AUTOREFERAT

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   - Master of Science (M.Sc.) degree (pol: *magister*) in astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Toruń, 2006.
     Thesis title: *Precision astrometry of visual binaries with adaptive optics.*
     Supervisor: Prof. Maciej Konacki.
   - Doctor of physical sciences (Ph.D.) in the field of astronomy, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, 2010.
     Thesis title: *Derivation of fundamental parameters of late-type stars in binaries using precise photometry, high-resolution spectroscopy, imaging with adaptive optics, and optical interferometry.*
     Supervisor: Prof. Maciej Konacki.

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   - Pontificia Universidad Católica, Departamento de Astronomia y Astrofisica (Chile), post-doctoral researcher, 2010-2013
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4. Habilitation Achievement:

   - Title of the Achievement:

The search and comprehensive study of rare and unusual detached eclipsing binaries

   - Publications included in the Achievement:

[H1] Hełminiak, K. G.; Konacki, M.; Różyczka, M.; Kałużny, J.; Ratajczak, M.; Borkowski, J.; Sybilski, P.; Muterspaugh, M. W.; Reichart, D. E.; Ivarsen, K. M.; Haislip, J. B.; Crain, J. A.; Foster, A. C.; Nysewander, M. C.; LaCluyze, A. P., *Orbital and physical parameters of eclipsing binaries from the All-Sky Automated Survey catalogue - IV. A 0.61 + 0.45 $M_\odot$ binary in a multiple system*, 2012, MNRAS, 425, 1245.

[H2] Hełminiak, K. G.; Brahm, R.; Ratajczak, M.; Espinoza, N.; Jordán, A.; Konacki, M.; Rabus, M., *Orbital and physical parameters of eclipsing binaries from the All-Sky Automated Survey catalogue. VI. AK Fornacis: a rare, bright K-type eclipsing binary*, 2014, A&A, 567, A64.

[H3] Hełminiak, K. G.; Graczyk, D.; Konacki, M.; Pilecki, B.; Ratajczak, M.; Pietrzyński, G.; Sybilski, P.; Villanova, S.; Gieren, W.; Pojmański, G.; Konorski, P.; Suchomska, K.; Reichart, D. E.; Ivarsen, K. M.; Haislip, J. B.; LaCluyze, A. P., *Orbital and physical parameters of eclipsing binaries from the ASAS catalogue - VIII. The totally eclipsing double-giant system HD 187669*, 2015, MNRAS, 448, 1945.

[H4] Hełminiak, K. G.; Ukita, N.; Kambe, E.; Konacki, M., *Absolute Stellar Parameters of KIC 09246715: A Double-giant Eclipsing System with a Solar-like Oscillator*, 2015, ApJL, 813, 25.

[H5] Hełminiak, K. G.; Ukita, N.; Kambe, E.; Kozłowski, S. K.; Sybilski, P.; Ratajczak, M.; Maehara, H.; Konacki, M., *HIDES spectroscopy of bright detached eclipsing binaries from the Kepler field - I. Single-lined objects*, 2016, MNRAS, 461, 2896.

[H6] Hełminiak, K. G.; Ukita, N.; Kambe, E.; Kozłowski, S. K.; Sybilski, P.; Maehara, H.; Ratajczak, M.; Konacki, M.; Pawłaszek, R. K., *HIDES spectroscopy of bright detached eclipsing binaries from the Kepler field - II. Double- and triple-lined objects*, 2017, MNRAS, 468, 1726.

[H7] Hełminiak, K. G.; Ukita, N.; Kambe, E.; Kozłowski, S. K.; Pawłaszek, R.; Maehara, H.; Baranec, C.; Konacki, M., *KIC 4150611: a rare multi-eclipsing quintuple with a hybrid pulsator*, 2017, A&A, 602, A30.

[H8] Hełminiak, K. G.; Tokovinin, A.; Niemczura, E.; Pawłaszek, R.; Yanagisawa, K.; Brahm, R.; Espinoza, N.; Ukita, N.; Kambe, E.; Ratajczak, M.; Hempel, M.; Jordán, A.; Konacki. M.; Sybilski, P.; Kozłowski, S. K.; Litwicki, M.; Tamura, M., *Orbital and physical parameters of eclipsing binaries from the All-Sky Automated Survey catalogue - X. Three high-contrast systems with secondaries detected with IR spectroscopy*, 2019, A&A, 622, A114.

[H9] Hełminiak, K. G.; Konacki, M.; Maehara, H.; Kambe, E.; Ukita, N.; Ratajczak, M.; Pigulski, A.; Kozłowski, S. K., *HIDES spectroscopy of bright detached eclipsing binaries from the Kepler field – III. Spectral analysis, updated parameters, and new systems*, 2019, MNRAS, 484, 451.

A&A = Astronomy & Astrophysics
ApJL = The Astrophysical Journal Letters
MNRAS = Monthly Notices of the Royal Astronomical Society

○ Description of research goals and results

Introduction

Detached eclipsing binaries (DEBs) are one of the most important objects in astronomy. With only few exceptions, their components evolve independently, have the same chemical composition and age. Their geometry and presence of eclipses allow for direct determination of such fundamental parameters as masses, radii, and luminosities, from which one can calculate further parameters: gravitational accelerations, bolometric and absolute magnitudes, distance, or age. It is also possible to estimate abundances of chemical elements, or at least the metallicity. Obtaining such a set of parameters with high precision is very difficult or even impossible for other kinds of objects. The information possible to deduce from the analysis of DEBs can later be used in other branches of astronomy, such as: the theory of stellar structure and evolution, celestial mechanics, asteroseismology, or exoplanet search.

Despite the fact that thousands of DEBs have been discovered by large photometric surveys, only a handful of them have been described precisely enough to be useful for reliable tests of stellar evolution models, i.e. their parameters (mainly masses and radii) are known with uncertainties at the level of 2-3% or better (Lastenet & Valls-Gabaud, 2002), and their effective temperature T_{eff} is known as well. The error level of 2-3% allows for determination of the evolutionary status, age and metallicity, although the latter two are in degeneration (Lastenet & Valls-Gabaud, 2002). A complete set of information about a given system must include T_{eff} and metallicity [M/H], in order to be useful for further studies. The DEBCat[1] catalogue (Southworth 2015), which is a collection of the best-studied detached eclipsing binaries, currently contains only 218 systems (Fig. 1), and any information on [M/H] or abundances of chemical elements is given for less than 100 (<45%). The metallicity is often estimated on the basis of a membership to a certain cluster, not from direct measurements.

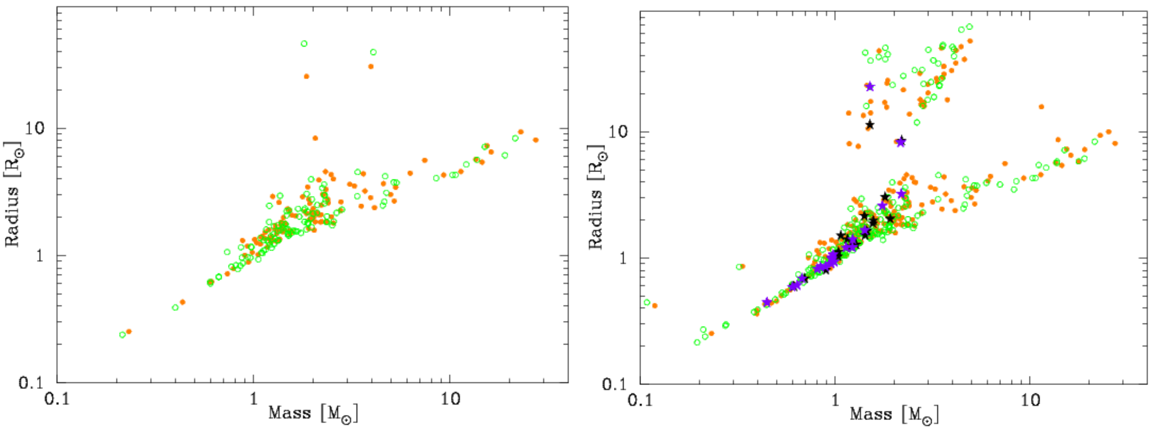

Fig. 1: Objects from the DEBCat catalogue on the mass-radius (*M-R*) plane. For a given pair, the more massive component is marked with orange, while the less massive with a green symbol. *Left:* Status for the end of 2010. *Right:* Current status (14.02.2019). Black and purple stars on right panel show DEBs this scientific Achievement (more and less massive, respectively). Some of them are currently listed in the DEBCat.

In a now-classic review article from 2010, Torres, andersen & Gimenez (2010) reanalyzed the data available that time for about a hundred of well-studied binaries, with the stress put on derivations of masses and radii. They pointed out that, on the mass-radius (*M-R*) diagram, there are many sparsely populated region, e.g. stars of masses below 0.9 or above 3 solar mass ($M_\odot$), pre-main-sequence (PMS) stars, or giants at various stages of evolution (Fig. 1). They also mention characteristics that can not be deduced from the *M-R* plane alone, such as: membership to a cluster or a multiple system, or presence of pulsations. Furthermore, they noted that for a majority of systems in their sample there is no information about [M/H] or chemical abundances, and that the evolutionary models very often did not manage to reproduce the observed properties, due to improper treatment of convection or

[1] http://www.astro.keele.ac.uk/~jkt/debcat

chromospheric activity, for example. Therefore, they defined a need of delivering new, well-studied DEBs, especially those containing stars of rare and unusual characteristics that could fill the “white spots” on the *M-R* diagram.

Additionally, till 2016 there was no star in the DEBCat that had errors in mass lower than 0.1%. This level of precision is needed to test the new generation of evolutionary models (Valle et al. 2017). This is a level required to observe influence of such phenomena as rotation, overshooting, or abundances of the α-process elements. Their impact on the stellar structure and parameters is still not properly understood; we need further theoretical studies, supported with a high-quality observational data. Currently, we know of only two systems with masses measured to such a precision.

Considering the above, and taking into account the technological advancement in stabilisation and efficiency of astronomical spectrographs, which allows one to obtain a larger number of precision radial velocity (RV) measurements (thus, estimation of mass) in shorter time, I decided to start systematic observations of a number of newly discovered DEBs, in order to identify and study the most interesting cases.

Methodology

Target selection

Vast majority of the systems observed in the survey have been identified as DEBs for the first time in the All Sky Automated Survey (ASAS; Pojmański 2002) and collected in the ASAS Catalog of Variable Stars (ACVS) database. The ASAS survey was the main source of targets until 2013, including objects described in publications H1, H3, and H8. The binary AK For, from the work H2, is also listed in the ASAS database, but that time has not been recognized as a variable, and is not in the ACVS. The second most important source of DEBs was the *Kepler* Eclipsing Binaries Catalog (KEBC; Prša i i n. 2011; Slawson et al. 2011; Kirk et al. 2017), from which I took targets described in papers H4 through H7, and H9. There are more *Kepler* than ASAS targets presented in this Achievement, because high-precision photometry has already been available for them, thus no additional photometric observations were necessary, and the total time devoted for analysis of one object was shorter. In both cases the target selection criteria were similar:

- The shape of the light curve (LC), revealing a detached configuration (relatively narrow eclipses, little or no brightness modulation out of them). In the KEBC it is parameterized by a quantity called *morph*, which takes values between 0 and 1, and a binary is considered to be detached when *morph* < 0.6 (arbitrary value).
- The apparent magnitude in $V < 12.5$ mag, in order to have the target within the brightness limit of a telescope. In case of smaller aperture telescopes (like 1.2-m Euler) the limit was set to 11.5 mag.
- The observed colour index $V - K > 1.1$ mag, or the effective temperature in a catalogue $T_{\rm eff} < 6700$ K, in order to observe stars of spectral types F, or later, which spectra show many features, used in RV measurements.

Additionally, I have rejected objects with precisely measured parameters available before the program started, unless new photometric data of significantly better precision were available.

After obtaining several RV measurements, an initial model was made in order to assess the absolute values of stellar parameters and check the characteristics of a given system. This step allowed me to locate the component on the *M-R* diagram, and thus to determine if a given system is potentially interesting and worth further observations or not. Apart from the location on the *M-R* diagram, some other characteristics were also taken into consideration. A given DEB has been selected for further studies when at least one of the following criteria was met:

- Mass of one or both components < 0.9 $M_{\odot}$.
- Mass of one or both components > 3 $M_{\odot}$.[2]
- The size of one or both components larger than predicted at the main sequence (MS),

2 Despite the colour index criterium applied earlier, several massive, early type systems ended up in the observing list due to a very strong reddening.

suggesting giants, sub-giants, or pre-main-sequence (PMS) objects.

- Multiplicity (trends in the RVs, more than 2 sets of lines in spectra, visual companion).
- Mass ratio $q < 0.8$.
- Presence of pulsations or oscillations.
- Presence of a total eclipse.
- Strong lithium lines at 6708 Å (suggesting the PMS phase).
- Standard deviation after the RV fit < 100 m/s (potentially high precision in masses and/or possibility of circumbinary planet search).

The objects that passed the selection were gathered in a target list for a project called *Comprehensive Research with Échelles on the Most interesting Eclipsing binaries* (CRÉME). It is worth mentioning that out of >200 DEBs taken from the ASAS survey alone, about 100 has been considered "interesting". Some of them have been described in publications not included in the presented Achievement (Coronado et al. 2015, Ratajczak et al. 2013, 2016), and for some others additional data are still being taken or analysis is ongoing. The systems presented in dedicated publications H1, H2, H3, and H8 are, therefore, a part of a larger list, but were chosen for standalone papers because of their characteristics.

Most of the objects from the *Kepler* field are described in collective publications H5, H6, and H9. Many of them can also be considered "interesting", according to the criteria above. However, because of the precise, satellite-borne photometry available for them, and relatively low number of objects (~20), all of them have been analysed in roughly the same time. Only two special cases were selected for standalone publications H4 and H7.

Observations and sources of data

The basic observable for deriving absolute masses of components of a spectroscopic binary are radial velocities. Accurate and precise RV measurements can be obtained from high-resolution ($R > 40000$) spectra taken with stable échelle spectrographs. In my work, I made use of 15 instruments of this type, with the majority of data collected between 2011 and 2018 with the following ones:

- CORALIE ($R \sim 70000$) at the 1.2-m Euler telescope in La Silla, Chile.
- CHIRON ($R \sim 90000$ or ~28000 in *slicer* or *fiber* mode, respectively) at 1.5-m SMARTS consortium telescope in Cerro Tololo, Chile.
- FEROS ($R \sim 48000$) at the 2.2-m MPG (former MPG/ESO) telescope in La Silla, Chile.
- HIDES ($R \sim 48000$) at the 1.88-m telescope OAO-188 in Okayama, Japan.
- HARPS (R ~ 115000) at the 3.6-m ESO telescope in La Silla, Chile.

Additionally, the paper H1 bases on earlier (2006-2009) observations from the 1.9-m Radcliffe telescope with the GIRAFFE spectrograph (SAAO), and the 3.8-m Anglo-Australian Telescope with the spectrograph UCLES (AAO), supplemented by one spectrum from the 3.5-m Shane telescope with the Hamilton spectrograph (Lick Observatory). The targets from the paper H8 were observed in infrared with the 8.2-m Subaru telescope with the IRCS instrument (Maunakea), and one of them also with the 3.5-m TNG telescope with HARPS-N (La Palma). Furthermore, in publications H4 and H5 I used publicly available spectra from the APOGEE survey and the Tillinghast telescope equipped with the TRES spectrograph. The vast majority of RV measurements were done with the cross-correlation method TODCOR (Zucker & Mazeh 1994), or by fitting tomographically disentangled spectra (see: *Methods of data analysis*) to the observed one (Konacki et al. 2010). In one case, ASAS J011328-3821.1 (paper H1), the RVs were also calculated from the positions of Hα emission lines, while in another, KIC 4150611 Aa (H7), from the absorption line Hβ.

A special case of RV measurements, used in works H5, H6, and the Appendix to H9, are the velocities of the centre of mass of an eclipsing binary, translated from eclipse timing variations (ETV). They were used for several objects from the *Kepler* sample, that turned out to be hierarchical triples, with a short-period (several days) DEB being orbited by a third body on a wide, long-period (several years) orbit. A combination of "direct" RVs of the third stars, with post-ETV measurements for the centre of mass of DEBs, allowed for determination of orbital parameters of outer orbits, and even for estimation of absolute radii of the inner DEB components (H5). The ETVs themselves were also used in several cases from the *Kepler* field (H5, H6, H7). These measurements have been performed by Dr. Stanisław Kozłowski, with the method described in Kozłowski et al. (2011).

Brightness measurements were at first taken from the ASAS survey (*V* band), but their quality was unsatisfying and did not enable to obtain stellar parameters with the desired precision. Therefore, they were supplemented by additional observations, like public data from the SuperWASP survey (papers H2 and H3), which show similar spread, but are taken with much shorter cadence, which leads to smaller parameter errors. However, as it turned out in cases of AK For (H2), HD 187669 (H3), or a multiple system V1200 Cen (Coronado et al. 2015, based on ASAS and SuperWASP photometry only), the SuperWASP data do not guarantee the desired precision. Thus, to really reach the parameter errors at the level of 2% or less, additional photometry, from instruments with apertures larger than telephoto lenses, had to be taken. For this purpose dedicated observations were conducted with the following instruments:

- The 1-m Elizabeth telescope in SAAO, South Africa, filters *V* and *I* (publication H1).
- Network of 0.5-m robotic telescopes PROMPT in CTIO, Chile, filters *V* and *I* (H1 and H3).
- The 0.5-m robotic telescope MITSuME in Okayama, Japan, w filters *g', R* and *I* (H8).

The necessity of obtaining additional photometry is the main reason why the number of presented systems from the ASAS survey is not large. Nevertheless, the publications they are described in resulted from long and thorough analyses.

For the *Kepler* field objects the required photometry was, of course, available immediately, and has been used in H4, H5, H6, H7, and H9. In single cases there were also LCs from the TrES survey (Devor et al. 2008) and ASAS-North[3] taken into account, buth usually they failed to bring any new, important information.

Apart from brightness and velocity measurements, in two cases - KIC 4150611 from the work H7, and ASAS J052743-0359.7 from H8 - there were also astrometric measurements used. Both objects are multiple systems, previously known as visual binaries, for which archival astrometric measurements are collented in the Washington Double Star Catalog (WDS). New observations of KIC 4150611 come from the Keck II telescope with the NIRC 2 camera, which worked with the adaptive optics system. The astrometry of ASAS J052743-0359.7 comes from speckle interferometry observations, performed at the SOAR telescope (Tokovinin et al. 2015, 2018).

Methods of data analisis

Radial velocity curves were fitted with the code V2Fit (Konacki et al. 2010). It utilizes a Levenberg-Marquardt algorithm to fit a Keplerian orbit of any spectroscopic binary (either single- or double-lined), with an option to include a trend: linear, quadratic, or periodical. In the last case V2Fit determines the parameters of the outer orbit of a third body around the spectroscopic pair. The code is also capable of finding differences between zero-points of different spectrographs. From the RV fits we get, for example: lower limits for masses and major semi-axis, both degenerated with inclination: $M_{1,2} \sin^3(i)$ and $a \sin(i)$, as well as orbital eccentricity e and argument of the pericentre ω.

The light curves (LCs) were analysed with one of the following codes: PHOEBE v0.32 (Prša & Zwitter 2005) or JKTEBOP v28/34 (Southworth et al. 2004a,b). PHOEBE bases on the well-known Wilson-Devinney program (WD; Wilson & Devinney, 1971) and it can fit a model to several LCs simultaneously, including spots on stellar surfaces. For these reasons it has been used in publications H1 and H8. With PHOEBE it is also possible to make a fit to the RVs, but without some effects that the V2Fit can take care off (e.g. trends).

The other code for LC modelling - JKTEBOP - is a simple and fast geometrical code, well-suited for detached eclipsing binaries. It can work with only one LC at a time, but, contrary to PHOEBE, it includes several methods of reliable estimation of errors. The newer versions (after v31) are also capable of analysing RV curves, but again not all effects are included. The JKTEBOP has been used in papers H2 to H7, and H9. The parameters possible to obtain are for example: inclination i, or fractional radii $r_{1,2} = R_{1,2}/a$. On the contrary to JKTEBOP, PHOEBE is a physical code, thus the parameters that are directly determined are the so-called modified Kopal potentials $\Omega_{1,2}$, which can be translated into $r_{1,2}$ later, with the aid of the mass ratio q. From the LCs one can also estimate e and ω, as well as the orbital period P (light curves with long time bases, of several years, are better for this

3 https://asas-sn.osu.edu/

purpose than the RV curves). By combining the outputs from V2Fit and one of the LC fitting codes, it is possible to obtain absolute values of masses and radii (and thus of their gravities $\log(g_{1,2})$ and the major semi-axis a).

The next step in the full analysis scheme was tomographic disentangling, which was done in order to obtain single, separate spectra of the components of a given spectroscopic binary. We used the method developed by Prof. Maciej Konacki (Konacki et al. 2010), which bases on a tomographic approach proposed by Bagnuolo and Gies (1991). The main condition for the method's feasibility was having at least 8 spectra of a given system obtained with the same spectrograph, and presence of only two sets of lines. Because of that, this step was not applied to all the objects. The disentangling, performed by Prof. Konacki, was used in publications H2, H3, and H9.

One of the main goals of the research described, was to obtain as complete a set of information about a given system as possible, not limited to masses and radii. As it was mentioned before, the key parameters are also effective temperatures of components $T_{\rm eff}$, and the metallicity [M/H]. The temperature can be assessed e.g. from $T_{\rm eff}$-colour index calibrations, ratio of depths of certain spectral lines, or from spectral analysis, which also gives information about [M/H][4]. The first approach was used in papers H1, H2, H3, and H9; the second method in H3 and H8, while the spectral analysis in H2, H3, H8, and H9. Additionally, literature values of $T_{\rm eff}$, and [M/H] were used in papers H5 and H7.

The spectral analysis was performed with several codes and on different kinds of spectra. The *Spectroscopy Made Easy* (SME; Valenti & Piskunov 1995) code was used in works H2 and H3 on tomographically disentangled spectra, and in H3 also on the spectrum recorded during the total eclipse (analysis done by Dr. Milena Ratajczak). Disentangled spectra were also analysed in the paper H9 (by myself), but with the code iSpec (Blanco-Cuaresma et al. 2014). Finally, in the work H8 the analysis was made (by Dr. Ewa Niemczura) on shift-and-stacked spectra of the primary components of two out of three systems described there. In this case, a method based on the spectra synthesis code SYNTHE (Kurucz 1993) was used. The spectra were first corrected for the influence of other components. This analysis also resulted in abundances of ~30 chemical elements.

The knowledge of masses, radii, temperatures and/or the metallicity allows for reliable assessment of age and evolutionary status of a given system, e.g. by comparing the resulting parameters with the models and finding the best-fitting isochrone. Such a comparison was done in every publication (with a small modification in H5, where single-lined binaries were studied), on the basis of several popular and widely approved sets of isochrones: mainly Padova/PARSEC (Bressan et al. 2012; Marigo et al. 2017; papers H1, H3, H4, H5, H6, H7, H8), but also Dartmouth (Dotter et al. 2007; papers H1 and H2), MESA (Paxton et al. 2011; Dotter 2016; paper H9), and Yonsei-Yale (Y2; Yi et al. 2001, Demarque et al. 2004; paper H1).

The final step was determination of distance, with the code JKTABSDIM[5], which was used in all publications. It is a simple code that uses the $T_{\rm eff}$ estimates to calculate luminosities L and a set of bolometric corrections, in order to estimate absolute magnitudes in given bands. These are compared to the apparent brightnesses, which enables calculation of the distance (it is required to make an assumption about the interstellar extinction). JKTABSDIM also calculates distances from several $T_{\rm eff}$-surface brightness relations.

The resulting distances were then compared with up-to-date geometric parallaxes, from *Hipparcos* and *Gaia* (DR1 and DR2) missions. The agreement achieved was usually good or very good, but for the more distant systems the errors from JKTABSDIM were smaller than from the parallaxes.

4 Depending on the software used, it can be metallicity [M/H] or iron abundance [Fe/H], which is often assumed to be equal to [M/H].

5 http://www.astro.keele.ac.uk/jkt/codes/jktabsdim.html

Results

Low-mass stars

The first group of objects of my interest were late-type dwarfs, for which I assumed 0.9 M☉ as the upper mass limit. These object are interesting not only because of a relatively low number of well-studied examples, but also due to discrepancies observed between the models and measurements. Low-mass stars in close eclipsing binaries are often, but not always, larger and colder than predicted by the theory. There are several promising explanations of this phenomenon, all including influence of magnetic fields and rotation (dynamo mechanism) on convection, but so far none of them provides satisfactory explanations for all cases.

The derivation of parameters of late-type stars was the topic of my Ph.D dissertation, and from the time of its preparation come the observations of ASAS J011328-3821.1 (ASAS-011), described in the paper H1. This publications still does not include the whole methodology (it misses for example the spectral analysis), and the resulting parameters were not derived with the desired precision of 3%, but ASAS-011 turned out to be a very interesting case for other reasons. It is a multiple system, of spectral type M, with the masses of components of the eclipsing pair A=Aa+Ab being 0.612 i 0.445 M☉. The brightness of the third light B is between Aa and Ab, thus it is also a late-type star. During the analysis it turned out that the B itself may be a binary, composed of two similar stars of masses 0.50-0.55 M☉. ASAS-011 shows strong chromospheric activity, which manifests in Hα emission from at least three stars, and presence of cool stellar spots that modified the shape of the LC. It is worth to note that the LC itself did not change much over the course of roughly one year, which was in contrary to many other low-mass systems known at that time[6]. Additionally, low mass ratio of the eclipsing pair (q = 0.73) puts the two components relatively far from each other on the M-R (and other) diagrams, which makes finding a common isochrone quite challenging. Therefore, despite not reaching the precision of 3%, the analysis of ASAS-011 turned out to be an important contribution to studies of M-type stars.

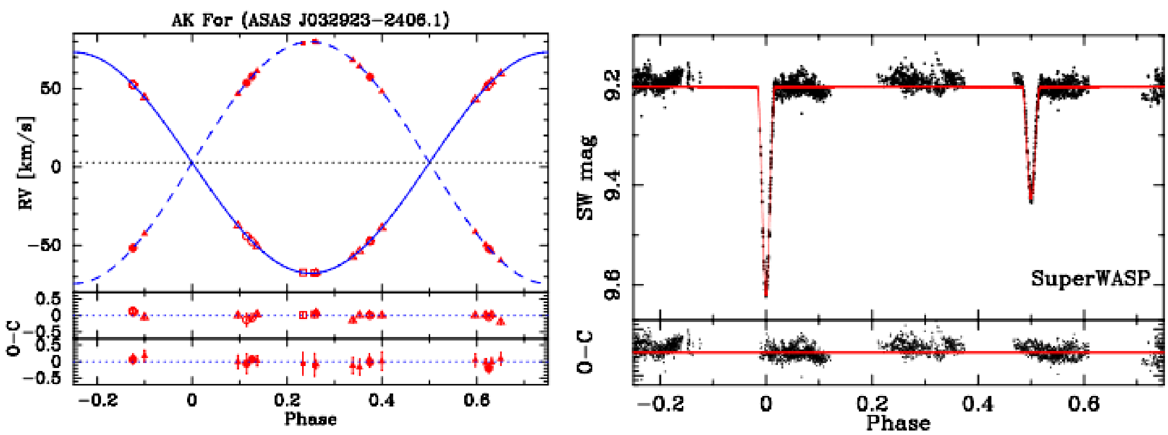

Fig. 2: Radial velocity curve (left) and SuperWASP light curve (right) of AK Fornacis. Figures taken from H2.

Another interesting low-mass system is AK Fornacis (Fig. 2), described in the work H2. Despite being known as a K3-type DEB (Gray et al. 2006), there was no analysis of this star published before 2014. It is the brightest (V = 9.14 mag) low-mass DEB known to date, and has one of the best mass measurements in the literature, with uncertainties reaching 0.14 and 0.11%. Precision in radii was, unfortunately, significantly worse: 2.9 and 2.6%. Incredibly small mass errors were possible to reach thanks to very precise RV measurements, with standard deviation (rms) of about 90 m/s - a level sufficient to detect massive circumbinary planets. Such a precision was reachable thanks to slow rotation of the components, related to a relatively long orbital period of 3.98 days. It is worth to note that the observed properties of AK For are well reproduced by the models, despite the fact that

6 As it was later revealed be observations from the *Kepler* satellite, the position of spots and shape of the LC can change in time scales of even single weeks, which was mentioned in papers H6 and H9.

the system is quite active, with Hα emission from both components, and presence of cold, evolving spots. The high level of activity can not be, therefore, explained with the dynamo mechanism, due to the slow rotation.

Apart from systems of two low-mass stars, several other pairs, with only the secondary being such a star, have been described. In these cases the primaries have earlier spectral types (F, G) and are significantly brighter. This brightness difference is the main obstacle in observations of such systems, as it makes the cooler secondary difficult or even impossible to detect in optical-band spectra. One of the possible ways to overcome this is to observe in the infrared (IR), where the contrast is lower. Such observations of three DEBs, ASAS J052743-0359.7 (ASAS-052), ASAS J065134-2211.5 (ASAS-065), and ASAS J073507-0905.7 (ASAS-073), have been performed at the Subaru telescope with the IRCS spectrograph, and described in publication H8. On the basis of optical spectra of ASAS-065 and -073 it was still possible to estimate RVs of the secondary, but these measurements were first considered unreliable, and their correctness was confirmed only after RV measurements from the IR spectra. On the other hand, in case of ASAS-052, the RVs of the cooler star come purely from IRCS data. ASAS-065 and -073 have since been included into DEBCat. The rms of the RV fit of the primary of ASAS-065 is only 19 m/s, which is a level that theoretically allows to search for circumbinary planets.

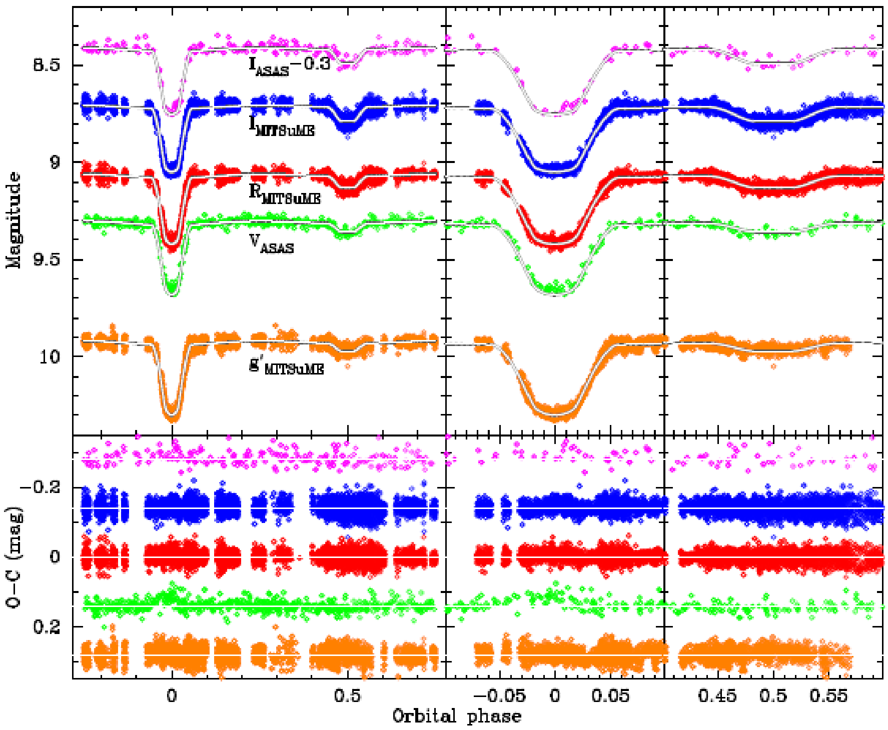

Fig. 3: ASAS-073 light curves from the ASAS survey (bands *V, I*) and MITSuME observations (bands *g', R, I*). This system contains a low-mass component, and is a very good candidate for a PMS eclipsing binary. It is now listed in the DEBCat. Figure taken from H8.

Additionally, in such systems the secondary minima are very shallow in the optical bands, with their depth being comparable to or even smaller than the spread of the data points from ASAS or SuperWASP. The successful LC analysis of the three described cases was possible to do only thanks to the MITSuME light curves (Fig. 3), obtained from dedicated observations. Spectral analysis was performed for ASAS-065 and -073, but only for their primaries, and in case of ASAS-052 the effective temperatures were estimated from T_{eff}-colour index relations, and metallicity from isochrone fitting. From these cases, only the secondary in ASAS-065 showed significant discrepancies between parameters resulted from the modelling, and those predicted by isochrones. It is also worth to note that the isochrone fit to ASAS-073 suggested age between 10 and 25 Myr, thus the PMS evolutionary phase. Together with V1200 Cen (Coronado et al. 2015), this system is the best PMS candidate in a DEB that was found in the ASAS sample, and also one of the brightest objects of this kind ($V = 9.30$ mag).

The fourth case of a G+K type pair is KIC 11922782, from the works H6 (derivation of masses and radii) and H9 (spectral analysis). In this case the contrast was small enough to enable RV measurements of the secondary from optical spectra, and the LC from the *Kepler* satellite enabled to reach a very good precision of results. However, the spectral analysis could also be done only for the primary, on its disentangled spectrum.

Giants

The second group of interesting targets were DEBs with evolved components - giants or subgiants. Especially pairs composed of two such stars. There are two such cases included in this Achievement: HD 187669 (from the work H3) and KIC 9246715 (first results in H4, improved in H9).

At the time of publication, HD 1875669 was the first case a of Galactic double-giant system with parameters calculated with such a high precision, and a topic of a press release[7]. Additionally, it shows a total primary eclipse, during which a high-resolution spectrum was taken. The publication H3 is a result of works of two independent teams (the other led by Dr. Dariusz Graczyk), which tackled the same set of photometric and spectroscopic data with different methods. Such an approach allowed for reliable assessment of systematic errors, and comparison of results from various methods, for example: atmospheric parameters obtained from tomographically disentangled spectra with those from the spectrum taken during totality (Fig. 4), or brightness ratios obtained with TODCOR vs. ratios derived from LC fitting. It is worth to note the precision of RVs at the level of 30-50 m/s, precision in masses of 0.26%, low uncertainty of the age of the system (150 Myr, 6%), and precision in distance determination (3%) better than from *Gaia* DR2 parallax (3.6%).

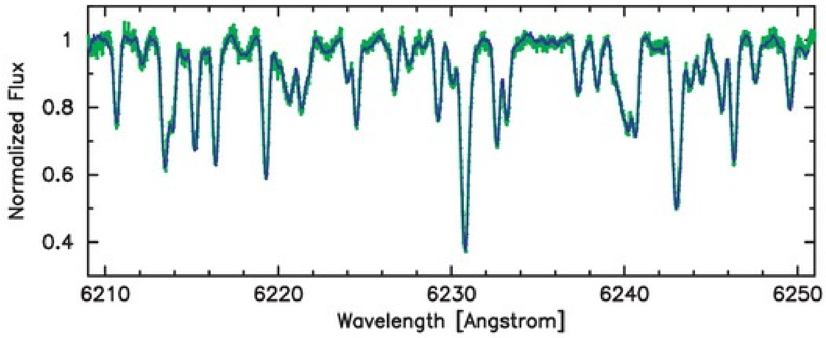

Fig. 4: Comparison of a tomographically disentangled (blue line) spectrum of the secondary, with a spectrum recorded during the total eclipse (green) of HD 187669. Figure taken from H3.

In the same year (2015) the paper H4 was published, the first one presenting KIC 9246715, which at that time was only the third case of a well-studied Galactic double-giant system. In H4 there were only 8 RV measurements presented, which hampered the final precision of mass determination. This system has been re-analysed in H9, where 17 measurements were used, and disentangled spectra of both components were analysed, resulting in determination $T_{\rm eff}$ of both components, and [M/H] of the system. Very high precision in RVs was reached in both papers (~50 m/s), which in H9 enabled obtaining one of the lowest relative uncertainties in mass to date (~0.15%). A comparison with isochrones revealed that the more massive component is currently a red clump giant, and recently had started burning helium in the core. Meanwhile, the secondary is at the red giant branch, and is growing rapidly.

Both HD 187669 and KIC 9246715 are currently listed in the DEBCat (they are shown in the right panel of Fig. 1 as the top four star symbols). Apart from their analysis, I have a significant contribution to analyses of other DEBs with giants and sub-giants: ASAS J010538-8003.7, ASAS J182510-2435.5, V1980 Sgr (Ratajczak et al. 2013), ASAS J184949-1518.7, BQ Aqr, and V1207 Cen (Ratajczak et al. 2016). I would also like to mention that several systems from the *Kepler* field - KIC 4851217, 8552540, 10031808, 10583181, and 11922782 - contain components that are

7 E.g.: http://www.national-geographic.pl/aktualnosci/polscy-astronomowie-zwazyli-olbrzymy http://naukawpolsce.pap.pl/aktualnosci/news%2C404327%2Cpolscy-astronomowie-dokladnie-zmierzyli-dwa-gwiazdowe-olbrzymy.html

close to the end of their MS evolution, but still burning hydrogen in cores. Several other cases also include giants, but they are single-lined spectroscopic binaries (SB1), and will be briefly described later.

Pulsating stars

An interesting feature of KIC 9246715 are the solar-like oscillations, detected in its light curve. It is a kind of pulsations induced by convection in the outer layers of the stellar atmosphere, similarly as in the Sun. The frequency of the strongest oscillations, ν_{max}, and the separation between frequencies, $\Delta\nu$, depend on the effective temperature, log(g), and the mean density of the star, therefore they allow to independently estimate mass and radius of the oscillator (Kjeldsen and Bedding, 1995; Kallinger et al. 2018). Thus, the solar-like oscillations are very important for the stellar astrophysics, and of high value are eclipsing binaries with an oscillating component, such as KIC 9246715, which allow for verification and calibration of the asteroseismic scaling relations for M and R (Brogaard et al. 2018). At the time when the paper H4 was published, KIC 9246715 was only the second such case, with masses and radii precisely estimated from the LC+RV analysis. In a work independent from mine, Rawls et al. (2016) have shown that the oscillations come from the component that is burning helium in the core, probably the more massive one. The errors in parameters were, unfortunately, too large to unambiguously define the more massive component, and the resulting radii appeared to be too small for the red clump phase. In order to reach consistency between models and measurements, the authors had to *ad-hoc* assume unusual values of parameters related to convection. The results of the later work H9 turned out to be more precise, and consistency with isochrones was straightforward, without additional assumptions.

Apart from KIC 9246715, in the *Kepler* sample there were several more solar-like oscillators. These are the same SB1 systems mentioned above, which will be described later, and one blend of a single, oscillating red giant with a background DEB (KIC 8718273).

Another kinds of pulsations present in systems from the *Kepler* sample are δ Scuti (dSct) and γ Doradus (gDor) pulsations. The former are pressure modes pulsations, showing periods of several hours, while the latter are gravitational modes with periods of an order of magnitude longer (0.5 - several days). Both can appear in similar stars, i.e. A- or F-type dwarfs, and can even be simultaneously present in the same star (called a hybrid pulsator). Currently, we know of only a handful of DEBs with such pulsators, and even fewer of them have their stellar parameters precisely measured. The DEBCat lists only two systems with gDor puslations, and only one with dSct.

The system KIC 4851217, from the paper H9, contains a dSct-type pulsating star. Oscillations in this pair had been known before (Gies et al. 2012), but their type was not determined. The work H9 was not the first one with RV measurements and mass determination, but the previous results (Matson et al. 2017) were much less precise. Unfortunately, due to rapid rotation (42 and 65 km/s) and large difference in brightness of the components, the final precision in stellar parameters cited in H9 is only 5-6%, instead of the desired 2-3%. Nevertheless, KIC 4851217 is an important case of a DEB with a pulsating component.

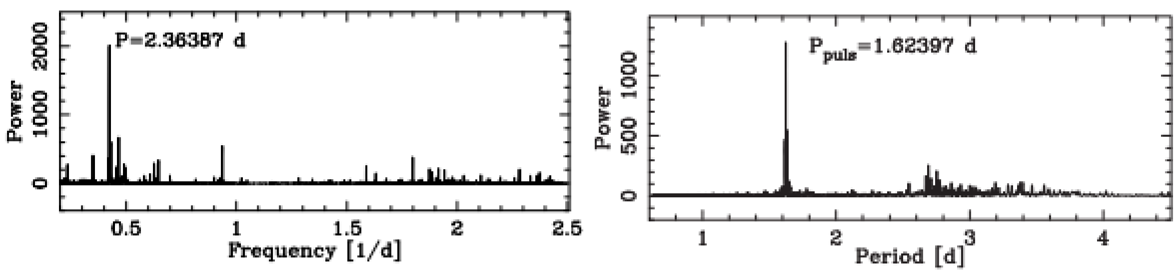

Fig. 5: Lomb-Scargle periodograms of the residuals of *Kepler* LC fits of KIC 10031808 (left, from H6) and KIC 10987439 (right, from H9). The detected frequencies strongly suggest gDor type pulsations.

A much better precision of stellar parameters has been reached for KIC 10031808 and KIC 10987439, two systems described in papers H6 (masses and radii) and H9 (spectral analysis). They both contain gDor-type pulsators (Fig. 5), which had not been noted before. KIC 10031808 on its own is one of the better studied systems from the *Kepler* sample, with atmospheric parameters of both components obtained from analysis of two disentangled spectra, precisely determined age (uncertainty of ~40 Myr), and a nearly perfect agreement between measurements and predictions from the theory of stellar structure and evolution. Comparison with isochrones suggests that pulsations more likely come from the lower-mass component, but the other one could have been pulsating in the past. KIC 10031808 is therefore an interesting case that might help to better understand the mechanism that sustains stable pulsation modes in this class of stars.

In KIC 10987439 the more massive component is the one that shows pulsations. Both masses and radii are calculated with a good precision, but only one disentangled spectrum was suitable for iSpec analysis and direct determination of T_{eff} and [M/H]. Interestingly, the amplitude of pulsations is very small, only 33 ppm, and the pulsator is located at the edge of the gDor instability strip on the H-R diagram, at the lower-mass side. Together with KIC 10031808, this system doubles the number of known, precisely measured stars of gDor type.

Another example that should be mention is KIC 4150611, where the dominant component is a hybrid gDor/dSct pulsator, but this is only one of many interesting features of this amazing object.

DEBs in multiple stellar systems

KIC 4150611 is a multiple composed of at least five stars, and the subject of publication H7. The uniqueness of this object comes, among others, from the fact that there are four different periods of eclipses observed in the *Kepler* light curve: 94.2, 8.65, 1.52 and 1.43 days. On high-angular-resolution images taken with AO systems, there are three point sources detectable, two of which constitute the visual binary ADS 12310 AB. The visual component A is in fact a hierarchical triple, composed of the aforementioned hybrid pulsator, transited every 94.2 days by a pair of M-type stars, which themselves form an eclipsing binary with the period of 1.52 d. The visual component B is a pair of G-type stars on an eclipsing, eccentric orbit with period of 8.65 d. The source of the 1.43 d period is still unclear. It is possibly related to the third point source - probably a background star. The complicated configuration is summarised in Fig. 6. This system was subject of a press note[8].

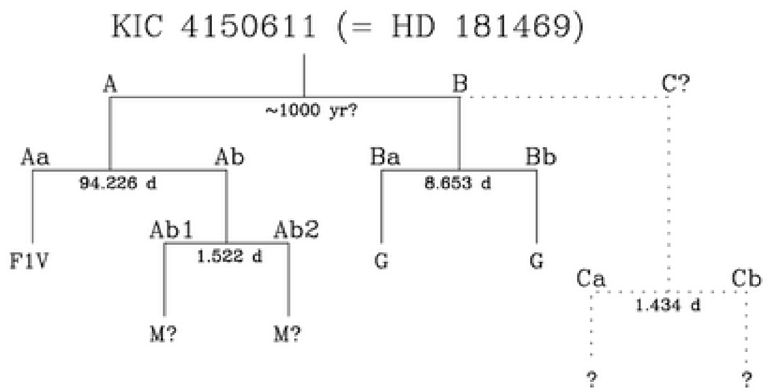

Fig. 6: Configuration of the multiple system KIC 4150611. Dashed lines present the putative situation, when the point source C, visible in images, would be the 1.43 day DEB, gravitationally bound to AB. The postulated additional body around A is not marked. Figure taken from H7.

The architecture of this multiple was finally confirmed in H7. In this work one can also find first RV measurements of the pulsator and the G-type pair, a full model (LC+RV) of the G-type pair (with 1.1% and 5.5% uncertainty in masses and radii, respectively), and estimation of the age of the system. Additionally, there are also hints (mainly from astrometry of the visual binary) of yet another body, that orbits the sub-system A with the orbital period of the order of single years. In such case, KIC 4150611 would be a sextuple, and there are only several such systems identified in the Galaxy.

8 E.g. https://phys.org/news/2017-03-astronomers-rare-multi-eclipsing-quintet-stars.html

There is still a possibility that this putative body is itself a binary, and is responsible for the 1.43 day period. Then, the whole system would be composed of seven stars (a septuple), which would only be a third case reported.

Many of the eclipsing systems included in this Achievement are in fact multiples. The "multiplicity" can manifest in several ways, for example:

- the DEB is a component of a visual binary (ASAS-011, ASAS-052, ASAS-065, KIC 4150611, KIC 5598639, KIC 10191056);
- the DEB shows periodic eclipse timing variations (KIC 4758368, KIC 5598639, KIC 6525196, KIC 7821010, KIC 10991989, probably also KIC 4851217);
- the DEB shows periodic modulation of the centre of mass velocity (KIC 6525196, KIC 10583181);
- spectral lines not coming from the DEB are seen in the spectra (ASAS-011, ASAS-052, KIC 415061, KIC 4758368, KIC 6525196, KIC 10191056, KIC 10991989).

Description of all cases would be too long, thus only the more interesting ones are briefly presented below.

The aforementioned ASAS-052 (paper H8), where the secondary of the eclipsing pair is a low-mass star for which the RVs could be calculated only from the IR spectra, is in fact a quadruple, composed of two spectroscopic binaries, A=Aa+Ab and B=Ba+Bb, seen on the sky as a visual pair (Fig. 7). It was possible to measure RVs of all components, and to determine the properties of the relative orbit of A and B, on the basis of archival and new astrometric measurements.

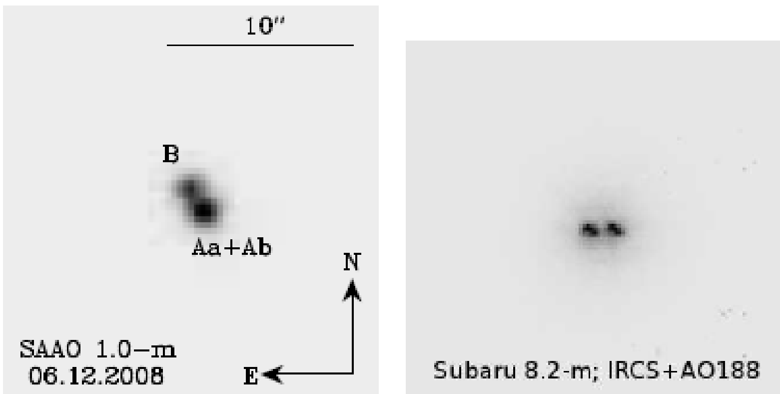

Fig. 7: Examples of DEBs as components of visual binaries. *Left*: ASAS-011 (H1) observed by the 1.0-m Elizabeth telescope in SAAO. The component marked Aa+Ab is the DEB. *Right*: ASAS-052 (H8) observed with the Subaru telescope with the IRCS camera and AO-188 adaptive optics system. The component on the right is the DEB, while the one on the left is a non-eclipsing SB2. Figure taken from conference proceedings Hełminiak et al. (2015a).

In the spectra of KIC 4758368 and 10991989 (paper H5) only one star is detectable, a red giant on a long-period, circumbinary orbit around a short-period DEB. The DEBs in these systems show strong eclipse timing variations (ETVs), which were transformed into the RVs of the centre of mass of a given DEB (Fig. 8), which, combined with direct RVs of the outer giants, enabled to determine the parameters of the long-period orbit. When the mass of the third star is known (the giant in KIC 10991989 shows solar-type oscillations), such situation enables to estimate the total mass of the eclipsing pair, and absolute values of individual radii. The outer orbit solution for KIC 4758368 has been improved in the Appendix of paper H9.

A similar case is KIC 6525196 (H6), but in his specta one can detect three sets of lines, thanks to which dynamical masses of three stars could have been measured with high precision (0.5-1.5 %). The RV of the center of mass of the DEB shows periodic modulation, in agreement with the ETVs from literature.

In the spectra of KIC 5598639 (H5), which is also a visual binary, again only the third star B is detectable, and the eclipsing A=Aa+Ab is not. However, in this case it is not possible to determine the parameters of the outer orbit, because the period is too long, and RV variations too small (at the level of the instrument's stability). But periodicity in ETVs was found, with a relatively short period of 81.6 d, suggesting an additional body around A. From the ETV's amplitude one can estimate the mass to be low, with the lower limit in the Brown Dwarf regime.

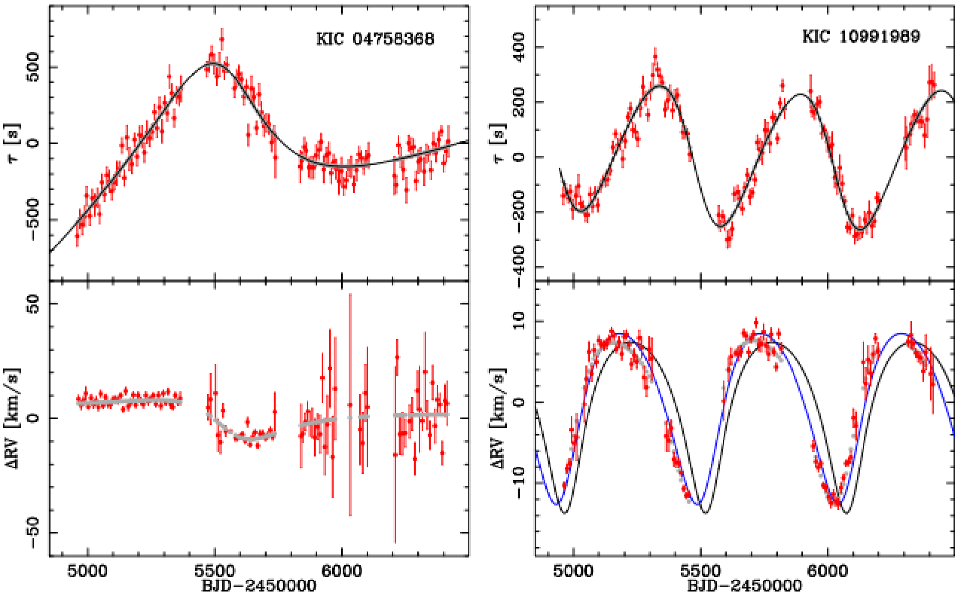

Fig. 8: Eclipse timing variations (top row) and RVs calculated from them (bottom row) for KIC 4758368 (left column) and KIC 10991989 (right column). Black lines in the top panels are the modelled ETVs, which was the base for the model RVs (grey dots in the bottom panels). Solid lines in the bottom right panel are variations of the centre of mass velocity predicted by the exact solution from Rappaport et al. (2013; black), and after taking uncertainties ephemeris into account (blue). Figure taken from H5.

Other systems with small parameter errors

Apart from a number of DEBs showing interesting and rare properties, and representing poorly studied classes of stars, in papers H6 and H9 there are cases of binaries with a complete set of very well measured properties (masses, radii, temperatures, metallicity, age, distance, etc.). These are: KIC 7821010, KIC 9641031 (both appeared first in H6 and were reanalysed in H9), and KIC 3439031 (in H9 only).

KIC 9641031, a.k.a. FL Lyrae, is the only system from my *Kepler* sample that had its properties precisely measured before the satellite's launch (Popper et al. 1986), and is listed in the DEBCat. It was included to the list of HIDES targets because it met the main criteria, and the use of satellite-borne photometry and a more stable spectrograph gave hope for a vast improvement of the parameter uncertainties. Indeed, the errors in masses given in H9 are 2-3 times smaller than in Popper et al. (1986), being at the level of 0.4-0.6%. The errors in radii are also better than before, but only slightly (1.8 and 2.6%), because of cool, rapidly evolving spots on both components. More importantly, the value of the radii in H9, especially of the secondary (0.900 $R_\odot$), are significantly different from the Popper's et al. solution (0.963 $R_\odot$). The reason is probably a different approach to estimate the ratio of radii, which in Popper et al. (1986) is based on obsolete and imprecise $T_{\rm eff}$-colour index calibrations. Supporting the correctness of the new solution from H9 is the fact, that it is in better agreement with modern models of stellar structure and evolution (Fig. 9). The case of FL Lyr clearly shows that many older results, widely considered as reliable, need to be revised and corrected with modern instrumentation and methods of analysis.

The system KIC 78210101 has been mentioned previously in the context of periodic timing variations. Since 2013 it has been presented at several conferences as a host to a circumbinary planet, with orbital period of 994 days, detected via timing[9]. These claims were later confirmed by Borkovits

9 E.g. http://www.astro.up.pt/investigacao/conferencias/toe2014/files/wwelsh.pdf

et al. (2016), but till now there is no proper publication describing this discovery. The paper H9 presents, at the moment, the most detailed analysis of this interesting object, with the precision in resulting parameters of 0.9-1.5%. It should be mentioned that the expected RV modulation induced by the planet, is at the level of 30-40 m/s, which is just at the level of precision of the HIDES spectrograph, and definitely within capabilities of other, more precise instruments.

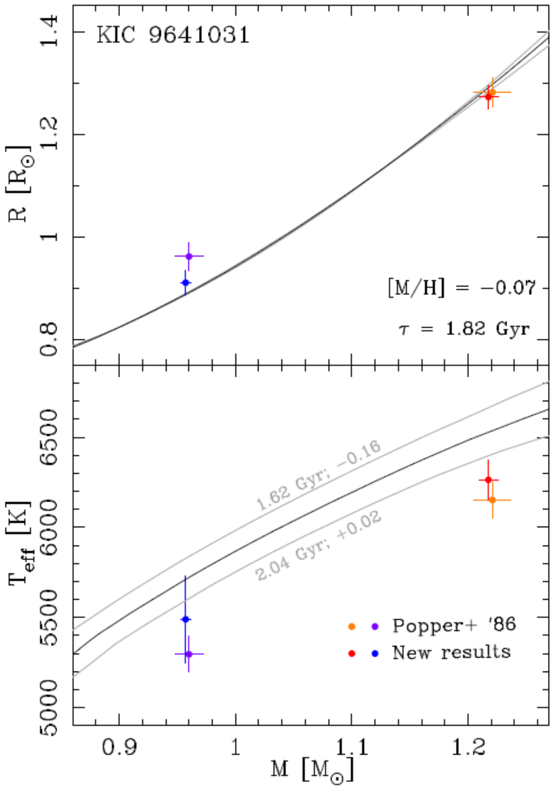

Fig. 9: Comparison of the results obtained for FL Lyr (KIC 9641031) with theoretical models on *M-R* (top) and *M-*T_{eff} (bottom) diagrams. Red and blue points show the results from the paper H9. The black solid line is the best-fitting isochrone, for metallicity obtained from iSpec analysis of both components. Gray lines are best-fitting isochrones for metallicities varied by the formal [M/H] error (±0.09 dex). The results from H9 are in agreement with models within error bars. Orange and violet points are the results from Popper et al. (1986), which can not be reproduced with a single isochrone on the *M-R* diagram, and on the *M-*T_{eff} one needs to assume an unlikely high value of metallicity.

KIC 3439031, described only in H9, is on the other hand a pair of twins. Both components have almost identical masses, radii, effective temperatures (agreement between components is better than 2σ), all with very small errors (down to 0.2%). Such systems potentially allow for empirical testing of the so called Vogt-Russell theorem, which states that the structure of a star, in hydrostatic and thermal equilibrium with all energy derived from nuclear reactions, is uniquely determined by its mass and the distribution of chemical elements throughout its interior. This assumption is absolutely fundamental for stellar astrophysics, although it has never been observationally confirmed.

Finally, I'd like to mention the system HD 149946 (EPIC 202674012), for which I collected 15 spectra between 2012 and 2015, and which was observed by the *Kepler* satellite during the C2 campaign of its *K2* mission in 2014. The analysis of the *K2* light curve was performed by Maxted & Hutcheon (2018), who also gave estimates of effective temperatures of both components, but used only four, publicly available spectra. In the research note[10] Hełminiak et al. (2018), I made use of their partial results, combined them with an RV fit to all of my measurements, and obtained a full set of absolute stellar parameters, with the level of uncertainties of 0.8 for masses and 0.3-0.5% for radii. Both components are still on the MS stage, but the primary is close to its end.

SB1 eclipsing binaries

The publication H5 is a bit unusual in comparison with other papers. In H5, the whole program of observations of targets from the *Kepler* field was introduced and described, and only systems with one set of lines present in the spectra were analysed. Some of them, which RVs do not coincide with the period of eclipses, have been mentioned previously (three multiples, one blend). The remaining five

10 It is a short form of a publication that is not peer, nor language reviewed, therefore it was not included in the Habilitation Achievement.

turned out to be single-lined spectroscopic (SB1) and eclipsing binaries. For one of them, KIC 10614012, only the orbital solution was updated (previously given in Beck et al. 2014), and for four others the LC modelling was done (for the first time), together with RV fits (Fig. 10). Metallicity of these systems was known beforehand (and given in KEBC), thus it was possible to estimate absolute masses of components and distances to these systems, using partial parameters from the LC fits, observed colour indices (especially *g'*- *r'*), and knowing which component (visible in the spectra or not) is the hotter one (from the behaviour of the RV curve during eclipses).

Such comparison revealed, that the components detectable in the spectra of KIC 8430105, 10001167, and 10015516 are evolved red giants, and their unseen companions are less massive, but hotter main-sequence stars of spectral types G or F. The first two systems also show solar-type oscillations, and the mass and radius estimates from isochrones are in a nice agreement with results from asteroseismology. Additionally, the giant in KIC 10015516 seems to be in an interesting evolutionary stage - at the end of burning helium in core, just before moving towards the asymptotic giant branch. The last pair, KIC 3120320, is composed of two main-sequence stars with masses 1.02 (seen in spectra) and 0.55 $M_\odot$, and thus resembles the eclipsing pair A of ASAS-052. Unfortunately, the secondary was not securely detected even in the IR spectra (from the APOGEE survey).

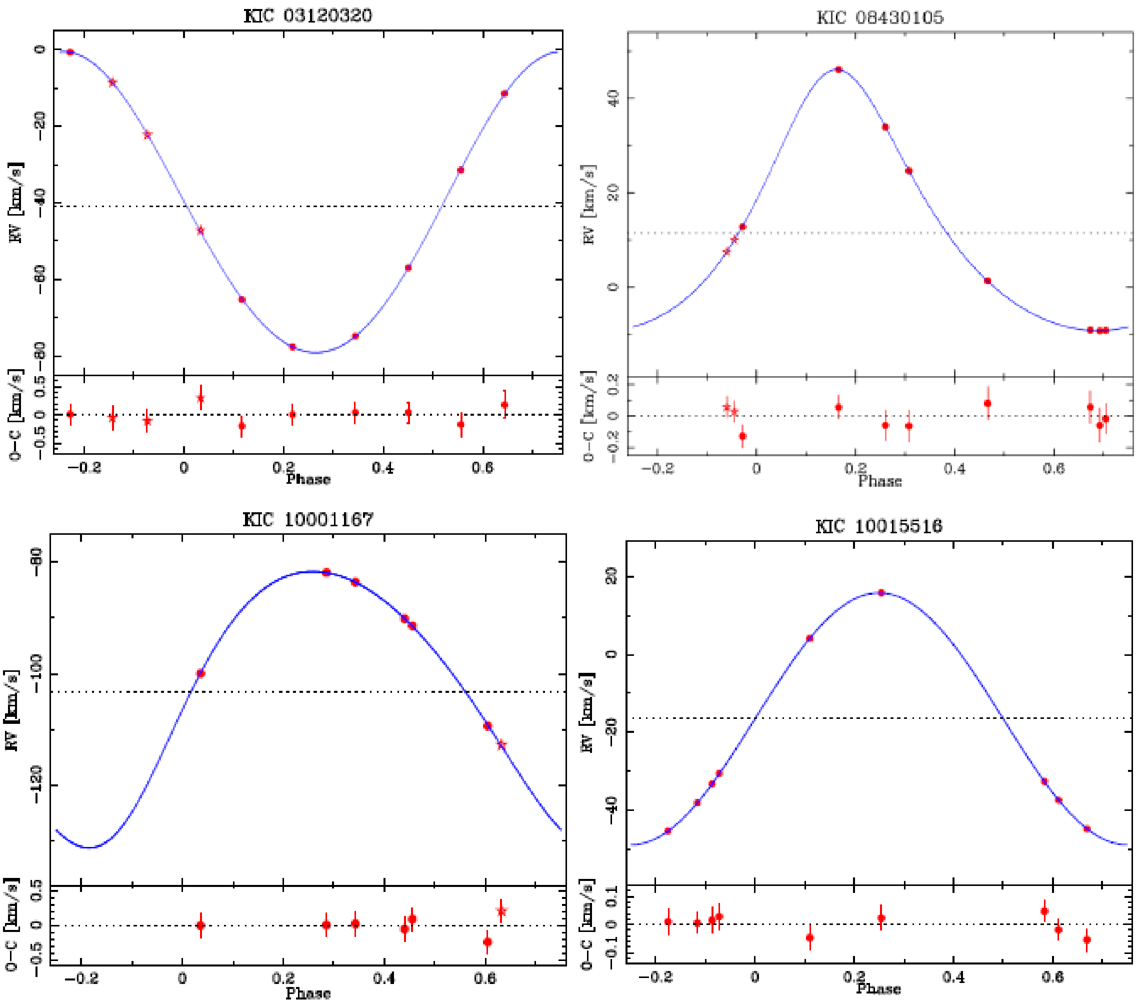

Fig. 10: Radial velocity curves of four SB1 systems from the paper H5, for which LC fitting was performed. Dots mark the measurements from HIDES data, and stars from the APOGEE survey.

5. Other scientific achievements

Studies of detached eclipsing binaries, especially with the use of high-resolution spectroscopy, is the main but not the only topic of my interest. During my first post-doc, at the Pontificia Universidad Católica de Chile, I joined the scientific team of the *Vista Variables in Via lactea* (VVV) project, which was a public ESO photometric survey of the Galactic bulge and part of the disk, made in several near IR bands (*Z,Y,J,H,K*), in order to e.g. identify a large number of new variable stars of various kinds, or determine the exact structure of the Milky Way around its centre and behind it. My contribution to the project was, for example, in the preparation of the *VVV Data Release 1* catalogue (Saito et al. 2012), activities of the "VVV Templates" group (Angeloni et al. 2014), or in organisation of several conferences from the "VVV Science Meeting" series. Apart from the two peer-reviewed publications, I co-authored six conference proceedings in the years 2011-2014.

The topic of my own research within the VVV project were, again, detached eclipsing binaries, but in the context of distance determination, and usefulness for studying the structure of the Milky Way. The effect was the paper Hełminiak et al. (2013), which presented a method of distance determination (together with stellar parameters) to a large sample of DEBs, on the basis of photometric data (from OGLE and VVV) only. One of the results was a sample of more than a dozen systems laying behind the Galactic bulge, including targets in the Sagittarius dwarf spheroidal galaxy (Sgr dSph). Unfortunately, due to observational difficulties (low brightness, probable early spectral type, crowdiness), there were no spectroscopic observations taken that were sufficient to create full models of these systems.

Apart from the VVV, during my stay in Chile I was also involved in an instrumental project of construction and commissioning of PUCHEROS - the first high-resolution spectrograph build in this country (Vanzi et al. 2012). I conducted one of the first scientific observations with this instrument, was testing its stability, and was a referee of the first diploma thesis that used PUCHEROS data, a B.Sc. dissertation of Johanna Coronado Martinez. The paper Coronado et al. (2015) describes some of the results of this bachelor thesis. Apart from the two peer-reviewed publications, I have contributed to two conference proceedings and two telegrams, which included PUCHEROS data. The experience I gained working with PUCHEROS was useful later, when I participated in commissioning of the BACHES spectrograph of the *Solaris* network, and the *astro-comb* module (a reference source for precise wavelength calibration) for the HIDES spectrograph.

Shortly after moving to Hawaii and starting the work for the Subaru Telescope, in 2013 I joined another international observing project - *Strategic Exploration of Exoplanets and Disks with Subaru* (SEEDS). It was a programme of detection and characterisation of exoplanets and disks via imaging with adaptive optics and coronagraphy. I have been interested in exoplanets and AO observations since my Master thesis, which was based on AO data, and in which I was testing the potential of planet detection with relative astrometry of visual binaries. Within SEEDS I've participated in the activities of the "Nearby stars" subgroup, and in observations for the project. I was also representing SEEDS on several international conferences, showing, for example, a review of the results (Hełminiak et al. 2015b).

The topic of my own research in SEEDS were stars with known RV modulation. The aim was a direct detection of a body that induces the trend, and, eventually, determination of orbital elements and dynamical masses of the components. It has been successfully achieved in the case of V450 Andromedae (Hełminiak et al. 2016), which was postulated to harbor a brown dwarf (Perrier et al. 2013). The body responsible for the velocity variations turned out to be an M-type dwarf, which has been spotted in SEEDS data four times. Several other bodies inducing long-term RV trends were also detected, and described in the paper Ryu et al. (2016), which I co-authored. As the aftermath of these activities, I was invited to give a talk at the XXXVIII general assembly of the Polish Astronomical Society in Zielona Góra (Hełminiak 2018). I continue the research on direct detection of planetary and brown dwarf candidates detected indirectly with other methods (i.e. RVs and ETVs) but within my own small observational program, which I conduct in collaboration with other Polish astronomers, and which focuses on bodies around eclipsing binaries. Test observations were made with the Subaru telescope, and currently a larger campaign is carried out at the VLT with the SPHERE instrument.

During my work on V450 And, I started to be interested in determination of atmospheric parameters from the spectra. It resulted in co-authorship of another SEEDS paper (Rich et al. 2017), and inspired the publication H9, included in the Habilitation Achievement.

In the context of my stay at Subaru, I should also mention my 2015-2016 participation in the Queue Mode Working Group. It is a group that designed, created, and finally implemented at the Subaru telescope a new *queue* mode of observations, initially only for the Hyper-Suprime Cam instrument. It was not a strictly scientific activity, but resulted in co-authorship of two peer-reviewed publications by Aihara et al. (2018a,b).

During my stay in Hawaii I've also become interested in another, relatively new type of observations: high-precision satellite-borne photometry. Initially regarding the *Kepler* satellite, but later also TESS and PLATO missions. It is a continuation of my interests in exoplanet detection (in this case via transits and ETVs).

In 2013 I joined the scientific team of the *Kepler* mission, becoming a member of a sub-group responsible for recognition of transit events and distinguishing from other kinds of variability (the "*Triage*" and "*Dispositioning*" steps). Direct results of the sub-group's work are catalogues of planetary candidates from 36 (Rowe et al. 2015) and 47 months of observations (Mullaly et al. 2015), as well as creation of automated algorithms for light curve classification. I've been included in the list of authors of both publications. My interest in satellite-borne photometry has later turned into the project of spectroscopic observations of DEBs from the original *Kepler* field and the *K2* mission, which resulted in papers H4, H5, H6, H7, and H9 of this Habilitation Achievement, and the research note Hełminiak et al. (2018).

With the successor of *Kepler*, the *Transiting Exoplanet Survey Satellite* (TESS), I am connected in two ways. First, in the year 2017 I joined the TESS consortium as a member of the sub-group SG1 of the *TESS Follow-up Observing Program* (TFOP). The SG1 makes ground-based imaging observations of transit candidates, in order to verify if an event is of a planetary origin, or was caused by a different phenomenon (nearby DEB, blend, instrumental systematics, etc.). As a member of this team, I conduct observations with the *Solaris* network of robotic telescopes. The first results of this collaboration have been recently presented (Quinn et al. 2019). For my own research purposes, in the frame of the *Guest Investigator* (GI) programme, I proposed acquiring TESS 2-minute-cadence light curves for a sample of ~200 selected DEBs, out of which 61 (as of 14.02.2019) have been observed. Together with my own RVs obtained so far, these data will be used for very precise determination of stellar parameters of an unprecedented number of stars simultaneously

In the future I intend to continue my collaboration in such space missione, especially in the *PLAnetary Transits and Oscillations of stars* (PLATO). I've joined the PLATO consortium in 2017 as well (group "*Photometric detection of circumbinary planets*", and the programme *PLATO Complementary Science*, PLATO-CS).

The *Solaris* network, mentioned already at several occasions, is another important project in which I participate (to date). It is a collection of autonomous observatories, based on 0.5-m telescopes dedicated to high-precision photometric observations, in several locations at the southern hemisphere (South Africa, Australia, Argentina). The characteristic feature of *Solaris* is the ability to conduct continuous (24/7) monitoring of a selected target. Since its initiation in 2010, I have participated in planning and preparations for the construction, but for logistic reasons I was directly involved in actual construction of only one observatory - SLR4 in Argentina (three installation visits in the CASLEO observatory in 2011 and 2013: preparation of the site, installation of the dome, the container, and the camera, first on-sky observations). Apart from that, I was involved in starting and commissioning of the BACHES spectrograph (Kozłowski et al. 2014, 2016), and represented the team during several international conferences. Since 2018, telescopes of the *Solaris* network have been supporting the TESS mission (Quinn et al. 2019).

During my scientific career, many times I have assisted other researchers with my experience in observations and RV measurements, and helped in gaining telescope time. Different kinds of my own observations (spectroscopy, photometry, or even optical interferometry) have been used in such publications as: Grellman et al.. (2013), Leloudas et al. (2015), Kahraman Aliçavuş et al. (2017), or Paunzen et al. (2018).

Toruń, 14.02.2019, ...

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