find such systems from the ground. Since the evolution on the giant branch is rapid, the number of binaries containing giant stars is low. The eclipses, if the inclination allows, are very shallow, on the order of the photometric accuracy from the ground, due to the large brightness difference between a red giant primary and its solar size or smaller secondary. And, the typically acquired data from the ground are not uniform or continuous.

In this paper, a few new eclipsing binaries are presented with active giant components observed by *TESS* and discovered by citizen scientists, which are worthy of further studies.

**Key words:** active stars – eclipsing binaries – space photometry

## 1. Introduction

Red giant stars in close binary systems often show signs of magnetic activity, like spots observable as rotational modulation, and flares (for example see Oláh et al. 2013). Some of these kinds of stars have huge amplitude variability both on rotational and long-term time-scales that span several tenths to about one magnitude in range. The photometrically observed stellar parameters thus also vary, and do not fit the theoretical evolutionary tracks corresponding their estimated mass (for example, see three such cases in Oláh et al., 2014). Studying active giants in eclipsing binaries can help to better constrain the stellar parameters, and through this the effect of the strong magnetic field on the stellar evolution. The first example of such an investigation which already involved citizen scientists has been published last year on EPIC 211759736 by Oláh et al. (2018).

## 2. Data and Methods

The depths of eclipses in a system containing a red giant primary and a solar size or smaller secondary is shallow and last for several hours to even days. The ground based observations are not continuous since one or at most a few datapoints are obtained on clear nights, and the data accuracy is similar to the depths of the eclipses. Data from space missions (*Kepler*, *TESS* satellites) overcome these drawbacks providing very accurate uninterrupted datasets with high time-resolution.

Visual surveyors of space-based light curves are very good at finding stars with variable light curves and shallow eclipses. Automated searches using BLS (box least squares) techniques can find them as well, but to our knowledge no one is pursuing this approach. The group of citizen scientists in the authorlist (and many more) spend a lot of their free time in searching for interesting objects in the databases. In the following a few intersting examples of their discoveries from the *TESS* database (Ricker et al., 2015) are presented, reduced from FFI images by FITSH (Pál, 2012).

## 3. Results

The main result of this survey is a (growing) list of potentially interesting active giant stars in eclipsing binaries. Detailed studies of satellite data supported with additional radial velocity measurements and multicolor photometry would allow us to get absolute stellar parameters. Table 1 lists five eclipsing binaries with active primaries, and their basic physical parameters as given in the *GAIA* DR2 catalog. These systems were found by citizen scientists.

The ground based observations to acquire radial velocity curve and starspot temperature from multicolor photometry are already ongoing to support a detailed study of TIC 375144608.

TIC 123153249 (Fig. 1) is a known active star in a binary system, V344 Pup. This star has published radial velocity data and multicolor ($UBVR_CI_C$) light curves dating back decades. It has never been discernible that the binary has

**Table 1.** Sample of interesting red giants in eclipsing binaries from *TESS* data. Physical parameters are from *GAIA* DR2 catalog, orbital periods are own estimates.

| TIC | $P_{orb}$ days | $T_{eff}$ K | radius $R_\odot$ | lum. $L_\odot$ | *TESS* mag. |
|---|---|---|---|---|---|
| 123153249 | 11.761 | 4780 | 7.73 | 28.07 | 5.924 |
| 271892852 | 4.150 | 4870 | 2.04 | 2.07 | 12.452 |
| 375144608 | 13.4893 | 4680 | 8.55 | 36.16 | 9.959 |
| 166974938 | 7.475 | 5230 | 5.03 | 14.11 | 11.310 |
| 220461013 | 50.8 | 4550 | 6.52 | 16.95 | 10.662 |

eclipses: they are too shallow to be noticed from the ground. In Fig. 1, left, the *TESS* long- and short, cadence light curves are presented while on the right an old V dataset is shown. The estimate of the inclination from the old data was about 45° (Stawikowski & Glebocki, 1994), while, concerning the eclipses, the true inclination is around $75 - 80°$, which results in a significant difference in the derived stellar parameters.

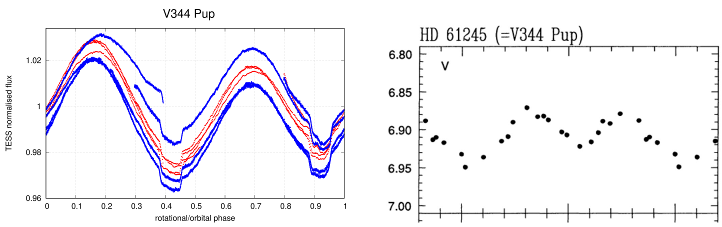


**Figure 1.** *Left:* TIC 123153249 = V344 Pup observed parallel in long cadence (blue) and short cadence (red, from the MAST site, https://mast.stsci.edu) modes. The shifts between the light curves are not real. *Right:* Detail of an old multicolor dataset from Cutispoto (1991), the deepest datapoint may reflect the eclipse.

TIC 271892852, plotted in Fig. 2, left panel, is observed in all *TESS* sectors 1-13. It shows slow but marked changes in its light curve presumably as its starspots evolve over time, and at least one big flare. The spots affect the shape of the eclipses, and their depths are 0.06 mag. and 0.02 mag. No radial velocity measurements exist for this very interesting object.

TIC 166974938, plotted in Fig. 2, middle, is observed in *TESS* sectors 1, 3-11, and 13. Its light curve is slowly evolving in time, and large flares occur. Both eclipse depths are on the order of 0.01 mag. The secondary eclipse shows an interesting variability pattern. No radial velocity data is available for the system.

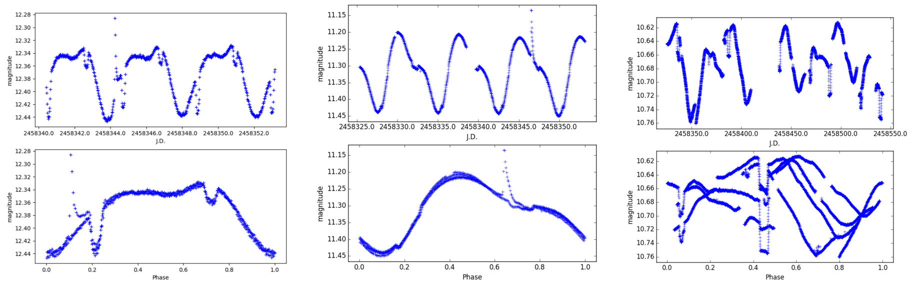

**Figure 2.** *From left to right:* example light curves of TIC 271892852, TIC 166974938 and TIC 220461013.

TIC 220461013, plotted in Fig. 2, right panel, is observed in *TESS* sectors 1-3 and 5-13. The star has longer orbital and rotational periods than the sector length of *TESS*. The rotational period of the giant star is definitely longer than the orbital period (about 54.9 days), and the orbit is eccentric. It is a possible triple system. No radial velocity data have been acquired.

All listed stars in Table 1 deserve further observations and modeling.

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# Eclipsing binary research with mini telescopes

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**Abstract.** Bright variable stars became neglected in the epoch of CCD cameras. In addition, in most surveys bright stars are not measurable, apart from specialized projects like *BRITE* and *SMEI*. In this poster we present an inexpensive solution to observing bright variable stars accessible to students, small observatories and amateur astronomers. We also present some results.

**Key words:** binaries: eclipsing – photometry – mini telescopes

## 1. Introduction

The history of photometric observations in astronomy is characterised by revolutionary changes. The first one was the usage of the telescope at the beginning of 17th Century. Then at the end of the 20th Century we had CCD cameras, and now since recently CMOS cameras. Nowadays many observatories and amateur astronomers can measure the brightness of faint stars (>10 mag) with an accuracy of up to several mmag, even with small telescopes (<1 m). However, stars brighter than 5-6 mag are usually too bright for the use of telescopes and cameras, or lack appropriate comparison stars near the target of interest. Such stars are also mostly too bright for the majority of surveys. Only thanks to projects like the set of nanosatellites of *BRITE*, we have new photometric measurements of these stars. However, how can we organize and manage follow-up observations after the *BRITE* mission?

We found an easy, inexpensive alternative solution. We can return to Galileo-sized telescopes (several centimeters in diameter) equipped with a CCD camera, a filter wheel and a set of photometric filters. Such a mini telescope can do an excellent job of photometric measurement of bright stars.

## 2. Mini telescopes

Our mini telescopes consist of old photo-objectives with an aperture up to 6 cm. We use small CCD cameras like ATIK16IC or Moravian instruments G2-402, eventually G2-4000. The mount is the table mount EQ1, EQ2-3, or the GO-TO mount AZ-GTI in EQ mode. The simplest set-up for photometry costs only about 500 EUR (excluding a laptop), weighs less than 5 kg and is quite

**Figure 1.** A mini telescope working from the window at a corridor.

small. Fig. 1 shows an example of a mini telescope set-up. Such a set-up has the following advantages:

– it is accessible to small astronomical clubs, schools, and amateurs, and not only in developed countries;

– it can be easily transported;

– it can be used for "window/balcony astronomy."

## 3. Photometry

The photometry obtained with these mini telescopes attached to CCD cameras is fully comparable with that obtained by large telescopes equipped with photoelectric photometers (see Fig. 2.)

## 4. Conclusions

Mini telescopes consisting of a photo-lens, CCD camera and simple mount have great potential.

On one side they help scientists doing follow-up observations or long-term monitoring of bright stars. Surveys that are capable of observing bright stars are usually done in one spectral band. Mini telescopes can make use of multi-colour photometry.

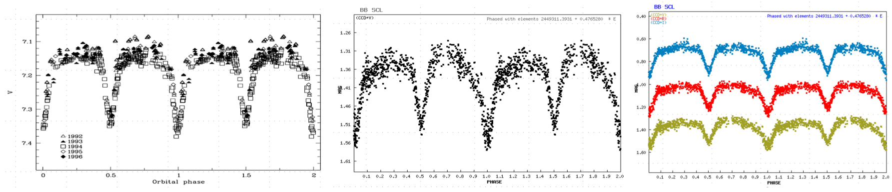

**Figure 2.** Light curves of BB Scl taken with the 0.6-m telescope at Mt. John observatory (Watson et al.,2001) (on the left) and the 0.5-m telescope at SAAO, Sutherland (in the middle) – both equipped with a one-channel photoelectric photometer. On the right, CCD observations made by a 4-cm telescope (Liška, 2011). The larger scatter in the light curve maxima is caused by real variability in BB Scl.

On the other side these mini telescopes can help raise new generations of scientists, attract pupils and students to the natural sciences. They can do their observations, process the frames, analyse the data, interpret the results and prepare a report on the results. This base in scientific work will facilitate their future studies and work in any branch of science.

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# WHOO! – White Hole Observatory Opava

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**Abstract.** Introduction of the observatory of Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava.

**Key words:** observatory – telescope – CCD camera

## 1. Introduction and basic informations about WHOO!

WHOO! is the observatory of the Silesian University in Opava – Institute of Physics, Faculty of Philosophy and Science. Research at the Institute of Physics is mainly focused on compact objects, including black holes, so the "white hole" in the name comes partly from this. The colour of the dome is white. "Whoo" also represents the sound of the nocturnal bird – the owl. From these connections comes the origin of the name.

The dome is on the roof of the university building located on Bezručovo nám. 13. The high position of the observatory provides the excellent view from the dome in all directions.

### 1.1. The main equipment and instruments in the dome

The diameter of the dome is 3.2 m. The main equipment is a Meade 10" LX200GPS telescope and an ATIK 383L CCD camera with an external filter wheel holding photometric BVRI and photographic RGB filters with Clear. The telescope can also be used for visual observations. For convenience, there is a flip-mirror system.

### 1.2. Visual and photometric observations

The telescope can be used by students and people from the Silesian University. Students and observers can do visual observations or observations with the

CCD camera – photometry of variable stars, astrophotography, bachelor thesis projects, ...

The telescope is also used for the popularization of astronomy – school visits (mainly pupils and high school students) – and for various groups of visitors. Several times each month public observing events are organized, as well as other special events for the public (European researchers night, lunar eclipses, ...).

### 1.3. Observations of variable stars

The CCD camera is mainly used to do photometry of eclipsing variable stars. Students and observers are currently focused on eccentric binaries, binaries with apsidal motion, binaries with a light-time effect, low mass binaries, and new variable stars.

Observational data and informations about the WHOO! observatory can be found on the website `http://whoo.slu.cz/`.

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# (Not so) hierarchical stellar multiples seen through the eyes of ***Kepler***, ***TESS***, and other missions

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**Abstract.** During the era of *Kepler*, *TESS*, and other related star-monitoring space-based missions, quasi-continuous observations of thousands of known and previously unknown eclipsing binaries for several months (or even years) has led to the discovery of hundreds of compact hierarchical triple (and multiple) star systems. Many of them produce spectacular observational effects that were never (or at least, rarely) seen before, for example: extra outer eclipses; third-body perturbation-dominated, large amplitude, non-sinusoidal eclipse timing variations; rapid eclipse depth variations, etc. Successful modeling of these phenomena is a great challenge; however, it does offer substantial astrophysical benefits. In this paper we review our two different approaches to these challenges: one of them is based on the analytical theory of third-body perturbations and is applied exclusively to the eclipse timing variations, while the other is a complex, numerical, spectro-photodynamical modeling of all the available observations of such systems. We discuss some recent results obtained for *TESS* systems.

**Key words:** binary and multiple stars – eclipsing binaries – celestial mechanics

## 1. Introduction

Past and recently operating space telescopes dedicated to searching for transiting extrasolar planets have been producing unprecedentedly high quality and long-term lightcurves of thousands of eclipsing binaries (EBs) for more than a decade. Many of these EBs have been found to be members of compact, hierarchical triple (CHT) stellar systems. A significant fraction of these triples are so compact, that the third component perturbs the motion of the EB which leads to eclipse timing variations (ETV) having a characteristic period of $P_2$ (i. e., the orbital period of the outer component) with an amplitude that can exceed that of the classic, well-known light travel-time effect by huge factors. Furthermore, these ETVs may also be accompanied by dramatic eclipse depth variations and/or extremely fast (sometimes retrograde) apsidal motion. A more spectacular and rare phenomenon observed for the first time by the *Kepler* mission are the extra eclipses in about a dozen CHTs (as well as a similar number of circumbinary planets), i.e., such dimmings occur when the outer component either eclipses one or both members of the inner binary or, is eclipsed by them.

The modeling of both the dynamical ETV curves and the light variations of systems with outer eclipses need special care, but offer substantial improvements in understanding the physics of binary and multiple stellar systems. Here we refer mainly for the accurate determination of the relative inclinations of the orbital planes of the inner and outer subsystem(s) which is a key parameter from the point of view of binary and multiple star formation and evolution (see e. g. Moe & Kratter, 2018, and further references thereins).

In this paper we discuss two different treatments developed by our groups to investigate these extraordinary phenomena.

## 2. Analytic ETV model and its applications

Three-body perturbations in a CHT are effective on three different timescales. The lowest amplitude ones have the shortest characteristic period on the order of the inner binary's period ($P_1$). The middle ones (both in amplitude and period) are effective on the timescale of the third body's orbital period ($P_2$), while the largest amplitude effects have a substantially longer timescale of $P_2^2/P_1$. While the first kind of perturbation usually remains below the limit of current detectability, and the largest ones, in general, become effective only over decades or even centuries, the middle ones may alter the ETVs and lightcurves of EBs orbiting in CHTs within months. This fact offers a good chance to determine accurate system parameters on these relatively short timescales.

The first efforts toward analytical modeling of dynamically perturbed ETVs of EBs were undertaken by Soderhjelm (1975) and Mayer (1990). The most detailed model, however, has been developed only recently by Borkovits et al. (2015). In the same paper the authors also describe their software package for solving the inverse problem. This treatment enables one to mine all the orbital elements of both the inner and outer orbits, including angular elements relative to both the tangential plane of the sky and the invariable plane of the system and, therefore, to obtain such dynamically and evolutionary important parameters as the relative inclination of the inner and outer orbits and the arguments of periastrons in the dynamical frame of reference. Moreover, in theory, physical masses may also be obtained, however, in most cases only with lower accuracy.

This approach was successfully applied to more than 60 CHTs in the original *Kepler* field (Borkovits et al., 2015, 2016). Later it was also applied to other triple system candidates observed by the *CoRoT* satellite (Hajdu et al., 2017) and *K2* mission (Borkovits et al., 2019a,b). Most recently, the ETVs of the first two CHTs measured by the *TESS* spacecraft are also under analysis (Borkovits *et al.*, 2020, in preparation). Illustrations are shown in Fig. 1.

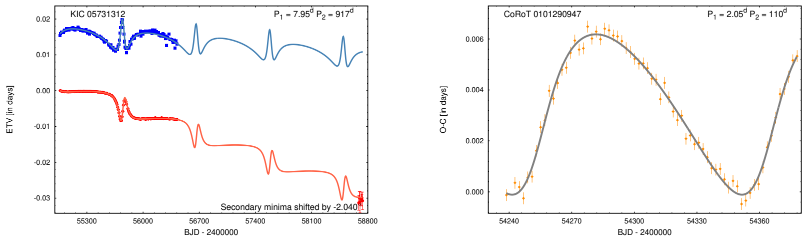


**Figure 1.** Dynamical ETV solutions for KIC 5731312 (left) and CoRoT 101290947 (right). For the *Kepler* system recent *TESS* observations are also included. Red points stand for primary eclipses, while blue boxes represent secondary ones. (For the epoch of the *TESS* measurements, the secondary eclipses have already disappeared due to the rapid precession of the orbital plane.)

## 3. A complex spectro-photodynamical approach in the modelling of different types of observational input data

While dynamical ETV analyses offer quick results for a large sample of CHTs, it omits a significant amount of other available relevant information which can be obtained from the same lightcurve observations (i.e., eclipse duration and depth variations, possible extra eclipses), not to mention other kinds of measurements such as, e.g., radial velocity (RV) observations, and spectral energy ('SED') measurements. In order to take into account all the available information we have initiated the development of a software package which allows joint, complex analyses of multi-band lightcurves, RV and ETV curves of binary, hierarchical triple and quadruple (both 2+2 and 3+1 hierarchies) systems. The orbital motions either be taken to be unperturbed Keplerian orbits or, can be calculated via numerical integration. Triple and multiple eclipses are also modeled. Moreover, a joint analysis including the SED of the two, three or four stars, as well as the optional use of PARSEC stellar isochrones (Bressan et al., 2012) have also been incorporated (see Borkovits et al., 2019b, and further references therein). Note, other recently developed software packages offer partly or fully similar services (see, e. g. Prša, 2018, and further references therein).

Most recently our software package has been used for the analysis of two CHTs discovered with *TESS* in and near to its southern continuous viewing zone. We identified both TICs 167692429 and 220397947 through their rapidly varying ETVs showing clear signs of the perturbations of a third stellar component. Furthermore, the former EB also manifests continuous eclipse depth variations and a clear feature (both in the timing and depth variations) of the periastron passage of a remarkably eccentric, and inclined third star.

Our analyses have revealed that both systems consist of inner eclipsing pairs of metal deficient, probably old F-type twin stars and less massive, late K or, early M-type outer components. In the case of TIC 1692429 ($P_1 = 10.26$ d, $P_2 = 331$) both orbits have significant eccentricity ($e_1 = 0.17$, $e_2 = 0.56$) and the relative inclination is $i_{\rm rel} = 27°$ which results in orbital plane precession with a period of $P_{\rm node} \approx 70$ yr. Within one precession cycle the inner pair exhibits eclipses during two $\sim 10-11$ yr-long intervals. Moreover, we found, that during one third of a precession cycle the system is expected to show outer eclipses. TIC 220397947, the tighter of the two systems ($P_1 = 3.56$ d, $P_2 = 77$ d) was found to be perfectly flat ($i_{\rm rel} \sim 0.5°$); however, there are some signs suggesting that the system might consist of a fourth star, too, revolving on an orbit having a period of $P_3 \sim 2700$ d and relative inclination $i_{\rm rel2} \sim 10-20°$. Detailed analysis of these systems will be published in the near future.

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# Eclipsing binaries hiding in the background: the *Kepler* Pixel Project

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**Abstract.** The aim of the *Kepler* Pixel Project is to discover new pulsating and other types of variable stars in the individual pixels of the original *Kepler* mission. In the framework of the project, 1272 eclipsing binary candidates were identified in the background pixels. After eliminating false positives and those stars that are already present in the *Kepler* Eclipsing Binary Catalog, we were left with 776 new eclipsing binaries. This is a substantial and significant addition to the 2922 eclipsing binaries present in the catalog. We present the methods we applied, examine the 4-year (Q1-Q17) light curves of selected newly found variable stars. The applied methods are automatic, therefore they can be used in the future to explore the vast amounts of data produced by other space missions (e.g. *TESS*, later *PLATO*).
**Key words:** binaries – data analysis – photometry – *Kepler*

## 1. Introduction

During its original mission, the *Kepler* space telescope measured the brightness of more than 160000 stars, producing a quasi-continuous 4-year-long run of observational data with unprecedented photometric precision. Targets investigated so far are mainly those listed in the *Kepler* Input Catalog (Brown et al., 2011), but more findings indicate that even the background pixels of *Kepler*'s data hold interesting new information waiting to be mined.

## 2. The *Kepler* Pixel Project

The *Kepler* Pixel Project (Szabó, 2018) sets the aim of discovering new pulsating and other type of variable stars in the original *Kepler* field. Since Q4 was a relatively quiescent observing period, we decided to start our search using this dataset.

We extracted each individual pixel of the long-cadence (30 min) files, which resulted in more than 6 million light curves. All pixels were examined, regardless of whether or not they belong to the main target. The initial goal was to look for faint background RR Lyrae stars, so we specified the filtering criteria accordingly. Our potential candidate list includes pixels that show periods between 0.25 and 1 day and have Fourier spectra with at least two harmonics of the main frequency with decreasing amplitude.

## 3. Results

The aforementioned criteria yielded ∼12500 candidate pixels. However, one pixel does not equal one candidate; in the majority of cases a couple of pixels are available for each candidate. Despite our specific criteria, ∼90% of our candidates are eclipsing binary stars. We successfully identified 1272 target pixel files containing an eclipsing binary candidate, in most cases located in the background.

Since the goal was to find new variable stars in the field, those candidates that are already listed in the *Kepler* Eclipsing Binary Catalog (Prša et al., 2011; Abdul-Masih et al., 2016) were excluded. This cross-match left us with 777 new candidates. One of our candidate's light curve was in fact the result of contamination by a bright nearby star, consequently it was removed from our candidate list as well. The final list of potentially new eclipsing binaries in the original *Kepler*-field has 776 candidates, which consist of 2778 individual pixels in total. In Fig. 1 and Fig. 2, typical candidate light curves are shown.

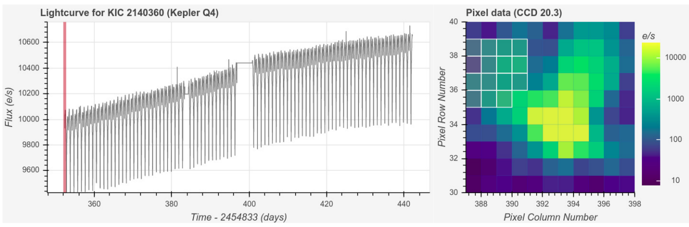


**Figure 1.** The Q4 light curve of the candidate found in the background of the main target KIC 2140360. The pixels containing the candidate are marked with white edges.

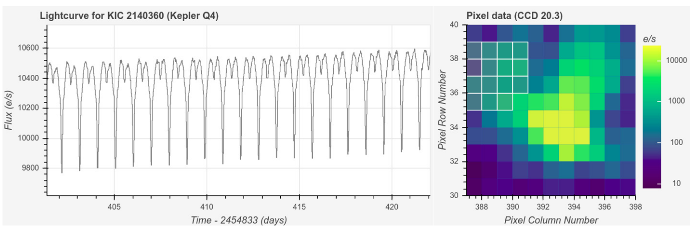


**Figure 2.** A 10-day-long zoom-in of the Fig. 1 Q4 lighcurve.

After identifying the Q4 candidates, their data from all the other quarters weer extracted. There were cases when the targets could not be measured in a particular quarter. For example, it is unfortunately quite common that the background pixels containing the candidate are located near the edge of the target pixel file, so in some quarters the candidates might be outside the image.

In the majority of the cases, however, the 4-year nearly continuous light curve was successfully created by stitching together the data of all 17 quarters. The 4-year light curves were stitched for each individual pixels automatically, then the pixels belonging to one candidate were summed.

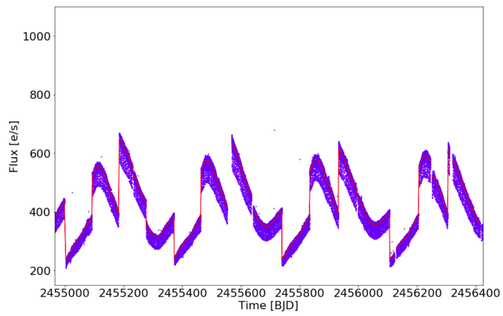


**Figure 3.** The Q1-Q17 light curve of the candidate found in the background of KIC 2140360. The different trends are quite apparent from quarter to quarter. The red line indicates the trend fitted with the Wötan code.

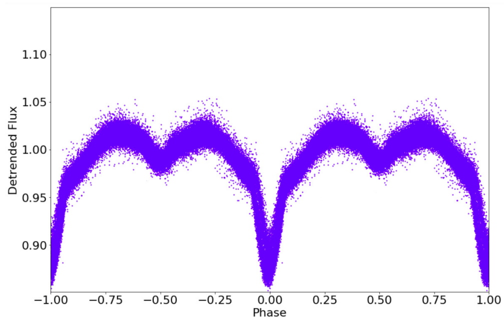


**Figure 4.** The folded light curve of a candidate with period 0.975 day, after de-trending.

Individual pixels almost always show long-term trends. Sometimes even adding up all candidate pixels doesn't remove the trends, only reduces them.

Moreover, trends change from quarter to quarter, therefore it is crucial to remove them in order to avoid uneven light curves. To remove these trends, we used the Wötan (Hippke et al., 2019) Python code. Figure 3 shows the stitched light curve for the candidate in the background of KIC 2140360, the folded light curve is seen in Fig. 4. The project is still ongoing, the first results will be published in more detail in a separate paper.

## 4. Summary

In the *Kepler* Pixel Project, by investigating each individual pixel of the original *Kepler* mission Q4 quarter images, we managed to find 1272 eclipsing binary candidates, and 776 of them turned out to be new (i.e., not in the *Kepler* Eclipsing Binary Catalog) candidates. We obtained the data from the other quarters as well, thus creating 4-year-long light curves. *Kepler*'s unprecedented photometric precision enables us to investigate the discovered systems in more detail. The algorithms developed for the project can be used for exploring other space mission data (e.g. *TESS*, later *PLATO*).

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# An investigation of low-mass-ratio EW systems from the Catalina Sky Survey

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**Abstract.** We have conducted a survey of overcontact binary systems (EW) with mass ratio $\leqq 0.25$ from the Catalina Sky Survey (CSS) that are considered strong merger candidates and are probable progenitors of FK Com-type stars and blue stragglers. The discovery of such extreme mass ratio overcontact binaries is vital to resolve the critical mass ratio ambiguity to merge, the mass loss process, and to refine the current theoretical models. So far only a few tens of such systems have been identified. To increase this sample, we selected and derived the physical parameters (mass, temperature and radius ratios, inclination and fill-out factor, along with their respective uncertainties) of 92 newly discovered totally eclipsing low-mass-ratio (LMR) EW systems based on their $V_{\rm CSS}$ light curves, using PHOEBE-0.31a scripter and Monte Carlo methods.

**Key words:** binaries: close – binaries: evolution

## 1. Introduction

Eclipsing W UMa-type binaries (EW) are a unique class of eclipsing binaries. Their components are main-sequence stars of A-K spectral type and share a common convective envelope from where the energy transfer occurs. These systems are characterized by short periods in the range of 0.22 days to around 1.0 day. In addition, their components are of different mass (usually expressed by the mass ratio of the less massive over the more massive component, $q = \frac{M_2}{M_1}$). The minimum mass ratio ($q_{\rm min}$) predicted by theoretical models is around $0.05 - 0.109$ (Li & Zhang, 2006; Arbutina, 2009), depending on the adopted approximations. According to Kiseleva-Eggleton & Eggleton (2001), EW systems with $q \leqq 0.25$ and fillout-factor[1] FF $\geqq 50\%$ are in the process of merging and they are probable progenitors of FK Com-type stars and blue stragglers.

[1] $\mathrm{FF} = \frac{\Omega_1 - \Omega}{\Omega_1 - \Omega_2}$, where $\Omega$ is the value of the potential at the common surface of the binary and $\Omega_1$, $\Omega_2$ are the values of the potentials at the first and second Lagrangian point, respectively.

## 2. Identification of LMR EWs in the CSS

In this study we used the light curves (LCs) of the 30,592 EW systems (sample 1) from the Catalina Sky Survey (CSS; Drake et al., 2014), combined with 44 LCs in the $V$ band of the confirmed LMR EW systems from the literature (sample 2). We first cleaned the light curves of sample 1 using a $3\sigma$ clipping along the phase-folded LC by adopting a pre-defined period from Drake et al. (2014). The initial epoch values were determined using an iterative procedure of fitting a 2-degree polynomial to the deeper eclipse. We then applied a Fourier decomposition technique to the phase-folded, normalized flux LCs of both samples based on the following equation (Eqn. 4 in Deb & Singh, 2009):

$$m(t) = A_0 + \sum_{j=1}^{10} \{a_j \sin[2\pi j \phi(t)] + b_j \cos[2\pi j \phi(t)]\}. \tag{1}$$

Our investigation on the Fourier coefficient space showed that the higher-order Fourier coefficients, especially $b_8$, are more efficient in identifying LMR systems. As a result the initial sample 1 was reduced to 2,101 LMR candidates and finally to 92, by visual inspection of the remaining LCs, focusing on totality and duration of the eclipses.

## 3. Physical parameters

To initialize the EB models, the systems' effective temperatures were adopted from the values given by Marsh et al. (2017) after cross-matching with our sample, resulting in 52 out of our 92 systems having a temperature determined in this manner. For the remainder of our sample, we averaged the temperatures from *Gaia* DR2 (Gaia Collaboration et al., 2018) and the $T_{eff}$ given by Pecaut & Mamajek (2013) and corresponding to the $J - H$ color index (Cutri et al., 2003).

### 3.1. Light Curve analysis using PHOEBE-scripter

In order to estimate the mass ratios of the LMR candidates, a 2-dimensional grid was constructed in the mass ratio ($q$) – inclination ($i$) plane. The $q$-$i$ range was set to $[0.1 - 0.6]$ and $[68^\circ - 90^\circ]$, with a step of 0.05 and $1^\circ$, respectively. Each pair of grid values was adopted and fixed to initialize each model. The $q$-$i$ scan method was performed using PHOEBE-scripter (Prša & Zwitter, 2005) in "overcontact not in thermal contact" mode. Gravity darkening and limb darkening coefficients were adopted according to the systems' effective temperature, while for the latter the van Hamme (1993) tables were used. The adjusted parameters were the temperature of the secondary component ($T_2$), the modified potential ($\Omega_{1,2}$), and the passband luminosities. After the successful completion of the fitting for every grid pair, the ranges of the grid were constrained around the minimum $\chi^2$ value region and a second search began, with $q$-step value of 0.01. The final model was constructed using the best $q$-$i$ pair and by adjusting also the inclination, the time of the primary eclipse, $HJD_0$, and the period of the system.

As a test of our method, a synthetic light curve was generated using PHOEBE-scripter that mimics the CSS photometric data ($V_{err} \sim$ 0.01 mag and $\sim$ 350 data points) for a system of $q = 0.096$ and $i = 81\overset{\circ}{.}4$. The derived solution corresponded to a system of $q = 0.1$ and $i = 83°$, which is in good agreement with the actual values.

As a result of the described method a final catalog with the physical parameters ($i$, $\frac{T_2}{T_1}$, $\frac{R_2}{R_1}$, FF, $HJD_0$, period) of 92 new LMR EWs was created. A representative example of an LMR EB from CSS data given in Fig. 1

### 3.2. Error estimation of the physical parameters

The formal errors from the LC fitting procedure heavily underestimate parameter true uncertainties. Thus, the estimation of the uncertainty of the physical parameters was done by performing Monte Carlo simulations (Papageorgiou & Christopoulou, 2015; Papageorgiou et al., 2019). A synthetic LC was created for each system from the observed one, by a random displacement of each point 1000 times, according to its photometric point error drawn from a normal distribution with zero mean and the photometric error as the standard deviation. Then, every synthetic LC was fitted by adjusting only $T_2$, $\Omega_{1,2}$, passband luminosity, and $i$. We finally extracted the lower and the upper error bounds from each parameter distribution ($\frac{T_2}{T_1}$, $\frac{R_2}{R_1}$, $\Omega_{1,2}$, $i$). This is the final error that is provided for each of these quantities in our final catalog.

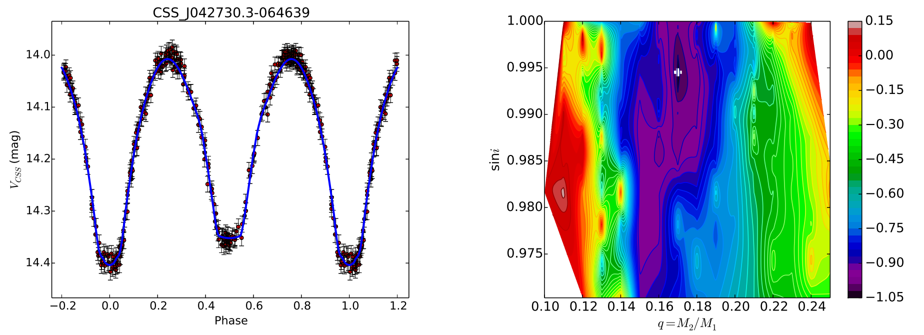


**Figure 1.** (*left*) Representative example of an EB from CSS data with $q = 0.17$ and $i = 83°$ plotted with the best fitted model (blue line). (*right*) A contour plot of $\log\chi^2$ in the $(q, i)$ plane. The white cross denotes the final solution.

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# Eclipsing binaries in the era of *Gaia*

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**Abstract.** The ESA mission *Gaia* is expected to detect a few million eclipsing binaries, most of them hitherto unknown. We present an outline of the processing of these objects in the *Gaia* Data Processing and Analysis Consortium pipeline, with an emphasis on the scientific validation of the software components.

**Key words:** stars: binaries: eclipsing, surveys

## 1. Introduction

The advent of large-scale photometric surveys since about three decades ago has led to the detection of an ever-increasing number of eclipsing binaries (EBs) in our Galaxy and in nearby extragalactic systems. This striking boom manifests itself, e.g., in the increase of the number of EBs from 882 in the *Hipparcos* catalog (ESA, 1997) to 11,076 ten years later in the All Sky Automated Survey (ASAS, Paczyński et al., 2006), to half a million another ten years later, in 2016, in the OGLE-4 survey that covers both the Galaxy and the Magellanic Clouds (Pawlak et al., 2016; Soszyński et al., 2016). This list is not exhaustive, but shows the rapid increase in the number of EBs becoming available to the astrophysics community.

The *Gaia* mission, an all-sky astrometric, (spectro-)photometric and spectroscopic survey currently in operation (Gaia Collaboration et al., 2016), will provide the next opportunity to increase the number of known EBs by an order of magnitude. The total number of EBs that will be detected by *Gaia* by the end of its nominal mission (five years of operations) is estimated to be on the order of several million (Eyer et al., 2013), distributed all over the sky. The current extension of the mission beyond its nominal duration by up to five years will allow to both increase the number of EB candidates and to better characterize them. The specific interest of *Gaia*, in addition to its all-sky coverage, lies in the provision of multi-color photometric time series (in the broad optical

$G$ band, the blue $G_{\rm BP}$ band, and the red $G_{\rm RP}$ band) to a precision reaching the milli-magnitude level. Furthermore, *Gaia* will provide astrometric time series and spectrophotometric (BP and RP) epoch data, as well as spectroscopic (RVS) epoch data and radial velocity time series for stars brighter than about $G = 15.5$ mag.

The data downlinked to Earth by the *Gaia* spacecraft is processed by the *Gaia* Data Processing and Analysis Consortium (DPAC). Within this consortium, the detection and processing of EBs is ensured by two Coordination Units (CUs): CU7, responsible for variable source detection, classification and characterization, and CU4, responsible for non-single star processing. Their respective roles in the processing of EBs are described in the next sections.

## 2. Detection of EBs and geometrical characterization of their light curves

Coordination Unit 7 within the *Gaia* Consortium identifies EB candidates from the classification of all variable objects, and derives their orbital period from their photometric time series (Holl et al., 2013, 2014). Additionally, CU7 characterizes the geometrical properties of their light curves using a two-Gaussian model (Mowlavi et al., 2017). The list of EB candidates is passed to CU4 for the derivation of binary model parameters (see next section).

## 3. Estimation of EB system parameters

The next step in the processing of an EB takes place in the CU4 Non-Single Stars section, and consists in modeling the observational data, namely the available light curves $(G, G_{\rm BP}, G_{\rm RP})$ as well as the radial velocity curve(s) if the object is also detected as a spectroscopic binary, with the aim of extracting the largest possible amount of information about the system given the observational and computational constraints. Depending on the viewing geometry and the physical properties themselves, this information can include the orbital parameters of the EB (inclination, eccentricity, argument of periastron) along with physical properties such as the stellar radii, temperatures and mass ratio.

This is accomplished by adjusting the sought-after parameters to the observational data in a maximum likelihood sense, through the use of an EB simulator capable of generating realistic light and radial velocity curves as a function of these parameters. An overview of this procedure, the *Gaia Eclipsing System Simulator and Solver (GESSS)*, is provided in Siopis & Sadowski (2012).

The massive scale of the data imposes the requirement of an automatic processing. The pipeline software that performs this functionality needs to be tested and validated from a software engineering as well as from a science perspective. This section touches upon the scientific validation part, which tests separately the two components of the software, namely the EB simulator and the optimizer,

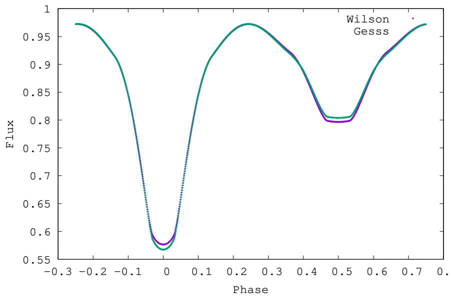


**Figure 1.** Comparison between the light curves generated at the same 1000 phases by GESSS and by the WD code shows that they overlap almost exactly. They were generated for the same set of physical parameters corresponding to the BW Eri system, shown in arbitrary flux units in Johnson *V*.

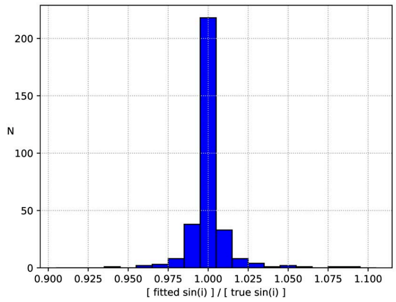


**Figure 2.** A histogram of the ratio of the fitted $\sin i$ over the true $\sin i$ for the 323 EBs from Terrell et al. (1992), sampled according to the *Gaia* scanning law, and with photometric uncertainties corresponding to those of a $G{\sim}13$ mag object.

the correctness of the former being of course a prerequisite for the correctness of the latter.

### 3.1. Validation of the EB simulator

The EB simulator calculates flux and radial velocity time series for a given set of input physical parameters. In order to validate the accuracy of the time series, they were compared against the time series produced by the Wilson-Devinney (WD) code (Wilson & Devinney, 1971; Wilson, 1979, 1990) using as input for both GESSS and WD the physical parameters of 323 EBs from Terrell et al. (1992). A black body atmosphere model was used in both GESSS and WD to avoid complications due to differences in the stellar atmosphere models used by default in the two codes. As shown in Fig. 1, the agreement is very good. Moreover, the normalized $\chi^2$ difference between the light curves generated by the two codes remains smaller than $\sim 10^{-5}$ for nearly all 323 EBs in the sample. There is a slight discrepancy around the minima that is visible in some cases, which is due to small differences in the limb darkening coefficients used by the two codes.

### 3.2. Validation of the optimizer

The optimizer performs a simultaneous adjustment to all available light and radial velocity time series to obtain the best-fit physical parameters for the EB.

The validation of the output is done in a variety of ways, including:

- Fitting synthetic EB observations produced either by the Gaia Object Generator (GOG), which is a CU2 (Simulations) project that approximates a realistic distribution of EB parameters, or internally at CU4 to focus on specific factors (stellar atmospheres, *Gaia* scanning law, data noise, etc.)

- Using real EB data from *Gaia* to perform statistical analyses of large numbers of anonymous objects, or of a small number of well-studied objects.

One type of testing uses again the physical parameters of 323 EBs in Terrell et al. (1992) to generate synthetic light curves of real EBs incorporating various noise levels (thus simulating the effect of varying mean magnitude) and various sampling strategies (uniform vs *Gaia* scanning law). Fig. 2 illustrates the distribution of the ratio of the sines of inclination, $\sin i$, in the calculated solutions over their true values. As $\sin i$ is crucial in determining mass ratios for simultaneously eclipsing and spectroscopic binaries, it is satisfying that the distribution is strongly peaked around unity.

## 4. Towards *Gaia* Data Releases 3 and 4

The full results of the nominal mission will be available in data release 4 (DR4), planned at earliest for 2024. But a fraction of these EBs will already be published in DR3 during the second half of 2021, thereby providing an early opportunity for the scientific community to study populations of EBs observed by *Gaia*.

The DR3 catalogs will contain the photometric ($G$, $G_{\mathrm{BP}}$ and $G_{\mathrm{RP}}$) time series of the published EB candidates, and the processing results of both CU7 (estimated period and geometrical characterization of the light curves) and CU4 (physical parameters for the subset of the sample for which binary system solutions are found).

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# On some strange features in *Kepler* EB light curves

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**Abstract.** We have scrutinized the approximately 3 thousand compiled eclipsing binary light curves of the *Kepler* mission in detail and found several typical and repeated common artifacts. We will present some of them and point out their possible origin.
**Key words:** binary stars – data processing

## 1. Introduction

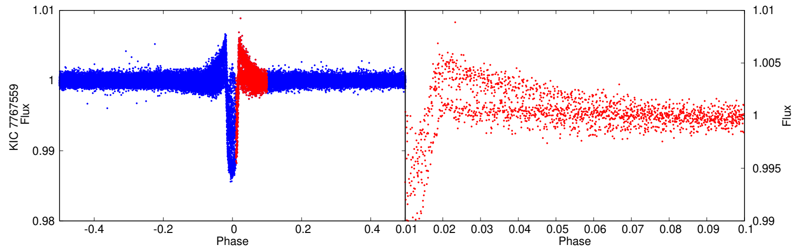
The *Kepler Eclipsing Binary Catalog - Third Revision* contains data for about 3000 systems (Prša et al, 2011). Enumerate all the papers connected to the database we could get around 1300 papers in the literature published during the last decade, so its impact is definitely huge.

One could suppose that this uniquely large database with unprecedented accuracy would provide a good foundation for detailed studies as it was advocated, e.g. in Wilson (2003), to look for an efficient, effective, and automatic processing of massive database secured by large-scale surveys but *'Eclipsing binary (EB) modeling naturally partitions into several areas, headed by the overall issue of how to find astrophysically useful numbers.'* (Wilson, 2006) However, the number of studies discussing astrophysical details is much more limited.

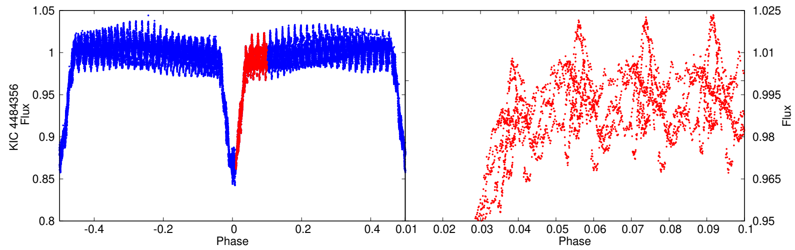
Pursuing this main goal, we have browsed through the catalog of corrected and detrended light curves in the database, and have found a few typical features created during data processing. These detections demonstrate that one must be careful around the details before using the data directly to deduce any physical conclusion. The artificial side effects contaminate the real data and can mimic otherwise pretty intriguing real effects.

## 2. Discussion

The first plot shows an upward trend distortion around eclipses arising from the applied detrending procedure. However, from a purely mathematical viewpoint, it could come from Gibbs overshooting at breakpoints of smooth functions cleaning the data. From physical point of view, considering possible non-radially




pulsating components in the system, it might be a physical effect from the amplification and modulation of hidden modes (l+m=odd) during partial eclipses. Even so, zooming into the plot one can disclose these latter origins and conclude that it comes from the data processing.




The phase folded light curve shows seemingly a pulsation like pattern. If it came from a physical oscillation, it would only be possible with locked synchronization to the orbital motion. Zooming into the plot the structure reveals that the observed pattern cannot be a real one. Considering the long term behavior one can recognize some slow variability of it, the real origin of the oscillation in the data series. The observed structure is only a moire noise pattern, due to that the ratio between the sampling rate commensurate with the period of variation and the period search algorithm could get better fitting with an incorrect value.

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# Hierarchical triple star systems towards the Galactic Bulge through OGLE's eye

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**Abstract.** We report the result of eclipse timing variation (ETV) analyses of OGLE-IV eclipsing binaries (EBs). We have identified around 1000 potential triple (or multiple) system candidates and, in addition, we determined the orbital parameters and we carried out statistical analyses of the properties of the candidates. We found that (i) the distribution of the outer eccentricity has a maximum around $e_2 = 0.3$; (ii) in most cases the estimated outer mass ratio is lower than $q_2 \sim 0.5$. Besides, we also present some systems that deserve special attention.

**Key words:** binaries: close – binaries: eclipsing – methods: numerical

## 1. Introduction

The investigation of triple stellar systems is not only important to understand the orbital evolution of the close binaries, but also to study their life (Toonen et al., 2016). Furthermore, the various formation theories of close binary systems, e. g. the so called Kozai Cycles with Tidal Friction (KCTF) mechanism (see, e. g. Kiseleva et al., 1998; Fabrycky & Tremaine, 2007; Naoz & Fabrycky, 2014), as well as the recently proposed different disk and core fragmentation processes (Tokovinin, 2018; Moe & Kratter, 2018), require the presence of a third component to explain the large number of non-evolved binary systems with very short orbital period.

The Optical Gravitational Lensing Experiment (*OGLE*) was designed for discovering dark matter using the microlensing technique in 1992 (Udalski et al., 1992). Recent and past OGLE surveys were found to be useful e.g. for exoplanet exploration (Bouchy et al., 2004) and for the investigation of variable stars (Soszyński et al., 2016). The Galactic Bulge part of the *OGLE-IV* survey with its approximately 450 000 EBs, which were identified by Soszyński et al. (2016) gives us a good chance to increase the number of the candidates of hierarchical triple stellar systems.

In this paper we present the results of searching for hierarchical triple star candidates towards the Galactic Bulge with ETV analyses of EBs observed during the *OGLE-IV* survey.

## 2. Third body effects on the ETV

One of the best known methods for the identification of a third companion around an eclipsing binary is based on the detection and analysis of the eclipse timing variations of the binary. If an EB has a distant, third companion, its distance from the observer varies periodically due to the EB's revolution around the common center of mass of the system. As a natural consequence, the light-travel time effect (LTTE) occurs.

If the third component significantly approaches the EB then other effects called dynamical perturbations also appear which have a very complicated dependence on the orbital elements. The most thorough discussion of these effects can be found in Borkovits et al. (2015).

## 3. Data processing

The *OGLE-IV* survey provided around 425 000 light curves of EBs. Unfortunately most of them do not contain enough data points for a detailed examination. Therefore we investigated only those systems whose light curves contain more than 4000 points. Applying this criterion, we reduced our sample to $\sim 80\,000$ systems.

To generate and analyse O−C (Observed minus Calculated) diagrams we used an automatic algorithm. It needs only the orbital period of the EB and its light curve (LC) as input. It uses the folded and binned LC of an EB to determine the phase borders of the eclipses and to generate template LCs for them.

To get more precise O−C curves for the ETV analyses we used several consecutive eclipses to determine only one point since mostly the individual cycle to cycle LCs are poorly covered. The program fits the parameters of the primary and the secondary minima at once, therefore we get a kind of averaged O−C diagram. As a next step, a combined grid-search and Levenberg-Marquardt algorithm was used to search for candidates and determine the parameters of the LTTE. More details about this method and the results can be found in Hajdu et al. (2019).

The above method is effective for searching systems with long tertiary periods. However, there are several systems which have relatively short periods and their ETV shows significant dynamical effects. These types of systems can be found if we determine all possible times of eclipse minima. This can be done in our case, if the LC is poorly covered, if we fit only the shifting parameter which represents the O−C point.

## 4. Results

In conclusion, we have found about a thousand hierarchical stellar system candidates with the first method. Four of them are possible quadruple systems based on their residual ETVs. A third component is a possible brown dwarf based on the its mass function and the mass of the W UMa close binary (Dimitrov & Kjurkchieva, 2015). We have also found several new triples with relatively short outer period ($P_2 < 300^d$) using the second method.

### 4.1. Statistical analyses of the parameters

Due to the large number of triple system candidates, it is worth while to examine distributions of the parameters determined with the LTTE delays.

Owing to the fact that the derived eccentricities have a large uncertainty, we used the Kernel Density Estimation method to determine the dispersion of the outer eccentricities. The distribution has a significant peak around $e_2 \approx 0.3$

Figure 1 represents the period-period correlation of the candidates which shows a grouping around outer period $P_2 \approx 2000^d$ which equals the length of the observation. It is possible that if the real outer period is significantly longer than our data length, then the LM-fit more likely converges to a lower period value that is closer to the duration of the time span.

In the absence of the known binary masses in our sample, the minimum masses of the tertiary components were estimated from the mass function with the assumption that $m_{AB} \simeq 2M_\odot$. Regarding our sample, one finds that the vast majority of the candidate systems have minimum outer masses less than $1M_\odot$, i.e. an outer mass ratio of $q_{2min} < 0.5$.

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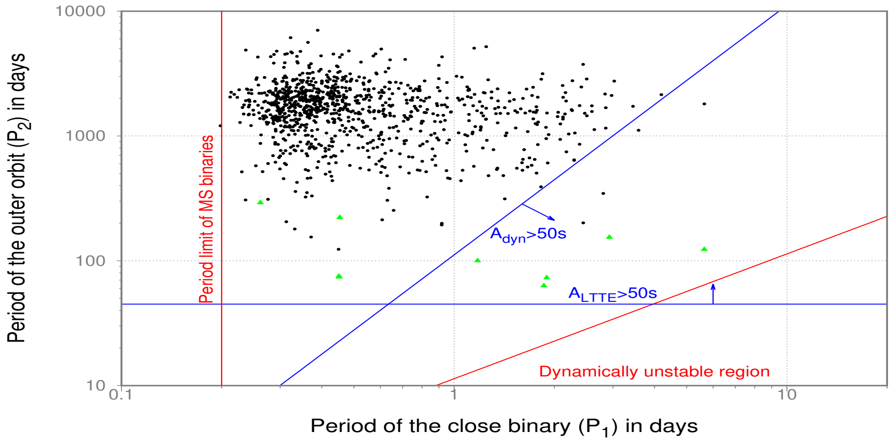


**Figure 1.** The location of the triple star candidates based on the first method (black dots) and based on the second method (green triangles) in the $P_1$ vs $P_2$ plane.


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# Galactic members in the New Online Database of Symbiotic Variables

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**Abstract.** Symbiotic variables belong to an interesting class of interacting binary stars. At the beginning of this century, a systematic search for these objects was begun and such surveys in the Milky Way and the Local Group have resulted in discoveries of many new symbiotics and dozens of candidates. Because the latest catalogue of symbiotic binaries has been outdated for almost two decades, we decided to prepare a new database of the Galactic and extra-Galactic symbiotic systems. We present it in this work. Our database is available online, allowing it to be up-to-date and available to the astronomical community at any time. The database also includes a web portal that allows easy data access without the necessity for any additional software or formatting of the data.

**Key words:** catalogues — binaries: symbiotic

## 1. Symbiotic stars

Symbiotic variables are the widest interacting binaries consisting of a cool giant (or a supergiant) of a spectral type K or M (rarely G) as the donor and a compact star, most commonly a hot (about $10^5$ K) white dwarf[1] as the accretor of transferred matter (Mikołajewska, 2007).

Mass transfer between the components most likely takes place via the cool giant's wind (e.g. Mikołajewska, 2007), which is also the source of a dense circumbinary environment. The spectra of these objects are therefore a superposition of three components of radiation – two stellar and one nebular (e.g. Skopal, 2005). The cool giant usually dominates the spectrum at longer wavelengths (in the IR) and the hot component mainly radiates in the UV and blue part of the optical region. Symbiotic spectra are often rich in emission lines (Balmer lines of H, and neutral and ionized He, Fe lines). Emission lines of a special interest are Raman-scattered lines of O VI which are an exclusive feature of symbiotic

[1] It is worth noting that several symbiotic binaries with accreting neutron stars have also been identified (e.g. Corbet et al., 2008; Enoto et al., 2014, and references therein).

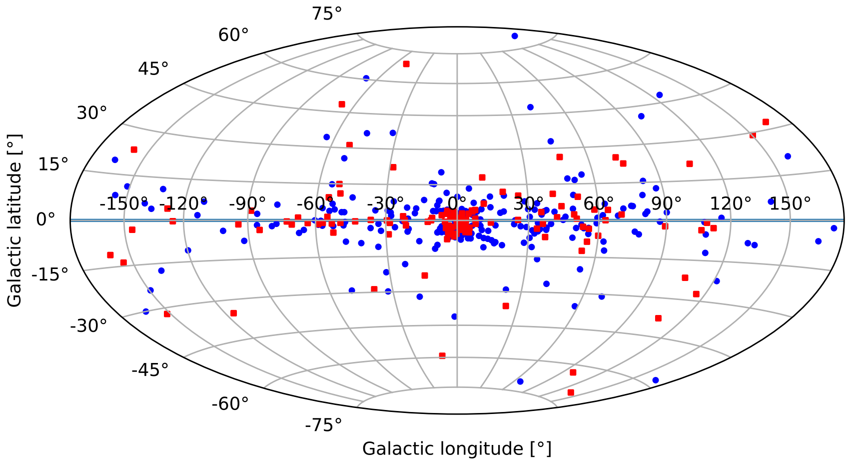


**Figure 1.** Distribution of the Galactic symbiotic stars according their Galactic coordinates. Confirmed and suspected symbiotic stars are denoted by blue dots and red squares, respectively.

binaries (Akras et al., 2019) and provide a strong criterion for spectroscopic identification of new symbiotics.

Since the beginning of the 21st century, a systematic search for symbiotic binaries has been running, and not only in the Milky Way (e.g. Miszalski et al., 2013; Miszalski & Mikołajewska, 2014) but also beyond it in nearby galaxies. Some surveys have resulted in the identification of new extra-Galactic symbiotic variables or at least promising candidates (e.g. Gonçalves et al., 2008, 2015; Kniazev et al., 2009; Mikołajewska et al., 2014, 2017). Thanks to these surveys, the number of known symbiotic systems is growing rapidly.

## 2. New Online Database of Symbiotic Variables

Based on the recent progress in the search for and study of symbiotic stars, we have decided to prepare a new database of these interacting binaries. The purpose of the database is not only to serve as a catalogue of data for all known symbiotics with consistent references, but we have also prepared a web-portal for easy access to this information. Making the database online allows us to add new objects as soon as they are discovered and update or complete data when new information becomes available. In this way, up-to-date lists of symbiotic variables and information about particular objects could be available to the astronomical community at any time.

The full version of the database contains all available data on the location of objects, their brightness in various spectral regions and other observational properties (such as the presence of outbursts, flickering, detectable X-ray or radio emission and symbiotic type). The database also provides information on orbital elements (periods, ephemerides, presence of eclipses etc.) and parameters of the binary components (spectral types, temperatures, masses, radii, luminosities, presence of pulsations etc.).

For the catalogued symbiotic stars, we have prepared specific object pages covering all available information included in the database. The data provided are accompanied by appropriate references that are directly linked to quoted articles in the ADS database, making it easier and faster to find them. The latest version of the New Online Database of Symbiotic Variables is available at the internet address `http://astronomy.science.upjs.sk/symbiotics/`.

The extra-galactic part of the database was presented by (Merc et al., 2019). We are continuing to prepare the Galactic part of the database. The list of all confirmed and suspected objects with their basic parameters is already available. The distribution of the Galactic symbiotic stars according their galactic coordinates is shown in Fig. 1.

Almost all Galactic symbiotic stars are located around the Milky Way equator ($|b| < 15°$). For the objects in the current version of the database, 89% of the confirmed and 83% of candidate symbiotics are located in this sky region. The distribution in Galactic longitude demonstrates that symbiotics are located mostly towards the galactic bulge (56% and 52% of the confirmed and candidate symbiotics within $|l| < 30°$, respectively). However these ratios are biased by a selective effect because surveys tend to focus on the surroundings of the Galactic equator and also the density of stars is higher in the Galactic disk.

## 3. Conclusions

Symbiotic binaries can serve as unique astrophysical laboratories in the study of accretion processes, winds and jets. Moreover, they are important for evolutionary models as they may be one of the type Ia supernova progenitors. However, a proper characterization of the symbiotic population is still lacking. The systematic search for these objects, which has begun recently, has caused the number of known systems to grow rapidly. This has led to the need for a new catalogue of symbiotic binaries that allows systematic studies. For this reason we are preparing the New Online Database of Symbiotic Variables, which would serve not only as a catalogue of all available information on particular symbiotic stars but also as a web portal for easy access to these data. The extra-Galactic part of the database is already filled and an updated list of Galactic symbiotic stars has been recently released.

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# How far can we trust published *TESS* periods?

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**Abstract.** Possible inaccuracies in the determination of periods from short-term time series caused by disregarding light curve instrumental effects are documented. As an example, we present a Lomb-Scargle period analysis of a simulated *TESS*-like light curve.

**Key words:** stars: variable – period analysis – *TESS* data

## 1. Introduction

*TESS* data are now one of the most popular sources of information about variable stars, including their periods. However, *TESS* data suffer from two shortcomings that significantly corrupt the results of period analyses with standard tools. The data are usually strongly affected by instrumental trends of various kinds, and secondly, they are obtained in non-standard short time intervals (for example 27 days for *TESS*) that are often comparable to the periods themselves. The majority of such days-long periods and their uncertainties are mere artifacts of the method used to determine them. At best, they are just estimates.

The most commonly used method is the so-called Lomb-Scargle method (Press & Rybicki, 1989) or its sophisticated versions, enabling to take into account the weights of individual measurements and to estimate the amplitudes of the found frequency peaks (Mikulášek et al., 2015). All of these methods give identical results because they are based on fitting the observation series with a first-order harmonic polynomial model using the least squares method.

The following demonstration based on a simulated periodic light curve resembling that of a rotating chemically peculiar stars with a period of 2.7 days (see Fig. 1) shows possible pitfalls of standard processing of these types of data.

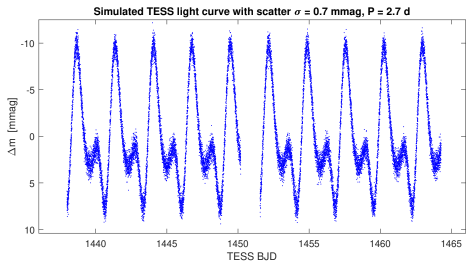


**Figure 1.** Simulated light curve without trends represented by 17 925 points.

## 2. Simulation of "*TESS*-like" data of a hypothetical CP star

Chemically peculiar (CP) stars are rotating stars with extensive photometric spots on their surface. The observed light changes of such objects are strictly periodic and can be described by a low-degree harmonic polynomial. For our example, we chose a two-wave curve represented by a third-degree harmonic polynomial, described by five parameters (Fig. 2) of the *phase function*, $\vartheta$ (for details see Mikulášek et al., 2008), $F(\vartheta, \mathbf{a})$, $P = 2.7\,\mathrm{d}$, with a maximum at phase $\varphi = 0$. We have

$$\vartheta = \frac{t - M_0}{P} = E + \varphi, \quad M_0 = 1450 + P\Delta\varphi, \quad E = \mathrm{IP}(\vartheta), \quad \varphi = \mathrm{FP}(\vartheta), \quad (1)$$

with

$$F(\vartheta, \mathbf{a}) = a_1 \cos(2\pi\vartheta) + a_2 \cos(4\pi\vartheta) + a_3 \cos(6\pi\vartheta) +$$
$$+ a_4 \left[2 \sin(2\pi\vartheta) - \sin(4\pi\vartheta)\right] + a_5 \left[3 \sin(2\pi\vartheta) + 6 \sin(4\pi\vartheta) - 5 \sin(6\pi\vartheta)\right], \quad (2)$$

where $t$ is the *TESS* BJD time of the observation ($t = \mathrm{BJD} - 2\,457\,000$), $M_0$ is the *TESS* BJD time of the initial light curve maximum, $\Delta\varphi$ is an optional *initial phase* parameter allowing for a horizontal shift of the simulated light curve, $E$ is the integer epoch and $\varphi$ the phase. IP and FP indicate the integer and fractional part of a variable. We also have $a_1 = -5$, $a_2 = -4.5$, $a_3 = -0.5$, $a_4 = -0.67$, and $a_5 = -0.17\,\mathrm{mmag}$. The simulated *TESS* light curve is represented by 17 925 points obtained at a cadence of 2 minutes (see Fig. 1). Upon demand the curve can include trends and Gaussian scatter.

## 3. The role of the initial phase $\Delta\varphi$

The amplitude frequency spectrum of the simulated light curve shows, as expected, three dominant, equidistant peaks with central frequencies $f_1, f_2$, and $f_3$ (Fig. 2), each carrying the period information: $1/f_1 = 2/f_2 = 3/f_3 = P$.

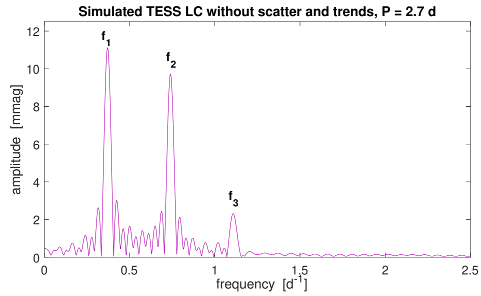


**Figure 2.** The amplitude periodogram of the simulated light curve without scatter and trends for $\Delta\varphi = 0$.

However, this is fulfilled only approximately. If we limit ourselves to two peaks, then for $\Delta\varphi = 0$ we get $P_1 = 1/f_1 = 2.7070(10)$ d, and $P_2 = 2/f_2 = 2.6977(8)$ d. The deviation from the baseline period $P = 2.7$ d thus is evident and far exceeds the limits given by the uncertainty of the positioning of the frequency peaks. Why such difference? Other simple period finders give the same results.

The discrepancy would only disappear if the light curves were purely sinusoidal without higher harmonics. If the light curves deviate from this ideal, the so-called 'periods' determined are not real periods, but only parameters found by regression with an inadequate model that differs (sometimes flagrantly) from the real frequency pattern. Fig. 3 shows that the values of those 'periods' found in the periodograms are a complex periodic function of the initial phase $\Delta\varphi$, whose amplitude is unacceptable in comparison with the formal determination of the uncertainty.

## 4. Influence of light curve trends

Both *TESS* and *Kepler* observations are strongly affected by aperiodic instrumental trends (Hümmerich et al., 2018; Mikulášek et al., 2019). Neglecting these has a devastating effect on period analysis (Fig. 4). Appropriate detrending of the observed light curves is highly desirable if we want to fully realize the benefits of the unprecedented accuracy of satellite photometry.

## 5. Modelling of light curves with trends

When applying the Lomb-Scargle method, we have to subtract from each data point the mean value of the data set. Subsequently, the data are fitted by the simplest possible model for a periodic light curve, i.e. a linear combination of a pair of harmonic functions $F = a_1 \cos(2\pi f) + a_2 \sin(2\pi f)$, where the amplitude $A = \sqrt{a_1^2 + a_2^2}$ is a function of the frequency, $f$, and plotted on the $A(f)$-$f$

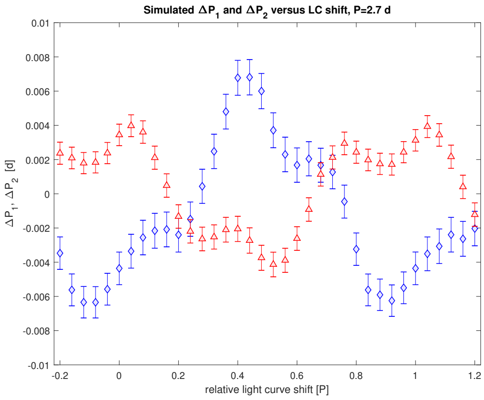


**Figure 3.** $\Delta P_1 = P_1 - P$ (blue diamonds) and $\Delta P_2 = P_2 - P$ (red triangles) differences as a function of the light curve shift $\Delta\varphi$.

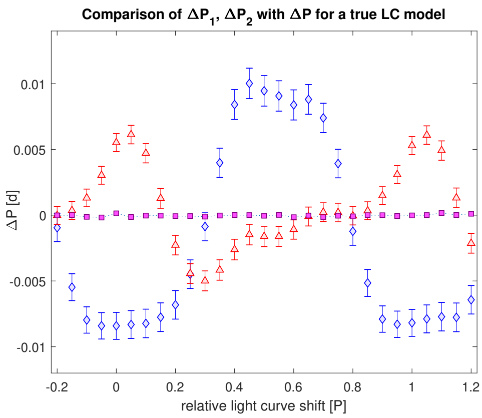


**Figure 4.** The comparison of $\Delta P_1$ (blue diamonds) and $\Delta P_2$ (red triangles) differences and true model ones (pink squares) for a non-detrended light curve as a function of the LC shift $\Delta\varphi$.

periodogram. The extrema of the plotted function are then searched for and interpreted. Uncertainties of the frequencies determined by least-squares tools are generally defective (most often they are underestimated) simply because the conditions for applying the least squares method are not fulfilled.[1]

It is apparent from the foregoing examples that the use of conventional low-parametric models is not sufficient for the description of high-precision real light

[1]Residuals do not have a normal distribution, consecutive residuals are not independent, etc.

curves provided by modern instruments, in particular satellites. It is, therefore, essential to use more advanced models to simultaneously fit a phase curve with a harmonic polynomial of at least third degree, while modeling trends by dividing the light curve into segments and describing each with a polynomial of the appropriate degree (Mikulášek et al., 2019; Hümmerich et al., 2018). Phase curves and trend models should be tailored to the actually observed light curves. The models should be functions of the parameters of the ephemeris of stellar periodicity, especially the reference time of the basic extremum, the mean period (or periods) and their time derivatives (Mikulášek, 2015, 2016).

Modern tools such as a chi-square approach, robust regression, bootstrapping, etc., can be used to find parameters (including period/periods) and their uncertainties. In Fig. 4 results of such a rigorous procedure are compared with the results obtained by standard trivial period analysis procedures. The comparison speaks for itself and no further comments are needed.

## 6. Conclusions

- Short-term observational series corrupted by instrumental trends are not the easiest observational material for accurate determination of periods.
- Lomb-Scargle and its derivatives are sources of serious errors both in the determination of periods and their uncertainties.
- In the period analysis of *TESS* data, the differences between the obtained and the real periods can be so huge that we are not able to predict the correct phase at a particular moment in time that differs more than a few months from the actual time of observation.

A rigorous solution to the problem is to move to realistic models of light curves, including a true description of phase curve/curves as well as instrumental trends. Only then will we fully use the information potential of short-term sets of observational data.

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# Photometric study of 61 totally eclipsing contact binaries from the ASAS, OGLE, HATNet, AST3 and *TESS* databases

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**Abstract.** Contact binaries form an interesting class of binaries which not only show mutual interactions through gravitationally bound periodic close orbits, but also dynamical interactions through mass transfer, angular momentum loss and modulation of their orbits due to the presence of tertiary components and magnetic activity. They are important as distance indicators and laboratories to study stellar evolutionary models. The current work highlights our photometric study of 61 totally eclipsing contact binaries from the ASAS, OGLE, HATNet, AST3 and *TESS* databases. Physical parameters are derived using PHOEBE. The selected binaries fall in a range of short periods (0.34-0.97 d), low mass ratios (0.076-0.504), F5-M0 spectral types, and a wide range of fillout factors (3-85%). Based on obtained fillout factors, 5 were classified as shallow/marginal contact, 41 as over-contact and 15 as deep-contact binaries. The absolute parameters are compared with those of well-studied binaries. Possible evolutionary states are discussed.

**Key words:** binaries: contact – eclipses: total – O'Connell effect

## 1. Introduction

Eclipsing binaries in pre-contact and marginal contact phases are important systems to help understand close binary evolution from detached to contact stages. The contact binary systems with mass ratios $< 0.25$ and fillout factors $> 50\%$ are prominent sources of interest, as they are progenitors of some fascinating objects and related to several key astrophysical processes (Liao et al., 2017).

## 2. Data collection and analysis

Photometric data of contact binaries with totality were collected from various archival databases like the All Sky Automated Sky Survey-3 (ASAS, Pojmanski, 2004), the Optical Gravitational Lensing Experiment-3 (OGLE, Udalski et al., 2008), the Hungarian Automated Telescope Network (HATNet, Hartman et al., 2004), the Antarctic Survey Telescope at Dome A (AST3, Wang et al., 2017), and the Transiting Exoplanet Survey Satellite (*TESS*,Stassun et al., 2018). We identified for further analysis a total of 61 variables from these databases (parameter ranges in Table 1) showing totality at one or both eclipses. Period

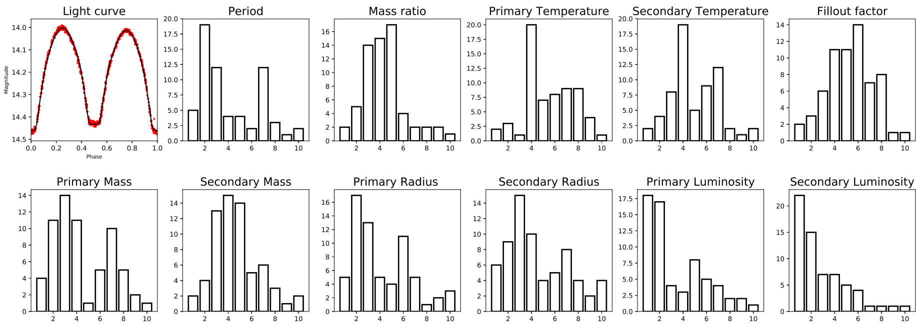


**Figure 1.** (a) Model light curve with observations shown as circles and the therotical fit as a solid line; (b) Histograms showing number distributions of various parametes for the 61 objects under study.

searches were performed using Persea (Schwarzenberg-Czerny, 1996) to derive ephemerides for all the variables. Phased light curves were then analysed using the software package PHysics Of Eclipsing BinariEs (PHOEBE) (Prša, 2006). Effective surface temperatures of the primary components ($T_1$) were taken from Gaia2 (Brown et al., 2018) for the OGLE, HATNet and AST variables, calculated using Allen's tables (Allen & Cox, 2000) for ASAS variables, and adopted from the *TESS* database (Stassun et al., 2018) for *TESS* variables. The gravity darkening coefficients $g_{1,2}$ (Lucy, 1967) and albedos $A_{1,2}$ (Rucinski, 1969) were adopted in accordance with the temperature of the stars. Adjusted parameters were $q$, $T_2$, $L_1$, $i$ and $\Omega$ and iterations were performed to get synthetic light curves with minimum $\Sigma(O-C)^2$ between observations and synthetic curves. For totally eclipsing binaries, Pribulla et al. (2003a) found that mass ratios derived from photometric data are comparable with those derived from spectroscopic analyses. Also, Terrell & Wilson (2005) came to a similar conclusion for over-contact systems. Hence, for our systems, mass ratios determined from light curves can be considered to be reliable. During the analysis, 16 variables showing asymmetry in their light curves, i.e. an O'Connell effect, (O'Connell, 1951) were fitted with spots. Fillout factors were calculated using the equation $F = (\Omega_{in} - \Omega)/(\Omega_{in} - \Omega_{out})$, where $\Omega_{in}$ and $\Omega_{out}$ are the potentials of the inner and outer Lagrangian equipotential surfaces, respectively. The variables were classified on the basis of fillout factors as shallow/marginal, over-contact and deep-contact binaries. The absolute parameters were derived using the Gazeas (2009) relations.

**Table 1.** Range of Parameter Values

| | ASAS | OGLE | HATNet |
|---|---|---|---|
| No. of Objects | 2 | 48 | 3 |
| Field | disk | bulge | disk |
| $P$ (days) | 0.3787-0.7419 | 0.3486-0.9598 | 0.4258-0.9731 |
| Distance (pc) | 227.8-321.1 | 659.2-3003.9 | 891.4-11299.4 |
| $T_1$(K) | 5475-6475 | 4092-6512 | 5574-6541 |
| $q$ | 0.197-0.220 | 0.132-0.380 | 0.096-0.180 |
| $\Delta T = T_1 - T_2$ (K) | 68-316 | 48-812 | 282-1009 |
| $F$ (%) | 11-35 | 3-85 | 21-49 |
| $M_1$ ($M_\odot$) | 1.29-2.11 | 1.16-2.52 | 1.42-2.65 |
| $M_2$ ($M_\odot$) | 0.28-0.42 | 0.21-0.64 | 0.14-0.36 |
| | AST3 | TESS | All |
| No. of Objects | 6 | 2 | 61 |
| Field | disk | disk | bulge/disk |
| $P$ (days) | 0.3672-0.7808 | 0.50449-0.53480 | 0.3486-0.9731 |
| Distance (pc) | 1536.8-4280.8 | 738.2-1196.5 | 227.8-11299.4 |
| $T_1$(K) | 4897-5873 | 5959-6450 | 4092-6541 |
| $q$ | 0.143-0.504 | 0.076-0.129 | 0.076-0.504 |
| $\Delta T = T_1 - T_2$ (K) | 220-410 | 415-508 | 48-1009 |
| $F$ (%) | 18-31 | 3-26 | 3-85 |
| $M_1$ ($M_\odot$) | 1.18-2.20 | 1.71-1.72 | 1.16-2.65 |
| $M_2$ ($M_\odot$) | 0.26-0.59 | 0.13-0.22 | 0.13-0.64 |

## 3. Results and conclusions

Light curve analyses were perfomed on 61 short period ($P < 1\,\mathrm{d}$), totally eclipsing contact binaries of later spectral types (F5-M0) using PHOEBE. The distribution of basic parameters is shown in Fig. 1 and listed in Table 1. We found that 16 variables were showing light curve asymmetries near maxima (O'Connell effect), and best fit solutions were obtained after incorporating starspots. Furthermore, the derived absolute parameters show that primary components are more massive than their companions. As all the binaries in this study are totally eclipsing, the derived mass ratios and basic parameters are more reliable. Most of the binaries in this study are found to be low mass ratio systems with primaries the more massive of the two stars. One system in particular shows a very low mass ratio ($q \sim 0.07$) and is similar to some of the well-known low mass ratio systems (Oh et al., 2007). Many of our systems are interesting sources for follow-up observations and for improving binary evolutionary models.

From the solutions we found 15 deep-contact ($F > 50\%$), 41 over-contact ($50\% > F > 10\%$) and 5 shallow/marginal contact binaries (F<10%). The ob-

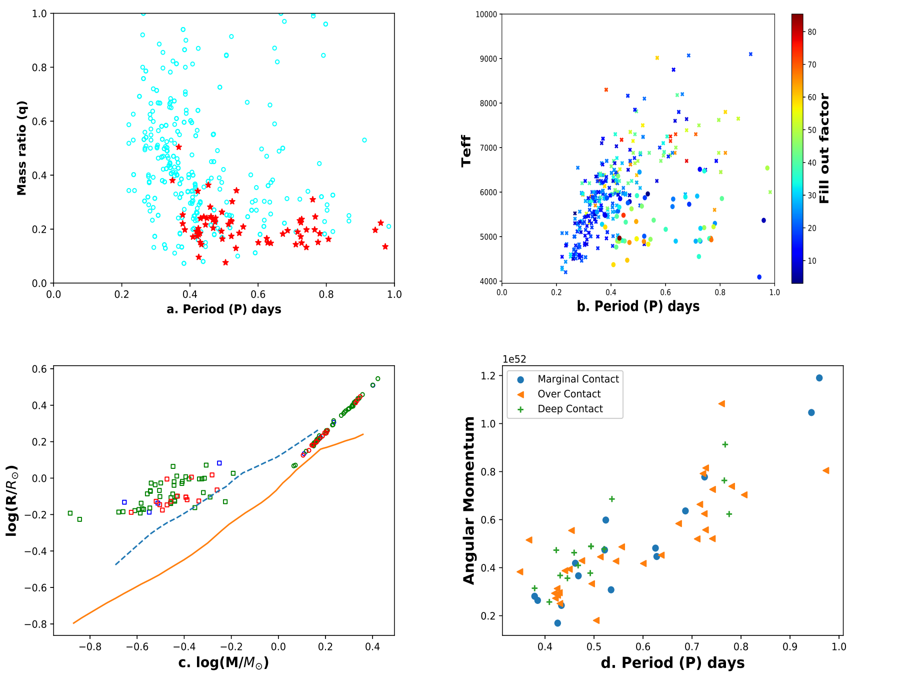


**Figure 2.** a. Orbital period vs. mass ratio for contact binaries, with red symbols indicating the 61 objects of this study, and circles representing the database of well studied contact binaries (Pribulla et al., 2003b; Csizmadia & Klagyivik, 2004; Deb & Singh, 2011); b. Orbital period vs. effective temperature, with colored bars representing fillout factors; c. $\log M$ vs. $\log R$, with circles for primary and squares for secondary components, and blue indicating marginal contact, green over-contact, and red deep-contact binaries. Solid and dotted lines represent ZAMS and TAMS stars; d. Orbital period vs. total angular momentum of the binaries.

jects in the direction of the Galactic bulge were all over-contact systems. Large temperature differences between components are observed in a few systems with low fillout factors and could be due to their evolutionary state of transition between contact and broken contact phases, as explained by the thermal relaxation oscillation (TRO) model. The $P$ vs. $q$ (Fig. 2) plot shows that most of the binaries are A-type W UMa systems, however with a wide range of fillout factors. The $\log M$ vs. $\log R$ and $P$ vs. $T_{eff}$ (Fig. 2) plots show that most of the systems are evolved and have secondaries that are overluminous for their main sequence masses. The results add to the existing evidence that in short period contact binaries, late-type systems are more frequent than early type systems. Studying a larger number of objects in the short period cut-off range will allow correlations to be tested and help the development of better evolutionary models.

**Acknowledgements.** We acknowledge the archival databases of ASAS, OGLE, HATNet, AST3D, *TESS* and Gaia2 and the financial support provided for this research by DST (Govt. of India) SERB grant EEQ/2017/000411.

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# Binary stars with RR Lyrae components – new candidates in the Galactic bulge

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**Abstract.** There is a significant lack of binary stars with RR Lyrae components. In this brief contribution, we introduce 20 new candidates in the Galactic bulge identified on the basis of the Light-Travel-Time Effect with expected orbital periods between 3 and 15 years.

**Key words:** Stars: RR Lyrae – stars: binaries – Galactic bulge

## 1. Introduction

The mass of a star can be independently determined only when it orbits a common center of mass with another body in a binary system. This is something that is sadly lacking for RR Lyrae stars. There is only one RR Lyrae type star that is known to reside in the binary system (Liška et al., 2016a), and about one hundred candidates (listed in the online database Liska & Skarka, 2016)[1] determined mostly indirectly via the Light-Travel-Time Effect (LTTE, e.g. Hajdu et al., 2015; Liška et al., 2016b) or through proper-motion anomalies (Kervella et al., 2019).

Together with Cepheids and other radially pulsating stars, RR Lyrae stars serve as classical distance standard candles, and thus, it is crucial to know their masses accurately. Unfortunately, their masses are known only roughly from evolutionary and pulsation models (e.g. Sweigart, 1987; Popielski et al., 2000). An independent and accurate mass determination might be possible if the RR Lyrae star is identified as an eclipsing binary component, which would

[1] https://rrlyrbincan.physics.muni.cz/

not be an easy task. Due to the advanced evolutionary state of the RR Lyrae star (a horizontal-branch giant) the companion would most probably have to be a degenerate stellar remnant or low-mass main-sequence star, and in both cases it would be a small, faint object producing only shallow or no eclipses. Binary systems with other horizontal-branch or red-giant star components would produce more distinct observables. Such binaries, however, are less likely to be observed due to the short life-time of these evolutionary phases.

In addition, in order to avoid mass transfer during the evolution of the system prior to the formation of the classical RR Lyrae star, only wide systems are expected to have RR Lyrae components (Karczmarek et al., 2017). Thanks to photometric observations spanning decades, sometimes even one century, the easiest way to reveal candidates is through the light-time-travel effect (LTTE) (Sterken, 2005). However, without confirmation using radial-velocity measurements, the candidates cannot be assumed to be binary stars (Skarka et al., 2018).

## 2. New candidates

In our study focused on searching for additional binary candidates via cyclic period variations (Prudil et al., 2019), we investigated over 9000 stars from the Galactic bulge. Because long-term period changes can be confused with the long-term Blazhko effect, we selected only stars without detectable modulation based on the study by Prudil & Skarka (2017). We used data from the OGLE-III and IV phases (Soszyński et al., 2011, 2014), and the KMTNet survey (Lee et al., 2014), which give us datasets sometimes spanning more than 20 observing seasons.

For the investigation of the period changes, we used the method developed by Hertzsprung (1919). Each observing season was divided into two bins which were fitted with Fourier series using the OGLE ephemerides. The time delay was estimated from the phase shift of the light curves.

Initially, we found 200 stars with suspicious O-C's. Among these stars, the binary candidates identified by Hajdu et al. (2015) were also detected. To strenghten the reliability of our candidates, we performed the test introduced by Shibahashi (2017). We ended up with 20 strong binary candidates. Period variations of these 20 candidates were fitted assuming binarity by using expressions introduced by Irwin (1952). After fitting we get the full characterization of the orbits. The parameter ranges of the orbital parameters are listed in Table 1, the particular values and the full list can be found in Prudil et al. (2019).

## 3. Summary and future prospects

We complemented the currently known sample of RR Lyrae binary component candidates with 20 additional stars. The values are in accordance with expecta-

**Table 1.** Orbital parameter ranges of our 20 candidtes.

| $P_{\rm orb}$ [d] | $a\sin(i)$ [au] | $e$ | $\omega$ [deg] | $K$ [km s$^{-1}$] | $f(M)$ [M$_\odot$] |
|---|---|---|---|---|---|
| 1180-5041 | 0.18-4.28 | 0.05-0.61 | −362-272 | 0.87-9.82 | 0.0002-0.412 |

tions given by the used data and are similar to those published by Hajdu et al. (2015). Three of our candidate stars have assumed orbital periods less than 10 years and rather large amplitudes. Assumed companions of two of these stars are supposed to have minimal masses comparable or larger than the RR Lyrae component. In some circumstances (horizontal or asymptotic-giant branch nature of the companion) possible eclipses could be observed. In any case, all our candidate stars must be confirmed by radial-velocity observations, which will be the natural next step. Untill the candidates are confirmed using radial velocity observations, all the companions, periods, orbital parameters, etc. are only suspected.

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# K dwarf triples and quadruples in the SUPERWIDE catalog of 90,000 nearby wide binaries

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**Abstract.** The SUPERWIDE catalog is an all-sky catalog of ∼90,000 wide binaries with projected orbital separations ∼100 to 100,000 AU, mostly located within 500 pc of the Sun. These consist of common proper motion (CPM) pairs of high proper motion stars (> 40 mas/yr). A Bayesian analysis using positions, proper motions and distances from *Gaia* Data Release 2 (DR2) shows these pairs to have probabilities > 99% of being gravitationally bound systems. Here, we examine K+K wide binaries, which allow for easy identification of unresolved higher-order systems because the K dwarf main sequence is narrow and unresolved subsystems are easily identified as over-luminous. We found 980 systems where at least one of the wide components is over-luminous, which means they are higher-order systems (triples and quadruples). Although metallicity efffects generally complicate the identification of over-luminous stars, we show that this can be easily accounted for in wide binaries, making the identification of unresolved subsystems relatively straightforward. Taking these effects into account, we calculate the higher-order multiplicity fraction to be 39.6%.

**Key words:** stars: binaries – stars: low mass

## 1. Examining the over-luminosity of K+K wide binary components

Through a Bayesian analysis of *Gaia* Data Release 2 (*Gaia* Collaboration et al. 2018), we compile a catalog of ∼90,000 CPM pairs with >99% probabilities of being wide binaries. From this sample, we assemble a subset of 2,227 K+K wide binaries through a color cut $1.01 < G_{BP} - G_{RP} < 1.81$ and set a primary star distance limit $d < 250$ pc, with the primary star being the bluer component. An examination of the color-magnitude diagram shows a doubling of the main sequence in this region, representing the single star main sequence and the over-luminous branch of unresolved binaries. To better determine which stars are over-luminous, we define an arbitrary dividing line near the limit of the single/double loci, and define an "over-luminosity factor" for every component calculated relative to that line.

Because stars in wide binaries have correlated metallicities, a comparison of the over-luminosity factor of the primary and secondary components is used to identify the over-luminous components (i.e. unresolved binaries) as shown in Figure 1, which we call the “lobster diagram.” True wide binaries, i.e. without unresolved subsystems, are represented by the linear concentration of points starting around −0.1, the “body” of the lobster. Pairs in the purple shaded region represent possible quadruple systems where both components are over-luminous. The pairs in the yellow shaded regions represent possible triple systems where only one of the components is over-luminous. Finally, the red dotted areas (the “claws”) represent the areas where equal mass unresolved binaries should exist. With this analysis, we identify 1,343 true wide binaries, 449 pairs with an over-luminous primary, 339 pairs with an over-luminous secondary and 96 pairs where both components are over-luminous. From this, we calculate the higher order multiplicity fraction of K+K wide binaries to be 39.6%. If we only select pairs with projected physical separations larger than 10,000 AU, this value drops to 38.3%. This is significant because most predictions put the higher order multiplicity of these wide systems to be much larger, ∼70% (Law et al. 2010). However, our method probably underestimates the number of unresolved companions as it requires the tertiary to contribute enough light to cause the system to be over-luminous.

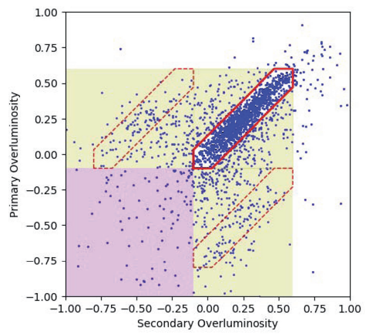


**Figure 1.** The “Lobster Diagram” showing the over-luminosity of the primary component plotted against the over-luminosity of the secondary component for the 2,227 K+K wide binaries.

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# Close binaries in hierarchical stellar systems

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**Abstract.** Many (but not all) close binaries are inner pairs in triple and higher-order hierarchical systems. The statistical relation between close binaries and hierarchical systems is well established. Although close binaries can form by a combination of Kozai-Lidov cycles with tides, the study of Moe & Kratter (2018) indicated that only a fraction of them could be produced by this mechanism and that many close binaries form even before stars contract onto the main sequence. The predicted statistical signatures of tidal formation, such as accumulation of periods just below the tidal cutoff, are not observed. Instead, the main channel of close-binary formation is likely accretion-driven migration. The relation between close binaries and triple stars is not casual, it derives from the common factor which is the accretion strength. High accretion creates massive stars that have a large fraction of close binaries and, at the same time, a large fraction of hierarchical systems.

**Key words:** binaries: close – binaries: multiple

## 1. Introduction

For those who study close binaries (ClBs), the presence of an additional "third" star in the system is an unwanted complication and a nuisance. Yet, it happens so often that many researchers have long suspected some profound relation between ClBs and triple (generally, multiple) systems. Batten (1973) suggested in his book that multiple systems may help us to understand the formation of ClBs that was (and still is) a mystery. Indeed, a nascent star collects gas from a large volume, hence two stars cannot form very close to each other and something must bring them together to make a ClB. Does the third star play a role in this process? Is its presence *necessary* for making a ClB?

Early data collected from the literature indicated that no less than 40% of solar-type binaries with $P < 10\,\mathrm{d}$ have additional companions, but the frequency of those companions decreases with binary period (Tokovinin, 1997). This finding stimulated further observations that confirmed the relation between ClBs and triples (Tokovinin & Smekhov, 2002; Rucinski et al., 2007; Tokovinin et al., 2006).

Gravitational interactions between stars in a non-hierarchical multiple system usually lead to ejections. The ejected star removes energy and angular momentum from the system, while the remaining binary hardens. However, the modest decrease in the binary separation by a factor of 3–10 is insufficient to make a ClB, unless the decaying system was itself already very compact. A much more elegant way to form a ClB in a *hierarchical* triple star was proposed by Eggleton & Kisseleva-Eggleton (2006). When the mutual orbit inclination exceeds 39°, it oscillates in the Kozai-Lidov cycles, accompanied by the periodic increase in the eccentricity of the inner orbit. The cycles are interrupted if the periastron distance in the inner orbit becomes so small that the tidal friction intervenes and modifies the dynamics of 3 gravitating masses. The Kozai cycles with tidal friction (KCTF) mechanism produces inner binaries with periods below the tidal cutoff ($P < 10\,\mathrm{d}$ for low-mass dwarfs) even in triple systems with wide tertiaries. Assuming randomly oriented orbits, Fabrycky & Tremaine (2007) predicted that the population of ClBs formed through KCTF has periods $P < 10\,\mathrm{d}$, while the mutual inclinations concentrate around 40° and 140°.

The KCTF mechanism, however, can be responsible for creating only a fraction of ClBs (Moe & Kratter, 2018). The frequency of ClBs in the pre-main sequence (PMS) and mature stellar populations is similar, while KCTF is too slow to operate at the PMS stage. Moreover, KCTF cannot produce binaries with periods substantially longer than the tidal cutoff. Further insights into the origin of ClBs can be obtained from a detailed study of their statistics.

## 2. Solar-type close binaries in multiple systems

In the 1990s, our knowledge of multiple systems was based on random discoveries, e.g., eclipse timing variations (ETVs) in eclipsing binaries, or visual companions to spectroscopic binaries. Yet, clean, volume-limited and complete samples are needed for statistics. The 25-pc sample of solar-type stars explored by Raghavan et al. (2010) contains only 54 hierarchical systems. The 67-pc sample (Tokovinin, 2014) is 10× larger, but many binaries discovered by radial velocity (RV) variations or astrometric accelerations have unknown periods.

Several observational programs were conducted to fill the gaps in the 67-pc sample. Of relevance here is the spectroscopic survey using the CHIRON echelle spectrometer. Observations of relatively wide visual pairs established that the frequency of subsystems in their primary and secondary components was comparable (Tokovinin, 2015); half of those 96 wide pairs contained a spectroscopic subsystem. A program to determine spectroscopic orbits of stars belonging to multiple systems in the 67-pc sample was started in 2014 and still continues, see references in (Tokovinin, 2019a); counting the Paper VI of these series (Tokovinin, 2019b), the total number of spectroscopic orbits is 45. With a complementary effort in the northern sky (Gorynya & Tokovinin, 2018), in the 67-pc sample there remain only 20 inner spectroscopic subsystems with unknown periods, mostly with slow or questionable RV variation.

Figure 1 shows the period-eccentricity relation for inner subsystems with dwarf primaries. The data were extracted from the current version of the multiple-

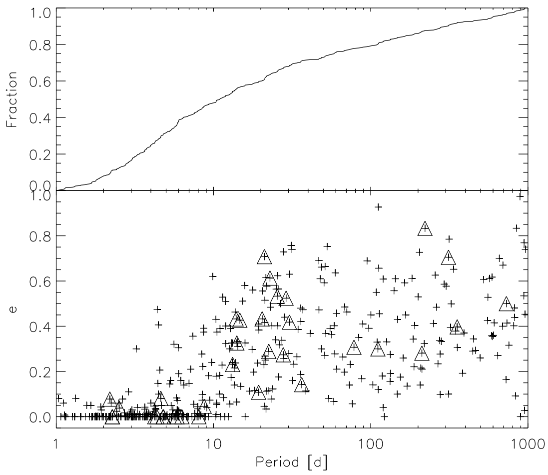


**Figure 1.** Period-eccentricity relation for inner subsystems of multiple stars from the MSC with masses below 1.5 solar (from Paper VI). Orbits resulting from the CHIRON survey are marked by triangles. The upper plot shows the cumulative distribution of periods. The absence of period accumulation just below 10 d is obvious: the distribution is smooth.

**Table 1.** Hierarchical multiplicity of close binaries in the 67-pc sample

| Period | Total | Solitary | Inner | $P_{\rm out} < 10^4$ d |
|---|---|---|---|---|
| <10 d | 111 | 47 | 64 | 8 |
| 10–100 d | 121 | 75 | 41 | 7 |

star catalog, MSC[1] (Tokovinin, 2018). Although this data collection is burdened by selection, it should not hide or distort sharp statistical features like the KCTF predicted drop in the number of subsystems with $P > 10$ d. The circularization is clearly seen in the $P-e$ plot, but the cumulative period distribution is smooth and featureless. A decrease at $P > 7$ d noted by Tokovinin & Smekhov (2002) was a selection effect because most inner subsystems known at that time were discovered by eclipses, with a strong preference of short periods. Nowadays, most subsystems are discovered spectroscopically. The absence of the accumulation of inner periods predicted by KCTF around $P \sim 10$ d in a sample of tight *Kepler* triples was also noted by Borkovits et al. (2016).

Table 1 shows the statistics of ClBs in the 67-pc sample, updated with all known orbits. At $P < 10$ d, a fraction 64/111=0.58 of binaries are inner subsystems in known hierarchies; this is a lower limit. For binaries with $10 < P < 100$ d (incomplete because not all those periods are known), only a fraction 41/121=0.34 are in known triples.

In both period groups, the outer systems are, mostly, wide, while the number of compact triples with $P_{\rm out} < 10^4$ d is relatively small. However, compact triples, especially those with low-mass tertiaries, are difficult to discover. Accurate accelerations measured by Brandt (2018) by combining the *Gaia* and

[1] Online access and latest versions at http://www.ctio.noao.edu/~atokovin/stars/index.html

*Hipparcos* catalogs reveal 93 stars with significant accelerations among our 232 binaries with $P < 100$ d. In this group, 62 are already known as multiple, although the accelerations are not necessarily produced by the known wide companions. The remaining 31 systems are potential new compact triples, hence their true number substantially exceeds 15.

The strong decline of the fraction of triple systems with the increasing period of the inner subsystem, emerging from the statistics in the 67-pc sample, was quantified by Tokovinin et al. (2006). They proved that *most binaries with $P >$ 10 d do not have tertiary companions.* This means that most close binaries were formed without the assistance of a tertiary, in agreement with Moe & Kratter (2018). Another argument against the predominance of the KCTF mechanism is the observed strong tendency for orbit alignment in multiple systems with outer separations below ∼50 AU (Tokovinin, 2017; Borkovits et al., 2016). Those triples are prime candidates for KCTF, but only a small fraction of them have mutual inclinations $> 39°$. This said, KCTF *must* operate in some cases.

## 3. Accretion-driven migration

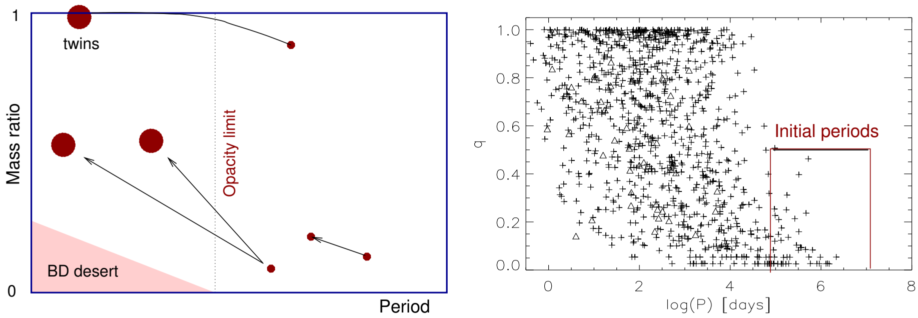


**Figure 2.** Left: cartoon showing formation and evolution of close binaries by disk fragmentation and accretion. Right: simulated population of solar-type binaries.

An alternative to the KCTF for forming ClBs is migration caused by accretion of gas during the build-up of stellar masses. The orbital angular momentum is extracted by gravitational waves in the circumbinary disks and by ejection of a fraction of the accreted matter. This can be described by

$$\mathrm{d}a/a = -\eta\,(\mathrm{d}m_2/m_2), \tag{1}$$

where $\mathrm{d}m_2$ is the mass accreted by the secondary component of a binary, $m_2$ is its current mass, and $a$ is the orbital separation. The parameter $\eta$ characterizes the speed and direction of migration. The interaction of a binary with accreting matter is extremely complex, and there is no general consensus among various studies. Most authors, however, find positive $\eta$ ranging between 1 and 5 (inward migration); see Tang et al. (2017) and references therein.

Figure 2 shows schematically the formation of ClBs. Companions form by fragmentation of a circumbinary disk at large separations $a > 40\,\mathrm{AU}$ (the so-called opacity limit to fragmentation). Accreted gas is preferentially grabbed by the secondary component and the mass ratio $q$ increases while the orbit shrinks and the total system mass grows. Companions that formed early have initially larger mass ratios and evolve into the $q = 1$ regime, producing twin binaries with nearly identical components. Conversely, companions that formed at the end of the mass assembly remain at larger separations and can retain small mass ratios. The brown dwarf desert – the lack of ClBs with brown dwarf companions – does not extend to long periods. Binary evolution in response to accretion depends on many factors and is stochastic; therefore, companions formed with equal initial parameters can end up in binaries with different $P, q$.

Tokovinin & Moe (2020) developed a mathematical model of accretion-driven migration using simplified prescriptions for the evolution of separation and mass ratio and exploiting its random character. The model successfully reproduces several features of the ClB statistics for both solar-type and massive stars. Massive stars accrete more and, consequently, have a larger multiplicity fraction, a larger fraction of ClBs, and a stronger migration. The distribution of $\log P$ of early B- and O-type binaries grows toward short periods and falls abruptly at $P < 0.6\,\mathrm{d}$ corresponding to the contact. This implies that a large fraction of massive binaries have merged during their formation. Merging helps to form very massive stars by delivering part of the final mass in the form of companions. However, strong accretion of gas is still necessary for merging. Assembly of very massive stars from "pre-fabricated" less massive components delays the nuclear evolution time; otherwise, an unrealistically strong accretion would be needed to form a 100 $M_\odot$ star before it explodes as a supernova.

If ClBs form, mostly, by disk fragmentation and accretion-driven migration, why do so many of them have tertiary components? Moe & Di Stefano (2017, Fig. 39) noted a tight correlation between the fraction of ClBs and the fraction of triples: both increase with the mass of the primary component. Formation of ClBs and hierarchies is not causally related, but, instead, driven by the common factor, namely the supply of gas during star formation. Strong accretion creates massive stars, and, at the same time, favors formation and migration of inner binaries and formation of further more distant companions from the same accretion flow.

As noted above, compact triple systems tend to be well aligned (nearly coplanar). This is natural if their formation and early evolution was driven by accretion from a common gas reservoir. A class of planetary-like hierarchies is emerging from recent observations. Their orbits are approximately aligned, period ratios are moderate (on the order of 20), and the orbits have small eccentricities. A good example is HIP 41431, a compact quadruple system of K7V dwarfs with periods of $2^{\mathrm{d}}.9$, 59 d, and 3.9 yr (Borkovits et al., 2019).

## 4. Summary and outlook

Recent years have witnessed a substantial progress in our understanding of the formation of ClBs and their relation to hierarchical systems. The decisive factor here are new observational data, especially multiplicity statistics in large and clean samples. The *Gaia* mission has opened a new era; much is expected from future data releases, especially when the measurements of resolved binaries and radial velocities become available. Large spectroscopic surveys such as APOGEE are also beginning to produce interesting results (Kounkel et al., 2019).

It is very important to extend the multiplicity statistics to very young, PMS populations. If companions formed sequentially by condensing from the accretion disk, young ClBs should not be exactly coeval (Stassun et al., 2008). Observations of interesting young or still forming (Tobin et al., 2016) hierarchical systems will bring new insights and constraints.

The KCTF mechanism of ClB formation is relegated to the second place, while modeling of accretion-driven migration is beginning to give promising results. Much remains to be done in this area, however. ClBs represent only a small fraction of the total binary population. The statistics of most common wide binaries, presumably formed by core fragmentation, still lack plausible theoretical models. The accretion-driven migration is unable to produce 2+2 hierarchies which, in fact, outnumber the planetary-type 3+1 quadruple systems (in the 67-pc sample, their ratio is 4:1). Hierarchical systems with misaligned orbits are also quite common, especially with wide separations.

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# Primordial mass segregation of star clusters: The role of binary stars

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**Abstract.** Observational results of young star-forming regions suggest that star clusters are completely mass segregated at birth. As a star cluster evolves dynamically, these initial conditions are gradually lost. For star clusters with single stars only and a canonical IMF, it has been suggested that traces of these initial conditions vanish at $\tau_{\rm v}$ between 3 and 3.5 half-mass relaxation times. Here, by means of numerical models, we investigate the role of the primordial binary population on the loss of primordial mass segregation. We found that $\tau_{\rm v}$ does not depend on the binary star distribution, yielding $3 < \tau_{\rm v}/t_{\rm rh} < 3.5$. We also conclude that the completely mass segregated clusters, even with binaries, are more compatible with the present-day ONC than the non-segregated ones.

**Key words:** methods: numerical, data analysis – star clusters: individual (ONC) – stars: formation, binaries

## 1. Introduction

Mass segregation is a prominent feature present in evolved star clusters due to their dynamical evolution (e.g. Chandrasekhar, 1943; Chandrasekhar & von Neumann, 1942, 1943) but not only there. Recent *ALMA* observations of the Serpens South star-forming region by Plunkett et al. (2018) suggest that young clusters are born completely mass segregated. Despite observing a general tendency of clusters to evolve towards higher mass segregation, it may both increase and decrease due to two-body encounters that lead to energy equipartition. In (Pavlík et al., 2019a, hereafter Paper I), we were the first to point out that the degree of mass segregation of a non-segregated and a completely segregated system is gradually settled at a similar level, their primordial differences vanish and both initial conditions become observationally indistinguishable after some time designated as $\tau_{\rm v}$. Based on our numerical $N$-body models with single stars, we estimated this time to $3 < \tau_{\rm v}/t_{\rm rh} < 3.5$ (where $t_{\rm rh}$ is the half-mass relaxation time; cf. Spitzer & Hart, 1971). Most (if not all) stars are preferentially born in binary systems (e.g. Kroupa, 1995; Goodwin & Kroupa, 2005) – 42 % of field (i.e. old) M-dwarfs (Fischer & Marcy, 1992), 45 % of K-dwarfs (Mayor et al., 1992) or 57 % of G-dwarfs (Duquennoy & Mayor, 1991; Raghavan et al., 2010) are reported in binaries, and the binary fraction increases with the stellar mass. Hence, for this conference contribution, we extend the work of Paper I by studying the evolution of mass segregation in star clusters that include primordial binaries.

## 2. Models

We evolved several realisations of $N$-body models with 2.4k stars (comparable number to the Orion Nebula Cluster, ONC, Pavlík et al., 2019b) and with the Kroupa (2001) IMF for several relaxation times using `nbody6` (Aarseth, 2003). For each model, we used two extreme primordial mass segregations according to a method of Baumgardt et al. (2008) – none or complete.

In all models, we injected a conservative 50% binary fraction initially (i.e. 601 binary stars in total), while the binary pairing was drawn from a uniform distribution of mass ratio ($0.1 < q < 1.0$) in the mass range above $5\,M_\odot$ and was random for the remaining stars up to the desired percentage (cf. Küpper et al., 2011) – the model is labelled `P:uni`. The semi-major axes were distributed according to Sana et al. (2012) and Oh et al. (2015) period distributions for stars with $m > 5\,M_\odot$ and according to Kroupa (1995) for lower-mass stars. Eccentricity distribution of high-mass systems is taken from Sana & Evans (2011) and is thermal for low-mass stars (cf. Heggie, 1975; Duquennoy & Mayor, 1991; Kroupa, 2008).

## 3. Results

Our clusters with binaries evolve in a similar fashion to the single star models presented in Paper I (compare the plots in Fig. 1). The primordially fully mass segregated clusters lose their initial ordering gradually before settling at some level of mass segregation. Clusters without initial mass segregation establish it dynamically and *again* settle almost at the same level. As in Paper I, we investigate the evolution of mass segregation using the spatial distribution of mean mass and the integral parameter $A$, i.e. for a $k$-th bin at radius $r_k$

$$A = \sum_{k=1}^{n_{\rm bin}} \frac{\langle m(r_k)\rangle}{\Delta r_k}\,, \text{ with } \langle m(r_k)\rangle = \frac{\sum_{i=1}^{k} m_i}{\sum_{i=1}^{k} n_i}\,, \tag{1}$$

where $n_i$ and $m_i$ are the number of stars and their total mass in an $i$-th bin, respectively, $\Delta r_k$ is the width of the $k$-th bin and $n_{\rm bin}$ is the total number of bins (bins here are logarithmically equidistant). In particular, $r_1 = 0.1\,\mathrm{pc}$, $r_{n_{\rm bin}} = 10\,\mathrm{pc}$ and $n_{\rm bin} = 50$.

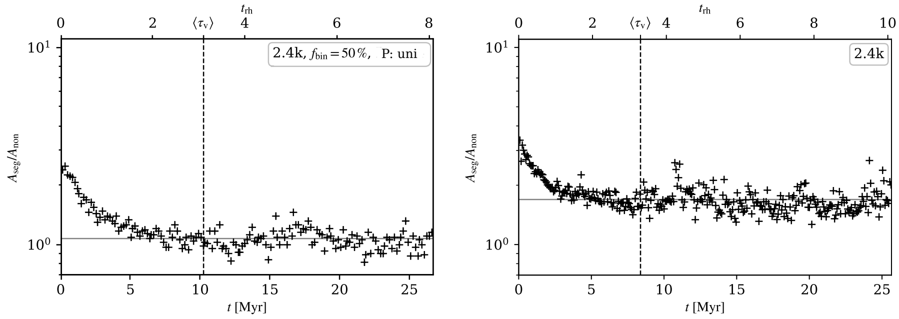


**Figure 1.** Evolution of the ratio given by Eq. (1) in time. The dashed line and the value $\langle \tau_{\rm v} \rangle$ represent the mean time when the slope of the data points became flat. The corresponding horizontal slope is plotted by a grey line. The left plot presents a model with initial binary population, the right plot is taken from Paper I for comparison.

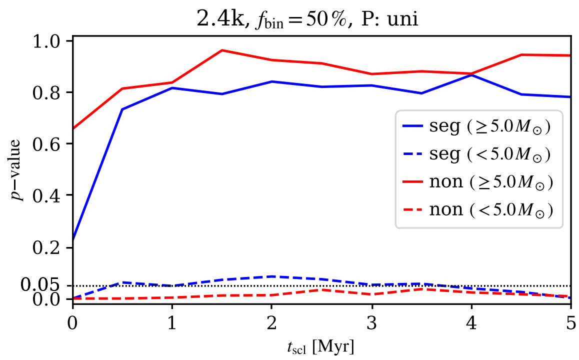


**Figure 2.** Results of the KS test between the ONC data and our model with 50 % binaries. Only the model with scaling and extinction is shown.

The time when the difference of initial conditions vanishes seems independent on the initial binary star fraction. Systems with 50 % binaries (`P:uni`) have $3 < \tau_{\rm v}/t_{\rm rh} < 3.5$ (see the left panel of Fig. 1) which is equivalent to the systems of similar population with single stars only from Paper I (see the right panel of Fig. 1).

We also tested whether the initial conditions with binaries are still compatible with the observed ONC. In the case of the primordially mass-segregated models, those where elongation (scaling) of the cluster and extinction was accounted for (cf. Sect. 4 in Paper I) have the KS test $p > 0.05$ at the time which is equivalent to the current age of the ONC, i.e. 2.5 Myr (see Fig. 2). In the case of the initially non-segregated models, none is compatible with the present-day ONC, not even with scaling and extinction.

## 4. Conclusions

This conference contribution is a follow-up of the work of Pavlík et al. (2019a, Paper I). We have started to investigate the role of a primordial binary star population on mass segregation in star clusters of the size of the ONC.

In the models with 50 % initial binary stars, the mean time when the primordially mass segregated and the non-segregated models became indistinguishable was $\langle \tau_{\rm v} \rangle \approx 3.2\, t_{\rm rh}$, i.e. comparable to the single star models presented in Paper I.

We have also compared our models with the present-day Orion Nebula Cluster. The only compatible model is the one with primordial mass segregation if we also account for interstellar extinction and scaling of the ONC, as presented in Paper I.

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# Evolution of low mass contact binaries close to the orbital period cut-off

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**Abstract.** The evolution of eclipsing binaries leads towards angular momentum and mass loss from the systems, due to stellar wind and magnetic braking. Observational investigations of low-temperature and low-mass contact binaries (or LMCBs) in the solar neighborhood provide the means for studying a large sample of such systems. The observed orbital period cut-off limit of 0.22 days is believed to be a result of evolutionary mechanisms, and such systems act as probes in investigating the very evolved stages of systems before their final coalescence. The main goal of this study is the determination of the stellar evolution tracks of these type of LMCBs, which might be correlated to the formation of blue stragglers and rapidly rotating stars.

**Key words:** binaries: contact – stars: physical parameters – stellar evolution

## 1. Introduction

Contact binaries are the most frequently observed type of eclipsing binary system. They are small, cool, low-mass, and occur in old stellar populations. In the framework of the *CoBiToM Project* a sample of contact binary systems was selected to be studied. The sample was chosen due to their ultra short orbital period ($< 0.26$ d), some of which exceed the orbital period cut-off of 0.22 d described by Rucinski (2007). These binary systems, also known as LMCBs (low mass contact binaries), are on the verge of coalescence, as a result of mass and angular momentum loss.

## 2. The current study

The observed light curves have been analysed, and the contact configuration investigated by verifying that both Roche lobes were overfilled. Correlation diagrams were examined (Fig. 1), in order to provide sustainable results and relations between the physical parameters. Thereafter it is possible to obtain solid conclusions, especially in cases when the evolutionary processes are not yet clarified. In the correlation diagrams shown here, the absolute physical parameters

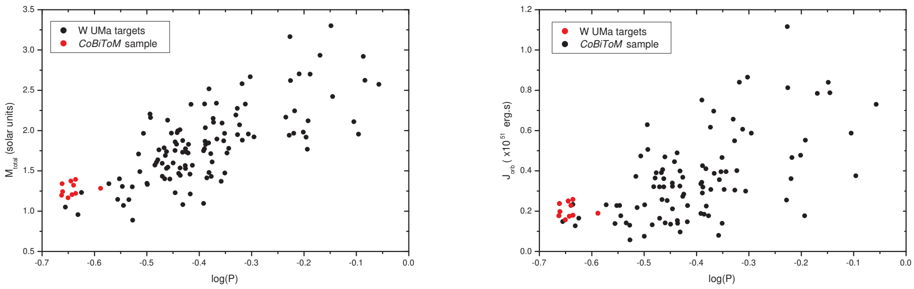


**Figure 1.** Total mass (left) and angular momentum (right) as a function of orbital period. The sample of *CoBiToM Project* targets (red circles at lower left of each panel) are shown along the list of W UMa systems with well-defined physical parameters.

of the 10 targets in this study are plotted along with a sample of 112 contact binary systems with well-defined physical parameters from Gazeas et al. (2006). For all 10 systems in our target list we provide high quality four-band photometry, which is essential for stellar models. The number of such systems is very limited and today we know very little about stellar systems close to merging.

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# Circumbinary planets – the next steps

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**Abstract.** The *Kepler* mission opened the door to a small but bonafide sample of circumbinary planets. Some initial trends have been identified and used to challenge our theories of planet and binary formation. However, the *Kepler* sample is not only small but contains biases. I will present a circumbinary plan for the future. Specifically, I will cover the BEBOP radial velocity survey, the latest *TESS* transit mission and a new technique for digging out small circumbinary planets in archival *Kepler* photometry.

**Key words:** exoplanets – circumbinary planets – transits – radial velocities

## 1. Introduction

Binary stars are common. Exoplanets are common. It is natural to seek planets in binaries. Planets in binary star systems come in two flavours: circumbinary planets on exterior orbits around tight binaries, and circumstellar planets on interior orbits around one of the two components of a wide binary. Here we will only consider circumbinary planets. The discovery of Kepler-16 (Doyle et al., 2011) really kicked off a search which had been anticipated since before the dawn of exoplanet discoveries (Borucki & Summers, 1984; Schneider & Chevreton, 1991). A dozen or so transiting circumbinary planets have been found by this mission (reviews in Welsh & Orosz, 2018; Martin, 2018), but this paper will look beyond the existing *Kepler* discoveries.

## 2. Trends and open questions In circumbinary planets

The dozen circumbinary planets discovered to date exhibit a few interesting trends and pose a few interesting questions.

1. ***There is a dearth of circumbinary planets orbiting the tightest eclipsing binaries (EBs).*** Most EBs have a very short period ($\sim$ 2–3 days) but the transiting planets are only around $>$ 7 day binaries (Fig. 1a). Muñoz & Lai (2015), Martin et al. (2015a), Hamers et al. (2016) explained

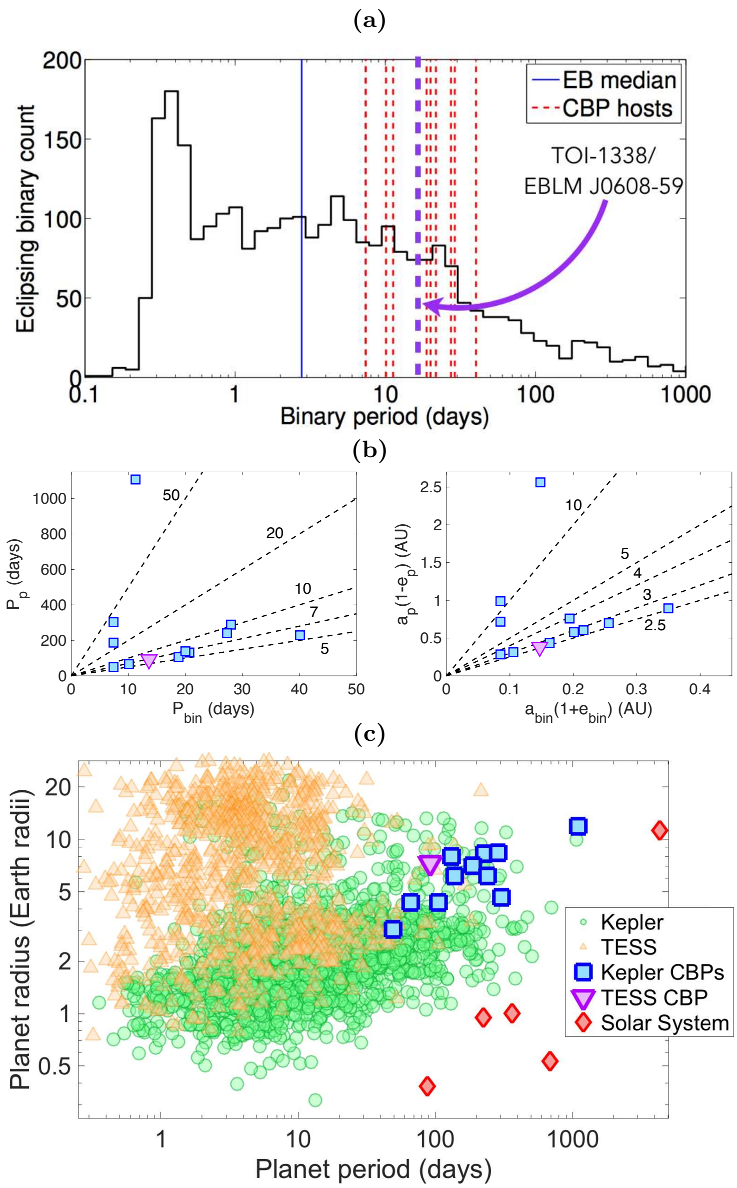


**Figure 1.:** (a) Histogram of *Kepler* eclipsing binary periods, compared with the periods of binaries known to host circumbinary planets, and the first *TESS* discovery of TOI-1338/EBLM J0608-59. (b) Left: planet and binary periods; right: planet periapse and binary apoapse. There is a tend for common ratios, which places the planets close to the stability boundary (Holman & Wiegert, 1999). (c) Size and period of *Kepler* and *TESS* planet discoveries around both single and multiple stars. Figures reproduced from Kostov et al. (under review) and Martin (2018).

this dearth by invoking a known formation mechanism of tight binaries under the influence of a misaligned third star and Kozai-Lidov cycles. The applicability of this story has been called into question lately by Moe & Kratter (2018), who deduce that Kozai-Lidov is only responsibility for the minority of tight binary formation. More theoretical work is needed. Additionally, Muñoz & Lai (2015), Martin et al. (2015a), Hamers et al. (2016) suggested that any planets found orbiting around very tight binaries would be likely small and/or misaligned, both of which have been difficult to find to date.

2. ***There is an over-abundance of planets orbiting near the dynamical stability limit.*** This is likely the result of migratory formation of the planets, stalling near the edge of an inner disc cavity, which roughly coincides with the dynamical stability limit (Holman & Wiegert, 1999; Kley et al., 2019). Whilst this is not the sole result of an observational bias (Fig. 1b), more detections are needed to determine its statistical significance (Martin & Triaud, 2014; Li et al., 2016). In particular, finding circumbinary planets by radial velocities (Martin et al., 2019) or microlensing (Bennett et al., 2016) would allow for planet detections at longer periods, farther from the stability limit.

3. ***All transiting circumbinary planets are larger than*** $3R_{\oplus}$. This is contrary to the abundant discoveries of small planets around single stars, with a comparison shown in Fig. 1c. If it were a real absense, it would be enlightening, however the lack of small circumbinary planets is a detection bias; the days-amplitude transit timing variations (TTVs, Armstrong et al., 2013) inhibit traditional planet detection techniques based on phase-folding on a fixed period. Only transits of giant planets could be found so far, by eye. Some algorithms have been proposed to find small circumbinary planets, using modified versions of Boxed Least Squares (BLS, Ofir, 2008) and the Quasiperiodic Automated Transit Search (QATS, Windemuth et al., 2019b), but no candidates have been reported yet.

## 3. A search for small transiting circumbinary planets in *Kepler*

The archival *Kepler* data remains the best source for finding small circumbinary planets, because of its long four-year baseline, high-precision photometry and well-characterised EB catalog (Prša et al., 2011; Windemuth et al., 2019b). In collaboration with Dan Fabrycky, a new transit search algorithm is being specifically designed for shallow transits of small circumbinary planets. It can successfully recover all known circumbinary planets, and also injected planets slightly smaller than Earth (Fig 2). Planet detection is assisted by a detrending algorithm designed specific to EBs, which accounts for the variable length of circumbinary planet transits as a function of the binary phase. Unique to this transit detection algorithm is building TTVs directly and exactly into the search. For each set of orbital parameters the algorithm produces a quasi-periodic mask of transit times and durations using a rapid N-body algorithm. This mask is matched to the photometric data similar to the cross correlation technique for high-precision RV fits to spectroscopic data. The N-body-derived mask fully incorporates the three-body geometry and both short and long-term dynamical variations of the planet's orbit. The search grid has been optimised using principles similar to those of Ofir (2014), but adapted to circumbinary planets.

Roughly two dozen detections are expected if planets have a similar size distribution around one and two stars (preliminary research suggests this is the case for gas giants, Martin & Triaud, 2014; Armstrong et al., 2014). Alternatively, it is possible that small circumbinary planets ***are rare or non-existent***. This would suggest that super-Earths form in situ rather than with significant migration, helping answer a hotly-debated topic (Ogihara et al., 2015); around single stars such a process is possible but around a binary it would be suppressed (Paardekooper et al., 2012).

## 4. The BEBOP radial velocity survey

Between 2013 and 2018 a blind survey for circumbinary planets was run on the Swiss Euler Telescope. It was given the delightful name BEBOP – "Binaries Escorted By Orbiting Planets." BEBOP uniquely targeted eclipsing, single-lined spectroscopic binaries. The eclipses add preferential biases in both radial velocity amplitude and transit probability (Martin & Triaud, 2015b; Martin, 2017). The single-lined binaries, composed of F/G primaries and M-dwarf secondaries, avoid the difficult problem of spectral contamination, and the need to deconvolve two moving sets of spectral lines. This is different to the SB2 search of TATOOINE (Konacki et al., 2009).

Over 1000 observations taken over more than 60 nights were compiled in Martin et al. (2019). The survey was sensitive down to $0.5M_{\rm Jup}$, but our lack of detections showed that circumbinary planets are typically sub-Saturn mass (Fig. 3). BEBOP was sensitive to planetary mass companions at periods of several years, much longer than the *Kepler* discoveries. BEBOP also demonstrated that there was not a large abundance of giant, misaligned planets, which were proposed by Martin & Triaud (2014); Armstrong et al. (2014) as compatible with the *Kepler* transit results. BEBOP has since been expanded to large programs on HARPS, SOPHIE and ESPRESSO.

## 5. The *TESS* transit mission

*TESS* presents different challenges and opportunities when compared with *Kepler*. *TESS* is observing most of the sky, in both hemispheres, and hence is targeting many more bright stars so ground-based follow-up is significantly eas-

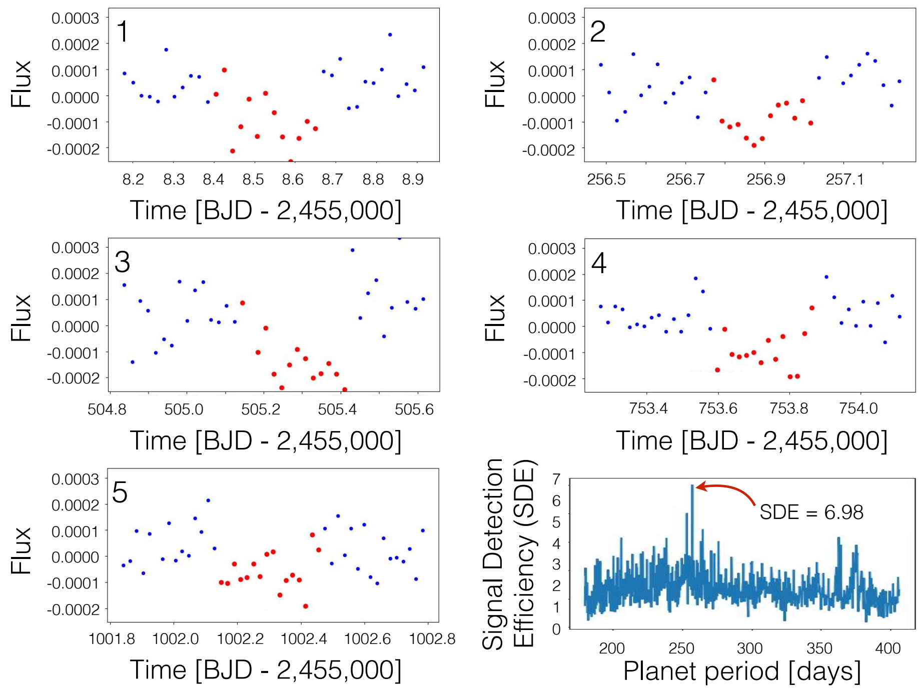


**Figure 2.:** Recovery of an injected $0.875R_\oplus$ circumbinary planet on Kepler-16 (real planet is over $8R_\oplus$) with the new automated algorithm. Injected transits were created using *BATMAN* (Kreidberg, 2015), with the duration scaled according to the relative planet-star velocity calculated by the *REBOUND* N-body algorithm (Rein & Liu, 2012)

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ier. However, two drawbacks are the smaller telescope size (10.5 cm compared with 95 cm) and shorter observing timespans (30 days for most of the *TESS* field). Only near the ecliptic poles does the *TESS* timespan increase to almost a year of continuous viewing, owing to the overlap of multiple sectors. Indeed, the single *TESS* planet found so far is near the continuous viewing zone: TOI-1338/EBLM J0608-59 (Kostov et al. under review, Fig. 4). The planet has very similar properties to the *Kepler* population of planets (it is highlighted in Fig 1). A unique aspect of this discovery, compared with the *Kepler* discoveries, is that the binary was already known and well characterised as a part of the EBLM (Triaud et al., 2017) and BEBOP (Martin et al., 2019) radial velocity surveys, and those measurements were vital to the planet's characterisation.

*TESS* is unlikely to significantly break into new parameter spaces of circumbinary planets, due to the shortened observational timespans and inferior

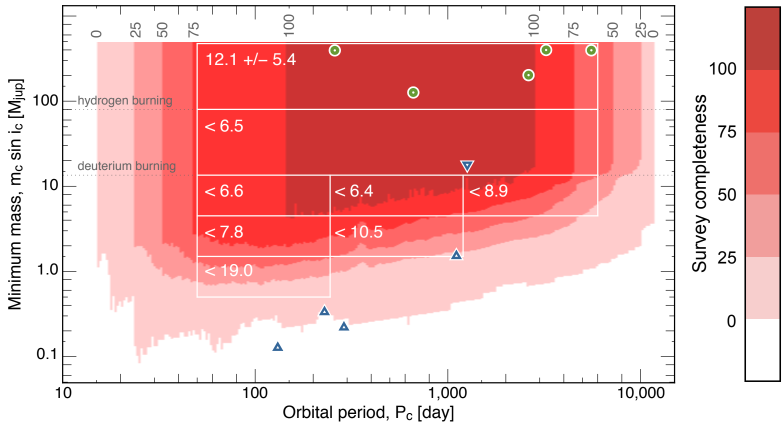


**Figure 3.:** BEBOP detection completeness, detected triple star systems (green circles), known transiting circumbinary planets with roughly-characterised masses (upwards blue triangles) and a known circumbinary brown dwarf (downards blue triangle). Numbers in white boxes indicate 95% confidence abundance bounds. Figure reproduced from Martin et al. (2019).

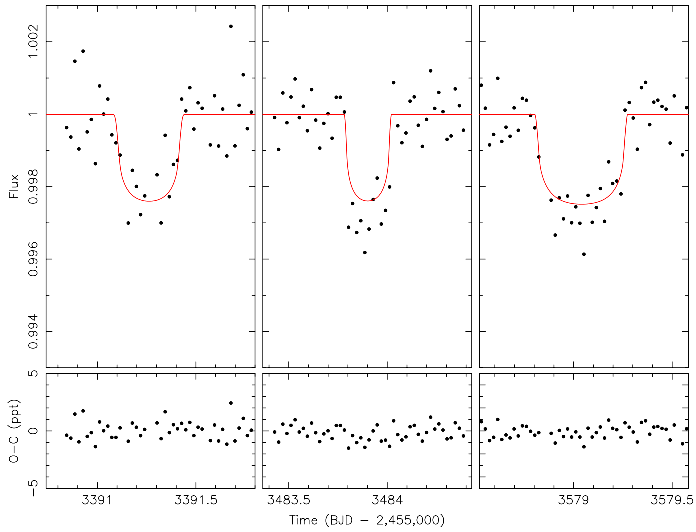


**Figure 4.:** Three primary transits of the circumbinary planet TOI-1338/EBLM J0608-59 and the photodynamical fit with its residuals (observed minus calculated). The variable transit duration, owing to a variable relative velocity between the star and planet, is a smoking-gun signature of a circumbinary planet. Figure reproduced from Kostov et al. (under review).

photometric precision to *Kepler*. Most detections will be harder than TOI-1338/EBLM J0608-59. What *TESS* will hopefully provide though is a significant increase in the statistics of circumbinary planets. The *TESS* circumbinary planet working group predicts 140 *TESS* circumbinary planets if we can detect them on a single passing that transits both stars, a “1-2 punch.” This is based on 400,000 eclipsing binaries, a *Kepler*-like circumbinary planet detection rate of 11/2800, a 30/180 chance of the median circumbinary period transiting during a one month window and a 1/2 chance of the planet transiting both stars (Martin, 2017). Based on *Kepler*, $\sim 70$ of these planets are expected to be in the habitable zone.

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# The explosive life of massive binaries

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**Abstract.** Massive stars are born predominantly as members of binary (or higher multiplicity) systems, and the presence of a companion can significantly alter their life and final fate. Therefore, any observed sample of massive stars or associated transients is likely to be significantly influenced by the effects of binarity. Here, we focus on the relationship between massive binary evolution and core-collapse supernova events. In the vast majority of the cases, the first core-collapse event happening in a binary system unbinds the two stars. Studying the population of companion stars, either at the supernova site, or as “widowed” stars long after the explosion, can be used to constrain the previous orbital evolution of the binary progenitor, and explosion physics of their former companion. Specifically, the population of “widowed” stars might provide statistical constraints on the typical amplitude of black hole natal kicks without seeing neither the black holes nor the transient possibly associated to their formation. Binarity also has a large impact on the predicted population of supernova sub-types, including hydrogen-rich type II supernovae, with a significant fraction of hydrogen-rich stars at explosions being either merger products or accretors.

**Key words:** stars: massive – binaries – supernovae

## 1. Massive stars and binarity

A variety of observations suggest that the vast majority of massive stars are born in binary (e.g., Mason et al., 2009; Sana & Evans, 2011; Almeida et al., 2017) or higher multiplicity systems (e.g., Tokovinin, 2008), and that up to $\sim 70\%$ of the O-type stars might exchange mass or merge with a companion before the end of their evolution (e.g., Sana et al., 2012).

This implies that observational samples of massive stars and/or transients is likely to contain binary evolution products (e.g., Langer 2012 for a review, and de Mink et al. 2014).

In the era of large surveys, such as *Gaia* (Gaia Collaboration et al., 2018) or ZTF (Bellm, 2014) and LSST (LSST Science Collaboration et al., 2009) in the time domain, we have the opportunity to investigate both the most common *and* the rare and exotic binary evolution paths.

Here, we focus on some aspects of the relationship between binarity and core-collapse supernova (CCSN) explosions. We refer interested readers for more details to our studies in Renzo et al. (2019); Zapartas et al. (2017a,b, 2019). We describe the population synthesis approach in Section 1.1. In Section 2, we focus on the consequences of the first CCSN explosion for the binary system, while in Section 3 we discuss the implications of binary evolution of the progenitors for the population of CCSN events.

### 1.1. Population synthesis

The evolution of a star is determined mainly by its initial mass, and secondly by its rotation rate and metallicity[1] (Z). Nevertheless, many uncertain or unknown parameters enter in the modeling of internal processes in stars (poorly known nuclear reaction rates, modeling of mixing processes, wind mass loss rates, etc.). Exploring the parameter space for single star evolution is a challenging task still being actively pursued (e.g., Woosley, 2017; Renzo et al., 2017; Sukhbold et al., 2018; Woosley, 2019; Farmer et al., 2019, for recent studies of single massive stars). When considering the evolution of two stars born together in a binary, i.e., the standard for massive stars, the number of dimensions of the parameter space increases very rapidly: not only the evolution of a massive binary system depends on the two initial masses of the stars, but also their initial orbital period and, possibly, eccentricity. Moreover, the number of free or poorly constrained parameters entering in the models also increases (e.g., stability and efficiency of mass transfer, angular momentum losses, treatment of common envelope), reflecting the current insufficient understanding of the physics of binary interactions.

The complexity of the problem and the vastness of the parameter space to explore require to resort to population synthesis techniques, i.e., broadly speaking, building synthetic populations by weighting with initial distributions pre-computed models. This can be done with grids of detailed binary evolution models (e.g., Justham et al., 2014; Marchant et al., 2016; Eldridge et al., 2017), which have the advantage of solving the differential equations describing the evolution and interaction of the two stars, but are limited to the values of unknown parameters for which the computation is numerically feasible.

The common alternative is to rely on pre-computed single star models (e.g., Pols et al., 1998; Hurley et al., 2000) paired with analytic algorithms to represent the binary interactions (e.g., Tout et al., 1997; Hurley et al., 2002), which allow for the exploration of larger portions of the parameter space of binary evolution at the cost of a reduced physical accuracy of the models, and thus limited predictive power of a single population. The results we present here

[1] Specifically, its initial iron content, e.g., Tramper et al. 2016.

were obtained with this approach, using the `binary_c` code (Izzard et al., 2004, 2006, 2009; Izzard et al., 2018).

The speed of these simulations (typically $\lesssim 0.1$ sec per binary) allows for reruns varying the uncertain parameters. If a particular result is found to survive all the parameter variations possible, the prediction can be considered robust. Vice versa, if a result is found to be sensitive to variations of a particular unknown parameter, the comparison with observed populations has the potential of constraining such parameter. The ranges reported below were obtained with one-by-one variations of uncertain parameters[2] in the models to assess the robustness of the predictions made.

## 2. How explosions can affect binaries

While the majority of massive stars are born with companion(s), only a small minority remain bound after the first core-collapse in the system (e.g. De Donder et al., 1997; Eldridge et al., 2011; Renzo et al., 2019). For compact objects (i.e., neutron stars and black holes), being in a binary system is the exception rather than the rule. This is counterintuitive, since binary interactions are often the main or only way to observe the compact objects (e.g., through X-rays and/or gravitational waves), especially in the case of black holes. In other words, the majority of (isolated) massive binaries evolves to form a single compact object and a "widowed" companion star.

The main reason why $86^{+11}_{-22}\%$ of binaries[3] are disrupted at the first core-collapse event appears to be supernova (SN) natal kicks (Renzo et al., 2019). The width of the range reported above is dominated by the uncertainties in the parametrization of the natal kicks, which allows to use the population of "widowed stars" to observationally constrain the explosion physics of their former companions in a statistical sense. In particular, the high-mass tail of the mass function of "widowed stars" is sensitive to the average black hole kick (Renzo et al., 2019): black holes are produced by on average more massive stars, which typically have more massive companion that can become single "widowed stars" if the black holes receive significant kicks at formation.

When assuming spherical symmetry of the collapse and explosion in the frame of the exploding star (i.e., no natal kick), only $\sim 16\%$ of binary systems are disrupted. In this cases, the change in gravitational potential due to the rapid loss of the SN ejecta from the binary (the so-called "Blaauw kick," Blaauw 1961) alone unbinds the binary (see also Boubert et al. 2017). However, typically Roche-lobe overflow will strip the envelope of the donor star which explodes first, limiting the amount of mass that can be ejected at explosion. Only for

[2] Note however that this approach neglects possible physical correlations between the parameters, see also, e.g., Andrews et al. 2018; Taylor & Gerosa 2018.

[3] This fraction excludes binaries that result in a stellar merger before the first CCSN.

wide, non-interacting binaries the "Blaauw kick" is sufficient to separate the companions.

If the core-collapse produces a successful explosion, the newly "widowed star" will be hit by the blast wave (e.g., Moriya et al., 2015; Hirai et al., 2018), which can alter its appearance for a few thermal timescales by depositing energy in the star and removing some mass, although the latter effect is typically small (e.g. Liu et al., 2015; Rimoldi et al., 2016).

Because of the binary disruption, the "widowed star" acquires a peculiar space velocity corresponding to first order to its pre-explosion orbital velocity. Occasionally, this can produce fast moving runaway stars (e.g., Blaauw, 1961; Hoogerwerf et al., 2001), however, it is much more common that this peculiar velocity is relatively slow ($\sim 10\,\mathrm{km\ s^{-1}}$), making them "walkaway stars" (Renzo et al., 2019). This happens because during the first stable Roche lobe overflow, long before the SN explosion, binaries tend to overall widen. Moreover, the mass transfer leads to an inversion of the mass ratio. Both effects decrease the orbital velocity of the secondary. The velocity distribution of "widowed stars," if observed, would add a constraint on the orbital evolution of massive binaries: their peculiar velocity with respect to their parent population relates to how close to the companion they were at the time of the explosion.

## 3. How binaries can affect the explosions

Binarity can have consequences on the rate and timing of CCSN events (e.g., Podsiadlowski et al., 1992; De Donder & Vanbeveren, 2003; Zapartas et al., 2017a). For example, it can allow stars born below the minimum mass to give a CCSN to ultimately explode (either because they accreted mass from a companion, or because of mergers). Zapartas et al. (2017a) showed that $15^{+9}_{-8}\%$ of all CCSNe might come from this type of evolutionary paths. These progenitor systems are generally longer-lived than normal massive stars, resulting in delayed SNe compared to the age of a given (co-eval) parent population. More convoluted evolutionary paths involving multiple phases of mass transfer (either stable or unstable) might also possibly generate non-standard pre-explosion stellar structures resulting in peculiar transients (e.g., Justham et al., 2014; Menon & Heger, 2017).

### 3.1. Stripped-envelope SNe

Binarity also impacts the observable properties of the stellar explosions themselves: as mentioned above, the most common binary evolution path involves a phase of stable mass transfer which typically removes the entire hydrogen-rich envelope of the donor star (e.g., Kippenhahn & Weigert, 1967; Yoon et al., 2017; Götberg et al., 2017, although this is known to be Z-dependent). Therefore, typically the first SN in the system will be a hydrogen-less type Ib or Ic SN, or possibly a IIb with only a little amount of hydrogen remaining, commonly referred to all together as stripped-envelope SNe (e.g., Smith et al., 2011; Eldridge et al., 2013).

Zapartas et al. (2017b) showed that about 2/3 of all stripped-envelope SNe are expected to occur in the presence of a main sequence companion, assuming an initial mixture of single and binary stars and sub-solar Z. This fraction drops below 1/2 only for parameter variations enhancing the wind mass loss, including super-solar Z. These SNe are those unbinding the binary and creating the “widowed” stars. Albeit common, the main sequence companions might be challenging to find at the SN site because of their possibly low mass (Zapartas et al., 2017b).

Most of the stripped-envelope SNe progenitors single at explosion were massive enough to get stripped through winds, either because they were initially massive enough or because they accreted mass or merged with a binary companion. In $5^{+12}_{-4}\%$ of the cases, the exploding star had a compact object companion.

### 3.2. H-rich SNe

Perhaps more surprisingly, binary products might also contribute to a significant fraction of hydrogen-rich SNe, despite the fact these can in principle be explained by single star evolution. Single star models struggle to explain the variety of light curve morphology and spectral evolution of these hydrogen-rich explosions. Using observationally motivated initial distributions, Zapartas et al. (2019) showed that accretion, and more importantly mergers in binaries can lead to stars exploding with a significant amount of hydrogen left in their envelope. These SNe with a binary-product progenitor could contribute to $45^{+8}_{-12}\%$ of all hydrogen-rich SNe (see also Eldridge et al. 2019). The “widowed” stars alone can contribute to $14^{+4}_{-11}\%$ of hydrogen-rich SNe.

## 4. Conclusions

Massive binary evolution can proceed through a complex variety of paths depending on both initial conditions and physical assumptions of the models. While theoretical understanding is far from final, the exploration of the vast parameter space is becoming possible. Existing and upcoming observational constraints from large surveys and gravitational waves are already guiding it. Loosely speaking, neglecting stellar mergers, each massive binary will produce a close-to hydrogen-less donor star and a hydrogen-rich accreting star. The outcome of stellar mergers depends on the evolutionary phases of the two stars when they happen. Accounting for binarity when dealing with observed samples of massive stars (even if presently single) and samples of CCSNe is important to not misinterpret the observations.

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# Spot migration on the eclipsing binary KIC 9821078

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**Abstract.** High precision and continuous light curves obtained from the *Kepler Space Telescope* provide significant information about the behavior of cool starspots. In this study, we obtain surface maps of the eclipsing binary KIC 9821078 with the help of the light curve inversion method to reveal longitudinal spot migration from *Kepler* long-cadence (LC) light curves. We also present an up-to-date solution from light and radial velocity curves. The inversion results find at least two dominant spot regions that migrate from lower to higher longitudes as a consequence of solar-like differential rotation.

**Key words:** Binaries: eclipsing – stars: magnetic activity – methods: light curve inversion – starspots: migration

## 1. Introduction

As we know from the Sun, stellar magnetic activity is one of the most important phenomena that affect stellar evolution as well as planet formation, although there are still unclear parts. Some methods, such as light curve inversion, give significant information about the underlying physics of stellar magnetic activity, using time-series light curves. Space telescopes (e.g. *Kepler* and *TESS*) offer unique opportunities to understand that phenomenon, with the help of high-precision, almost continuous data, covering long time intervals. We investigate longitudinal star-spot behavior and differential rotation of KIC 9821078 via light curve inversion (hereafter LCI) and frequency analysis (Lomb-Scargle periodogram) of high-precision and continuous *Kepler* light curves. We also derived up-to-date physical parameters.

KIC 9821078 is an Algol-type eclipsing binary with an orbital period of $\approx$ 8.43 days, in which the components are late type (K5/M0) (Pourbaix et al., 2004) low mass stars. The first detailed study of the system was by Devor et al. (2008). They mentioned that the component masses are consistent with current mass-radius models. They also derived physical properties from ground-based radial velocity and light curve data. Han et al. (2019) investigated cool spots on the components and pointed out that they are occulted during primary and secondary eclipses. They also argued that the components are synchronized with spots evolving over time, by examining residuals from a best-fit model. The system was described by Lurie et al. (2017) as having star-spot modulations. They measured multiple rotation periods with a combination of auto-correlation and the Lomb-Scargle periodogram.

## 2. Observations and data reduction

There are 17 quarters of long-cadence (hereafter LC) and 3 quarters of short-cadence *Kepler* light curve data for KIC 9821078. To eliminate brightness variations caused by instrumental or systematic influences, we reprocessed the photometry using the Python PyKE task (for more details see Özavcı et al. (2018)). In this work, we used only LC light curves, since they have sufficient data points in each cycle to perform LCI.

## 3. System parameters and spot modelling

To apply LCI we need parameters such as radii, mass ratio, and inclination. Therefore, we performed simultaneous analysis of *Kepler* light curves and radial velocity curve data from Han et al. (2019) to derive system parameters using PHOEBE software (Prša & Zwitter, 2005). Derived parameters are highly compatible with those by Devor et al. (2008) and Han et al. (2019) and are listed in Tab. 1.

**Table 1.** Results from the light curve analysis of KIC 9821078

| Stellar Parameters | Value | Absolute Parameters | Value |
|---|---|---|---|
| $T1$ (K) | 4300 | $M_1$ ($M_\odot$) | 0.697(3) |
| $T2$ (K) | 3500(3) | $M_2$ ($M_\odot$) | 0.539(3) |
| $i$ (°) | 88.97(1) | $R_1$ ($R_\odot$) | 0.642(2) |
| $a$ ($R_\odot$) | 18.69(2) | $R_2$ ($R_\odot$) | 0.552(1) |
| $q$ | 0.7734(16) | $L_1$ ($L_\odot$) | 0.142(1) |
| $V_\gamma$ (km/s) | −24.02(5) | $L_2$ ($L_\odot$) | 0.041(1) |
| $e$ | 0.00070(4) | $\log g_1$ [cgs] | 4.666(1) |
| ... | ... | $\log g_2$ [cgs] | 4.687(1) |

LCI is one of the techniques commonly used to obtain starspot-induced brightness distributions of star surfaces from light curves. We first phase the light curves into chunks. If the system is synchronized, as assumed by Devor et al. (2008) and Han et al. (2019), then we can use the orbital period for phasing. However, using auto-correlation and Lomb-Scargle periodograms, Lurie et al. (2017) found that the rotational and orbital periods differ significantly. In this context, we computed the generalized Lomb-Scargle periodogram from out-of-eclipse *Kepler* LC light curves and found two strong peaks that correspond to 9.775 and 10.113 days, similar to those estimated by Lurie et al. (2017). The light curves and the periodogram are in Fig. 1(a). Those periods can be related to component rotations and/or spot migration. Those two periods as well as the orbital period were applied for the cycle chunk phasing.

We used the DoTS code (Collier Cameron, 1997) to perform LCI. We first used the orbital period ($P_{orb} = 8.429$ days) to reconstruct the surface map for each cycle. Afterwards, we obtained a measure of the relative spot filling factor as a function of longitude and examined how starspots behave as a function of time, throughout $\approx 4$ yr. This process was performed for two other periods mentioned above. The resultant starspot patterns for three periods are in Fig. 2.

## 4. Results and discussion

We have presented a detailed investigation of activity variations and differential rotation in the K5 type primary component. We applied the LCI method assuming the spots to be on the primary component since, a) the primary has most of the light ($\approx 80\%$) and b) light curves, in general, have only limited information for identifying the spotted component. We obtained three longitudinal spot variations and corresponding drift rates using periods 8.429, 9.775 and 10.113 days. It is not possible to measure directly the drift rate(s), since the periods determined from frequency analysis include not only the rotation periods but the migration rates. It is clear from Fig. 2 that period differences affect only the drift rates (slopes), while it is still possible to infer the drift directions and estimate spot latitudes with $\approx 4$ years of time-series data. This is best visible in Fig. 2(b) that gives clues on the presence of at least two spot regions that migrate toward increasing longitudes with different drift rates between cycles 60 and 80. Furthermore, spot regions that are formed and disappeared in different longitudes can also be clearly seen over time. We also find two magnetic activity cycles of about 0.78 yr and 2.02 yr with Lomb-Scargle peridograms for variations of total spot coverage fraction (see Fig. 1(b)).

We also determined the amount of surface shear, as computed from the periods determined with the generalized Lomb-Scargle periodogram in Fig. 1(a). More details on the determination of surface shear can be found in Reinhold & Arlt (2015). We obtained the amount of surface shear as $\alpha \cong 0.033$, which indicates the existence of solar-like differential rotation.

Time-series high-resolution spectra are needed to better understand the system's activity.

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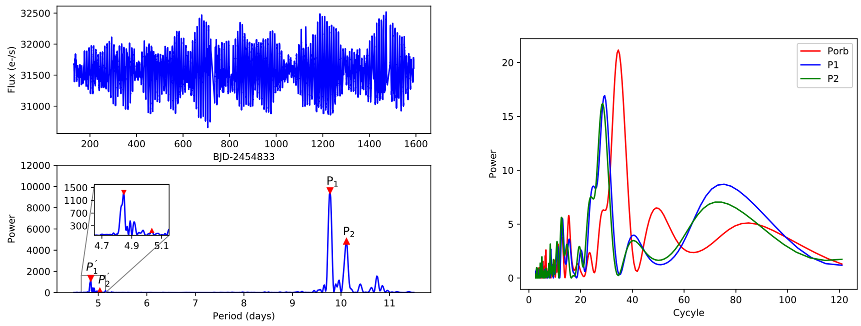
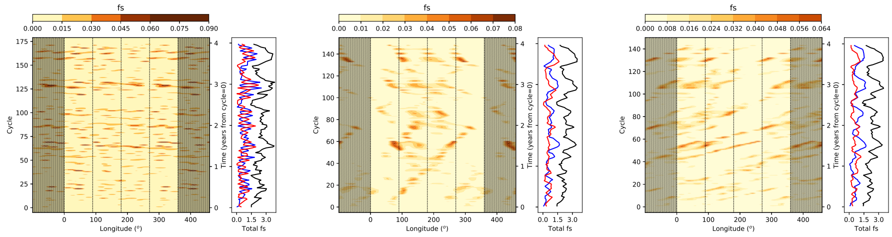



(a) (b)

**Figure 1.** (a-top): Full *Kepler* light curves of the system without eclipses and generalized Lomb-Scargle periodogram for the light curves. $P_1$ and $P_2$ show two strong peaks in the diagram at 9.775 and 10.112 days, respectively, while $P_1'$ and $P_2'$ are their first harmonics (a-bottom). (b): Lomb-Scargle periodogram for variations of total spot coverage fraction over time.




(a) (b) (c)

**Figure 2.** KIC9821078 time-longitude diagrams for the periods 8.429 days (a), 9.775 days (b), and 10.112 days (c). The right panels of each diagram show variations of total (black line) and two sets of opposite longitudinal hemispheres spot coverage fraction over time.

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# On the variability of the accretion disk of AU Monocerotis

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**Abstract.** AU Monocerotis is a well studied interacting binary star and a member of a group called Double Periodic Variables, whose principal characteristic is the existence of a long photometric cycle lasting on average about 33 times the orbital period. We made use of spectra covering from 2008 to 2015 to construct H$\alpha$ Doppler maps. We found higher activity in the accretion disk during the low state of the system, similar to that found in HD 170582.

**Key words:** stars: binaries: eclipsing – stars: binaries: spectroscopic

## 1. Introduction

AU Monocerotis (GCRV 4526, HD 50846, HIP 33237) is an eclipsing interacting Algol-type binary with an orbital period of 11.113 days, and a member of the class called Double Periodic Variables (DPVs), with a long photometric cycle of 411 days (Lorenzi, 1985; Desmet et al., 2010; Mennickent, 2017). The system has shown a complex structure, with a permanent accretion disk and a transient high temperature accretion region, (Peters & Polidan, 1984; Atwood-Stone et al., 2012) which have been revealed through spectroscopic studies.

Very few of the spectroscopic studies of DPVs take into account the high and low states of the long cycle separately. The most remarkable system in this sense is HD 170582, a Galactic DPV whose Doppler tomography in the low state shows higher disk emissivity with respect to the high state (Mennickent et al., 2016). This finding is consistent with the scenario proposed by Peters (1994) for AU Mon's long cycle, viz. mass transfer changes due to a variable radius of the donor star.

## 2. Data

We acquired a total of 225 spectra between 2008 and 2015 in the visual range. The spectra were collected with 5 different telescopes and spectrographs: 172 at the San Pedro Martir (SPM) observatory, 39 with the CORALIE spectrograph, 7 with HARPS and 4 with the FEROS spectrograph, while 3 others were obtained with the echelle instrument at the DUPONT telescope. They were reduced and calibrated with IRAF. We separated them in two groups according to their long-cycle phase $\phi_L$ using the ephemerides given by Desmet et al. (2010): those with $\phi_L$ between 0.75 and 0.25 are referred to as high state and those with $\phi_L$ between 0.25 and 0.75 as low state. Most of the spectra fall in the high state of the long cycle (166 vs. 59), which is due to the high number of spectra taken at SPM during 2011 (86), covering almost an entire orbital cycle during the high state.

## 3. Doppler tomography

Doppler tomography is a technique that allows us to reconstruct the velocity space of the system from the available spectra in order the study the structure of the system (Marsh & Horne, 1988).

For the construction of the Doppler maps we separated our data into three groups: the first one corresponds to the observations taken during 2011 with SPM (86), which cover almost an entire orbital cycle, the second one corresponds to the spectra catalogued as high state that are not part of the 2011 SPM observations (80), and the third group corresponds to the spectra catalogued as low state (59). For the creation of the Doppler maps we made use of the $DTTVM$ code (Uemura et al., 2015).

The Doppler map of the 2011 SPM observations shows a structure fairly similar to the one observed by Atwood-Stone et al. (2012), with an accretion disk in emission, an emission source following the stream path and consistent with a hot-spot or the stream itself, a strong emission source in the fourth quadrant, similar to that observed in the map by Atwood-Stone et al. (2012), plus other emission zones between the third and fourth quadrants. Aside from the emission zones, we can observe a strong absorption bulge close to the primary star, which can be interpreted as evidence for the impact of the stream on the surface of the star (Richards et al., 2014).

The maps of the high and low state show a similar structure. However, we observe a difference in the emissivity of both maps, with the low state showing a greater emissivity in the first quadrant with respect to the high state. The rest of structures show a similar behaviour between both maps.

To check if this behaviour is due to data sampling, we created synthetic spectra of an accretion disk using the code *Shellspec3.9* (Budaj & Richards, 2004). For the parameters of the disk we used the physical parameters reported by Atwood-Stone et al. (2012). We emulated the orbital phases of both sets of data, high and low, and then created a Doppler map for the synthetic spectra. The resulting maps do not show a strong emissivity during the low states, suggesting that the higher emissivity during the low state observed in the real Doppler maps is intrinsic to the system.

## 4. Conclusions and discussion

For the first time we performed Doppler tomography for AU Mon in its high and low states, finding a strong emission feature at the first quadrant during the low state of the cycle.

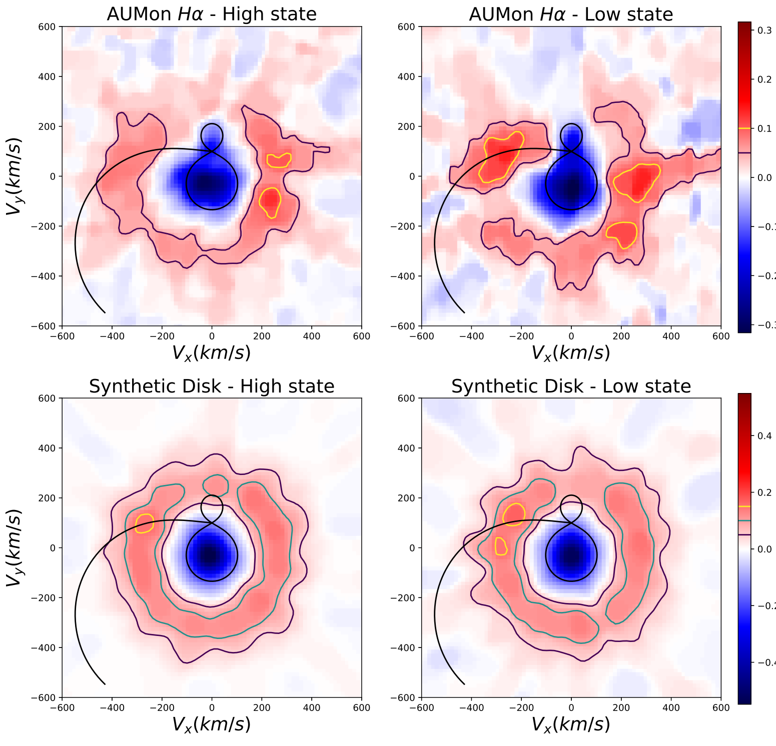


**Figure 1.** Doppler tomography for AU Mon in H$\alpha$ in High and Low state (up) and for the synthetic accretion disk (bottom). The contour lines indicate levels of emission of 0.05,0.1 and 0.15 above the continuum level.

This behaviour is also observed in HD 170582, and it can be interpreted as evidence of an optically thinner disk during the low state of the long cycle. This is consistent with the scenario of variable mass transfer proposed by Peters

(1994) for AU Mon. Eventually, we may expand this model not only for AU Mon, but for DPVs in general, where the long cycle should be produced by this variable mass transfer due to a variation of the radius of the secondary star. This scenario is further developed in the dynamo model by Schleicher & Mennickent (2017).

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# Starspot trek: The motion picture

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**Abstract.** The longitudinal spot migration can be traced with the observation of the O'Connell effect and maxima separation variations. Judging by the correlations between the light curve parameters, the migration processes are confined to the polar regions of the more massive star in a contact binary.

**Key words:** binaries: close – stars: activity – starspots

## 1. Introduction

Light curves of W UMa-type contact binaries are known to be prone to asymmetries. The most often reported distortion is the uneven levels of the brightness maxima (the so-called *O'Connell effect*). Such a distortion is usually explained with a presence of a starspot on the binary surface. The origin of spots is unclear, but since the work of Mullan (1975), the general approach is that they might be magnetically-driven cool starspots. Therefore, the asymmetry coming from the existence of a subluminous region affects a larger part of the light curve, not just one of the extremum at a time. Moreover, it can vary in time, making the whole phased light curve "shake." This wobbling, or *intrinsic variability*, of a light curve can be studied using long-time base photometry (Debski et al., 2015). Assuming the light curve intrinsic variability comes from the changes of the starspot itself, it is possible to trace the variations of the spot parameters using, e.g. the standard approach of numerically modeling with the employment of the Wilson-Devinney code (Debski et al., 2014). This approach is focused on the longitudinal spot migration, with little consideration to the spot latitude, temperature, or size. Lacking the ability to pinpoint the spot latitude, it is usually modeled on the stellar equator. This numerical modeling method also requires a considerable computational time and resources, and some input parameters describing the system itself are needed.

## 2. Tracing of the spot longitudal migration

An alternative method of tracing the longitudinal spot migration can be adopted by analyzing the evolution of the O'Connell effect. If we assume that there is only one dominating spot, which is circular, cool and located on the primary

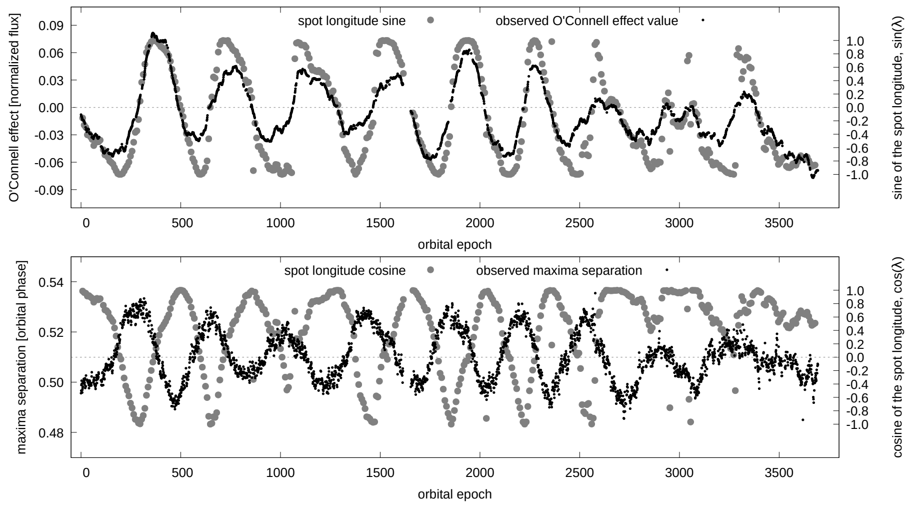


**Figure 1.** Comparison of the spot longitude found with the numerical modeling methods and the O'Connell effect (top panel) and the maxima separation variations (bottom panel).

component, then the longitude of a spot center would be $\lambda = 270°$, if the O'Connell effect would be maximally negative (i.e the brightness maximum at orbital phase $\phi = 0.25$ would be at its lowest, with respect to the brightness maximum at $\phi = 0.75$). Subsequently, the spot would be centered at the longitude $\lambda = 90°$ when the O'Connell effect would be maximally positive. The relation between the spot longitude and the O'Connell effect in case of a contact binary KIC 6118779 is shown in the top panel of Fig. 1. The longitude of the spot comes from the numerical modeling process presented in Debski et al. (2014), while the O'Connell effect has been measured with the improved version of the code used in Debski et al. (2015). The spot location is expressed with the sine of the longitude for a better visual aid. The most noticeable fact is that the spot longitude sine is always positive when the O'Connell effect is positive (and vice versa). The numerically-determined spot longitude after epoch $\approx 2500$ is rather chaotic, despite the continued variations of the O'Connell effect. This means that the single-spot longitudinal migration can be traced numerically only if the 'value' of the O'Connell effect varies more or less symmetrically around zero. Tracing the spot migration with the analysis of the O'Connell effect bears no such burdens.

Another light curve parameter that can be used to study the spot migration is the amount of separation between the brightness maxima. As it turns out, this parameter is perfectly anticorrelated with the cosine of the spot longitude (see the bottom panel of Fig. 1). Here, the maxima separation reaches its greatest

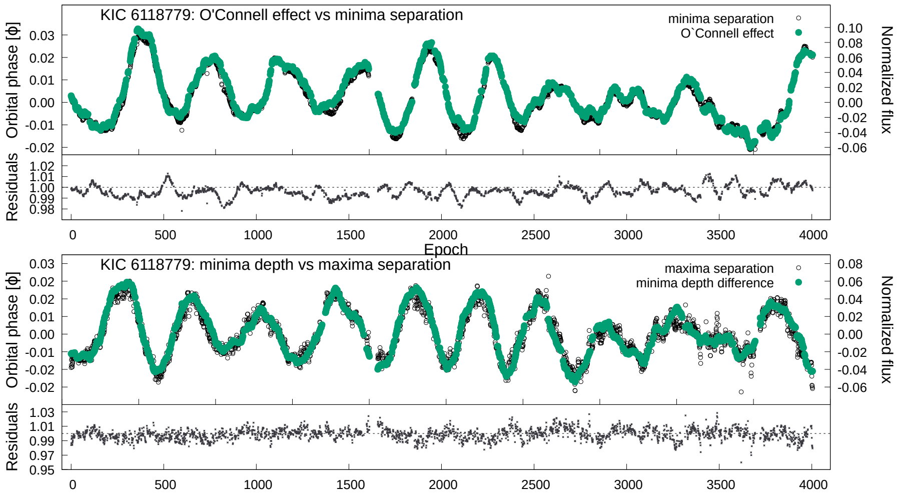


**Figure 2.** Comparison of the spot longitude found with the numerical modeling methods and the O'Connell effect (top panel) and the maxima separation variations (bottom panel).

value when the dark spot resides on the longitude $\lambda 180°$, i.e. lies in the back of a primary component. Alternatively, the maxima are closest to each other when the spot is at $\lambda = 0°$. Combining the analysis of the maxima separation variations and the evolution of the O'Connell effect leads to the information about the direction of the spot migration. In case of KIC 6118779 the dark spot moves in descending longitudes. The preliminary analysis of contact binaries observed with the *Kepler* spacecraft (Borucki et al., 2010) results in a conclusion that all studied systems experience descending-longitude spot migration.

It might be interesting to point out a following fine detail in the spot longitude - maxima separation relation. The cosine on the spot longitude is not always negative, when the maxima separation is less than its the median value (marked with a dashed line in the bottom panel of Fig. 1). Instead, the longitude cosine changes its sign always when the maxima separation crosses a value slightly larger (about $0.517\,\phi$ instead of the median $0.50994\,\phi$). This observation might lead to further interesting results when confronted with the analysis of the median maxima separation relation with the mass ratio for contact binaries (Debski, 2019).

## 3. Migration latitude and spot size

In addition to the two above light curve parameters, one can measure the equivalents in their extrema counterparts. The next two light curve parameters are therefore the minima depth difference and the separation of the brightness minima. It is most interesting that the variations of the O'Connell effect are the same as the variations of the separation of the brightness minima (with a scaling factor applied). The same situation happens for the evolution of the maxima separation and the minima depth difference variations. This high correlation between light curve parameters is shown in the Fig. 2. Using the means of the numerical simulations, we have established that such occurrence may happen only if the migrating spot is located very close to the stellar pole and must be rather large (radius of a spot reaches about $r = 40°$).

## 4. Conclusions

The longitudinal motion of a spot on a contact binary can be traced with the analysis of the O'Connell effect and the maxima separation variations. Since the light curve parameters vary in a highly correlated fashion, the spot is confined to the polar regions of the more massive component of the binary. That, combined with the fact that the spot must be considerably large, produces a picture of a tilted, precessing polar 'cap.' Our preliminary analysis of the contact binaries observed within the *Kepler* mission shows that systems with edge-on inclinations nearly always experience a light curve intrinsic variation lead by at least double modulation. At the same time, systems with a very low inclination tend to exhibit just a single-spot caused light curve variations. It is therefore very tempting to end with a conclusion that the spot migration in contact binaries occurs in a form of a precession of large polar spots residing on both poles of the more massive component. That, in turn, opens new possibilities for studying the properties and behavior of the global magnetic field structure in these exotic systems.

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# The population of W Ursae Majoris-type binaries in the solar neighborhood

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**Abstract.** W Ursae Majoris-type binaries belong to the old population of our Galaxy, while their metallicity is close to solar. Their physical properties, kinematics and spatial distribution reflect the properties of their stellar progenitors. This study focuses on the spatial distribution of W UMa's in our solar neighborhood within a 500 pc radius, with a combined astrometric, photometric and spectroscopic determination of their stellar parameters. The sample is carefully selected, in order to fulfill certain criteria, and has well defined metallicity and distance parameters. H-R diagram, as well as similar correlation plots (mass-radius and mass-luminosity), show that the primary (more massive) components in such systems are located close or below the ZAMS region, while secondary components seem to be evolved, as a result of their common envelope geometry. Some prominent outliers are carefully examined in order to judge the environmental properties and evolution in certain locations of the Milky Way. It is found that metallicity is not correlated with distance, but there is a weak correlation between metallicity [M/H] and evolution state, as it is expressed by the location of the systems in the H-R diagram, the type of binary (A or W), and temperature.

**Key words:** binaries: W UMa-type – stars: physical parameters – stellar evolution

## 1. Introduction

W Ursae Majoris-type binaries[1] are frequently observed as field targets, as well as within multiple stellar populations, open and globular clusters. Their combined photometric and spectroscopic study is a key tool for absolute physical property determinations, such as mass, radius, temperature, and therefore luminosity. It is well known that W UMa binaries belong to the old population of our Galaxy and their metallicity is close to solar. Certain empirical relations, extracted from various correlation diagrams, show that their physical parameters can be predicted up to a certain level, which, in turn, can be used as a tool

[1] W UMa binaries are overcontact systems of sufficiently late spectral type to have convective outer envelopes.

for distance indication. Various studies (Hilditch et al., 1988; Gazeas & Niarchos, 2006; Gazeas & Stępień, 2008; Gazeas, 2009; Michel et al., 2019) showed that this tool can be widely used, since it results from their evolution status. The metallicities have been recently studied in detailed work by Rucinski et al. (2013) who performed a thorough study of 90 targets and concluded that W UMas have roughly solar metallicity, with the majority (52 targets) showing: $0.32 < (B-V)_0 < 0.62$ or $0.65 < [M/H]_1 < +0.50$ (trend adjusted). They also showed that their kinematic properties are close to solar, while they belong to the thin disk population (age between 3.5-5 Gyr), based on the F-spectral type systems.

## 2. The current study

This study focuses on the spatial distribution of W UMa binaries in our solar neighborhood within a 500 pc radius, using combined astrometric, photometric and spectroscopic determination of their stellar parameters. The sample is carefully selected, in order to fulfill certain criteria and have well defined metallicity and distance parameters. H-R diagram, as well as similar correlation plots (Mass-Radius and Mass-Luminosity) show that the primary (more massive) components are located close or below the ZAMS, while secondary ones seem to be evolved, as a result of their common envelope geometry. Some outliers are still prominent and are carefully examined in order to judge environmental properties and evolution in certain locations of the Milky Way. These outliers are connected with either a "third light" parameter (they are members of multiple systems), or have low inclination (causing large uncertainties in physical parameters) and/or are magnetically active (resulting in light curve asymmetries).

## 3. Results

The [M/H] distribution of W UMas in distance is shown in Fig. 1. The metallicities are concentrated on the solar value (zero). A few systems are prominently higher than the entire sample (AB And, SW Lac, MS Vir, V502 Oph, V523 Cas, and V2357 Oph). These six systems are W UMa binaries of the W-subtype, i.e. the more massive component in the system is the cooler one. None of these prominent systems belong to the A-subtype, i.e. where the more massive component in the system is the hotter one. (MS Vir is not determined yet, but there is strong evidence for W-subtype). The spatial distribution of W UMas is shown in Fig. 2 in equatorial coordinates. Three of the above outliers (AB And, SW Lac, and V523 Cas) are relatively close to each other on the sky (left panel in Fig. 2), while the other three (MS Vir, V502 Oph, and V2357 Oph) are in the opposite sky direction (right panel in Fig. 2). Examining the spatial distribution in Cartesian coordinates (Fig. 3), we see that all high metallicity systems ex-

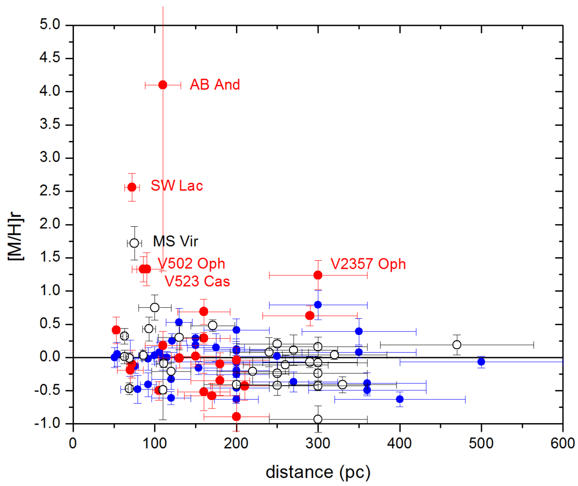


**Figure 1.** The majority of W UMa binaries have solar metallicity, although six outliers are prominent, with five being at a distance of ≈ 100 pc (see text for details).

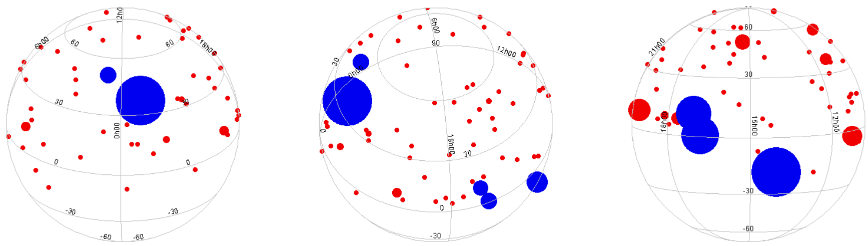

**Figure 2.** Spatial distribution of W UMa binaries in equatorial coordinates. High--metallicity systems (large blue circles) are located in two separate and opposite directions. Low-metallicity targets (small red circles) are spread towards all directions.

cept V2357 Oph are very close to the Sun, at distances of ≈ 100 pc. This is also prominent in Fig. 2, where the five systems are at a roughly the same distance, while V2357 Oph is much farther. This study has found that the metallicity is not correlated with distance (within $r < 500$ pc) but there is a weak correlation between metallicity [M/H] and evolution state (expressed by the H-R diagram location, and A- or W-subtype). High metallicity systems are located in two almost opposite directions: towards the Andromeda-Cassiopeia-Lacerta region and towards the Ophiuchus-Libra-Virgo region. There is a weak connection with Galactic coordinates, since the six outliers are close to the Galactic plane. High metallicity systems have certain properties: they are very close to the solar neighborhood, clumped in certain directions and all are W-subtype.

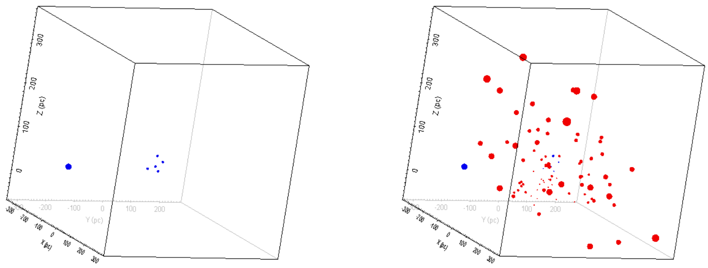

**Figure 3.** Spatial distribution of W UMa binaries in Cartesian coordinates. High-metallicity systems (left panel) are located close to our solar vicinity, while low-metallicity targets are covering all distance scales up to 500 pc.

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# Photometric study of selected X-ray binaries

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**Abstract.** We present results of a long-term photometric multicolor optical monitoring project of selected low-mass and high-mass X-ray binaries carried out at the TÜBİTAK National Observatory (TUG). New long-term $VRI$ multicolor observations of three selected X-ray binaries with neutron star components (HZ Her, ScoX-1, SAX J2103.5+4545) were observed between 2015 and 2019 with the TUG 60-cm telescope. The light variations of the systems are presented and discussed.

**Key words:** binaries: X-ray – neutron stars

## 1. Introduction

Flux variations of X-ray binaries consisting of an evolved component and a compact object (neutron star/black hole) can be observed both at X-ray and optical wavelengths. In these binary systems, the optical component usually fills its Roche lobe. Long-term light variations of both low-mass (LMXB) and high-mass (HMXB) X-ray binaries provide information on astrophysical processes, particularly on hot stellar winds of the companion star, stellar activity, mass transfer between components, non-conservative mass loss and angular momentum loss from the system. In this context, long-term multi-color optical changes of selected low and high mass X-ray binaries with neutron star components, previously discussed and catalogued by İçli & Yakut (2015), İçli (2016), are presented in this study.

Within the context of our observational project, eight X-ray binaries with neutron star components (HZ Her, Sco X-1, PSR J1023+0038, X Per, BQ Cam, V934 Her, SAX J2103.5+4545, XTE J1946+274) were examined. Some parameters of the selected systems are summarized in Table 1. Here we present long-term observational results for HZ Her, Sco X-1, and SAX J2103.5 + 4545 and we obtain a new period for the SAX J2103.5+4545 system from our new observations.

Sco X-1, which is known as the brightest LMXB, was discovered by Giacconi et al. (1962). Its optical component is V818 Sco (Sandage et al., 1966). The system has an orbital period of 0.78 days and consists of a 1.4 $M_\odot$ neutron star and a 0.42 $M_\odot$ optical component (Steeghs and Casares, 2002). Based on optical observations, the spectral type is thought to be earlier than G5. The distance of the system is 2.8±0.3 kpc (Bradshaw et al., 1999) and the system exhibits a high and low state (Bandyopadhyay et al., 1999).

Discovered by observations of the UHURU satellite in 1972 (Tananbaum et al., 1972), Her X-1 (HZ Her, 4U 1656+35) is classified as an eclipsing LMXB system with an A7 spectral type (Middleditch & Nelson, 1976; Leahy & Scott, 1998, İçli et al., 2019). The system has an orbital period of 1.7 days and consists of an accreting neutron star with a mass of 1.5 $M_{\odot}$ and an optical component with a mass of 2.2 $M_{\odot}$ (Reynolds et al., 1997; Leahy & Abdallah, 2014, İçli et al., 2019). Its distance is 6.6 kpc (Reynolds et al., 1997). The system has been observed at different wavelengths (optical, ultraviolet, radio and X-ray bands), see, e.g., Shakura et al. (1997); Cherepashchuk et al. (1974); Simon et al. (2002); İçli & Yakut (2015); İçli (2016). The X-ray flux exhibits a 35-day period variation related to the accretion disc (Scott et al., 2000; Leahy & Abdallah, 2014; Postnov et al., 2013).

Another system within the scope of this study is SAX J2103.5+4545, discovered in 1997 with *BeppoSAX*. It pulsates with a period of 358.61 s (Hulleman et al.,1998). The system is composed of a 20 $M_{\odot}$ optical component with a B0 Ve spectral type (Reig et al., 2010). The orbital period of the binary system is 12.6 days (Baykal et al., 2007).

## 2. New observations

New observations were made between February 2015 and July 2019, with varying exposure times between 5, 20 and 60 seconds. Multicolour ($VRI$) light curves were obtained with the 60-cm robotic telescope at the TÜBİTAK National Observatory (TUG). Three systems were observed, HZ Her, ScoX-1, and SAX J2103.5+4545. Their respective periods are 1.7, 0.78, 12.6 days, and their $V$ band brightness lies between 12.5 and 13.8 magnitudes. Observations were handled with the standard difference photometry method in each observation term. IRAF/PHOT and AstroImageJ (Collins et al., 2017) were used in the reduction stage. The frame reduction was performed by subtracting the bias and dark frames and dividing by flat-field frames. Following the time correction, we performed differential photometry as we did in our prevous studies (İçli et al., 2013, Çokluk, et al., 2019, Koçak et al. 2019). AAVSO-135, AAVSO-132, AAVSO-50(1) (for HZ Her), AAVSO-115, AAVSO-126, AAVSO-113 (for ScoX-1) and ID-72,131,136 (for SAX J2103.5+4545 (Reig & Fabregat, 2015) were chosen as comparison stars. Light variations of the systems are plotted in Fig. 1.

## 3. Discussion and conclusions

X-ray binary systems consist of an early- or a late-type star and a black hole or neutron star. The presence of an accretion disk, mass loss from the system and stellar activity on the companion star affect the multi-wavelength light curves

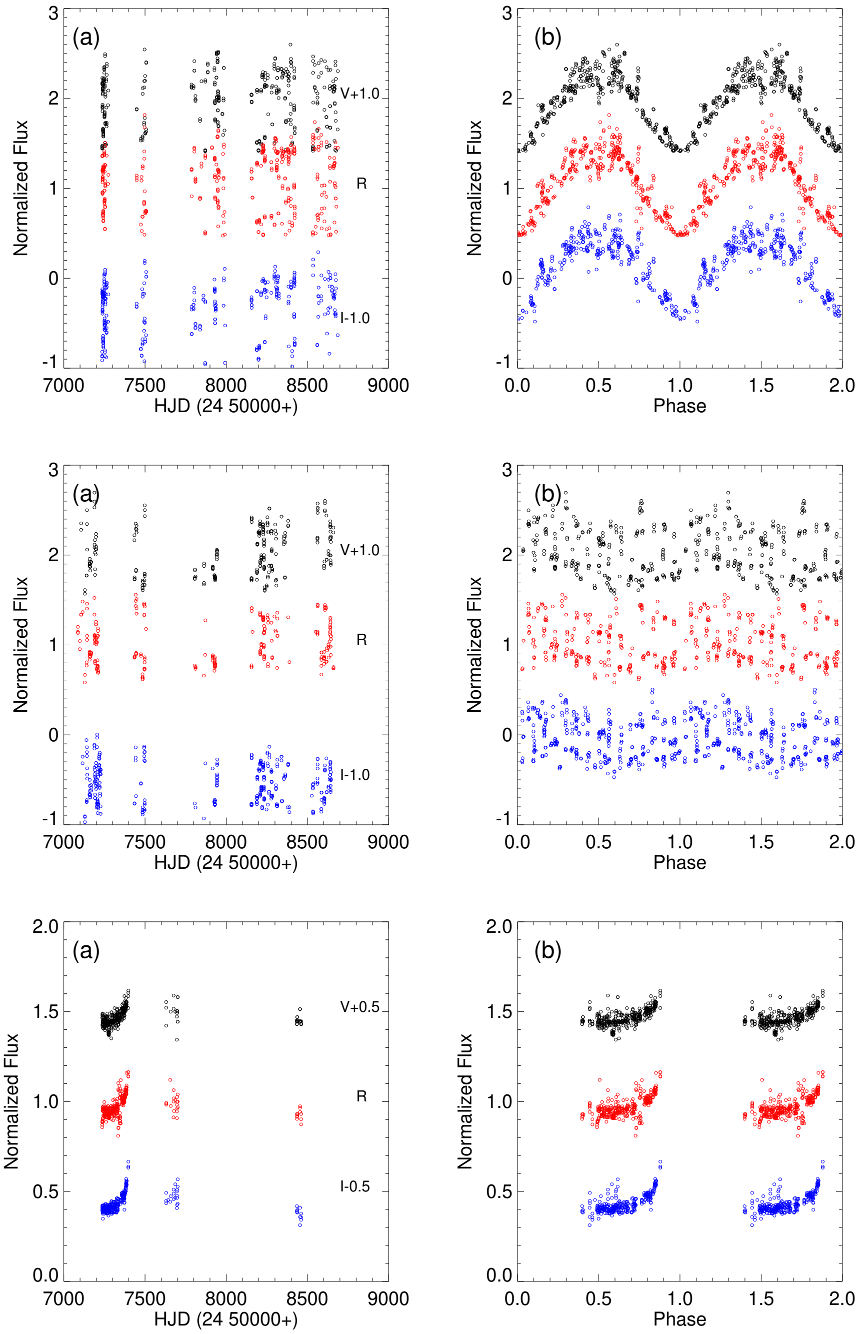


**Figure 1.** Long-term $VRI$ light variations of the systems in the time (a) and phase (b) domain for HZ Her (top), Sco X-1 (middle), and SAX J2103.5+4545 (bottom).

**Table 1.** Parameters of selected X-ray binaries

| System | Alias | Type | $\alpha$ | $\delta$ | $V$ (mag) | $P_{\rm orb}$ (d) | OTime | $N_{\rm obs}$ |
|---|---|---|---|---|---|---|---|---|
| PSR J1023+0038 | AY Sex | LMXB | 10 23 48 | +00 38 41 | 17.5 | 0.198 | 7731-8447 | 337 |
| Sco X-1 | V818 Sco | LMXB | 16 19 43 | −15 39 08 | 12.5 | 0.787 | 7106-8644 | 847 |
| Her X-1 | HZ Her | LMXB | 16 57 49 | +35 20 33 | 13.6 | 1.7 | 7236-8687 | 1145 |
| SAX J2103.5+4545 | | HMXB | 21 02 55 | +45 43 25 | 14.2 | 12.6 | 7236-8461 | 1029 |
| V0332+52 | BQ Cam | HMXB | 03 34 60 | +53 10 23 | 15.4 | 34.67 | 7059-8759 | 2126 |
| XTE J1946+274 | | HMXB | 19 45 35 | +27 20 43 | 16.9 | 169.2 | 7271-8659 | 466 |
| 3A 0352+309 | X Per | HMXB | 03 55 36 | +31 00 25 | 6.7 | 250.3 | 7360-8461 | 620 |
| 4U 1700+24 | V934 Her | LMXB | 17 06 35 | +23 58 19 | 7.6 | 4391 | 7137-8461 | 1230 |

of the binary systems. We obtained multicolor ($VRI$) observations of X-ray binaries with neutron star components between 2015 and 2019 with the TUG T60 telescope. Periodic and non-periodic changes have been observed in these systems. For HZ Her, the amplitude of the light variation in the $V$ band is 1.5 mag. The middle panel of Fig. 1 shows the multicolor optical light variation of V818 Sco. The light curves of the system show amplitude variability in the $VRI$ bands. Orbital light curves of the V818 Sco (Fig. 1, middle-right panel) can differ significantly from the mean orbital light variation ($\sim$ 35%). Based on observations obtained over a span of five years, a period of 412 days for the HMXB SAX J2103.5+4545 was determined using the Period04 (Lenz & Breger 2005) software. A non-periodic period variation seems to be present in the long-term observations.

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# Spectroscopic observations of eccentric eclipsing binary systems

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**Abstract.** Eccentric eclipsing binaries (EEBs) are detached binary stars. Many EEBs show apsidal motion. EEB fundamental physical parameters allow us to test stellar evolution models and to estimate the internal stellar structure constants through apsidal motion analysis. We started a programme to study EEBs at the UBT60 telescope of Akdeniz University located at TÜBİTAK National Observatory. In this paper, we present spectroscopic orbital parameters of some selected EEBs.

**Key words:** stars: binaries: detached – stars: binaries: eclipsing – techniques: spectroscopic

## 1. Introduction

Eclipsing binary systems are important objects that help us understand stellar and binary evolution in astrophysics. Eccentric eclipsing binaries (EEBs) are precious astrophysical laboratories to study apsidal motion and test general relativity. The rotation of the eccentric orbit is known as apsidal motion. The study of the apsidal motion provides information on the internal structure constants of the components. The internal structure constants and precise absolute parameters of the components can be used to test evolutionary models. The physical properties of the components of the systems can be derived from the study of spectroscopic and photometric observations. Light curves of binaries with long orbital periods can be obtained from published photometric catalogues. However, it is difficult to obtain complete radial velocity curves of eclipsing binary systems with long orbital periods. This study is in part a continuation of our programme of spectroscopic observations of long-period eclipsing binary systems. We collected the spectra of two early type eccentric eclipsing binaries, V839 Cep and V850 Cep, and obtained their spectroscopic orbital parameters.

The light elements of V839 Cep (GSC 3964-0741) were given by Otero et al. (2006) as $T_0(\mathrm{HJD}) = 2451448.645$ and period $P = 9.9634\,\mathrm{d}$. Detailed apsidal motion studies were performed by Zasche et al. (2018) and Volkov et al. (2019). Here we derive absolute parameters of the system.

V850 Cep (GSC 04257-00906) was listed as an eccentric binary system by Otero et al. (2006) who list ephemeris parameters $T_0$ (HJD) = 2451475.710 and period $P = 12.922$ d.

## 2. Observations and data reduction

Observations were carried with the Akdeniz University 0.6-m telescope (UBT60) located at TÜBİTAK National Observatory. The eShel spectrograph equipped with a QSI632s CCD camera (pixel size 6.8 $\mu$m, gain 0.9 $e^-$/ADU, readout noise 7 $e^-$i was used to collect the spectral data. The eShel spectrograph, which has a resolution power of 12000 and covers a 4045-8100 Å wavelength range in 27 orders, is connected to the telescope with fiber optics.

In each observation night, we obtained bias, dark frames, flat spectra from a Tungsten lamp, and wavelength calibration spectra from a ThAr lamp for the calibration of the spectra. The IRAF[1] echelle package was used for extracting order apertures, elimination of scattered light through the orders, wavelength calibrations of spectroscopic data and measuring the radial velocities (RVs) of components.

**Table 1.** The orbital parameters of V839 Cep and V850 Cep.

| | V839 Cep | V850 Cep |
|---|---|---|
| $T_{per}$ (HJD) | $2458371.83872 \pm 0.47141$ | $2457972.65588 \pm 1.05112$ |
| $P$ (days) | 9.9633 (fixed) | 12.9285 (fixed) |
| $\omega$ (deg) | $31.58 \pm 15$ | $284 \pm 14$ |
| $e$ | $0.20 \pm 0.04$ | $0.37 \pm 0.15$ |
| $K_1$ (km s$^{-1}$) | $80.3 \pm 5.0$ | $80 \pm 15$ |
| $K_2$ (km s$^{-1}$) | $79.7 \pm 5.0$ | $84 \pm 17$ |
| $V_\gamma$ (km s$^{-1}$) | $-32.2 \pm 3.0$ | $-25.7 \pm 6.1$ |
| $a_1 \sin i$ (km) | $108 \pm 9 \times 10^5$ | $13.2 \pm 3.4 \times 10^6$ |
| $a_2 \sin i$ (km) | $107 \pm 9 \times 10^5$ | $13.8 \pm 3.7 \times 10^6$ |
| $M_1 \sin^3 i$ ($M_\odot$) | $1.99 \pm 0.33$ | $2.41 \pm 1.50$ |
| $M_2 \sin^3 i$ ($M_\odot$) | $2.00 \pm 0.33$ | $2.31 \pm 1.43$ |

## 3. Preliminary Results

The RVs were measured by applying Gaussian profiles to the central parts of the H$\alpha$ (6563 Å) line. The least-squares method was used to fit the RV equation

[1]IRAF is distributed by the National Optical Observatories, operated by the Association of Universities for research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

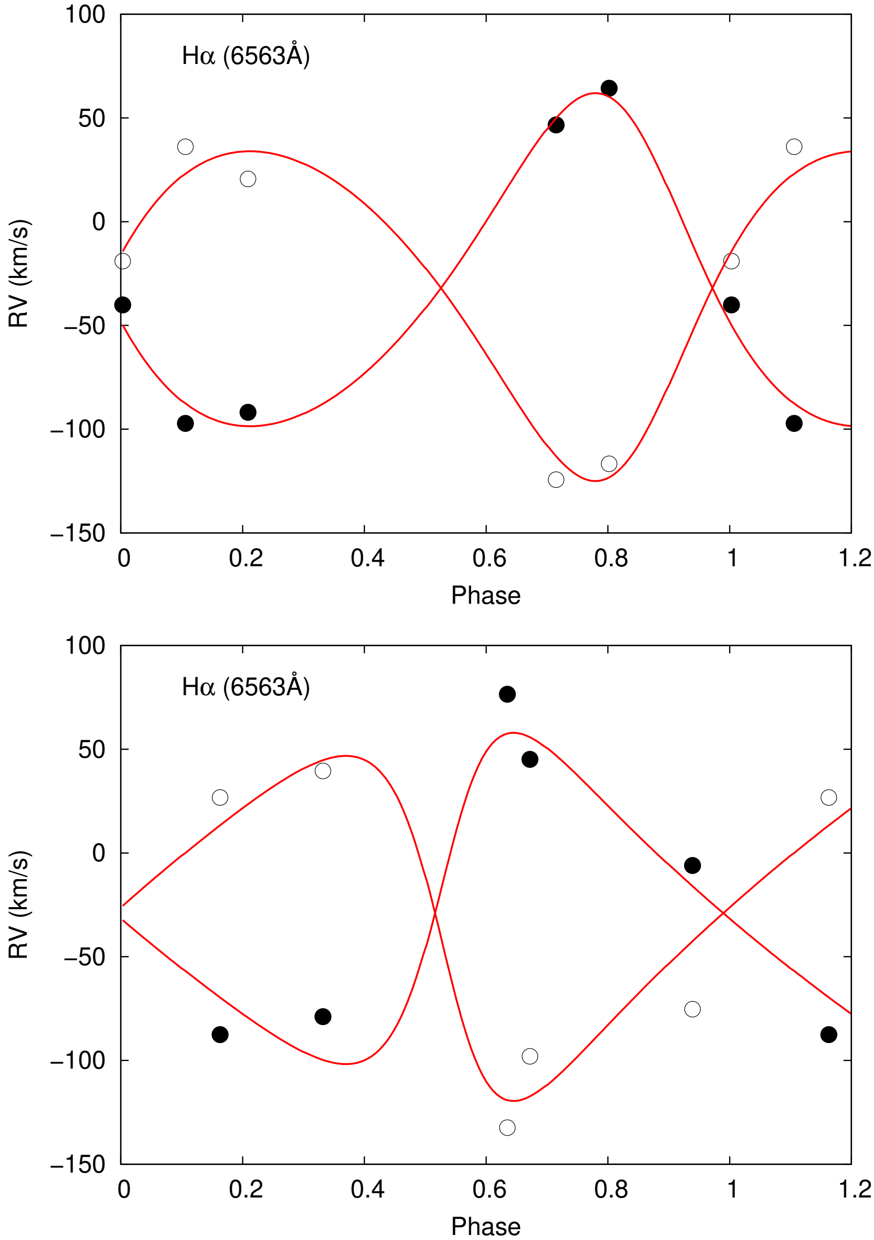


**Figure 1.** Radial velocities of V839 Cep (upper panel) and V850 Cep (lower panel).

to the measured RVs. Radial velocity curves (RVCs) and the theoretical orbital fitting can be seen in Fig. 1 for V839 Cep and V850 Cep. Filled and empty dots represent the RVs of the primary and secondary component, respectively. Dashed red lines are synthetic curves fitted to the RVs. We used the light elements parameters given by Kreiner (2004) as initial parameters and kept periods fixed during the solutions. The results of the RVC solutions for the systems are given in Table 1.

Orbital parameters for V839 Cep and V850 Cep are presented based on new spectroscopic observations. The theoretical curves fit the RVs well for V839 Cep and orbital parameters of the system were obtained. Simultaneous RV and light curve solutions allow us to derive the absolute parameters of the components. The large error values of the orbital parameters of V850 Cep are due to the small number of RV data points. More spectroscopic observations are needed for this system to obtain more accurate orbital parameters.

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# Photometric study of close binary stars in the M35, M67, and M71 Galactic clusters

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**Abstract.** We obtained new multicolour photometry of close binary stars in the young open cluster M35, the solar-age open cluster M67, and the globular cluster M71. New observations have been carried out at the TÜBİTAK National Observatory (TUG) by using the 100 cm (T100) telescope. We present observational results for eclipsing binary systems in the selected Galactic clusters. New accurate light curves for 2MASS J19532554 + 1851175, 2MASS J19533427 + 1844047, 2MASS J06092044 + 2415155, and AH Cnc were obtained. We analysed the light curves and derived some of the orbital parameters of the systems.

**Key words:** stars: binaries: close – clusters: open – clusters: globular

## 1. Introduction

Stellar clusters are very important tools for studying stellar formation and evolution, as well as the formation, structure, and dynamical evolution of the Galaxy. There are more than three thousand open clusters and about a hundred and fifty globular clusters in the Milky Way. Globular clusters are important in determining the lower limit of the age of the Universe. Open clusters are made up of relatively young stars, while globular clusters are composed of very old and metal-poor stars. Typical globular and open clusters contain stars with very different masses and with different properties in the HR diagram. The binary systems in the star clusters, especially at the turn off point of the main sequence, provide great opportunities for studying the evolution of both the clusters and the binary systems. Therefore star clusters are ideal laboratories for testing and calibrating stellar evolution theories. For details, see Meynet et al. (1993), Harris (1996), Elmegreen & Efremov (1997), Chantereau et al.(2015), Chantereau et al.(2016), Hurley et al. (2005),Prantzos & Charbonnel (2006), Decressin et al. (2007), Yakut et al. (2009), Bilir et al. (2012), Yakut et al. (2015).

Galactic globular clusters are compact and old systems which contain more than 1 million stars. So, there is a very high probability of collision of the stars with each other. Globular clusters host a lot of binary stars. Studying binaries in a cluster has some advantages. For instance, all binaries are at equal distances from us, have (almost) same chemical composition and (almost) same age. Nevertheless, the masses of the stars differ from one to another. By using stellar parameters of binary system, we can test the theoretical evolutionary models and elucidate some poorly understood astrophysical phenomena such as mass loss, mass transfer, physical parameter variations during the evolution, angular momentum problem, etc.

The distance to the M71 globular cluster is about 4 kpc and it is fairly metal-rich, low-density globular cluster in the Galaxy (Grundahl et al. 2002). M71 is an important laboratory for studying the formation of exotic objects such as blue strugglers, cataclysmic variables, low-mass X-ray binaries and millisecond pulsars (Ferraro et al. 1997; Pooley et al. 2003; Heinke et al. 2005). NGC 6791 is the oldest open cluster in the Galaxy with an age of $7.7\times10^9$ years (Yakut et al., 2015). Be 17 and NGC 188 are also among the oldest galactic clusters (Phelps 1997; Meibom et al., 2009). NGC 2168 (M35), classified by Trumpler in 1930, is a rich open cluster of almost 180 Myr old and its distance is about 900 pc. The open cluster M67 (NGC 2682) is located at a distance of 840 pc. This cluster has many different types of binary stars. The cluster is also important because of its solar age and solar-like chemical composition (Yakut et al., 2009). The chemical abundance and age of the cluster is very close to those of the Sun, which is important for testing stellar evolution models. M67 includes many blue stragglers that are bluer and brighter than the stars at the turn-off point of the cluster. Moreover, the cluster contains close and interacting binary stars like AH Cnc, ES Cnc, and EV Cnc.

## 2. New observations

We have obtained high precision new multi-colour observations of close binary systems in the open cluster M35, M67, and in the globular cluster M71. New observations were obtained using the 100 cm telescope at the TÜBİTAK National Observatory (TUG). M71 was observed during 15 nights in the $V$ and $R$ filters. M35 is scattered over an area of the sky almost the size of the full moon. Therefore, we observed it by dividing the CCD field into four regions. New CCD observations of M35 and M67 in the $V$, and $R$ filters were obtained on 12 and 4 nights, respectively.

Data reductions were performed by subtracting the bias and dark frames and dividing by the flat frame. We studied each night separately following the time correction and performed differential photometry similar to our earlier study (İçli et al., 2013). In the data reduction we used IRAF/DAOPHOT and AstroImageJ (Collins et al., 2017). For the contact binary AH Cnc we used *Kepler* satellite observations. The raw data show some fluctuations due to common instrumental effects (Jenkins et al., 2010). We eliminate these systematic variations by applying cotrending and detrending processes, as we did in our earlier *Kepler* studies (Çokluk, et al., 2019; Yakut et al., 2015). Fig. 1 shows the light variation of the selected systems in the galactic clusters M35 (2MASS

J06092044+2415155), M67 (AH Cnc), and M71 (2MASS J19533427+1844047, 2MASS J19532554+1851175).

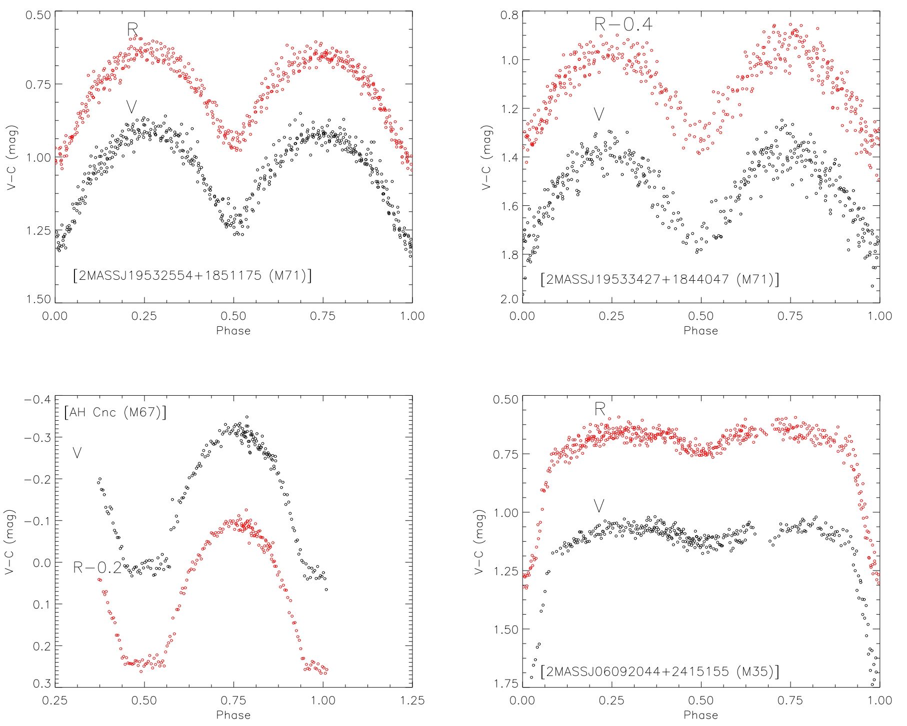


**Figure 1.** $V$, $R$ and Kepler ($K_p$) light curves of some close binaries in the Galactic clusters M71, M67, and M35.

## 3. Results

In this study, accurate multicolor light variations of some eclipsing binary systems in several galactic open and globular clusters were obtained. Using new observations, synthetic light curves were modelled with Phoebe (Prša & Zwitter, 2005; Wilson & Devinney, 1971; Wilson, 1979). During the light curves analysis, the limb darkening coefficients (from van Hamme, 1993), albedos (from Rucinski, 1969) and the values of the gravity-darkening coefficients (from Lucy 1967) were taken as fixed parameters. Preliminary analysis resulted in the determination of the orbital inclination ($i$), the mass ratio ($q$), and the fractional radii of

**Table 1.** Light curve solution parameters and formal $1\sigma$ errors for 2MASS J06092044+2415155, AH Cnc, 2MASS J19533427+1844047, and 2MASS J19532554+1851175.

| | J06092044 | AH Cnc | J19533427 | J19532554 |
|---|---|---|---|---|
| $i$ (deg) | $69.1 \pm 0.7$ | $87.9 \pm 0.2$ | $71.8 \pm 0.2$ | $71.2 \pm 0.4$ |
| $q$ ($M_2/M_1$) | $0.71 \pm 0.01$ | $0.147 \pm 0.004$ | $0.13 \pm 0.01$ | $0.22 \pm 0.01$ |
| $r_1$ ($R_1/a$) | $0.3022 \pm 0.0013$ | $0.5660 \pm 0.0005$ | $0.567 \pm 0.015$ | $0.333 \pm 0.008$ |
| $r_2$ ($R_2/a$) | $0.3482 \pm 0.0013$ | $0.2483 \pm 0.0008$ | $0.232 \pm 0.047$ | $0.424 \pm 0.007$ |

the primary ($r_1$) and secondary ($r_2$) components for the selected binaries listed in Table 1.

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# Binarity among objects with the Be and B[e] phenomena

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**Abstract.** Many B-type stars exhibit two phenomena that are symbolized Be and B[e]. The former refers to presence of a circumstellar gaseous disk without significant circumstellar dust, while the latter have dust. Although neither phenomenon is fully understood, growing evidence suggests that binarity plays an important role. Recent results on Be and B[e] binaries, along with methods of their discovery, are reviewed.

**Key words:** Stars: emission-line, Be, B[e] – Stars: binaries: spectroscopic

## 1. Introduction

Two emission line phenomena, found almost exclusively in stars of spectral type B, are due to large amounts of circumstellar material. These Be and B[e] stars were not expected to be mostly in binary systems, but their estimated binary fractions have steadily grown with time.

The Be phenomenon was discovered at the dawn of astronomical spectroscopy in the middle of the 19th century by visual observing of hydrogen emission lines in the spectrum of $\gamma$ Cassiopeae (Secchi, 1866). The B[e] phenomenon was discovered 110 years later in the course of an early near-infrared (IR) photometric survey combined with optical spectroscopy. It was defined as the presence of both permitted and forbidden line emission along with a large IR excess due to radiation of circumstellar (CS) dust (Allen & Swings, 1976). Major features of both phenomena are summarized in Table 1.

## 2. Properties of objects with both phenomena and connections to binary systems

### 2.1. The Be phenomenon

One of the main features of the Be phenomenon is rapid rotation that may be due to initial fast rotation or to later mass transfer in a binary system. Many B–type stars with broad absorption lines (known as Bn stars) have not been found to exhibit emission lines, thus suggesting that fast rotation alone may not be the only mechanism for the phenomenon creation, especially in strong-lined Be stars. A binary hypothesis as a reason for the phenomenon was first proposed by Kriz & Harmanec (1975) and initially attributed to ongoing transfer of mass and angular momentum to the B–type component. However, this hypothesis was taken with caution because only $\sim$40 binaries were recognized among over 1000 known Be stars by the end of the 20th century (e.g., Gies, 2000; Harmanec, 2001). The advent of high-resolution spectroscopy, including a large contribution from the amateur community collected in the BeSS database (Neiner et al., 2011), allowed to observe Be stars more frequently and sharply increased the number of confirmed Be binaries. Currently 14 out of the brightest 24 Be stars ($V \leq 4$ mag) and 75 out of 237 Be stars with $V \leq 7.5$ mag are known binary systems (Miroshnichenko, 2016). Apparent decrease of the binary fraction toward fainter objects is due to observational selection effect, as fainter stars are not observed as frequently as brighter ones.

The line emission in Be stars is variable at different levels. Some objects show very little variation for decades (e.g., $\beta$ CMi), while others exhibit periods of strong line emission followed by "normal" star phases, when the emission lines and IR excess disappear completely. Some examples of the latter include $\pi$ Aqr (Bjorkman et al., 2002), 66 Oph, and $\phi$ And (see Fig. 1, left panel). Be disks may also reappear unexpectedly in previously known Be stars (e.g., $\pi$ Aqr, Zharikov et al., 2013) or form around B–type stars for the first time (e.g., $\delta$ Sco, Miroshnichenko et al., 2001). It has been suggested that disk formation can be triggered by non-radial pulsations (see Rivinius et al., 2013, for a recent review) or by periastron passages in highly eccentric binaries ($\delta$ Sco). The disks are

**Table 1.** Main features of the Be and B[e] phenomena

| Feature | Be | B[e] |
|---|---|---|
| Emission lines | Permitted transitions:<br>H I, Fe II except the coolest | Permitted and forbidden transitions:<br>same + Na I |
| | no forbidden lines | [O I], [Fe II], [N II], [S II]<br>[O III] – B0–B2 |
| IR-excess | free-free + free-bound CS gas | CS gas + dust thermal radiation |
| Rotation | close to break-up velocity | slower than that of Be stars |

typically Keplerian, but the CS gas may both fall back onto the star or move away due to viscosity.

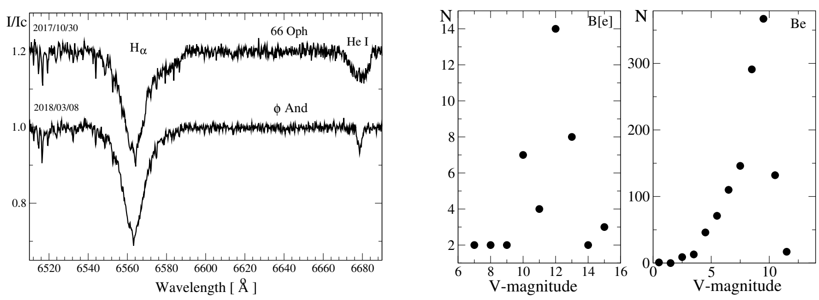


**Figure 1. Left panel:** Parts of the spectra of two Be stars that lost their disks. The spectra were taken with a 0.81 m telescope of the Three College Observatory in North Carolina, USA, with a spectral resolving power of $R \sim 12,000$. The dates of observation along with the objects names and spectral lines shown are indicated. The intensity is normalized to the local continuum, the wavelength scale is given in Angströms. **Right panel:** Brightness distribution of Galactic Be stars and FS CMa objects with the B[e] phenomenon.

## 2.2. The B[e] phenomenon

The B[e] phenomenon is present in objects of 4 groups with known nature (pre-main-sequence Herbig Ae/Be stars, a small group of supergiants, symbiotic binaries, and some proto-planetary and planetary nebulae, Lamers et al., 1998). However, half of the originally found 65 objects were not classified, because they either had no reliable luminosity estimates or showed properties of more than one of the groups. Recently Miroshnichenko (2007) suggested that most unclassified objects with the B[e] phenomenon may actually be binary systems that have undergone non-conservative mass transfer, which was responsible for formation of the CS material, including dust. This group was named FS CMa type objects after the prototype object with the B[e] phenomenon (Swings, 2006). The group's SEDs show a lack of cold dust compared to young stars and planetary nebulae and typically very strong emission-line spectra. The group has been expanded several times (Miroshnichenko et al., 2007, 2017) and nearly 20 binary systems have been found among its members by various methods, including five with measured orbital periods. It is harder to reveal their binarity than in Be stars due to a more complicated structure and variability of the CS medium, as well as their lower brightness (see Fig. 1, right panel). However a growing number of their observations, especially at big telescopes (including SALT, CFHT, the 2.1 m telescope of the Observatorio Astronómico Nacional San Pedro Martir, and 2 m Himalayan Chandra Telescope) will eventually result in verifying the binary hypothesis.

## 3. Conclusions

There is growing evidence that many stars with the Be and B[e] phenomena are binary systems, most of which have undergone mass transfer between the components due to Roche lobe overflow. The number of confirmed Be binaries is steadily growing. The situation with B[e] objects is similar: symbiotic systems are binaries by definition, while most B[e] supergiants and a number of FS CMa objects have been found to be binaries as well. Binarity can be revealed with several methods, which include observing regular radial velocity variations or orbital phase locked intensity variations of double-peaked emission-line profiles (in weak-lined Be stars Zharikov et al., 2013), eclipses, and resolving individual components with interferometry and spectro-astrometry. Spectroscopic methods are still the most successful but require long-term observing campaigns and collaboration between professional and amateur astronomers.

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# The 35-day cycle in the X-ray binary HZ Her/Her X-1

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**Abstract.** We present the results of modelling the 35-day superorbital changes in the $B$ and $V$ lightcurves and X-ray flux of HZ Her/Her X-1. The model is implemented in a computer program written in the C programming language, with a module for parameter optimisation written in Python. The model includes a tilted precessing and warped accretion disc around a freely precessing neutron star. The disc is warped near its inner edge due to interaction with the rotating neutron star magnetosphere. The magnetic torque depends on the precessional phase of the neutron star. The neutron star X-ray emission flux also depends on the free precession phase, which modulates the X-ray illumination of the optical star's atmosphere and the intensity of gas streams. We demonstrate that this model is able to reproduce both the optical observations of HZ Her and the behaviour of the system's 35-day X-ray cycle.

**Key words:** binaries: accretion discs, X-ray – neutron stars

## 1. Model

The donor star shape is defined by an equipotential surface of the Roche potential. The effective temperature of the donor star varies across the surface due to gravity darkening and X-ray irradiation. The disk in the model is warped and tilted. The disk casts a complex X-ray shadow on the surface of the donor star.

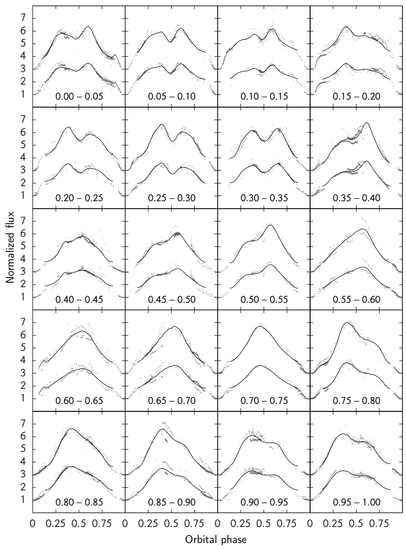


**Figure 1.** Relative $B$ and $V$ flux, with dots representing the observations and solid lines the theoretical light curves. The numbers in the cells indicate a phase interval in the 35-day cycle. Data in the $B$ band are shifted up 2 units with respect to $V$ data. The optimum theoretical lightcurve for every phase is shown.

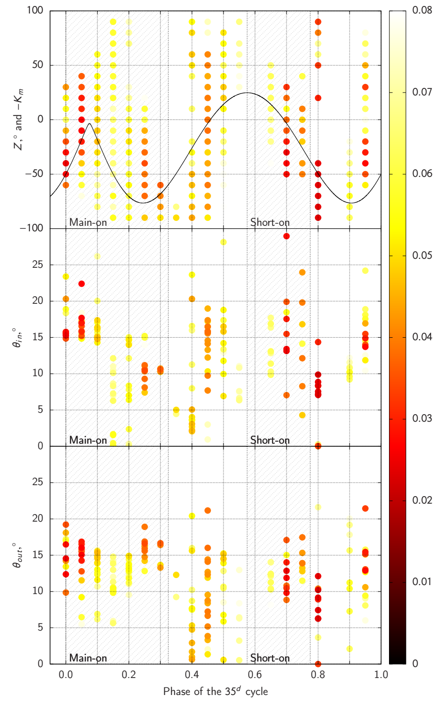


**Figure 2.** $Z$ is the angle between the nodal lines of the inner and outer edges of the disk. $\theta_{in}$ and $\theta_{out}$ are the angles between the disk's inner or outer edge and the orbital plane. The solid line on the first graph is the theoretical magnetic torque $K_m$ acting on the disk's inner edge.

We suggest that the disk is warped mostly near the neutron star due to magnetic torque. Near orbital phase 0.5 the disk passes in front of the donor star. We use a ray-tracing technique to determine which parts of the star's surface are obscured by the disk. We have not yet modelled orbital phases near 0.0, when the disk passes behind the donor star. The neutron star's X-ray intensity is adopted from Postnov et al. (2013). The neutron star is under free precession (Landau et al., 1976) with a period close to 35 days. The code is free and available from `https://github.com/eliseys/discostar`.

## 2. Results

Here we show model parameters as a function of phase of the 35-day cycle and light curves corresponding to the minimum of sum of squared residuals between model and observations (Fig. 1). The most interesting result is that the angle $Z$, which is a measure of the torsion of the disk, follows the theoretical magnetic torque $K_m$ acting on the disk's inner edge (Fig. 2, $Z$). The inner edge of the disk tends to be close to the neutron star's equator when the magnetic torque reaches a maximum value (Fig. 2, $\theta_{in}$), which was predicted by Lipunov et al. (1981).

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# Temporal evolution of the magnetically active eclipsing binary DV Psc

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**Abstract.** The existence of magnetic activity on the eclipsing binary DV Psc has been known for almost two decades. However, until recently, no evidence of periodic behaviour relevant to this activity had been found. In this study, long-term photometric observations of DV Psc are used to analyze the system's magnetic activity, seek a possible magnetic cycle and determine orbital and physical parameters. The combination of photometric and spectroscopic observations results in a unified model that describes the system over time in terms of variable spot activity. New times of minimum light are determined and an accurate astronomical ephemeris and updated O-C diagram are constructed for a total span of 19 years (1997-2017). The intense magnetic activity, as indicated by strong asymmetries in the light curves (O' Connell effect), and the periodic variation of the O-C diagram are combined to explain the system's behaviour. The existence of a third body, orbiting the eclipsing binary in an eccentric orbit, as well as a magnetic cycle are the most likely scenario.
**Key words:** stars: activity – binaries: close – binaries: eclipsing

## 1. Introduction

The eclipsing binary DV Psc was discovered to be a variable by Robb et al. (1999). It belongs to the class of RS CVn systems, exhibiting strong magnetic activity. Several studies of this target exist in the literature (Lu et al., 2001; Parimucha et al., 2010), some of which resulting in contradicting conclusions (Zhang & Zhang, 2007; Pi et al., 2012, 2014).

## 2. The current study

Our observations confirm the highly variable magnetic activity, which changes the light curve dramatically on a small time scale. The observed light curve asymmetries affect the calculation of times of minima, resulting in a variable O-C diagram (Fig.1). Times of minimum light determined from our observations, as well as those available in the literature, are used for the O-C analysis in the current study. We found both components to be slightly evolved dwarfs, located well inside the Main Sequence. The cyclic behavior of the O-C diagram suggests a possible third body, orbiting the binary, as well as the presence of prominent magnetic activity, both of which affecting the times of minima. The orbit of the third body is estimated to have a period of $9.79 \pm 0.60$ yr, while the magnetic cycle of the system is estimated to last $14.74 \pm 0.84$ yr.

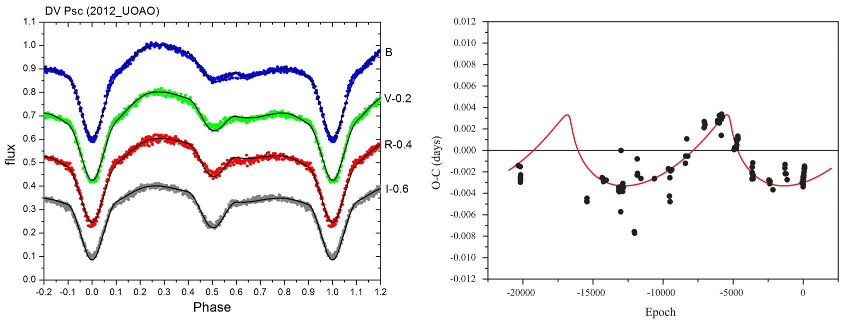


**Figure 1.** An example of multi-band photometric variability of DV Psc for data obtained in 2012. Solid curves represent theoretical models. The right panel shows the cyclic behavior of the O-C diagram extracted from the times of minimum light.

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# An analytic self-gravitating disk model: inferences and logical structure

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**Abstract.** The foundations of an analytic Accretion-Decretion (A-D) disk model, based on equipotential theory, for mass-transfer binaries are examined. Gravitation of stars 1 and 2 and the disk, as well as disk and star rotation, are included and relevant morphology is explored. Expected applications are to disks with morphologically significant mass and substantial optical thickness. Anticipated targets include classical novae, nova-like variables, and W Serpentis binaries, with the concept invoking knowledge about Be stars and the classically strange binary $\beta$ Lyrae. The model's ideas and resulting character differ from those usually applied to optically thick disks – for example there is no need to truncate the model arbitrarily at an outer or inner limit, because it closes naturally at both places. The disk is a volume emitter with attenuation of internally generated light. Computations intrinsically produce phenomena that are characteristic of circumstellar disks in binaries – in particular tidal and rotational gravity brightening and an outer effective gravity null point that do not occur in the common axisymmetric disk model. Impersonal analysis in terms of the model (Least Squares criterion) is applied to light curves of recurrent nova CI Aquilae.

**Key words:** binaries: eclipsing, binaries: spectroscopic, stars: $\beta$ Lyr, CI Aql

## 1. Introduction

Prior to a half-century ago, a school of thinking disbelieved in overcontact (OC) binaries (W UMas and more massive OCs), apparently because computation of their light curves was impractical with existing computers. The likely thinking was, "If we can't do the computations, an OC model is beyond consideration." This mental barrier delayed meaningful progress on W UMas and other OCs because the adopted morphology (detached or at most point-contact) did not match the reality of overcontact (see Sec. 4.3 of Wilson, 1994, for discussion). But what do OC binaries have to do with disks? The connection is the analogous developmental situation for significantly massive disks in tight binaries – disbelief in self-gravitating (i.e. significantly massive, SG) disks for lack of a way to do the proper computations (light curves, radial velocities, . . . ). However the point at issue is *not* that most disks in binaries are significantly massive – just that *some* very interesting ones may be, and that possibility needs investigation.

**Binary morphology – role of limiting lobes**

Early thoughts on semi-detached and detached morphology concerned the strange and still not thoroughly understood object $\beta$ Lyrae (Kuiper, 1941), with circumstances of those two conditions later quantified by Kopal (Kopal, 1955, 1959). Overcontact morphology was treated by Lucy (1968a,b) and soon after by several others such as Mochnacki & Doughty (1972a), Mochnacki & Doughty (1972b), Mauder (1972), Lucy (1973), Wilson & Devinney (1973), Rucinski (1973) and Rucinski (1974). The fourth morphological type, which logically involves super-synchronous rotation for at least one of the component stars, has both stars accurately filling their lobes and was defined by Wilson (1979). Examples of double contact systems are not easy to authenticate, but claimed identifications continue to appear, as by Wilson et al. (1985), Terrell (2005), Linnell et al. (2006), Terrell & Nelson (2014), Çakirli et al. (2015) and Palma et al. (2016). See Wilson (2001) for a brief history of the four categories.

Quantitative modeling for analysis of globally self-gravitating disks in binaries begins with consideration of the relevant morphology. Figuratively one can say, *"...In the garden of binaries, conceptual morphology is the gateway and analytic morphology is the pathway – so enter the gateway and follow the pathway."* In other words, morphology is fundamental to *understanding* and to *computation*. So is there a preferred morphology for production of massive disks? What about double contact, which can be suspected because mass transfer *creates* the essential conditions as natural consequences of large scale or long-continued mass transfer. That is, transfer spins up an accreting star so as to inhibit easy net flow from disk to star. "Inhibit" does not mean "stop" and modest slowing of accretion may suffice to cause back-up of disk matter.

## 2. An alternative to essentially massless disk models

Many examples of the truncated disks currently applied are illustrated in the literature, for example Fig. 2 of Linnell and Hubeny (1996) and Fig. 1 of Hachisu and Kato (1999). Although at least several computer *programs* are represented by such published illustrations, their essential disk models are nearly the same, with the main differences being in parameter values, presence or absence of a splash from the impacting stream, and ways of tiling the disk surface. Commonalities in these contributions are assumptions that disk masses are small enough not to affect disk figures, and abrupt truncation on the outside so as not to come unduly close to the companion. Another is that all observable disk light comes from its surface, while almost all companion star light that encounters the disk is completely blocked (not just attenuated). The sharply defined edges of such optically thick disks may be a good match to reality in some or even most of the chosen objects. However allowance for possible semi-transparent edges would seem a prudent strategy as we move forward, because many disks are known to be optically thin and intermediate examples can be expected. Truncated

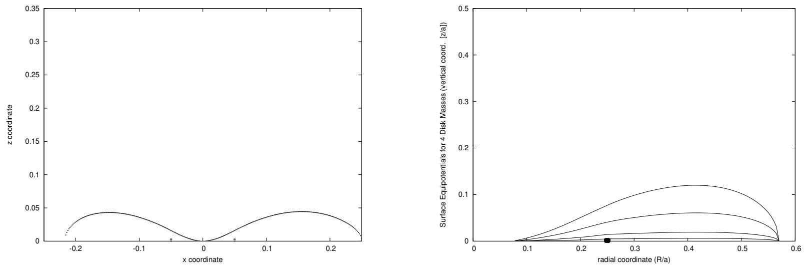


**Figure 1.** Left panel: a cut through CI Aql's disk surface equipotential in the $x, z$ plane at $y = 0$, showing the tidal stretching that leads to several observable effects. Right panel: the $\beta$ Lyr disk surface equipotentials at positive $x$ for (disk mass)/(star mass) of 0.0400, 0.0100, 0.0010, and 0.0001. More massive $\longrightarrow$ larger $z$ height.

massless disk models have been useful to demonstrate essential optical and geometrical thickness of selected CV disks, while incorporation of self-gravity, disk tides, disk gravity brightening, surface semi-transparency, and double contact morphology can now explore previously neglected features. The disk model applied here (Wilson, 2018) is a volume (not surface) emitter whose figure closes without need for truncation under the influence of disk self-gravity (Wilson, 1981). Its full characteristics and extensive reference list cannot be covered in this brief account, but an important ingredient to overall logic is that Accretion (companion star to disk and then to disk's central star) and Decretion (central star to disk) occur *together* or over short cycle times – thus leading to the designation A-D disk. The A-D concept may apply to CVs and W Sers and leans on knowledge about Be stars and $\beta$ Lyr. It is not likely to be useful for optically thin disks, but semi-transparent edges could be interesting. Most light curve analyses for binary circumstellar disks have been based on a non-SG, entirely opaque, axisymmetric model. In contrast, the A-D model naturally produces phenomena that are characteristic of SG disks in binaries, in particular tidal variation with gravity brightening and an outer null-gravity point whose location can now be computed accurately (Wilson, 2018).

Why might structurally significant disk mass be seriously entertained, considering that massive disks are seldom mentioned? One reason is that substantial mass helps a disk to survive nova explosions that would blow a fluffy disk away. The only blast wave particles likely to be present in substantial quantity and not blocked by a disk that is thoroughly optically thick are neutrinos – everything else that impinges on the disk communicates its kinetic and thermal energy to the disk, so the problem essentially simplifies to energetics alone. The issue is just whether the added energy augments the disk's orbital energy to positive values. Fig. 7 of Wilson (2018) illustrates results for seven explosion energies from $10^{43}$ to $10^{47}$ erg and 17 disk masses from $10^{-5}$ to $10^{-1}\,M_\odot$, assuming that the disk intercepts 40% of the blast geometrically. So do the disks of classical novae survive the explosions? Only novae that are observed both before and after eruption can tell us – realistically this has meant very few. However recurrent nova CI Aql was so observed by R. K. Honeycutt (Wilson & Honeycutt, 2014) with the light curve and overall brightness being about the same before and after, as illustrated by comparison of figs 5 and 6 of Wilson (2018). Accordingly, the disk – by far the brightest light source in the system and the only cause of eclipses of the mass donor star – *was not blown away.*

## 3. Where might massive disks reside?

Large amounts of transferred mass favor major spin-up of an accreting star and also favor having significant accumulated mass in a disk. A few percent – perhaps as little as 1% of the accreting star's mass – could be structurally sufficient, as shown by numerical experiments of Wilson (1981). W Serpentis stars (like $\beta$ Lyr) have large mass-transfer rates and classical novae transfer at low rates for long times. Accordingly, W Sers, classical novae, and nova-like variables are candidate locales. How can a massive disk be recognized? Figs 10 and 11 of Wilson (2018) show dependence of disk thickness on disk mass and several other parameters, although quantitative analysis is needed to distinguish among several parameters that affect disk thickness and other disk characteristics. However, serious observational problems stand in the way of useful disk mass determinations. These include wild light curve excursions owing to disk disturbances, novae being mainly observed only in and just after outburst when disks are most disturbed, and the mass-receiving stars in many systems being hidden within the disk, so unobservable.

## 4. Impersonal results by Differential Corrections

The CI Aql and $\beta$ Lyr solutions of Wilson (2018) were by subjective (trial and error) adjustments, while objective solutions based on a weighted Least Squares criterion can now be done with an extension of the Differential Corrections (DC) program that is part of the public W–D model (Wilson & Devinney, 1971; Wilson, 1979, 1990, 2008; Wilson & Van Hamme, 2014). Results are in Table 1, where $a = a_1 + a_2$ is the semi-major axis of the relative binary orbit, $F_1$ is the ratio of star 1's surface angular rotation to the orbital angular rotation, $\rho_{\rm disk}$ is mean disk density over optically visible depths, $u_{\rm wire}$ is the radius of the wire-like mass concentration, $x_{\rm outer}$ is the $x$ coordinate of the disk's outer surface, $x_{\rm null}$ is the outer null effective gravity $x$ coordinate where material becomes unbound to the disk (see section 5.9 of Wilson (2018)), $x_{\rm max}$ is the x-coordinate of greatest disk thickness, and $z_{\rm max}$ is the disk half-thickness at $x_{\rm max}$. See section 6.4.1 of Wilson (2018) for definitions of computed angular velocity exponents $n_{\rm inner}$ and $n_{\rm outer}$. Quantities without standard errors were adopted from the literature

**Table 1.** Parameter Results from CI Aql DC Solution

| | | | |
|---|---|---|---|
| $a$ | $4.5719\,R_\odot$ | $T_{\rm eff}^{disk}$ | $15729 \pm 785\,{\rm K}$ |
| $P_{\rm orb}$ | $0\overset{\rm d}{.}6183619$ | $\rho_{\rm disk}$ | $3.43 \pm 0.17 \times 10^{-11}\,{\rm g\,cm^{-3}}$ |
| $F_1$ | 6000 | $M_2/M_1$ | 2.50 |
| $i$ | $67\overset{\circ}{.}49 \pm 0\overset{\circ}{.}45$ | $M_{\rm disk}/M_1$ | $0.0325 \pm 0.0037$ |
| $T_{\rm eff,1}$ | $15000\,{\rm K}$ | $u_{\rm wire}/a$ | $0.044 \pm 0.011$ |
| $T_{\rm eff,2}$ | $6100\,{\rm K}$ | $x_{\rm outer}/a$ | $0.212 \pm 0.013$ |
| $M_1/M_\odot$ | 0.96 | $R_1/R_\odot$ | 0.0069 |
| $M_2/M_\odot$ | 2.42 | $R_2/R_\odot$ | 2.04 |
| $n_{\rm inner}$ | -1.493544 | $x_{\rm null}/a$ | 0.416547 |
| $n_{\rm outer}$ | -1.894034 | $x_{\rm max}/a$ | 0.17134 |
| $L_1/(L_1+L_2)_V$ | $1.44 \pm 0.12 \times 10^{-4}$ | $z_{\rm max}/a$ | 0.15411 |

without adjustment. As DC's numerous and thoroughly tested provisions for performance enhancement are already in place within the disk-revised version, expectations for reliable disk model solutions from the start appear to be realistic. This paper's DC solution is compared with a subjective light curve fit from Wilson (2018) in Fig. 2.

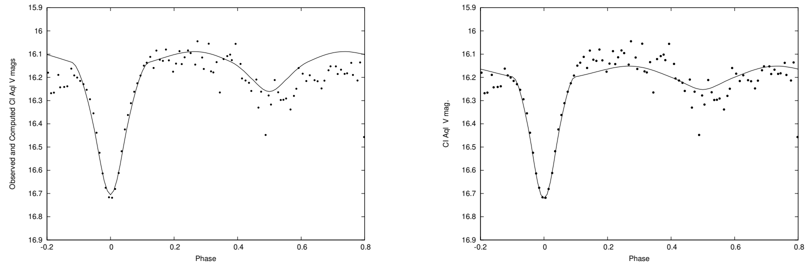


**Figure 2.** Comparison of trial and error light curve fit (Wilson, 2018) (left panel) and this paper's impersonal (DC) solution (right panel). The impersonal solution splits the height difference between the maxima, rather than favoring maximum I, and represents the eclipse of the disk noticeably better. It also supplies standard error estimates.

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# Upcoming support for triple stellar systems in PHOEBE

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**Abstract.** Eclipsing binary stars allow for the direct measurement of stellar parameters and distances and are therefore an important tool in the calibration of stellar relationships. In benchmark cases, we can achieve a precision of 2-3% in fundamental stellar parameters. Due to tighter constraints caused by mutual eclipse events, systems with additional companions allow achieving precision as low as 0.5%. Triple systems have also been proposed as a mechanism for explaining an overabundance of short-period tight binaries. Despite all of this, we do not yet have a complete model for these multiple star systems that include tight binaries. In order to precisely and accurately model these complex systems, we must take into account several considerations, including: light time effects, perturbations to orbital elements, and the distortion of the stellar surfaces. Including all of these into a comprehensive treatment of triple and higher order systems within PHOEBE is currently under development and planned for an upcoming release.

## 1. Introduction

Detailed modeling of benchmark eclipsing binary systems can result in an accuracy of fundamental parameters (masses, radii, and temperatures) of $2-3\%$ for $\sim$100 main-sequence (Torres et al., 2010) and $\sim$15 pre-main-sequence stars (Stassun et al., 2014). These benchmark systems are used to callibrate a number of stellar models and relationships, and often our ability to discriminate between models is being limited by this precision. For example, Torres et al. (2010) shows a scatter in the luminosity-mass relationship that is larger than the uncertainties on the individual systems. This variation is likely due to varying evolutionary stages and metallicities among the population, but in order to better understand these trends we need to model more eclipsing binary systems and continue to push the limits of precision.

We can take several steps towards improving the precision and accuracy in modeled parameters of eclipsing binary systems. In recent years, photometric precision has seen significant improvement from *Kepler* and other space-based missions. In order to handle this increase in observational precision, we have actively been working to improve our models to account for higher-order effects, remove assumptions, and minimize computational noise. These improvements in both observation and model precision now allow us to approach the 1% level in fundamental parameters (Prša et al., 2016; Horvat et al., 2018). But ultimately, we are still limited by the inherent degeneracies – caused by the highly non-linear and correlated parameter space – of these systems which provide a “floor” on the achievable precision. For example, the width of an eclipse can be increased by increasing the radius of either star or slightly increasing the orbital inclination, resulting in a degeneracy in the model which limits our ability to achieve better precision in these fundamental parameters.

In certain cases, adding a third star into the system allows for breaking some of these inherent degeneracies and therefore allows for directly measuring these fundamental parameters to a precision an order of magnitude better than for eclipsing binary systems without companions.

## 2. Benefits to modeling triple systems

Triple (and higher-order multiple systems) allow for much more stringent constraints on these fitted fundamental parameters – by as much as an order of magnitude improvement over binary systems, finally breaching into sub-percent uncertainties (cf. Carter et al., 2011; Doyle et al., 2011; Welsh et al., 2012). Imagine a third star crossing in front of the inner-binary with the degeneracy between radius and inclination – the exact timing and shape of the resulting eclipse places stringent geometric constraints that break the previous degeneracies, resulting in a unique solution with unprecedented uncertainties (see KOI-126 in Carter et al. 2011 for an example).

In addition to this increased precision, the presence of additional bodies enables us to study and test the effects of their mutual gravitational influence. For example, eclipsing binaries in large photometric surveys exhibit a peak in the orbital period distribution on the order of 1 day (Devor, 2005; Paczyński et al., 2006; Derekas et al., 2007). Binary formation theory, however, struggles to explain the creation of these close binaries in situ, and capture seems unlikely to produce the large number of observed close binaries (Bonnell, 2001). Kozai-Lidov Cycles and Tidal Friction (KCTF) have been proposed as a formation mechanism for these short-period binaries through the interaction with a third star on an eccentric and inclined orbit with respect to the inner-binary (Kozai, 1962; Lidov, 1962; Fabrycky & Tremaine, 2007; Naoz et al., 2013). Fabrycky & Tremaine (2007) used simulations of systems undergoing KCTF to provide testable distributions in the final mutual inclination between the resulting close inner-binaries and their companions. Other methods including disk migration have also been proposed to accomplish the same result of tight inner-binaries, resulting in a testable difference in the expected distributions of orbital parameters. In order to test these theories, we need to *accurately* and *precisely* model a large number of observed triple systems, specifically those containing tight inner-binaries, so that we can compare these theoretical distributions against observations.

Tokovinin et al. (2006) found that 60% of binaries with orbital periods less than 3 days have a tertiary component, compared to only 34% of binaries with periods greater than 12 days. Many of these short-period tight binaries could have tertiary components on wide or inclined orbits, making the triple nature difficult to detect in the light curves, radial velocity curves, or eclipse timing variations. Searches of eclipse timing variations among *Kepler* eclipsing binary systems (Prša et al., 2011; Slawson et al., 2011; Kirk et al., 2016), show that about $15 - 20\%$ of short-period binaries show evidence of tertiary components within the ~4 year time-baseline of *Kepler* (Gies et al., 2012; Rappaport et al., 2013; Conroy et al., 2014). This still leaves a large number of tight binaries in which the expected tertiary component cannot easily be detected in the light curve or eclipse timing variations. The dynamics of these distorted eclipsing binaries may still be subject to the effects of a tertiary companion, even if that companion is not detected directly.

For all of these reasons, it is necessary to develop a code that can robustly handle triple and higher-order systems, including all the advanced high-order effects required to adequately model *Kepler*-like photometry, as well as both dynamical and surface distortion effects.

## 3. Future implementation in PHOEBE

To address the need to model these systems, we plan to include support for generic hierarchies with any number of components into the `PHOEBE`[1] eclipsing binary software package (Prša & Zwitter, 2005; Prša et al., 2016; Horvat et al., 2018).

We plan to allow for flexible generic hierarchies and parameterization, such that any system can be defined through any number of nested Keplerian orbits. Although the systems would be defined in this strictly hierarchical manner, the dynamics would then be handled through an n-body integrator initialized by the Keplerian orbits at some time, $t_0$. As is currently the case for binaries with Keplerian orbits, the position of each component would be offset in its orbit such that its light reaches the barycenter of the system at any requested observation time – effectively handling any light travel time effects.

In order to handle the tight inner-binaries in higher-order systems, it is important to have the capability to handle surface distortion, rather than falling back on the spherical assumption for all the components in the system. To do this, we plan to use the n-body dynamics to determine instantaneous Keplerian representations of the current position of each individual component at any given time. From the Keplerian elements (period, semi-major axis, eccentricity), we can then use the Roche framework to determine the distortion of each star

[1] http://phoebe-project.org

caused by its "sibling" in the hierarchy using the same assumption of instantaneously adapting surfaces to conserve volume currently used in the two-body scenario. This "hybrid" approach allows for a model that accounts for both the dynamical interaction between multi-bodies, as well as the surface distortion caused by tight pairs of stars and the resulting effects on the observables.

By implementing support for any higher order system into `PHOEBE`, we will have a code capable of *robustly* modeling these systems taking advantage of all the higher-order effects incorporated into the code for binary systems. However, this all comes at computational cost. In many cases (particularly for stable systems without dynamical effects or those where surface distortion can be ignored), existing codes are fully capable and may be significantly cheaper. We hope to provide wrapper convenience functions for these other codes – both to make it easier to compare the outputs of the codes but also to use the backend that is most efficient given the restrictions and valid assumptions for any particular system.

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# PyWD2015 – A new GUI for the Wilson-Devinney code

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**Abstract.** A new, modern graphical user interface (GUI) for the 2015 version of the Wilson-Devinney (WD) code is developed. PyWD2015 is written in *Python* 2.7 and uses the *Qt*4 interface framework. At its core, the GUI generates lcin and dcin files from user inputs and sends them to WD, then reads and visualises the output in a user friendly way. It also includes some useful tools for the user, which makes technical aspects of the modelling process significantly easier. While multiple sky surveys and space missions generate, reduce and categorize large amounts of observational data, it's up to dedicated studies to analyse peculiar or anomalous systems and make further progress in the field of physics of eclipsing binaries. We believe PyWD2015 will be a great "dedicated study" suite for such systems.

**Key words:** binaries: eclipsing – methods: data analysis

## 1. Introduction

In the age of space telescopes and large surveys, automated data pipelines play a major role. While these automated pipelines are very efficient for sorting and cataloguing large amounts of data, anomalous and interesting systems need individual attention and manual analyses. These analyses often require physical modelling of the system in question, specifically in the case of eclipsing binaries.

The Wilson-Devinney code (Wilson & Devinney, 1971) for eclipsing binary modelling is generally considered a standard in the field. The code is proven reliable and carries a long legacy of outputting correct science, therefore it is suited well for performing detailed analysis on various types of interesting eclipsing binaries.

However, it is not free from caveats. It requires strictly formatted input files for operation and lacks any visualisation of output results. Creating and formatting input files and reading outputs have a tendency to become technical hurdles, which slows down the whole analysis process. In order to avoid these hurdles and provide some additional physics, the PHOEBE 1.0 project (Prša & Zwitter, 2005) was developed by adopting ithe WD code as backend. However, PHOEBE 1.0 is mainly based on ithe 2003 version of the WD code, while the latest version is 2015 (Wilson & Van Hamme, 2014).

In this contribution, a GUI for the latest (2015) version of the WD code, named “PyWD2015,” is presented. The GUI covers almost all features of the code with some additional tools.

## 2. Overview

PyWD2015 is, at its core, a “GUI wrapper” for the WD code. It does not abstract or redefines any WD functionality, but merely provides a convenient interface for inputting parameters and running the DC and LC programs. When the user runs any WD tool, the GUI takes input parameters and observations, formats them automatically, writes them onto disk in an input file and finally executes the LC or DC binary. Then, after WD completes its run, the GUI reads the output file and visualises the outputs in a user-friendly and convenient way.

PyWD2015 provides a main menu for inputting global parameters for a system, but has separate windows for LC and DC inputs. Each LC functionality has its own separate window but they share the same LC specific parameters. DC, on the other hand, has a single window which runs the DC program and shows optimized parameters accompanied with an embedded plot window for visualising results. Some of these windows can be seen in Fig. 1. The only WD feature that is not supported by PyWD2015 is the “subset” functionality of DC, but that is planned to be included in a future release.

In addition to providing a GUI wrapper for WD, PyWD2015 also has some user-friendly features:

- Most of the tooltips of labels are filled with the excerpts taken from the WD manual,[1] and some of them have alternative, longer explanations.
- The “Star Positions” window of the LC tool has the ability to draw critical Roche potentials of the system. This has been written into the GUI and does not depend on WD. Calculations are adopted from Kopal (1959) and Kallrath & Milone (2009).
- The DC tab has a “Solution Explorer” window, which tracks subsequent DC iteration results. Each parameter can be plotted with its standard deviation as an error bar to help the evaluation of solution progress.
- The DC window also has an “external iteration” variable, which is different from the WD parameter *NITER*. This variable tells the number of times the GUI needs to iterate the DC solution externally, thus enabling the “Solution Explorer” window to track solution progress. After each iteration, the DC window automatically updates the outputs and copies results to input parameters.

[1] ftp://ftp.astro.ufl.edu/pub/wilson/lcdc2015/ebdoc.6jun2016.pdf


**Figure 1.** Representative windows of PyWD2015. Top left are the main and LC windows. The "Star Positions" window is at the top right. Below is the DC window.

- GUI also has some numerous colour-temperature calibrations adopted from various references (Gray, 2005; Drilling & Landolt, 2000; Flower, 1996; Popper, 1980; Tokunaga, 2000). These are implemented by using 7th order polynomials (except for Gray (2005), who adopts 4th order polynomial for cool stars and 5th order polynomial for hot stars).
- Additional simple and useful tools, such as time (JD-UT) conversion and dimensionless potential calculations based on mass ratio, fractional radius, rotation parameter and instant separation, are available.
- The GUI can save and load project files to enable project management.

Some external *Python* libraries were used in PyWD2015. *Matplotlib* library (Hunter, 2007) was used for plot widgets. *Numpy* (Oliphant, 2015) and *SciPy* (Jones et al., 2001) libraries were used for numerical calculations.

## 3. Conclusion

In this contribution, a GUI for the 2015 version of the WD code is presented. The GUI is a wrapper for the WD code with user friendly features. It covers almost every WD functionality with added visualisation tools. The code and user manual can be found on GitHub.[2]

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[2] https://github.com/Varnani/PyWD2015

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# Beyond DC and MCMC: alternative algorithms and approaches to fitting light curves

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**Abstract.** The parameter space of binary star light curve models is highly complex and degenerate, thus basic fitting approaches often fail to yield a good (and correct) estimate of the parameter values and their uncertainties. On the other hand, we have an increasingly large number of fitting and sampling algorithms available that can be relatively easily interfaced with open-source eclipsing binary packages, like PHOEBE 2. We showcase several fitting methods, including local and global minimizers, nested sampling and machine learning methods, and evaluate their performance on fitting a light curve model with PHOEBE 2.

**Key words:** binaries: eclipsing – methods: numerical – methods: statistical

## 1. Introduction

Robust fitting of the light- and radial velocity curves has been an outstanding issue in the field of binary stars for several decades now. As Prša & Zwitter (2005) showed, the parameter space of the binary star models is highly complex and degenerate, which leads to correlations between certain parameter and poses difficulties to finding the global optimum, as well as estimating the parameter uncertainties. With the advancements made in both technology and computing, we now have much better data and more precise models. The development of PHOEBE 2 (Prša et al., 2016) as a `python` package has opened up a new world of possibilities when it comes to fitting, since it can be easily interfaced with the many open-source optimizing packages that `python` offers.

In order to showcase the performance of several different approaches to fitting light curve data, we attempt to retrieve the true values of the parameters used to generate a synthetic light curve with PHOEBE 2 with added non-white noise. We fit for the mass ratio ($q$), inclination (incl), eccentricity ($e$), argument of periastron ($\omega$), fractional radii ($r_1$, $r_2$), effective temperature of the primary ($T_{\mathrm{eff},1}$), temperature ratio ($T_{\mathrm{eff},2}/T_{\mathrm{eff},1}$), passband luminosity (pblum) and third light ($l3$).

## 2. Minimizers

The simplest approach to fitting is through using an optimizing algorithm. Optimizing algorithms can be local, meaning they would typically find a local minimum close to the initial point, or global, which explore the parameter space stochastically and more robustly in search for a global minimum. We have applied four optimizing algorithms from the `scipy.optimize` library: Nelder-Mead Simplex (NMS), Powell's and L-BFGS-B (local) and differential evolution (DE, global). The minimization results are given in Fig. 1 and show that differential evolution outperforms the local minimizers. However, the price in accuracy is being paid by the computation time, which is significantly longer for global minimizers.

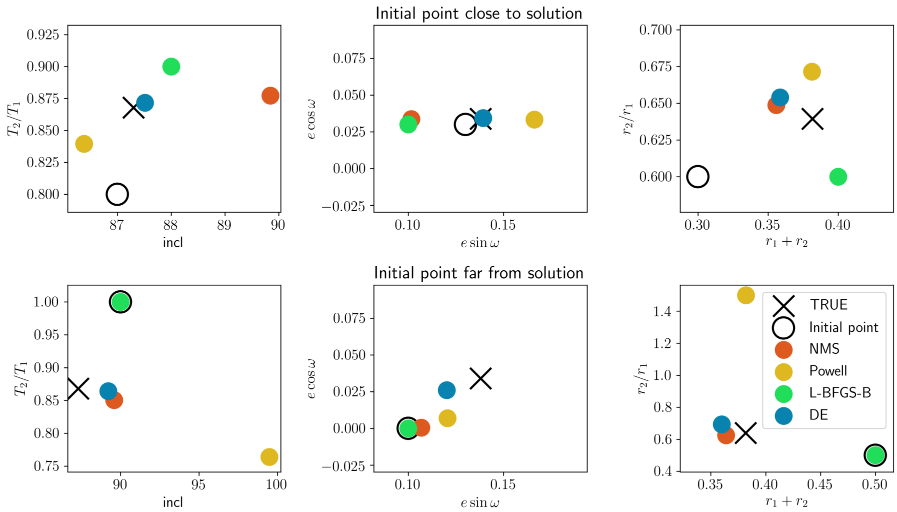


**Figure 1.** Cross-sections of the minimizer solutions in two-parameter space, with the chosen initial point relatively close to the true solution (top) and relatively far from the true solution (bottom).

## 3. Samplers

As we demonstrated in Section 2, global minimizers, at the cost of computational time, can yield a solution close to the global minimum. However, samplers are more robust in terms of exploring the topology of the parameter space around the global minimum and, thus, yield more reliable parameter uncertainties. Using MCMC for this purpose has become very common in our field, but it comes with certain caveats. MCMC is not a search algorithm or optimizing algorithm (Hogg & Foreman-Mackey, 2018) and as such, only performs well once initialized close to the global minimum. Otherwise, we risk abuse of the algorithm at the cost of prohibitively long convergence times and incorrect interpretation of the results. Fig. 2 shows the results of sampling the parameter space of our synthetic light curve with the package `emcee` (Foreman-Mackey et al., 2013), with both bad use of MCMC (using it as a search algorithm for the global minimum) and good use of MCMC (using it to sample the posterior around the global minimum).

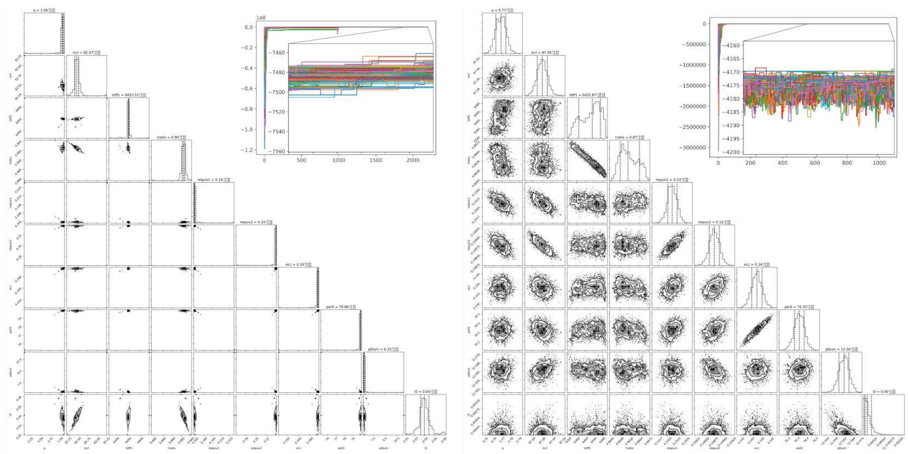

**Figure 2.** Examples of sampling the posterior with MCMC using `emcee`. Left: wide initial sampling range and use as a search algorithm to find the global minimum. The $\log p$ plot in the top right corner shows the solution is still converging. Right: initial sampling range in a tight ball around the global minimum. The $\log p$ plot in the top right corner shows oscillations around a constant value, which is a good indicator of a converged sampling.

Fortunately, other sampling algorithms can yield more robust results if we are not completely certain of the position of the global minimum. Based on our synthetic light curve test, nested sampling (Skilling, 2004) begins to reveal structure around the true global minimum in the likelihood of some parameters after several hundred iterations. Fig. 3 shows the trace plots of the position of the live points in all parameters for a nested sampling run with the package `dynesty` (Speagle, 2019). The sampling has not completely converged, but the values of the parameters that the light curve is sensitive to quickly move towards the global optimum.

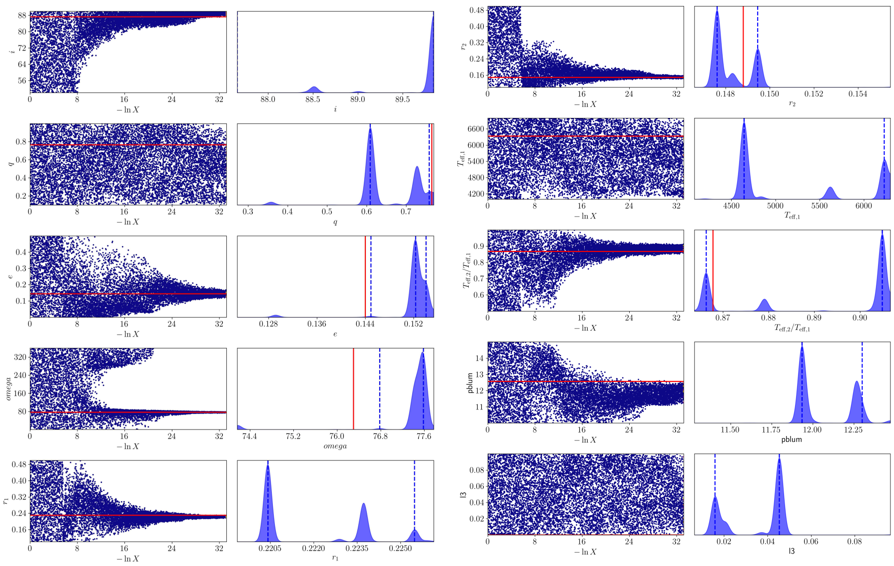

**Figure 3.** Trace plots of the positions of the live points in each parameter for a non-converged run of nested sampling with `dynesty`. The true parameter values are represented by red lines.

## 4. Machine Learning

Finding an initial solution for the light curve parameters usually involves a lot of manual work (adjusting the parameters and comparing the model with the data, initializing minimizers from different starting points, etc.). This approach becomes ineffective when dealing with large data sets. To address this, we have explored simple approaches using pre-computed synthetic databases and an algorithm based on nearest-neighbors search. Estimates of the model parameters found in this way are based on light curve similarity between the fitted light curves and a pre-computed database. The parameter estimates are computed as a distance-weighted mean (dw-mean) from the parameter values of the light curve's nearest neighbors, while the range of possible values (min/max) is taken as the minimum and maximum of the parameter values across the nearest neighbors. This can be useful for providing the boundaries of the prior distributions used in MCMC or nested sampling.

Table 1 shows the parameter estimates from a nearest-neighbors distance-weighted computation for our test light curve. Because our data constrain the model well, our results are very close to the true parameter values. This is not always the case due to the parameter degeneracies in our model, but is a useful first step towards finding a better fit that eliminates the need for manual fitting.

**Table 1.** Distance-weighted estimates of the parameter values from a nearest neighbors search algorithm and their respective minimum and maximum values, compared to the true parameter values used to generate the test light curve.

| | *min* | *dw-mean* | *max* | *TRUE* |
|---|---|---|---|---|
| **q** | 0.5117 | 0.764 | 0.993 | 0.765 |
| **incl** | 80.915 | 85.925 | 89.996 | 87.3 |
| **r1+r2** | 0.323 | 0.397 | 0.489 | 0.3817 |
| **r2/r1** | 0.558 | 0.678 | 0.798 | 0.6394 |
| **Teff1** | 5013 | 6053 | 6992 | 6332 |
| **T2/T1** | 0.771 | 0.879 | 0.962 | 0.8678 |
| **esinw** | 0.014 | 0.145 | 0.246 | 0.1379 |
| **ecosw** | 0.009 | 0.031 | 0.052 | 0.03339 |
| **pblum** | 10.17 | 11.75 | 13.29 | 12.5664 |
| **l3** | 0.001 | 0.045 | 0.1 | 0 |

In some cases, the solution is not as well constrained because the nearest neighbors algorithm is not as sensitive to changes in certain parameters. To visualize this, we can use a dimensionality reduction technique, like t-SNE (van der Maaten & Hinton, 2008), to demonstrate the parameter value distributions across the parameter space in terms of light curve similarity. Fig. 4 showcases the value distributions of inclination, temperature ratio, mass ratio and fillout factor for a data set of synthetic contact binary light curves. It is clear that the light curve similarity is driven by the inclination and temperature ratio (top row), while the fillout factor and mass ratio values (bottom row) are distributed relatively uniformly across the map. Fitting for these two parameters with a nearest-neighbor search would thus yield results that are not as reliable as those for inclination and temperature ratio.

## 5. Conclusion

The best way of modeling eclipsing binaries remains a careful, hands-on approach. However, the era of big data is urging us to explore automated methods and advanced treatment of our data and model uncertainties. With the development of open source packages for modeling in wide-spread programming languages like `python`, a plethora of methods become available to us, but not all are suitable for our particular problem. The findings presented here are an initial step towards learning more about the fitting methods available to us and how to best apply them to our problem. Using a test synthetic light curve and PHOEBE 2, we have demonstrated that: global optimizers outperform local optimizers at the cost of large computation times, simple machine learning approaches can give us initial estimates of the parameter values and potential prior ranges, while samplers come in many flavors, some of which are suitable

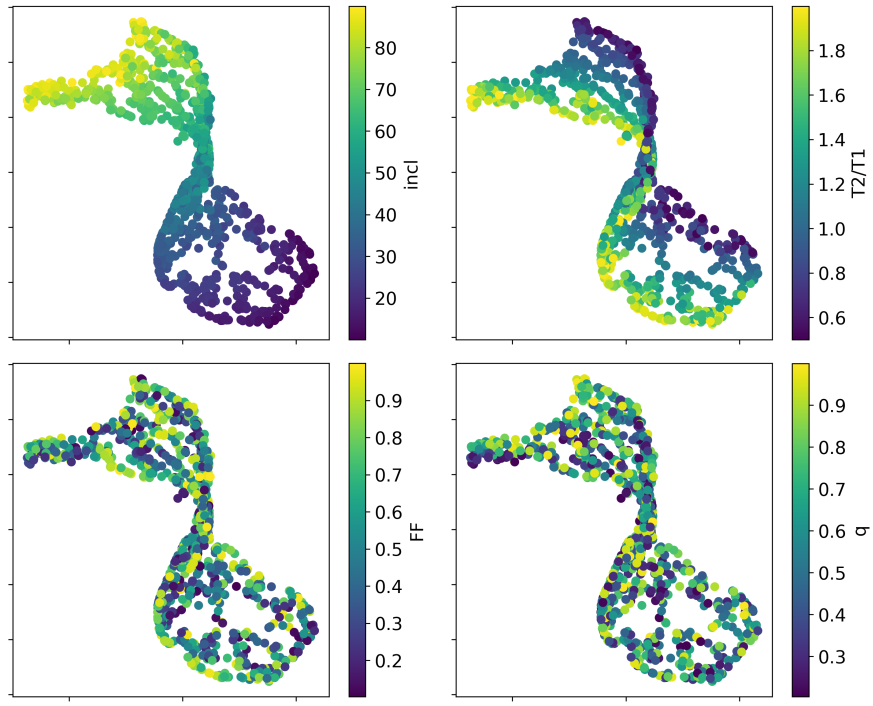


**Figure 4.** Parameter distributions over a 3D projection of the 4D parameter space in a contact binary light curve database generated with PHOEBE 2.

for posterior estimation near the global minimum, like MCMC, and others, like nested sampling, can reveal the underlying structure of the likelihood when we do not have a good estimate of the position of the global minimum.

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# Composite spectrum hot subdwarf binaries

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**Abstract.** The formation of hot subdwarf stars (sdB) is closely related to binary evolution on the red giant branch. Observations show that hot subdwarfs are either in close binaries with low mass K-M type or white dwarf companions, or in wide binaries with more massive F-G type companions. A small fraction is most strikingly single. In close binaries the radiative interactions give rise to the reflection effect and produces a variable composite spectrum. More massive companions bear similar optical luminosities as sdB stars and therefore double-lined spectra are observed. To investigate such systems in detail and precision spectral decomposition/disentangling is needed. I describe our wavelength space disentangling method and bring examples why such an approach to composite spectra offers a potential to find the history of hot subdwarfs.

**Key words:** stars – hot subdwarfs – spectroscopy – composite spectra

## 1. Introduction

Hot subdwarf (sdB) stars are 0.5 $M_\odot$ core helium burning stars with very thin hydrogen envelopes. The mass loss required to form such stars is still poorly understood. The fact that the envelope loss happens by the time the core ignites helium makes it likely that binarity and enhanced wind mass loss act together on the red giant branch. Passing through the core helium flash, these low mass stars settle on the blue extension of the horizontal branch and burn helium at a constant luminosity for $\sim$100 Myrs. Following this stage these stars evolve to white dwarfs without ever ascending the giant branch again (Heber, 2016).

Hot subdwarfs are interesting objects that show a multitude of atmospheric processes, which make them complex, yet unique laboratories to get insights into intermediate age stars. A significant fraction of hot subdwarfs show pulsations, signatures of atomic diffusion in the atmosphere along with diverse binary properties. Hence, their analysis requires similarly complex approaches that, in turn, offers a chance to connect those fields, and open new windows in exploration.

A significant fraction (near 20%) of hot subdwarfs are identified in double-lined composite spectrum systems, while in numerous close binaries spectral contamination is visible. All binaries with less than 0.5 day orbital period and low mass main sequence companions are expected to show reflection effect. All such systems require appropriate decomposition or disentangling techniques.

## 2. Hot subdwarf binary populations

Since the first spectroscopic and radial velocity surveys it is known that the binary fraction of hot subdwarfs is high, between 43 and 67%. The large scatter is due to different methods and selection effects. In fact, the high fraction was expected, as population synthesis by Han et al. (2002) predicted an even higher fraction, near 80%. The remaining 20% forms by double white dwarf mergers.

In a recent radial velocity study Kawka et al. (2015) found that 43% of the subdwarf population is indeed in binaries. Projecting onto the whole hot subdwarf population, 13-17% have white dwarf companions and 26-30% have low mass main sequence companions or near the substellar limit. About 20% has more massive main sequence companions (Németh et al., 2012).

Binaries with main sequence companions separate into two very diverse subgroups: (1) Systems that form a subdwarf through common-envelope evolution have typically a low mass companion and due to the spiral-in process the orbital period is less than 30 days. At the shortest periods the small separation gives rise to a reflection effect in the light curve and this reflected (in fact it is reprocessed) light makes such systems composite spectrum binaries. (2) In contrast, binaries that form subdwarfs through Roche-lobe overflow have more massive F-G-K type main sequence companions and much longer orbits, in the range of 400-1500 days. These systems show remarkable double-lined composite spectra as the optical luminosities of the members are similar.

Single hot subdwarfs, as well as single-lined binaries cannot give the necessary insights into their formation history or progenitor systems because the atmospheric investigations are limited to one component. The key to understand hot subdwarfs, therefore, is thought to be in composite spectrum populations. In a variety of long-period double-lined binaries and reflection effect short-period binaries, a careful analysis is able to reveal radial velocities, stellar masses, ages and chemical compositions. However, such tasks require specially designed, delicate methods.

## 3. Modeling composite spectra

### 3.1. Fit or decomposition

One can talk about spectral fitting as long as a single model reproduces all observed features of an object. With composite spectra this is not the case. In some situations one can apply data reduction techniques, remove components, or part of the data that is not reproduced by the model to investigate the object of interest. However, at least a decomposition approach with a combination of multiple models is needed to reproduce an observation. Such as the combination of two (or more) models for double-lined binaries and reflection effect systems. Although the combination of the models is a tricky and cumbersome part of the process, it provides invaluable information on the components and of the system as a whole (Østensen, 2012).

A simple approach to spectral decomposition is to reproduce the spectral energy distribution. Using broad band photometry and color indices the components can be characterized this way easily and applied in large surveys. Unfortunately, this method lacks precision. As no radial velocities, abundances or precise atmospheric parameters can be derived, this method is suitable only for coarse population studies, and even then it needs spectroscopic confirmation.

### 3.2. Disentangling wide binaries

There are two major sets of dependent parameters when one is dealing with composite spectra: the radial velocities and the spectral types of the binary members. The radial velocities can be measured by cross-correlation techniques, which provide the orbital properties. The spectral appearance can be reproduced by keeping radial velocities fixed and decomposing the spectrum into its components either by successive subtractions or by co-adding models. To generalize these steps to any kind of composite binary spectrum, one needs disentangling, in which both the velocities and the spectral types are determined simultaneously. Disentangling is a complex task which has two major approaches: Fourier Space (KOREL, Hadrava 2009) and the direct Wavelength Space Disentangling (Simon & Sturm, 1994). Both methods seek for the same set of parameters and the steps are analogous within the two frameworks. However, both have different benefits and limitations. The Fourier method is based on the recognition of regularities over the orbital period in the Fourier transformed spectra, while wavelength space disentangling applies a linear combination of synthetic spectra to reproduce the observed composite spectrum at any instance.

The Fourier method provides a clear mathematical formalism that allows an easier reduction and generalization for multiple systems. However, it is done at the cost of a fair observational sampling of the orbital period and assumes clean spectral features of the members. In contrast, the direct decomposition requires only one spectrum and can overcome heavily blended spectral features.

Both approaches have extensions to cope with higher order effects, such as broken symmetries of the spectroscopic line profiles. One typical situation for these are partial eclipses in binaries, where the radial velocities, limb-darkening and dilution factors change during an eclipse and the radial velocity does not reflect the center of mass velocity. Similar line profile variations may be present due to external irradiation, pulsations, spots, ellipticity, mass-loss, etc.

It is obvious that the direct wavelength space disentangling is more suitable for long period hot subdwarf binaries with cool main sequence companions. Due to the long period there is usually an insufficient orbital coverage for the Fourier approach and the broad Balmer and He lines of the hot subdwarf are heavily blended with the Balmer and the numerous metal lines of the companion, as in Fig. 1.

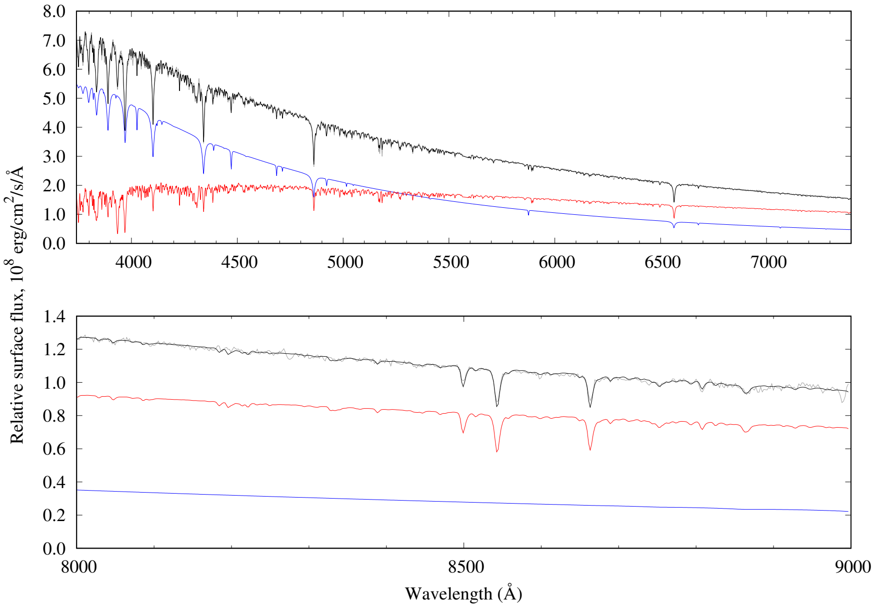


**Figure 1.** TLUSTY/XTGRID binary fit for the LAMOST DR1 composite spectrum of BD-7 5977 (grey line). The black model shows how the sum of an sdB (blue) and a G0V type model (red) fits the observation across the entire optical range. Further examples can be found at `https://astroserver.org/KW32YZ/`.

### 3.3. External irradiation in close binaries

Another very important advantage of the direct wavelength space decomposition is the easier implementation of modeling orbital spectral variations. These variations occur in close binaries (also in planet+host star systems) where a hotter component heats up the substellar point of its cooler companion. This phenomena cause not only the reflection effect in the light curve, but introduce characteristic orbital phase dependent emission components as in Fig. 2, and spectral variations in the composite spectrum. Once the spectral variations are reproduced by models, all such binaries can be turned into double-lined systems and mass estimates can be made.

Unlike at long-period composite spectrum binaries, where the linear combination of the mean fluxes can fully describe the orbital spectral variations, in reflection effect systems one must apply a surface integration of the specific intensities to recover the composite spectrum. This is a lot more demanding quantitative task. However, future instruments will be more capable to deliver observational data to such investigations and extend the number of feasible hot subdwarf binaries from the currently available few to over a 100.

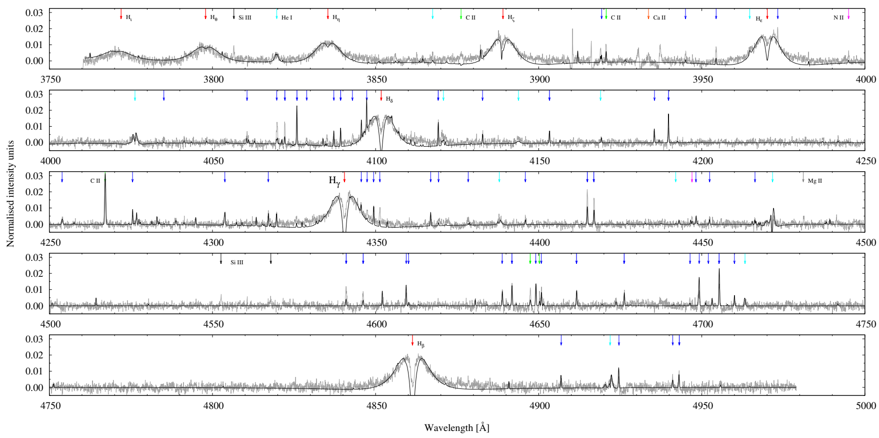


**Figure 2.** TLUSTY/XTGRID fit for the irradiated hemisphere of the cool companion in AA Doradus (Vučković et al., 2016). An animated version showing the spectral variations over the orbit is available online at `https://youtu.be/QMsXSnw_zm8`.

### 3.4. Composite spectroscopy with XTGRID

XTGRID (Németh et al., 2012) is a spectral analysis procedure that wraps around the non-Local Thermodynamic Equilibrium model atmosphere and synthetic spectrum codes TLUSTY/SYNSPEC (Hubeny & Lanz 2017a,b,c). In addition to TLUSTY models the procedure can include further components to build composite spectra and fit the observations of binary and multiple systems. The fitting method is based on an iterative chi-square minimization using a downhill simplex method. The main focus of the procedure is to fit hot star binaries or hot stars with cool companions. The companion spectra are calculated in parallel threads using TLUSTY, or extracted from pre-calculated spectral grids, such as the PHOENIX (Husser et al., 2013) or BOSZ (Bohlin et al., 2017) libraries. XTGRID has been employed to solve subdwarf binary orbits for 28 systems with UVES spectroscopy (Vos et al., 2018) and showed consistent results with the independent GSSP code (Tkachenko, 2015) for the cool companions. These analyses found a positive correlation between orbital period and eccentricity and an anti-correlation between orbital period and mass ratio (Vos et al., 2019). In some systems the companion shows chromospheric activity based on the near infrared calcium triplet.

TLUSTY is a sophisticated code that can model external irradiation in close binaries and the spectra of radiatively heated companions. This allows one to calculate specific intensities and integrate the emergent spectra from the visible surface elements of the companion, as demonstrated by Vučković et al. (2016).

## 4. Conclusions

Spectral disentangling seems to be the key, and the way to go, to understand hot subdwarf formation and evolution. It is absolutely necessary for any precision analysis of long-period double-lined subdwarf binaries with main-sequence companions. Many such systems are simply neglected in surveys because of their complexity, or modelled as single stars leading to large systematic discrepancies. The situation is more severe for close binaries where a composite spectrum may remain unnoticed. If reflection effect is observed in the light curve one can be assured that the companion contributes to the spectrum and this may invalidate the surface parameters derived with single star models. Even though a careful analysis and windowing can remedy the situation, with a simultaneous analysis of the components one can achieve more comprehensive results of the systems. Such a procedure is also available within the Sandbox services of Astroserver.org at `https://xtgrid.astroserver.org/sandbox/`.

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# Binary star analysis with intrinsic pulsation

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**Abstract.** Strategies are introduced for coherent measurement of pulsational waveforms, amplitudes, periods, and period change rates, where 'coherent' means that the model stars indeed pulsate, with no artificial alternation between pulsation without binary effects and binary effects without pulsation. Capabilities of the more advanced eclipsing binary (EB) light curve models are in place, such as simultaneous solutions of multiband data and radial velocities with inclusion of tides, mutual irradiation, and proper datapoint weighting. An application to the Algol-type EB V1352 Tau exhibits possibilities.

**Key words:** binaries: eclipsing, binaries: spectroscopic, stars: pulsating

## 1. Introduction

This contribution describes an analytic model to measure parameters from light and radial velocity (RV) curves of radially pulsating binary components. The modeled stars actually pulsate and there is no need for removal of pulsational variation from the data, in contrast to the pulsation subtraction schemes of most binary system pulsation models. Accordingly, all variation phenomena are handled within the model and the data are analyzed as observed, whether they are fluxes, magnitudes, or RVs. Tidal and rotational distortions of star figures and their accompanying surface brightness variations are built in, and there is no limitation to spherical stars. A major advantage and driver of the development has been that eclipse effects on pulsation arise as in the real stellar systems, since pulsations are eclipsed along with the model stars, of which they are an intrinsic feature, and geometric pulsations also affect eclipses via changes in eclipsing horizons. A present simplification is that pulsation is assumed slow enough to be computed as a sequence of equilibrium states. Although no pulsational dynamics are now in the model, they can be added later. Many capabilities of the more advanced EB light/velocity curve models are in place within the direct (curves from parameters) and inverse (parameters from curves) pulsational computer programs, which are extensions of the corresponding Wilson-Devinney (W-D) public modeling programs (Wilson and Devinney, 1971; Wilson and Sofia, 1976; Wilson, 1979, 1990, 2007, 2008; Wilson and Van Hamme, 2010; Wilson, 2012; Wilson and Van Hamme, 2014) such as proper datapoint weighting, simultaneous solution of RV and multi-band curves, tidal/rotational star figures, reflection effect, eclipses, etc.

Further intuitive comments on basic pulsational analysis for binaries do not fit within the space limit, but see Riazi and Abedi (2006) for coupled illustrations and explanations from their work on AB Cas and synthetic binaries. Kopal (1982a) and Kopal (1982b) cover historical items as well as advanced issues such as precession and nutation of non-aligned rotational axes. The impressive mathematical developments in these two papers remain to be applied in published binary system analyses.

## 2. What else does the development accomplish?

Several features add to the model's impersonal parameter adjustment performance from unaltered light/RV curve data – for systems with tides, rotational distortion, mutual irradiation, eccentric orbits, and other tight binary phenomena. Among these is coherent and impersonal resolution of a pulsation waveform into a geometric and a radiative part. Color information from multiple photometric bands can improve the separation of geometric and radiative behavior. Also, mathematics (Wilson, 2005) developed for orbital ephemerides ($T_0$, $P$, $dP/dt$), applies as well to pulsation ephemerides, and enhances both areas of ephemeris accuracy considerably, especially for $dP/dt$.

## 3. How are the computations done?

Coherent separation of geometric and radiative behavior is deduced from observations (Least Squares criterion) for each recognized periodicity, allowing comparisons with structural pulsation computations. Implementation is via multiplicative waveforms in mean radius (geometric) and mean effective temperature (radiative), each being a Fourier series in a fundamental and two harmonics. Of course, more harmonics can be added if needed. The Fourier coefficients are parameters to be determined from the data. The leading constant term is fixed at unity due to the series' multiplicative role. Thus the series evaluates to unity if all the determinable coefficients are zero (no pulsation). Multi-mode pulsation is handled by having additional periodicities in a given submission (thus more coefficients) or by successive applications, each with its initial parameter estimates. The geometric multiplier ($R_{wave}$) is converted to a volume multiplier at given pulsation phase via $V = R^3_{wave}$. Next $V(phase)$ is converted to $potential(phase)$, the star figure is computed as an equipotential [see Wilson (1979)], and local effective gravities are computed from the local potential gradients. Then, light or magnitude or RV are computed by appropriate integra-

**Table 1.** V1352 Tau Solution Parameters

| | |
|---|---|
| $a$ ($R_{\odot}$) | 6.66924 |
| $i$ (deg) | $89.82 \pm 0.23$ |
| $T_1$ (K) | 9000 |
| $T_2$ (K) | $5819 \pm 23$ |
| $\Omega_1$ | $5.4689 \pm 0.0079$ |
| $\Omega_2$ | 2.25374 |
| $m_2/m_1$ | $0.20850 \pm 0.00054$ |
| $T_0$ (BJD) | $2457819.48312 \pm 0.00028$ |
| $P_0$ (d) | $6.909673 \pm 0.000040$ |
| $L_1/(L_1 + L_2)_{(\mathrm{KEPLERband})}$ | $0.76620 \pm 0.00044$ |
| $\ell_{3(\mathrm{KEPLERband})}$ | $0.00763 \pm 0.00057$ |
| $T_{0\,\mathrm{puls}}$ (BJD) | $2457860.1086 \pm 0098$ |
| $P_{\mathrm{puls}}$ (d) | $0.0917305 \pm 0.0000021$ |
| $dP_{\mathrm{puls}}/dt$ | $+0.37 \pm 1.16 \times 10^{-7}$ |
| Radius $\cos\theta$ coefficient | $-0.0025 \pm 0.0014$ |
| Radius $\sin\theta$ coefficient | $-0.0014 \pm 0.0017$ |
| Temperature $\cos\theta$ coefficient | $-0.0007 \pm 0.0014$ |
| Temperature $\sin\theta$ coefficient | $-0.0017 \pm 0.0011$ |

tions over the surface. So the procedure does *not* just fit a wave to a light curve but operates at a deeper conceptual level. Note that all W-D model capabilities are in place, such as solution constraints, three kinds of weighting, solutions optionally in absolute units, direct distance estimation, etc.

## 4. Initial application: V1352 Tauri

The *KEPLER* mission light curve of V1352 Tau is a good start-up example for a pulsation model due to the binary's total-annular eclipses, high orbital inclination, and well resolved, steady pulsations. The observations cover 11 cycles of the 6.909673-day orbital period over 80 days, with a typical cycle shown in Fig. 1. The separate geometric and temperature parts of the overall solution within one of the maxima are compared with the observations in Fig. 2. Fig. 3 has the combined and separate waves on a magnified scale. $P_{\mathrm{puls}}$ is measured to be $0.0917305 \pm 0.0000021$ days, although the pulsations are not seen in existing ground based datasets. $dP_{\mathrm{puls}}/dt$ is nil within its uncertainty. A full list of parameter values is in Table 1. A small amount of third light, $0.0076 \pm 0.0006$ of maximum system light, is indicated. Power spectra of light curve residuals show V1352 Tau to be a multi-mode pulsator with several periods longer than the orbital cycle. At least one likely periodic variation extends beyond *KEPLER*'s timewise observing window. Much more pulsational analysis will surely follow these preliminary results.

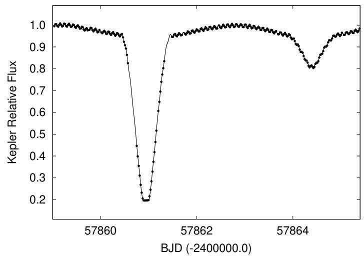


**Figure 1.** One orbit cycle of the V1352 Tau *KEPLER* light curve with solution curve.

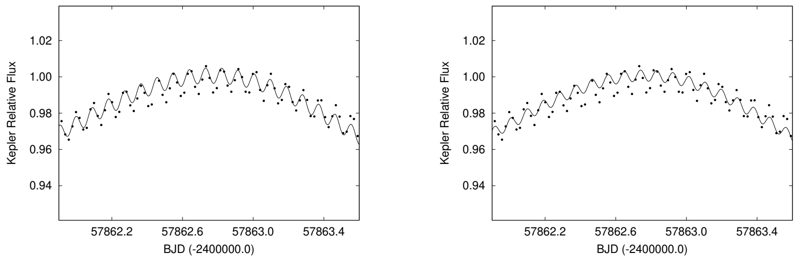


**Figure 2.** Pulsational lightcurve waveform in one of the maxima due only to geometric (i.e. mean radius) variation (left panel), and due only to temperature variation (right panel). Neither phenomenon alone accounts for the full variation.

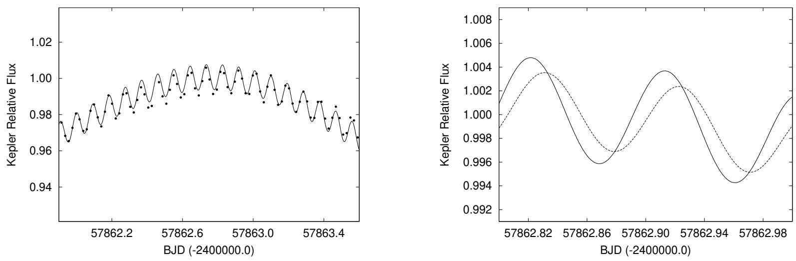


**Figure 3.** The lightcurve waveform in one of the maxima that results from the combined geometric and radiative pulsational variations (left panel). The right panel shows the separate geometric (continuous curve) and radiative (dashed curve) waveforms over about two pulsation cycles.

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# MAVKA: Investigation of stellar brightness extrema approximation stability for various methods

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**Abstract.** We developed the software package MAVKA for the determination of characteristics of extrema (moment of extremum, magnitude) and their errors. The program realizes the application of 11 basic functions for approximation of extrema. We tested all these methods in two parts. In the first part we used generated data sets (various smooth curves with noise). We investigated deviations between generated and computed values of moments of extremum and magnitude, as well as execution time for different extrema parameters. In the second part we used real observations of different variable stars using photometric and visual observations from different databases.

**Key words:** Stars: variable – photometric observations – visual observations – brightness extrema

## 1. Introduction

MAVKA is a software program for approximating moments of extrema (both maxima and minima) of stellar light curves developed by Kateryna Andrych and Ivan Andronov during the period 2015-2019 (Andrych et al., 2017; Andrych & Andronov, 2019). Preliminary investigations of different methods were done in Andrych et al. (2015). There, photometric series of 147 stars were processed and 6509 extrema were obtained. To determine extrema with best accuracy, MAVKA is pointed to the "near-extremum" parts of the light curve. Approximations of complete eclipse shapes were compared in Andronov et al. (2017). Currently there are 9 methods included in the MAVKA algorithm of extrema fitting: algebraic polynomials in general form, "symmetric" algebraic polynomials, the New Algol Variable (NAV, Andronov, 2012), the function of Prof. Z. Mikulášek (Mikulášek, 2015), the "Asymptotic Parabola" (AP, Andronov & Marsakova, 2006), the Wall-Supported Parabola (WSP, Andrych et al., 2017), the Wall-Supported Line (WSL), the "Wall-supported Asymptotic Parabola"

(WSAP), the “Parabolic Spline of defect 1” (spline). Note, throughout this paper we mean both maxima and minima for the term “extrema” and times of maxima and minima for “moments of extrema.”

## 2. Generated data

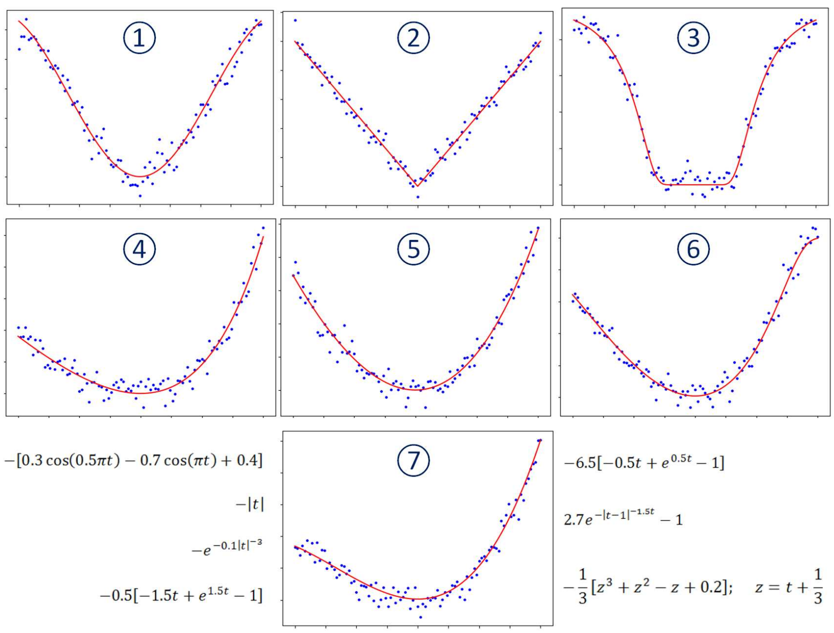


**Figure 1.** All minima shapes used in MAVKA. The number of the shape is the large number in the circle; for each shape, the corresponding formula is listed.

We generated 7 different shapes of minima (see Fig. 1) for testing various possible cases of the symmetric and asymmetric extrema with artificial noise. Formula (1) corresponds to a common minimum shape, formula (2) to a sharp one, formula (3) to a flat minimum. Formulas (4)-(7) are models of different shapes of asymmetric extrema.

Coefficients for all formulas correspond to the minimum position (0,0) and the amplitude equals 1. For each shape we changed the noise, number of points, and (for shapes 1-3) completeness of one or both branches. For each value of noise, number of points and degree of completeness we generated 25 extrema and processed them with the MAVKA method. Then, we obtained the average values of deviation between generated and computed moments of minima as well as magnitude.

## 3. Real observations

MAVKA was already used in several articles: Savastru et al. (2017); Tvardovskyi et al. (2017, 2018); Andrych et al. (2020). In these papers we used the AAVSO observations of different observers. All the data were used for further O-C analyses.

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# Backprojection informatics of RU Monocerotis-type binary system light curves

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**Abstract.** This paper presents the results of our mathematical experiment with light curves of variable stars with large apsidal motion. We have treated our photometric data for different positions of longitude of periastron with our reconstruction algorithms.

**Key words:** informatics – computer tomography – binaries: eclipsing

## 1. Introduction and methods

The mathematical basis of computer tomography (CT) has penetrated many scientific disciplines since the times of J. K. A. Radon, G. Hounsfield and A. MacLeod Cormack. Astronomy is no exception. For many years we have had at our disposal the results of Marsh (2001), Richards et al. (2014) and co-workers. All these authors dealt with applications of reconstruction algorithms in some very interesting branches of astronomy. We began working in this branch of science only recently when we studied the changes in the primary minimum of the $\beta$ Lyrae system, in a similar way to the study of light curves of accretion discs in eclipsing cataclysmic variables (Horne & Stiening, 1985). At this point we would like to emphasize that our scientific effort is to study the minima of $\beta$ Lyrae in a fully independent way from that discussed by other authors. However, their results fully support our work even though we have only published our results in their full complexity just recently (Bahýl et al., 2019). These first results encouraged us to continue the study of full light curves of selected variables with the CT method.

Plenty of books and papers on the subject of tomographic reconstruction of the internal structures of very different objects have been written. However, in our opinion, the world's best book in this field is that by Kak & Slaney (1988). In accordance with the formalism given in this book we have realized our own software with the C++ Builder.

Of course, there is not enough space in this paper to present the formalism used in our work in full detail. However, we would like to stress that we have not worked with a so called “black box” downloaded from the internet! We have written our own software based on relevant mathematical fundamentals.

## 2. Data results and conclusions

There are many types of variable stars, but in our experience, not all of them are suitable for tomographic reconstruction of their light curves. We have selected Algol-type variables with very large apsidal motion. A prototype of such systems is RU Monocerotis, mainly because it has been well observed from the beginning of the last century and its apsidal motion is very large (Martynov, 1966).

The basic task in CT is to get so called projections of the tomographed object, and subsequently, to obtain a reconstruction of the internal structure of the object. In accordance with the general approach, we have accepted the light curves of the selected system at different longitudes of periastron as the projections.

At this point we would like to mention that we have at our disposal many observational data listed on the Czech Astronomical Society web page
`http://var2.astro.cz`.
All relevant data which we have used are referenced on that site.

We have decided to work with 18 projections in the process of back-projecting and internal structure reconstruction. In the process of modelling the given light curve with the BM3 software system we have determined in the longitudes of periastron. An example of our set of light curves for the RU Mon-type system MU Cas is shown in Fig. 1. When we put these data as input into the tomo-

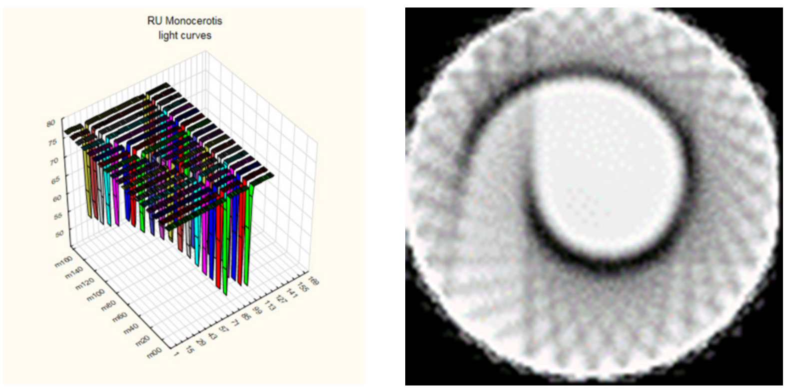


**Figure 1.** Left: the set of the MU Cas light curves for different longitudes of periastron. Right: tomographic reconstruction of the set of light curves of the MU Cas system.

graphic reconstruction software, we obtain the result in the right-hand panel. There are two semicircles. The half circle which corresponds to the secondary minima is larger and begins at the right-hand end of the smaller half circle which corresponds to the primary minima. The lines radiating from the semicircles are so called ghosts which appear because we only use eighteen projections. These ghosts can be easily suppressed computationally.

We have also reconstructed the system V456 Ophiuchi. This system has zero eccentricity, and as expected, in accordance with the theory, both half circles establish a single full circle.

Since its inception CT has found its way into almost all branches of human activity, including astronomy. We have successfully used Doppler tomography in astronomy. We feel that our effort demonstrates that we have the possibility of applying computer tomography to the analysis of light curves of at least some special kinds of variable stars. Or better still, we hope that CT light curve analyses can yield new insights into the problems of changes of the positions of light curve secondary minima.

Lastly we would like to emphasize that we are very familiar with the Wilson–Devinney, Phoebe and MP3 methodologies to determine close binary system parameters. With our work we are not trying to change, improve or replace these methods. Simply, our goal is to take a very small additional step and apply the CT method to obtain system parameters. In this we feel we have been successful.

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# Light curve modelling of close eclipsing binaries

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**Abstract.** We present an easy to use software package fully written in Python designed for light curve modelling of eclipsing close binaries. The software provides full treatment of the Roche geometry and irradiation effects utilizing symmetries of tidally deformed stellar surfaces and eccentric orbits in order to reduce overall computational time. Additionally, the software package allows modelling of spots and low-amplitude radial and non-radial pulsations.

**Key words:** binaries – computational astrophysics – stars: pulsations

## 1. Introduction

Research on low-amplitude stellar oscillations of eclipsing binary components requires a robust numerical model capable of dealing with phenomena such as pulsations of deformed stellar surfaces, amplitude variation of modes during eclipses, and tidal locking of pulsation modes. Therefore, we present a package[1] that utilizes a modular approach in which every functionality is treated as a separate object that ensures easy addition of new features.

## 2. Capabilities of the package

Among the capabilities of the presented package are modelling of surfaces of single and binary systems utilizing surface symmetries in order to reduce overall computational time (Fedurco et al., 2019). This package also allows the modelling of binary systems with eccentric orbits, where the surface geometry changes with orbital phase. However, symmetry of component surfaces for orbital positions placed symmetrically around the apsidal line enabled us to greatly reduce the number of required re-calculations of component surfaces.

Using external atmospheric models (Castelli & Kurucz, 2004) and limb darkening models (van Hamme, 1993) we are able to generate light curves of binary systems for a variety of commonly used bands and instruments.

With such model in place we are able to model surface inhomogeneities such as pulsations and spots. Current capabilities of the package include modelling of low-amplitude oscillations represented by spherical harmonics with an

[1] github.com/mikecokina/elisa

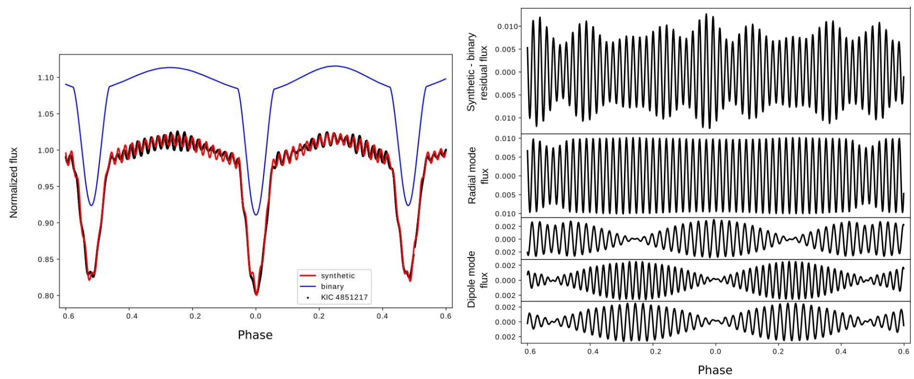


**Figure 1.** The left panel shows the light curve of the oscillating eclipsing binary KIC 4851217 overlayed with its fitted light curve in red. Variations due to binarity are indicated with a blue line. The right panel shows variations caused by oscillations decomposed to their constituent modes.

option of mode axis misalignment, and modelling of temperature spots on assynchronously rotating components.

## 3. Conclusions

Future versions of this package will support modelling of light curves of single star systems and also will be capable of producing radial velocity curves with full implementation of the Rossiter-McLaughlin effect and effects of pulsations on radial velocity curves.

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# The brave new world of eclipsing binary modeling

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**Abstract.** This contribution highlights some of the open questions identified by the binary star community in attendance, based on a 45-min discussion in lieu of an ex-cathedra talk. As photometric and spectroscopic data accuracy reach unprecedented levels, it is crucial to identify and address these open questions. In what follows are concise minutes from the discussion with minimal commentary, in an effort to stimulate further discussion and promote focused studies dedicating to answering these open questions.

**Key words:** binaries: eclipsing – stars: fundamental parameters

## 1. Introduction

The landscape of eclipsing binary modeling is changing rapidly. Gone are the days where we would spend a few nights at a telescope, acquire an eclipsing binary light curve (and, if we have access to precious spectrographs, radial velocity curve), throw it all into the Wilson & Devinney code and publish the resulting parameters. We know now how to do better: how to study parameter correlations and degeneracies robustly, how to estimate heuristic (instead of formal) errors and how to combine diverse, possibly heteroscedastic datasets efficiently and, above all, statistically correctly. We also came to realize that modeling noise is crucial for proper estimation of parameter posteriors and that simplifying assumptions regarding noise/instrumental processes are rarely – if ever – adequate. The data have become ubiquitous and precise, and the literal firehose of data about to hit us from the upcoming missions such as LSST is simply astounding. On top of all that, there is a number of open questions when modeling eclipsing binary observables that we have yet to fully answer. I discuss some of these questions in what follows below.

Thinking about what the "brave" new world of eclipsing binaries boils down to, I would argue that we need to:

– figure out *why* we do what we do: what new insights will the scientific study provide beyond simply having the data that make that study possible;

– critically examine what we consider current best practices over and over again;

– adopt proven best practices from other fields – we have a lot to learn from fields like exoplanets that witnessed early adoption of advanced astrostatistical methods;

– report null results in peer-reviewed literature – let the community know when something does not work; and

– embrace the fact that eclipsing binary modeling is both *difficult* and *computationally expensive.*

For the purpose of this discussion, I asked the audience the following questions:

**How do we handle data noise efficiently?** With noise all but gaussian, do we rely on overly-simplified assumptions, incorporate an explicit noise model, resort to gaussian processes, or do something else entirely?

**How do we parametrize our models?** The efficiency of finding the right solution depends strongly on the choice of parameters that appear in the model. Is our choice of parameters the best one we can make?

**How do we robustly solve the inverse problem?** Using differential corrections and other deterministic minimizers benefits from speed, but suffers from the limited understanding of the parameter space topology; do we jump right into Bayesian inference, importance sampling, Markov Chain Monte Carlo sampling, nested sampling, or do the old methods still have clear merit?

**What does it take to determine fundamental parameters to 1% (0.1%)?** If data precision allows this accuracy, does the model allow it as well? Is the precision in determined parameters really equivalent to their accuracy?

**How do we handle a deluge of data coming our way?** The ongoing and upcoming surveys such as *Gaia*, ZTF and LSST will swamp us with data. What are we hoping to learn from those data, and what needs to happen to enable us to process those data?

**How do we classify binaries based on their light curve morphology?** The crude separation of all binaries into detached, semi-detached and contact is barely more informative than claiming that the object is an eclipsing binary; how can we do better?

**Do we handle contact binaries correctly?** There is a large number of simplifying assumptions that are difficult to justify, most notably the "merging" in the neck area. Can we do better?

**How do we bridge binarity with stellar populations and stellar evolution?** With only a few notable exceptions, stellar evolution focuses on single stars; what needs to happen to enable the reliable model of binary and multiple populations and their evolution, and how would such models be able to constrain eclipsing binary modeling further?

Forty-five minutes is obviously too short a time to answer all these questions, so we focused on a subset deemed most pertinent by the audience. The minutes of the discussion are provided below.

## 2. Discussion notes

- Why are we doing what we are doing? What are the fundamental questions we are trying to answer with binary star science?
  - Pushing the accuracy of fundamental parameters (3% → 1% → 0.1%)
    - The role of Helium – He fraction affects evolution, mass/luminosity and therefore limits accuracy. The tables of evolutionary models do not include variable He abundance. He abundance determined by theory but not from observations
    - How do we define effective temperature from spectroscopy?
    - Understanding the role of binary interactions – a lot if left unanswered because of the limitations on accuracy
  - Stellar evolution in binary stars
  - Extreme low-mass WD forming in 1 AU orbits where they should not – test speculations of stable mass transfer that leaves them in those orbits
  - Paying more attention to observations to get answers
  - Problems that arise in modeling when introducing rotational models
  - Magnetic fields
  - Constraints from EBs also constrain single star parameters
- Handling data noise
  - If the original model is slow, it gets harder to add more modeling on top of it → optimize the model (or buy a supercomputer)
  - Include the noise model
  - Our field is doing well compared to other fields – (ground-based) observations tend to not have any systematic error due to standard processing techniques. This does not apply to surveys that push the limit of accuracy
  - We should not assume our data uncertainties are realistic

  - More advanced techniques (AO, speckle) require detailed modeling of the noise in concert with instrumentation (not simple shot noise!), therefore returning the uncertainty as one number is unreliable
    - Is the burden on the observers or modelers to handle this?
    - Modelers should understand exactly what is going on in the instrument (beyond empirical evidence) but it can get complicated
    - Division of labor between observers and users - instrument scientists should deliver reduced data and noise models. How do we get there? Impose standards
    - Use standards to retrieve the noise model from observations where we know it should not be
  - Disentangling instrumental trends from actual astrophysical signals?
  - Pipelines: users overlook the uncertainties that the pipeline introduces - should also go in the noise model
- Large surveys: ZTF, *Gaia*, LSST - how do we handle data?
  - Do we need millions EBs and what do we do with them?
  - If we do not have enough follow-up with RVs it does not matter if we have millions of LCs
  - Advantage: we will finally be able to see the stellar populations on the low-mass end
  - Make reasonable approximations to get masses, radii, distances (better to have 10,000 objects with precision of 15% than 10 with 3%)
  - Find the ones that are really special (example SDB with non-conservative mass transfer)
  - Classical novae and follow-up triggers – not much incentive for observers to observe novar in quiescence and these surveys can fill those gaps. *TESS* is doing this right now, however the problem remains that people do not publish data of these objects in quiescence
- The choice of parameters
  - We rely on parameters driven by physics, but with that impose correlations and degeneracy implicitly which limits our ability to derive accurate parameters
  - Parameters with respect to each other: how do we address treating parameters/parameter ranges equally when they probably should not be?

– Parameters with respect to the data: test whether data are sensitive to our parameters of choice before fitting for them

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# Binary fraction of magnetic chemically peculiar stars

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**Abstract.** Magnetic chemically peculiar stars of the upper main sequence are slowly rotating early B to early F-type objects with elemental overabundances of several orders of magnitude compared to the Sun. The driving mechanism is diffusion in the calm stellar atmosphere intensified by the presence of a stable organized magnetic field. The binary fraction is vital to understanding the formation and evolution of these objects as well as possible operating angular momentum loss mechanisms. The available literature on the binary fraction is reviewed and a list of needed future working steps is presented.

**Key words:** binaries: general – stars: chemically peculiar – stars: magnetic fields

## 1. Introduction

Chemically peculiar (CP) stars are upper main sequence objects (spectral types early B to early F) whose spectra are characterized by abnormally strong (or weak) absorption lines that indicate peculiar surface elemental abundances. CP stars constitute about 10% of upper main sequence stars and are commonly subdivided into four classes (Preston, 1974): metallic line (or Am) stars (CP1), magnetic Bp/Ap stars (CP2), HgMn stars (CP3), and He-weak stars (CP4).

The CP2 and CP4 stars are set apart by the presence of stable, globally-organized magnetic fields with strengths from about 300 G to several tens of kG. CP1 and CP3 stars do not show strong, organized magnetic fields; the presence of weak fields (less than 100 G) has been claimed but remains controversial. Common to all subgroups is their apparent slow rotation as compared to normal stars of the same spectral types.

In general, the binary fraction among main sequence stars is depending on mass, orbital period and eccentricity (Moe & Di Stefano, 2017). Different observational methods are sensitive to different types of binary systems. All this has to be taken into account when determining the overall incidence of binary systems in a specific spectral type range. It is also known that single and binary stars evolve differently, which is particularly true for close systems (Iben, 1991).

The investigation of single magnetic CP (mCP) stars and mCP stars in binary systems is important to study the formation and evolution of their stable magnetic fields and the loss of angular momentum that these objects undergo. For nearly fifty years (Abt & Snowden, 1973), the binary fraction among magnetic CP stars has been investigated. Published values range from 20% to about 50%. Here, an overview of the literature and an outlook of what needs to be done is given.

## 2. The importance of the binary frequency

It has been well established that CP stars rotate on average more slowly than normal stars of the same spectral types, and that this discrepancy is not due to CP stars being rapid rotators seen pole-on (Netopil et al., 2017). It has therefore been suggested that slow rotation (equatorial velocity $< 120\,\mathrm{kms}^{-1}$) is a necessary (but not sufficient) preliminary condition for the development of chemical peculiarities. CP stars do not simply constitute a slowly rotating tail of "normal" A-type stars; instead, their rotational velocities follow a Maxwellian distribution with an average value three to four times lower. Close binaries might play an important role in the loss of angular momentum on the main sequence.

The origin of the magnetic fields in mCP stars is still a matter of some controversy, the main competing theories (Moss, 2004; Braithwaite & Spruit, 2004) being the dynamo theory (field generated by dynamo action in the convective core) and the fossil field theory (field is a relic of the "frozen-in" interstellar magnetic field). Another interesting theory was proposed by Ferrario et al. (2009), who suggested a merger scenario: towards the end of the formation process, after the development of a substantial radiative envelope, a small fraction of stars merge. Such late mergers would result in a brief period of strong differential rotation and give rise to large-scale magnetic fields in the radiative envelopes. This could explain the observed small fraction of magnetic stars that increases with mass. Consequently, we would not expect to find a large fraction of close binary systems among mCP stars.

## 3. Published binary fractions

It is important to note that almost no single CP1 stars are known out of a sample of 4300 objects. The situation is similar for CP3 stars: at least 2/3 out of a sample of about 170 objects are in SB2 systems. The literature concerned with the magnetic subgroups is not conclusive and the results depend on the employed methods and the observational material. In the following, an overview of the most comprehensive papers is given.

- Abt & Snowden (1973): **20%** out of a sample of 45 stars
- Gerbaldi et al. (1985): **46%** out of a sample of 113 stars
- Carrier et al. (2002): **43%** out of a sample of 119 stars

– Rastegaev et al. (2014): **23%** out of a sample of 273 stars

– Mathys (2017): **51%** out of a sample of 43 stars

These references include SB1, SB2 and wide binary systems. Up to now, no system harbouring an mCP stars is known with an orbital period less than 1.5 d. The number of known eclipsing binary systems hosting a magnetic CP star is still below five (Skarka et al., 2019). In summary, it can be said that up to 50% of all mCP stars are part of a binary system. A modern sound statistical analysis of the orbital periods, mass ratios, and ages is very much needed to test the different theories.

## 4. Conclusions and outlook

The importance of determining the binary fraction of mCP stars has been outlined. A comparison of single and binary objects will help to put tight constraints on the formation and evolution of this star group. In particular, further investigations should be carried out concerning the merging scenario during the end of the pre-main sequence phase and the apparent need for angular momentum loss to enable effective diffusion in the stellar atmospheres.

The currently available investigations are based on widely different observational material and therefore suffer from various biases. To overcome this unsatisfactory situation, the following research items are suggested:

– comprehensive analysis of known binary systems with a magnetic component using archival spectroscopic and photometric data;

– search for eclipsing binary systems with a spotted upper main sequence primary star in *CoRoT*, *Kepler* and *TESS* data;

– search for short orbital period spectroscopic binaries with an mCP star component;

– spectropolarimetric measurements of known binary systems to detect new mCP star components.

This workflow should guarantee a new observational basis for testing and improving the current models.

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# The good, the bad and the really ugly: composite-spectrum binaries

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**Abstract.** Composite-spectrum binaries (containing a cool giant primary and a hot dwarf secondary) should be an answer to a theoretician's prayer. Because of their luminosity difference, both spectra are visible in the near UV, a region that includes several valuable luminosity and temperature indicators. If we just measure the radial velocity (RV) of the secondary at different dates, and construct an SB2 orbit, we immediate get the mass ratio of the component stars. A guess of the mass of the dwarf, and one thence obtains the mass of the cool giant – a unique and immensely valuable method. But *just* measure a hot dwarf's RV?? It raises many problems, mostly caused by the nature of the star. A hot (late-B or early-A) dwarf has few lines, most are weak, they can be very blurred by rotation, and they get hidden by the crowded spectra of the giant. Spectral subtraction works a treat in separating the two spectra, but the residue is inevitably rather noisy. Nevertheless, results from well over half of the 45 brightest northern composite-spectrum binaries have been published; about 1 in 6 are triple systems, and a few have characteristics that defy any theoretician to explain. Several are 'bad' because their giant primaries have high luminosity and finding a matching standard for the subtraction process is troublesome, while the 'really ugly' include an Am star in a simple SB2 binary with a period of 75 years, a pair of early-A dwarfs in a 3-day orbit with amplitudes of  100 $\mathrm{km\,s^{-1}}$ and which show absolutely no rotational broadening at all, and another whose secondary (apparently a single star) is more that twice as massive as its primary giant. But 8 of the sample are also eclipsing, and manifest the hugely important phenomenon of chromospheric absorption – those are the 'really good' systems. The talk showed examples of each kind.

**Key words:** stars: binaries – stars:composite-systems – stars:stellar evolution

## 1. Introduction

Composite-spectrum binaries, whose component stars are a cool (G-K-M) giant and a hot (B-A, and maybe F) dwarf, form an important sub-branch of spectroscopic binaries because they exhibit the spectra of both component stars (a property that was recognized over 100 years ago by the classifiers of the *Henry*

*Draper Catalogue*). Measurements of both spectra enable SB2 orbits to be constructed, and thence the mass ratio of the component stars to be determined. Since stellar mass is the property that controls the rate at which a star evolves, the star that is now a cool giant must be the more massive of the two, and thereby the more luminous. But although the spectral energy distributions of the two stars are of course highly different, their gradients are such that, in the near-UV and blue spectral regions, they are tolerably comparable. Both spectra can therefore been seen in those wavelength regions, so the mass *ratio* can be determined. It then requires an estimation of the mass of the hot dwarf (the latitude of those values is quite small) in order to determine, with reasonable precision, the mass of the giant star – certainly a much-welcomed determination of a property that is otherwise particularly elusive.

An ongoing project to study composite-spectrum binaries is working with a sample of 45 of the brightest systems visible from the northern hemisphere (see Table 1). Analyses of well over half have now been published – for example, Griffin & Griffin (1986) (Paper 1), or Griffin & Griffin (2018) (Paper 22), among others, those remaining are necessarily 'difficult' in some respect.

**Table 1.** Table 1. Statistics of the sample of 45 binaries

| | Cool primary (evolved)** | Hot secondary (much less evolved) |
|---|---|---|
| 1. Range of spectral types | G0 - M2 | B5 - F2 |
| 2. Am stars | 1 (o Leo) | 9 (20%) |
| 3. Range of periods | 14 days - 65 years | |
| | < 120 days: 11 (24%) | |
| | 0.3 - 3 years: 12 (27%) | |
| | > 3 years: 22 (49%) | |
| 4. Triple systems | 6, maybe 7 (14%) | |
| 5. Eclipsing systems | 8 (18%) | |
| 6. Astrometric orbits (in addition to those in # 5) | 8 (18%) | |

** *Except for o Leo, the components are separated by the Hertzsprung gap.*

Our method is to obtain high S/N spectra of a system at numerous orbital phases, particularly at or near nodes. The spectrum of the giant star is then subtracted away, pixel by pixel, from the spectrum of the binary by using the spectrum of a standard star of known spectral type. The best match indicates the spectral type and luminosity class of the giant in the binary. The residue is the spectrum of the hot component, which can then be classified, matched to synthetic spectra, and measured for RV. Knowing the RV of the giant on the respective dates from its SB1 orbit, we can in principle derive an SB2 orbit for the system. An example of how the procedure works is shown in Fig. 1. In this

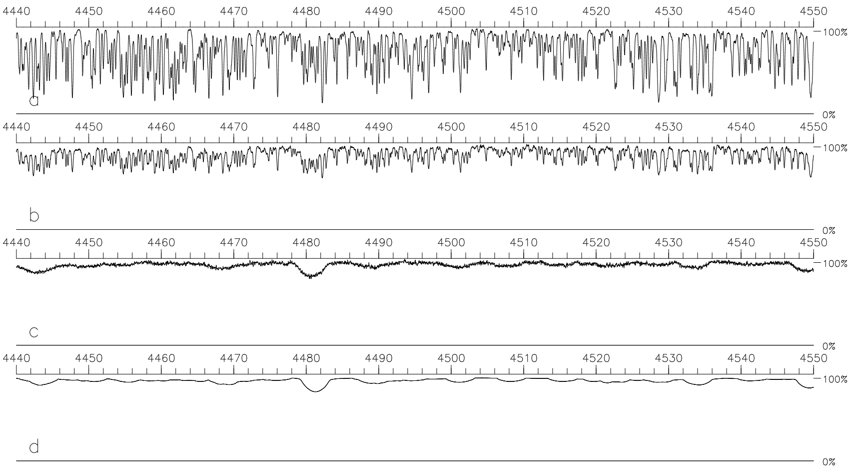


**Figure 1.** Separating component spectra of 45 Cnc by subtraction. The spectrum of an appropriate cool-giant standard, in panel (a), is subtracted point-by-point from the spectrum of the composite system in panel (b). The residue, seen in panel (c), is the spectrum of the hot dwarf secondary; it matches closely a synthetic spectrum, calculated in this case for $T_{\rm eff} \doteq 8500, \log g = 3.5$, solar abundances (but with [Mg/Fe] raised by 0.3 dex), and blurred to mimic rotation of $130\,{\rm km\,s^{-1}}$.

figure, the spectrum of an appropriate G-giant spectrum, panel (a), is subtracted from the observed composite spectrum in panel (b), leaving the spectrum of the secondary star, 45 Cnc B – see panel (c) – as a residue. Panel (d) shows a synthetic spectrum, calculated with SPECTRUM[1]; it forms a close match to that of the hot dwarf in panel (c). The goodness of the match of the standard star is demonstrated by the general lack of 'mis-match' spikes (artefacts) in the residue. To optimize the procedure, it is important to align both the composite and the standard spectra in the same (stellar) rest-frame, rather than try to shift spectra to correct for stellar RVs.

## 2. The good: unparallelled studies of stellar chromospheres

One bonus of this research has been the discovery of the chromospheric eclipses which 9 of the sample manifest. All stars possess chromospheres. The solar chromosphere is relatively shallow compared to the diameter of the disk, but in a cool giant, especially a supergiant, it is markedly extensive. Near to eclipse, when the hot dwarf passes behind such a region, its radiation is absorbed selectively by the cool chromosphere, generating narrow features that contain highly valuable information about the conditions and chemistry of the giant's chromosphere –

[1]www.appstate.edu/ grayro/spectrum/spectrum.html

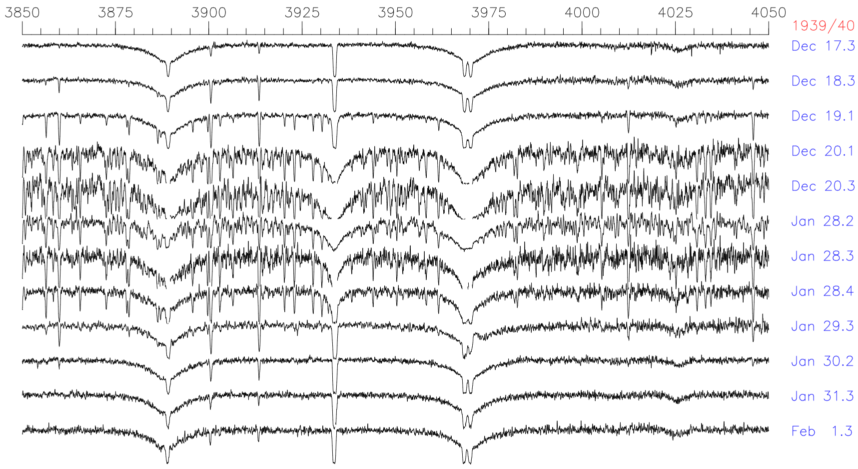


**Figure 2.** Sequence of selected chromospheric spectra, superimposed on spectra of the hot dwarf as it passes behind the chromosphere of the supergiant primary from ingress to egress on the dates shown. Total eclipse lasted for ∼36 days; mid-eclipse was close to 1940 January 8. The changing strengths of the chromospheric lines as the dwarf aproaches, and then recedes from, the limb of the giant reflect the density gradient in the chromosphere.

information that is simply not attainable in any other way, so these eclipses are precious phenomena. $\zeta$ Aur, the first system in which the possibility of such eclipses was recognized, and detected by Guthnick (1934), has given its name to this sub-class. Analyses of the chromospheres of several $\zeta$ Aur systems indicate that chromospheres are by no means static or homogeneous, that they contain local concentrations of material and a lot of empty space, and that a series of eclipse spectra (see Fig. 2) differs at each eclipse from every other set. Those findings launched a fresh programme of investigation into the properties of the chromospheres of cool giants and supergiants. One fascinating outcome is the suspicion that cool giants undergo activity cycles analogous to the sunspot cycle; eclipses in 32 Cyg are grazing, and changes in the degree of chromospheric absorption at the pole of the supergiant primary in different eclipses are similar to the changing shape of the solar corona between sunspot maxima and minima.

## 3. The bad: difficulties of analysis imposed by Nature

The hot dwarf featured in Fig. 1 is rotating at $\sim$130 km s$^{-1}$, fast enough to create a challenge for precise RV measurements. The subtraction procedure subtracts the signal but adds the noise, so even a well-exposed spectrum can exhibit considerable noise when (as often happens) over half of the signal has been subtracted. Taking multiple observations and co-adding them is a good solution in such binaries, but an early-A or a late-B dwarf does not have many lines in its spectrum anyway; the Ca II line is relatively blend-free and should in principle be a good for RG measurements, but it is often contamiated with an *IS* feature, making it unuseable for precise velocity measurements in practice.

## 4. The really ugly

The majority of the systems analyzed so far prove to have component stars whose properties – mass, luminosity and age – are in accordance with current stellar evolutionary theory (though it was a bit surprising to discover such a high percentage of triple systems). However, a few do not, and it is those misfits which should cause us to worry. The talk singled out two.

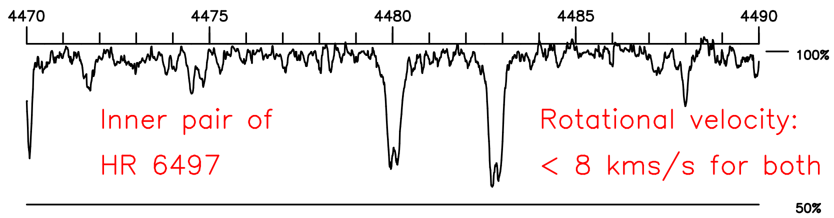


**Figure 3.** Portion of the secondary spectrum of HR 6497, showing the two component lines of Mg II near λ 4481 Å. The lack of any visible rotational velocity in the line of sight cannot readily be explained without adopting some highly unlikely model.

(1) HR 6497 ($P$ = 3.3 years) is an hierarchical triple system, whose inner pair form a tight binary ($P$ = 3.75 days); see Griffin & Griffin (2012). What is strange is that the two secondary stars each have orbital velocities around 100 km s$^{-1}$ *and yet they show no rotation at all.* Fig. 3 reproduces a portion of the uncovered spectrum of the secondary system to show the strong, narrow Mg II lines at λ 4481 Å in each component, widely separated in velocity when near a node in the 3.75-day orbit. The Mg II line is actually a close doublet with a separation close to 0.2 Å, and its partial resolution as seen here is very puzzling as it indicates almost zero rotation of the stars along our line of sight. The inner orbit is tilted at about 72$^{o}$, and it does not seem at all likely that the two stars should be tipped to that extent so that they appear face-on: the likelihood of such a coincidence must be vanishingly small, and additionally very unlikely to occur in a sample of only 45 systems.

(2) Another system, HD 193350, appears to be a simple binary; its SB2 orbait is illustrated in Fig. 4; see Griffin & Griffin (2018). No trace of a third body has been detected, but the secondary proves to be more than twice as massive as the primary. There is no evidence of mass transfer in its history. The only feasible conclusion is a merger (e.g., of a pair that used to form a double secondary,

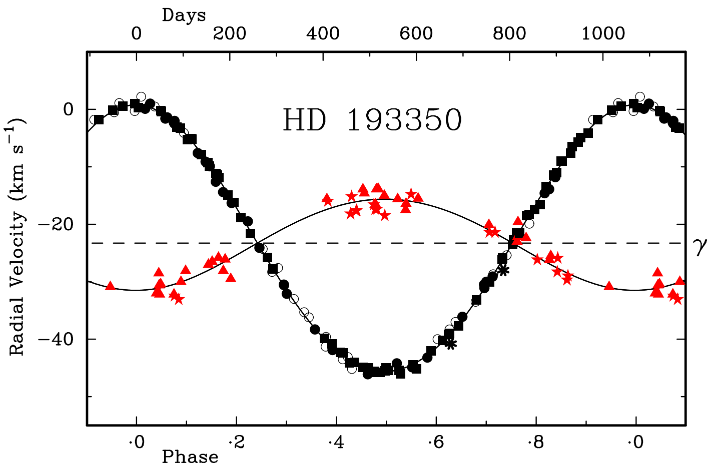


**Figure 4.** SB2 orbit for HD 193350. The orbit of the secondary (the less populated curve, featuring asterisks and filled triangles) indicates that the (unevolved) secondary star is substantially more massive than the (evolved) primary.

as in HR 6497 now). It must have occurred long enough ago for the resulting binary system to have become totally quiescent, because there is no evidence in the form of emission features that might be expected when such a violent event takes place.

(3) The secondary of HD 88021 is a confirmed Am star, but contrary to many assertions that Am stars undergo chemical separation by diffusion because they are held quiescent in tidally-locked binaries, HD 88021 B shows no sign that it is in a close binary – in fact, the only orbit involved combines it with its cool giant primary, and has $P = 75$ years.

These problem cases need to worry us. If we cannot explain why they seem to defy some of the basic concepts of stellar astrophysics, why are we straining to understand all the *other* stars in the Galaxy?

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# Improved physical properties of the quadruple sub-system with the eclipsing binary QZ Carinae*

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**Abstract.** Using a collection of 79 spectra of the quadruple system QZ Car, we were able – for the first time in the optical region – to measure radial velocities of both components of the eclipsing subsystem Ac, and in combination with the photometric solution to obtain masses and radii of both bodies. We confirm that the Ac binary is a semi-detached system with a brighter primary Ac1 and a more massive secondary Ac2. Variations due to the light-time effect and secular

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* Based on spectra from observations made with ESO telescopes at La Silla and Paranal Observatories under programmes 076.C-0431(A), 081.C-2003(A), 083.D-0589(A), 089.D-0975(A), 095.A-9032(A); the program TYCHO P2; on the BESO spectra and spectra from CTIO, and on Hipparcos, ASAS3 and our *V* photometry.

† Pavel Mayer passed away on the day of his 86$^{\text{th}}$ birthday, Nov. 7, 2018

changes in the systemic velocities of both binaries, Aa and Ac, allowed us to estimate the period of mutual orbit of binaries Aa and Ac to be about 11700 d. Preliminary improved basic properties of the system and its components are provided.

**Key words:** Stars: binaries: eclipsing – Stars: early-type – Stars: fundamental parameters – Stars: individual: QZ Car

## 1. Introduction

The massive multiple system known as HD 93206 (HIP 52526), a member of the open cluster Collinder 228, is known to consist of at least eight stars, four of them belonging to two binary systems in a mutual orbit, known as QZ Car. Components Aa1 and Aa2 form a spectroscopic binary ($P = 20\overset{d}{.}7$, $e = 0.35$) while components Ac1 and Ac2 form an eclipsing binary ($P = 5\overset{d}{.}9987$, $e = 0$). There is also a close component Ab[1] and more distant faint components B, C, and D – see Fig. 1.

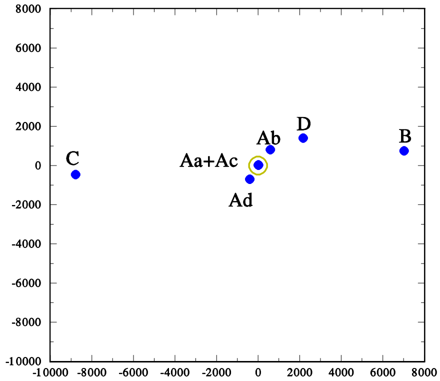


**Figure 1.** A sketch of the multiple system HD 93206 drawn in mas scale on both axes.

QZ Car was identified as an eclipsing binary by Walker & Marino (1972). Morrison & Conti (1979) reported the presence of two spectroscopic binaries in the spectra of the star, the secondary Aa2 being too faint to be detected. Mayer et al. (2001) improved the ephemerides of both orbits and derived new orbital elements for them. Considering the light-time effect they suggested the period of mutual orbit of the Aa and Ac binaries to be 40 to 50 yrs. Stickland & Lloyd (2001) obtained radial velocities (RVs) of components Aa1, Ac1, and Ac2 from 9 SPW IUE spectra and derived new orbital elements of both orbits. For the Ac1-Ac2 subsystem, they obtained a mass ratio $M_1/M_2 = 1.07$. So far the

[1]Another close component named Ad was reported during this conference – see Reggiani, Rainot and Sana.

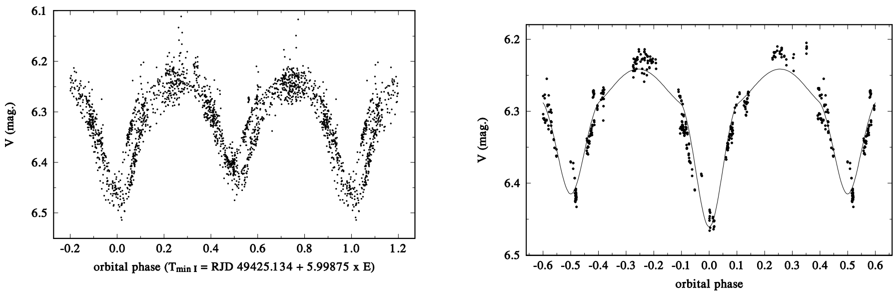


**Figure 2.** Left: Light curve of eclipsing system Ac based on all homogenised yellow-band observations. Right: Standard $V$ observations fitted with PHOEBE.

most detailed study was published by Walker et al. (2017) who list references to numerous previous studies.

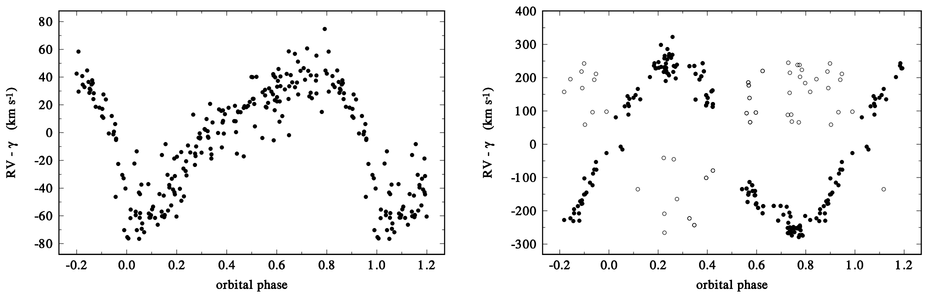


**Figure 3.** RV curves of component Aa1, and components Ac1 and Ac2.

## 2. Our analyses and results

We reduced and analysed 79 digital spectra from the FEROS, BESO, and CHIRON echelle spectrographs, and measured RVs in them. We also collected and homogenised all photometric observations available to us, including the discovery observations by Walker & Marino (1972). Using all yellow photometry, we derived the mean period of the Ac system as $5\overset{d}{.}99875$. The light curve in the left panel of Fig. 2 shows the changes in the local times of minima due to the light-time effect. We derived new orbital solutions for both subsystems with the program FOTEL (Hadrava, 2004a) in such a way that we allowed calculation of individual $\gamma$ velocities over intervals not longer than about 100 d. The solutions

**Table 1.** New orbital solution for all RVs of component Aa1 with locally derived systemic ($\gamma$) velocities, and the same for components Ac1 and Ac2. All epochs are in HJD-2400000.0. The rms values are for a single observation.

| Element | Aa1 | Ac1 & Ac2 |
|---|---|---|
| $P$ (d) | 20.73514(33) | 5.998728(22) |
| $T_{\rm periastr.}$ | 42529.54(36) | – |
| $T_{\rm upper.conj.}$ | 42528.50 | 49425.031(24) |
| $T_{\rm max.RV}$ | 42524.26 | – |
| $e$ | 0.351(34) | 0.0 fixed |
| $\omega$ (°) | 128.5(7.2) | – |
| $K_1$ (km s$^{-1}$) | 52.3(1.9) | 256.8(4.9) |
| $K_2$ (km s$^{-1}$) | – | 193.5 |
| $M_2/M_1 = K_1/K_2$ | – | 1.327(90) |
| No. of RVs | 203 | 176 |
| rms (km s$^{-1}$) | 11.98 | 43.62 |

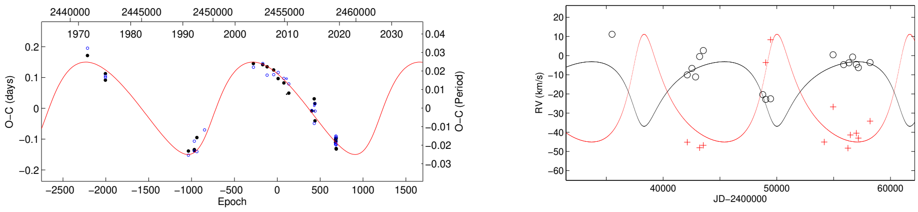


**Figure 4.** Left: The $O-C$ variations due to the light-time effect plotted vs. phase with the 11700 d period. Right: Systemic velocities of component Aa1 (circles) and component Ac1 (crosses) plotted with the same period.

are in Table 1 and the corresponding phase curves in Fig. 3. It is encouraging that the RV solution for the binary Ac led to the same mean period as photometry within the error limits.

We derived a mean light-curve solution with `PHOEBE` 1 (Prša & Zwitter, 2005) and used it as a template to derive local epochs of minima from subsets of time sorted data. The $O-C$ solution is in the left panel of Fig. 4 while the right panel shows the model fit to the systemic velocities.

Keeping all elements of all three orbits fixed, we disentangled the line profiles of components Aa1, Ac1, and Ac2 with the program `KOREL` (Hadrava, 2004b) and derived their radiative parameters from the comparison with interpolated synthetic spectra using `PYTERPOL`.[2] Fixing the resulting $T_{\rm eff}$ in `PHOEBE` 1, we

[2]Kindly provided by J. Nemravová.

**Table 2.** Masses, radii, effective temperatures, relative luminosities, and projected rotational velocities of components Aa1, Ac1, and Ac2 based on our preliminary analysis. The orbital inclination and semi-major axis of the eclipsing system Ac are $i = 73\overset{\circ}{.}18 \pm 0\overset{\circ}{.}16$, and $a = 55.77 \pm 0.87\ \mathcal{R}^{\mathrm{N}}_{\odot}$, respectively.

| Quantity | Aa1 | Ac1 | Ac2 |
|---|---|---|---|
| $M$ ($\mathcal{M}^{\mathrm{N}}_{\odot}$) | – | 27.8 | 36.9 |
| $R$ ($\mathcal{R}^{\mathrm{N}}_{\odot}$) | – | 19.8 | 15.2 |
| $T_{\mathrm{eff}}$ (K) | 32700 | 32700 | 38440 |
| $L$ | 0.42 | 0.32 | 0.24 |
| $v \sin i$ (km s$^{-1}$) | 85 | 134 | 342 |

arrived at the improved properties of the system listed in Table 2.

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# Improved model of Delta Orionis

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**Abstract.** We present an improved model of triple star Delta Orionis A. For the first time we were able to disentangle the very weak spectral lines of the secondary in the blue parts of the optical spectrum and derive a reliable mass ratio $q = 0.415$. Along with light-curve solutions, based on photometry from the *SMEI*, *MOST* and *BRITE* satellites, we obtained realistic masses and radii of both components of the close binary.

**Key words:** eclipsing binary stars – spectroscopic analysis – light curves

## 1. Introduction

The object $\delta$ Ori A (HD 36486, HIP 25930, HR 1852; $V = 2.23$ mag.; average position angle 162.35° Niesten, 1904) is a triple star in the multiple star system $\delta$ Orionis (Mintaka, ADS 4134) in the constellation of Orion (for the structure of the system see Harvin et al., 2002). The star $\delta$ Orionis A consists of an eclipsing binary with the orbital period of $P = 5.732$ d and a distant tertiary with an orbital period of the order of several thousand days.

The binary system has been studied many times. Harvin et al. (2002) carried out a tomographic separation of UV and optical spectra and concluded that the components have unexpectedly low masses: $M_1 = 11.2\,\mathcal{M}^{\rm N}_{\odot}$ and $M_2 = 5.6\,\mathcal{M}^{\rm N}_{\odot}$. Than Mayer et al. (2010) pointed out that the second system of spectral lines in Harvin's study belongs to a tertiary and showed that primary and tertiary dominate the optical spectra. They concluded that the system has normal masses and estimated a mass ratio of about 0.4. Harmanec et al. (2013) indeed reported a similar mass ratio, detecting the secondary in the He I 6678 Å line. A series of detailed studies was published by Corcoran et al. (2015), Nichols et al. (2015), Pablo et al. (2015) and Shenar et al. (2015).

† Pavel Mayer passed away on the day of his 86$^{\rm th}$ birthday Nov. 7, 2018

## 2. Observational material used and data analysis

All electronic spectra covering the blue and green spectral region (RJD between 50031 and 58405) obtained at the Ondřejov 2-m reflector were used. These were complemented by spectra from the Haute Provence Observatory Elodie echelle spectrograph and the ESO LaSilla Feros echelle spectrograph. The space-based photometric data was obtained with instruments on board *SMEI*, *MOST* and *BRITE*[1] (RJD between 52676 and 56995).

Normalization of spectra, removal of residual cosmic rays and radial-velocity (RV) measurements were carried out with the program `SPEFO` (Horn et al., 1996; Škoda, 1996), developed by Mr. J. Krpata (Krpata, 2008). We disentangled the spectra in `KOREL` (Hadrava, 2004) in two steps: we first disentangled the strong spectra of the primary and tertiary and then we disentangled the spectrum of the faint secondary in the residual spectra from the first step. They were then fitted by interpolated synthetic spectra with the help of the program `PYTERPOL`[2] to fit the profiles of the components (see Fig. 1). For the final combined RV and light-curve solutions we used the program `PHOEBE` 1[3] (Prša & Zwitter, 2005).

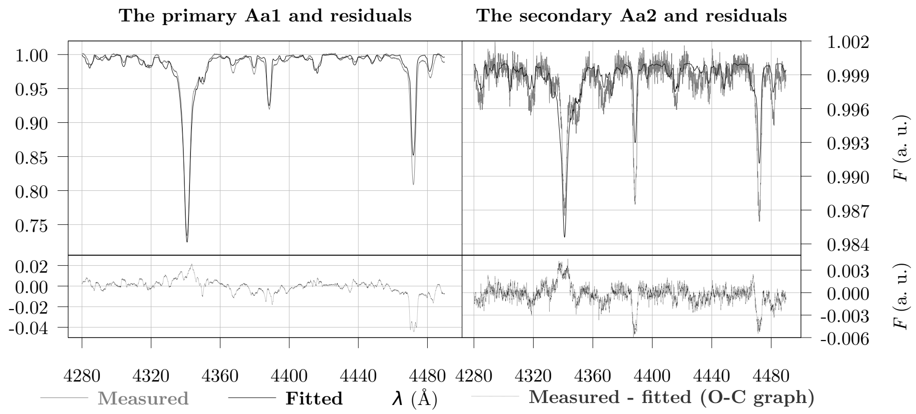


**Figure 1.** Comparison of disentangled spectra of the primary and secondary with the best-fit synthetic spectra found by `PYTERPOL`.

[1]Based on data collected by the *BRITE* Constellation satellite mission, designed, built, launched, operated and supported by the Austrian Research Promotion Agency (FFG), the University of Vienna, the Technical University of Graz, the University of Innsbruck, the Canadian Space Agency (CSA), the University of Toronto Institute for Aerospace Studies (UTIAS), the Foundation for Polish Science & Technology (FNiTP MNiSW), and National Science Centre (NCN).

[2]https://github.com/chrysante87/pyterpol/wiki

[3]http://phoebe-project.org/1.0

## 3. Results

The final elements are in Table 1. It was found that the solution based on the *SMEI* data led to a high inclination and an anomalously small radius for the secondary. A realistic solution was found with the *BRITE* and *MOST* photometry together. Fig. 2 displays the fitted light curves. Using *SMEI* we arrived at reasonable masses and radii for both the primary (cf. Martins et al., 2005) and secondary (see Harmanec, 1988).

**Table 1.** Solution

| Parameters | BRITE | SMEI |
|---|---|---|
| $a/\mathcal{R}^{\mathrm{N}}_{\odot}$ | $41.91 \pm 0.18$ | $40.71 \pm 0.21$ |
| $\omega/^{\circ}$ | $148.73 \pm 1.49$ | $158.37 \pm 0.71$ |
| $\gamma$/km s$^{-1}$ | $21.96 \pm 0.33$ | $22.28 \pm 0.41$ |
| $i/^{\circ}$ | $78.1 \pm 0.3$ | $91.6 \pm 0.4$ |
| $M_1/\mathcal{M}^{\mathrm{N}}_{\odot}$ | 21.1 | 19.4 |
| $M_2/\mathcal{M}^{\mathrm{N}}_{\odot}$ | 8.8 | 8.1 |
| $R_1/\mathcal{R}^{\mathrm{N}}_{\odot}$ | 13.6 | 10.4 |
| $R_2/\mathcal{R}^{\mathrm{N}}_{\odot}$ | 3.7 | 1.71 |
| $M_{\mathrm{bol}_1}$/mag | −8.28 | −7.69 |
| $M_{\mathrm{bol}_2}$/mag | −4.55 | −2.87 |
| $L_{\mathrm{R}_1}$ | 0.690 | 0.712 |
| $L_{\mathrm{R}_2}$ | 0.037 | 0.014 |
| $\log_{10} g_1$ | 3.50 | 3.70 |
| $\log_{10} g_2$ | 4.24 | 4.88 |
| $\chi^2_{\mathrm{N}}$ | 11.389 | 1.008 |

| Fixed param. | Values |
|---|---|
| $P$/d | 5.732436* |
| $\dot{\omega}/^{\circ}$ d$^{-1}$ | 0.004220* |
| $q = M_2/M_1$ | 0.41549** |
| $e$ | 0.07583** |
| $T_{\mathrm{eff}_1}$/K | 31401*** |
| $T_{\mathrm{eff}_2}$/K | 25442*** |
| $L_{\mathrm{R}_3}$ | 0.273*** |

* Mayer et al. (2010)
** from `KOREL`
*** from `PYTERPOL`

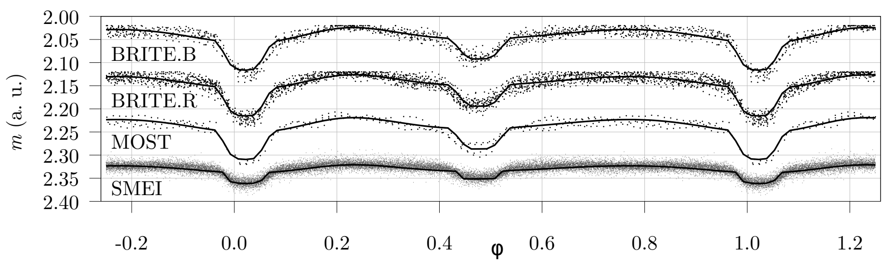


**Figure 2.** Fitted light curves (from the program `PHOEBE`)

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# High-contrast imaging of massive stars: the example of QZ Car

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**Abstract.** The formation of massive stars remains one of the most intriguing questions in astrophysics today. Several formation theories, that could potentially be tested by the multiplicity properties of their outcome, have been proposed. There are, however, observational challenges preventing us from discriminating between the different formation scenarios: massive stars are rare and found at relative large distances from us, they form on short timescales and evolve in multiple stellar systems within the gas-rich environment from which they are born. Taking advantage of the extreme-adaptive optics capabilities of VLT/SPHERE, we observed more than 70 galactic O stars, about half in the Carina nebula and another half in the galactic field or clusters and associations, aiming at characterizing their multiplicity properties. SPHERE offers unprecedented imaging contrasts which allows us to detect even the faintest companions around massive stars. Here, we illustrate its capabilities by focussing on the high-order multiple system QZ Car.

**Key words:** stars: massive – stars: binaries – stars: formation

## 1. Introduction

How do massive stars form? This is still one of the most important questions in astrophysics today (Tan et al., 2014). From the observational point of view, addressing this question implies facing the fact that massive stars are rare, thus are found at large distances from us, and the timescales of their formation processes are very short. In addition, massive stars are deeply embedded in the cloud of gas and dust they accrete from during their formation. Some of the main formation scenarios that have been proposed are core accretion, competitive accretion, and stellar collisions and merging (Bonnell et al., 1998; Tan et al., 2014). Although most theories agree on the existence of dense and massive accretion disks, which are unstable to fragmentation (Kratter et al., 2010) and may lead to the formation of companions, we lack quantitative model predictions. Finding correlations between multiplicity characteristics may help distinguishing among the different mechanisms of massive star-formation and guide the development of future theoretical models.

In this context, the binary fraction and multiplicity properties of massive stars have been studied by recent surveys, either through the spectroscopic analysis of young massive stellar clusters (Sana et al., 2012) and OB associations (Kiminki & Kobulnicky, 2012), or thanks to high-angular resolution observations of massive stars (Sana et al., 2014; Aldoretta et al., 2015). Among those, the VLT SMaSH+ survey (Sana et al., 2014) was the first survey to cover the gap between spectroscopic and classical-imaging observations. Combining optical interferometry (VLTI/PIONIER), aperture masking (NACO/SAM) and imaging (NACO), SMaSH+ searched for bright companions ($\Delta H < 4$) in the $0\farcs001$-$0\farcs2$ angular separation regime around a large sample of O-type stars, and fainter ($\Delta H < 8$) companions up to $8''$. The 260 companions found span the entire range of separations, including several faint stars at angular separations above $1''$. After correcting for contamination due to spurious alignment, SMaSH+ measured a multiplicity fraction of $f_{\rm m} = 0.91 \pm 0.03$, demonstrating that almost all massive stars form as part of a multiple stellar system. The high number of faint companions at large separations ($> 1''$), which could correspond to the outer edge of the accretion disk, may result either from fragmented clumps of the accretion disk, or from tidal capture. Probing the existence of such faint companions at closer separations is therefore crucial to understand their origin.

The Extreme AO high-contrast imaging capabilities of the VLT Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE), combined with dedicated image post-processing algorithms, now allow us to unveil the multiplicity properties of massive stars in a parameter space unexplored so far.

## 2. The CHIPS survey

The Carina High-contrast Imaging Project of massive Stars (CHIPS) aims to probe the multiplicity properties of 92 massive stars in the Carina star-forming region, in the $0\farcs15$-$5\farcs5$ angular separation range ($\sim$ 350-12,500 au) and down to mass-ratios of 0.03 (on the main sequence). So far, we have carried out SPHERE observations for half of the targets, allowing us to constrain the binary frequency in the separation range probed by SPHERE with a precision better than 7%. Here, we illustrate the capability of SPHERE by using the example of QZ Car.

### 2.1. QZ Car

QZ Car is a high-order multiple system, composed of two spectroscopic binaries (Aa & Ac), separated by $0\farcs030$, and other three previously imaged companions within $7''$ Ab, E & B (Sana et al., 2014; Sanchez-Bermudez et al., 2017).

We observed QZ Car in October 2016 in IRDIFS-EXT mode, which combines the Integral Field Spectrograph and the Infra-Red Dual-beam Imaging and Spectroscopy sub-systems. Such observations enabled us to combine the smaller IFS field-of-view ( f.o.v.), probing the close-environment of the star, with IRDIS images that provide information on the local density of faint objects. The observations were conducted in pupil tracking mode, to allow for both Angular (ADI) and Spectral (SDI) Differential Imaging techniques, to disentangle the signal of potential companions from the background noise. After obtaining the reduced (centered, flat fielded, background subtracted) data from the SPHERE data center, we used the Vortex Image Processing package (VIP, Gomez Gonzalez et al., 2017) to apply Principle Component Analysis (PCA). Figure 1 shows the final PCA images for IFS and IRDIS. In total we detected 19 sources with a signal to noise ratio greater than 5, including the previously known stars Ab and E, as well as a new companion in the IFS f.o.v., Ad. Although most of the distant and faint sources have high spurious association probabilities (see Rainot et al., submitted), Ab, E, and Ad are all likely bound companions. We extracted the IFS spectrum for Ad and for the central star spectral channel by spectral channel, by adopting a Simplex Nelder-Mead optimization and a Markov-Chain-Monte-Carlo (MCMC). As a YJH flux calibrated spectrum of the central star was not available to flux calibrate the measured spectrum for Ad, we modelled the four components of QZ Car separately using the non-Local Thermodynamic Equilibrium atmosphere code FASTWIND (Puls et al., 2005). We then compared the flux calibrated spectrum for Ad with model spectral energy distributions from the ATLAS9 LTE atmosphere models (Castelli & Kurucz, 2004) and the pre-main sequence evolutionary tracks of Siess et al. (2000). We obtain the best agreement for a 2.2 $M_\odot$ star with $T_{\rm eff}$ = 9700 K, $L = 25.5$ $L_\odot$ and $R = 1.77$ $R_\odot$, corresponding to a spectral type A0. According to Siess et al. (2000) evolutionary tracks, its estimated age is 7.7 Myr, in fair agreement with the estimates for QZ Car (Walker et al., 2017).

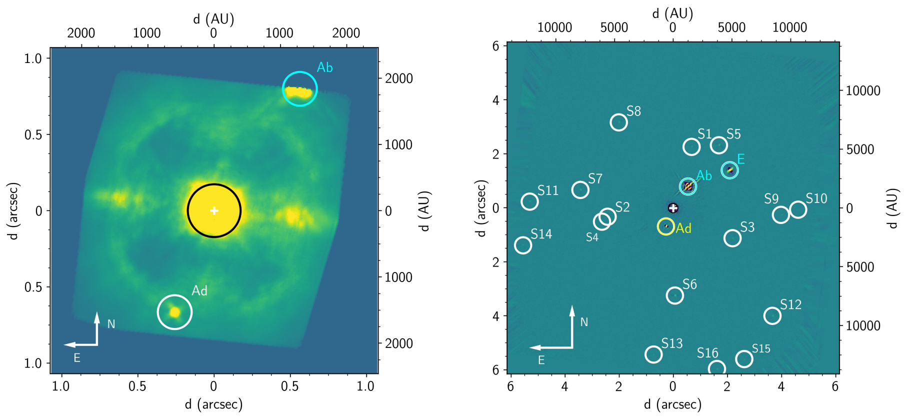


**Figure 1.** Final PCA images for IFS (left) and IRDIS (right; Rainot et al., submitted).

## 3. Conclusions and future prospects

We have presented here the first SPHERE observations of QZ Car, a known quadruple system in the Carina region, as part of a survey aiming to characterize the multiplicity properties of O stars in the Carina region. Combining SPHERE IFS and IRDIS observations, we detected 19 sources in a $12'' \times 12''$ f.o.v., 17 of which are new detections. Although most of the them can be explained by spurious alignment given the stellar density around QZ Car; Ad, Ab, and E are likely physical companions. They are consistent with ages between 4-8 Myr, suggesting that they are coeval with the inner quadruple system. If all three stars are confirmed as bound by proper motion follow-up observations, QZ Car may become one of the highest-order multiple systems known.

Besides 42 stars in the Carina region, we collected SPHERE observations for 15 stars in the the Sco OB association and for a dozen targets from the SMaSH+ catalog. The characterization of all companions in the $0\farcs1$-$1''$separation regime will soon enable us to compare the multiplicity properties of massive binaries in different environments, as a function of angular separation, cluster age, or environment density.

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# First Doppler imaging of the RS CVn binary FF UMa

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**Abstract.** We present the first Doppler Imaging (DI) study of the chromospherically active RS CVn binary FF Ursae Majoris. New mid-resolution ($R \sim 13500$) time series spectral data were acquired using the echelle spectrograph attached to the 0.4-m Kreiken Telescope at the Ankara University Kreiken Observatory. We applied a spectral subtraction technique to the $H_\alpha$ line to reveal the phase behavior of the chromospheric activity of the system. The results derived from DI and spectral subtraction analyses show that both components exhibit photospheric and chromospheric activity. The time series spectral data also enable us to obtain the most recent radial velocity curve of the system and re-determine the physical parameters.

**Key words:** stars: activity  stars: imaging

## 1. Introduction

Understanding the underlying astropyhsical processes of magnetic activity in binary stars is complicated, especially due to tidal interactions that significantly affect the mechanisms responsible for stellar activity. In this context, RS CVn-type binaries are crucial laboratories to reveal the effects of tidal interaction, for instance, surface differential rotation (Kővári et al., 2017). Among the methods used to investigate stellar magnetic activity, Doppler imaging (DI) is a powerful and widely used technique that allows us to obtain stellar spot distributions by means of spot filling factors or temperature maps. Signal enhancing techniques like LSD (Donati et al., 1997) provide a higher SNR of spectral lines and hence more precise surface maps, even with the lower resolution. In this study, we performed the first DI study of the RS CVn-type binary FF UMa and we used the spectral synthesis method to investigate the activity nature of both components of the system. We also obtained the most recent orbital parameters of FF UMa with the help of the radial velocity analysis of the spectral data.

The activity nature of FF UMa was first identified by Pounds et al. (1993) using the ROSAT Wide Field Camera all-sky survey. Several studies concerning the system in the literature (Jeffries et al., 1995; Henry et al., 1995; Fekel, 1997; Strassmeier et al., 2000; Griffin, 2012) investigate determinations of orbital parameters, $v \sin i$, spectral types, as well as estimates of masses and radii, since there is no information on the orbital inclination due to the non-eclipsing geometry of the system. The most detailed activity-related study of FF UMa was performed by Gálvez et al. (2007), who carried out an extensive study of the optical indicators of chromospheric activity, revealing that both components are quite active. They also found a remarkable orbital period variation that is attributed to the presence of magnetic activity. Another detailed study by Strassmeier et al. (2012) with high-precision photometry and spectroscopy clearly showed that both components are subgiants showing significant amounts of activity. The above results from the literature together with a lack of any DI study of the RS CVn-type binary FF UMa in the literature led us to investigate the system.

## 2. Observations and data reduction

We observed the system spectroscopically using the mid-resolution echelle spectrograph attached to the 0.4 m Kreiken Telescope at the Ankara University Kreiken Observatory. The average resolution of the spectrograph is $R \sim 13500$ and the wavelength range is between 4340 and 7400 Å. We gathered 17 spectra within 4 months of observing run, with an exposure time of 3600 seconds and a signal-to-noise ratio (SNR) between 43 and 76. The current spectral resolution together with the average $v \sin i$ values gave us a spot resolution of $\sim 27°$. We also observed standard stars HD 161053 (K7∼III), HD 158332 (K1∼IV) and HD 182488 (K0∼V) that are required by both the spectral synthesis method and the DI analysis to represent spotted and unspotted photospheres. We used the AudeLA software (Klotz et al., 2012) for data reduction and wavelength calibration and performed normalization using our own code that is developed in Python.

## 3. Analysis

### 3.1. Radial velocities and radii

We used the profiles obtained using the LSD technique by Donati et al. (1997) to determine the radial velocity data points. In this context, with the help of a Python code, we generate synthetic models and adjust the width, depth and the center of the rotational profile using the the nonlinear least-squares minimization Python package `lmfit` (Newville et al., 2018). The SNR values of the profiles obtained using $\sim 2800$ lines are between 843 and 1094. We used the `rvfit` code by Iglesias-Marzoa et al. (2015) to determine the orbital parameters and found $q = M_2/M_1 = 0.4587 \pm 0.0076$, $K_1 = 29.217 \pm 0.442$ km/s, $V_\gamma = -2.97 \pm 0.27$ km/s, $T_0(\text{HJD}) = 2454067.01947 \pm 0.001689$ and $P = 3.27487 \pm 0.00004$ d. The rv fits are shown in the left panel of Fig. 1. Since there is no (or negligible) eclipse due to the low orbital inclination of the system, the absolute parameters are limited by $\sin i$. In addition to the orbital inclination, the determination of the radii is also crucial for the DI analysis. Therefore, with the help of the $T_{\rm eff}$-$\log g$ parameters of the components obtained by Strassmeier et al. (2012), we used pre-main-sequence PARSEC isochrones (Bressan et al., 2012) to determine radii upper and lower limits by considering the uncertainties of the $T_{\rm eff}$ and $\log g$ parameters given by Strassmeier et al. (2012). We obtained the radii of primary and secondary components as $R_1 = 2.65 \pm 0.79\,R_\odot$ and $R_2 = 2.17 \pm 0.85\,R_\odot$, respectively. The isochrones as well as the locations of the components of the system are shown in the right panel of Fig. 1.

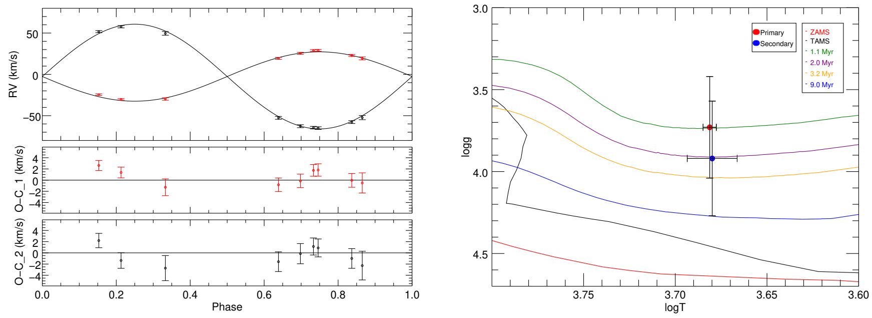


**Figure 1.** Left panel: RV curve of FF UMa. The red and black open circles represent the RV data of the primary and secondary components, respectively, while the solid black line represents the RV fit to the data. Right panel: Locations of primary and secondary components of FF UMa in a gravity-temperature diagram.

### 3.2. Doppler imaging and chromospheric activity

In order to Doppler image both components of FF UMa, we used the DI code `DoTS` by Collier Cameron (1997), which performs surface reconstruction by means of spot filling factors based on a two-temperature model using the Maximum Entropy Method (MEM). It is also possible to fine-tune and/or obtain some astrophysical parameters using the `DoTS` code with the help of a grid search depending on the chi-square minimization. In this context, we performed a multi-dimensional grid search by adjusting the orbital inclination ($i$), radii ($R_{1,2}$) and LSD line strengths of both components ($EW_{1,2}$). From the grid search, we obtained an orbital inclination of $i = 50\overset{\circ}{.}5$, and radii $R_1 = 2.95\,R_\odot$ and $R_2 = 2.30\,R_\odot$. The resultant surface reconstructions of both components as Mercator projections are given in Fig. 2.

To study the chromospheric activity behavior of FF UMa and search for a possible correlation with the photospheric activity, we applied the spectral subtraction technique using the $H_\alpha$ line to look for the equivalent width (EQW) variation along with the orbital phase. We used HD 158332 as non-active stan-

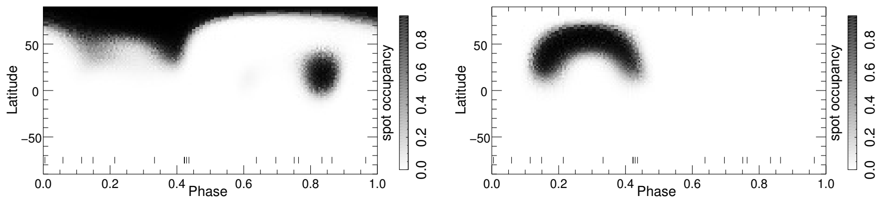


**Figure 2.** The Mercator projections of the primary (left panel) and the secondary (right panel) components of FF UMa.

dard star and obtained the EQW values using Gaussian fits, and finally plot them versus orbital phase as shown in Fig. 3. As seen from the right panel of Fig. 3, there are two inconsistent points showing high EQW values that may be a consequence of a flare phase (pre- or post-flare). In order to investigate that inconsistency we also looked at the He I D3 line but due to the low SNR and resolution, we could not clearly distinguish if this line is in emission or not.

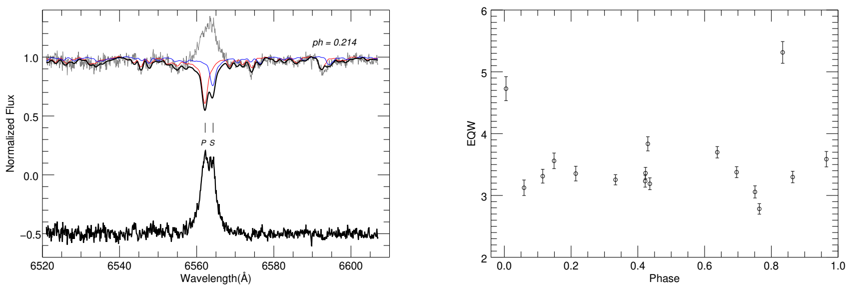


**Figure 3.** The spectral subtraction of the $H_\alpha$ line at phase 0.214 (left panel). The grey solid line represents the normalized spectrum of FF UMa. The red and blue solid lines show the spectra of the primary and secondary components, respectively, while the black solid line represents the total flux. The EQW variation of the system throughout the orbital phase with $3\sigma$ errors is shown in the right panel.

## 4. Discussion and conclusion

We performed the first Doppler imaging of the RS CVn type binary FF UMa and revealed that both components have high latitude spots, while the primary has a low-to-mid spot feature at around phase 0.8 (see Fig. 2). As also clear from Fig. 2, the spot feature on the secondary is predominant between phases

0.1 and 0.45, approximately. We also determined the orbital parameters with the help of the radial velocity curve analysis. The results are consistent with those obtained in the literature.

It is also possible to generate synthetic light curves using the resultant DI map with the code `DoTS`, which allows us to compare the photospheric and chromospheric behavior of the system. In this context, we generated a $V$-band light curve using the surface reconstructions of both components. After removing two inconsistent points that may be the consequence of a possible flare event, we compared the variation of EQW and the synthetic light curve with the orbital phase as shown in Fig. 4. The similarity between the equivalent width and flux

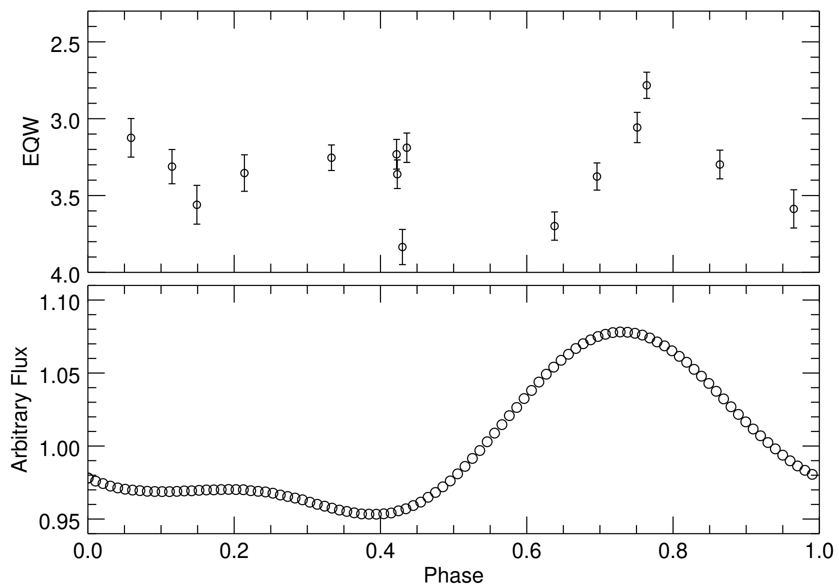


**Figure 4.** A comparison of EQW variation of the $H_\alpha$ line and the sysnthetic light curve obtained from surface reconstructions of both components of FF UMa.

variations is clear from Fig. 4, as the highest flux in the synthetic light curve corresponds to the lowest equivalent width. The overall variations also show similarities. This results also showed that the surface maps obtained in this study are reliable even for the mid-resolution spectral data. The light curve of the system observed by Strassmeier et al. (2012) is also quite similar to that obtained in this study from DI maps, which again shows the reliability of spot distributions from DI. That similarity may also be a consequence of long-lived polar spots. Frequent monitoring with higher resolution spectroscopy as well as photometry would enlighten the activity nature of this interesting system.

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# Search for invisible satellites in eclipsing binary systems using photometric methods

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**Abstract.** We discuss small anomalies in the multicolour photometric light curves (LCs) of eclipsing binary stars which may indicate the presence of additional satellites in the systems.

## 1. Introduction

When investigating detached eclipsing binaries we often find that the systems are multiple. The periodic LIght Time Effect (LITE) in Eclipse Timing Variation (ETV) diagrams directly indicates the multiplicity of the system. Usually however, one needs to observe the system for a long time before the LITE reveals itself in an ETV diagram. In the short term, certain LC features may indicate the presence of a third body. They are:

1. Colour indices during eclipses show anomalies;
2. LC solutions show a large amount of third light;
3. System models based on LCs show inconsistencies with theoretical predictions.

Next we illustrate the above with examples.

## 2. Unusual colour index behavior in minima and extra light

V577 Oph was the first system in our observational program (Volkov & Volkova, 2009) that showed colour index anomalies in the minima, see Volkov (1990) and Fig. 1. We continued our observations and found that extra red light in the minima belongs to a third red companion orbiting the eclipsing star with a period of 20 years (Volkov & Volkova, 2010), see Fig. 1.

RW CrA and DX Vel are other eclipsing binaries demonstrating the presence of third light, not only indicated by colour index anomalies during eclipses, see

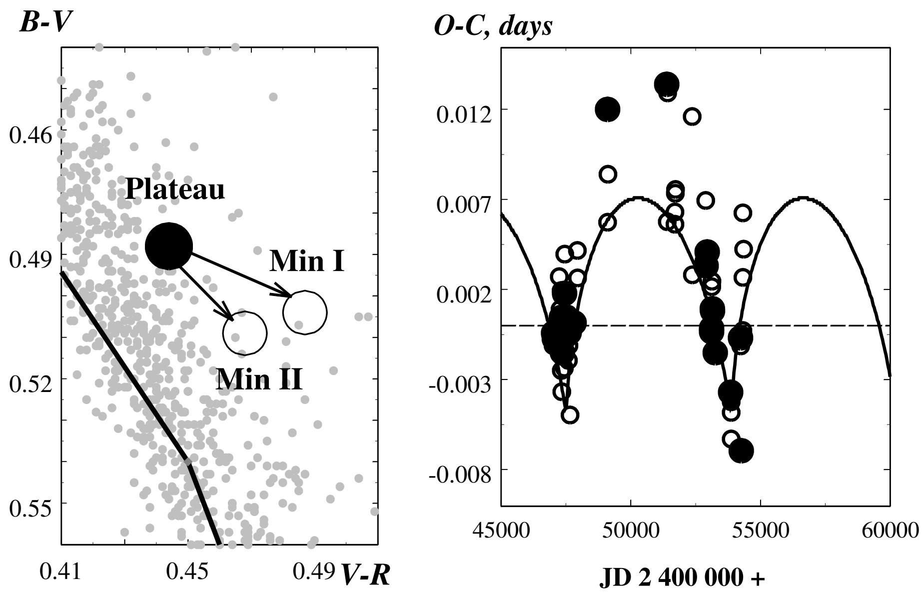


**Figure 1.** Left panel: V577 Oph in a $(B-V)$, $(V-R)$ diagram. The solid line is the standard main sequence from Straižys (1992). The grey points represent observations in the $WBVR$ system for stars in the Kornilov et al. (1991) catalogue. The filled circle marks the colour index of the combined light for V577 Oph. Open circles indicate colour indices in the minima. The right panel shows the ETV diagram of V577 Oph based on 20 years of observations, which strongly supports the idea of multiplicity of the system. Solid circles – LITE in eclipse timings; open circles – LITE in $\delta$ Sct pulsations of the main component.

Fig. 2 and Fig. 3, but also from their LC solutions. To fit the observations one needs to include large amounts of third light – 20 and 40 percent, respectively. Continuing the observations we found that these systems are multiple (Volkov et al., 2017), see the ETV diagrams in Fig. 2 and Fig. 3.

## 3. Model discrepancies

EQ Boo is a well known visual double system. One of the components is an eclipsing variable at a separation of $0\rlap{.}''9$, so we observe only the combined light of the triple system. Our first solution of the LC has shown discrepancies in the

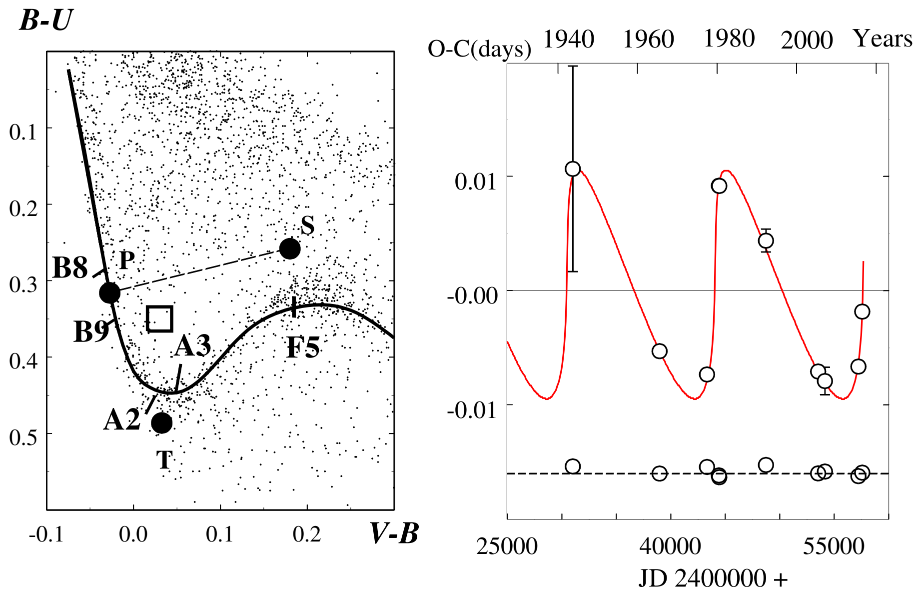


**Figure 2.** Left panel: RW CrA in a $(B-U)_W$, $(V-B)_W$ diagram. The solid line is the normal colour index sequence from Walraven & Walraven (1977). The points represent observations in the Walraven system from the Nitschelm & Mermilliod (1990) catalogue. The open square marks the colour index of the combined light. Observed indices of the primary (P) and secondary (S) components are designated by full circles. We see that the combined light does not lie on the line connecting the individual components, which indicates the presence of third light – (T). Right panel: the LITE in minima timings of RW CrA.

ages of the components (Volkov et al., 2011), see Fig. 4. The visual component should have a higher temperature and lower age than indicated by the LC solution. So we surmise the existence of one more dim red star in the system (Volkov et al., 2012). After decades of observations we found a small amplitude LITE in the ETV diagram of the system with a period of 5.62 years, see the right panel of Fig. 4, which we declare here for the first time. One should continue the observations of the system in order to correct this value.

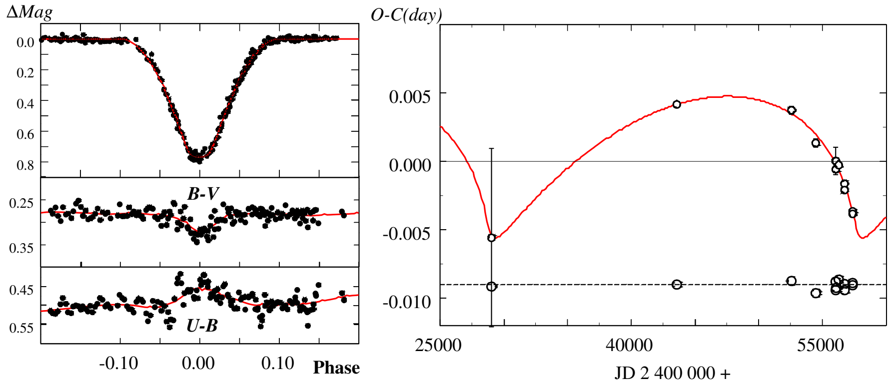


**Figure 3.** Left upper panel: DX Vel observations in primary minimum. Left bottom panels: the corresponding colour indices $B - V$ and $U - B$. Right panel: the LITE in minima timings of DX Vel.

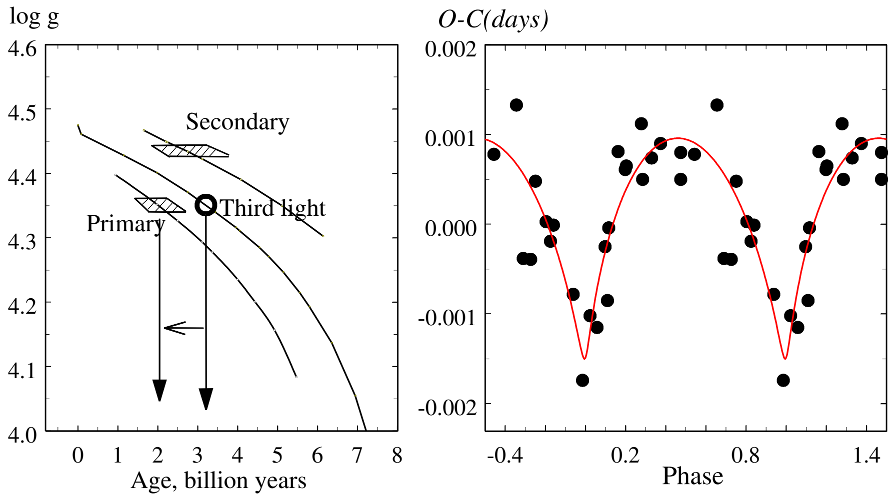


**Figure 4.** Left panel – the evolutionary tracks for stars with the same parameters as the EQ Boo components. If we suppose that all of the third light belongs to a single star we obtain a discrepancy in age with the primary component. Right panel – the ETV diagram for EQ Boo. A possible solution with a fourth body is shown with the red line.

## 4. Conclusions

The suggested LC features and LC solutions which can be found during the early stages of an eclipsing variable investigation may indicate the presence of invisible satellites in the system. Additional systems from our observational program such as V961 Cep (Volkov et al., 2010) and V491 Vul (a visual double similar to EQ Boo) require significant amounts of third light in their LC solutions. We expect that they will also be multiple star systems.

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# Quadruple systems with two eclipsing binaries

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**Abstract.** Bound pairs of eclipsing binaries have been studied for the last 10 years as parts of more complex multiple systems. We present new findings on these somewhat neglected objects, as well as motivation for their study. Detection methods, parameter distributions, resonances, and interesting sky distributions are discussed.
**Key words:** stars: binaries: eclipsing – stars: fundamental parameters

## 1. Introduction

Doubly eclipsing systems, i.e. 2+2 quadruples with two eclipsing binaries, are still rather overlooked and attract no special attention. However, as we have shown in Zasche et al. (2019), several aspects make these objects worthy of study.

Their occurrence in stellar populations is much higher than anticipated, so we should be able to identify many more. A huge majority are real quadruples, as opposed to pairs of doubles projected into the same direction, and we should be able to measure relative component motions. They also can be used to complete the statistics of 2+2 quadruples, which are still very incomplete. Finally, the 3:2 resonance in 2+2 systems seems the most prominent one, a result not noticed prior to analysis of our large compilation of doubly eclipsing stars. These resonances should play an important role in multiple-star system formation and evolution.

## 2. Why study 2+2 quadruples?

Several justifications for a special focus on 2+2 quadruples can motivate analysts and observers and underscore the importance of knowledge about star formation, evolution, dynamics, and the Universe.

### 2.1. Under-occurance in the northern hemisphere

Due to reduced numbers of doubly eclipsing systems in the northern sky (see Fig. 1), our analysis led to a suspicion that undiscovered northern examples exist, available for observers with smaller-size telescopes. Possibly surveys like *TESS* can observe enough data points for particular objects to measure both periods. However, a significant number were discovered by chance in the northern sky, where no systematic search was done, by amateur astronomers (typically monitoring other targets in the same field). See Zasche et al. (2019) for a list. Therefore, we propose a special attention to northern doubly eclipsing systems, possibly to initiate a focused search.

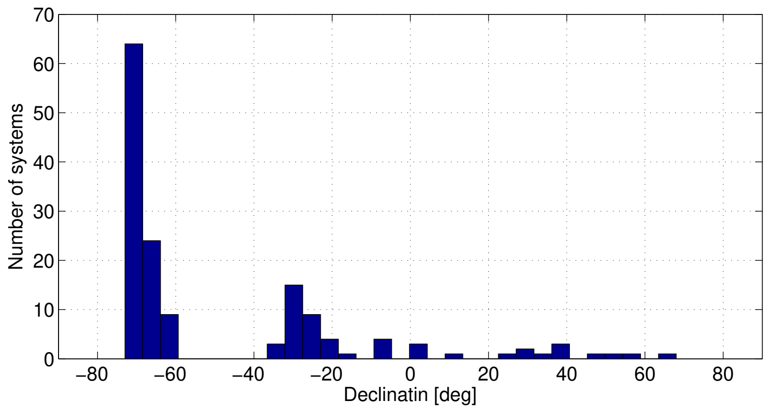


**Figure 1.** Distribution of currently known doubly eclipsing systems on the sky with respect to their declination. Southern peaks (mostly due to the OGLE surveys) are clearly visible.

## 2.2. Long term monitoring

We also call for long-term photometric monitoring of these systems. This should be quite easy for observers with relatively small telescopes. Our request for these observations follows from the period of the two doubles around their barycenter being typically of the order of several years to decades. Hence, collecting only times of eclipses would be very fruitful for deriving the large orbit. Some photometric surveys are doing well, but their cadency and time span are not always suitable for these studies.

## 2.3. More detailed view missing

A huge majority of doubly eclipsing systems lack detailed analysis. Most were only discovered as showing two distinctive periods, but light curve analysis of both pairs is typically missing. In-depth analyses of light curves and radial velocities, with some attempt to study the eclipse timing variations (hereafter

ETV) signals, were done only for several systems such as V994 Her, V482 Per, 1SWASP J093010.78+533859.5, and a few stars from the *Kepler* and *Corot* fields. Such analysis is missing for the others and urgently needed for subsequent analysis as a quadruple, to obtain physical parameters of all four components and their orbits. Unfortunately, most are rather faint for obtaining their spectra with smaller telescopes.

## 2.4. Distribution of periods

The ratio of the two eclipsing periods shows a remarkable tendency. As in our paper (Zasche et al., 2019), a peak near a ratio of 1.5 corresponds to the 3:2 mean motion resonance (see Fig. 2). A much less significant excess close to ratio 2.5 is also visible, as well as a dearth of systems close to 2:1 resonance. It is still not very clear why a peak at 3:2 resonance is present even where the respective orbital periods are of the order of a decade or even more, where dynamical interaction of the two pairs should be very weak. Detailed modelling of formation and subsequent orbital evolutionary scenarios should be done to reveal true origins. A theory for these resonant systems is still missing, although a first attempt in this respect was a publication on 1:1 mean motion resonance by Breiter & Vokrouhlický (2018), but with a strict limitation to planar configurations. In some respects this treatment resembles a distribution of periods in exoplanetary systems, as pointed out e.g. by Quinn et al. (2019).

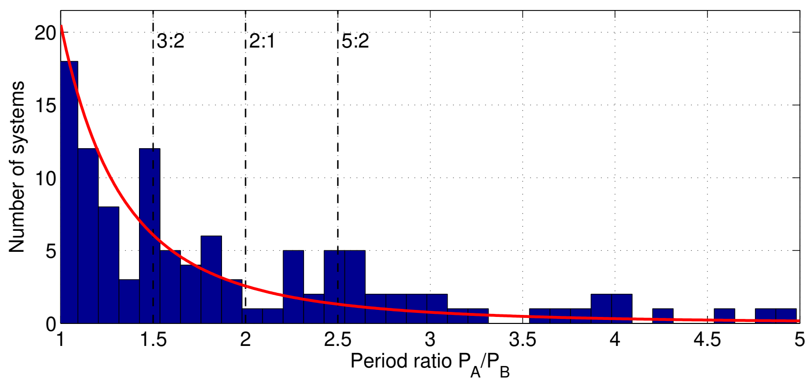


**Figure 2.** Distribution of period ratios of known doubly eclipsing systems.

## 3. Detection prospects and limitations

Selection effects influence our parameter statistics. For example, doubly eclipsing systems composed of equal mass pairs (i.e. $M_{\mathrm{Pair\ B}}/M_{\mathrm{Pair\ A}}$ close to 1) are preferentially discovered since, with very incomparable pairs, the dominant one causes the the other pair's eclipses to be very shallow and hardly detectable. For example, the doubly eclipsing system KIC 4247791 (or KOI-28, see Lehmann et al. 2012), with its rather shallow eclipses of Pair B, would probably be missed with our detection limits. The inclinations of the inner pairs can cause a similar effect. On the other hand, the inclination of the outer orbit can cause the amplitude of ETV to increase and decrease as this angle is changed from coplanar orientation. Also the limitations of the orbital periods (of inner as well as outer orbits) play an important role in analysis. However, the latter can be changed with dedicated observations of better precision (hence detecting also shallower eclipses) and increased time span (hence convincingly detecting longer outer orbit periods over 2 decades, which was our principal limitation with OGLE data).

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# Photometric observations of an extreme mass ratio overcontact binary

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**Abstract.** Our $R_C$ and $I_C$ light curves of CSS J135012.1+272259 were analyzed with the Wilson-Devinney (W-D) program. The results reveal that CSS J135012.1+272259 is an extreme mass ratio overcontact binary with mass ratio $q = 0.147$. It may be in the final evolutionary stage of cool short-period binaries and merge into a single rapid-rotation star to form a blue straggler or FK Com type star. Also, 25 extreme mass ratio overcontact binary systems ($q \leq 0.15$) are collected for long-term monitoring. These targets will improve understanding of the pre-outburst state of overcontact binaries and enrich knowledge of the merger mechanism.

**Key words:** binaries: eclipsing – binaries: photometry – light curves – stellar mergers

## 1. Introduction

Stellar mergers are estimated to be common events in the Galaxy. Theoretical models predict that an overcontact (OC) binary system will merge when its mass ratio reaches $q \approx 0.07 - 0.09$ (Arbutina, 2012). Only a handful of these transients have been noted in the Milky Way: V4332 Sgr (Hayashi et al., 1994), V838 Mon (Brown et al., 2002), V1309 Sco (Nakano et al., 2008), and OGLE-2002-BLG-360 (Tylenda et al., 2013). The red nova V1309 Sco is the best studied stellar merger case to date. The discovery of V1309 Sco (Nova Scorpii 2008) and the fact that its progenitor is an extreme mass ratio OC system with a rapidly decreasing orbital period triggered our interest on extreme mass ratio OC systems. Photometric and spectrometric data on OC binaries have been accumulating rapidly over the past few decades, owing to large sky survey projects such as the Optical Gravitational Lensing Experiment (Rucinski, 1997), the All Sky Automated Survey (Jayasinghe et al., 2019), the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (Qian et al., 2019) and the *Gaia* mission (Gaia Collaboration et al., 2016). Also, many extreme mass ratio OC systems or potential stellar merger candidates have been reported.

## 2. Photometric investigations of CSS J135012.1+272259

CSS J135012.1+272259 is a short period OC system. $R_C$ and $I_C$ light curves were obtained on March 8th, 2018 with the 2.4-m telescope at Thai National Observatory, National Astronomical Research Institute of Thailand (Soonthornthum, 2018). The ephemeris is:

$$\mathrm{Min.I(HJD)} = 2458186.4009 + 0.232465 \times E. \tag{1}$$

The effective temperature is 6137 K, as given by the LAMOST survey. The Wilson-Devinney program (Wilson & Devinney, 1971; Van Hamme & Wilson, 2007; Wilson & Van Hamme, 2014) of version 2013 was applied to model the light curves, with solutions in Table 1. A q-search diagram and light curves are in Fig. 1.

**Table 1.** CSS J135012.1+272259 Phorometric Solutions

| Parameters | Values without $l_3$ | Values with $l_3$ |
|---|---|---|
| $T_1(K)$ | 6137(fixed) | 6137(fixed) |
| q $(M_2/M_1)$ | 0.114(±0.004) | 0.147(±0.011) |
| $i(^\circ)$ | 75.9(±1.3) | 79.1(±1.6) |
| $\Omega_1 = \Omega_2$ | 1.98(±0.01) | 2.06(±0.03) |
| $T_2(K)$ | 5838(±43) | 5891(±55) |
| $\Delta T(K)$ | 299 | 246 |
| $T_2/T_1$ | 0.951(±0.007) | 0.960(±0.009) |
| $L_1/(L_1+L_2)$ $(R_c)$ | 0.8931(±0.0004) | 0.863(±0.009) |
| $L_1/(L_1+L_2)$ $(I_c)$ | 0.8905(±0.0004) | 0.860(±0.009) |
| $L_1/(L_1+L_2+L_3)$ $(R_c)$ | | 0.705(±0.036) |
| $L_1/(L_1+L_2+L_3)$ $(I_c)$ | | 0.702(±0.038) |
| $L_3/(L_1+L_2+L_3)$ $(R_c)$ | | 0.183(±0.039) |
| $L_3/(L_1+L_2+L_3)$ $(I_c)$ | | 0.184(±0.041) |
| $r_1(pole)$ | 0.530(±0.003) | 0.518(±0.005) |
| $r_1(side)$ | 0.590(±0.005) | 0.572(±0.008) |
| $r_1(back)$ | 0.610(±0.005) | 0.596(±0.008) |
| $r_2(pole)$ | 0.202(±0.015) | 0.223(±0.032) |
| $r_2(side)$ | 0.211(±0.018) | 0.234(±0.039) |
| $r_2(back)$ | 0.247(±0.040) | 0.278(±0.092) |
| $f$ | 18.6 %(±20.1 %) | 34.0 %(±30.8 %) |
| $\Sigma\omega(O-C)^2$ | 0.0051 | 0.0045 |

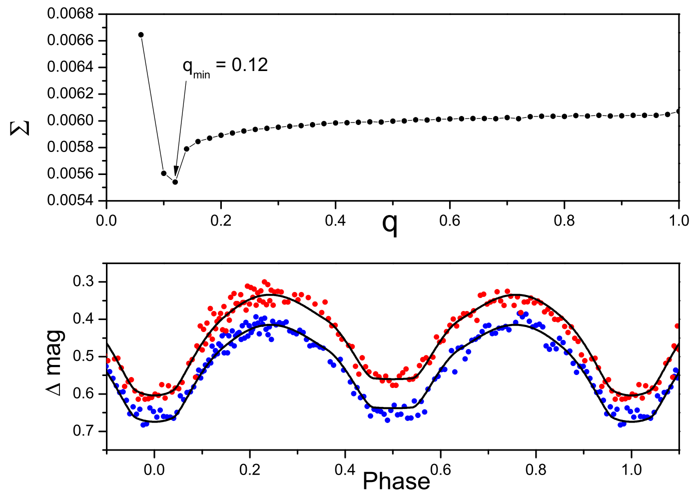


**Figure 1.** In the upper panel, the minimum mass ratio is determined to be $q_{min} = 0.12$ with the q-search method. In the lower panel, the red and blue circles are $R_C$ and $I_C$ light curves, respectively. The black lines are theoretical light curves.

## 3. Discussion and conclusions

Photometric solutions show that CSS J135012.1+272259 is an A-subtype extreme mass ratio OC binary with mass ratio $q = 0.147$ that is predicted to merge and make a blue straggler or FK Com type star in the center (Tylenda et al., 2011; Ferreira et al., 2019). A-type is a sub-type of the W UMa's, and the W UMa's are a sub-type of the OCs (Binnendijk, 1970). More observations of extreme mass ratio OC systems are needed since only a few stellar merger events have been reported and there are some discrepancies between observed features and theoretical models. Thus, 25 targets with mass ratio $q \leq 0.15$ have been collected: V857 Her, ASAS J083241+2332.4, SX Crv, V53 (a member of the Globular Cluster M4), AW UMa, ZZ Ps, V870 Ara, AW CrB, DN Boo, ASAS J082243+1927, V1191 Cyg, CK Boo, GR Vir, FG Hya, AL Lep, V776 Cas, V345 Gem, V410 Aur, V710 Mon, DZ Psc, HV Aqr, CSS J135012.1+272259, XY LMi, EM Psc, and TYC 4157-683-1. All of these targets will be monitored long-term.

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# A new spectroscopic and eclipsing binary BD -20 4369

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**Abstract.** Absolute physical and geometrical parameters of the system are derived. BD -20 4369 is a strongly evolved stellar system after the first mass exchange.

**Key words:** stars: individual: BD -20 4369 – stars: eclipsing binaries – methods: observational – techniques: spectroscopy, photometry

## 1. Introduction

BD -20 4369 was found to be an Algol-type eclipsing binary from the 2007 *MOST* photometry (see Pribulla et al., 2010). Due to its southern location it is rather difficult to obtain precise photometrical data from the northern hemisphere. The shallow secondary minimum occurs at phase 0.5 indicating a circular orbit for this detached binary. BD -20 4369 was observed by the ASAS program, but was not identified as a variable.

## 2. Observations and data reduction

Photometric observations were made during 2015-2019 in Simeiz Observatory of INASAN on Mt. Koshka (Crimea). We used a FLI PL09000 CCD camera with a $BVRcIc$ filter set mounted on a 1-m reflector, and a VersArray512UV with $UBVRIRc$ filters on a 60-cm telescope. We analyzed the photometric data using the methods described in our earlier work (Volkov & Volkova, 2009; Volkov et al., 2017).

High-resolution echelle spectra were obtained at the LCO observatory in Chile during 2008. Spectra were analyzed using the broadening-function technique developed by Rucinski (1992). The radial velocity curve is presented in Fig. 1.

Here we present the analysis of our $V$ observations combined with the radial velocity curve. Observations in other bands are not completed yet and should be continued in the future.

The light curve in $V$ phased with the ephemeris

$$\mathrm{HJD(Min)} = 2453321.01010(5) + 3.099035(1) \times E \quad (1)$$

is presented in Fig. 1. The best solution for the photometric $V$ observations was found for a very large level of third light, $L_3 = 0.55$. This fact should be explained by future investigations as we did not find the lines of the third component in our spectra. The values of the derived parameters of the system are presented in Table 1. The obtained photometric parallax is close enough to the *GAIA* value $\pi = 0\farcs0055(2)$. BD -20 4369 is a strongly evolved stellar system after the first mass exchange.

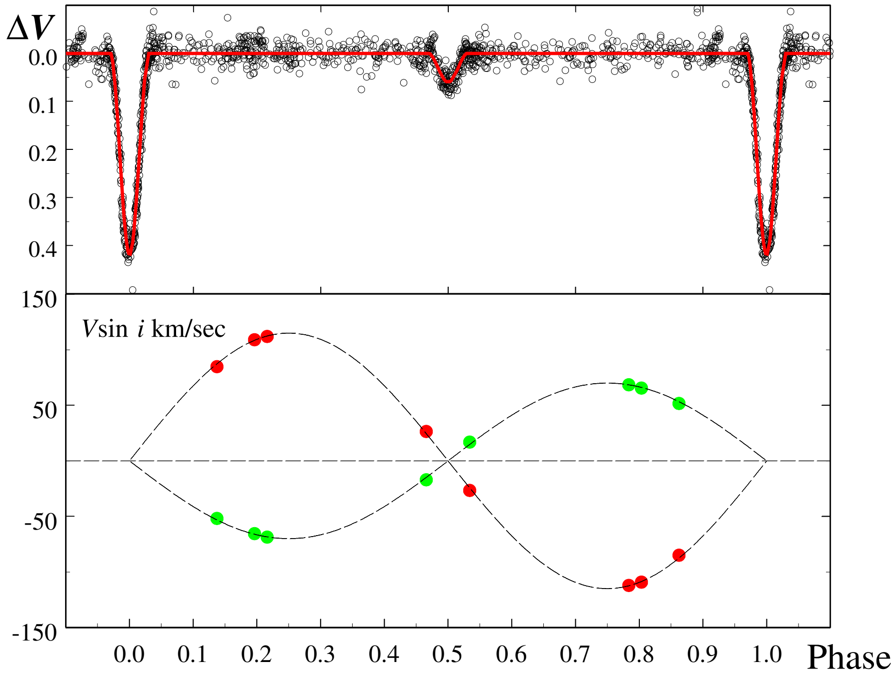


**Figure 1.** Upper panel: Light curve in $V$ of BD -20 4369, with the red line representing the model. Lower panel - the radial velocities curve, $V_\gamma$=-21.1±0.2 km/s been moved to the zero point.

**Table 1.** The parameters of the BD -20 4369 system

| Parameter | Primary | Secondary |
|---|---|---|
| $K$ [km s$^{-1}$] | 70 ±1.5 | 115 ±1.4 |
| $M/M_\odot$ | 1.27 ±0.02 | 0.80 ±0.015 |
| $R/R_\odot$ | 0.83 ±0.03 | 1.38 ±0.04 |
| $\log g$ | 4.71 ±0.02 | 4.04 ±0.02 |
| $T$ [K] | 6600 ±100 | 4770 ±80 |
| $E(B-V)$ | 0.20 ±0.04 | |
| Inclination, $i$ [°] | 87.6 ±0.1 | |
| Semi-major axis, $a$ [$R_\odot$] | 11.3 ± 0.2 | |
| Parallax, $\pi$ [″] | 0.0057 ± 0.0004 | |

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# About the dependency of the spin maxima on orbital phase in the intermediate polar MU Cam

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**Abstract.** Long term monitoring of intermediate polars is performed as part of the Inter-Longitude Astronomy campaign. High-quality and long time series observations allow us to investigate fine effects on complex light curves. In the case of MU Cam we have investigated the periodic modulation of the spin phases with the orbital phase. This dependency was already described by Kim et al. (2005). As an explanation they proposed inhomogeneous accretion flow from the secondary. However, based on our new data, we propose as a simple explanation the influence of orbital sidebands in the periodic signal produced by the intermediate polar. This explanation is supported by the fact that the changes in spin maxima phase are observed mainly when the sideband frequency is dominant in the periodogram.

**Key words:** stars: individual: MU Cam – stars: novae, cataclysmic variables – accretion, accretion discs

## 1. Observations and data analysis

MU Cam (1RXS J062518.2+733433) was classified as an intermediate polar by Staude et al. (2003) and Araujo-Betancor et al. (2003). They determined spin and orbital periods of the system.

Our observations of MU Cam were taken as part of the Inter-Longitude Astronomy Campaign (Andronov et al., 2003). The goal of the campaign is the monitoring of selected intermediate polars for spin period changes. In this work we analyze data from the Astronomical Observatory on Kolonica Saddle and from M.R. Štefanik Observatory in Hlohovec. We used the Vihorlat National Telescope VNT 1000/9000 mm and Cassegrain 600/2500 mm. Ensemble photometry was performed using C-Munipack, CoLiTecVS (Kudzej et al., 2019) and MCV (Kim et al., 2004) software packages.

We have constructed the O-C diagram of spin pulse maxima based on the ephemeris $BJD_{max} = 2452682.4181 + 0.01374116815 \times E$. Residuals from the quadratic fit $BJD_{max} = 2452682.4181 + 0.0137412342412802 \times E - 1.52 \times 10^{-12} \times E^2$ show unexpected scatter. As a possible source of these deviations we have investigated the dependency of spin maxima timings on orbital phase.

Mean spin maxima were determined for 10 phase intervals: 0.0-0.1; 0.1-0.2, etc. Only long time series were used to achieve higher precision. The amplitude and shape are changing, but there is no unambiguous dependency on orbital phase.

Periodogram analysis reveals two correlations:

1. High amplitude O-C variations of spin maxima – strong sideband signal. Low amplitude – low or no sideband signal.
2. Orbital sideband appears mainly in low states of the long term light curve.

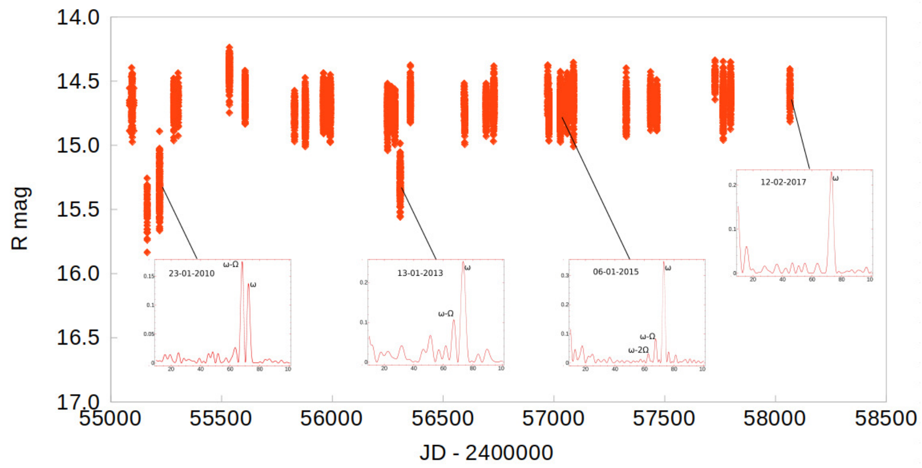


**Figure 1.** Selected periodograms depicted on the long-term light curve.

## 2. Conclusions

We performed photometric observations of MU Cam, analysed the new and previously published data, and obtained the following results:

– Spin maxima phase changes are caused by the interaction with the orbital sideband frequencies.

– The presence of orbital sidebands is more prominent in low states.

– The origin of orbital sidebands can be direct accretion from the stream or/and reprocessing of X-rays at some part of the system which rotates with the orbital period.

– The low states in intermediate polars are connected with lower mass transfer in the system. In that situation the disc-fed accretion should be lower. The disc can completely disappear as was demonstrated by Hameury & Lasota (2017) for the FO Aqr case.

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# The enigmatic highly peculiar binary system HD 66051

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**Abstract.** HD 66051 (V414 Pup) is an eclipsing and spectroscopic double-lined binary, hosting two chemically peculiar stars: a highly peculiar B star as primary and an Am star as secondary. It also shows out-of-eclipse variability that is due to chemical spots. Using a set of high-resolution spectropolarimetric observations, a weak magnetic field on the primary was found. The investigation of the new high-resolution UVES spectrum of HD 66051 allowed us to decide on the chemical peculiarity type of both components with more reliability.

**Key words:** binaries: eclipsing – Stars: chemically peculiar

## 1. Introduction

Chemically peculiar (CP) stars comprise about 10% of upper main-sequence stars (spectral types early B to early F). They are characterized by peculiar atmospheric abundances which deviate significantly from the solar composition. Two groups of CP stars are relevant to this investigation. The Bp/Ap stars are set apart by the presence of stable, globally-organized magnetic fields with strengths from about 300 G to several tens of kG. The origin of the observed magnetic fields is still a matter of some controversy, the main competing theories being the dynamo theory (field generated by dynamo action in the convective core) and the fossil field theory (field is a relic of the frozen-in interstellar magnetic field). Another important group is made up of the so-called Mercury-Manganese (HgMn) stars. As their name implies, these stars are characterized by their unusually strong lines of Hg and Mn. These stars do not show strong, organized magnetic fields, the presence of weak fields has been claimed but remains controversial.

## 2. Prior analysis of HD 66051

Niemczura et al. (2017) and Paunzen et al. (2018) analyzed high-resolution spectra and photometric time series allowing them to determine the atmospheric parameters, the preliminary chemical composition of both stars, and orbital parameters ($P = 4.749218\,\mathrm{d}$) of the system. The primary component was found to be a slowly rotating late B-type star with a highly peculiar composition reminiscent of the primary in the SB1 system HD 65949, which seems to be its closest analogue. Some light elements such as He, C, Mg and Al are depleted, while Si and P are enhanced. For atomic numbers $Z > 20$ all elements are overabundant with the single exception of Ni, which has generally been found deficient in HgMn stars. The secondary component was estimated to be a slowly rotating A-type star. Later on Kochukhov et al. (2018) challenged this first analysis on the basis of high-resolution spectropolarimetric observations. This situation motivated us to perform a new analysis of this system using all already published photometric as well as spectroscopic data. In addition, new photometric data from the *TESS* satellite and a high-resolution, high signal-to-noise UVES spectrum obtained in the framework of the ESO DDT program 2102.D-5017(A) were used.

## 3. Results

As already known, the primary star is a highly peculiar object. In the spectrum of this star we found some light elements (He, Mg, Al) underabundant and all analyzed iron-peak elements except Ni enhanced. Similarly, heavy and rare-earth elements are overabundant in its spectrum. An overabundance of these elements indicates that the primary is a Bp star. On the other hand, we identified lines of Mn, Xe, Pt, and Pb in its spectrum. Abundances of these elements are enhanced, suggesting an HgMn type. Most importantly, up to the present, Xe and heavy element overabundances were observed exclusively in HgMn stars, but never in Bp star atmospheres. The lines that we could identify with the secondary star indicate an abundance pattern with overabundant iron-peak, heavy, and rare-earth elements and depleted Sc, which agrees very well with the definition of Am-type objects.

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# Apsidal motion in the massive binary HD 152248

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**Abstract.** The eccentric massive binary HD 152 248, hosting two very similar O7.5 III(f) stars, is the most emblematic eclipsing O-star binary in the very young and rich open cluster NGC 6231. Measuring the rate of apsidal motion in such a binary system gives insight into the internal structure and evolutionary state of the stars composing it.

**Key words:** stars: early-type – stars: individual (HD 152 248) – stars: massive – binaries: spectroscopic – binaries: eclipsing

## 1. Introduction

The majority of massive stars belong to binary systems. In double-line spectroscopic eclipsing binaries, combining the photometric eclipses and the radial velocities obtained with spectroscopy allows to determine the masses and radii of the stars in a model-independent way. If the binary is eccentric and shows a significant apsidal motion, measuring this rate provides a diagnostic of the internal mass-distribution of the stars, which is otherwise difficult to constrain. It also offers a test of our understanding of stellar structure and evolution.

## 2. Methods and results

From a set of optical spectra of HD 152 248, we reconstruct the individual spectra of the stars and establish their radial velocities using a disentangling code. We analyse the reconstructed spectra with the `CMFGEN` model atmosphere code (Hillier & Miller, 1998) to determine stellar and wind properties of the system, notably effective temperatures $T_{eff}$ of $34\,000 \pm 1000$ K and $\log g = 3.48 \pm 0.10$ (cgs) for both stars. We stress that the disentangling method introduces artefacts in the wings of broad lines. In addition, `CMFGEN` does not account for binarity. Hence, $\log g$ is underestimated and $T_{eff}$ is only an average over the visible surface of the stars. The optical light curve of the binary is analysed with the `Nightfall` binary star code (Wichmann, 2011) to constrain the Roche lobe filling factors of both stars to a value of 0.86 and derive an orbital inclination of $(68.6^{+0.2}_{-0.3})^{\circ}$. `Nightfall` uses the Roche potential to describe the shape of the stars, accounts for reflection effects (mutual irradiation) and adopts a quadratic limb-darkening law. Absolute masses of $28.9^{+0.9}_{-0.8}$ and $29.1^{+0.9}_{-0.5}$ $M_{\odot}$ are derived for the primary and secondary star respectively and mean stellar radii of $14.2 \pm 0.4$ $R_{\odot}$ are obtained for both stars. Combining radial velocity measurements spanning seven decades (see Fig. 1), we show that the system displays an apsidal motion at a rate of $(1.750^{+0.350}_{-0.315})^{\circ}$ yr$^{-1}$.

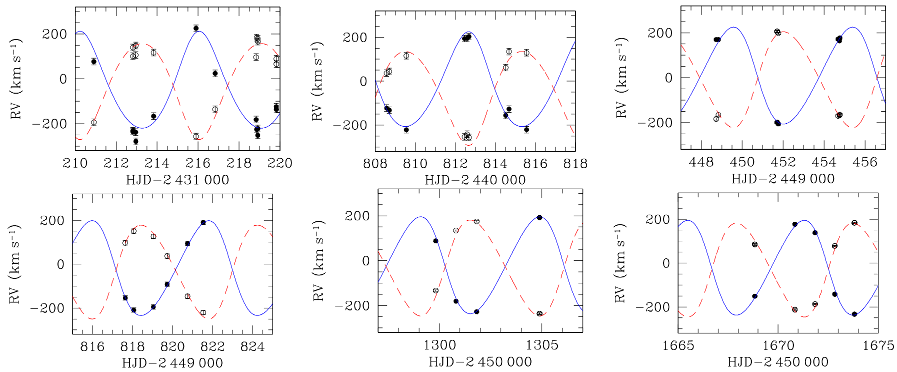


**Figure 1.** Comparison between the measured RVs of the primary (filled dots) and secondary (open dots) and the RV curves obtained with the best-fit parameters. Top panels correspond, from left to right, to data from Struve (1944), Hill et al. (1974) and one epoch of data from Mayer et al. (2008). Bottom left panel yields one epoch of *IUE* data from Penny et al. (1999) while bottom middle and right panels correspond to RVs re-derived in this work (see Rosu et al. 2020, accepted).

## 3. Conclusion

The properties of HD 152 248 render the system an interesting target to study tidally induced apsidal motion from a theoretical point of view. As a next step, we will build stellar evolution models to determine a theoretical rate of apsidal motion, which could, by comparison with the observed rate, allow to constrain the internal mixing processes occurring inside the stars as well as to infer an age estimate for the binary system.

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# A comprehensive study of the sdB+dM binary TYC 3315-1807-1

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**Abstract.** TYC 3315-1807-1 is an sdB+dM binary first reported by Kawka et al. (2010). Archival photometric data indicate the presence of a secondary companion causing a large reflection effect. Spectroscopic observations of the object were carried out from Vainu Bappu Observatory, Kavalur, to probe the nature of the secondary companion and to understand the post common-envelope evolution of such objects. Spectral line equivalent widths (EW) exhibit orbital phase dependent variations, indicating the probable contribution from the secondary. A period variation study of the object was carried out using times of minima obtained from the literature and suggesting a decrease in period. The evolutionary state of the system is evaluated and discussed.

**Key words:** binaries: subdwarfs – binaries: period variation – stars: spectroscopy: Balmer lines – stars: spectroscopy: equivalent widths

## 1. Introduction

Subdwarf (sdB) stars are core helium burning stars with a very thin hydrogen envelope. They lie on the Extreme Horizontal Branch (EHB) and a significant fraction are close binary systems (Morales-Rueda et al., 2003; Maxted et al., 2001). The object TYC 3315-1807-1 (03h21m39.62s, $+47°27'18''.79$) is listed in the MUCHFUSS catalogue of subdwarfs (Kupfer et al., 2015). Kawka et al. (2010) classified the system as a sdB+dM binary. Phase resolved spectroscopy may help to understand the nature of the companion, so an attempt was made to obtain low-resolution spectroscopic observations at various phases.

## 2. Period Variation from Archival Data

A total of 4575 $V$ band data points with a mean photometric error of $\sim 0.01$ mag were collected from SuperWASP archives. A Python code was run to sift through the data to find local light curve minima. After searching for contiguous blocks of data near the minima, a SciPy curve fitting routine was used to make Gaussian fits to the data and determine the minima ($HJD_0$). We obtained a total of 10 times of minima. The O-C values are calculated by using the linear ephemeris $\mathrm{Min\,I} = 2455045.5820 + 0.2658519 \times E$. The O-C diagram shows a decreasing parabolic trend corresponding to a period decrease $\frac{dP}{dt}$ of $-1.81733 \times 10^{-5}$ days/yr.

## 3. Observations

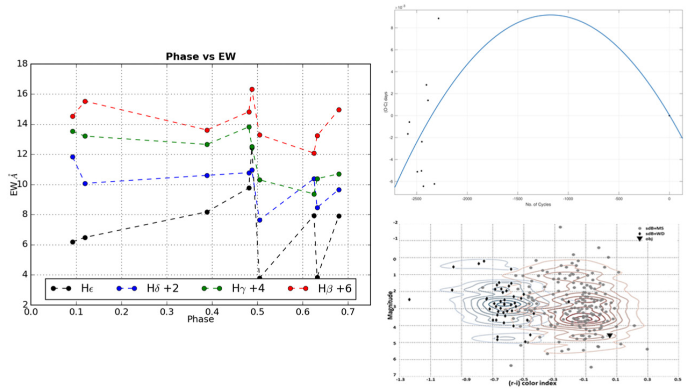


**Figure 1.** Left panel: Balmer lines equivalent width vs. phase. Upper right panel: O-C diagram for studying the period variation. Lower right panel: magnitude vs. $r-i$ color for sdB+MS (left contour) and sdB+WD (right contour) systems. The inverted triangle shows the position of TYC 3315-1807-1.

Spectroscopic data were obtained using the 2.3-m telescope at Vainu Bappu Observatory, India, during 3 nights of January 2019. Nine low-resolution spectra were obtained at 6.7 Å per pixel. The spectra were centered around the H$\beta$ line at 4800 Å.

## 4. Discussion and Results

The Balmer lines EW (Fig. 1) derived from the spectroscopic observations show phase dependent variation. The O-C diagram (Fig. 1) indicates a decreasing trend in the period at a rate of $\frac{dP}{dt} = -1.81733 \times 10^{-5}$ days/yr. Fig. 1 also shows a color magnitude diagram of known sdB+dM systems, with two different contours representing the location of sdB+Main-Sequence and sdB+White-Dwarf systems, respectively. It is observed that TYC 3315-1807-1 (inverted triangle) is located within the sdB+MS area.

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# On the first $\delta$ Scuti-like pulsating Ap star in an eclipsing binary

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**Abstract.** HD 99458 was recently discovered to be a first object of its kind: a short-period eclipsing binary hosts a spotted, chemically peculiar A-type primary star that is a $\delta$ Scuti pulsator, and an M-dwarf secondary. These phenomena should not co-exist at the same time. Based on new photometric data we find that the previously published period of the main pulsation mode is a Nyquist alias of the true period (0.036 d, and not 0.052 d) given by the *Kepler* sampling.

**Key words:** Stars: HD 99458 – Stars: chemically peculiar – binaries: eclipsing – Stars: pulsations

## 1. Introduction

The class of magnetic chemically peculiar stars that show rotational variations due to spots (CP2 class) is characterized by an overabundance of heavy elements (Preston, 1974). From the interaction with the secondary component, a magnetic field is not expected in close binaries and only a few candidates are known (e.g. Carrier et al., 2002; Landstreet et al., 2017). Pulsations of $\delta$ Scuti type also have been rarely seen among CP2 stars (Bowman et al., 2018). Here we provide additional results on the reported discovery of a binary star with an A-type CP2 star that shows all the mentioned properties.

## 2. HD 99458

Skarka et al. (2019) discovered HD 99458 to be a 2.72-day eclipsing binary that shows rotational modulation, overabundance of Si, Ti and other elements, and eclipses that were assumed to be due to a planetary transit (Barros et al., 2016). Skarka et al. (2019) showed that the companion is a $0.45\,M_\odot$ M-dwarf star.

Multi-mode stellar pulsations with the main period of 19.2 c/d were detected in the *Kepler K2* data.

After obtaining new photometric data in 2019 (Fig. 1, left panel), we found that the main pulsation frequency originally detected in the *K2* data is actually the Nyquist alias of the true frequency (Fig. 1, right-hand panel).

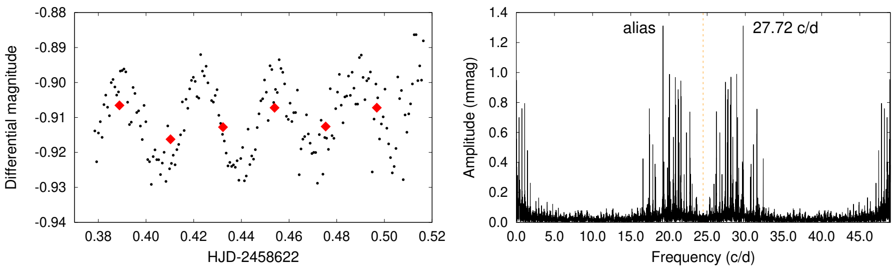


**Figure 1.** Data in Johnson *B* (left panel) and frequency spectra from the *Kepler K2* mission with identification of the main pulsation frequency and its alias. The red diamonds in the left panel are 30-min bins simulating the *K2* cadence.

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# Long-term spectroscopic survey of seven interesting CP stars

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**Abstract.** We present a long-term spectroscopic monitoring of seven CP stars in which binarity has either been established or signs of possible companions have been indicated. The primary goal of the survey was to examine the radial velocities (RVs) variations of the stars published earlier and to study multiplicity of the objects.

**Key words:** stars: chemically peculiar; stars: binaries

## 1. Introduction

This campaign was motivated by the presentation of Juraj Zverko at the conference "Observing techniques, instrumentaion and science for metre-class telescopes" held in Tatranská Lomnica in 2013 (Zverko, 2014), where these stars were recommended for observations with this class of telescopes. Initially the stars became interesting for their apparently different projected rotational velocities when determined using two different spectral lines, namely the Ca II at 3933 Å and Mg II 4481 Å. In studies cited in Zverko (2014) signs of their possible binary nature had been identified, that become evident via varying RVs, an uniform reduction of line depths and/or an incidence of spectral lines of a companion. The spectroscopic observations were performed at the observatories SL (Pribulla et al., 2015) and SP,[1] and RVs were determined by means of CCF (Zverko et al., 2007). The RVs were measured in the blue part of the spectrum, where the Mg II 4481 Å is the strongest metallic line in these stars. Here we present a summary of up-to-date status of observations. The commentaries

[1] https://www.ta3.sk/l3.php?p3=sto

below for each of the investigated stars refer to figures that are accessible in https://www.ta3.sk/∼vanko/RVs/.

## 2. The current status of the study

**HD 2913** (51 Psc, B9V, $V = 5.9$). We acquired 37 SL and 14 SP spectra that disclose a RV curve with values from -3 to +28 $\mathrm{km\,s^{-1}}$ following the previous values introduced in Zverko et al. (2011) and the literature cited there. An extreme value occurs in the SP data, namely the one, reaching +41 $\mathrm{km\,s^{-1}}$ near the maximum of the curve. Observations are continued to complete the curve, to explain that one extreme value, as well as to investigate the scatter reaching nearly 10 $\mathrm{km\,s^{-1}}$ within an individual observing windows.
**HD 47152** (53 Aur, B9Mn+F0m, $V = 5.7$). Fifty-eight SL and 26 SP spectra cover approx. 1/9 portion of the supposed period 38.9 y. The measured values spread within $\sim$ 10 $\mathrm{km\,s^{-1}}$ in both SL and SP spectra.
**HD 47964** (HR 2461, B8III, $V = 5.7$). Although former studies show RV to vary within 0 and 20 $\mathrm{km\,s^{-1}}$, no signs of a secondary spectrum were detected with a S/N=1100 (Zverko et al., 2013). We acquired 45 SL and 5 SP spectra that do not outline any rational RV curve except the increase between HJD 2458200 and 2458600 which calls for further observations.
**HD 90569** (CX Leo, B8V, $V = 3.4$) This magnetic sharp-lined CP star is an SB1 binary with a long period $P = 34.6$ years, showing low velocity variations (Abt & Snowden, 1973). We monitor whether our modern observations confirm the orbit derived in Pourbaix et al. (2005). We obtained 56 SL and 17 SP. A slow increase from -10 to -9 $\mathrm{km\,s^{-1}}$ during the campaign is indicated. In order to confirm the unsure long period continuing observations would be advisable.
**HD 138527** (12$\tau^2$ Ser, B9V, $V = 6.2$). We obtained 56 SL and 12 SP spectra which do not show any long-term increase or decline over the time-span of our campaign. Anyhow, the values spread between -24 and -11 $\mathrm{km\,s^{-1}}$, in compliance with earlier results where RV-s go from -6 to -26.5 $\mathrm{km\,s^{-1}}$
**HD 183986** (HR 7419, B9.5III, V = 6.2). We acquired 43 SL and 11 SP spectra. Earlier measurements of RVs showed values from -6 to +22 $\mathrm{km\,s^{-1}}$. Our observations allow to discover a radial velocity curve suggesting $P_{\rm orb} \approx 1300$ d. We hope to cover the anticipated peak during spring of 2020.
**HD 214923** (42 Peg, B8V, V = 3.4) is a small-amplitude, slowly pulsating B (SPB) star oscillating in a non-radial g-mode with a period of $P = 0.95633$ day, with amplitude ∼0.5 mmag (Goebel, 2007). Thirty-seven SL spectra show a weak increase from $\approx +5$ $\mathrm{km\,s^{-1}}$ at the beginning of the campaign to $\approx +7$ $\mathrm{km\,s^{-1}}$ at its end, similarly 16 SP spectra show an increase from ≈+2 $\mathrm{km\,s^{-1}}$ at the beginning to $\approx +4$ $\mathrm{km\,s^{-1}}$ at its end. The figure also shows a scatter reaching 5 km/s in each of the observing windows. Taking into account that the star is slowly pulsating, the spread of the data may be due to the pulsations.

## 3. Conclusion

This is a progress report on our long-term monitoring of seven CP stars suspected of binarity. Two of them were known as very long-period binaries before: HD 47152 and HD 90569. Our observations lasting for 6 yrs cover only a fraction of their orbital periods. In the case of HD 2913 and HD 183986 their binarity is confirmed. HD 47964 does not show a varying RV except for the last group of observations, with a RV increase of about 3 $\mathrm{km\,s^{-1}}$. HD 138527 and HD 214923 embodies a remarkable scatter of the values reaching 7-10 $\mathrm{km\,s^{-1}}$ inside each observational window, that advert to possible slow pulsations that stars of this spectral types undergo. The internal accuracy of our single RV measurement is better than 1 $\mathrm{km\,s^{-1}}$ corroborated with HD 90569 and HD 183986. This reveals that the remaining stars, with the scatter extending beyond a few $\mathrm{km\,s^{-1}}$, are worth further observations aiming at disclosing pulsations. Helpful and conclusive will be additional photometry (e.g. space based photometry, *BRITE*, *SMEI*, *TESS*, etc.).

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# Apsidal motion in $\alpha$ CrB

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**Abstract.** We present a new derivation of apsidal motion in the well known eclipsing eccentric binary $\alpha$ CrB.

## 1. Introduction

The eclipsing binary $\alpha$ CrB ($P = 17\overset{\mathrm{d}}{.}36$, $V = 2\overset{\mathrm{m}}{.}21$, $e = 0.33$, Sp A0 V + G7 V) was identified as a spectrscopic binary (Hartmann, 1903) more than 100 years ago. The star was one of the objects in pioneering electrophotometric observations by J. Stebbins, Stebbins (1928), who discovered a shallow $0\overset{\mathrm{m}}{.}1$ primary minimum in 1912. The secondary minimum, when a faint red companion is eclipsed by the bright A0 star, was not detected but later found with a red-sensitive photocell by Kron & Gordon (1953). The next observations of the secondary minimum, necessary to measure the rate of apsidal motion, were by Volkov (1993). That value was later corrected in Volkov (2005) from Schmitt (1998) X-ray observations. Problems related to the observed rate of apsidal rotation to its theoretical value were discussed in Volkov (2015).

## 2. Apsidal motion

We performed new observations of the system in 2009–2019 and have built one mean primary and one mean secondary minimum, see Fig. 1 so as to find a new value of the periastron advance rate: $\dot{\omega}_{obs} = 0\overset{\circ}{.}16(3)\,\mathrm{yr}^{-1}$, $U = 23000 \pm 4000$ years.

We have the most accurate value of the apsidal rotation speed in $\alpha$ CrB to date. To improve the value, it is necessary to get more precise orbital elements by continuing photometric observations, especially in the secondary minimum.

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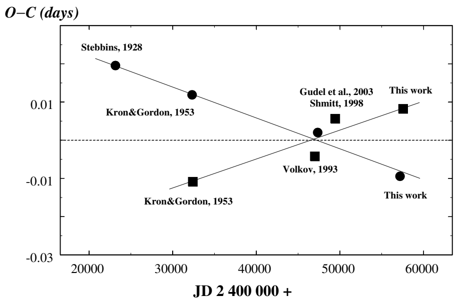


**Figure 1.** The ETV diagram of the system built with the mean value of $P1$ and $P2$. One more X-ray timing by Güdel et al. (2003) blends with the Schmitt (1998) point. The errors of secondary minima timings (squares) are 5 minutes, and those of the primaries (circles) are 3 minutes.

stars, relativistic objects and galaxies'). In our observations we used the 60-cm Zeiss-600 reflector of INASAN Simeiz Observatory and the 60-cm Zeiss-600 of near Moscow Zvenigorod Observatory.

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# Possible companions in low-mass eclipsing binaries: V380 Dra, BX Tri, and V642 Vir

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**Abstract.** We present the new results of our long-term observational project to analyze the orbital period variations of low-mass eclipsing binaries. More then 200 new precise mid-eclipse times recorded with a CCD were obtained for three eclipsing binaries with short orbital periods: V380 Dra ($P = 0\overset{\text{d}}{.}49$), BX Tri ($0\overset{\text{d}}{.}19$), and V642 Vir ($0\overset{\text{d}}{.}52$). Observed-minus-calculated diagrams of the stars were analyzed using all reliable timings, and new parameters of the light-time effect were obtained. We derived for the first time the short orbital periods of possible third bodies of 10–20 years for these objects. We calculated that the minimum masses of the third component are close to 0.2 $M_{\odot}$, which corresponds to the mass of M4 – M5 red dwarfs. The multiplicity of these systems also plays an important role in the precise determination of their physical parameters.

**Key words:** binaries: eclipsing – stars: late-type – stars: fundamental parameters – stars: individual (V380 Dra, BX Tri, V642 Vir)

## 1. Introduction

Low-mass binaries (LMBs) and their multiple systems play an important role in stellar astrophysics. Their origin and evolution is still an unresolved question in the star formation theory. Moreover, observations of low-mass stars show a discrepancy between estimated and modeled parameters, where the models give some 10% smaller radii than observations while their effective temperatures are some 5% higher (e.g. Ribas et al. 2008). Our previous period studies of similar eclipsing LMBs presented in Wolf et al. (2016, 2018) revealed several triple

**Table 1.** The LITE parameters of three selected LMBs: orbital and third body periods (in days and years), amplitudes, eccentricities, expected masses of binary components, minimal masses of the possible third body, and numbers of primary and secondary mid-eclipse times used in our calculation.

| System | V380 Dra = NSVS 1178845 | BX Tri = NSVS 6550671 | V642 Vir = NSVS 10441882 |
|---|---|---|---|
| $T_0$ [HJD-2400000] | 54272.4586 | 51352.0695 | 51274.6257 |
| Period [day] | 0.493736 | 0.192635 | 0.516644 |
| $P_3$ [day] | 5595 | 3161 | 7405 |
| $P_3$ [year] | 15.5 | 8.65 | 20.3 |
| Amplitude [day] | 0.0041 | 0.00465 | 0.00487 |
| Eccentricity | 0.34 | 0.55 | 0.31 |
| Omega [deg] | 202 | 330 | 61 |
| Time of periastron | 52020 | 55285 | 51640 |
| $M_1 + M_2[M\odot]$ | 0.77+0.62 | 0.51+0.26 | 0.67+0.63 |
| $M_{3,min}[M\odot]$ | 0.163 | 0.216 | 0.147 |
| $K$ [km/s] | 1.55 | 3.8 | 1.32 |
| $N_{pri} + N_{sec}$ | 45+34 | 320+75 | 38+32 |
| $\Sigma w(O-C)^2$ | 0.00023 | 0.00059 | 0.00008 |

systems (e.g. GU Boo and YY Gem). Here we report on a long-term mid-eclipse times campaign of three more selected LMBs. These systems are all relatively well-known low-mass binaries with short orbital periods up to 12 hours.

## 2. Observations

The systematical long-term CCD eclipse and light-curve monitoring of many eclipsing LMBs has been performed since 2006. These relatively faint objects with a short orbital periods, and rapid and deep eclipses, are good targets for practical exercises in photometry. The 0.65-m Mayer reflecting telescope (D65) in Ondřejov observatory, Czech Republic, CCD camera G2-3200, *VRI* filters, and remote access was used. Precise photometry was also carried out at the Valašské Meziříčí observatory using the 0.3-m Celestron Ultima telescope, and with the 0.4m Jan Šindel Telescope operated in the dome of the Astronomical Society in Hradec Králové. The Bootes-2 telescope[1] in Spain (0.6-m RC telescope and CCD camera Andor iXon, Jelinek et al. 2016) was also used during several nights. A standard calibration (dark frame, flat field) was applied to the observed CCD frames. APHOT, an aperture photometry and astrometry software, was used at Ondřejov observatory. C-MUNIPACK[2] was used to reduce our CCD time series obtained at Valašské Meziříčí and Hradec Králové. Differential

[1]http://bootes.iaa.es/

[2]http://c-munipack.source.forge.net/

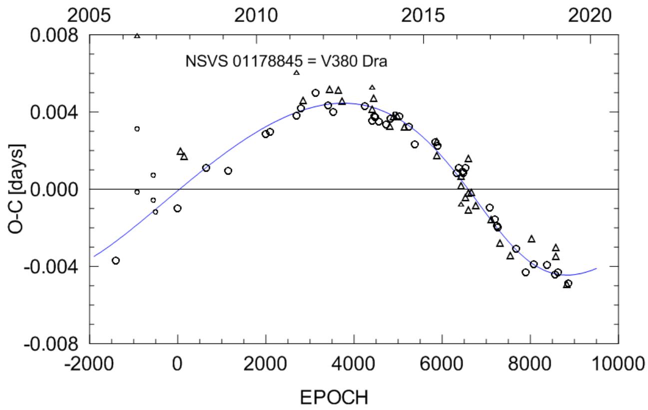


**Figure 1.** The current O-C diagram of the eclipsing binary V380 Dra. Primary and secondary eclipses are plotted as circles and triangles, respectively. Larger symbols correspond to more precise CCD measurements. The sinusoidal curve represents our solution of the LITE with the period of 15.5 yr and the amplitude of 6 min.

photometry was performed using suitable comparison stars. All new times of primary and secondary minima and their errors were generally determined by fitting the light curve by Gaussians or polynomials of the third or fourth order; we used the least squares method.

## 3. Period variation and light-time effect

The period analysis of three selected LMBs was performed using all available mid-eclipse times found in the literature as well as our newly measured times. One of the best method to detect the third body orbiting the eclipsing binary is the light travel delay, or so-called *light-time effect* (LITE), associated with orbital motion of the third body (e.g. Mayer 1990). The precise mid-eclipse time estimation enabled us to find small apparent period changes and derive the minimum mass of the body on the wider orbit. Seven independent variables were determined in this procedure: the orbital period of the binary, the orbital period of the third body, the semiamplitude of LITE, the eccentricity of the outer orbit, the periastron passage time of the third body, the zero epoch of the eclipsing binary, and finally the corresponding position of the periastron. All computed LITE parameters are given in Table 1, and the corresponding O-C diagrams are shown in Figs. 1, 2, and 3.

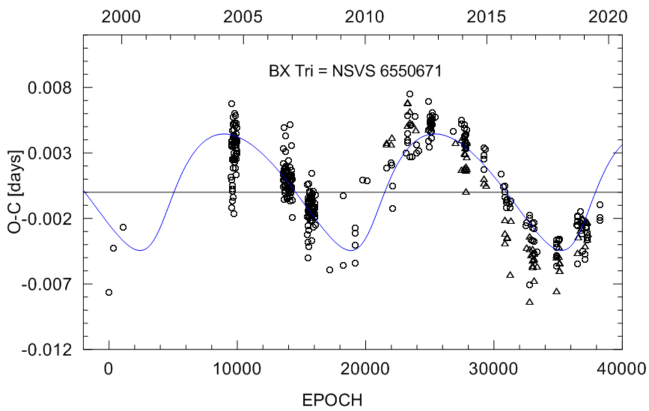


**Figure 2.** Cyclic period changes in the current O-C diagram of BX Tri. See legend to Fig. 1. The curve represents our solution of LITE with the short period of 8.65 yr.

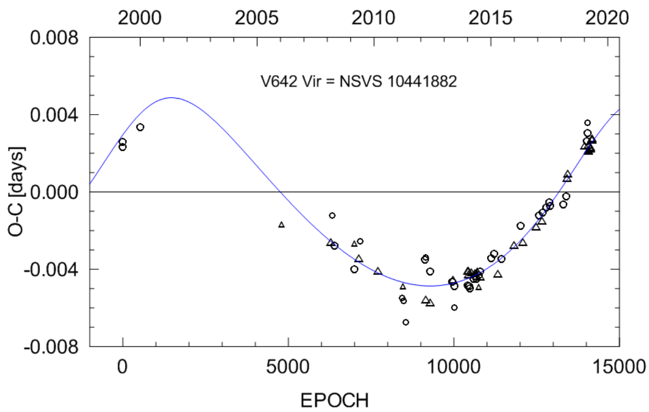


**Figure 3.** The O-C diagram of V642 Vir. See legend to Fig. 1. The sinusoidal curve represents the LITE with the period of 20.3 yr and an amplitude of 7 min.

## 4. Conclusions

Our study provides accurate information on period changes of three main-sequence LMBs. The LITE period has been presented here for the first time. For V380 Dra and V642 Vir the third-body orbital period is not covered satisfactorily, so these results must be taken as preliminary. The minimal masses of possible third bodies correspond to red-dwarf stars of spectral types M4–M5 (Pecaut & Mamajek 2013)[3] with significant third light. The sample of well-known LMBs

[3]http://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt

needs to be increased, so observations of additional systems would be very useful. It would be also desirable to obtain new spectroscopic observations.

To date about 20 LMBs and hundreds of their light curves are displayed in our database. These objects were selected originally from Shaw & López-Morales (2007). The interesting post-common-envelope binaries (HW Vir, NY Vir) and well-known cataclysmic variables (HT Cas, EX Dra, DQ Her, RW Tri, TT Tri, DW UMa) are also included. All objects mentioned above are open to future collaboration. The multicolor photometry of individual systems and the list of precise mid-eclipse times are available on request.

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[4]http://var.astro.cz/ocgate/

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