HIDES spectroscopy of bright detached eclipsing binaries from the Kepler field – III. Spectral analysis, updated parameters, and new systems.

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ABSTRACT

We present the latest results of our spectroscopic observations and refined modelling of a sample of detached eclipsing binaries (DEBs), selected from the Kepler Eclipsing Binary Catalog, that are also double-lined spectroscopic binaries (SB2). New high-resolution spectra obtained with the HIDES spectrograph, attached to the 1.88-m telescope of the Okayama Astrophysical Observatory supplemented the previous observations, allowing to improve physical parameters of some systems, and characterize three previously omitted. All the obtained radial velocities (RVs) were combined with Kepler photometry, in order to derive a full set of orbital and physical parameters.

Ten out of eleven SB2s have their component spectra tomographically disentangled, and spectral analysis was performed with ispec, in order to derive effective temperatures of components and metallicities of the systems. By comparing our results with theoretical models, we assess the age and evolutionary status of the studied objects. We find a good match to all but one systems. We have derived distances from thus determined parameters, and compare them with those from the Gaia Data Release 2. For systems previously studied by other authors, our new results lead to better consistency between observations and models.

Key words: binaries: spectroscopic – binaries: eclipsing – stars: evolution – stars: fundamental parameters – stars: late-type – stars: individual: KIC 3439031, KIC 4851217, KIC 7821010, KIC 8552540, KIC 9246715, KIC 9641031, KIC 10031808, KIC 10191056, KIC 10583181, KIC 10987439, KIC 11922782, KIC 4758368

1 INTRODUCTION

A great source of absolute fundamental parameter of stars are detached eclipsing binaries (DEBs) that are also double-lined spectroscopic binaries (SB2). They have been used for decades in stellar astrophysics (but not only) for many purposes, like testing models of stellar structure and evolution or for creating empirical relations between various stellar parameters, later used as calibrations for studies of single stars, like exoplanet hosts. To be useful, the resulting quantities must be known with sufficient precision (believed to be ~2-3 per cent in masses and radii Lastennet & Valls-Gabaud 2002; Torres et al. 2010), the set of presented parameters must be as complete as possible, and should include individual effective temperatures of components and, preferably, information about the chemical composition, such as metallicity and/or abundances of the most important elements (e.g. He, Fe, α-elements). The precision in absolute physical parameters can be reached with high-quality radial velocities (RVs) and time series photometry. The former can be calculated from high-resolution spectra obtained with spectrographs of sufficient stability. The most precise photometry comes from space-based observatories, such as CoRoT, Kepler, or TESS. The atmospheric parameters usually come from the analysis
of stellar spectra, provided that the individual spectra are properly separated from each other.

All these were the motivation for our program of high-resolution spectroscopic monitoring of a sample of bright DEBs from the original Kepler field, aimed for as precise and complete characterisation of the observed system, as possible, with the aid of unprecedented precision of the Kepler light curves (LCs). The programme was conducted between July 2014 and November 2017 on the 1.88-m telescope of the Okayama Astrophysical Observatory (OAO), equipped with the High-Dispersion Echelle Spectrograph (HIDES; Izumiura 1999). In this paper we present new spectroscopic observations, including three new objects, updated orbital solutions, and, for the first time in this project, spectroscopic analysis of tomographically disentangled spectra, from which we mainly obtain the effective temperatures and metallicities, that are later used for determination of ages. The manuscript is organized as follows. In Section 2 we present our final sample of eclipsing SB2s; in Sect. 3 we present the methodology, with the focus put on new data and spectroscopic analysis; Sect. 4 presents the results, including extended set of parameters, comparison with literature data and theoretical models that utilizes the newly obtained atmospheric parameters, and new hypothesis regarding the tertiary companion to an eclipsing SB2; Sect. 5 concludes our findings; and finally in Sect. A of the Appendix we present updated information about one SB1 system from our project, that was also re-observed recently.

2 THE FINAL SAMPLE OF TARGETS

In our spectroscopic programme dedicated to bright objects from the Kepler Eclipsing Binary Catalog (KEBC; Prša et al. 2011; Slawson et al. 2011; Kirk et al. 2016)\(^1\), we observed a total of 22 systems with various characteristics: from blends with background stars, through single- and double-lined spectroscopic binaries, to multiples containing as much as 5 components. The basic target selection criteria were as follows:

(i) Kepler magnitude \(k_{mag} < 11.5\), to have the targets within the brightness range of the telescope. This criterion was initially \(k_{mag} < 11.0\), but has changed in 2016, when several systems, fainter than \(k_{mag} = 11\) were included.

(ii) Morphology parameter (Matijević et al. 2012) \(m_{orph} < 0.6\) to exclude contact and semi-detached configurations.

(iii) Effective temperature \(T_{\text{eff}} < 6700\) K to have only late type systems, with many spectral features. We queried the temperatures from the Kepler Input Catalog (KIC; Kepler Mission Team 2009), although some of our objects turned out to be hotter.

Out of the 22 systems observed, to date we published data and analysed 19 of them: 9 single-lined binaries were studied in Helminiak et al. (2016, hereafter: Paper I), 8 double- and triple-lined systems in Helminiak et al. (2017a, hereafter: Paper II), the double-giant system KIC 9246715 was presented in Helminiak et al. (2015a, hereafter: K924), and a multi-eclipsing quintuple KIC 4150611 in Helminiak et al. (2017a). In this paper we focus on 11 systems, presenting new data for four objects, and three entirely new pairs, not yet studied. One of the previously described targets with new observations – KIC 10191056 – is a triple-lined system, that includes an eclipsing SB2 component (KIC 10191056 A). This system is the only one in this work for which we did not perform spectral disentangling and analysis. Spectral analysis of another triple-lined system – KIC 6525196 – is a subject of another dedicated paper (Alicavus et al., in preparation). Flux of the multiple KIC 4150611 is dominated by a hybrid \(δ\) Scuti/γ Doradus pulsator, which itself was also studied spectroscopically, and his metallicity and age have been estimated (Niemczura et al. 2015; Helminiak et al. 2017a). Here we also introduce three new SB2s, for which we apply the same working approach as to the rest of the sample.

Below we briefly describe the new objects. Similar descriptions of other targets can be found in Paper II and K924. Unless stated otherwise, this work is the first detailed study for a particular object.

\[ \text{KIC} 3439031 = \text{KOI} 4980, \text{TYC} 3134-978-1: \] This system, shows nearly equal, deep (>50 per cent) eclipses, suggesting it is composed of two very similar stars. Except brightness and position measurements, no literature data important for this study are available.

\[ \text{KIC} 4851217 = \text{KOI} 6460, \text{HD} 225524, \text{HAT} 199-10019, \text{ASAS} J194320+39571: \] The LC of this system shows strong ellipsoidal variations and, despite the short orbital period (2.47 d), separation of two minima in phase is different than 0.5, meaning a non-zero eccentricity. Identified as an eclipsing variable by the HATNET Variability Survey (Hartman et al. 2004), also listed later in the catalogue of variable stars in the Kepler field of view of the All Sky Automated Survey (ASAS-K; Pigulski et al. 2009). Its eclipse timing variations (ETV) were studied by Gies et al. (2012, 2015) and Conroy et al. (2014), and a long-term, parabolic trend in timing of both primary and secondary minima was noted. Furthermore, Gies et al. (2012) reported pulsations in the LC, which were later confirmed to be of a \(δ\) Scuti (dScut) type (Fedurco, priv. comm.). Finally, Matson et al. (2017) collected a number of medium-resolution spectra \((R \approx 4000 – 6200)\), and derived a preliminary set of orbital and physical parameters (e.g. \(M_1 = 1.43(5)\) and \(M_2 = 1.55(5)\) \(M_\odot\)), which we can compare with our results.

\[ \text{KIC} 10583181 = \text{KOI} 7344, \text{T-Lyr1-01013}, \text{TYC} 3544-2565-1: \] This system has been known as a DEB before the launch of Kepler. It has been identified by the Trans-atlantic Exoplanet Survey (TrES; Alonso et al. 2004). The Kepler light curve shows that the secondary eclipse is flat (occultation). By analysing the TrES data only, Devor et al. (2008) estimated the masses of both components: \(1.749(19)\) and \(1.049(15)\) \(M_\odot\) for the primary and secondary, respectively. Our spectroscopy allows us to revise these values. Later, Borkovits et al. (2016) detected strong ETVs with the period of \(-3.2\) yr, and derived parameters of the outer orbit. Their solution predicted that the modulation of the systemic velocity \(y\) of the eclipsing pair will be about 13 \(\text{km s}^{-1}\) (peak-to-peak), large enough to be detectable with our spectroscopy.

\(^1\) http://keplerebs.villanova.edu/
3 DATA AND ANALYSIS

We follow the same methodology as in Papers I, II, and K924. They present the observations, sources of publicly available data, RV calculations, and approach to RV and LC fitting. Here we only describe them briefly, and focus more on those that were not previously used.

3.1 New spectroscopy and RVs

As in previous works, the HIDES instrument was fed through a circular fibre, for which the light is collected via a circular aperture of projected on-sky diameter of 2.7 seconds of arc, drilled in a flat mirror that is used for guiding (Kambe et al. 2013). An image slicer is used in order to reach both high resolution (R ~ 50000) and good efficiency of the system. Spectra extraction was done under IRAF, using procedures dedicated to HIDES. Wavelength solution was based on ThAr exposures taken every 1-2 hours, which allows for stability of the order of ~40 m s$^{-1}$. The resulting spectra span from 4360 to 7535 Å.

The newly presented HIDES observations were done during several runs between May 2016 and November 2017, with the new observations of objects previously described taking place after October 2016. During that time a new queue scheduling mode was introduced at the OAO-1.88, and the final observations were done this way, instead of visitor mode.

As in Paper I, we also made use of the data collected by the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Allende Prieto et al. 2008; Majewski et al. 2017). We have extracted six individual visit spectra$^2$ of KIC 4851217, but this time we calculated the RVs ourselves, instead of using the values given by the survey, as in Paper I. Unfortunately, only three of them were recorded when the velocity difference between the components was large enough to be securely measured. Additionally, single archival spectra of KIC 4851217 and KIC 10191056 have been found on their ExoFOP-Kepler websites$^3$. These spectra (R ~ 40000) were taken on July 14, 2014 (KIC 10191056), and June 11, 2015 (KIC 4851217) with the TRES spectrograph, attached to the 1.5-m Tillinghast telescope of the Fred Lawrence Whipple Observatory (FLWO) in Arizona, USA. Two more targets have their TRES spectra available through ExoFOP – KICs 3439031 and 8552540 – but these observations do not influence the final solution significantly, and measured RV agree with models.

Finally, RVs of several of our targets have been reported and analysed by Matson et al. (2017). Apart from the aforementioned KIC 4851217, these are KICs 8552540 and 10191056. For the latter two objects, the agreement between Paper II and Matson et al. (2017) is, generally, very good. We do not include their RVs in our analysis, as the spectra were taken with lower resolution, and their inclusion does not change our results significantly.

RV measurements were done with our own implementation of the TODCOR technique (Zucker & Mazeh 1994), which finds velocities of two stars $v_1$ and $v_2$ simultaneously. As templates for the HIDES and TRES data we used synthetic spectra computed with ATLAS9 and ATLAS12 codes (Kurucz 1992), which do not reach wavelengths longer than 6500 Å. For the APOGEE observations we used synthetic spectra from the library of Coelho et al. (2005), which cover both optical and IR regions (3800-18000 Å), but have lower resolution than the ones from ATLAS9/12. Single measurement errors were calculated with a bootstrap approach (Helminiak et al. 2012), and used for weighting the measurements during the orbital fit, as they are sensitive to the signal-to-noise ratio (SNR) of the spectra and rotational broadening of the lines. All (previous and new) individual RV measurements are presented in Table B1 in the Appendix.

3.2 Kepler photometry

The RVs were supplemented by the long- and short-cadence Kepler photometry, which is available for download from

$^2$ http://dr12.sdss3.org/advancedIRSearch

$^3$ https://exofop.ipac.caltech.edu/
the KEBC. We used the de-trended relative flux measurements \( f_{\text{m}} \), that were later transformed into magnitude difference \( \Delta m = -2.5 \log(f_{\text{m}}) \), and finally the catalogue value of \( km\text{a} \) was added. From the systems presented here, only KICs 9246715 and 10987439 do not have short-cadence data available.

Even though our new systems have time-series photometry available from other sources, like the TrES survey, we only work on the Kepler data. Comparison of solutions based on Kepler observations with ones that base on TrES or ASAS data, has been discussed in Paper II.

3.3 Orbital solutions

The orbital solutions were found using our own procedure called \texttt{v2fit} (Konacki et al. 2010). We used it mainly to fit a double-Keplerian orbit to a set of RV measurements of two components, utilizing the Levenberg-Marquardt minimization scheme. The fitted parameters are: orbital period \( P \), zero-phase \( T_0 \), systemic velocity \( \gamma \), velocity semi-amplitudes \( K_1, K_2 \), eccentricity \( e \) and periastron longitude \( \omega \). Depending on the case, we also included such effects as: the difference between systemic velocities of two components, \( \gamma_2 - \gamma_1 \), linear and quadratic trends, or periodic modulation of \( \gamma \) caused by a circumbinary body on an outer orbit, parametrized analogously by orbital parameters \( P_3, T_3, K_3, e_3, \omega_3 \). In such case \( \gamma \) is defined in the code as the systemic velocity of the whole object. Whenever applicable, we simplified our fit by keeping the orbital period on the value given in the KEBC. Whenever \( \gamma_2 - \gamma_1 \) or \( e \) were found to be not significantly different from zero, the fit was repeated with those parameters fixed to 0. For KIC 4851217 we also searched for the difference between zero points of HIDES and APOGEE. This was not done for HIDES vs. TRES zero-points, because only one TRES spectrum per target is available.

Systematics that come from fixing a certain parameter in the fit are assessed by a Monte-Carlo procedure, and other possible systematics (like coming from poor sampling, low number of measurements, pulsations, etc.) by a bootstrap analysis. All the uncertainties of orbital parameters given in this work already include the systematics.

Moreover, to obtain reliable formal parameter errors of the fit, and the final, reduced \( \chi^2 \) to be close to 1, we were modifying the RV measurement errors either by adding a systematic term (jitter) in quadrature, or multiplying by a certain factor. Adding the jitter works better for active stars, when the RV scatter is caused by spots, and is compensated with the additional term. However, since \texttt{v2fit} weights the measurements on the basis of their own errors, which are sensitive to SNR and rotational velocity, we mainly used the second option, in which the weights are preserved.

3.4 Light curve solutions

The Kepler light curves were fitted with the version 28 (v28) of the code \texttt{JKTEBOP} (Southworth et al. 2004a,b), which is based on the EBOP program (Popper & Etzel 1981).

The short-cadence data, due to their denser time sampling, may include information that is missing in the long cadence, e.g. better represent short-time-scale brightness variations, like egress and ingress of some eclipses. We have therefore fitted both kinds of Kepler photometry, taking into account availability of the short-cadence data, and compared the output.

For long-cadence data, the errors were estimated with a residual-shift (RS) method (Southworth et al. 2011), run on data from each quarter separately, as described in Paper I. This was done in order to properly account for strong systematic effects of different time scales (short-term pulsations or long-term evolution of spots). For short-cadence data, the same approach would take months of computer time, so instead of RS we used the available Monte-Carlo (MC) option, also run on each quarter separately. In both cases, to get the final uncertainties, we added in quadrature the formal error of a weighted average of all available quarters, and the \( \text{rms} \) of the results from each quarter or set (Paper I).

Starting values of eccentricity \( e \) and periastron longitude \( \omega \), as well as mass ratio \( q \) (here held fixed), were taken from \texttt{v2fit} runs. We fitted for the period \( P \), mid-time of the primary (deeper) minimum \( T_0 \), sum of the fractional radii \( r_1 + r_2 \) (where \( r = R/a \)), their ratio \( k \), inclination \( i \), surface brightness ratio \( J \), maximum brightness \( S \), as well as for \( e \) and \( \omega \) (their final values are from the \texttt{JKTEBOP} runs, unless stated otherwise). Third light contribution \( t_l/\text{host} \), which can be significant in Kepler data, was also initially fitted for, but when it was found not significantly different from zero, or even negative, the fit was repeated with fixed \( t_l/\text{host} = 0 \). The gravity darkening coefficients were always kept fixed at the values appropriate for stars with convective envelopes (\( g = 0.32 \)). We did not fit for limb darkening (LD) coefficients, but we found them iteratively, as described in Paper II, and perturbed them in the RS or MC stage.

The final values of \( P \) and \( T_0 \) were derived from the complete long-cadence curves. However, since various systems show different LC characteristics (width of eclipses, ellipsoidal variations, pulsations, evolving spots, flares, timing variations, etc.), each binary has been treated individually. In Subsections describing results obtained for each target, we explicitly state if the adopted results come from short- or long-cadence LCs, if from fit to a complete curve, or the weighted average from single-quarter curves, and which approach (RS or MC combined with \( \text{rms} \)) has been used to obtain uncertainties.

3.5 Tomographic spectra disentangling

In order to obtain separate spectra for each component, we performed tomographic disentangling (TD) of composite spectra of 10 systems. This was done when at least 8 good quality observations were available, and only two sets of lines were clearly seen. For this reason we omitted the triple-lined KIC 10191056, but included double-lined KIC 10583181, where significant third light was noted in the Kepler LC (Section 4).

We used the method described in Konacki et al. (2010), which is based on tomographic approach proposed by Baguolo & Gies (1991). It utilizes prior RV measurements, which were made with \texttt{TODCOR}. The algorithm works on each echelle order separately, and is fragile to low-signal
Table 2. Summary of TD information. Number of input spectra (N sp.), final wavelength range, and SNRs are given.

| KIC     | N sp. | Wavelength ranges [Å]                  | SNR₁ | SNR₂ |
|---------|-------|----------------------------------------|------|------|
| 3439031 | 8     | 5030.555 – 6222.286                    | 70   | 69   |
| 4851217 | 8     | 5030.316 – 6221.982                    | 47   | 115  |
| 7821010 | 15    | 5365.545 – 6222.346                    | 129  | 94   |
| 8552540 | 8     | 5030.468 – 6222.174                    | 136  | 37   |
| 9246715 | 17    | 5030.582 – 5204.669; 5216.799 – 5400.960; 5417.327 – 5901.768; 5930.232 – 6222.319 | 123 | 117 |
| 9641031 | 14    | 5030.575 – 5400.956; 5417.321 – 6155.450 | 272  | 64   |
| 10031808| 16    | 5030.582 – 5400.958; 5417.326 – 5841.582; 5930.227 – 6222.319 | 136  | 170  |
| 10583181| 9     | 5030.323 – 6221.987                    | 146  | 14   |
| 10987439| 10    | 5469.778 – 5841.463; 5868.371 – 6222.195 | 20   | 134  |
| 11922782| 10    | 5030.582 – 5204.667; 5216.978 – 6222.319 | 149  | 22   |

data. For this reason the edges of each order were first trimmed, not every order was included or produced a satisfactory solution, and, in particular, we only used the orders from the “green” chip of the HIDES detector. Therefore, the wavelength range of final spectra varies from target to target. In a low number of cases, a given low-SNR spectrum was not used for TD, but still gave reasonably precise RV measurements. Before the TD, each order has been continuum-normalized. In the final steps, we merged the orders into single, long, 1-dimensional spectra. In Table 2 we show for each star how many input spectra were used, what was the final wavelength range (inc. gaps), and what were the SNRs of disentangled primary and secondary spectra. Since the primary is defined by the LC, it is not always the brighter component.

We should note that two HIDES orders (96 and 97) containing the sodium D lines (around 5890 Å) did, formally, give a tomographic solution. However, the contamination from the interstellar Na introduced a third set of strong lines, therefore pieces of final spectra around the D lines are not recovered correctly and were not used in further analysis.

Before further analysis, the resulting TD spectra needed to be renormalized, in order to obtain the true intensities of the spectral lines. This can be done with the aid of additional information about the ratio of fluxes at a given wavelength (here: echelle order), which can be taken from T0DOCOR. The value of flux ratio $\alpha$ that maximizes the height of the cross-correlation can be calculated with a relatively simple analytical relation (equation A4 in Zucker & Mazeh 1994). The usage of T0DOCOR flux ratios has been shown to give proper results for example in Helminiak et al. (2015b) or Bright & Torres (2017).

3.6 Spectroscopic analysis

The main motivation for this work was to complete the set of stellar parameters of the studied DEBs with effective temperatures and metallicities, which are necessary for further determination of the age and evolutionary status. For this we used the v2018.06.08 version of the freely distributed code ISPEC (Blanco-Cuaresma et al. 2014), and our TD spectra. Each spectrum was first corrected for a residual RV shift, introduced in the TD stage (typically 0.3–0.5 km s$^{-1}$), and resampled with the wavelength step of 0.05 Å. The TD output is severely oversampled, so this step allowed to reduce the number of data points in each spectrum, making the analysis about 10x faster, while keeping the original HIDES resolution (R $\sim$ 50000). To ensure the uncertainties given by ISPEC are trustworthy, we used the program to calculate reliable flux errors, basing on the measured SNR of the spectra. With these errors the reduced $\chi^2$ of the fit was typically close to 1, with the exception of low-SNR spectra (<50), which analysis we do not find reliable.

To find the atmospheric parameters we used the spectral synthesis approach, utilising the code SPECTRUM (Gray & Corbally 1994), the MARCS grid of model atmospheres (Gustafsson et al. 2008), and solar abundances from Grevesse et al. (2007). ISPEC synthesizes spectra only in certain, user-defined ranges, called “segments”. We followed the default approach, where these segments are defined as regions ±2.5 Å around a certain line. We decided to synthesize spectra around a set of lines carefully selected by the the Gaia-ESO Survey (GES: Gilmore et al. 2012; Randich et al. 2013) in such way, that various spectral fitting codes reproduce consistent parameters from a reference solar spectrum (Blanco-Cuaresma et al. 2010).

With several exceptions, described below, we run the fit with the following parameters set free: effective temperature $T_{\text{eff}}$, metallicity [M/H], alpha enhancement [$\alpha$/Fe], and microturbulence velocity $v_{\text{mic}}$. The resolution $R$ was always fixed to 50000, and gravity log(g) to the value corresponding to absolute values of mass and radius (see next Section), which is more precise than log(g) we could find from spectroscopy. In case of short-period, circular (or nearly circular) orbits, where stars rotate (pseudo-)synchronously with the orbital period, the rotational velocity $v_{\sin(i)}$ was also fixed and set to values expected from the synchronous rotation. In only three cases we set $v_{\sin(i)}$: KIC 7821010, 9246710 and 10031808. In the first two the lines are quite narrow, so $v_{\text{mic}}$ was automatically calculated by ISPEC from an empirical relation found by the GES Consortium and incorporated into the ISPEC program (GES Consortium, priv. communication). Lines of KIC 10031808 are rotationally broadened and independent fit for $v_{\text{mic}}$ was possible. The macroturbulence velocity $v_{\text{mac}}$, which degenerates with rotation, was at all times calculated on-the-fly by ISPEC from a similar empirical relation found by the GES Consortium.

As final values of systemic [M/H] and [$\alpha$/Fe] we adopted averages of values obtained from each component. As their
conservative uncertainties we added in quadrature the formal parameter errors from ispec and half the difference between two individual results. For example, for KIC 10031808 from $[\text{M}/\text{H}]_1 = -0.17(5)$ and $[\text{M}/\text{H}]_2 = -0.05(5)$, we got $[\text{M}/\text{H}] = -0.11(8)$. This particular example, and the metallicity of KIC 9641031 ($[\text{M}/\text{H}]_1 = -0.15(6)$, $[\text{M}/\text{H}]_2 = 0.00(6)$, adopted $[\text{M}/\text{H}] = -0.07(9)$) are the only two where individual values differ by more than formal $1\sigma$, but still within $2\sigma$. When only one component could be analysed, we adopted its $[\text{M}/\text{H}]$ and $[\alpha/\text{Fe}]$ for the whole system. Abundances of specific elements were not calculated.

3.7 Calculation of absolute parameters

The partial results of LC and RV solutions were later combined in order to calculate the absolute values of stellar parameters using the jktabsdim code, available together with the jktebop. As an input, this simple procedure takes orbital period, eccentricity, fractional radii, velocity semi-amplitudes and inclination (all with uncertainties), and returns absolute values of masses and radii (in solar units), log($g$) and rotational velocities, assuming tidal locking and synchronization.

jktabsdim can also calculate distance to an object, using effective temperatures of two components, approximate metallicity (given with precision of 0.5 dex), $E(B-V)$ and apparent magnitudes. The code does not work on brightnesses in Kepler band, so, unless stated otherwise, for the distance estimation we used $B, V, J, H$ and $K$-band entries from Simbad (Wenger et al. 2000). We only used the temperatures and $[\text{M}/\text{H}]$ from the ispec analysis. As the final value of distance we adopt a weighted average of five values, calculated for each band from the surface brightness-$T_{\text{eff}}$ relations of Kervella et al. (2004). The results can be compared with parallaxes from the Gaia Data Release 2 (GDR2; Gaia Collaboration 2016, 2018).
Table 3. Orbital and physical parameters of eleven double-lined eclipsing binaries from our survey, including results of spectral analysis, when possible. When “a” is given in parenthesis instead of uncertainty, the parameter was calculated automatically from an empirical relation.

| Parameter | Value |
|-----------|-------|
| $P_{\text{orb}}$ (d) | 5.95202634(74) |
| $T_0$ (JD-2454900) | 57.0440099(11) |
| $T_\text{P}$ (JD-2454900) | 56.34(79) |
| $K_1$ (km s$^{-1}$) | 79.71(37) |
| $K_2$ (km s$^{-1}$) | 79.27(84) |
| $\gamma_1$ (km s$^{-1}$) | 27.03(52) |
| $\gamma_2$ - $\gamma_1$ (km s$^{-1}$) | 0.0(0) |
| $\theta$ | 1.001(14) |
| $M_1$ (M$\odot$) | 1.2258(24) |
| $M_2$ (M$\odot$) | 1.2274(28) |
| $a$ (sin$i$) (R$\odot$) | 18.646(13) |
| $e$ | 0.00142(16) |
| $\omega$ (°) | 47(48) |
| $r_1$ | 0.05754(10) |
| $r_2$ | 0.07524(13) |
| $l$ (°) | 89.57(1) |
| $I$ | 0.0970(26) |
| $I_\text{h}$ | 0.9331(51) |
| $I_{1/2}$ | 0.232(23) |
| $V_\text{rot}$ (km s$^{-1}$) | 1.2259(24) |
| $V_\text{mac}$ (km s$^{-1}$) | 18.646(13) |
| $\log g_1$ | 4.2300(13) |
| $\log g_2$ | 4.2323(15) |
| $T_\text{rot}$ (K) | 6530(200) |
| $T_\text{d} (R)$ | 720(215) |
| $\log g_1$ (L$\odot$) | 0.45(46) |
| $\log g_2$ (L$\odot$) | 0.46(46) |
| $v_\text{rot}$ (km s$^{-1}$) | 11.96(2) |
| $v_\text{mac}$ (km s$^{-1}$) | 1.63(21) |
| $d_0$ (pc) | 477(15) |
| $r_{\text{rms}} Q_1$ (km s$^{-1}$) | 0.15 |
| $r_{\text{rms}} Q_2$ (km s$^{-1}$) | 0.17 |
| $r_{\text{rms}} LC$ (mmag) | 0.36 |
| $r_{\text{rms}}$ | 0.58 |

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a) Mid-time of the primary (deepest) eclipse, calculated from the complete Q0-Q17 curve.
b) Time of pericentre or quadrature.
c) If “a” is given after the uncertainty, it is the velocity of (pseudo-)jovian rotation given by rotate. Otherwise, it is $v_\text{sin}$ calculated by $v_\text{sin}$.d) The $V_\text{rot}$ distance $d_0$ is calculated only when both $T_\text{d}=a$ were found with $\text{spec}$.e) The $rms$ of residuals of the fit to the complete long- (LC) and short-cadence (EC) Kepler curve.
3.8 Comparison with isochrones and age estimation

We use our results to assess the age $\tau$ and evolutionary status of each system. We compare them to isochrones generated with Modules for Experiments in Stellar Astrophysics (MESA) with the aid of MESA Isochrones & Stellar Tracks (MIST v1.2) web interface\(^6\) (Paxton et al. 2011; Choi et al. 2016; Dotter 2016). To assess the age $\tau$ of a system, we searched for the best-fitting isochrone simultaneously on the $M/R$ plane for both components, and $M/T_{\text{eff}}$ for one or two stars, depending on how many $T_{\text{eff}}$ are known from spectroscopy. We adopt metallicities from the ispec analysis, and followed the assumption used in MIST that $[\text{Fe/H}] = [\text{Z}/\text{H}]$. In current version MIST assumes protosolar abundance $Z = 0.0142$ from Asplund et al. (2009).

4 RESULTS

4.1 Parameters of eclipsing binaries

In this section we present results of the combined v2fit + jktebop + ispec analysis of ten double-lined eclipsing binaries, and updated v2fit + jktebop of KIC 10191056 A, which is the close pair in a triple-lined hierarchical system. They can be found in Table 3. Observed and modelled RV and LC curves are presented in Figures 1 to 13.

4.1.1 KIC 3439031

This system has been observed with HIDES 8 times, and was not studied so far. It is the faintest target in our sample. We found it is composed of two nearly identical F-type stars. Despite the number of RV measurements is low, the $rms$ of the fit is very good, hence the mass uncertainty is low as well: $\sim 0.2$ per cent (including systematics coming from the low number of data points).

This system has the $Kepler$ short-cadence photometry available for parts of quarters Q02 and Q04, and for entire quarters Q11 and Q12. Eclipses in the short-cadence curve are deeper and last shorter, meaning that the long-cadence data suffered from the longer exposure time and averaging the brightness variability. However, this system is quite stable out of eclipses, and we decided that the short-cadence data (presented in Figure 1) are sufficient to analyse it properly. Furthermore, in both short- and long-cadence data we noticed that the residuals in the eclipses behaved differently from quarter-to-quarter, e.g. the model eclipses were too shallow in long-cadence quarters Q04 and Q05, then suddenly change to too deep in Q06 and Q07. We suspect that it is a systematic related to the rotation and orientation of the telescope. To compensate for it, we decided to analyse the LC of KIC 3439031 quarter-by-quarter and adopt weighted averages as final values of parameters. The uncertainties were calculated with the previously described procedure that combines $rms$ of results of single-quarter fits with individual errors from a Monte-Carlo analysis.

Apart from eclipses and ellipsoidal variations, the LC shows little variability. The $rms$ of the fit is therefore quite low (0.33 and 0.58 mmag for long- and short-cadence curves, respectively), hampered mainly by the systematics coming from imperfect de-trending and telescope’s pointing stability. Final precision in radii is at a very good level of $\sim 0.15$-0.18 per cent. The ispec analysis gave similar results for both components, which was expected for a pair of nearly identical stars. The system appears to be slightly more metal rich than the Sun, and $a$ elements are not significantly enhanced. Stars are rotating synchronously with the orbital period, and the orbit is nearly circular. The time scale of circularisation (as given by jktabsdim) is $4.27$ Gyr, which may be treated as an upper limit of the system’s age. Effective temperatures are representative of the F6 spectral type, and are about 200 K higher than estimates from KEBC or GDR2, but this is within the error bars of our values. Disentangled spectra of higher SNR are needed to lower the uncertainties. When used in jktabsdim, the $T_{\text{eff}}$ give the distance $d = 477(15)$ pc, which is in a reasonable agreement with $486(6)$ pc from GDR2. The distance calculation assumes no reddening, as the consistency between distances derived for different bands was already quite good.

The set and precision of parameters we provide for KIC 3439031, and the fact that it consist a pair of “twins”, make this target valuable for testing stellar formation and evolution models.

4.1.2 KIC 4851217

Comparison of jktebop output for short- and long-cadence data showed that the two LCs are indistinguishable in shape, and the resulting parameters differ typically by less than 1/5 of the obtained errors. We therefore adopted the result of a fit to the complete Q00-Q17 long-cadence curve as the final one. The long-cadence uncertainties were slightly higher (by roughly 10-20 per cent) from those from the short-cadence curve, and we decided to use them, as they are the more conservative ones, probably better coping with the influence of pulsations. Figure 2 shows the long-cadence curve.

We observed this system 8 times with HIDES, and additionally used three APOGEE and one TRES spectra. We did this to double-check and strengthen our orbital solution (Fig. 2), which initially was in disagreement with that from Matson et al. (2017). Our data clustered around phase $\phi \sim 0.3$ and between $\phi = 0.8 - 1.0$. With the additional spectra, our sampling is more uniform, and the velocity am-

Table 4. Comparison of updated results for KIC 4851217 with parameters from Matson et al. (2017).

| Parameter | This work | Matson et al. |
|-----------|-----------|---------------|
|           | (Table 3) | (2017)        |
| $P$ (d)   | 2.4702836(17) | 2.47028283(-) |
| $K_1$ (km s$^{-1}$) | 131.0(2.6) | 115(2) |
| $K_2$ (km s$^{-1}$) | 114.6(2.7) | 107(2) |
| $a$       | 1.143(35)  | 1.08(3)       |
| $i$ (°)   | 77.11(26)  | 77.8(-)       |
| $M_1$ (M$_\odot$) | 1.19(10)  | 1.43(5)       |
| $M_2$ (M$_\odot$) | 2.18(10)  | 1.55(5)       |
| $rms_1$ (km s$^{-1}$) | 3.8 | 7.0 |
| $rms_2$ (km s$^{-1}$) | 4.8 | 7.2 |

\(^6\) http://waps.cfa.harvard.edu/MIST/
Figure 1. Radial velocity (left) and light (right) curves of KIC 3439031. The best-fitting models are plotted with blue lines. Filled circles on the RV plot refer to HIDES data for the primary, and open ones for the secondary. On both sides the phase 0 is set for the deeper eclipse mid-time, according to the definition in jktebop.

Figure 2. Same as Fig. 1, but for KIC 4851217 and with additional RV measurements from APOGEE (stars) and TRES (triangles).

Amplitudes ($K_1 = 131 \pm 3$, $K_2 = 115 \pm 3 \text{ km s}^{-1}$; Table 3) are much better constrained. The original solution from Matson et al., in which $K_1 = 115 \pm 2$, $K_2 = 107 \pm 2 \text{ km s}^{-1}$, suffers from a similar problem (data only for $\phi = 0.25 - 0.5$ and $0.8 - 0.1$), which may explain the disagreement. A full comparison is shown in Table 4. A recent re-analysis of these data results in higher $K$ (and masses), closer to our results (M. Fedurco, in prep.).

The lines are clearly broadened by rotation, which itself is synchronized with orbital period, despite the small but detectable eccentricity. Fast rotation of both components hampers our RV precision, thus the errors in masses, which in this case are $\sim 5$ per cent. The precision in absolute radii is only slightly better (2-4 per cent), with error budget strongly influenced by uncertainties of fractional radii. The 4.3 mmag rms of the LC is obviously caused by pulsations of the dSct type. In the Lomb-Scargle periodogram of the residuals of jktebop fit we detect strong peaks at frequencies 15-21 d$^{-1}$, typical for dSct stars. A separate publication with very detailed analysis of pulsations in KIC 4851217 is in preparation (by M. Fedurco), therefore we did not tackle this problem in this work.

Most of the flux comes from the cooler, but more massive and larger secondary. The ispec analysis of its spectrum (SNR=115) showed it to be an early F type star with $T_{\text{eff,2}} = 7250(215)$ K. This is in agreement with e.g. $7306^{+225}_{-164}$ K from GDR2. We therefore expect the primary to be of spectral type A, with $T_{\text{eff,1}}$ exceeding 8000 K. Unfortunately its disentangled spectrum is not good enough for proper analysis (SNR=47). We made several attempts to retrieve $T_{\text{eff,1}}$ with ispec fixing as many parameters as possible (dynamical $\log(g)$, metallicity from secondary, etc.), and using model atmospheres appropriate for hotter stars, but we failed to reach such high temperatures. From the secondary’s spectrum we estimate the metallicity to be subsolar, and without significant $\alpha$ enhancement. Without independent assessment of $T_{\text{eff,1}}$ we can not estimate the dis-


4.1.3 KIC 7821010

This system has been reported on several occasions to harbour a circumbinary planet, detected with ETVC7 (Borkovits et al. 2016), but the proper publication is still to be announced (Fabrycky et al., in prep.). Since the publication of Paper II we obtained seven HIDES spectra of the system. We have previously reported the uneven quality of the data, and that in favouring observing conditions our observations result in SNR sufficient to obtain good precision RV measurements (<100 m s^{-1}). New observations aimed to increase the number of “good” spectra, improve the precision of absolute stellar parameters, and possibly detect the RV signature of the planet, estimated from the solution of Borkovits et al. (2016) to be 30-40 m s^{-1}, which is at the level of instrumental precision in our programme (Paper I).

For the new orbital solution we did not use RVs coming from one of the older spectra, from May 05, 2015 (JD=2457148.2), which had very low SNR (<15). Therefore, the final solution, and spectra disentangling, was based on 15 observations. The resulting TD spectra are of a good quality (SNR = 127 and 108 for the primary and secondary, respectively).

The short-cadence Kepler photometry of this pair is available from Q02 and Q09-Q17 (9 quarters). When comparing the light curves, we found that the eclipses in the long-cadence LC are slightly shallower and wider, likely because short-time-scale brightness variations were averaged out with the longer exposure time. For this reason our results based on the short-cadence data only. We do not see significant out-of-eclipse variations, but we saw the influence of the circumbinary planet on \( T_0 \) and \( P \) in each quarter. The fit to a complete LC left characteristic residuals around eclipses, therefore we adopted the weighted averages from single-quarter fits. In Figure 3 we present the short-cadence LC, but the lower panel shows summarised residuals of single-quarter fits. Some systematic residuals, coming from imperfect de-trending, are clearly visible.

Mass uncertainties in the new solution (Tab. 3) are about 1/3 lower than in Paper II (~0.8 per cent for both components), and, thanks to improved \( \sin(i) \), also the uncertainty in radii is quite good (0.8 and 1.1 per cent for the primary and secondary, respectively). The \( rms \) of the orbital fit also decreased. With the selection of only the best RV measurements (10 for the primary and 8 for the secondary) we can lower it even further, to 55 and 60 m s^{-1}, respectively. This is, unfortunately, larger than the expected RV signal from the planet. While attempting to fit for this influence, basing on the orbital parameters from Borkovits et al. (2016), we obtained a solution that was only marginally better (52+55 m s^{-1} \( rms \)).

The ispec analysis resulted in similar effective temperatures of the components, which is not surprising considering a mass ratio slightly lower than 1. The system’s metallicity is likely higher than solar (+0.10(8) dex, with two individual results being different by only 0.01 dex). We found no evidence for enhancement of \( \alpha \)-elements in neither component. With ispec we also fitted for the projected rotational velocities \( v \sin(i) \). Lines of both components are quite narrow, but some degree of broadening was expected for the secondary (from the width of cross-correlation function). Indeed, we found the secondary rotating faster (8.9±1.1 km s^{-1}) than expected in pseudo-synchronous case (2.53±0.03 km s^{-1}). The formal error of the primary’s \( v \sin(i) \) is larger than the best-fitting value – 1.3±4.8 km s^{-1} – therefore the result is inconclusive. But from the secondary alone we can conclude that KIC 7821010 did not reach the tidal equilibrium, therefore should be younger than 3.6 Gyr, which is the time scale of synchronisation of rotation with orbital period (from JKTABSDM).

The two effective temperatures were used in JKTABSDM to estimate the distance \( d_2 \). The result – 342(13) pc – is in a reasonable agreement with 360(5) pc from GDR2. To ensure the consistency between individual distances from various bands, we assumed \( E(B-V) = 0.11 \) mag. Without reddening, values corresponding to bands \( R \) and \( V \) are ~60 pc larger than those corresponding to \( J,H,K \). The equivalent width of interstellar sodium D 1 line is 0.21(1) \( \AA \), and correctly reproduces \( E(B-V) = 0.11 \) mag, according to calibrations by Munari & Zwitter (1997).

4.1.4 KIC 8552540 (V2277 Cyg)

The LC of this system is strongly affected by rapidly evolving spots. Short-cadence data are available only for fractions of quarters Q02, Q03, and Q14, and are not enough to cover the evolution of spots properly and obtain reliable results. We therefore use the fit to a complete Q00-Q17 long-cadence curve (shown in Fig. 4), with uncertainties calculated with our RS approach, i.e. the results from Paper II remain intact. For the record, we give the \( rms \) of the best fit to the short-cadence LC as well.

Furthermore, this system has no new HIDES observations, thus the only new addition is the ispec spectroscopic analysis. As KIC 4851217, this binary also has large ratio of component fluxes, and significantly different SNRs of disentangled spectra: 136 and 37 for the primary and secondary, respectively. It is the shortest-period binary in our sample, with two rapidly rotating components, therefore the final

| Parameter | This work\(^a\) (Table 3) | Matson et al. (2017) |
|-----------|-----------------|---------------------|
| \( P \) (d) | 1.06193441(4) | 1.06193426(-) |
| \( K_1 \) \( (\text{km s}^{-1}) \) | 121(0.16) | 121(1) |
| \( K_2 \) \( (\text{km s}^{-1}) \) | 145.9(2.0) | 153.2 |
| \( q \) | 0.829(16) | 0.79(1) |
| \( i \) (°) | 85.83(46) | 80.7(-) |
| \( a \) \( (\text{R}_\odot) \) | 5.619(54) | 5.83(5) |
| \( M_1 \) \( (\text{M}_\odot) \) | 1.153(36) | 1.32(3) |
| \( M_2 \) \( (\text{M}_\odot) \) | 0.956(28) | 1.04(2) |
| \( rms_1 \) \( (\text{km s}^{-1}) \) | 3.0 | 4.1 |
| \( rms_2 \) \( (\text{km s}^{-1}) \) | 5.3 | 6.3 |

\(^a\) The same as in Paper II.

\({\text{http://www.astro.up.pt/investigacao/conferencias/toe2014/files/jkab.pdf}}\)

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7 e.g.: http://www.astro.up.pt/investigacao/conferencias/toe2014/files/jkab.pdf
mass precision is relatively poor (∼3 per cent). The rapidly evolving spots affect the precision of the LC fit (the largest $r_{\text{rms}}$ LC ≃ 13 mmag). It is worth noting that the secondary may be considered a solar analogue. It has also been reported in Matson et al. (2017). The comparison is shown in Table 5. There is an overall agreement, except $K_2$. This is not very surprising, considering low precision of RV measurements of the faint and rotationally broadened secondary, which affected both the studies.

The ispec analysis of the primary’s spectrum was done with $v\sin(i)$ fixed to the value predicted by tidal locking. We ended up with $[\text{M/H}] = -0.27(11)$ dex (lowest in our sample), no significant $\alpha$-element enhancement, and $T_{\text{eff,1}} = 6060(200)$ K. It agrees with $5870^{+290}_{-118}$ K from GDR2. Due to strong rotational broadening of lines, the uncertainties are relatively large. Spectrum of the secondary had its SNR too low for secure analysis, so without $T_{\text{eff,2}}$ we are not able to calculate the distance with $jktabsdim$ at this stage. Attempts made on isochrone-based values are described in Section 4.2.

### 4.1.5 KIC 9246715

This system was previously described in a dedicated paper (K924), and since then it has been observed 9 more times with HIDES, making the total number of spectra 17. No Kepler short-cadence data are available. Except eclipses the long-cadence curve shows systematics, presumably coming from imperfect de-trending, also affecting some of the eclipses. It should be noted that the long period of this system (171 d) causes that both minima are not always recorded during one quarter. The approach to the LC fit was, therefore slightly different, and is described in details in K924. We do not repeat the LC analysis here.

KIC 9246715 is one of the most interesting cases in our sample. It is composed of two red giants, one of which shows solar-type oscillations. At the time of publication it was only the third example of a Galactic double-giant eclipsing binary with masses and radii measured with precision below 2 per cent. It was simultaneously and independently analysed by Rawls et al. (2016), who used their own set of 24 high-resolution spectra (from TRES, ARCES, and APOGEE),
and derived parameters in agreement with K924. Comparison of these results with K924 and this work is shown in Table 6. The full set of our parameters is presented in Table 3. Additionally, Rawls et al. (2016) estimated temperatures and iron abundance from the disentangled component spectra, analysed pulsations, and compared the binary with models. They concluded that one of the components is in a helium (He) burning phase.

The fact that KIC 9246715 contains a solar-type oscillator makes it useful for testing and calibrating the astero-seismic relations (Gaulme et al. 2016; Brogaard et al. 2018). The analysis of oscillations is dependent on the evolutionary status of a star, which requires very precise observables to be securely established. One should note that in K924 there were only 8 RV measurements used, and resulting precision of K1.2 severely suffered from that fact, even though the $\text{rms}$ of the orbital fit was only ~50 m s$^{-1}$ (close to the stability level of HIDES in our survey; Paper I). Also, the spread of RV residuals in Rawls et al. (2016, Fig. 6) reaches ±2 km s$^{-1}$, suggesting the $\text{rms}$ of the order of few hundred m s$^{-1}$, and clearly shows systematic effects (residuals for one component strongly correlated with the other). It is therefore likely that their uncertainties of K1.2 (40-50 m s$^{-1}$) are underestimated, as are the errors of masses. We followed KIC 9246715 in order to improve the orbital, and therefore physical parameters of its components.

We doubled the number of HIDES spectra, but the quality of the orbital fit remained almost unchanged. With more data and better sampling we downed the systematics in velocity amplitudes $K_{1,2}$ and also improved our estimate of eccentricity, which, as it turns out, has large influence on the final errors of masses. The final precision in ~0.15 per cent for both components. The precision in $R$ is 1.4 + 1.0 per cent, analogously. Results for radii did not change much, as we did not re-analyse the LC.

Both disentangled spectra have decent SNR (123 and 117), and their ispec analysis gave similar temperatures of components: 4890(50) and 4905(60) K for the primary and secondary, respectively. Individual values of $\text{[M/H]}$ and $\text{[a/Fe]}$ in good agreement, and pointed towards chemical composition indifferent from solar. Rotational velocities $\nu\sin(i)$ were fitted for, and we found them to be in very good agreement with those predicted by pseudo-synchronisation: 2.51(4) and 2.42(3) km s$^{-1}$ (from JKTABSDM). It is, however, unlikely that at such separation tidal forces influenced the rotation and synchronised it with the orbital period during the life time of the system. The observed rotation is rather primordial.

We used JKTABSDM and our values of $T_{\text{eff}}$ to estimate the distance. We found it to be 573(13) pc, assuming $E(B-V) = 0.13$ mag, which is significantly less than 616(11) pc from GDR2. When no reddening is assumed, individual distances in $B$ and $V$ are larger from those in $J, H, K$ by ~150 and 100 pc, respectively. The IR values themselves are all around 600 pc, still too low for GDR2.

| Parameter | This work | K924 (Table 2) | Rawls et al. (2016) |
|-----------|-----------|----------------|-------------------|
| $P$ (d)   | 171.2770(6) | 171.27688(1)   |                   |
| $K_1$ (km s$^{-1}$) | 33.21(2) | 33.18(16) | 33.19$^{+0.04}_{-0.03}$ |
| $K_2$ (km s$^{-1}$) | 33.63(2) | 33.58(14) | 33.53$^{+0.03}_{-0.02}$ |
| $e$       | 0.3552(4) | 0.3587(9) | 0.359$^{+0.002}_{-0.001}$ |
| $r_1$     | 0.04008(58) | 0.0396$^{+0.0003}_{-0.0003}$ |                   |
| $r_2$     | 0.03870(40) | 0.0389(1)   |                   |
| $i$ (°)   | 87.049(31) | 87.051$^{+0.03}_{-0.02}$ |                   |
| $M_1$ (M$_\odot$) | 2.187(3) | 2.169(24) | 2.171$^{+0.003}_{-0.002}$ |
| $M_2$ (M$_\odot$) | 2.160(3) | 2.143(25) | 2.146$^{+0.008}_{-0.007}$ |
| $R_1$ (R$_\odot$) | 8.49(12) | 8.47(13) | 8.37$^{+0.07}_{-0.08}$ |
| $R_2$ (R$_\odot$) | 8.20(9) | 8.18(9) | 8.30$^{+0.04}_{-0.03}$ |
| $T_{\text{eff},1}$ (K) | 4890(50) | 4900(90) |                   |
| $T_{\text{eff},2}$ (K) | 4905(55) | 5030(80) |                   |
| $\text{[M/H]}_1$ | -0.01(2) | -0.22(12)$^a$ |                   |
| $\text{[M/H]}_2$ | 0.03(2) | -0.10(9)$^a$ |                   |
| $r_{\text{rms},1}$ (km s$^{-1}$) | 0.046 | 0.045 | 0.55$^b$ |
| $r_{\text{rms},2}$ (km s$^{-1}$) | 0.051 | 0.052 | 0.55$^b$ |

$^a$ $\text{[Fe/H]}$ obtained with MOOG.

$^b$ Not given directly in Rawls et al. (2016), therefore it was calculated in this work with v2rr using their exact solution.

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**Figure 5.** Same as Fig. 1, but for KIC 9246715.

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Table 6. Comparison of updated results for KIC 9246715 with parameters from K924 and Rawls et al. (2016).
Table 7. Comparison of updated results for KIC 9641031 (FL Lyr) with parameters from Paper II and Popper et al. (1986).

| Parameter          | This work (Table 3) | Paper II (Table 2) | Popper et al. (1986) |
|--------------------|---------------------|--------------------|----------------------|
| $P$ (d)            | 2.17815425(7)       | 2.1781542(3)       |                      |
| $K_1$ (km s$^{-1}$)| 93.34(10)           | 93.23(12)          | 93.5(5)              |
| $K_2$ (km s$^{-1}$)| 118.75(35)          | 118.19(30)         | 118.9(7)             |
| $r_1$              | 0.1361(25)          | 0.1389(25)         | 0.140(3)             |
| $r_2$              | 0.0984(26)          | 0.0995(27)         | 0.105(3)             |
| $i$ ($^\circ$)     | 87.13(71)           | 85.36(71)          | 86.3(4)              |
| $M_1$ (M$_\odot$)  | 1.2102(76)          | 1.2041(76)         | 1.218(16)            |
| $M_2$ (M$_\odot$)  | 0.9512(39)          | 0.9498(46)         | 0.958(11)            |
| $R_1$ (R$_\odot$)  | 1.2444(23)          | 1.269(23)          | 1.283(30)            |
| $R_2$ (R$_\odot$)  | 0.9000(24)          | 0.9084(24)         | 0.905(30)            |
| $T\text{eff,}1$ (K)| 6264(112)           |                    | 6150(100)            |
| $T\text{eff,}2$ (K)| 5490(247)           |                    | 5300(100)            |
| [M/H]              | -0.07(9)            |                    | 0.32(−)              |

4.1.6 KIC 9641031 (FL Lyr)

This binary has a very extensive set of short-cadence data points, starting in quarters Q01 and Q02, through almost entire quarters Q07 and Q08, and with a nearly continuous coverage since Q13 till the end of the mission. In this case, we also noted slightly different eclipse depths in short- and long-cadence data, therefore the final values come from a fit to a complete short-cadence curve (also in Figure 6), although the long-cadence curve gives similar results. However, both components of this pair seem to have prominent, rapidly evolving spots, which make the shape of the LC changing in relatively short time scales (a significant change is seen after only several orbits). The complete long-cadence light curve, whose coverage in time is much more complete, seems to probe the evolution of spots more uniformly, and their influence on the phase-folded LC appears to be averaged out. This kind of situation favours the RS method over the MC for error determination, therefore, the uncertainties quoted in Table 3 come from the combined RS+rms analysis of single-quarter long-cadence data.

We observed this system with HIDES three more times since Paper II, increasing the number of spectra to 15 (14 of which were used in TD). The new data were taken mainly to test the hypothesis of a low-mass circumbinary body on a 103-day orbit, based on ETVs from Paper II. We do not detect any RV modulation at the expected level (∼1.26 km s$^{-1}$), therefore we conclude that the observed ETVs were likely caused by evolution of spots. The overall precision of RV data and level of uncertainties are similar to those from Paper II (0.5-0.7 per cent in mass, 1.8-2.6 per cent in radii). In principle, in comparison to the previous extensive study of this system by Popper et al. (1986), we reach 2-3 times lower errors in mass, and comparable (though slightly lower) in radii. To decrease errors of $R_1$ one would have to remove the influence of spots on the LC, but for this, a knowledge about their location (which component is affected) is required, in order not to hamper the depths of the eclipses. Rapid evolution of spots on this system makes such an analysis quite challenging.

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Our updated parameters are in better agreement with Popper et al. (1986) than in Paper II, due to larger $K_2$. Direct comparison is presented in Table 7. We now also add effective temperatures and metallicity of KIC 9641031, obtained from spectra. Popper et al. estimated $T\text{eff}$ from the $V-R$ colours from their photometric solution and on the basis of calibrations from Popper (1980), and metal content $Z = 0.04$ from comparison with isochrones on mass-temperature plane. They also admit that not all uncertainties were included in temperature errors. Our $T\text{eff}$ estimates from ispec are in a formal agreement (due to error bars) but both are larger. When compared to a modern calibration, from Worthey & Lee (2011), the adopted $V-R$ indices (0.46 and 0.61 mag for the primary and secondary, respectively) actually predict temperatures about 1000 K lower, or themselves are 0.15 mag too high. One should also note that the calibrations from Popper (1980) played a role in establishing the ratios of radii $k$ and fluxes in Popper et al. (1986). Our approach is calibration-independent, and resulted in different values of $k$ and (subsequently) $R_2$. The issue with uncertainties of $r$ and $R$ in Popper et al. (1986) was already raised in Paper II. For these reasons we advise to treat the results from Popper et al. (1986) with caution. The difference in metallicity will be discussed in Sect. 4.2.

The temperatures from Tab. 3 were used to estimate the distance with $jktabsdim$. The resulting value of 130(5) pc is in a good agreement with 135.0(5) pc from GDR2, but a small amount of reddening ($E(B-V) = 0.04$ mag) had to be assumed to reach consistency between distances from $B$ and $V$ bands with those from $J$, $H$, $K$. Without reddening, the $B$, $V$ distances were systematically larger by 5-10 pc.

4.1.7 KIC 10031808

In the LC analysis of KIC 10031808 we did not use short-cadence data, as they are only available for a fraction of quarter Q02. In general, the shapes and depths of eclipses agree in both short- and long-cadence photometry. Figure 7 depicts the long-cadence curve, and the final parameters were taken from a fit to a complete Q00-Q17 set, i.e. results presented in Paper II remain unchanged.

This system has no new HIDES observations since Paper II, but is one of the most interesting targets in the sample. It contains a γ Doradus (γ Dor) type pulsator, and is one of only few known cases of such a star in an eclipsing binary with precisely measured parameters (i.e. 0.4-0.8 per cent in both masses and radii). The DEBCat lists only two systems with γ Dor stars: CoRoT 102918586 (Maceroni et al. 2013) and KIC 11285625 (Debosscher et al. 2013). There are, of course, other cases known, but they do not have parameters derived with sufficient precision. Comparison of our values of $T\text{eff}$, log(g), and $V_{\text{mac}}$ of both components with the distributions of those parameters in Kahraman Aliçavaş et al. (2016) suggests the 1.74 M$_\odot$ primary is the pulsator. In particular, in Kahraman Aliçavaş et al. (2016) there is no case of a γ Dor pulsator with log(g) lower than 3.8 dex.

We found the metallicity of this system to be slightly sub-solar (−0.11 ± 0.08 dex), but both components shown a clear α-enhancement (0.16 ± 0.06 dex). The obtained effective temperatures are close to those predicted in Paper II, but the resulting $d_1 = 445(15)$ pc is only in a ∼2σ agreement with one from GDR2. Our distance estimate assumes

8 There are no Kepler data from Q04.
\( E(B - V) = 0.125 \) mag, which is required to obtain consistency between distances calculated for each band. A better match with GDR2 is found when \( E(B - V) \approx 0.08 \) mag, but in such case distances from \( B \) and \( V \) bands are systematically larger than those from \( J, H, K \) by about 30 pc. The equivalent width of sodium D1 line is 0.43(5) Å, and, according to calibrations from Munari & Zwitter (1997), favours the value of \( E(B - V) = 0.125 \) mag.

### 4.1.8 KIC 10191056 A

The triple-lined KIC 10191056 was observed 8 additional times since Paper II, but here we did not use low-SNR spectrum taken on October 10, 2016 (JD\( \approx 2547671.97 \)), thus the total number of HIDES spectra is 18. The main goal was to monitor the variations of systemic velocity \( \gamma \) of the eclipsing pair A, and the motion of the tertiary B, which will be described in details in Section 4.3. The TRES spectrum was included in this study because of the time between it was taken and our first observations (nearly 450 days), so we hoped to detect long-term variations with higher significance. Analysis of the newly added data confirmed that there is no significant variation of \( \gamma \) in time, which was already proposed in Paper II. When fitted for, the linear RV trends for both components were \( \sim 10 \) times smaller than their uncertainties. Analysis of the newly added data confirmed that there is no significant variation of \( \gamma \) in time, which was already proposed in Paper II. When fitted for, the linear RV trends for both components were \( \sim 10 \) times smaller than their uncertainties.

**Table 8.** Comparison of updated results for KIC 10191056 with parameters from Paper II and Matson et al. (2017).

| Parameter          | This work (Table 3) | Paper II (Table 2) | Matson et al. (2017) |
|--------------------|---------------------|--------------------|----------------------|
| \( P \) (d)        | 2.42749488(2)       | 2.42749484(-)      |                     |
| \( K_1 \) (km s\(^{-1}\)) | 106.96(58)          | 107.0(1.3)         | 100(2)              |
| \( K_2 \) (km s\(^{-1}\)) | 118.34(33)          | 119.3(1.0)         | 119(2)              |
| \( q \)            | 0.9038(55)          | 0.897(13)          | 0.83(2)             |
| \( i \) (°)        | 81.33(8)            | 81.35(8)           | 80.5(-)             |
| \( a \) (R\(_{\odot}\)) | 10.938(33)          | 10.986(80)         | 10.7(2)             |
| \( M_1 \) (M\(_{\odot}\)) | 1.564(12)           | 1.590(32)          | 1.50(5)             |
| \( M_2 \) (M\(_{\odot}\)) | 1.413(16)           | 1.427(36)          | 1.25(4)             |
| \( \text{rms}_{\gamma 1} \) (km s\(^{-1}\)) | 1.7                 | 2.5                | 6.8                 |
| \( \text{rms}_{\gamma 2} \) (km s\(^{-1}\)) | 1.1                 | 2.3                | 6.9                 |
we also show the short-cadence data very well even without applying any zero-point shift (Fig. 8). The total time-span is now 1182 d with TRES, and 737 d without. The meaning of the RV variations of component B will be discussed later.

In Table 3 we present updated orbital and physical parameters of KIC 10191056 A, under assumption of constant γ, and utilising new jktebop results. The long-cadence LC shows shallower eclipses, the amount and time span of the short-cadence data is sufficient (quarters Q02, Q04 and Q06–Q10), and no obvious spot-like modulation or pulsations are present, thus the usage of short-cadence data is preferable and justified. We adopted results of the fit to the complete short-cadence set, and this is the LC shown in Figure 8.

With respect to Paper II we have significantly reduced the errors in $K_{1,2}$ and dependent parameters, i.e. the relative mass uncertainties are now 0.8 and 1.1 per cent for the primary and secondary, respectively. The errors in radii are now slightly better as well – 1.2 and 1.6 per cent. In Table 8 we compare our current and previous results with those of Matson et al. (2017). We note a significant discrepancy in $K_3$, which leads to disagreement in other parameters. It could be caused by the fact that Matson et al. (2017) used few observations in phases around eclipses, when the RV difference is small, and lines are blended.

Without the spectral analysis, we do not have independent $T_{\text{eff}}$ and [M/H] estimates.

### 4.1.9 KIC 10583181

This system was observed 10 times with HIDES, but we acquired only 9 measurements of the faint secondary, therefore 9 spectra were used in TD. In the orbital fit with v2fit we took into account the presence of the circumbinary body reported by Borkovits et al. (2016). The circumbinary orbit was assumed to be Keplerian, and parametrized by period $P_3$, eccentricity $e_3$, moment of pericentre passage $T_3$, longitude of pericentre $\omega_3$, and semi-amplitude of modulation of the inner binary’s systemic velocity $K_3$. In such mode, the parameter $\gamma$ in v2fit is defined as the systemic velocity of the whole triple system. Parameters of the outer orbit were found simultaneously with those of the inner binary.

The time span of our HIDES observations is 482 d, while $P_1 = 1169.2$ d, therefore we could not set the outer period free in our fit (although we have data taken around the pericentre passage). We also fixed $e_3 = 0.06$, and $\omega_3 = 279^\circ$ – values given by Borkovits et al. (2016), and only searched for $K_3$ and $T_3$. Resulting parameters of the inner orbit (only) are given in Table 3. Figure 9 shows only the RV curves of the inner binary, while the modulation of $\gamma$ induced by the third body is shown in Fig. 10.

Borkovits et al. (2016) do not give the value of amplitude of the ETVs, but list the $a \sin(i_3)$, from which we can estimate the expected scale of RV variation. From $a \sin(i_3) = 154.0(1)$ $R_\odot$, and using $P_3$ and $e_3$ given above, we expect $K_3$ to be $6.674(7)$ km s$^{-1}$. Our orbital solution gives $7.2(1.6)$ km s$^{-1}$, in agreement with the expected one. For the record, our value of $T_3 = 4494(53)$ d (JD-2450000) is also in agreement with the value from Borkovits et al. (2016) – 4503(6) d. Larger errors are, of course, the effect of poor time coverage of the outer orbit. The minimum companion mass, from our solution, is 0.66(14) $M_\odot$.

Overall, our orbital solution is satisfactory, considering relatively poor precision of the RVs. Our measurements are hampered by fast rotation (30 and 19 km s$^{-1}$ for the primary and secondary, respectively), and small contribution of the secondary to the total flux (~10 per cent). Yet, the $rms$ of the fit for the primary is only 0.7 km s$^{-1}$. Relative mass uncertainties are also quite low: 2.3 and 1.7 per cent for primary and secondary, respectively.

In Figure 9 we also show the short-cadence Kepler light curve, taken during quarters Q02, Q03, and Q7-Q10. Due to the presence of the third body, which strongly influences moments of eclipses, for the LC fit we used a similar approach as for KIC 7821010, and analysed the data quarter-by-quarter. Additionally, we noted variations of the depth of minima, especially the flat (total) secondary. The lower

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9 In v2fit $\omega_3$ is defined for the outer body, while in Borkovits et al. (2016) for the inner binary, therefore we added $\pi$ ($180^\circ$) in our fit.
Figure 9. Same as Fig. 1, but for KIC 10583181. The RV modulation coming from the circumbinary body has been removed.

Figure 10. RVs of KIC 10583181 as a function of time after removing the inner Keplerian orbit. Symbols are the same as in Fig. 9. The black line is the best-fitting model of centre of mass velocity $\gamma$ variation. The grey line is $\gamma$ variation predicted by the exact solution from Borkovits et al. (2016). The plot is stretched to JD=2458350 to show the total scale of velocity variation.

The overall LC fit is quite good ($rms \approx 1.7$ mmag), hampered mildly by the evolution of spots, and led to relatively low uncertainties of spots: 0.7 and 1.0 per cent for the primary and secondary, respectively. We note that the primary is very similar, only slightly smaller, than the primary of KIC 10191056. The orbital periods and major semi-axes are also alike, both pairs accompanied by other bodies, and the main difference between them are, obviously, the secondaries. Moreover, the secondary in KIC 10583181 has almost identical mass as the secondary in KIC 8552540. It would be interesting to compare a number of such pairs (identical primaries with different secondaries, or vice versa) and search for differences that could be caused by influence of different companions, e.g. interaction of magnetic fields, influence of rotation on the internal structure and activity, etc.

The ispec analysis was possible only for the primary. The influence of the third light was assumed to be constant across the spectrum, which is probably not entirely correct, but, given that we have no additional information about $l_3$, was the only reasonable assumption we could make. Depths of spectral lines were probably affected in a non-uniform way, therefore the results of this analysis should be treated with caution. We found that the system’s chemical composition is probably similar to solar, and the primary is cooler than expected for the Main Sequence (MS). Our $T_{\text{eff,1}} = 6730(140)$ K is, however, larger than 6425$^{+260}_{-180}$ K from GDR2, although formally in $1\sigma$ agreement. We found no literature estimates of $T_{\text{eff}}$ that would match values expected at MS for this mass and solar metallicity. At the same time, the primary’s radius $R_1$ is larger than predicted for the zero-age MS, which suggests it has evolved significantly. More detailed discussion is presented in Sect. 4.2.

Without both effective temperatures, and information about the third light in bands other than Kepler’s, we are unable to estimate $d_2$. We estimate the distance on the basis of isochrone-calibrated absolute magnitudes $M_{\text{kep}}$ in Sect. 4.2.

Finally, we compare our direct determination of absolute masses with indirect approach from Devor et al. (2008).
By comparing parameters obtained from analysing the TrES light curve (T-Lyr-01013) and apparent magnitudes of the whole system with theoretical isochrones, Devor et al. obtained the most probable masses (and age) of the components: 1.749(19) and 1.049(15) \( M_\odot \). The disagreement with absolute values from Tab. 3 is obvious, but, surprisingly, the mass ratio agrees. This is another case (more are given in Paper II) which shows that without any spectroscopic information, it is impossible to obtain reliable stellar parameters for eclipsing binaries.

4.1.10 KIC 10987439

This system has no new HIDES observations since Paper II, and only long-cadence Keplerm photometry is available, thus the we rely on our previous results. It is another case of a high-contrast pair (low flux ratio), for which the disentangled spectrum of the fainter component is not sufficient for reliable spectroscopic analysis (SNR=20). It is, however, an important target, since we reached excellent precision in masses (0.34 and 0.32 per cent), and also very good in radii (1.6 and 2.0 per cent for the primary and secondary, respectively). Please note that, as in KIC 4851217 or 10031808, the primary is actually the fainter star.

The ispec analysis of the TD spectrum of the secondary (SNR=134) gave the \( T_{\text{eff,2}} = 6490(90) \) K, the systems metallicity and \( a \)-enhancement indistinguishable from solar: \(-0.03(5)\) and \(0.05(16)\) dex, respectively. The temperature is in excellent agreement with \( 6450^{+20}_{-25} \) K from GDR2. During the analysis we assumed pseudo-synchronous rotation, because the predicted time scale of synchronisation (from jktabsdim) is only 93 Myr. Again, we could not use jktabsdim to calculate distance. We do it on the basis of isochrone-calibrated values in Sect. 4.2.

However, in addition to Paper II, in this work we run a Lomb-Scargle periodogram on the residuals of our fit. We detected a single, dominant peak at \( \approx 1.624 \) d with two sidelobes at \( \Delta T \approx \pm 0.0068 \) d (or \( \Delta T \approx \pm 0.00258 \) d\(^{-1}\) in frequency domain), and a variety of lower, but still very prominent peaks at periods between 2.5 and 4 days (Figure 12). The amplitude of the dominant pulsation is only 33 ppm. We tentatively interpret this as \( \gamma \)-Dor-type pulsations, originating most likely from the brighter, more massive secondary, but a detailed analysis is required. Comparison of our values of \( T_{\text{eff}}, \log(g) \), and \( v_{\text{mic}} \) with distributions of those parameters in Kahraman Alicavus et al. (2016) tends to confirm our conclusion, although KIC 10987439 resides at the lower-mass edge of distributions. If pulsations are confirmed, KIC 10987439 together with KIC 10031808, would double the number of precisely measured eclipsing binaries with \( \gamma \)-Dor-type stars.

4.1.11 KIC 11922782

This system also has no new HIDES observations, and we kept the results of the analysis of the complete long-cadence LC (shown in Fig. 13) from Paper II. Short-cadence data are available only for pieces of Q02 and Q03. Similarly to KIC 8552540, the LC is affected by rapidly evolving spots, so two incomplete \( \text{Kepler} \) quarters of data would not be sufficient for proper fitting. Moreover, the depths and widths of the minima in the long-cadence curve has not been affected by longer exposure time.

The star is another case of a low flux ratio binary. For the record, the precision in masses (from Paper II) is 0.9 + 0.7 per cent for the primary and secondary, respectively, and 3.8 + 7.4 per cent analogously in radii. The uncertainty of secondary’s fractional radius \( r_2 \) is mainly affected by strong activity and rapid evolution (in a time scale of days) of prominent, cool spots. Notably, secondary is the lowest-mass star (0.85 \( M_\odot \)) in our entire \( \text{Kepler} \) sample of SB2s. The primary, on the other hand is an evolved and older analogue of the Sun, with a similar mass but significantly larger radius. The whole system is therefore interesting for several reasons.

Spectral analysis with ispec was possible only on the TD spectrum of the primary (SNR=149), KIC 11922782 was found to be metal-poor with respect to the Sun, which was expected for an older system. Also \( T_{\text{eff,1}} = 6000(110) \) K, which is higher than solar, is explainable considering the metal depletion. It is however in disagreement with \( 5620^{+66}_{-72} \) K from GDR2. Rotationally broadened lines point strongly towards synchronous rotation, which, according to the theory, should be achieved after 20 Myr. The circular orbit is also not surprising, as the time scale of circularisation is only about 220 Myr. Lack of independent estimates of \( T_{\text{eff,2}} \) prevents us from using jktabsdim for distance calculations.

4.2 Age and evolutionary status

In Figures 14 and 15 we show the comparison of the results of our analyses with theoretical MESA isochrones. For each system we determine the age, on which the observed or calculated properties of both components are best represented. Since the stellar mass \( M \) is the most robust resulting parameter, that also strongly determines the evolution of a star, we compare our data on mass-radius (\( M/R \)) and mass-effective temperature (\( M/T_{\text{eff}} \)) planes. The former is prone to age-metallicity degeneration, meaning the same \( M/R \) combination can be reproduced by various pairs of [M/H] and \( r \). On the other hand, the \( M/T_{\text{eff}} \) plane is relatively insensitive to changes in \( r \), when a star is on the MS, but very sensitive to [M/H]. Therefore, a combination of \( M/R \) and \( M/T_{\text{eff}} \) planes can be used to determine the age and evolutionary status securely, as long as [M/H] and at least one \( T_{\text{eff}} \) is estimated.

For systems with only one effective temperature determined with ispec, we use the best-fitting isochrone, and the dynamical mass estimate for the faint companion, to check the \( T_{\text{eff}} \) predicted for the given mass and metallicity at the given age. We use this isochrone-based \( T_{\text{eff}} \) together with the other \( T_{\text{eff}} \) as input in jktabsdim to evaluate the distance \( d \). This distance is then compared with a value from GDR2. In case of KIC 10191056, both temperatures are estimated such way, and solar metallicity is assumed.

4.2.1 KIC 3439031

This is a system with two nearly identical stars residing on the MS, but somewhat evolved with respect to the Zero-Age Main Sequence (ZAMS). The age of 3.07 Gyr is, as expected, below the upper limit for orbit circularisation –
4.27 Gyr. The agreement of the model with temperatures is quite good, but mainly due to relatively large errors in $T_{\text{eff}}$ and [M/H]. Notably, individual values of [M/H] and [$\alpha$/Fe] from ispec were almost identical: [M/H] = 0.09(13) and 0.10(13) dex for the primary and secondary, respectively, and [$\alpha$/Fe] = 0.02(14) and 0.03(14) dex, analogously. At the same time, the temperatures we adopted led to $d_J$ that agrees very well with GDR2, therefore we suspect that it is the metallicity scale that is systematically shifted off, rather than the temperatures. Even so, the age will still be $>2.5$ Gyr, and the conclusions about the evolutionary status remain unchanged.

4.2.2 KIC 4851217

Only one estimate of $T_{\text{eff}}$ from spectra is available for this pair. We estimated the age of this system to be 760 Myr, and conclude that the more massive secondary has nearly finished its MS evolution. From the $M/R$ diagram only, this system would be younger, but then the temperature of the secondary would be significantly larger. At the same time, the temperatures we adopted led to $d_J$ that agrees very well with GDR2, therefore we suspect that it is the metallicity scale that is systematically shifted off, rather than the temperatures. Even so, the age will still be $>2.5$ Gyr, and the conclusions about the evolutionary status remain unchanged.

4.2.3 KIC 7821010

This pair consists of two MS components, therefore the strongest age constraints (for a particular value of [M/H]) come from the $M/R$ diagram, while the $M/T_{\text{eff}}$ plane helps to assess the metal content. Assuming the ispec value of [M/H] = +0.10 dex, we get the best overall fit for $\tau$ = 0.99 Gyr, with the model matching our results on the mass-radius plane very well, and within 2$\sigma$ on the $M/T_{\text{eff}}$ diagram. A better match ($\sim 1\sigma$) is obtained for lower [M/H] = +0.02 dex ($-1\sigma$ from the ispec value), for which the best overall fit is found for $\tau$ = 0.87 Gyr. We can therefore securely conclude that KIC 7821010 is younger than the Sun, so the small metal enhancement is not surprising. Notably, the secondary is similar in mass to both components of KIC 3439031, but is significantly smaller (and likely hotter). Also, both systems have similar metallicites. All this is consistent with KIC 7821010 being younger, than KIC 3439031 ($\tau$ = 3.1 Gyr).

4.2.4 KIC 8552540 (V2277 Cyg)

The primary of KIC 8552540 comes to the end of its MS evolution, which is supported by its oversized radius and lower temperature. The best-fitting isochrone, assuming the ispec value of [M/H] = -0.27 dex, is found for $\tau$ = 4.0 Gyr. Varying the metallicity by its 1$\sigma$ uncertainty, changes $\tau$ by 0.3–0.5 Gyr. The “older” value, for higher metal content than what we obtained, is worth to remember that the secondary is a fast rotator, which might have affected our analysis, but in any case its evolutionary stage is established securely.

The isochrone-predicted effective temperature $T_{\text{eff}}$ of the fainter but hotter primary is 8250(300) K (uncertainty includes error in [M/H], see Figure 14). When used in jktab-sdim together with $T_{\text{eff}}$ from ispec, the predicted distance $d_J$ is 1090(70) pc, assuming $E(B-V)$ = 0.03 mag to reach consistency between all bands. The agreement with 1195(53) pc from GDR2 is therefore quite good. This shows that, despite we do not have complete information about KIC 4851217, our results are reliable.
of $-0.16$ dex, seems to better match the $T_{\text{eff}, 1}$, but still the agreement between our temperature determination from ispec and the prediction for [M/H] = $-0.27$ dex is formally within 2σ. As in the case of KIC 4851217, the component analysed with ispec rotates rapidly ($\sim 67$ km s$^{-1}$), which might have affected the results of spectral analysis.

The formally best-fitting 3.98 Gyr, $-0.27$ dex isochrone predicts the temperature of the fainter secondary to be $T_{\text{eff}, 1} = 6050(230)$ K, which is almost exactly the same as $T_{\text{eff}, 1}$. This is clearly in contradiction to the fact that the Kepler LC shows two very much uneven eclipses (Fig. 4), which (for $e = 0$) means different surface brightnesses, hence temperatures. Even though a formal agreement with isochrones exists, our temperature and/or metallicity scales are likely affected, presumably by the rotation, as already mentioned. Notably a solar-composition model can reproduce our $T_{\text{eff}, 1}$, and the $M/R$ diagram quite well for $\tau = 5$ Gyr.

For the distance estimates with JKTABSDIM we used several pairs of isochrone-predicted temperatures, taken from isochrones ranging from [M/H] = 0.0 dex (5 Gyr) to $-0.38$ dex (3.72 Gyr). All the resulting distances are significantly above the value of 231(1) pc from GDR2, i.e.: 269 pc for [M/H] = $-0.38$ dex, $T_{\text{eff}, 1} = 6630$ K, $T_{\text{eff}, 2} = 6180$ K, $E(B-V) = 0.09$ mag; 267 pc for $-0.27$ dex, 6440 K, 6050 K, 0.06 mag; 266 pc for $-0.16$ dex, 6360 K, 5910 K, 0.03 mag; and 259 pc for 0.0 dex, 6060 K, 5700 K, and 0.0 mag. In all cases we assumed 200 K errors in temperatures, obtained $\sim 9$ pc uncertainty in distance, and the $E(B-V)$ value was found by forcing individual distances from $V, I, J, H, K$ bands to give the lowest spread\(^{10}\).

We could not obtain an ispec fit with the assumed [M/H] higher than our result from Table 3. Nevertheless, we conclude that KIC 8552540 is probably more metal abundant, and its components hotter than what we have found. Additional problems with more reliable age and [M/H] assessment come from the fact that the precision in masses is relatively poor, which prevents us from using other information (i.e. flux ratio, absolute magnitudes from GDR2 distance) to discriminate between various [M/H]−$\tau$−$T_{\text{eff}}$ scenarios. Nevertheless, our results are good enough to conclude that both components are still at the MS (with the primary approaching its end), and the system is a few Gyr old.

\(^{10}\) In this case we used $I$ instead of $B$, because it was available in Simbad, and the $B$ band magnitude was giving distances very much deviated from the other bands.
Figure 14. Comparison of our results with MESA isochrones on \(M/R\) (upper) and \(M/T_{\text{eff}}\) (lower) planes. Primaries are shown with red, and secondaries with blue symbols, both with 1\(\sigma\) errorbars. Black lines are isochrones for metallicities adopted from ispec analysis that best match both components on both planes simultaneously, with \([M/H]\) and best-fitting age \(\tau\) also labelled in black. When a \(T_{\text{eff}}\) has not been measured, dotted lines of a corresponding colour on the \(M/T_{\text{eff}}\) plane mark the mass and \(\pm 1\sigma\) error of the component, in order to evaluate its \(T_{\text{eff}}\). Grey lines represent isochrones for metallicity varied by \(\pm 1\sigma\), that best match all available data on both planes. On \(M/R\) they are often indistinguishable from the black line, because of the age-metallicity degeneration. Their corresponding \(\tau\) and \([M/H]\) are given on \(M/T_{\text{eff}}\) panels. This Figure shows the results for KICs: 3439031, 4851217, 7821010, 8552540, 9246715, and 9641031.

4.2.6 KIC 9641031 (FL Lyr)

The notable differences between our recent solution and the one from Popper et al. (1986), are smaller \(R_2\), lower \([M/H]\), and larger \(T_{\text{eff}}\) (Tab. 7). All this results in a much better match to the isochrones than previously. As can be seen in Figure 14, both components are nicely represented by a 1.58 Gyr, \([M/H] = -0.07\) dex model on the \(M/R\) plane, as well as on the \(M/T_{\text{eff}}\) plane when \([M/H]\) uncertainty is taken into account. The agreement on the \(M/R\) diagram would not be possible with Popper et al.’s parameters, and their very high metal content (+0.32 dex) was assumed to match the effective temperatures, which themselves were derived from now-outdated calibrations, and were indirectly dependent on the flux and radius ratio in their solution. We claim this work’s results to be more credible.

Notably, FL Lyr is listed in the DEBCat\(^{11}\), which is

\(^{11}\) http://www.astro.keele.ac.uk/~jkt/debcat/
a collection of the best-studied detached eclipsing binaries (Southworth et al. 2015). Even very recently it has been used for creating state-of-the-art calibrations of fundamental stellar parameters (e.g. Eker et al. 2015; Graczyk et al. 2017). Its case shows, however, that many systems studied several decades ago may need a revision, and their parameters need to be updated with better precision and accuracy, if they are to be used for the purposes of modern astrophysics.

4.2.7 KIC 10031808

Comparison of our results with the MESA isochrones shows an excellent match on both $M/R$ and $M/T_{\text{eff}}$ diagrams for the age of 1.28 Gyr. The overall uncertainty in $\tau$ is well below 100 Myr (taking into account errors in all parameters), which makes the estimate of the age of this system especially important for asteroseismology. KIC 10031808 is one of a very few examples of a well-studied eclipsing binary with a $\gamma$ Doradus pulsator, which in this case we suspect is the hotter, less massive primary. The cooler secondary could also have been a pulsator in the past, but currently may be too evolved for stable pulsation modes. Considering that the two masses do not differ very much, it is therefore interesting to see a system in which both components are close to the end of their MS lifetimes, but (probably) only one is still showing pulsations. With a complete set of high-precision and high-accuracy stellar parameters, and a good age est-
timate, KIC 10031808 should be a subject of a dedicated, detailed asteroseismic study, which we strongly encourage.

4.2.8 KIC 10191056 A

In this case, where we have no independent estimates of effective temperatures, we decided to repeat the approach from Paper II, and fit a solar-composition ([M/H]=0.0) isochrone to the M/R only, but using the updated parameters and MESA models. We also assumed 0.1 dex as the 1σ uncertainty in [M/H] to estimate the variations in age and the temperatures.

The best fit, within ~1σ agreement, was found for τ = 1.51 Gyr. The primary's radius suggests a significant deviation from the ZAMS. The predicted values of $T_{\text{eff}}$, respectively. These values come from fitting the corrected for the third light: 11.19(17) and 10.51(5) mag, predicted by isochrones, the $l_{\text{primary}}/l_{\text{secondary}}$ ratio in the $\text{Kepler}$ band is 0.61(17), which agrees within errors with 0.68(4) from the LC fit.

We can also estimate the isochrone-predicted mass of the tertiary component KIC 10191056 B. For the $I_{\text{primary}}/I_{\text{secondary}}$ value predicted by isochrones, the $I_{\text{primary}}/I_{\text{tertiary}}$ contribution of 0.16(9) is reproduced by a star of $M_{\text{B}} = 1.23(3) \, M_\odot$. The GDR2 lists GP magnitudes of both A and B. The assumed isochrone predicts the total absolute GP magnitude of A 1.73(12) mag, and the magnitude difference from GDR2 is 1.923(6) mag, thus the absolute GP magnitude of B would be 3.65(12) mag. This value is reproduced by a star of $M_{\text{B}} = 1.230(25) \, M_\odot$, which is the same as the previous value. This consistency suggests that the component B is an F-type star, gravitationally bound to the eclipsing pair A.

4.2.9 KIC 10583181

In this system both primary and secondary are much larger than expected at ZAMS. While this can be easily explained by evolution for the primary, the reason why the secondary is oversized must be different. Most likely it is related to activity and fast rotation. This is not surprising, as similar or even higher level of inflation is observed in other short-period systems with nearly-solar-mass components, such as for the primary of HIP 18 Aur ($P = 1.42 \, d$, $M = 0.954 \, M_\odot$, $R = 1.028 \, R_\odot$; Lacy et al. 2014), the secondary of ZZ UMa ($P = 2.30 \, d$, $M = 0.972 \, M_\odot$, $R = 1.16 \, R_\odot$; Lacy & Sabby 1999), or the secondary of KIC 8552540 ($P = 1.06 \, d$, $M = 0.956 \, M_\odot$, $R = 1.02 \, R_\odot$; Tab. 3). On the other hand, the secondary of KIC 9641031 ($P = 2.18 \, d$, $M = 0.951 \, M_\odot$, $R = 0.900 \, R_\odot$; Tab. 3) does not show such behaviour. The exact reason of the radius discrepancy of KIC 10583181 B is unclear to us.

We could not find a satisfactory fit to both components simultaneously, therefore we decided to search for the age of the system basing on the primary only. An isochrone for τ = 1.43 Gyr nicely reproduces its position on the M/R plane, and in a decent agreement with our $T_{\text{eff}}$ estimates. As expected, it predicts the primary to be near the end of the MS stage. The match is better when [M/H] error is taken into account, which resembles the situation with KICs 4851217 and 8552540. In all these cases the possible factor affecting the $\text{ispec}$ analysis is probably the rotational velocity. Nevertheless, the agreement is still acceptable, and the evolutionary stage is determined securely.

The adopted best-fitting isochrone predicts the secondary to have $T_{\text{eff}} = 5630(160) \, K$. Unfortunately, because this system is a triple with significant flux contribution from the third body, and we have no information on $I_3$ in bands other than $\text{Kepler}$, we can not use $\text{KE ТаRSDIM}$ to estimate the distance. Instead, we calculate the apparent magnitude of the primary, and compare it to the absolute one, predicted by MESA isochrones. As stated above, we suspect $I_3$ was varying slightly throughout the $\text{Kepler}$ observations, therefore for the following analysis we take its conservative uncertainty, and assume its contribution to be 0.12(2).

With the primary’s contribution to the total flux of 0.796(20), its apparent magnitude should be 11.26(3) mag. The absolute brightness, estimated from the isochrone, is 2.28(20) mag, with uncertainty in [M/H] and mass taken into account. Analogously, for the secondary we obtain the apparent brightness of 13.70(4) mag, and absolute of 4.95(18) mag. The weighted average of the distance module is therefore 8.85(19) mag, which translates into distance (without extinction) of 589(52) pc. To level it with the GDR2 value of 445(5) pc, one needs to assume $E(B-V) = 0.20$ mag. This would require the EW of the sodium D 1 line to be around, 0.4 Å but in the spectra we measured it to be only 0.192(16) Å ($E(B-V) < 0.1$ mag; Munari & Zwitter 1997). We would also like to note that the isochrone-predicted flux ratio $I_2/I_1$ of 0.086(30) agrees with the value of 0.105(3) from the LC fit.

We do not attempt to estimate the mass of the tertiary from isochrones, as this object may be a binary itself, and its true contribution to the total flux in the $\text{Kepler}$ band is actually uncertain.

A better insight into this system would be possible with additional information about the secondary and tertiary. The former can come from analysis of a higher-SNR disentangled spectrum, which requires additional observations with a telescope larger than OAO-188cm, and/or advanced post-processing. The latter can be achieved with multi-colour photometry, even from the ground. A ~2 mmag precision observations are certainly possible, and the flat secondary eclipse helps to constrain the fluxes in the LC analysis.

4.2.10 KIC 10987439

With masses and radii measured to a very high precision, this system poses a challenge to isochrone fitting. A good

\footnote{We do not take into account the uncertainty of the satellite's photometric zero point, but we understand it may introduce additional source of error.}
fit (within $2\sigma$) is achieved on the $M/R$ plane to both components with an isochrone of $\tau = 1.26$ Gyr. The more massive secondary, which dominates the total flux of the system, does not seem to be very evolved, and the primary not significantly inflated (similarly to KIC 9641031 B). Unfortunately, the ispec value of $T_{\text{eff,2}}$ is significantly ($\sim 500$ K) lower than 7000(110) K that the isochrone predicts. This cannot be explained by the rotation (v sin i) = 7.16 km s$^{-1}$, nor the SNR of the disentangled spectrum ($\sim 135$). All the ispec runs, for which the starting $T_{\text{eff}}$ was set to 7000 K or much higher, converged to values around 6500 K. Also when the initial [M/H] was set to higher values ($\sim 0.2-0.3$ dex) the result was the same. In an additional check, we used four line depth ratio (LDR) vs. $T_{\text{eff}}$ calibrations from Kovtyukh et al. (2004), that utilise lines in the available wavelength regions and have the smallest rms (below 50 K). In this way we obtained the average $T_{\text{eff,2}} = 6380(100)$ K, supporting the ispec result. This discrepancy between models and ispec is puzzling, however, we believe that the key is the metalliclicity scale, which might have been affected for the shortest wavelength range, on which the analysis was performed. The blue end of the TD spectrum is at 5470 Å, while in case of other stars it is at 5030 Å (except KIC 7821010).

We get a very good match to the $T_{\text{eff,2}}$ value on the MS for [M/H]=+0.30 dex isochrones. The formally-best fit was found for the age of $\sim 1.3$ Gyr. We plot this model in Fig. 15 as well, for comparison. The flux ratios $I_2/I_1$ predicted by the isochrones are 7.00(25) and 6.37(77) for [M/H]=+0.30 and -0.03 dex, respectively. While the latter is much closer to the value obtained from LC fit – 6.5(1.1) – both are in formal agreement within error bars.

The effective temperatures predicted by the [M/H] = -0.03 dex, $\tau = 1.26$ Gyr isochrone are $T_{\text{eff,1}} = 5750(80)$ K and $T_{\text{eff,2}} = 7000(110)$ K. The distance obtained with JKTABSDIM for these values is 339(11) pc, under the assumption of $E(B-V) = 0.1$ mag, made to reach the consistency between various bands. When the ispec value of $T_{\text{eff,2}}$ is used, the distance is 333(13) pc with $E(B-V) = 0.0$ mag. Finally, $T_{\text{eff,1}}$ predicted by the [M/H] = +0.30 dex, $\tau = 1.30$ Gyr isochrone is 5330(80) K. Together with $T_{\text{eff,2}}$ from ispec, it leads to the distance of 326(11) pc at $E(B-V) \leq 0.1$ mag. We measured the EW of the interstellar sodium D 1 line from GD2R. In any case, both components of KIC 10987439 are currently at the MS, and the age of the systems seems to be $\sim 1.3$ Gyr. With the gDor-type pulsations detected from the dominant (secondary) star, which has its parameters well constrained, KIC 10987439 is worth further detailed studies. It offers an interesting insight into the mechanisms of pulsations and their stability conditions, especially considering that the pulsator seems to reside at the low-mass edge of the gDor instability strip.

### Table 9. New HIDES RV measurements of KIC 10191056 B

| BJD  | $v$  | $e$  | $e_{\text{exp}}$ | SNR |
|------|------|------|------------------|-----|
| -2450000 | 6852.954108 | -22.329 | 0.387 | 480 |
| 7815.288473 | -24.192 | 0.257 | 1500 |
| 79.277236 | -24.292 | 0.175 | 1500 |
| 7845.230234 | -24.143 | 0.127 | 1500 |
| 7983.090781 | -24.027 | 0.178 | 1500 |
| 7984.159592 | -24.399 | 0.242 | 1800 |
| 7991.044165 | -24.458 | 0.151 | 1630 |
| 7955.090230 | -24.011 | 0.096 | 1511 |
| 8003.009297 | -24.568 | 0.121 | 1588 |

Table 10. Parameters of orbital solutions to the RVs of KIC 10191056 B for different ($\times$) eccentricities, and mass of the host $M_B = 1.23(M_\odot)$. Uncertainties are formal fit errors.

| e  | P  | K  | a sin i | f(m) | m sin i |
|----|----|----|--------|------|--------|
| 0.0 | 2186±380 | 1.08±0.140 | 0.22±0.01 | 0.30±0.05 | 80±11 |
| 0.1 | 2530±1320 | 1.16±0.328 | 0.25±0.06 | 0.35±0.20 | 83±80 |
| 0.2 | 2800±1990 | 1.17±0.436 | 0.28±0.13 | 0.46±0.33 | 91±46 |
| 0.3 | 3680±1450 | 1.18±0.514 | 0.35±0.06 | 0.58±0.24 | 99±45 |
| 0.4 | 4920±1430 | 1.13±0.535 | 0.41±0.05 | 0.70±0.21 | 104±48 |
| 0.5 | 6750±1720 | 1.17±0.539 | 0.47±0.05 | 0.78±0.24 | 109±51 |
| 0.6 | 9760±2640 | 1.17±0.534 | 0.54±0.06 | 0.88±0.29 | 113±53 |
| 0.7 | 15000±4530 | 1.17±0.538 | 0.61±0.07 | 0.99±0.35 | 118±57 |
| 0.8 | 29260±9130 | 1.17±0.536 | 0.68±0.09 | 1.10±0.44 | 122±58 |

The rms of a fit varies from 196 m s$^{-1}$ for e = 0.0 to 189 m s$^{-1}$ for e = 0.8.

### 4.2.11 KIC 11922782

This system shows one of the lowest metallicities, and is also the oldest. The best-fitting [M/H] = -0.22 dex isochrone was found for $\tau = 6.17$ Gyr. The primary, which is similar in mass to the Sun, but much larger, is currently at the end of its MS life. Notably, the 6.17 Gyr isochrone matches both components on the $M/R$ plane very well, which is not always observed in stars of mass similar to the secondary. The agreement with measured $T_{\text{eff,1}}$ is also quite good, within $2\sigma$, and even better when [M/H] error is taken into account. In terms of masses and metallicity, KIC 11922782 is similar to V636 Cen vs. 0.849 R$\odot$ and even better when [M/H] error is taken into account.

#### Table 11. Parameters of orbital solutions to the RVs of KIC 11922782

| BJD  | $v$  | $e$  | $e_{\text{exp}}$ | SNR |
|------|------|------|------------------|-----|
| -2450000 | 6852.954108 | -22.329 | 0.387 | 480 |

4.3 KIC 10191056 Bb – a candidate M dwarf

In Paper II we presented two hypotheses about the origin of RV variations of KIC 10191056 B. First, that we observe motion on the orbit around common centre of mass with the eclipsing pair A. Second, that we see a short-period (10-20 d) modulation induced by a massive planet or low-mass brown dwarf (BD). The new HIDES observations, supported with the TRES spectrum from July 2014, make the former very
unlikely, and rule out the latter. New observations do not match any of the previously proposed solutions. The motion of B is, however, very clear.

In Figure 16 we show all the RV measurements for KIC 10191056 B. The new ones are presented in Table 9. New HIDES data (after JD=2457800) cluster at lower values, while the TRES point is at a similar level as the earliest ones from HIDES (no zero-point shift was assumed, see Sect. 4.1.8). We clearly see a gradual drop in velocity, with some curvature. Since we do not see a significant long-term upwards trend in $\gamma$ of the pair A, this observed RV drop must be due to another body in the system (Bb), that is orbiting B with a period much longer than the time span of our observations.

With only a fraction of the orbit covered, we can not fit for $P$ and $e$ simultaneously. Instead, we run a number of fits with fixed eccentricity that varied from 0.0 to 0.8. Their results are shown in Table 10. Solutions with $e > 0.8$ lead to very long orbital period and showed problems with convergence, therefore we decided not to present them. Nevertheless, such high eccentricities are not impossible. The circular ($e = 0$) solution sets the lower limit on the period of Bb at 2180(380) d. All solutions have similar quality, with $rms \approx 190$ m s$^{-1}$.

Independently of the assumed $e$, all solutions lead to RV amplitude of $\sim 1.1$ km s$^{-1}$, which strongly constrains the minimum mass of the companion. We obtained $m \sin(i)$ between 80 and 122 Jupiter mass ($M_J$), with large uncertainties coming mainly from the unknown $P$, and assuming a theoretically-predicted mass of the host 1.23(3) $M_\odot$. This means that the companion is most likely a late-M type star, or, rather unlikely, a massive BD. More observations are needed to set further limits on orbital parameters and $m \sin(i)$. Even a few observations taken throughout 2019 will allow to distinguish between low- and high-eccentricity solutions. The spectra need to be of a sufficiently high resolution, and taken around quadratures of the pair A, to have the narrow lines of B distinguishable and well separated from broad lines of the pair A. Unfortunately, the available observations from LAMOST (e.g.; Frasca et al. 2016; Zong et al. 2018), or those used by Matson et al. (2017), do not have sufficient spectral resolution. A better estimate of $M_B$ would also be welcome.

5 CONCLUSIONS

We presented updated results for 11 (3 new) DEBs from the original Kepler satellite observing field, based on new observation, refined light curve fits, and/or additional, complementary methods of analysis. We improve our knowledge on the systems, mainly by adding new information, crucial for assessing the age and evolutionary status of the studied targets. In this work we studied a variety of interesting systems, including a double-giant pair with one of the components at the core He burning phase, a probable quadruple, various pairs with components at vastly different phases of MS evolution, three DEBs with pulsating (dSct and gDor) components, a pair of twins, and a pair with a low-mass (0.85 $M_\odot$) secondary. A significant number of systems have their physical absolute parameters derived with $< 2$ per cent uncertainties. For two targets – KIC 9246715 and KIC 9641031 (FL Lyra) – our updated results are in better consistency with evolutionary models than in the previous studies. There are still open questions and things to improve in some cases. First, the light curves could be cleaned from influence of spots or pulsations, and a more careful de-trending could be performed. The effective temperatures of fainter components could be derived, but this requires more spectroscopic observations and higher SNR spectra. We also encourage the community to study the pulsations in presented systems.

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**APPENDIX A: NEW OBSERVATIONS OF KIC 4758368**

Apart from the sample of double- and triple-lined spectroscopic systems, we re-observed KIC 4758368 (KOI 6448). This target is a hierarchical triple, with a short-period ($P \approx 3$ days) eclipsing binary, orbited by a third star on an eccentric, long-period orbit. The third star, which is a red giant, is the dominant source, and we see its lines in spectra. In Paper I we used our 13 HIDES spectroscopic observations and 6 APOGEE data points for the third star, and a set of RVs of the centre of mass of the inner DEB, obtained from its eclipse timing variations (post-ETV RVs).
Table A2. New and previous orbital solutions and parameters of KIC 4758368.

| Parameter          | Paper I          | This work         |
|--------------------|------------------|-------------------|
| Outer orbit        |                  |                   |
| $P_{AB}$ (d)       | 2553(80)         | 5030(1160)        |
| $T_0$ (BJD-2450000) | 5581(9)          | 5570(7)           |
| $K_A$ (km s$^{-1}$) | 8.81(41)         | 8.72(37)          |
| $K_B$ (km s$^{-1}$) | 12.9(1.4)        | 16.8(2.8)         |
| $\sigma_{AB}$     | 0.672(37)        | 0.80(6)           |
| $\omega_A$ ($^\circ$) | 142(2)          | 134(6)            |
| $\gamma$ (km s$^{-1}$) | -24.0(1.2)      | -29.4(1.9)        |
| $M_A \sin(i)$ ($M_\odot$) | 0.65(18)     | 1.2(7)            |
| $M_B \sin(i)$ ($M_\odot$) | 0.45(5)        | 0.63(32)          |
| $a_{AB} \sin(i)$ (AU) | 3.77(32)       | 9.3(2.1)          |
| $N_A$              | 106              | 106               |
| $N_B$              | 19               | 21                |
| $rms_A$ (km s$^{-1}$) | 6.9              | 6.9               |
| $rms_B$ (m s$^{-1}$) | 57              | 63                |

$^a$JKTEBOP solution

| Parameter          | Paper I          | This work         |
|--------------------|------------------|-------------------|
| $P_A$ (d)$^a$      | 3.74993552(43)   |                   |
| $R_{AB} + r_{AB}$  | 0.4252(64)       |                   |
| $r_{AB}/r_{A}$     | 1.22(21)         |                   |
| $ln/l_{tot}$       | 0.725            |                   |

Absolute values

| Parameter          | Paper I          | This work         |
|--------------------|------------------|-------------------|
| $d_{GDR2}$ (pc)    | 1910(80)         |                   |
| $M_B$ ($M_\odot$) | 1.43$^b$         |                   |
| $i_{AB}$ ($^\circ$) | 43(5)            | 50(16)            |
| $M_A$ ($M_\odot$) | 2.1(6)           | 2.7(1.6)          |
| $a_{AB}$ (AU)      | 5.54(72)         | 12(4)             |
| $a_{AB}$ (mas)     | 2.9(4)           | 6.4(2.0)          |
| $a_A$ (R_\odot)    | 15(1)            | 14(3)             |
| $R_{AB}$ (R_\odot) | 2.48(35)        | 2.7(7)            |
| $R_B$ (R_\odot)    | 3.04(27)         | 3.3(8)            |

$^b$Orbital period of the eclipsing inner pair.

APPENDIX B: NEW RV MEASUREMENTS OF SB2S

In that work, our data coverage was too short to securely establish the outer period, thus we observed this target in May and July 2017, recording two more spectra. The previous solution predicted a small but measurable rise of the RVs, which would help to constrain the period. Instead, we continued to observe a downward trend, which clearly means the outer period is much longer than what we have obtained previously. The new measurements are listed in Table A1.

As in Paper I, we treated the system as a double-lined binary, with post-ETV RV measurements for one component (designated A), and directly measured RVs for the other (designated B). We followed the same fitting procedure with v2fit as previously. Table A2 and Figure A1 show comparison of old and new solutions. The most obvious difference is the much longer orbital period, and other parameters dependent on it ($a_{AB} \sin(i)$, $M_{AB} \sin^2(i)$). Large relative uncertainty in $P$ also leads to large uncertainties in other parameters.

As in Paper I, we assumed the mass of B to be 1.43 $M_\odot$ (taken from the Kepler Input Catalog) and JKTEBOP results of LC fit (details in Paper I), and estimated other values, such as: inclination of the outer orbit $i_{AB}$, its absolute ($a_{AB}$) and angular ($\theta_{AB}$) major semi-axes, total mass of the inner pair $M_A$, and absolute radii of the inner pair components $R_{AB}$. We conclude, that the inner pair is likely composed of two sub-giant stars, slightly more massive than the Sun, although the uncertainties are very large. Interestingly, the orbital motion of B around common centre of mass is strong enough to be detectable astrometrically with AO facilities.

There are other estimates of $M_B$ in the literature, reaching up to 2.09 $M_\odot$. For such scenario, the inner pair’s total mass would be ~4.0 $M_\odot$, and its components radii would be 3.0-3.7 $R_\odot$, making them comparable in flux or even brighter than the apparently dominant star B. We thus find it unlikely. Other $M_B$ estimates are below solar mass (0.7-0.85 $M_\odot$), but then the system would have to be significantly older than 10 Gyr for B to be a giant.

Figure A1. Directly measured RVs of KIC 4758368 B (red symbols), with two orbital solutions: from Paper I (orange dashed line) and this work (blue solid). The APOGEE, old HIDES, and new HIDES data are marked with open stars, open circles, and filled circles, respectively. The post-ETV velocities of the inner pair A were also used in the fit, but we omit them in the Figure for clarity.
Table B1. All RVs of SB2 pairs used in this work. Complete Table is available in the on-line version of the manuscript.

| BJD         | $v_1$ (km s$^{-1}$) | $\epsilon_1$ | $v_2$ (km s$^{-1}$) | $\epsilon_2$ | KIC          | $t_{exp}$ (s) | SNR | Note$^a$ |
|-------------|---------------------|---------------|---------------------|---------------|--------------|---------------|-----|----------|
| 7673.020510 | 100.172             | 0.131         | -46.325             | 0.219         | 3439031      | 1500          | 24  |          |
| 7812.327593 | -50.460             | 0.137         | 104.593             | 0.098         | 3439031      | 1500          | 29  |          |
| 7846.330225 | 60.889              | 0.199         | -6.204              | 0.210         | 3439031      | 1500          | 25  |          |
| ...         |                     |               |                     |               |              |               |     |          |
| 5823.726555 | -122.76             | 6.00          | 54.11               | 3.96          | 4851217      | 3386          | 119 | A        |
| 5849.578427 | 48.68               | 5.13          | -81.25              | 5.63          | 4851217      | 2002          | 142 | A        |
| 5851.648819 | -79.27              | 4.62          | 13.59               | 6.14          | 4851217      | 2002          | 134 | A        |
| ...         |                     |               |                     |               |              |               |     |          |
| 6867.030540 | -46.473             | 0.092         | 13.313              | 0.145         | 7821010      | 1800          | 48  |          |
| 6869.142604 | -38.627             | 0.361         | 5.871               | 0.532         | 7821010      | 1500          | 23  |          |
| 6914.079695 | -51.604             | 0.102         | 18.896              | 0.132         | 7821010      | 1500          | 63  |          |

$^a$ Spectra taken with facilities other than OAO-188cm/HIDES are marked: “A” for APOGEE, and “T” for TRES.