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OBSERVATIONAL VERIFICATION OF LIMB DARKENING LAWS FROM MODELING OF LIGHT CURVES OF CONTACT BINARIES OBSERVED BY THE KEPLER SPACECRAFT

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RESUMEN

Basaándonos en sistemas de binarias eclipsantes por contacto observadas por el satélite *Kepler*, hemos desarrollado un proyecto encaminado a determinar cual de las tres leyes de oscurecimiento del limbo ajustan mejor sus curvas de luz. En la primera parte de este trabajo, investigamos cómo el modo de larga cadencia de *Kepler* (con resolución de 30 min) influencia la forma de la curva de luz de las binarias. Como ejemplo, hemos simulado curvas de luz de binarias eclipsantes de contacto con periodos en el rango 0,2−1,6 días, exhibiendo mínimos secundarios planos. Hemos encontrado que el "binning" causa un decrecimiento de las amplitudes de las variaciones geomètricas y cambia la forma del mínimo. Hemos modelado las curvas de luz simuladas con un código que no considera el "binning". Al comparar los parámetros derivados con los introducidos, resulta que sólo cuando el periodo de la binaria es superior a 1,5 días, la solución es adecuada.

Hemos seleccionado una serie de binarias de contacto observadas por *Kepler*, exhibiendo un mínimo secundario plano pero sin actividad intrínseca. Con las conclusiones expuestas anteriormente en mente, hemos ajustado las curvas de estos sistemas aplicando el código de Wilson-Devinney, que tiene en cuenta el "binning" y el coeficiente de enrojecimiento por el limbo, teniendo en cuenta las distribuciones lineales, logarítmicas y por raíz cuadrada tabuladas por van Hamme. Hemos derivado los parámetros del sistema y comparado las soluciones para las tres leyes de enrojecimiento del limbo. Para nueve sistemas, el mejor ajuste se obtuvo para la distribución lineal de enrojecimiento del limbo, mientras que la ley de la raíz cuadrada ajustaba mejor siete sistemas, y sólo uno en el caso de la logarítmica.

ABSTRACT

We undertook a project aimed at the observational determination of the best fitting linb darkening law for contact binaries. Our sample consisted of systems exhibiting total eclipses, observed by the *Kepler* spacecraft. We focused our study on three most commonly used limb darkening laws: linear, logarythmic and square root.

In the first part of this work, we investigate how the long cadence mode in the *Kepler* mission (resolution of about 30 minutes) influences the shape of light curves of eclipsing binaries. As an example we used simulated light curves of contact binaries with periods between 0.2 and 1.6 days, exhibiting flat bottom secondary minima. We found that the binning causes a decrease of amplitude of geometrical variations and change of the shape of minima. We modeled the simulated light curves with a code that does not account for binning. By comparing the derived parameters with the input ones, it turned out that only when a binary period is longer than about 1.5 days, the solutions derived with a code that does not account for binning, would be accurate.

We selected a sample of contact binaries observed by *Kepler*, exhibiting a flat bottom secondary minimum and no intrinsic activity. With the above conclusion in mind, we solved the light curves of selected systems with the most recent version of the Wilson-Devinney code, which accounts for binning and incorporates the limb darkening coefficients for linear, logarithmic and square root distributions, tabulated by Van Hamme. We derived the systems parameters and compared the solutions obtained for the three limb darkening laws. For nine systems, the best fit was derived for the linear limb darkening distribution, while the square root law for seven systems, and for just one, the logarithmic low was preferred.

Key Words: binaries: eclipsing — binaries: close — stars: fundamental parameters

1. INTRODUCTION

Eclipsing binary stars are very often used to derive fundamental parameters of stars, their masses, radii and luminosities. Reliable values description of the components can be obtained if accurate photo-

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metric light curves (preferably multicolor) and radial velocity measurements are available. A reasonable accuracy still can be achieved from the photometry alone, when the analysis is performed for light curves with a flat bottom minimum (Terrell & Wilson 2005). Furthermore, the information about at least temperature of one component is crucial.

The Wilson-Devinney (W-D) code is most commonly used to derive parameters of eclipsing binaries (Wilson & Devinney 1971; Wilson 1979). After its first release in seventies, the code has been significantly modified (Wilson et al. 2010; Wilson & Van Hamme 2014) with the most recent releases in 2013 and 2015. The latest version is now capable of simultaneous treatment of light and radial velocity curves as well as the period behavior.

Accurate data on many stars have been recently provided by the *Kepler* spacecraft, launched in 2009 (Borucki et al. 2010). Though, it was primarily aimed at searching for planets (with an ultimate goal to find a rocky planet in a habitable zone), it monitored about 150,000 stars. The spacecraft collected data in two modes. The short cadence (SC) was built up of 9 exposures of 6.02 sec each followed by 0.52 sec overhead. This resulted in about 1 minute time resolution. The long cadence (LC) consisted of 270 exposures resulting in almost 30 min resolution.

In this paper we present the results from modeling of a sample of contact binaries observed by the *Kepler* spacecraft. It was aimed at derivation of systems parameters and comparing the solutions obtained for the three limb darkening laws: linear, logarithmic and square root. We also investigate how long exposures, if not accounted for, influence derived physical parameters of components in contact systems. A similar subject was undertaken by (Kipping 2010). He studied distortions of shapes of planetary transits, due to long exposure times, observed by the *Corot* and *Kepler* missions. Kipping (2010) proposed an analytical approach to correct for phase smearing and investigated how incorrect parameters of host stars would be derived in the case when this effect was not accounted for, and concluded that one should never do modeling of binned data with an unbinned model, since this would provide incorrect physical parameters.

2. SAMPLE SELECTION

The initial selection of targets was done using the *Kepler* Eclipsing Binary Catalogue maintained at the Villanova University (Prsa et al. 2011). We visually inspected light curves in the database and based on their shapes, the range of variability, and

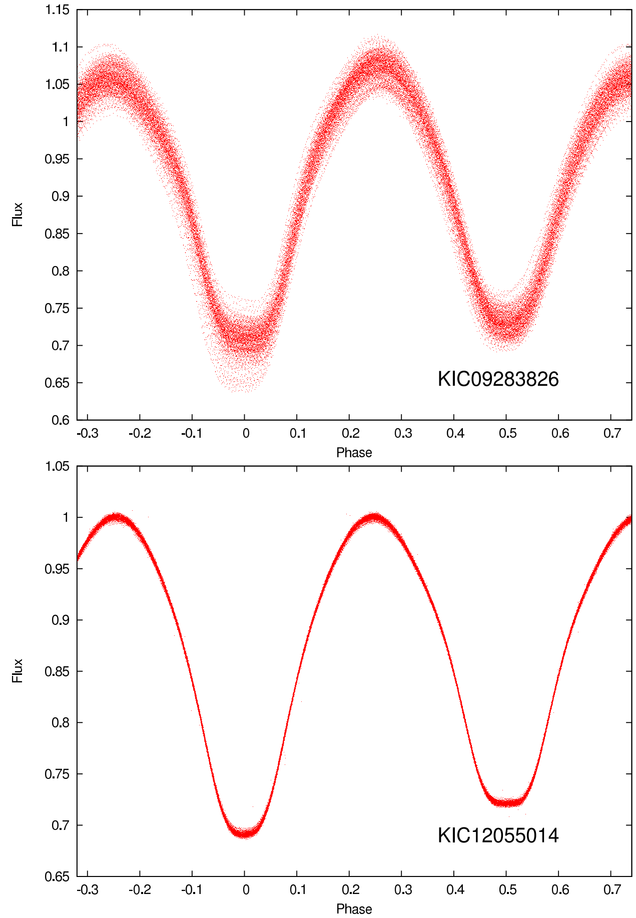

Fig. 1. An example of two light curves with flat bottom minima observed by the *Kepler* mission. A light curve of an highly active KIC09283826 system is shown in the top panel while that of KIC12055014, shown in the bottom panel, exhibits no or negligible intrinsic variability.

the flat bottom features (even short ones), we selected a rather large sample. To make this step quite fast, the initial selection was done based on just few orbital cycles. In the second step, we checked the stability of the light curves shape over time. It turned out that light curves of many eclipsing binaries in the sample, had undergoing changes on the timescale of tens or hundreds of orbital periods. These intrinsic variations, like asymmetries and the varying O'Connell effect (O'Connell 1951), are most likely due to the magnetic activity, which is very often observed in contact binaries.

The rejected systems due to their intrinsic variability, became the target of a different project aimed at investigating spot(s) migration on the surface of components. The preliminary results from such an analysis were published in Debski et al. (2014, 2015). The sample analyzed in this work consists of systems

TABLE 1

SAMPLE OF CONTACT SYSTEMS WITH FLAT BOTTOM MINIMA AND LACK OF INTRINSIC ACTIVITIES

Name	Period [d]	M_0 [JD]	Kepmag
KIC03104113	0.846786	2454965.28462	13.45
KIC03127873	0.671526	2454964.98287	15.15
KIC05439790	0.796087	2454953.70843	13.25
KIC05809868	0.439390	2454964.79773	12.96
KIC07698650	0.599155	2454965.21499	15.23
KIC08145477	0.565784	2454965.07604	14.79
KIC08265951	0.779958	2454954.24434	12.73
KIC08539720	0.744499	2454953.98345	12.93
KIC08804824	0.457404	2454964.69995	14.72
KIC09350889	0.725948	2454954.24293	13.57
KIC09453192	0.718837	2454964.88954	14.02
KIC10007533	0.648064	2454965.03994	13.88
KIC10229723	0.628724	2454953.68537	11.97
KIC10267044	0.430037	2454964.86234	14.04
KIC11097678	0.999716	2455002.84578	13.22
KIC11144556	0.642980	2454954.06058	13.55
KIC12055014	0.499905	2454965.04124	13.54

with hard to notice variations of their light curves shape over all fifteen quarters. An example of a magnetically active and an inactive systems light curves are shown in Fig. 1.

Instead of using the data stored in the Villanova database we prepared the light curves by downloading the FITS files as collected by the Flight System and described in the *Kepler* Instrument Handbook [3]. First, we extracted the fluxes and then we removed systematics added by the spacecraft. The PyKE application was used for this purpose. We used 15 quarters of observations taken in the LC mode. Since the sets for each target contain a huge number of points (more than 65,000) and in order to speed up initial computations, we calculated average points from the detrended data. To do so, we phased the observations with the ephemerides derived from times of primary minima determined over the whole datasets. After folding data over orbital period, we made additional checks to eliminate system with scatter not noticed earlier during the preliminary search. The final sample, consisting of 17 systems (out of a few dozens initially selected), along with ephemerides, are presented in Tab. 1.

[3]https://archive.stsci.edu/kepler/documents.html

TABLE 2

RESULTING PARAMETERS DERIVED FROM MODELING OF SYNTHETIC LIGHT CURVES

P [d]	i [deg]	T_2 [K]	Ω_1	q	L_1
0.2	73.0	6130	1.861	0.086	11.103
0.3	79.2	6112	1.927	0.101	11.174
0.4	82.5	6110	1.948	0.105	11.202
0.5	82.9	6115	1.951	0.106	11.196
0.6	85.3	6113	1.962	0.108	11.209
0.7	85.3	6115	1.963	0.108	11.206
0.8	87.2	6115	1.968	0.109	11.213
0.9	87.2	6116	1.968	0.109	11.211
1.0	87.1	6116	1.969	0.110	11.209
1.1	87.2	6116	1.969	0.110	11.208
1.2	87.2	6116	1.969	0.110	11.208
1.3	87.2	6116	1.970	0.110	11.207
1.4	87.3	6115	1.970	0.110	11.207
1.5	88.9	6120	1.970	0.110	11.213
1.6	89.0	6120	1.970	0.110	11.212
input	89.0	6120	1.971	0.110	11.210

3. SIMULATION OF THE FINITE EXPOSURE TIME EFFECT

Kipping (2010) showed the importance of accounting for the Finite Exposure Time Effect (FETE) in the case of planetary transits. Following his findings, we decided to investigate, how much FETE can distort light curves of eclipsing binaries and influence the parameters derived from the light curve modeling. Finding a threshold orbital period at which this effect becomes unimportant was our second goal. The procedure applied to achieve these two goals was as follows. Using the W-D code we simulated dense (one point every 10 seconds) synthetic light curves, spanning over a period of time comparable to that of the *Kepler* mission. This was done for a range of periods from 0.2 to 1.6 days with a step of 0.1 days. The input parameters chosen for this simulation are listed in the bottom of Tab. 2. We chose them in such a way that the simulated light curve corresponds to a typical contact system with a flat bottom secondary minimum. This feature allows the visualization of the differences between binned and unbinned light curves to be more pronounced and helps finding global solutions. The simulated light curves have been binned every 30 min, corresponding to the *Kepler* LC mode. Then, the binned points have been phased and the resulting light curves are shown in Figs. 2 and 3 (periods:

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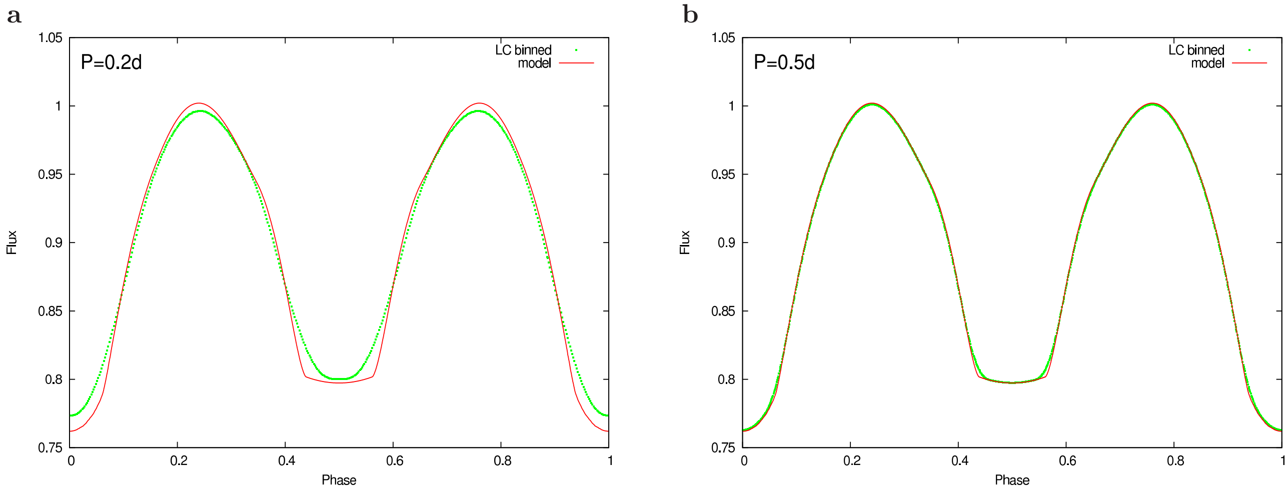

Fig. 2. Original and binned (LC rate) light curves for periods 0.2 (a) and 0.5 days (b).

0.2, 0.5, 0.8 and 1.2 days). The system light is given flux (in arbitrary units) normalized to 1 at the phase 0.25.

As expected, there are discrepancies between the shape of binned and unbinned light curves of systems with shortest periods. This is clearly seen in Fig. 2. They can be seen in both minima but also in maxima. Binning data for a system with a period of $P = 0.4$ days decreased the amplitude of light variations and shortened the duration of the flat bottom minimum. For shorter periods, these effects become more pronounced and the flat bottom part even disappears (see left panel plot of Fig. 2). For this reason, one cannot find light curves with flat bottom minima of systems with periods shorter than about 0.3 days in the database of *Kepler* LC observations. The smearing effect will significantly decrease for longer periods. For $P = 0.8$ days, the shape differences are very small at the secondary minima, and barely noticeable at the maxima. For periods of about a day, both curves fit perfectly everywhere except from phases close to the second and third contact of the flat bottom secondary eclipse.

We investigated how data binning influences the parameters of components when a model that does not account for this effect is applied for light curve modeling. Computations for an unbinned light curve were also done for check purposes. For the light curve modeling we used an older version of the W-D code which does not account for FETE. However, instead of the differential correction search algorithm, we applied the Monte Carlo method. Usage of this global search method, allows finding the global minimum to be more likely. We assumed the same temperature of the primary as the value used to compute the synthetic light curve and kept this parameter fixed. The following parameters were adjusted: system inclination (i), temperature of the secondary (T_2), potentials ($\Omega_{1/2}$), the mass ratio ($q = M_2/M_1$) and luminosity of the primary (L_1). In the case of the contact configuration, $\Omega_2 == \Omega_1$ and it was not adjusted. Albedos and gravity darkening were set to their theoretical values, while the limb darkening coefficients were taken from the Claret et al. (2013) tables, again, in the same way as in the synthetic light curves simulations. Convergence was achieved in each case and the resulting parameters are listed in Tab. 2.

We were able to recover the input parameters accurately when unbinned data were used, and also for binned data of systems with relatively long periods. Starting from the period of about 1.5 days, the resulting parameters agree with the input ones very well. We found out that if an unbinned model is used, some of the resulting parameters did not differ much from the input ones, if the period of an eclipsing binary is longer than about 0.8 days. This concerns the system mass ratio, the common potential and the secondary star temperature. The largest discrepancies were obtained only for the system inclination. We were not able to obtain good fits for systems with shortest periods considered (0.2-0.3 days). The resulting parameters differ significantly and, in the case of period equal 0.2 days, we were not able to reproduce reliably. the input configuration. The inspection of the results allowed us to put a threshold period of about 1.5 days. Our results indicate that for modeling of the light curves of binary systems with the threshold and longer periods, observed in the *Kepler* LC mode, it is safe to use a model that

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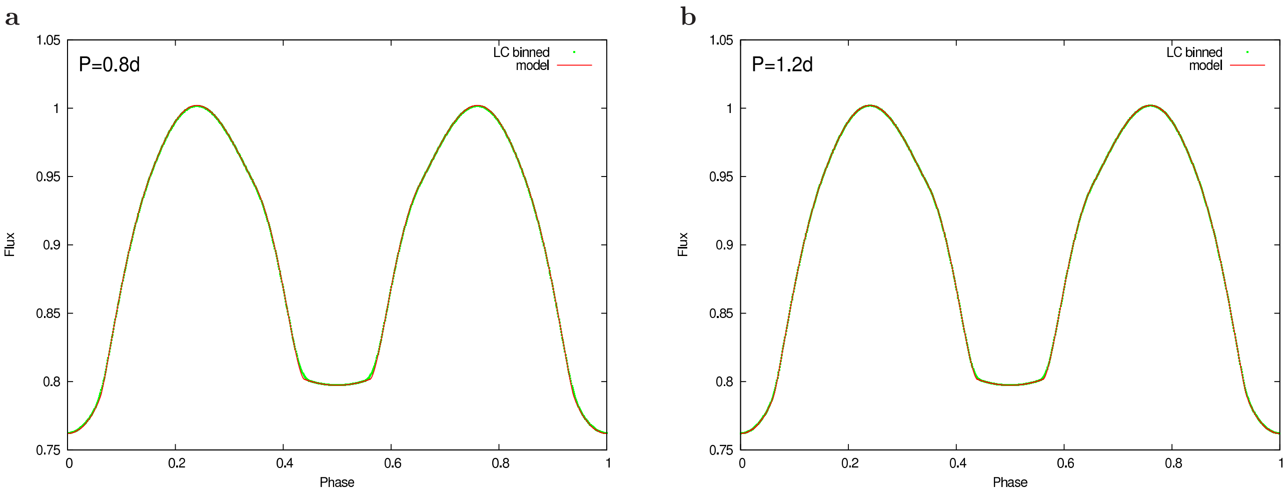

Fig. 3. Same as in Fig. 3 but for periods 0.8 (a) and 1.2 days (b).

TABLE 3

PARAMETERS OF COMPONENTS DERIVED FROM LIGHT CURVE MODELING

Name	i [deg]	T_1 [K]	T_2 [K]	Ω_1	q	L_1	l_3	f	LD
KIC03104113	79.41 (11)	5910 *	5990 (3)	2.0526 (4)	0.1675 (2)	0.8032 (4)	0.0 *	90%	log
KIC03127873	90.00 (**)	6070 *	5864 (11)	1.9078 (18)	0.1027 (10)	0.8848 (1)	0.238 (10)	89%	sqr
KIC05439790	82.72 (10)	6566 *	6412 (2)	2.1691 (11)	0.1925 (3)	0.8234 (2)	0.0 *	37%	sqr
KIC05809868	89.40 (26)	6880 *	6365 (2)	2.1738 (19)	0.2005 (10)	0.8456(41)	0.206 (3)	47%	lin
KIC07698650	85.15 (28)	6110 *	6077 (5)	1.9692 (22)	0.1218 (10)	0.8590(20)	0.149 (7)	69%	lin
KIC08145477	87.71 (19)	6800 *	6494 (3)	1.9190 (9)	0.1007 (4)	0.8948(45)	0.159 (4)	64%	lin
KIC08265951	79.75 (18)	7044 *	6771 (4)	2.0770 (25)	0.1546 (6)	0.8565 (3)	0.0 *	39%	sqr
KIC08539720	84.23 (13)	6350 *	6113 (5)	2.0311 (12)	0.1551 (7)	0.8453(62)	0.476 (3)	86%	sqr
KIC08804824	89.25 (15)	7200 *	6735 (7)	1.9375 (21)	0.1085 (11)	0.8954(26)	0.180 (8)	67%	lin
KIC09350889	83.09 (25)	6725 *	6767 (4)	1.9306 (9)	0.1137 (4)	0.8536(38)	0.127 (3)	94%	sqr
KIC09453192	89.30 (24)	6730 *	6246 (3)	2.0456 (2)	0.1517 (9)	0.8708(53)	0.260 (4)	63%	lin
KIC10007533	89.50 (23)	6810 *	6357 (6)	1.9093 (13)	0.1002 (7)	0.9018(85)	0.174 (6)	76%	lin
KIC10229723	83.91 (21)	6201 *	6010 (3)	2.0639(30)	0.1489(13)	0.8578(75)	0.179 (6)	38%	lin
KIC10267044	86.61 (25)	6808 *	6688 (2)	2.2290 (20)	0.2304(11)	0.7906(32)	0.125 (3)	53%	sqr
KIC11097678	84.92 (14)	6493 *	6399 (5)	1.8888 (11)	0.0943 (5)	0.8839(65)	0.244 (5)	86%	lin
KIC11144556	76.12 (8)	6428 *	6302 (2)	2.0126 (9)	0.1516 (4)	0.8339(22)	0.342 (1)	97%	sqr
KIC12055014	90.00 (**)	6456 *	6438 (2)	2.0615 (9)	0.1602 (5)	0.8342(29)	0.120 (3)	67%	lin

* — fixed parameter, (**) – assumed maximum value, LD - limb darkening: lin - linear, sqr - square root, log - logarithmic

does not account for binning.

4. VERIFICATION OF LIMB DARKENING LAWS

The periods of systems in our sample are between 0.43 to 1 day. Taking into account the results from previous sections, to derive parameters as accurate as possible, we have to account for FETE. Therefore, the most recent, 2015 version of the W-D code (WD2015) was applied for modeling systems selected in our sample since this code accounts for data binning. However, this code also requires to provide estimation of starting values of parameters. The preliminary parameters of the sample were determined with an older version of the W-D code appended with the Monte Carlo search method Zola et al. (2015). We assumed these as the initial values for the WD2015 code. We used the code in the automatic iteration mode, and to account for data binning, the control parameter NGA was set to 3. Furthermore, the *Kepler* magnitudes were recalculated into flux normalized to 1 at the maximum light (phase = 0.25). The results from the Monte Carlo search Zola et al. (2015) indicated that all 17 systems are in the contact configuration. Therefore, mode 3 of the code and a grid of N=60 were used. In order to speed up computations, we calculated about 800 mean points for each system light curve.

We fixed the temperature of the primary, taken from the *Kepler* Input Catalogue, while albedos and gravity darkening were set to their theoretical values. The limb darkening coefficients, were taken from the tables build into the program (Van Hamme 1993). We repeated computations for all three limb darkening laws supported by the code: linear, logarithmic and square root. The following parameters were adjusted: phase shift, orbital inclination (i), temperature of the secondary (T_2), dimensionless potential (Ω_1), the system mass ratio (q), luminosity of the primary (L_1) and, if necessary, the third light parameter (l_3). As mentioned by Zola et al. (2015), all but three systems required an additional light, otherwise, the shapes of the observed light curves could not be reproduced. This, unfortunately, complicated derivation of solutions since l_3 is strongly correlated with other parameters. For two systems, the search algorithm preferred inclination over 90 degrees. When this happened, we stopped computations, assumed the inclination value to be exactly 90 degrees and proceeded with this parameter fixed. After convergence was achieved, the mean values of resulting parameters for each limb darkening law were calculated and, in the final computations, we kept all but the luminosity of the primary fixed. The solutions were compared and the one with lowest sum of residuals was chosen as the best one. The resulting parameters derived for the best models are listed in Tab. 3. Except from the parameters listed above, also the fill out factor f is given. The listed errors are standard errors given by the WD2015 code.

Unexpectedly, for nine out of seventeen contact systems considered, we derived the best fits for the linear limb darkening law coefficients. The two-parameter limb darkening distributions, the square root and the logarithmic ones were preferred for seven and just one system, respectively. We plan to check the dependence of the derived results on the values of assumed grid and the NGA parameters. We will also perform similar computations for the limb darkening coefficients published by Claret et al. (2013).

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