

# Low-mass eclipsing binaries in the WFCAM Transit Survey: the persistence of the M-dwarf radius inflation problem

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## ABSTRACT

We present the characterization of five new short-period low-mass eclipsing binaries (LMEBs) from the WFCAM Transit Survey. The analysis was performed by using the photometric WFCAM J-mag data and additional low- and intermediate-resolution spectroscopic data to obtain both orbital and physical properties of the studied sample. The light curves and the measured radial velocity curves were modelled simultaneously with the JKTEBOP code, with Markov chain Monte Carlo simulations for the error estimates. The best-model fit have revealed that the investigated detached binaries are in very close orbits, with orbital separations of  $2.9 \leq a \leq 6.7 R_{\odot}$  and short periods of  $0.59 \leq P_{\text{orb}} \leq 1.72$  d, approximately. We have derived stellar masses between 0.24 and  $0.72 M_{\odot}$  and radii ranging from  $0.42$  to  $0.67 R_{\odot}$ . The great majority of the LMEBs in our sample has an estimated radius far from the predicted values according to evolutionary models. The components with derived masses of  $M < 0.6 M_{\odot}$  present a radius inflation of  $\sim 9$  per cent or more. This general behaviour follows the trend of inflation for partially radiative stars proposed previously. These systems add to the increasing sample of low-mass stellar radii that are not well-reproduced by stellar models. They further highlight the need to understand the magnetic activity and physical state of small stars. Missions like *TESS* will provide many such systems to perform high-precision radius measurements to tightly constrain low-mass stellar evolution models.

**Key words:** techniques: spectroscopic – binaries: eclipsing – stars: fundamental parameters – stars: late-type.

## 1 INTRODUCTION

Approximately half of the stars in our galaxy are part of binary systems (Duquennoy & Mayor 1991; Raghavan et al. 2010) and that these systems are expected to be formed at the pre-main-sequence phase. Binary systems can be formed, for instance, by the fragmentation of proto-stellar discs, where they are gravitationally bound before the discs are dissipated by stellar winds (Tobin et al. 2013, and references therein). However, several formation and evolutionary processes are still not completely understood, for example, the loss of angular momentum that results in the migration of these binaries to closer orbits, with short periods of just a few days (Nefs et al. 2012).

Binary systems can be separated in three groups – detached, semidetached, and contact binaries – that can be interpreted as different evolutionary stages. As the most massive component of a close binary system evolves, a mass transfer episode starts and the system goes from a detached to a semidetached stage. If this mass transfer happens in a very high rate, both binary components share the same envelope and become a contact binary. At the end of this process, the system has a smaller orbital separation and is composed by a main-sequence (MS) and an evolved star, starting a second detached phase. Further binary angular momentum losses may lead to Roche lobe contact of the less massive component which starts to transfer mass to the evolved component, a white dwarf, for example, and starts a second semidetached phase. This system is known as a cataclysmic variable (CV), and define a class of semidetached binaries of short period where the secondary component is typically a low-mass star. Then, the evolution of current short-period close

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binary systems can be associated with phenomena like CVs and Type Ia Supernovae.

Eclipsing binaries (EBs), and particularly the detached spectroscopic double-lined systems, give the most precise ways to derive the physical parameters of low-mass stars without the use of stellar models (Andersen 1991; Torres, Andersen & Giménez 2010, and references therein). However, only a small number (a few tens) of well-characterized low-mass eclipsing binaries (LMEBs) can be found in the literature (Southworth et al. 2015). These known systems present an intriguing trend when compared to stellar models: the measured stellar radii are usually 5 to 10 per cent bigger than the expected value (e.g. López-Morales & Ribas 2005; Kraus et al. 2011; Birkby et al. 2012; Nefs et al. 2013; Dittmann et al. 2017). This behaviour is known as the radius anomaly of low-mass stars and it is a recurrent problem that should not be neglected.

A significant radius anomaly has also been observed in low-mass stars that are synchronous members of semidetached binaries. This phenomenon is often attributed to the significant companion mass-loss by its Roche lobe overflow (Knigge, Baraffe & Patterson 2011). In this case, the thermal and mass-loss time-scales of the companion star may be comparable, leading to a slight deviation from thermal equilibrium and larger radii.

A few theories have been appeared on the literature as attempts of explaining the radius anomaly in detached binary systems. One that is largely discussed considers the magnetic activity as a possible reason for the radius inflation (Torres et al. 2006; Chabrier, Gallardo & Baraffe 2007). The majority of well-characterized M-dwarf EBs are in very close systems, with periods of less than 2 d. These short-period systems should be synchronized and in circular orbits due to tidal effects (Zahn 1977), which would enhance the magnetic activity as a consequence (Chabrier et al. 2007; Kraus et al. 2011; Birkby et al. 2012). This activity enhancement hypothesis is sustained by observations of H $\alpha$  and X-ray emission from one or both of the binary components (e.g. Chabrier et al. 2007; Huélamo et al. 2009; Kraus et al. 2011).

It is unquestionable the need for a greater sample of well-characterized LMEBs to study the radius inflation and its effect on the evolution of low-mass stars as components of detached and semidetached binary systems. Thus, the discovery and the characterization of every single new LMEB is significantly important to help understand the radius inflation issue. We, then, present here the characterization of five new low-mass systems from the WFCAM Transit Survey.

## 2 THE WFCAM TRANSIT SURVEY

The WFCAM Transit Survey (WTS, Birkby et al. 2011; Kovács et al. 2013) was a photometric long-term back-up programme running on the 3.8-m United Kingdom Infrared Telescope (UKIRT) at Mauna Kea, Hawaii. This survey had two main aims: the search for exoplanets around cool stars and the detection of a great number of LMEBs. The survey objectives and prospects were already presented and described in detail by Birkby et al. (2011, 2012); Kovács et al. (2013), thus, only a brief summary is presented in this section.

### 2.1 The UKIRT/WFCAM photometry

The photometric data was acquired with the Wide-Field Camera (WFCAM, Hodgkin et al. 2009), in the *J* band (1.25  $\mu$ m), close to the maximum of the spectral energy distribution (SED) of low-mass stars. Individual images were also obtained with the five near-infrared WFCAM filters (*Z*, *Y*, *J*, *H*, *K*) for the characterization of

the observed objects. The survey observed four different regions of the sky centred at right ascension (RA) hours of 03, 07, 17, and 19h, providing targets for all year. Each field covered 1.5° of the sky every 15 min (9-point jitter pattern  $\times$  10 s exposure time  $\times$  8 pointings + overheads), for a cadence of 4 points per hour.

The data processing and the generation of light curves (LCs) followed the procedures described by Irwin et al. (2007). Succinctly, the image processing was performed by the Cambridge Astronomical Survey Unit pipeline to remove instrumental signature for infrared arrays, dark and reset anomaly. This pipeline also performs flat-fielding, decurtaining, and sky subtraction. The photometric calibration was done by using catalogued point-sources present in the same frame and according to Hodgkin et al. (2009).

Additional details on the image reduction and LC generation procedures are deeply reported in Kovács et al. (2013, and references therein).

### 2.2 Eclipse detection and candidate selection

An automated search for eclipses was performed in all generated LCs. For that, the Box-Least-Squares (BLS) algorithm (OCCFIT, Aigrain & Irwin 2004) was chosen as the simplest approach to look for planetary transit-like events (the main goal of the survey). The code searches for a periodic dim in the LC, compared to the mean stellar flux, and designs a box-shaped eclipse adopting a single-bin method. This procedure considers all in-occultation data points as a single bin and generates a box-shaped eclipse-like event. This simplistic method is efficient for detection purposes (Birkby et al. 2012, 2014) and the significance of the eclipses detected with OCCFIT was already discussed by Miller et al. (2008, and references therein).

As performed previously by Birkby et al. (2012) for the WTS 19 h field, we ran OCCFIT on the LCs of the 17 h field as well. The OCCFIT detection statistic *S* (see Pont, Zucker & Queloz 2006, for more details), which assesses the significance of the detections, was defined to be always  $S \geq 5$  and the derived orbital period should be outside the interval  $0.99 > P_{\text{orb}} > 1.005$  d, a common window-function alias of the WFCAM Transit Survey.

The detailed description of the eclipse detection procedure and the EB candidates selection can be found in Birkby et al. (2012); Kovács et al. (2013).

Within the whole list of EB candidates found in the WTS 17 h and 19 h fields, targets were selected for a spectroscopic follow up on the basis of two main criteria. First, the shape of the LC should clearly show a detached EB system, in order to exclude interacting binaries. Secondly, effective temperature estimates from the SED obtained with the available broad-band photometry (described later on Section 4.1) should be compatible with late-K and M dwarfs.

Among the candidates selected through these criteria, we have chosen five EB candidates for spectroscopic characterization, being two candidates from the 17 h field and three from the 19 h field. The objects are: 17e-3-02003, 17h-4-01429, 19c-3-08647, 19f-4-05194, and 19g-2-08064. We maintained the naming system described in Birkby et al. (2012), which is based on the RA of the object, the correspondent pointing, the WFCAM chip, and the target's sequence number in the WTS master catalogue.

The WTS LCs were folded on the preliminary found period and a very few outliers could be found. To identify and clean the LC from these outliers, we first excluded the primary and secondary eclipses in order to keep only the LC baseline. Then, all non-consecutive data points outside a three sigma boundary from the median value of the LC baseline were considered as outliers and were discarded.

**Table 1.** LCs for the five LMEBs from the WFCAM Transit Survey reported in this paper. (This table is fully published online.)

Binary Name	MHJD* (d)	J <sub>WFCAM</sub> (mag)	$\sigma$ WFCAM (mag)
17e-3-02003	54552.58495455	15.2560	0.0060
17e-3-02003	54552.59788564	15.2566	0.0073
17e-3-02003	54552.60936660	15.2586	0.0067
17e-3-02003	54552.62178764	15.2498	0.0063
17e-3-02003	54561.60691676	15.2545	0.0056
17e-3-02003	54561.61840766	15.2510	0.0058
17e-3-02003	54561.62972854	15.2637	0.0058
17e-3-02003	54561.64101942	15.2596	0.0060
...	...	...	...
17h-4-01429	54552.59361278	15.8130	0.0102
17h-4-01429	54552.60507375	15.8056	0.0098
17h-4-01429	54552.61752480	15.7893	0.0096
17h-4-01429	54552.62876574	15.8100	0.0101
17h-4-01429	54561.61413894	15.8180	0.0085
17h-4-01429	54561.62545983	15.8257	0.0087
17h-4-01429	54561.63675072	15.8200	0.0085
17h-4-01429	54561.64797160	15.8244	0.0083
...	...	...	...
19c-3-08647	54317.31101480	14.7889	0.0048
19c-3-08647	54317.32307474	14.7915	0.0046
19c-3-08647	54317.33442468	14.7937	0.0047
19c-3-08647	54317.34567462	14.7973	0.0048
19c-3-08647	54317.35998455	14.7940	0.0048
19c-3-08647	54317.37133449	14.7874	0.0046
19c-3-08647	54317.38281444	14.7761	0.0046
19c-3-08647	54317.39393439	14.7986	0.0047
...	...	...	...
19f-4-05194	54628.50806538	15.9730	0.0097
19f-4-05194	54628.52266592	15.9825	0.0097
19f-4-05194	54628.53653644	15.9773	0.0097
19f-4-05194	54628.54783686	15.9798	0.0094
19f-4-05194	54628.56008731	16.0452	0.0098
19f-4-05194	54628.57152774	16.1470	0.0109
19f-4-05194	54628.58606828	16.2154	0.0111
19f-4-05194	54628.59773871	16.1351	0.0106
...	...	...	...
19g-2-08064	54317.30968224	14.5019	0.0041
19g-2-08064	54317.32174217	14.4965	0.0041
19g-2-08064	54317.33308211	14.4966	0.0042
19g-2-08064	54317.34434204	14.4919	0.0041
19g-2-08064	54317.35865196	14.4889	0.0040
19g-2-08064	54317.36975190	14.4843	0.0040
19g-2-08064	54317.38149183	14.4875	0.0040
19g-2-08064	54317.39259177	14.4824	0.0041
...	...	...	...

Note. \*MHJD = HJD – 2400000.5.

The final LCs are shortly presented in Table 1 (a complete version of this table is available online).

### 3 LOW- AND INTERMEDIATE-RESOLUTION SPECTROSCOPY

#### 3.1 Data acquisition

We have dedicated a total of 10 nights at the Calar Alto Observatory (CAHA), in Spain, distributed in four observing runs between 2011 July and 2012 July, to spectroscopically classify and solve the selected five low-mass EB systems. The data were acquired with the Cassegrain TWIN Spectrograph mounted on the 3.5-m telescope.

We used the red arm only because we did not expect much flux at shorter wavelengths, since the targets were supposed to be late-type stars.

The great majority of the observing time was dedicated to measure radial velocity (RV) shifts by taking intermediate-resolution spectra, with a dispersion of  $\sim 0.39 \text{ \AA pix}^{-1}$  ( $R \sim 10\,000$ ), with the grating T10 and a 1.2 arcsec slit. The spectral coverage of around  $800 \text{ \AA}$  was chosen to be centred at  $H\alpha$ , spanning from 6200 to  $7000 \text{ \AA}$ . We also obtained low-resolution data to spectroscopically classify the components of the systems, with the grating T07. These spectra cover a wavelength range of around  $2100 \text{ \AA}$ , going approximately from 6000 to  $8100 \text{ \AA}$ , with a dispersion of  $\sim 1.62 \text{ \AA pix}^{-1}$  ( $R \sim 2300$ ). This range comprehends several spectral features, such as molecular bands, which are crucial for performing further spectral typing.

The exposure time and other observational details can be found in columns 2 to 5 of Table 2 for the objects from the 17 and 19 h fields. Arc images were also acquired before and after each target observation for the wavelength calibration.

The data reduction was performed by using the IRAF<sup>1</sup> software package following a standard procedure for CCD processing and spectrum extraction.

#### 3.2 Radial velocity measurements

The intermediate-resolution spectroscopic data were used to measure radial velocities of each EB candidate. The presence of a double-lined  $H\alpha$  in emission in the observed spectra allowed the measurement of RVs from both components.

First, RV corrections were computed with IRAF's RVCORRECT (RV package), where we set the Solar velocity (VSUN) to be  $0 \text{ km s}^{-1}$  in order to obtain heliocentric systemic velocities of the objects. We then used FXCOR (IRAF's RV package) to compute radial velocities via Fourier cross-correlation. Due to the lack of other emission lines in our spectra, we applied the cross-correlation function (CCF) only around the  $H\alpha$ -line region. This was done to improve the CCF signal-to-noise ratio (S/N) since this feature appears in emission in all cases. For that, a single-Gaussian template covering the same wavelength region was generated to be used as cross-correlation kernel. This template is totally flat, except at the  $H\alpha$  region where there is a Gaussian with full width at half-maximum (FWHM) given by the instrumental resolution, measured from arc lines images. This procedure aims at measuring the velocity shifts of narrow emission components in the observed  $H\alpha$  profile.

The obtained velocities for each stellar component of the investigated binaries are shown in columns 7 and 8 of Table 2, as well as the orbital phase of the observations, in column 6.

### 4 CHARACTERIZATION OF THE LOW-MASS ECLIPSING BINARIES

The characterization of our LMEBs was performed in three different but complementary ways: a photometric characterization through a SED fitting, a spectral typing using spectral indices, and a spectroscopic characterization through a comparison to a library of synthetic spectra.

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

**Table 2.** Summary of the spectroscopic observations and measured radial velocities for all five LMEBs from the WTS. Gratings T07 and T10 represent the low- and intermediate-resolution spectra, with resolutions of approximately  $R \sim 2300$  and  $R \sim 10\,000$ , respectively. Columns 2 to 5 present the observational details of each acquired spectrum. For the intermediate resolution spectra, the orbital phase of the observation is shown in column 6, and the respective measured RV for the primary and the secondary components are shown in columns 7 and 8.

Object name	MJD (HJD-2400000.5)	Grating number	Exposure time (s)	Airmass	Phase	RV <sub>1</sub> (km s <sup>-1</sup> )	RV <sub>2</sub> (km s <sup>-1</sup> )
17e-3-02003	55761.93893508	T10	1200	1.23	0.7848	115.7	-75.2
	55762.06949593	T10	1200	2.37	0.8914	81.3	-54.4
	55762.92592164	T10	1200	1.22	0.5903	75.5	-42.8
	55762.94045863	T10	1200	1.24	0.6022	80.9	-49.1
	56090.91266077	T10	1000	1.38	0.3304	-55.1	122.9
	56090.92488191	T10	1000	1.33	0.3404	-46.6	120.2
	56090.93710247	T10	1000	1.29	0.3504	-44.8	101.3
	56090.95029776	T10	1000	1.25	0.3611	-54.5	93.6
	56090.96251949	T10	1000	1.23	0.3711	-43.8	95.2
	56090.97474642	T10	1000	1.21	0.3811	-38.1	97.1
	56091.93748988	T10	1100	1.28	0.1674	-57.7	122.7
	56091.95086866	T10	1100	1.24	0.1784	-54.2	121.7
	56091.96425265	T10	1100	1.22	0.1893	-79.1	128.3
	56092.02624221	T10	1100	1.22	0.2399	-71.4	129.6
	56092.03962851	T10	1100	1.24	0.2508	-68.0	121.8
	56092.05300728	T10	1100	1.28	0.2617	-72.9	123.8
	56114.94131237	T07	1800	1.20	-	-	-
17h-4-01429	55761.95640436	T10	1000	1.27	0.7931	-11.3	-206.4
	55761.96863360	T10	1000	1.31	0.8015	-10.5	-173.3
	55762.03884468	T10	1000	1.80	0.8501	-21.6	-176.9
	55762.89122851	T10	1000	1.20	0.4400	-112.9	-47.1
	55762.90346065	T10	1000	1.20	0.4485	-121.7	-37.0
	56088.88960980	T10	1200	1.59	0.1115	-142.7	-28.9
	56088.90415779	T10	1200	1.48	0.1216	-133.0	-4.1
	56088.91871272	T10	1200	1.39	0.1317	-144.1	-15.4
	56089.02424900	T10	1100	1.21	0.2043	-175.8	10.1
	56089.03763298	T10	1100	1.22	0.2136	-169.6	8.2
	56089.05104475	T10	1100	1.25	0.2229	-167.2	2.0
	56089.11092395	T10	1200	1.50	0.2647	-157.6	6.5
	56089.12547309	T10	1200	1.61	0.2748	-167.9	8.8
	56091.06888000	T10	1000	1.31	0.6196	-31.3	-
	56091.08110577	T10	1000	1.36	0.6281	-26.8	-157.2
	56091.09332576	T10	1000	1.43	0.6366	-27.3	-179.1
	56091.10670222	T10	1200	1.51	0.6466	-20.9	-170.4
	56091.12133008	T10	1200	1.63	0.6567	-7.8	-175.6
	56091.13587749	T10	1200	1.78	0.6668	-23.5	-176.5
	56091.89204349	T10	1100	1.50	0.1899	-169.7	5.0
	56091.90542227	T10	1100	1.42	0.1991	-184.6	10.1
19c-3-08647	56091.91880394	T10	1100	1.35	0.2084	-167.2	14.7
	56114.96730472	T07	2100	1.22	-	-	-
	55782.89011630	T10	700	1.03	0.7069	96.1	-93.8
	55782.89880434	T10	700	1.02	0.7170	83.7	-95.2
	55782.91765525	T10	700	1.01	0.7387	97.3	-90.2
	55783.92105359	T10	700	1.00	0.8952	88.3	-71.6
	55783.93034186	T10	700	1.00	0.9059	98.8	-60.4
	55783.93904843	T10	700	1.00	0.9159	77.5	-50.4
	55784.91226546	T10	700	1.01	0.0384	-8.9	29.4
	55784.92096450	T10	700	1.00	0.0484	6.7	40.1
	55784.92966123	T10	700	1.00	0.0585	-22.5	65.0
	56092.06873895	T10	1100	1.01	0.1263	-33.3	95.9
	56092.08211483	T10	1100	1.00	0.1417	-38.6	88.4
	56092.09549650	T10	1100	1.00	0.1571	-32.2	82.6
	56092.11057526	T10	1200	1.00	0.1752	-14.5	119.3
	56092.12515219	T10	1200	1.01	0.1920	-33.1	134.1
	56092.13970365	T10	1200	1.03	0.2088	-46.8	90.6
19f-4-05194	56115.08250551	T07	1800	1.03	-	-	-
	55782.98843010	T10	1200	1.03	0.6870	112.9	-157.4
	55783.00298503	T10	1200	1.06	0.7117	103.2	-
	55783.01753302	T10	1200	1.09	0.7364	74.6	-158.1
	55783.87315996	T10	1200	1.05	0.1874	-112.9	133.3



Table 2 – continued

Object name	MHJD (HJD-2400000.5)	Grating number	Exposure time (s)	Airmass	Phase	RV <sub>1</sub> (km s <sup>-1</sup> )	RV <sub>2</sub> (km s <sup>-1</sup> )
	55783.89008688	T10	1200	1.03	0.2161	-119.2	130.2
	55783.90463660	T10	1200	1.00	0.2408	-105.2	–
	56088.06386718	T10	1000	1.02	0.1711	-136.5	146.5
	56088.07611900	T10	1000	1.01	0.1919	-131.3	178.7
	56088.08878525	T10	1000	1.00	0.2133	-101.5	135.3
	56088.10219008	T10	1000	1.00	0.2361	-75.3	135.7
	56088.11444479	T10	1000	1.00	0.2569	-117.2	104.4
	56088.12670124	T10	1000	1.01	0.2776	-90.7	155.6
	56088.98096796	T10	1100	1.21	0.7275	88.3	-113.2
	56088.99448449	T10	1100	1.16	0.7504	103.3	-131.3
	56089.00793504	T10	1100	1.12	0.7732	116.8	-125.3
	56090.99015047	T10	1000	1.15	0.1355	-93.2	151.3
	56091.00237277	T10	1000	1.12	0.1563	-89.1	136.6
	56091.01459391	T10	1000	1.08	0.1770	-120.1	135.1
	56091.02789165	T10	1000	1.06	0.1995	-103.3	126.2
	56091.04011395	T10	1000	1.04	0.2203	-94.1	111.7
	56091.05233567	T10	1000	1.02	0.2410	-83.7	120.7
	56091.98183247	T10	1100	1.17	0.8187	108.1	-125.1
	56091.99521299	T10	1100	1.13	0.8414	71.7	-129.5
	56092.00859060	T10	1100	1.09	0.8641	87.8	-106.4
	56114.99812036	T07	2100	1.01	–	–	–
19g-2-08064	56087.98405758	T10	1000	1.22	0.1398	74.8	-92.1
	56087.99634992	T10	1000	1.17	0.1469	56.4	-101.0
	56088.00865904	T10	1000	1.13	0.1541	56.2	-105.7
	56088.02227224	T10	1000	1.10	0.1620	74.1	-82.5
	56088.03456978	T10	1000	1.07	0.1691	46.0	-106.4
	56088.04681292	T10	1000	1.05	0.1762	72.6	-97.9
	56088.93719029	T10	1100	1.47	0.6940	-92.9	88.9
	56088.95108885	T10	1100	1.38	0.7021	-98.3	91.4
	56088.96452203	T10	1100	1.30	0.7099	-101.2	94.1
	56089.06693907	T10	1100	1.02	0.7694	-110.7	79.8
	56089.08031379	T10	1100	1.01	0.7772	-102.6	90.0
	56089.09369662	T10	1100	1.00	0.7850	-100.7	88.6
	56115.13183924	T07	1800	1.14	–	–	–

Note. The spectra observed with grating T10 have a mean S/N, measured at the continuum, of 2.3 and 5.0 for the 17 and 19 h fields, respectively.

#### 4.1 Broad-band photometric characterization with SED fitting

In order to confirm at first the low-mass nature of the binaries in study, we used the Virtual Observatory tool called VOSA<sup>2</sup> (Virtual Observatory SED Analyzer, Bayo et al. 2008) to perform a SED fitting. For that, we used the broad-band photometry available in the literature as well as those obtained from the WFCAM photometry. For all selected five LMEBs, we considered the broad-band photometry from WFCAM *Z*, *Y*, *J*, *H*, *K* (Wide-Field Camera, Hodgkin et al. 2009), 2MASS *J*, *H*, *K* (Two Micron All Sky Survey, Skrutskie et al. 2006), and WISE W1, W2 (Wide-field Infrared Survey Explorer, Wright et al. 2010). Additionally, for the 19 h field objects only, we also considered the available SDSS *u*, *g*, *r*, *i*, *z* filters (Sloan Digital Sky Survey Data Release 7, York et al. 2000). The photometry data used are shown in Table 3.

We then obtained an estimate for the effective temperature ( $T_{\text{eff}}$ ) of each binary system by using NextGen models (Baraffe et al. 1998; Hauschildt, Allard & Baron 1999, and references therein), where the best-fitting model was chosen through a  $\chi^2$  minimization (for details, see Bayo et al. 2008). Note that we fixed the metallicity

to be solar. The surface gravity ( $\log g$ ) was also free to vary, although the SED fitting has a low sensitivity to this parameter and the values obtained from the fit should be taken with caution.

The obtained atmospheric parameters are presented in Table 4 (columns 2 and 3), with uncertainties corresponding to the step-size in the used model grid, which are 100 K and 0.5 for  $T_{\text{eff}}$  and  $\log g$ , respectively. These parameters were considered as first estimates and are not the final values adopted for each component of the binary. However, they are good approximations that confirm the expected low-mass nature of our objects.

#### 4.2 Spectroscopic characterization with spectral indices

The acquired low-resolution spectra (described in Section 3) were used for spectral typing. As mentioned previously, the observed spectral range was chosen to include some features that are characteristic of the late-type stars, specially M dwarfs. These features, as for instance the titanium oxide (TiO) and vanadium oxide (VO) bands, are good markers to distinguish early- and late-M dwarfs (Keenan & Schroeder 1952; Kirkpatrick et al. 1991).

Three spectral indices were selected to derive the spectral type of our LMEBs. The first index used is the *Ratio A* index (7020–7050 Å/ 6960–6990 Å), defined by Kirkpatrick et al. (1991). This

<sup>2</sup> VOSA is an open VO tool that can be accessed at <http://svo2.cab.inta-csic.es/theory/vosa/>

**Table 3.** LMEBs coordinates and the broad-band photometry used to perform the SED fitting. The EBs from 19 h field have additional photometry from SDSS DR7, given in AB magnitudes. All other magnitudes are given in the Vega system.

Filter	17e-3-02003	17h-4-01429	19c-3-08647	19f-4-05194	19g-2-08064
RA (J2000)	17:13:01.2	17:15:39.6	19:37:13.6	19:31:15.0	19:36:40.6
Dec. (J2000)	+03:50:40.2	+03:47:09.7	+36:48:54.1	+36:35:25.9	+36:09:45.8
SDSS-u	—	—	21.026 ± 0.094	21.60 ± 0.18	20.057 ± 0.051
SDSS-g	—	—	18.623 ± 0.008	19.188 ± 0.011	17.729 ± 0.005
SDSS-r	—	—	17.339 ± 0.005	17.983 ± 0.007	16.520 ± 0.004
SDSS-i	—	—	16.537 ± 0.004	17.436 ± 0.006	15.962 ± 0.004
SDSS-z	—	—	16.083 ± 0.007	17.107 ± 0.012	15.592 ± 0.006
UKIDSS-Z	16.114 ± 0.049	16.93 ± 0.078	15.609 ± 0.035	16.802 ± 0.096	15.275 ± 0.018
UKIDSS-Y	15.808 ± 0.097	16.48 ± 0.18	15.321 ± 0.054	16.67 ± 0.17	14.993 ± 0.034
UKIDSS-J	15.272 ± 0.060	15.84 ± 0.12	14.812 ± 0.030	16.013 ± 0.091	14.466 ± 0.017
UKIDSS-H	14.718 ± 0.017	15.148 ± 0.019	14.210 ± 0.002	15.320 ± 0.006	13.858 ± 0.002
UKIDSS-K	14.407 ± 0.027	14.904 ± 0.034	14.001 ± 0.010	15.167 ± 0.032	13.673 ± 0.002
2MASS-J	15.315 ± 0.059	15.888 ± 0.075	14.877*	16.053 ± 0.075	14.477 ± 0.029
2MASS-H	14.575 ± 0.068	15.001 ± 0.094	14.258 ± 0.054	15.272 ± 0.076	13.863 ± 0.033
2MASS-Ks	14.434 ± 0.078	14.93 ± 0.15	13.918*	15.23 ± 0.17	13.715 ± 0.050
WISE-W1	14.215 ± 0.028	14.777 ± 0.033	13.730 ± 0.030	15.061 ± 0.043	13.608 ± 0.027
WISE-W2	14.172 ± 0.048	14.769 ± 0.078	13.678 ± 0.040	15.76 ± 0.22	13.686 ± 0.044

Note. \*These values are only upper limits.

**Table 4.** Atmospheric parameters and spectral types for our five LMEBs obtained from three different methods: SED fitting (columns 2–3), spectral indices (columns 4–7), and comparison to synthetic spectra (columns 8–12). The errors are of 100 K for  $T_{\text{eff}}$  and 0.5 for  $\log g$ . The spectral types have an uncertainty of one subclass.

Object	SED fitting			Spectral indices			Synthetic spectra				
	$T_{\text{eff}}$ (K)	$\log g$	Ratio A	TiO-a	$\mathfrak{H}$ -index	Type <sup>a</sup>	$T_{\text{eff}, 1}$ (K)	$\log g_1$	$T_{\text{eff}, 2}$ (K)	$\log g_2$	Type <sup>b</sup>
17e-3-02003	3600	5.5	1.108	1.111	1.267	M1	3800	4.5	3500	4.5	M0+M2.5
17h-4-01429	3500	4.0	1.228	1.509	2.133	M3.5	3400	4.5	3200	5.0	M3+M4
19c-3-08647	3800	5.0	1.125	1.184	1.300	M1	3900	4.5	3000	4.5	M0+M5
19f-4-05194	4200	5.0	1.027	1.034	1.090	K7	4400	4.5	3500	5.0	K5+M2.5
19g-2-08064	4200	5.0	1.044	1.072	1.124	K7	4200	4.5	3100*	5.0	K6+M4.5*

Notes. <sup>a</sup>EB's spectral type from measured spectral indices. <sup>b</sup>EB spectral-type combination according to  $T_{\text{eff}}$ .

\*This value is discrepant with respect to the expected effective temperature and should be taken with caution (for more details, see Section 5.2).

index is based on the calcium monohydride (CaH) molecule, which is a strong feature that appears in early-M stars and is a good luminosity indicator. The *TiO-a* index (7033–7048 Å/7058–7073 Å, Kirkpatrick et al. 1999) is the second one used, which is based on the TiO molecular band and is stronger for early- and mid-M dwarfs. Finally, the third index used is the  $\mathfrak{H}$ -index (7485–7515 Å/7120–7150 Å), derived more recently by Aberasturi et al. (2014), and measures the minimum of the same TiO band.

As a comparative way to derive the spectral type of our targets, we have applied the same indices to a set of M-dwarf template spectra from the literature. A total of 58 M-dwarf templates, 39 spectra from Leggett et al. (2000), and 19 spectra from Cruz & Reid (2002) were used, covering M-dwarf subclasses from M0.5 V to M9.5 V. All spectra, templates and those from this work, were normalized to a pseudo-continuum before measuring all indices to avoid any flux calibration discrepancy. The measured values for our five LMEBs are presented in Table 4 (columns 4 to 6). In column 7, we show the assigned spectral type for the binary, which is the averaged type obtained from all indices, with an uncertainty of one subclass. It is worth to mention that the spectral type defined here is not assigned to each component of the binary but to the composite spectrum.

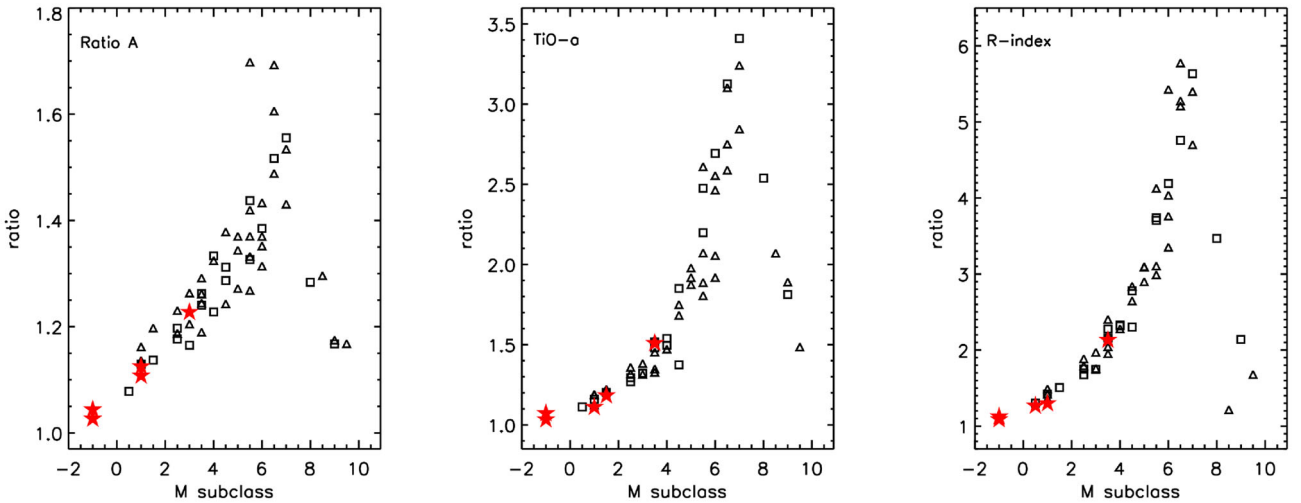
Fig. 1 shows the behaviour of the spectral types versus the measured values for the three used indices. The open triangles represent

the templates from Leggett et al. (2000) and the open squares are templates from Cruz & Reid (2002). Our objects are illustrated as filled stars. The y-axis displays the value measured for each index (*Ratio A* on the left panel, *TiO-a* at the centre, and  $\mathfrak{H}$ -index on the right-hand panel). The x-axis shows all M subclasses. Note that the numerical scale here represents each M-dwarf subclass, going to M0 to M9, where 0 is the M0 subclass, 1 is the M1 subclass, successively. Negative numbers represent earlier types, where –1 represents the K7 subclass and –2 represents the K5 subclass. This convention was used by Kirkpatrick et al. (1991, fig. 6) and it was also adopted here.

### 4.3 Spectroscopic characterization by comparison to synthetic spectra

The last procedure for the characterization of our objects was to perform a comparison to a library of synthetic spectra, using our observed flux-calibrated low-resolution spectra. For that, we selected the BT-Settl model spectra from Allard, Homeier & Freytag (2012), Allard et al. (2013),<sup>3</sup> computed with the updated solar abundances

<sup>3</sup> All synthetic spectra used are available at <https://phoenix.ens-lyon.fr/Grids/BT-Settl/>



**Figure 1.** Stellar spectral types versus spectral indices. The M-dwarf templates from Leggett et al. (2000) are represented by open triangles and the templates from Cruz & Reid (2002) are represented by open squares. The filled stars are the five LMEBs from this work. The left-hand panel shows the *Ratio A* index (Kirkpatrick, Henry & McCarthy 1991), the central panel shows the *TiO-a* index (Kirkpatrick et al. 1999), and the right-hand panel shows the *R-index* (Aberasturi et al. 2014).

from Asplund et al. (2009). This library uses the PHOENIX code for 1D-model atmospheres (Allard et al. 1994, 1997, 2001) to generate high-resolution spectra (0.02 Å, at optical wavelengths). The BT-Settl models were chosen because they are valid for all temperatures, reaching therefore the low-temperature regime of our objects.

We have composed a grid of BT-Settl spectra with effective temperatures ranging from 3000 to 5000 K, with a step of 100 K, always assuming solar metallicity ([Fe/H] = 0.0) and no  $\alpha$ -element enhancement ([ $\alpha$ /H] = 0.0). The surface gravities were 4.5 and 5.0. Before performing the comparison, the whole grid was degraded to the same resolution as our spectroscopic data.

With the objective of determining the effective temperatures of both components of the system, two synthetic spectra were combined to reproduce the observed spectrum of the binary in question. It is worth to mention that, within the observed spectral range, there are some telluric absorption features that should not be accounted for the fit, such as telluric H<sub>2</sub>O and O<sub>2</sub> molecular bands. Hence, we have performed the comparison considering only a few windows to exclude such telluric contamination. We also took into account that the borders of our observed spectra present flux-calibration issues, thus, they were also excluded from the fit. This way, we applied our comparison method only for the following wavelength intervals: from 6350 to 6490 Å, 6670 to 6850 Å, 6950 to 7160 Å, and 7320 to 7580 Å. Note that the region around the H $\alpha$  line was also excluded since this feature appears in emission in all observed spectra. It is also important to have in mind that a synthetic spectrum cannot perfectly reproduce an observed spectrum, therefore, some discrepancies are still present within the chosen wavelength intervals.

The best-fitting model was obtained via  $\chi^2$  minimization, providing a pair of parameters ( $T_{\text{eff}}$ ,  $\log g$ ) for each component of the binary. In this procedure, the  $T_{\text{eff}}$  was set free to vary within the range specified earlier. However, the  $\log g$  values for the primary and secondary components were fixed to the values obtained from the LC modelling.<sup>4</sup> The LC modelling procedure is described later

on Section 5. We adopted nearest 0.5 dex values for  $\log g$ , for instance, for a star with a derived surface gravity of 4.8 we used a synthetic spectra computed with  $\log g = 5.0$ .

The derived atmospheric parameters for all LMEB systems are shown in Table 4 (columns 8 to 11), with errors of 100 K and 0.5 for the effective temperature and the surface gravity, respectively (the step-size in the model grid). In column 12, we present the composition of spectral types for each binary system. These spectral types were determined on the basis of the resulting temperatures and the effective temperature scale published by Pecaut & Mamajek (2013). It is important to mention that the  $T_{\text{eff}}$  value obtained for the secondary component of EB 19g-2-08064 is highly discrepant regarding the value expected from the phase-folded LC, which will be discussed later on Section 5.2. For this reason, this particular temperature should be taken with caution.

To illustrate our results, Fig. 2 presents the best-fitting model for the five LMEB systems from the combination of two synthetic spectra. All spectra are flux-calibrated and normalized to 1 at  $\lambda = 7500$  Å, where an arbitrary constant was added for visualization. The observed spectra are shown in black and the models are presented in red. The regions featured in grey show the wavelength intervals sampled to perform the fitting.

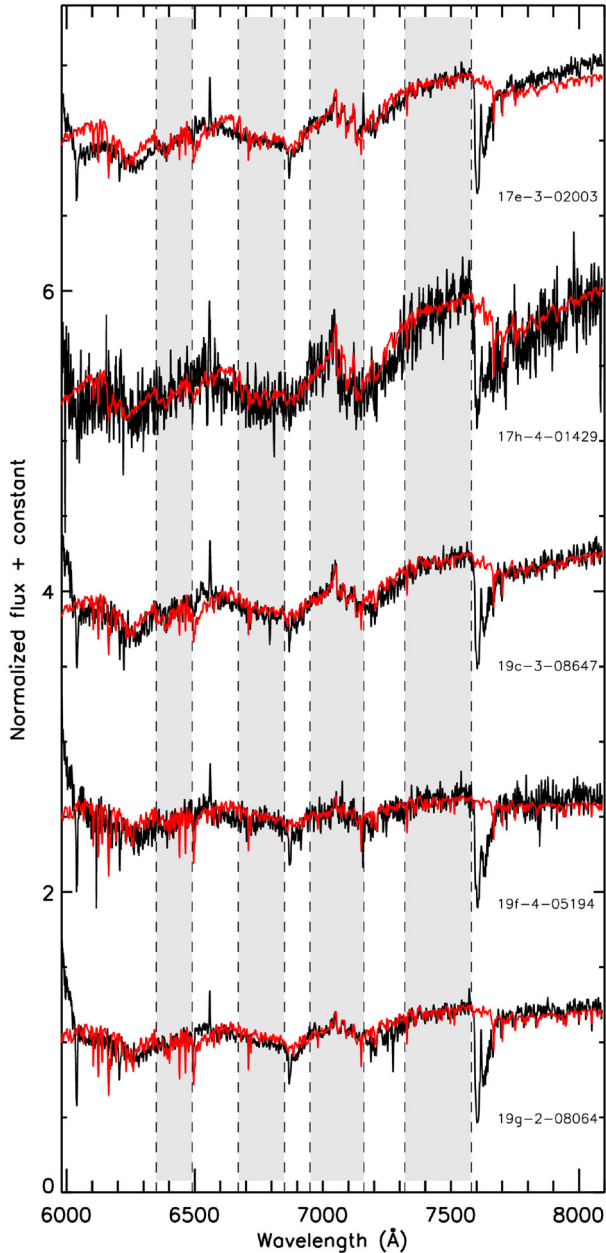
## 5 SOLVING THE FIVE NEW LMEB SYSTEMS

### 5.1 Modeling light curves and radial velocity shifts

All five LMEB systems were solved through the analysis of the photometric and spectroscopic data combined. The LCs and the measured RV shifts were simultaneously modelled with the JKTEBOP<sup>5</sup> code (Southworth, Maxted & Smalley 2004; Southworth 2013). This code was considered as the best option for the analysis of our systems, since it provides integrated fitting of LCs with RV data and is suitable for nearly spherical stars in detached binaries.

<sup>4</sup> The used  $\log g$  values were obtained from previously performed trial runs of the LC modelling code.

<sup>5</sup> JKTEBOP is a modified version of EBOP (Eclipsing Binary Orbit Program, Etzel 1981; Popper & Etzel 1981), available at <http://www.astro.keele.ac.uk/jkt/codes/jktebop.html>.



**Figure 2.** Observed low-resolution spectra (black) and the best-fitting model (red) obtained from a combination of two synthetic spectra. All spectra are flux-calibrated and normalized to 1 at  $\lambda = 7500$  Å. The atmospheric parameters of these models are presented in Table 4 (columns 8 to 11). The grey regions show the wavelength intervals used for the comparison.

JKTEBOP uses the Nelson–Davis–Etzel model for EBs (NDE model, Nelson & Davis 1972; Popper & Etzel 1981) to model LCs of and the best-fitting model is chosen by a Levenberg–Marquardt minimization algorithm (MRQMIN, Press et al. 1992). Several parameters of the system were allowed to vary:

- surface brightness ratio ( $J$ ),
- both stellar radii ( $r_1, r_2$ ), defined as  $r_1 = R_1/a$  and  $r_2 = R_2/a$ , where  $R$  is the stellar radius,  $r$  is the fractional radius, and  $a$  is the orbital separation,
- reference time of primary minimum ( $T_0$ ), given in days,
- orbital period ( $P_{\text{orb}}$ ), also given in days,

- orbital inclination angle ( $i$ ), given in degrees, and
- light scale factor, which defines the baseline level of the LC, and in this case is given in magnitudes.

In fact, in order to derive the radii of both components ( $r_1, r_2$ ), the code actually fits the radii sum and ratio,  $r_1 + r_2$  and  $k$ , respectively.

Some other LC parameters were kept fixed to a certain value. The *photometric mass ratio* ( $q_{\text{phot}}$ ), which accounts for the small deformation of the objects, was determined from the expected mass of the stars based on a few trial runs in the code, and kept fixed. It is important to emphasize that the derived stellar masses result from the RV curve analysis. We also used a fixed value for the *gravity-darkening coefficients* ( $\beta$ ) of 0.32, which is a reasonable value for late-type stars with convective envelopes (Lucy 1967), and since our LCs do not have enough precision to fit for this parameter.

We have adopted a square-root law for the limb darkening (LD) since, according to van Hamme (1993), this law is more appropriate for infrared LCs. We used JKTEBOP<sup>6</sup> code (Southworth, Bruntt & Buzasi 2007) associated with JKTEBOP, to obtain LD coefficients by interpolating the values within theoretical tables. We selected the values computed by Claret (2000), which are based on PHOENIX models (Allard et al. 1997) and are more suitable for our temperature range. For that aim, we considered the atmospheric parameters ( $T_{\text{eff}}$ ,  $\log g$ ) obtained from the analysis of low-resolution spectra (see Section 4.3). We also considered a solar metallicity and a microturbulence velocity of  $2.0 \text{ km s}^{-1}$ . These coefficients were also kept fixed due to the limited precision of the photometric data.

A few assumptions were made when performing the model fit, for instance, we assumed null orbital eccentricity for the systems. This is a good approximation, since the orbital periods of all LMEBs are small enough to consider that the systems are circularized by tidal forces. We also considered the reflection coefficients to be initially zero, however, we allowed JKTEBOP to adjust these coefficients depending on the system geometry. Finally, we also assumed the absence of a third light source in the system.

The latest version of the JKTEBOP code (Southworth 2013), used for the present analysis, also models RV measurements simultaneously, where the following parameters were fitted:

- both velocity amplitudes ( $K_1, K_2$ ), and
- the systemic velocity ( $\gamma_{\text{sys}}$ ).

All obtained velocities are given in  $\text{km s}^{-1}$ . It is important to emphasize that  $\gamma_{\text{sys}}$  is a free parameter for the primary star only. In the case of the secondary component, the systemic velocity was kept fixed to the value found for the primary.

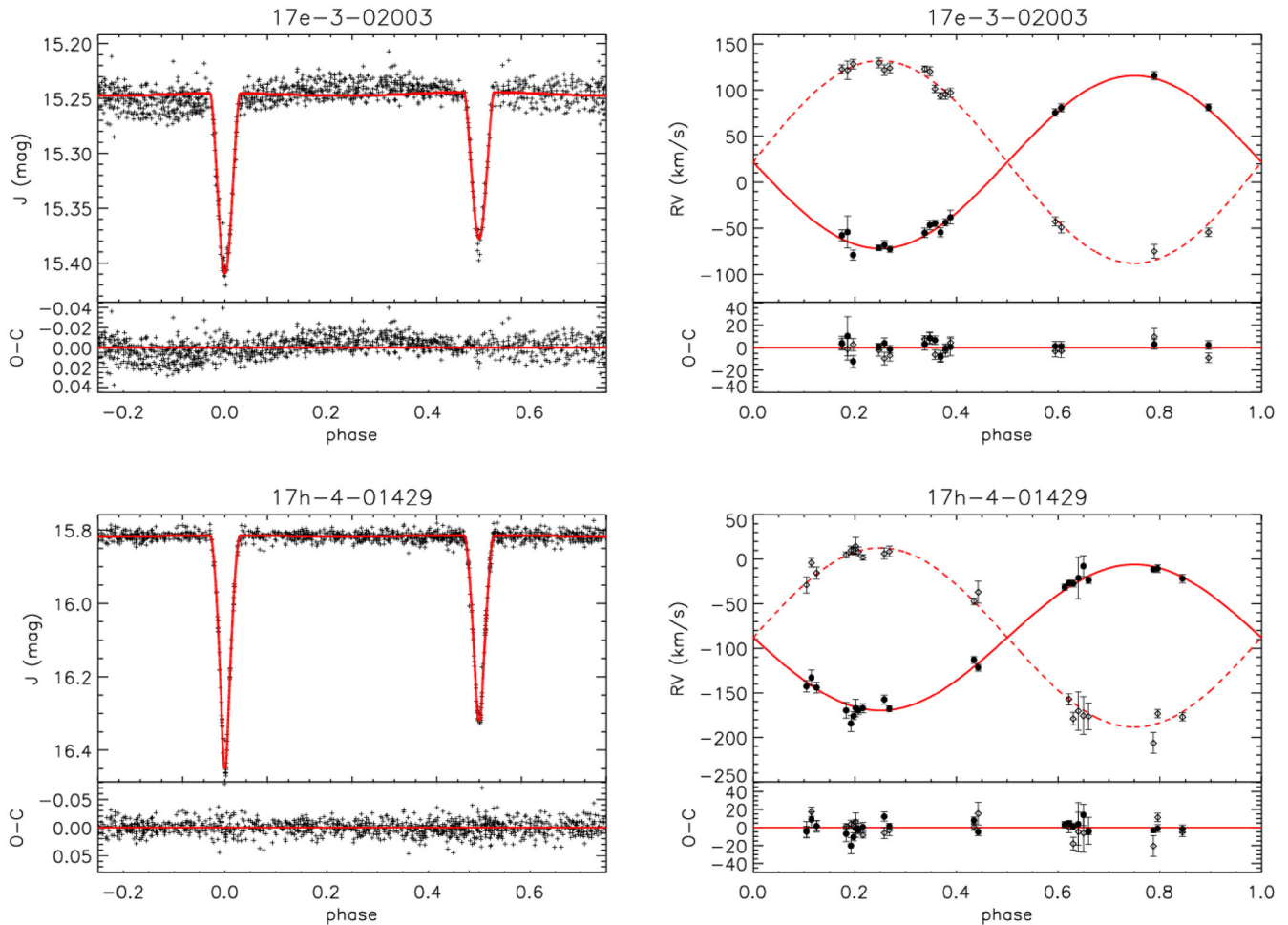
## 5.2 Results

The JKTEBOP code allows the user to choose between several internal algorithms designed for different purposes. Two of them were selected to model fitting and access the parameter uncertainties. First, a MRQMIN algorithm (Press et al. 1992) was performed to find the best-fitting model via a least-squares optimization (JKTEBOP task 3) for each binary.

Figs 3 and 4 present the best-fitting models obtained for the LMEBs from the 17 and 19 h fields, respectively. The WTS LCs are shown on the left-hand side as function of the orbital phase, where

<sup>6</sup> <http://www.astro.keele.ac.uk/jkt/codes/jktld.html>.





**Figure 3.** LCs (left-hand panels) and RV shifts (right-hand panels) of the LMEBs from the 17 h field as function of the orbital phase. The observational data are presented in black and the best-fitting models from the *JKTEBOP* code are shown in red. The obtained parameters are listed in Table 5. Each individual plot brings below itself the residuals from the fit ( $O - C$ ).

each cross (black) represents an individual observation. The RV curves are illustrated on the right, where the filled circles are the RV measurements of the primary component and the open diamonds are RVs of the secondary component. The red solid and dashed lines show the best-fitting RV models obtained with *JKTEBOP*. The residuals from the fit ( $O - C$ ) are presented at the lower panel of each plot.

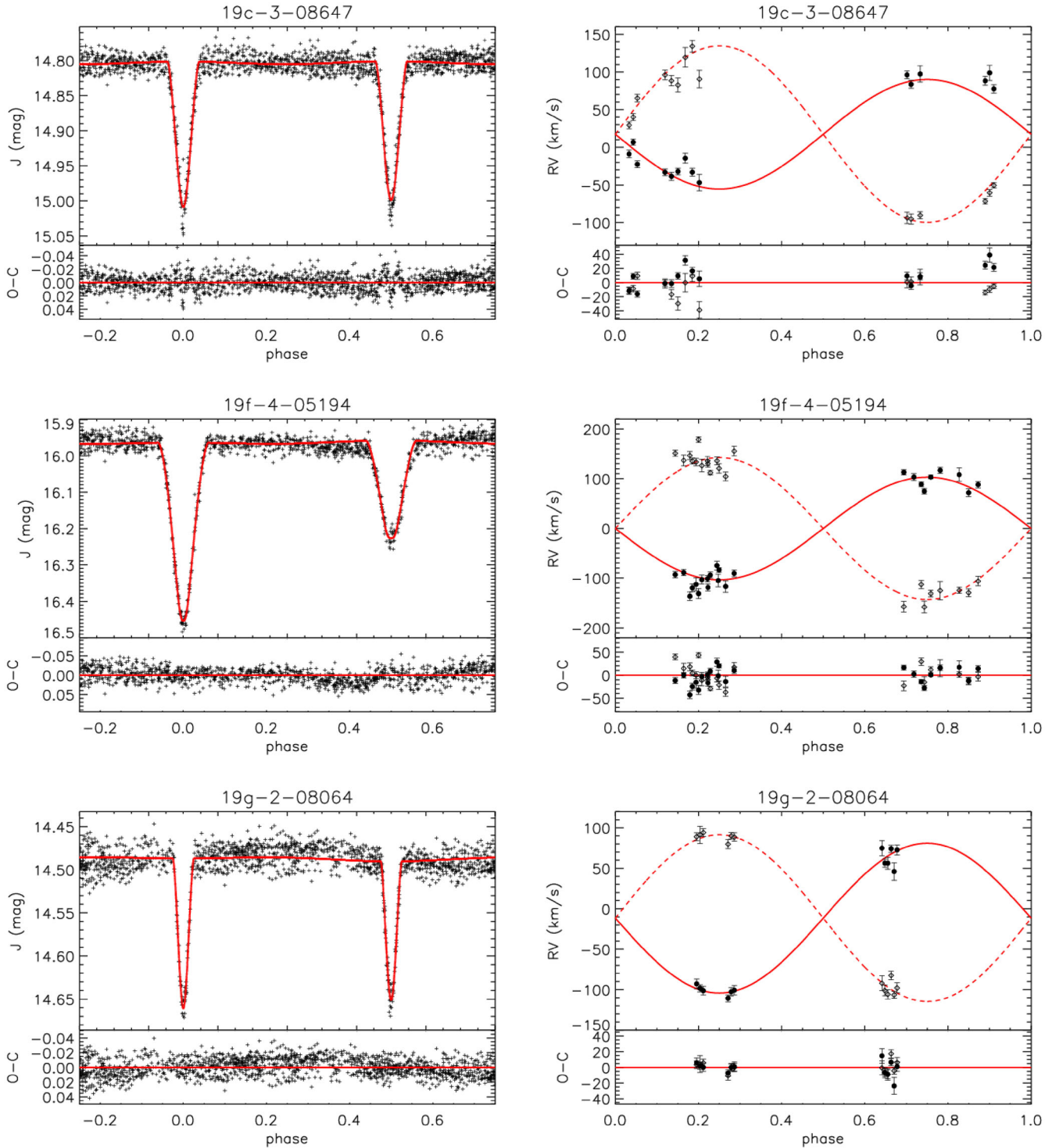
Some of the phase-folded LCs present out-of-eclipse sinusoidal-like modulations, that could be due to ellipsoidal variations. We have then verified the sphericity of each binary component considering the Roche geometry. We have calculated the Roche equipotentials for each binary and we have found that for four EBs we do not expect any deformation (in a  $10^{-8}$  level). Just one system, 19f-4-05194, presents a small deformation of around 0.2 per cent of the derived radius, which can be expressed as  $0.42 \cdot R_{L1}$ , where  $R_{L1}$  is the distance to the inner Lagrangian point  $L1$ . The radius uncertainties obtained from LC fitting procedure are much larger than the expected deformation, therefore, negligible ellipsoidal modulations are expected.

We also have blocked the eclipses and fitted a sine function to the baseline modulation present in the folded LC before performing the analysis with the *JKTEBOP* code. The modelled sine function

was then added to the LC model and it was kept fixed. The new model presented better fitted residuals, nevertheless, the best-fitting parameters did not change significantly and presented values within the estimated errors. Therefore, we adopted the simpler analysis in order to avoid unnecessary modifications of the folded LC before the LC synthesis procedure.

The errors given with the best-model parameters by *task 3* are only formal errors and they are considered too optimistic. The errors obtained from this task are usually underestimated when one or more parameters are kept fixed during the fitting procedure, because correlations between parameters are discarded (Torres et al. 2000). Thus, we have performed a Markov chain Monte Carlo (MCMC) simulation to obtain a more reliable error analysis (*JKTEBOP task 8*), which included the photometric errors. By adding a Gaussian noise to the best-fitting model, the MCMC simulation provides the uncertainties from the distribution of best-fitting solutions after many trials. We used 10 000 chains to obtain a  $1\sigma$  uncertainty for the best-model parameters, which corresponds to the 68 per cent quartile half-width of the parameter distribution.

The final parameters derived for all five LMEBs are presented in Table 5. We have determined stellar masses between 0.244 and  $0.717 M_{\odot}$  and radii from 0.421 to  $0.670 R_{\odot}$ . Our detached



**Figure 4.** LC (left-hand panels) and RV shifts (right-hand panels) of the LMEBs from the 19 h field as function of the orbital phase. The details are the same as described in Fig. 3.

binaries are in very close orbits, with small orbital separations of  $2.872 \leq a \leq 6.692 R_{\odot}$  and short periods of  $0.59 \leq P_{\text{orb}} \leq 1.72$  d, approximately.

The primary and secondary eclipses shown in the EB 19g-2-08064 LC (see Fig. 4) have similar depths indicating that the binary components should have similar masses and therefore similar

temperatures. This is supported by the RV data, from which reliable masses of  $0.71$  and  $0.64 M_{\odot}$  could be found for the primary and the secondary components, respectively. However, the spectral analysis suggested a  $T_{\text{eff}}$  of only  $3100$  K for the secondary component (see Section 4.3). It is possible that flux calibration problems could have led to such discrepant temperature.

**Table 5.** Summary of the results obtained for the five LMEBs.

Binary	17e-3-02003	17h-4-01429	19c-3-08647	19f-4-05194	19g-2-08064
FITTED PARAMETERS					
$J$	$0.783 \pm 0.028$	$0.8677 \pm 0.0051$	$0.898 \pm 0.027$	$0.5660 \pm 0.0044$	$0.8492 \pm 0.0111$
$(R_1 + R_2)/a$	$0.2304 \pm 0.0048$	$0.17931 \pm 0.00084$	$0.2783 \pm 0.0038$	$0.3745 \pm 0.0019$	$0.1955 \pm 0.0021$
$k$	$0.88 \pm 0.35$	$0.8189 \pm 0.0081$	$0.86 \pm 0.30$	$0.6531 \pm 0.0048$	$0.95 \pm 0.24$
$R_1/a$	$0.123 \pm 0.019$	$0.09858 \pm 0.00051$	$0.150 \pm 0.021$	$0.2266 \pm 0.0010$	$0.1002 \pm 0.0117$
$R_2/a$	$0.108 \pm 0.023$	$0.08073 \pm 0.00070$	$0.128 \pm 0.023$	$0.1480 \pm 0.0013$	$0.0954 \pm 0.0134$
$i$ ( $^\circ$ )	$81.77 \pm 0.43$	$89.15 \pm 0.13$	$81.29 \pm 0.39$	$85.62 \pm 0.20$	$83.33 \pm 0.20$
Light scale (mag)	$15.2503 \pm 0.0006$	$15.8191 \pm 0.0003$	$14.8092 \pm 0.0006$	$15.9724 \pm 0.0004$	$14.4830 \pm 0.0005$
$T_0$ (MHJD–54000.) ( $d$ )	$553.12520 \pm 0.00027$	$553.15187 \pm 0.00012$	$318.00600 \pm 0.00010$	$317.60678 \pm 0.00014$	$318.30802 \pm 0.00015$
$P_{\text{orb}}$ (d)	$1.2250078 \pm 0.0000003$	$1.4445891 \pm 0.0000002$	$0.86746584 \pm 0.00000008$	$0.58953012 \pm 0.00000008$	$1.7204091 \pm 0.00000003$
$K_1$ (km s $^{-1}$ )	$93.80 \pm 1.45$	$81.89 \pm 1.15$	$72.70 \pm 2.07$	$103.28 \pm 1.40$	$92.56 \pm 1.73$
$K_2$ (km s $^{-1}$ )	$109.93 \pm 1.71$	$100.71 \pm 1.43$	$117.19 \pm 2.22$	$142.61 \pm 1.81$	$102.99 \pm 1.71$
$\gamma_{\text{sys}}$ (km s $^{-1}$ )	$21.86 \pm 1.01$	$-87.89 \pm 0.79$	$17.37 \pm 1.03$	$-0.33 \pm 1.07$	$-11.63 \pm 1.15$
ABSOLUTE DIMENSIONS					
$L_2/L_1$	$0.62 \pm 0.60$	$0.584 \pm 0.011$	$0.69 \pm 0.58$	$0.264 \pm 0.004$	$0.84 \pm 0.43$
$a$ ( $R_\odot$ )	$4.982 \pm 0.049$	$5.212 \pm 0.053$	$3.292 \pm 0.054$	$2.872 \pm 0.027$	$6.692 \pm 0.082$
$q$	$0.853 \pm 0.020$	$0.813 \pm 0.016$	$0.620 \pm 0.021$	$0.724 \pm 0.013$	$0.899 \pm 0.023$
$M_1$ ( $M_\odot$ )	$0.597 \pm 0.020$	$0.503 \pm 0.016$	$0.393 \pm 0.019$	$0.531 \pm 0.016$	$0.717 \pm 0.027$
$M_2$ ( $M_\odot$ )	$0.510 \pm 0.016$	$0.409 \pm 0.013$	$0.244 \pm 0.014$	$0.385 \pm 0.011$	$0.644 \pm 0.025$
$R_1$ ( $R_\odot$ )	$0.611 \pm 0.095$	$0.514 \pm 0.006$	$0.494 \pm 0.069$	$0.651 \pm 0.007$	$0.670 \pm 0.078$
$R_2$ ( $R_\odot$ )	$0.54 \pm 0.11$	$0.421 \pm 0.006$	$0.422 \pm 0.077$	$0.425 \pm 0.006$	$0.638 \pm 0.090$
$\log g_1$	$4.64 \pm 0.14$	$4.717 \pm 0.008$	$4.65 \pm 0.13$	$4.536 \pm 0.007$	$4.64 \pm 0.10$
$\log g_2$	$4.69 \pm 0.18$	$4.801 \pm 0.010$	$4.57 \pm 0.16$	$4.766 \pm 0.009$	$4.64 \pm 0.13$
$\rho_1$ (g cm $^{-3}$ )	$2.6 \pm 1.6$	$3.706 \pm 0.067$	$3.3 \pm 1.8$	$1.928 \pm 0.030$	$2.38 \pm 0.83$
$\rho_2$ (g cm $^{-3}$ )	$3.3 \pm 2.2$	$5.49 \pm 0.16$	$3.2 \pm 1.8$	$5.01 \pm 0.14$	$2.5 \pm 1.3$
$\log L_1$ ( $L_\odot$ )	$-1.15 \pm 0.14$	$-1.497 \pm 0.052$	$-1.29 \pm 0.13$	$-0.844 \pm 0.040$	$-0.90 \pm 0.11$
$\log L_2$ ( $L_\odot$ )	$-1.41 \pm 0.19$	$-1.776 \pm 0.056$	$-1.88 \pm 0.17$	$-1.611 \pm 0.051$	$-1.47 \pm 0.21$
$M_{\text{bol},1}$ (mag)	$7.63 \pm 0.36$	$8.49 \pm 0.13$	$7.98 \pm 0.32$	$6.86 \pm 0.10$	$7.00 \pm 0.28$
$M_{\text{bol},2}$ (mag)	$8.27 \pm 0.48$	$9.19 \pm 0.14$	$9.46 \pm 0.42$	$8.78 \pm 0.13$	$8.42 \pm 0.52$
$d$ (pc)	$875 \pm 117$	$805 \pm 62$	$571 \pm 66$	$1400 \pm 118$	$731 \pm 75$

The JKTEBOP code<sup>7</sup> (Southworth, Maxted & Smalley 2005), another resource associated with JKTEBOP, was used to obtain distance estimates for the binary systems. This procedure takes the results from JKTEBOP as inputs and accounts for a carefully performed error propagation. Among other quantities, JKTEBOP calculates distances with a semi-empirical method based on the surface brightness– $T_{\text{eff}}$  relation by Kervella et al. (2004), as described in Southworth et al. (2005), and which is suitable for MS stars with effective temperatures from 3600 to 10 000 K. Despite this temperature range, Kervella et al. (2004) have presented indicators that this method is also valid in the infrared for dwarfs with temperatures as low as  $\sim 3000$  K (Kervella et al. 2004, fig. 3).

The interstellar extinction has a strong effect at shorter wavelengths and may be significant at the near-infrared for the Galactic latitudes of our fields. Thus, we decided to perform an approximate reddening correction. The extinction was estimated for all five LMEBs by adopting the 3D extinction model by Arenou, Grenon & Gomez (1992), which was computed with the help of their on-line service,<sup>8</sup> and was considered for the distance estimation by the JKTEBOP code. The computed distances range from 571 to 1400 pc and are presented in Table 5.

As a summary of the obtained results, we have characterized completely all five LMEBs, where the derived stellar masses lie

between  $0.24$  and  $0.72 M_\odot$  and radii between  $0.42$  to  $0.67 R_\odot$ , with orbital separations ranging from  $2.87$  to  $6.69 R_\odot$ .

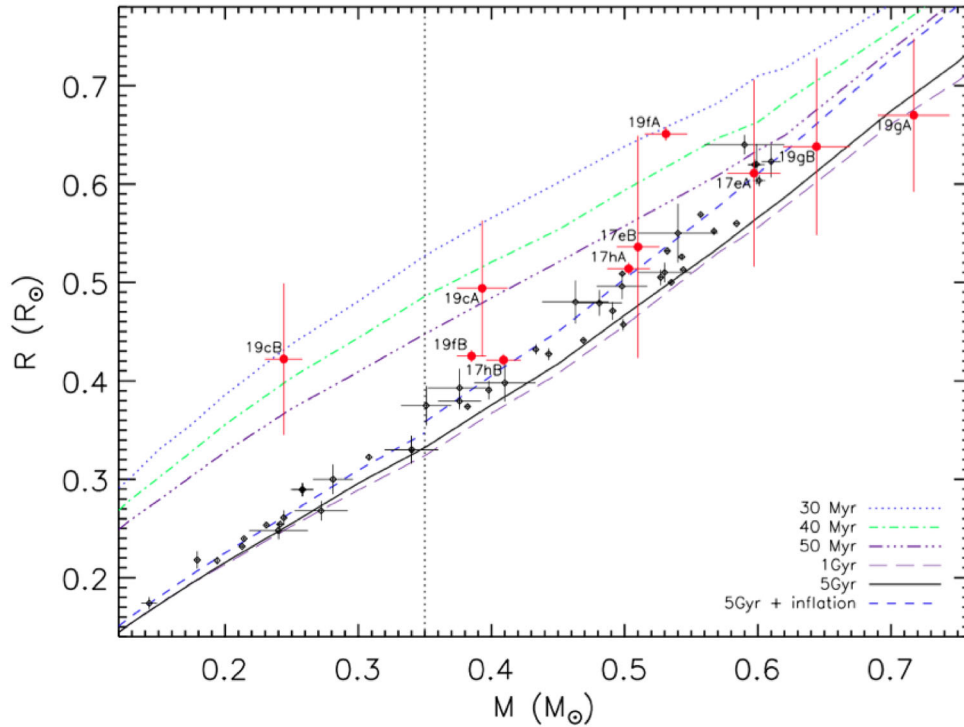
## 6 DISCUSSION

Two of the studied LMEB systems, 17h-4-01429 and 19f-4-05194, were well-characterized where the radii were determined with uncertainties of around only 1 per cent. For three of our LMEBs, the WTS photometric data present a clear limitation on the accuracy of the measurements. Non-sequential time series with long time lapses between sampled cycles can be an issue when dealing with LC modelling. This is noticeable through the visible dispersion of the data points in out-of-eclipse portions of the phase-folded LCs (Figs 3 and 4). Such dispersion in phase-folded eclipses is reflected on the estimated error bars of the model-fit parameters, where the radii of both components are derived with larger uncertainties. This is the case of 17e-3-02003, 19c-3-08647, and 19g-2-08064, where the dispersion present in their folded LCs is not ideal. The variability seen in the photometric data could be intrinsic to the objects. Phenomena like stellar spots, which could not be properly modelled with the data at hand, may differently affect in- and out-of-eclipse levels. Unfortunately, for these three binaries, additional multi-wavelength photometric follow up are needed in order to get more accurate radii with discriminating errors.

Nevertheless, despite other limitations on the spectroscopic data such as low S/N and incomplete phase coverage, the stellar masses

<sup>7</sup> <http://www.astro.keele.ac.uk/jkt/codes/jktebop.html>.

<sup>8</sup> Available at <http://www.whip.obspm.fr/cgi-bin/afm>.



**Figure 5.** Mass–radius diagram. The isochrones of 30, 40, and 50 Myr and for 1 and 5 Gyr are the standard models from Baraffe et al. (1998) ( $[M/H] = 0$ ,  $Y = 0.275$ ,  $L_{\text{mix}} = H_p$ ). The additional 5 Gyr inflated evolutionary model was determined by Knigge et al. (2011). The LMEBs from this work are represented by red filled circles and those gathered from the literature (with errors of less than 6 per cent) are illustrated as black small diamonds. Note that the EB components are presented here with shortened names for clarity of the figure.

of our whole sample (10 late-type stars) were derived with a very good precision. We obtained masses with errors of only 2.90 per cent and 5.64 per cent for the better and the worst cases, where the later was obtained for the least massive secondary component in our sample.

### 6.1 The mass–radius diagram and the radius anomaly problem

We have displayed our results on a mass–radius diagram along with selected well-studied low-mass EBs from the literature, which are shown in Fig. 5. In this plot, the LMEBs from our sample are represented by red filled circles. The low-mass binaries from the literature are shown as black small diamonds and they are listed in the Appendix (Table A1).

Several isochrones are also plotted, for 30, 40, and 50 Myr, and for 1 and 5 Gyr. These isochrones are the standard models from Baraffe et al. (1998), calculated for a solar metallicity ( $[M/H] = 0$ ), a helium abundance of  $Y = 0.275$ , and with a convective mixing length equal to the scale height ( $L_{\text{mix}} = H_p$ ). An additional isochrone for 5 Gyr is illustrated by a blue dashed line that considers a radius inflation on the model of 4.5 and 7.9 per cent for different mass intervals of  $M \leq 0.35 M_{\odot}$  and  $M > 0.35 M_{\odot}$ , respectively. These values were determined by Knigge et al. (2011) by separating their sample in two groups: fully convective stars with  $M \leq 0.35 M_{\odot}$  and partially radiative stars with  $M > 0.35 M_{\odot}$ . This  $0.35 M_{\odot}$  mass limit is represented in Fig. 5 as a vertical dotted line.

Our two well-characterized LMEB systems, 17h-4-01429 and 19f-4-05194, are placed in the region of partially radiative stars and seem to have inflated radii (see Fig. 5). The 17h-4-01429 system, for example, follows the 5 Gyr isochrone modified for a radius inflation

of 7.9 per cent, where the primary 17h-4-01429 A and the secondary 17h-4-01429 B components are found just above this curve. In fact, we measured a higher radius inflation of 9.4 and 9.9 per cent for the primary and the secondary, respectively, when the obtained radii are compared to the 5 Gyr model-isochrone (black solid line, with no inflation). The primary and secondary components are presented in Fig. 5 with shortened names (17hA and 17hB) for clarity of the figure.

The 19f-4-05194 system is the most interesting binary in our sample for being highly inflated when compared to the 5 Gyr model-isochrone, according to our results, where we estimated 31.1 and 17.2 per cent of radius inflation for the primary and secondary components, 19f-4-05194 A (19fA) and 19f-4-05194 B (19fB), respectively. Huélamo et al. (2009) have found an EB system, HIP 96515 A, where the primary component is also more inflated than the secondary with a radius inflation of around 15 and 10 per cent, respectively, in comparison to evolutionary models. This system is part of a triple system with the white dwarf HIP 96515 B. According to Huélamo et al. (2009), the EB HIP 96515 A shows a fast rotation period and strong X-ray emission, what could be interpreted as signs of enhancement of the magnetic activity. Recently, another short-period EB KELTJ041621-620046 was found to have such radius anomaly, where the primary and the secondary components in this system are 28 and 17 per cent inflated, respectively (Lubin et al. 2017). Nevertheless, the KELTJ041621-620046 system should be further characterized with more precision to confirm the observed large inflation, as the derived mass errors are of the order of  $\sim 11$  per cent.

Despite the uncertainty on the derived parameters, the LMEB 17e-3-02003 also seems to follow the same global inflation trend for partially convective stars (see Fig. 5). In this case, the primary



and the secondary components (17eA and 17eB) present an inflation of 8.6 and 12.5 per cent, respectively.

The LMEB 19c-3-08647 is another interesting case that deserves further investigation. These objects compose the less massive binary and yet the most inflated components in our sample, with 33.6 and 68.6 per cent of radius inflation for the primary 19c-3-08647 A (19cA) and the secondary 19c-3-08647 B (19cB), respectively, when compared to the expected radii for a 5 Gyr model. Nevertheless, this binary, in particular, is placed closer to isochrones of younger stars, between the 30 and 50 Myr evolutionary models shown in the mass-radius diagram. If this LMEB is in fact a young system, with an age of around 40 Myr (green dot-dashed line, Fig. 5), it would justify then such inflated radii for both components. It is not possible though to ensure the age of the system based only on isochrones. Therefore, additional high-resolution spectroscopic data with good S/N are needed to look for other age tracers.

The most massive binary in our sample, 19g-2-08064 ( $M_{\text{pri}}=0.71$  and  $M_{\text{sec}}=0.64 M_{\odot}$ ), seems to be the less inflated system. The secondary 19g-2-08064 B (19gB) presents an inflation of around 6.0 per cent when compared to the 1 Gyr model-isochrone (purple long-dashed line, Fig. 5) and the primary 19g-2-08064 A (19gA) does not show any inflation. When compare to the 5 Gyr model-isochrone, 19gB is only 4.1 per cent inflated.

As a general remark, the great majority of the LMEBs in our sample has an estimated radius far from the predicted values according to evolutionary models, where the studied low-mass stars seem to be significantly inflated. In particular, the components with derived masses of  $M < 0.6 M_{\odot}$  present a radius inflation of  $\sim 9$  per cent or more. This result supports a global trend of inflation for partially-radiative stars ( $M > 0.35 M_{\odot}$ ), as discussed by Knigge et al. (2011), for low-mass stars in close detached low-mass binary systems, with a possible exception for the components of the EB that could be a young system.

As mentioned briefly at the beginning of this paper, the radius inflation problem is not a new issue in the field and a few theories have been discussed for some time in the literature as attempts of finding the processes that are causing this radius anomaly. For example, Chabrier et al. (2007) suggested that the observed inflated radii of low-mass stars in binary systems maybe be caused by a less efficient heat transport. An enhanced magnetic activity was pointed out then as the possible causer of the radius inflation (Torres et al. 2006; Chabrier et al. 2007).

Indeed, considering that these low-mass stars are in close but still detached systems with short orbital periods (of around 2 d), they should be synchronized and in circular orbits due to tidal effects (Zahn 1977). This synchronization, or tidal-locking, causes an enhancement of the magnetic activity that becomes an important process that should be taken into account. According to Chabrier et al. (2007), the magnetic activity may reduce the convective efficiency in partially radiative stars – where a smaller convective mixing length leaves a larger amount of heat to be transported via radiation –, which results in a cooler and more inflated star in order to keep thermal equilibrium. This hypothesis is sustained in the literature by observations of H $\alpha$  and X-ray emission from one or both of the binary components. It is worth to emphasize then that all LMEB systems in our sample have spectra with chromospheric H $\alpha$  emission from both components of the system.

As a counterexample, the recent study of the chromospherically active LMEB T-Cyg1-12664 by Han et al. (2017) shows that neither component of the binary is inflated with respect to models considering their new derived stellar physical parameters, with radii of 0.92 and 0.47  $R_{\odot}$  and masses of 0.91 and 0.50  $M_{\odot}$  for the primary and

secondary components, respectively. However, this EB's primary component is placed in a region of more massive primary stars than the objects discussed in this work ( $M < 0.7 M_{\odot}$ ).

Moreover, the chromospheric activity can also be correlated with rotation (Bouvier 1990), thus, fast rotators may have inflated radii. In fact, fast rotators during the early pre-MS phase may have their radii enlarged by strong magnetic fields (Somers & Pinsonneault 2014; Barrado et al. 2016, and references therein).

It is not of the scope of this work to unveil the causes of the radius inflation but to provide additional measurements in the intriguing scenario of inflated components in LMEBs. Given the restricted known sample, every single new well-characterized low-mass system is significant on the pursuit of the causes of the radius anomaly. Then, these systems add to the increasing sample of low-mass stellar radii that are not well-reproduced by stellar models and they highlight the need to understand the magnetic activity and physical state of small stars. Space missions, like *TESS*, for example, will provide many such systems to perform high-precision radius measurements to tightly constrain low-mass stellar evolution models.

## 7 CONCLUSIONS

The performed analysis was dedicated to the characterization of five new short-period LMEBs from the WFCAM Transit Survey, with periods of less than 2 d.

Low- and intermediate-resolution spectroscopic data were acquired in order to obtain stellar atmospheric parameters and to measure RV shifts via cross-correlation. The low-resolution spectra have confirmed the low-mass nature of the binaries, with effective temperatures ranging from 3000 to 4400 K. The higher resolution spectra have revealed double-peaked H $\alpha$  emission, indicating the presence of chromospheric activity in both components of the systems.

The WFCAM *J*-band LCs and the RV shifts were modelled together with the JKTEBOP code. From the best-model fit, we derived stellar masses between 0.24 and 0.72  $M_{\odot}$  and radii from 0.42 to 0.67  $R_{\odot}$ . The completely characterized binaries are in very close orbits, with orbital separations of  $2.87 \leq a \leq 6.69 R_{\odot}$  and short periods of  $0.59 \leq P_{\text{orb}} \leq 1.72$  d, approximately. We also estimated that these detached systems are at distances from 0.5 to 1.4 kpc.

The stellar masses of our 10 late-type stars were determined with a precision of 6 per cent or better. Two LMEBs, 17h-4-01429 and 19f-4-05194, were well characterized with the analysed data, where we obtained radius errors of around 1 per cent. For the EBs 17e-3-02003, 19c-3-08647, and 19g-2-08064, the radii were determined with much higher uncertainties due to the limited precision of the WTS photometric data, but still indicate notable inflation above the radii expected from standard stellar models.

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## SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](https://academic.oup.com/mnras/article/476/4/5253/4919628) online.

**Table 1.** LCs for the 5 LMEBs from the WFCAM Transit Survey reported in this paper.

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## APPENDIX A: LOW-MASS BINARIES FROM THE LITERATURE

Table A1 shows the list of LMEBs found in the literature that are illustrated in Fig. 5. The components of these systems are low-mass stars, with  $R \leq 0.7 R_{\odot}$  and  $M \leq 0.7 M_{\odot}$ . Only EB systems where both components are low-mass stars were considered. These systems also have orbital periods of less than 5 d. It is important to mention that these are selected as well-characterized systems, with errors of less than 6 per cent on the radii and masses. Only three stars listed in Table A1 have mass errors greater than 6 per cent (but less than 10 per cent). Nevertheless, they were kept in the sample because they present radii defined with good precision.

**Table A1.** Low-mass binaries from the literature with  $P_{\text{orb}} \leq 5$  d. The following binaries present radius errors of less than 6 per cent. The errors in mass are typically smaller than 6 per cent, with a few exceptions.

Star	Period (d)	Mass ( $M_{\odot}$ )	Radius ( $R_{\odot}$ )	Reference
NSVS01031772 A	0.368	$0.5428 \pm 0.0028$	$0.5260 \pm 0.0028$	Southworth et al. (2015)*
NSVS01031772 B	0.368	$0.4982 \pm 0.0025$	$0.5087 \pm 0.0031$	Southworth et al. (2015)*
SDSS-MEB-1 A	0.407037	$0.272 \pm 0.020$	$0.268 \pm 0.010$	Blake et al. (2008)
SDSS-MEB-1 B	0.407037	$0.240 \pm 0.022$	$0.248 \pm 0.0090$	Blake et al. (2008)
GU Boo A	0.489	$0.6100 \pm 0.0071$	$0.6230 \pm 0.0163$	Southworth et al. (2015)*
GU Boo B	0.489	$0.5990 \pm 0.0061$	$0.6200 \pm 0.0203$	Southworth et al. (2015)*
MG1-1819499 A	0.6303135	$0.557 \pm 0.001$	$0.569 \pm 0.002$	Kraus et al. (2011)
MG1-1819499 B	0.6303135	$0.535 \pm 0.001$	$0.500 \pm 0.003$	Kraus et al. (2011)
GJ 3236 A	0.77126	$0.376 \pm 0.016$	$0.3795 \pm 0.0084$	Irwin et al. (2009)
GJ 3236 B	0.77126	$0.281 \pm 0.015$	$0.300 \pm 0.015$	Irwin et al. (2009)
YY Gem A	0.814	$0.5974 \pm 0.0047$	$0.6196 \pm 0.0057$	Southworth et al. (2015)*
YY Gem B	0.814	$0.6009 \pm 0.0047$	$0.6035 \pm 0.0057$	Southworth et al. (2015)*
MG1-116309 A	0.8271425	$0.567 \pm 0.002$	$0.552 \pm 0.004$	Kraus et al. (2011)
MG1-116309 B	0.8271425	$0.532 \pm 0.002$	$0.532 \pm 0.004$	Kraus et al. (2011)
CM Dra A	1.268	$0.2310 \pm 0.0009$	$0.2534 \pm 0.0019$	Southworth et al. (2015)*
CM Dra B	1.268	$0.2141 \pm 0.0009$	$0.2396 \pm 0.0015$	Southworth et al. (2015)*
19b-2-01387 A	1.49851768	$0.498 \pm 0.019$	$0.496 \pm 0.013$	Birkby et al. (2012)
19b-2-01387 B	1.49851768	$0.481 \pm 0.017$	$0.479 \pm 0.013$	Birkby et al. (2012)
MG1-506664 A	1.5484492	$0.584 \pm 0.002$	$0.560 \pm 0.001$	Kraus et al. (2011)
MG1-506664 B	1.5484492	$0.544 \pm 0.002$	$0.513 \pm 0.001$	Kraus et al. (2011)
MG1-78457 A	1.5862046	$0.5270 \pm 0.0019$	$0.505 \pm 0.008$	Kraus et al. (2011)
MG1-78457 B	1.5862046	$0.491 \pm 0.002$	$0.471 \pm 0.009$	Kraus et al. (2011)
LP133-373 A	1.6279866	$0.34 \pm 0.02$	$0.330 \pm 0.014$	Vaccaro et al. (2007)
LP133-373 B	1.6279866	$0.34 \pm 0.02$	$0.330 \pm 0.014$	Vaccaro et al. (2007)
MG1-646680 A	1.6375302	$0.499 \pm 0.002$	$0.457 \pm 0.006$	Kraus et al. (2011)
MG1-646680 B	1.6375302	$0.443 \pm 0.002$	$0.427 \pm 0.006$	Kraus et al. (2011)
19e-3-08413 A	1.67343720	$0.463 \pm 0.025$	$0.480 \pm 0.022$	Birkby et al. (2012)
19e-3-08413 B	1.67343720	$0.351 \pm 0.019$	$0.375 \pm 0.020$	Birkby et al. (2012)
MG1-2056316 A	1.7228208	$0.4690 \pm 0.0021$	$0.441 \pm 0.002$	Kraus et al. (2011)
MG1-2056316 B	1.7228208	$0.382 \pm 0.002$	$0.374 \pm 0.002$	Kraus et al. (2011)
KOI126 B	1.76713	$0.2413 \pm 0.0030$	$0.2543 \pm 0.0014$	Carter et al. (2011)
KOI126 C	1.76713	$0.2127 \pm 0.0026$	$0.2318 \pm 0.0013$	Carter et al. (2011)
HIP 96515 Aa	2.3456	$0.59 \pm 0.03$	$0.64 \pm 0.01$	Huélamo et al. (2009)
HIP 96515 Ab	2.3456	$0.54 \pm 0.03$	$0.55 \pm 0.03$	Huélamo et al. (2009)
19g-4-02069 A	2.44178	$0.53 \pm 0.02$	$0.51 \pm 0.01$	Nefs et al. (2013)
19g-4-02069 B	2.44178	$0.143 \pm 0.006$	$0.174 \pm 0.006$	Nefs et al. (2013)
CU Cnc A	2.771	$0.4333 \pm 0.0017$	$0.4317 \pm 0.0052$	Southworth et al. (2015)*
CU Cnc B	2.771	$0.3980 \pm 0.0014$	$0.3908 \pm 0.0095$	Southworth et al. (2015)*
1RXSJ154727 A	3.5500184	$0.2576 \pm 0.0085$	$0.2895 \pm 0.0068$	Hartman et al. (2011)
1RXSJ154727 B	3.5500184	$0.2585 \pm 0.0080$	$0.2895 \pm 0.0068$	Hartman et al. (2011)
HATS557-027 A	4.077017	$0.244 \pm 0.003$	$0.261^{+0.006}_{-0.009}$	Zhou et al. (2015)
HATS557-027 B	4.077017	$0.179^{+0.002}_{-0.001}$	$0.218^{+0.007}_{-0.011}$	Zhou et al. (2015)
LP661-13 A	4.7043512	$0.30795 \pm 0.00084$	$0.3226 \pm 0.0033$	Dittmann et al. (2017)
LP661-13 B	4.7043512	$0.19400 \pm 0.00034$	$0.2174 \pm 0.0023$	Dittmann et al. (2017)
19c-3-01405 A	4.9390945	$0.410 \pm 0.023$	$0.398 \pm 0.019$	Birkby et al. (2012)
19c-3-01405 B	4.9390945	$0.376 \pm 0.024$	$0.393 \pm 0.019$	Birkby et al. (2012)

Note. \*And references therein.

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