Properties and nature of Be stars

30. Reliable physical properties of a semi-detached B9.5e+G8III binary BR CMi = HD 61273 compared to those of other well studied semi-detached emission-line binaries^{★,★★}

P. Harmanec¹, P. Koubský², J. A. Nemravová¹, F. Royer³, D. Briot³, P. North⁴, P. Lampens⁵, Y. Frémat⁵, S. Yang⁶,
H. Božić⁷, L. Kotková², P. Škoda², M. Šlechta², D. Korčáková¹, M. Wolf¹, and P. Zasche¹

¹ Astronomical Institute of the Charles University, Faculty of Mathematics and Physics, V Holešovičkách 2, 180 00 Praha 8 – Troja, Czech Republic

e-mail: Petr.Harmanec@mff.cuni.cz

² Astronomical Institute, Academy of Sciences of the Czech Republic, 251 65 Ondřejov, Czech Republic

³ GEPI/CNRS UMR 8111, Observatoire de Paris, Université Paris Denis Diderot, 5 place Jules Janssen, 92910 Meudon, France

⁴ Laboratoire d'astrophysique, École Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland

⁵ Royal Observatory of Belgium, Ringlaan 3, 1180 Brussel, Belgium

⁶ Physics & Astronomy Department, University of Victoria, PO Box 3055 STN CSC, Victoria, BC, V8W 3P6, Canada

⁷ Hvar Observatory, Faculty of Geodesy, University of Zagreb, Kačićeva 26, 10000 Zagreb, Croatia

Received 20 July 2014 / Accepted 25 October 2014

ABSTRACT

Reliable determination of the basic physical properties of hot emission-line binaries with Roche-lobe filling secondaries is important for developing the theory of mass exchange in binaries. It is a very hard task, however, which is complicated by the presence of circumstellar matter in these systems. So far, only a small number of systems with accurate values of component masses, radii, and other properties are known. Here, we report the first detailed study of a new representative of this class of binaries, BR CMi, based on the analysis of radial velocities and multichannel photometry from several observatories, and compare its physical properties with those for other well-studied systems. BR CMi is an ellipsoidal variable seen under an intermediate orbital inclination of $\sim 51^\circ$, and it has an orbital period of 12^d919059(15) and a circular orbit. We used the disentangled component spectra to estimate the effective temperatures 9500(200) K and 4655(50) K by comparing them with model spectra. They correspond to spectral types B9.5e and G8III. We also used the disentangled spectra of both binary components as templates for the 2D cross-correlation to obtain accurate radial velocities and a reliable orbital solution. Some evidence of a secular period increase at a rate of (1.1 ± 0.5) s per year was found. This, together with a very low mass ratio of 0.06 and a normal mass and radius of the mass gaining component, indicates that BR CMi is in a slow phase of the mass exchange after the mass-ratio reversal. It thus belongs to a still poorly populated subgroup of Be stars for which the origin of Balmer emission lines is safely explained as a consequence of mass transfer between the binary components.

Key words. binaries: close – binaries: spectroscopic – stars: emission-line, Be – stars: individual: BR CMi (HD 61273) – stars: fundamental parameters

1. Introduction

In spite of the concentrated effort of several generations of astronomers, the very nature of the Be phenomenon – the presence of the Balmer emission lines in the spectra of some stars

of spectral type B and their temporal variability on several time scales – is still not well understood. The competing hypotheses include (i) outflow of material from stellar photospheres, facilitated either by rotational instability at the stellar equator, by stellar wind, or by non-radial pulsations (or a combination of these effects); and (ii) several versions of mechanisms facilitated by the duplicity of the objects in question. It is true that the number of known binaries among Be stars is steadily increasing, but clear evidence that the Balmer emission is a consequence of the binary nature of the Be star in question exists only for Be stars, which have a mass-losing secondary that fills its Roche lobe. The number of known systems of this type with reliably determined physical properties is still rather small, and finding new representatives of this subgroup of Be binaries is desirable, not only for understanding Be stars but also from the point of view of the still developing theory of mass transfer in semi-detached binaries (see, e.g., the recent studies by [Deschamps et al. 2013](#) or [Davis et al. 2014](#)). This paper deals with one such system.

[★] Based on new spectroscopic and photometric observations from the following instruments: Elodie spectrograph of the Haute Provence Observatory, France; CCD coudé spectrograph of the Astronomical Institute AS ČR at Ondřejov, Czech Republic; CCD coudé spectrograph of the Dominion Astrophysical Observatory, Canada; HERMES spectrograph attached to the *Mercator* Telescope, operated on the island of La Palma by the Flemish Community, at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias; 7-C photometer attached to the *Mercator* Telescope, La Palma, *UBV* photometers at Hvar and Sutherland, and *H_p* photometry from the ESA HIPPARCOS mission.

^{★★} Appendices are available in electronic form at <http://www.aanda.org>

Table 1. Journal of RV data sets.

Spg. No.	Time interval (HJD-2 450 000)	No. of RVs	Wavelength range (Å)	Spectral res.
1	0071.5–3430.4	34	3850–6800	42 000
2	4000.6–5649.4	56	6280–6730	12 700
3	4733.0–5994.8	14	6150–6760	21 700
4	5278.4–5649.4	19	8400–8900	17 000
5	5589.6–5912.7	8	3800–8750	40 000–90 000
3	6031.7–6383.8	5	6310–6920	21 700

Notes. Column “Spectrograph No.”: 1 OHP 1.93 m reflector, Elodie echelle spg.; 2 Ondřejov 2.0 m reflector, coudé grating spg., CCD detector, red spectra; 3 DAO 1.22 m reflector, coudé grating McKellar spg., CCD Site4 detector; 4 Ondřejov 2.0 m reflector, coudé grating spg., CCD detector, infrared spectra; 5 *Mercator* 1.2 m reflector, HERMES echelle spg.

BR CMi (HD 61273, BD+08°1831, SAO 115739, IRAS 07361+0804, HIP 37232) has not been studied much. Its light variability was discovered by [Stetson \(1991\)](#) from his *uvby* observations, but his individual observations have never been published. The variability was rediscovered by [Perryman & ESA \(1997\)](#) with the HIPPARCOS satellite, and a period of 6^d.46 was reported by them. [Kazarovets et al. \(1999\)](#) classified it as a α^2 CVn variable and assigned it a variable-star name BR CMi. [Paunzen et al. \(2001\)](#) included this star into their list of λ Boo candidates but conclude that it is a normal star of spectral type A6V. In preliminary studies, [Briot & Royer \(2009\)](#) and [Royer et al. \(2007\)](#) announced that the object is actually a semi-detached Be dwarf and K0 giant binary and an ellipsoidal variable with an orbital period of 12^d.9190 and a mass ratio $M_K/M_B = 0.14$. Hereafter, we call the Be star component 1 and the cool giant component 2. [Renson & Manfroid \(2009\)](#) included the object into their catalogue of Ap, HgMn, and Am stars, giving it a spectral class A2, while [Dubath et al. \(2011\)](#), who were testing automatic classification procedures, classified it as an ellipsoidal variable with a period of 12^d.913. We present the first detailed study of the system, based on a rich collection of spectral and photometric observations.

2. Observations and reductions

Spectroscopy: the star was observed at the Haute Provence (OHP), Ondřejov (OND), Dominion Astrophysical (DAO), and La Palma observatories. Table 1 gives a journal of all radial velocity (RV) observations. Details about the spectra reductions and RV measurements are given in Appendix A.

Photometry: we attempted to collect all available observations with known dates of observations. Basic information about all data sets can be found in Table 2 and the details on the photometric reductions and standardisation are in Appendix B. For convenience, we also publish all of our individual observations together with their HJDs there (in Tables B.3–B.6).

3. Finding reliable orbital elements

One always has to be cautious when analysing binaries with clear signatures of the presence of circumstellar matter in the system. The experience from other such systems shows that the RV curve of the Roche-lobe filling component is usually clean and defines its true orbit quite well, while the absorption lines of

Fig. 1. O–C residuals from the circular-orbit solution 2 for all RVs of component 2.**Table 2.** Journal of available photometry for BR CMi.

Station	Time interval (HJD–2 400 000)	No. of obs.	Passbands	Ref.
61	47 912.6–49 061.9	111	V	1
37	52 307.4–52 384.4	24	7-C	2
93	52 032.5–54 836.8	135	V	3
11	55 567.4–55 579.5	19	UBV	2
01	55 574.5–56 015.3	103	UBV	2

Notes. Individual observing stations are distinguished by the running numbers they have in the Prague/Zagreb photometric archives – see column “Station”: 01 Hvar 0.65 m, Cassegrain reflector, EMI9789QB tube; 11 SAAO 0.5 m reflector, *UBV* photometry; 37... Geneva 7-C system: observations secured with the *Mercator* reflector at La Palma; 61 HIPPARCOS all-sky H_p photometry transformed to Johnson V; 93 ASAS data archive ([Pojmanski 2002](#)).

Notes. Column “Ref.”: 1) [Perryman & ESA \(1997\)](#); 2) this paper; 3) [Pojmanski \(2002\)](#).

the mass-gaining component can be affected by the circumstellar matter, and their RV curves do not follow the true orbital motion (cf. [Harmanec & Scholz 1993](#); [Desmet et al. 2010](#)).

To derive an improved ephemeris and an orbital solution for component 2, we used all its RVs measured in SPEF0 (see Appendix A for details) and the program FOTEL ([Hadrava 1990, 2004a](#)). These solutions are summarised in Table 3. In solution 1, individual systemic (γ) velocities were derived for each spectrograph. Since our correction of the RV zero point via RV measurements of selected telluric lines clearly worked well (the γ velocities of all four instruments being nearly identical), we assumed that all RVs are on the same system and derived solution 2 with a joint systemic velocity. In this solution, we weighted the individual datasets 1–4 by weights inversely proportional to the squares of rms errors per one observation for each dataset from solution 1. As one can see in Fig. 1, the O–C residuals from the circular-orbit solution 2 define a low-amplitude double-wave phase curve. For that reason, we also tentatively derived an eccentric-orbit solution. It indeed led to an eccentricity of $e = 0.0085 \pm 0.0012$, which is statistically significant according to the test by [Lucy & Sweeney \(1971\)](#). However, the corresponding longitude of periastron (referred to component 1) was $\omega = 93.3 \pm 8.5$ degrees, which is suspect. It is known that for tidally distorted components of binaries, the difference between the optical and mass centre of gravity leads inevitably to a deformation of the RV curve, which manifests itself by a false eccentricity with values of ω either 90° or 270° ([Sterne 1941](#); [Harmanec 2003](#); [Eaton 2008](#)). This is what also occurs for BR CMi and similar binaries, e.g. AU Mon ([Desmet et al. 2010](#)) or V393 Sco ([Mennickent et al. 2012b](#)).

Table 3. Trial FOTEL orbital solutions based on RVs of component 2 measured in the program SPEFO.

Element	Solution 1	Solution 2
P (d)	12.919050 ± 0.000021	12.919046 ± 0.000022
$T_{\text{super. c.}}$	54600.3786 ± 0.0029	54600.3806 ± 0.0030
e	0.0 assumed	0.0 assumed
K_2 (km s $^{-1}$)	89.2086 ± 0.0068	89.1787 ± 0.0070
γ_1 (km s $^{-1}$)	-14.04 ± 0.12	—
γ_2 (km s $^{-1}$)	-14.12 ± 0.15	—
γ_3 (km s $^{-1}$)	-14.02 ± 0.13	—
γ_5 (km s $^{-1}$)	-14.49 ± 0.28	—
γ_{joint} (km s $^{-1}$)	—	-14.088 ± 0.088
rms (km s $^{-1}$)	0.905	0.781
No. of RVs	117	117

Notes. All epochs are in RJD = HJD-2 400 000; rms is the rms per 1 observation of unit weight. The systemic velocities γ of individual spectrographs are identified by their numbers used in Table 1.

Consequently, we adopted the circular-orbit solution 2 in Table 3 as a basis for a working new ephemeris (1)

$$T_{\text{super. c.}} = \text{HJD } 2\,454\,600.3806(30) + 12^{\text{d}}919046(22) \cdot E. \quad (1)$$

Next we measured and analysed the $H\alpha$ profile. Selected $H\alpha$ profiles stacked with increasing orbital phase are shown in Fig. 2. For binary Be stars with strong $H\alpha$ emission, this is the best measure of the true orbital motion of the Be component – see Božić et al. (1995), Ruždjak et al. (2009) and Peters et al. (2013). This is not so for BR CMi, since its $H\alpha$ emission rises to only 20% above the continuum level, and the measured RV curve of the $H\alpha$ emission wings is poorly defined and has a phase shift with respect to expected orbital motion of component 1. In Fig. 2 one can also note that the width of both peaks of the double $H\alpha$ emission varies systematically with the orbital phase, being largest shortly after both conjunctions. Figure 2 also shows the secular stability of the strength of $H\alpha$ emission, with the observed changes mainly due to RV shifts of two absorption components, the stronger one associated with component 2 and a weaker one associated with material in the neighbourhood of component 1. It exhibits a RV curve, which is not in exact antiphase to that of component 2.

In another attempt we used the program KOREL¹ developed by Hadrava (1995, 2004b) for spectra disentangling. Since the expected semi-amplitude of the orbital RV curve of component 1 is low, we decided to only analyse high-resolution Elodie and Hermes spectra from the blue spectral region between 4397 and 4608 Å. This region contains a number of He I and metallic lines but no Balmer line (to avoid contamination by the circumstellar matter). It turned out that because of relatively broad and not very numerous line profiles of component 1 and a low semi-amplitude of its RV curve, comparably good solutions could be obtained for a wide range of mass ratios. We note, however, that for the same reasons the disentangling of individual spectra is robust and can be trusted.

We then decided to try a cross-correlation in two dimensions, suggested (and realized as the program TODCOR) by Zucker & Mazeh (1994). In this technique, the individual observed spectra are compared to the two template spectra, which should closely correspond to the spectra of the two binary components, both in the spectral type and the projected rotational broadening. The

Fig. 2. Selected $H\alpha$ line profiles of BR CMi stacked with increasing orbital phase. Profiles are identified by cycle numbers and orbital phases with respect to ephemeris (1) and by RJDs = HJDs-2 400 000.0. Symbols E, O, D, and H stand for Elodie, Ondřejov, DAO, and Hermes spectrographs.

¹ The freely distributed version from Dec. 2004.

Fig. 3. One observed Elodie spectrum and the disentangled spectra of components 1 and 2 in the wavelength interval 4397–4608 Å. The disentangled spectra were renormalised to their own continua and are compared to a model fit (see Sect. 4.1).

RVs for both binary components are derived for each observed spectrum. A similar program to TODCOR was written by one of us (YF) under the name *asTODCOR* and has already been successfully applied to the case of AU Mon (Desmet et al. 2010). In practice, the Fourier transform of the observed and template spectra is computed via the FFT technique (Press et al. 1993). To meet the requirements of the FFT algorithm (see e.g. David et al. 2014), the spectra were rebinned to a smaller, constant, $\log \lambda$ bin size and apodised at both edges by means of a cosine-bell function. David & Verschueren (1995) showed that the combination of an even and uneven number of points correctly chosen around the CCF summit allows reducing the impact of discretisation on the measurement of its location, hence on the RV determinations. This approach was therefore also implemented in *asTODCOR* by combining the results of a parabola fit through three and four points.

It is usual practice to use suitable synthetic and properly rotationally broadened spectra as the templates. In this case, we used the spectra of both components disentangled by KOREL as the templates, adopting a preliminary estimated luminosity ratio $L_2/L_1 = 0.25$. The wavelength interval 4397–4608 Å was used (see Fig. 3), and we verified that the disentangled spectrum of component 1 had the same systemic velocity as component 2. The procedure worked remarkably well and returned well-defined RV curves for both binary components. This is seen in Fig. 4, which is the phase plot of these curves for ephemeris (1). We publish all individual SPEFO RVs for component 2 and *asTODCOR* RVs for both components, together with their HJDs in Tables A.2 and A.3.

In Table 4 we provide the circular-orbit solutions based on RVs resulting from 2D cross-correlation. Solution 3 is based on RVs of component 1 and solution 4 on RVs of component 2 alone. Their comparison shows that the epochs of superior conjunction of component 1 from both solutions agree with each other within the limits of their respective errors. They also agree with the epoch derived from a more numerous set of RVs from the red spectral region measured in SPEFO (see solution 2 of Table 3). Since the 2D cross-correlation puts no constraint on the derived RVs, this seems to prove that the RVs of component 1, found to be in exact antiphase to those of component 2, indeed reflect the true orbital motion of component 1. In addition, both solutions have identical RV zero points within its rms error of 0.1 km s⁻¹, confirming that using disentangled spectra has not introduced any biases. We therefore derived another solution 5,

Fig. 4. *Top:* orbital RV curve of both components of BR CMi based on RVs derived via 2D cross-correlation. *Bottom:* zoomed RV curve of component 1 from the upper panel showing how accurately the RVs were derived via the 2D cross-correlation.

which is based on RVs for both binary components. It defines the $M_{1,2} \sin^3 i$ values and the mass ratio $M_2/M_1 = 0.0593$.

4. An estimate of basic physical elements of the binary components and the whole system

Since BR CMi is not an eclipsing but an ellipsoidal binary, its light curves can almost equally well be fitted for a wide range of possible orbital inclinations. For that reason, we proceeded in an iterative way, trying to describe all system properties in a mutually consistent way and taking all limitations we have at

Table 4. FOTEL circular-orbit solutions individually for components 1 and 2 and for both stars together, based on RVs obtained via a 2D cross-correlation.

Element	Solution 3	Solution 4	Solution 5
$T_{\text{sup. conj.}}$	0.427 ± 0.059	0.3807 ± 0.0032	0.3808 ± 0.0033
K_1 (km s $^{-1}$)	5.26 ± 0.15	–	5.26 ± 0.14
K_2 (km s $^{-1}$)	–	88.71 ± 0.14	88.71 ± 0.15
rms (km s $^{-1}$)	0.694	0.630	0.666
No. of RVs	41	41	41/41

Notes. The orbital period was fixed at 12^d919046 in all cases. All epochs are in HJD-2 454 600; rms is the rms of 1 observation of unit weight.

our disposal into account. In particular, we used the disentangled spectra of both binary components in several spectral regions to obtain good estimates of the effective temperatures of both stars via a comparison of disentangled and synthetic line profiles. These were then kept fixed in the combined light-curve and orbital solutions for a given inclination. Since the masses and radii thus obtained define $\log g$ quite accurately, we kept them fixed in the determination of T_{eff} .

4.1. Comparing the disentangled and interpolated model spectra

We used a program of J.A. Nemravová (see [Nasseri et al. 2014](#)) that interpolates in a precalculated grid of synthetic stellar spectra sampled in the effective temperature, gravitational acceleration, and metallicity. The synthetic spectra are compared to the disentangled ones for two or more components of a multiple system (normalised to the joint continuum of all bodies) and the initial parameters are optimised by minimisation of χ^2 until the best match is achieved.

Since the fractional luminosities within a considered spectral region are treated as independent of wavelength, we fitted the following six disentangled spectral bands separately: 4002–4039, 4142–4191, 4381–4435, 4446–4561, 4910–4960, and 8400–8880 Å. The interpolation was carried out in two different grids of spectra: AMBRE grid computed by [de Laverny et al. \(2012\)](#) was used for component 2, and the Pollux database computed by [Palacios et al. \(2010\)](#) was used for the hotter component 1.

It would not be wise to derive all physical parameters via free convergence in all considered spectral regions. Since the combined light and orbital solution can provide very tight values of $\log g$ and systemic velocity γ , we kept these values fixed in each superiteration between model spectra and combined solution. The infrared region 8400–8880 Å is the most appropriate region for the T_{eff} determination of component 2, since its fractional luminosity is much higher there (~ 0.5 compared to less than 0.2 in the blue regions) and its spectrum is rich there.

Having the effective temperature of component 2 determined with an accuracy of ~ 50 K, we kept it fixed in all five blue spectral regions, where the fractional luminosity of component 2 is low. The uncertainty of the fitted parameters has two components. The first is the statistical one connected with the photon noise and represents a minor contribution since the disentangled profiles have very high S/N. The second is influenced by the approach to the minimisation and can be estimated by repeating the fitting procedure and the need for (re)normalisation of the

Table 5. Average results of the final best fit of the interpolated grid of synthetic spectra to the observed ones in the six considered spectral regions.

Quantity	Component 1	Component 2
T_{eff} (K)	9514 ± 171	4655 ± 50
$v \sin i$ (km s $^{-1}$)	130.98 ± 3.27	20.11 ± 2.71

Notes. The majority of the physical properties affecting the line profiles were kept fixed from the final combined orbital and light-curve solution. T_{eff} of component 2 is based on the fit in the IR region alone – see the text for details.

disentangled profiles². The former source of systematic error is not taken into account, because our program does not normalise the disentangled spectra. Therefore, we estimated the uncertainties of the optimised parameters as a mean of the best fit values obtained for each modelled spectral band, which should (at least to some degree) account for the need for (re)normalisation of the disentangled profile. The only exception is the uncertainty of the effective temperature of component 2, which was estimated via a simple Monte Carlo simulation. This is justified since the disentangled continua of component 2 were very close to a straight line in all regions. The results of the final minimisation averaged over all considered spectral regions are summarised in Table 5.

4.2. A combined orbital and light-curve solution

We used the program PHOEBE (version 1.0 with a few custom passbands added; [Prša & Zwitter 2005, 2006](#)), all photometric data sets available to us, RVs of both components from the 2D cross-correlation and also RVs of component 2 measured in SPEFO because they give almost the same RV curve as the RVs from 2D cross-correlation but represent a much more numerous data set. For all Elodie and Hermes spectra, for which both sets of RVs of component 2 exist, we set their weights to 0.5 in both subsets. We assumed that component 2 fills the Roche lobe, fixed the mass ratio $M_2/M_1 = 0.0593$, which follows from the orbital solution for the cross-correlated RVs from spectra with high S/N (see solution 5 of Table 4).

An unsuccessful attempt to converge T_{eff} of component 1 was carried out. Changes of the T_{eff} did not lead to any improvement in the cost function value, and the program merely adjusted the radii of both components to adapt the model to the new temperature. We therefore decided to fix the effective temperatures of both components obtained from the fit of synthetic spectra to the disentangled ones. We adopted $T_{\text{eff}} = 4655$ K for component 2. The effective temperature of component 1 is rather uncertain. We therefore computed three sets of trial solutions for three different T_{eff} of the component 1 corresponding to the estimated 1σ bars given in Table 5: $T_{\text{eff}} \in \{9343, 9514, 9685\}$ K. The solution that has the least χ^2 of all trial solutions is listed in Table 6. Error bars presented in Table 6 were estimated as the difference between the maximal (minimal) result of each parameter, which did not have the χ^2 greater than 1% of the χ^2 of the best solution, and the best solution. The bolometric albedos were estimated for the corresponding effective temperatures from Fig. 7 of [Claret \(2001\)](#) and the coefficients of gravity brightening from Fig. 7 of [Claret \(1998\)](#). Logarithmic limb-darkening coefficients were

² Since the disentangling in KOREL is carried out in Fourier space, it happens in almost every practical application that the resulting disentangled spectra after inverse Fourier transformation have slightly warped continua and need some re-normalisation.

Table 6. Combined RV curve and light-curve solution.

Element	Orbital properties	
P (d)	$12.919059 \pm_{-0.000015}^{+0.000015}$	
T_{min} (RJD)	$54\,600.38186 \pm_{-0.00206}^{+0.00206}$	
M_2/M_1	0.0593*	
i (deg)	$50.85 \pm_{-2.70}^{+5.33}$	
a ($R_{\odot}$)	$31.21 \pm_{-2.08}^{+1.28}$	
Component properties		
	Component 1	Component 2
T_{eff} (K)	9685*	4655*
Ω	$277.2 \pm_{-26.8}^{+5.0}$	22.82^*
$\log g$ [c_{gs}]	$4.228 \pm_{-0.118}^{+0.031}$	$2.095 \pm_{-0.033}^{+0.018}$
M ($M_{\odot}$)	$2.31 \pm_{-0.43}^{+0.29}$	$0.137 \pm_{-0.026}^{+0.017}$
R ($R_{\odot}$)	$1.93 \pm_{-0.00}^{+0.13}$	$5.49 \pm_{-0.37}^{+0.22}$
F	22.40**	1.00**
M_{bol}	$1.080 \pm_{-0.066}^{+0.101}$	$1.991 \pm_{-0.085}^{+0.152}$
$L_{\text{Johnson-U}}$	$0.953 \pm_{-0.009}^{+0.008}$	$0.047 \pm_{-0.008}^{+0.009}$
$L_{\text{Johnson-B}}$	$0.890 \pm_{-0.014}^{+0.018}$	$0.110 \pm_{-0.018}^{+0.014}$
$L_{\text{Johnson-V}}$	$0.740 \pm_{-0.022}^{+0.035}$	$0.260 \pm_{-0.035}^{+0.022}$
$L_{\text{Geneva-U}}$	$0.994 \pm_{-0.001}^{+0.001}$	$0.006 \pm_{-0.001}^{+0.001}$
$L_{\text{Geneva-B1}}$	$0.984 \pm_{-0.003}^{+0.003}$	$0.016 \pm_{-0.003}^{+0.003}$
$L_{\text{Geneva-B}}$	$0.963 \pm_{-0.006}^{+0.007}$	$0.037 \pm_{-0.007}^{+0.006}$
$L_{\text{Geneva-B2}}$	$0.936 \pm_{-0.009}^{+0.011}$	$0.064 \pm_{-0.011}^{+0.009}$
$L_{\text{Geneva-V1}}$	$0.816 \pm_{-0.018}^{+0.027}$	$0.184 \pm_{-0.027}^{+0.018}$
$L_{\text{Geneva-V}}$	$0.800 \pm_{-0.019}^{+0.029}$	$0.200 \pm_{-0.029}^{+0.019}$
$L_{\text{Geneva-G}}$	$0.739 \pm_{-0.021}^{+0.036}$	$0.261 \pm_{-0.036}^{+0.021}$
L_{Hp}	$0.804 \pm_{-0.022}^{+0.029}$	$0.196 \pm_{-0.029}^{+0.021}$

Notes. The optimised parameters are given with only their formal errors. (*) Parameters that were fixed during the optimisation. (**) The synchronicity parameter F of component 1 was kept fixed during each iteration, but it was recalculated for new radius and inclination after each iteration, using $v \sin i$ from Table 5. A spin-orbit synchronization was assumed for the Roche lobe-filling component 2.

automatically interpolated after each iteration in PHOEBE from a pre-calculated grid of model atmospheres.

A test of the robustness of the final solution presented in Table 6 was carried out using the scripter environment of PHOEBE. We fitted the photometric observations and RVs from the 2D cross-correlation starting the convergence for 29 different initial orbital inclinations i ranging from 30 to 86 degrees. During each run, 30 iterations were computed, although the solution usually converged in less than ten iterations. The rotation parameter F (a ratio of spin to orbital revolution) of component 1 was not converged in PHOEBE, but it was optimised after each iteration using the new values of the component 1 radius and of the orbital inclination, while keeping the value of $v \sin i$ fixed from Table 5. A comparison of the optimal PHOEBE model light curves with the observed ones is in Fig. 5.

The free convergence of the orbital period and epoch, now based not only on RVs but also on photometry, led to an improved linear ephemeris (2)

$$T_{\text{super. c.}} = \text{HJD } 2\,454\,600.38187(42) + 12^{\text{d}}9190594(7) \cdot E. \quad (2)$$

To check on a secular constancy of the orbital period, we split the RVs and photometry into two subsets: HJD 2 448 705–53650 containing 460 data, and HJD 24 540 00–56295 containing 505 data. This particular choice ensured that both subsets contain a representative mixture of RVs and photometry. Local

Fig. 5. Comparison of the photometric observations (black points) with the PHOEBE model light curve corresponding to the χ^2 minimum for several photometric passbands (solid/blue line). The fits for the remaining passbands look similar. Phases from ephemeris 2 are used. Note the colour dependence of the amplitude of photometric changes on the wavelength.

PHOEBE solutions for these two subsets led to the following linear ephemerides (3) and (4)

$$T_{\text{super. c.}} = \text{HJD } 2\,450\,724.6695(47) + 12^{\text{d}}919018(30) \cdot E, \quad (3)$$

$$T_{\text{super. c.}} = \text{HJD } 2\,454\,600.37787(30) + 12^{\text{d}}919165(45) \cdot E. \quad (4)$$

They imply a secular increase in the orbital period for 3.8×10^{-8} days per day or 1.2 s yr^{-1} . We therefore ran another PHOEBE solution on the complete data set, this time also allowing for the convergence of the secular period change. It provided a marginal support for the reality of a secular period increase of $(3.5 \pm 1.6) \times 10^{-8} \text{ d d}^{-1}$, the corresponding quadratic ephemeris (5) being

$$T_{\text{super. c.}} = \text{HJD } 2\,454\,600.3800(22) + 12^{\text{d}}919107(26) \cdot E + 2.31 \cdot 10^{-7} \cdot E^2. \quad (5)$$

The original HIPPARCOS parallax (Perryman & ESA 1997) is $0''.00670 \pm 0''.00088$. In van Leeuwen (2007b,a) an

Table 7. List of some basic properties of well-observed semi-detached emission-line binaries.

Binary	HD	Sp1+Sp2	P_{orb} (d)	$\dot{P}$ (s/yr)	Cyclic changes(d)	$M_1 + M_2$ ($M_{\odot}$)	M_2/M_1	r_1/r_1^{Roche}	i ($^{\circ}$)	Principal references
RX Cas	–	B5:+K1III	32.31	+19.86	516.1	5.8+1.8	0.30	0.06	80	1
SX Cas	232121	B5:+K3III	36.56	–4.80	?	5.1+1.5	0.30	0.07	79	2
AU Mon	50846	B5+G2III	11.11	0.0	416.9	7.0+1.2	0.17	0.24	79	3
BR CMi	61273	B9.5+G8III	12.92	0.0	no	2.31+0.14	0.06	0.08	51	4
UX Mon	65607	B7:+K0III	5.904	–0.260	yes	3.38+3.90	1.15	0.36	81	5
TT Hya	97528	B9.5+G5III	6.953	0.0:	?	2.77+0.63	0.23	0.17	83	6
V393 Sco	161741	B3+A8III	7.713	<0.5	253.0	7.8+2.0	0.25	0.25	80	7
CX Dra	174237	B3+F5III	6.696	0.0	yes	7.3+1.7:	0.23	0.25	53	8
β Lyr	174638	B0:+B6-8II	12.94	+18.93	282.4	13.1+2.96	0.23	?	86	9
V448 Cyg	190967	O9.5V+B1Ib	6.520	0.0	no	24.7+13.7	0.56	0.37	88	10
V360 Lac	216200	B4:+F9III	10.09	+5.5?	322.2	7.45+1.21	0.16	0.48	65	11

Notes. In all cases, component 1 is the gainer and component 2 is the Roche-lobe-filling mass losing star. The mass ratio is always the mass of the mass-losing star over the mass of the gainer.

References. 1 Andersen et al. (1989), 2 Andersen et al. (1988), 3 Desmet et al. (2010); Atwood-Stone et al. (2012), 4 this paper, 5 Olson et al. (2009); Sudar et al. (2011), 6 Miller et al. (2007), 7 Mennickent et al. (2012a,b), 8 Koubský et al. (1998); Richards et al. (2000), 9 Harmanec et al. (1996); Bisikalo et al. (2000); Harmanec (2002); Ak et al. (2007), 10 Djurašević et al. (2009), 11 Hill et al. (1997); Linnell et al. (2006).

improved value of the HIPPARCOS parallax of BR CMi, $0''.00579 \pm 0''.00061$ is given. These values imply a distance 132–172 pc for the original, and 156–193 pc for the improved value. A standard dereddening of UBV magnitudes of component 1 using the fractional luminosities of Table 6 gives $V_0 = 7^m08$, $(B-V)_0 = -0^m03$, and $(U-B)_0 = -0^m11$. These colours correspond to a normal B9.5 star, in agreement with the mean $T_{\text{eff}} = 9685$ K adopted as the best from the combined model fit of Table 6 for component 1. Consulting the tabulation of normal stellar masses and radii by Harmanec (1988), we find that the mass and radius of component 1, which follow from our solution, also correspond to a normal star of spectral type B9.5–A0 V. The range of $M_{\text{bol}} = 1^m01$ – 1^m18 for it implies $M_V = 1^m19$ – 1^m36 and a distance range of 139–151 pc. Our combined solution thus agrees with the observed distance of BR CMi. In passing, we also note that the effective temperature of component 2, based on the comparison of model and disentangled spectra, 4655 K, corresponds to spectral type G8 III according to a calibration by Popper (1980). The mass of component 2 is, however, much lower than the mass of a normal G8 giant, as usually found for the mass-losing stars in binaries.

5. BR CMi among other known emission-line semi-detached binaries

As already mentioned, the number of Be stars with known binary companions has been increasing steadily. However, many of them are single-line spectroscopic binaries and the nature of their companions is not known. There are some visual binaries among Be stars (Oudmaijer & Parr 2010). It is not clear how strong the mutual interaction between the components of such systems can be, although there is a suspicion of strong interaction during periastron passages in some systems with highly eccentric orbits like δ Sco (cf. Meilland et al. 2013, and references therein). Another distinct subgroup of Be binaries are systems with hot and compact secondaries, the prototype of such systems being φ Per (Gies et al. 1998; Božić et al. 1995). Only five such systems are known (see Koubský et al. 2012, 2014, and references therein). Finally, a subgroup of mass-exchanging semi-detached binaries exists in which the Be components are the mass-gaining components as predicted by the original binary

hypothesis of the Be phenomenon (Kříž & Harmanec 1975; Harmanec & Kříž 1976).

There has also been recent progress in modelling the process of mass exchange in binaries (e.g. Siess et al. 2013; Deschamps et al. 2013; Davis et al. 2014) and obtaining reliable physical properties of mass-exchanging binaries is therefore essential for testing the predictions of new models. In Table 7, we collected a list of well-studied semi-detached emission-line binaries known to us and their published basic properties. We note that the spectral types quoted for mass gainers refer to the stellar bodies, not to the observed spectral classes affected by circumstellar matter. A zero secular change of the orbital period means that no significant change was detected in the available data.

The systems similar to those listed in Table 7 may not actually be very rare. We included only systems with reasonably safe evidence that one of the stars is filling its Roche lobe. The same might be true for the systems listed in Table 8, for which complete orbital and/or light-curve solutions and information on a secular orbital period change are still missing. Their detailed studies are very desirable. (Here, we have not included into consideration a number of short-periodic semi-detached binaries, for which transient $H\alpha$ emission was reported in the astronomical literature.)

The list in Table 7 is too short to be statistically significant, but we use it to point out that there still might be a long way to a detailed comparison between observations and theory:

1. One important observable is the equatorial rotational velocity of the gainer, but it is not often available even in new studies. For instance, Mennickent et al. (2012a) considered two models in their study of V393 Sco: spin-orbit synchronisation of the gainer and gainer with a break-up velocity. Available line profiles of the gainer show that its $v \sin i$ is somewhere in between these two cases, but this piece of information was not used. Our present study of BR CMi is probably one of the few where the synchronicity parameter F was changed after each iteration to correspond to the observed $v \sin i$ of the gainer.
2. It is not obvious why some of these systems exhibit cyclic (if not periodic) light and colour changes on a time scale that is an order of magnitude longer than their respective orbital periods. For three of such variables, β Lyr, AU Mon,

Table 8. Other possibly semi-detached emission-line binaries.

Binary	HD/ CoD	P_{orb} (d)	Principal references
V617 Aur	37 453	66 ^d .75	1
V395 Aur	43 246	23 ^d .17	2
HZ CMa	50 123	28 ^d .601	3
HIP 33657	51 956	107 ^d .4	4
BD-17°2010	59 771	~90 ^d	5
PW Pup	-30°5135	158 ^d .0	5
BY Cru	10 4901	106 ^d .4	6
HL Lib	127 208	24 ^d .615	7
V1914 Cyg	207 739	140 ^d .782	8
KX And	218 393	38 ^d .9	9

Notes. 1 Parsons et al. (1988); 2 Dempsey et al. (1990); 3 Sterken et al. (1994); 4 Burki & Mayor (1983); Parsons & Bopp (1993); 5 Eggen (1983); Bopp et al. (1991); 6 Daems et al. (1997); 7 Dempsey et al. (1990); 8 Griffin et al. (1990); Szabados (1990); 9 Štefl et al. (1990); Tarasov et al. (1998).

and V393 Sco, the presence of bipolar jets was considered. Similar jets were also considered for TT Hya, so a study of its long-term photometric behaviour would be of interest. Non-orbital light changes were also observed for UX Mon, but no clear periodicity was found. It is remarkable that UX Mon is a rare system at the early phase of the mass transfer before the mass ratio reversal. The differences in the orbital inclination also do not provide a clue. BR CMi and CX Dra are the only two non-eclipsing binaries in the considered sample, and while BR CMi seems to be secularly constant, CX Dra exhibits rather strong non-orbital long-term changes.

3. Deschamps et al. (2013) tried to classify semi-detached binaries into three classes: I. systems before the mass ratio reversal; II. systems after the reversal but with still high rate of mass transfer; and III. systems in the quiescent final stages of mass transfer. We warn that the real situation may be even more complex and note that the secular period decrease would qualify SX Cas as a candidate for class I, while its observed masses clearly show that this is a system after mass reversal. Obviously, secular period changes may also be caused by other effects than the mass transfer between the components, for instance, by the presence of other bodies in the system. We can only conclude that the results of our study provide solid evidence that BR CMi is a system at the quiescent stages of mass transfer after the mass ratio reversal. It has the lowest mass ratio of all systems of Table 7.

Acknowledgements. This study uses spectral observations obtained with the HERMES spectrograph, which is supported by the Fund for Scientific Research of Flanders (FWO), Belgium, the Research Council of K.U. Leuven, Belgium, the Fonds National de la Recherche Scientifique (F.R.S.-FNRS), Belgium, the Royal Observatory of Belgium, the Observatoire de Genève, Switzerland and the Thüringer Landessternwarte Tautenburg, Germany, spectral observations with the Elodie spectrograph attached to 1.9 m reflector of Haute Provence Observatory, CCD spectrograph of the Ondřejov 2 m reflector, and CCD spectra from the spectrograph attached to the 1.22 m reflector of the Dominion Astrophysical Observatory. It also uses photometric observations made at the observatory of La Palma (*Mercator*), Hvar, and South African Astronomical Observatory (SAAO), and by the ESA HIPPARCOS satellite. We gratefully acknowledge the use of spectrograms of BR CMi from the public archives of the Elodie spectrograph of the Haute Provence Observatory and the use of the latest publicly available versions of the programs FOTEL and KOREL written by Dr. P. Hadrava. Our sincere thanks are also due to Dr. A. Prša, who provided us with a modified version of the program PHOEBE 1.0 and frequent consultations on its usage. We thank Drs. M. Ceniga, A. Kawka, J. Kubát, P. Mayer, P. Nemeth,

M. Netolický, J. Polster, and V. Votruba, who obtained several Ondřejov spectra used in this study and to Dr. K. Uytterhoeven, who participated in photometric observations at La Palma. The comments of an anonymous referee helped to shorten the text and improve the presentation of the main results a great deal. This research was supported by the grants 205/06/0304, 205/08/H005, and P209/10/0715 of the Czech Science Foundation, by the grant 678212 of the Grant Agency of the Charles University in Prague, from the research project AV0Z10030501 of the Academy of Sciences of the Czech Republic, and from the Research Program MSM0021620860 *Physical study of objects and processes in the solar system and in astrophysics* of the Ministry of Education of the Czech Republic. The research of P.K. was supported from the ESA PECS grant 98058. H.B. acknowledges financial support from the Croatian Science Foundation under the project 6212 “Solar and Stellar Variability”. P.N. thanks the Swiss National Science Foundation for its support in acquiring photometric data in the Geneva 7-C system. We acknowledge the use of the electronic database from the CDS, Strasbourg, and the electronic bibliography maintained by the NASA/ADS system.

References

- Ak, H., Chadima, P., Harmanec, P., et al. 2007, A&A, 463, 233
Andersen, J., Nordstrom, B., Mayor, M., & Polidan, R. S. 1988, A&A, 207, 37
Andersen, J., Pavlovski, K., & Pirola, V. 1989, A&A, 215, 272
Atwood-Stone, C., Miller, B. P., Richards, M. T., Budaj, J., & Peters, G. J. 2012, ApJ, 760, 134
Baranne, A., Queloz, D., Mayor, M., et al. 1996, A&AS, 119, 373
Bisikalo, D. V., Harmanec, P., Boyarchuk, A. A., Kuznetsov, O. A., & Hadrava, P. 2000, A&A, 353, 1009
Bopp, B. W., Dempsey, R. C., & Parsons, S. B. 1991, PASP, 103, 444
Božić, H., Harmanec, P., Horn, J., et al. 1995, A&A, 304, 235
Briot, D., & Royer, F. 2009, Be Star Newsletter No. 39, 15
Burki, G., & Mayor, M. 1983, A&A, 124, 256
Claret, A. 1998, A&AS, 131, 395
Claret, A. 2001, MNRAS, 327, 989
Daems, K., Waelkens, C., & Mayor, M. 1997, A&A, 317, 823
David, M., & Verschueren, W. 1995, A&AS, 111, 183
David, M., Blomme, R., Frémat, Y., et al. 2014, A&A, 562, A97
Davis, P. J., Siess, L., & Deschamps, R. 2014, A&A, 570, A25
de Laverny, P., Recio-Blanco, A., Worley, C. C., & Plez, B. 2012, A&A, 544, A126
Dempsey, R. C., Bopp, B. W., Parsons, S. B., & Fekel, F. C. 1990, PASP, 102, 312
Deschamps, R., Siess, L., Davis, P. J., & Jorissen, A. 2013, A&A, 557, A40
Desmet, M., Frémat, Y., Baudin, F., et al. 2010, MNRAS, 401, 418
Djurašević, G., Vince, I., Khruzina, T. S., & Rovithis-Livaniou, E. 2009, MNRAS, 396, 1553
Dubath, P., Rimoldini, L., Süveges, M., et al. 2011, MNRAS, 414, 2602
Eaton, J. A. 2008, ApJ, 681, 562
Eggen, O. J. 1983, AJ, 88, 1676
Gies, D. R., Bagnuolo, Jr., W. G., Ferrara, E. C., et al. 1998, ApJ, 493, 440
Griffin, R. F., Parsons, S. B., Dempsey, R., & Bopp, B. W. 1990, PASP, 102, 535
Hadrava, P. 1990, Contr. Astron. Obs. Skalnaté Pleso, 20, 23
Hadrava, P. 1995, A&AS, 114, 393
Hadrava, P. 2004a, Publ. Astron. Inst. Acad. Sci. Czech Rep., 92, 1
Hadrava, P. 2004b, Publ. Astron. Inst. Acad. Sci. Czech Rep., 92, 15
Harmanec, P. 1988, Bull. Astron. Inst. Czechosl., 39, 329
Harmanec, P. 1998, A&A, 335, 173
Harmanec, P. 2002, Astron. Nachr., 323, 87
Harmanec, P. 2003, in Publ. Canakkale Onsekiz Mart Univ.: New Directions for Close Binary Studies: The Royal Road to the Stars, 3, 221
Harmanec, P., & Horn, J. 1998, J. Astron. Data, 4, 5
Harmanec, P., & Kříž, S. 1976, in Be and Shell Stars, ed. A. Slettebak, IAU Symp., 70, 385
Harmanec, P., & Scholz, G. 1993, A&A, 279, 131
Harmanec, P., Horn, J., & Juza, K. 1994, A&AS, 104, 121
Harmanec, P., Morand, F., Bonneau, D., et al. 1996, A&A, 312, 879
Hill, G., Harmanec, P., Pavlovski, K., et al. 1997, A&A, 324, 965
Horn, J., Kubát, J., Harmanec, P., et al. 1996, A&A, 309, 521
Kazarovets, E. V., Samus, N. N., Durlevich, O. V., et al. 1999, IBVS, 4659, 1
Koubský, P., Harmanec, P., Božić, H., et al. 1998, Hvar Observatory Bulletin, 22, 17
Koubský, P., Kotková, L., Votruba, V., Šlechta, M., & Dvořáková, Š. 2012, A&A, 545, A121
Koubský, P., Kotková, L., Kraus, M., et al. 2014, A&A, 567, A57
Kříž, S., & Harmanec, P. 1975, BAICz, 26, 65

- Linnell, A. P., Harmanec, P., Koubský, P., et al. 2006, *A&A*, 455, 1037
- Lucy, L. B., & Sweeney, M. A. 1971, *AJ*, 76, 544
- Meilland, A., Stee, P., Spang, A., et al. 2013, *A&A*, 550, L5
- Mennickent, R. E., Djurašević, G., Kołaczkowski, Z., & Michalska, G. 2012a, *MNRAS*, 421, 862
- Mennickent, R. E., Kołaczkowski, Z., Djurašević, G., et al. 2012b, *MNRAS*, 427, 607
- Miller, B., Budaj, J., Richards, M., Koubský, P., & Peters, G. J. 2007, *ApJ*, 656, 1075
- Moore, C. E. 1945, *Contributions from the Princeton University Observatory*, 20, D23
- Nasseri, A., Chini, R., Harmanec, P., et al. 2014, *A&A*, 568, A94
- Olson, E. C., Henry, G. W., & Etzel, P. B. 2009, *AJ*, 138, 1435
- Oudmaijer, R. D., & Parr, A. M. 2010, *MNRAS*, 405, 2439
- Palacios, A., Gebran, M., Josselin, E., et al. 2010, *A&A*, 516, A13
- Parsons, S. B., & Bopp, B. W. 1993, in *American Astronomical Society Meeting Abstracts*, BAAS, 25, 1376
- Parsons, S. B., Dempsey, R. C., & Bopp, B. W. 1988, in *ESA SP*, 281, 225
- Paunzen, E., Duffee, B., Heiter, U., Kuschnig, R., & Weiss, W. W. 2001, *A&A*, 373, 625
- Perryman, M. A. C., & ESA 1997, *The HIPPARCOS and TYCHO catalogues, Astrometric and photometric star catalogues derived from the ESA Hipparcos Space Astrometry Mission (Noordwijk: ESA Publications Division) ESA SP Series 1200*
- Peters, G. J., Pewett, T. D., Gies, D. R., Touhami, Y. N., & Grundstrom, E. D. 2013, *ApJ*, 765, 2
- Pojmanski, G. 2002, *Acta Astron.*, 52, 397
- Popper, D. M. 1980, *ARA&A*, 18, 115
- Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1993, *Numerical Recipes in FORTRAN; The Art of Scientific Computing*, 2nd edn. (New York: Cambridge University Press)
- Prša, A., & Zwitter, T. 2005, *ApJ*, 628, 426
- Prša, A., & Zwitter, T. 2006, *Ap&SS*, 36
- Raskin, G., Burki, G., Burnet, M., et al. 2004, in *Ground-based Instrumentation for Astronomy*, eds. A. F. M. Moorwood, & M. Iye, *SPIE Conf. Ser.*, 5492, 830
- Raskin, G., van Winckel, H., Hensberge, H., et al. 2011, *A&A*, 526, A69
- Renson, P., & Manfroid, J. 2009, *A&A*, 498, 961
- Richards, M. T., Koubský, P., Šimon, V., et al. 2000, *ApJ*, 531, 1003
- Royer, F., Briot, D., North, P., Burki, G., & Carrier, F. 2007, in *IAU Symp.* 240, eds. W. I. Hartkopf, E. F. Guinan, & P. Harmanec, 211
- Ruždjak, D., Božić, H., Harmanec, P., et al. 2009, *A&A*, 506, 1319
- Siess, L., Izzard, R. G., Davis, P. J., & Deschamps, R. 2013, *A&A*, 550, A100
- Škoda, P. 1996, in *Astronomical Data Analysis Software and Systems V*, *ASP Conf. Ser.*, 101, 187
- Štefl, S., Harmanec, P., Horn, J., et al. 1990, *BAICz*, 41, 29
- Sterken, C., Vogt, N., & Mennickent, R. 1994, *A&A*, 291, 473
- Sterne, T. E. 1941, *PNAS*, 27, 168
- Stetson, P. B. 1991, *AJ*, 102, 589
- Sudar, D., Harmanec, P., Lehmann, H., et al. 2011, *A&A*, 528, A146
- Szabados, L. 1990, *A&A*, 232, 381
- Tarasov, A. E., Berdyugina, S. V., & Berdyugin, A. V. 1998, *Astron. Lett.*, 24, 316
- van Leeuwen, F. 2007a, in *Astrophys. Space Sci. Lib.* 350 (Berlin: Springer)
- van Leeuwen, F. 2007b, *A&A*, 474, 653
- Zucker, S., & Mazeh, T. 1994, *ApJ*, 420, 806

Appendix A: Details of the spectral data reduction and measurements

The initial reduction of all Ondřejov and DAO spectra (bias subtraction, flat-fielding, creation of 1-D spectra, and wavelength calibration) was carried out in IRAF. For Elodie and Hermes spectra, dedicated reduction pipelines were used, combined with some IDL routines in the case of Elodie. See [Baranne et al. \(1996\)](#) and [Raskin et al. \(2011\)](#) for detailed descriptions of the Elodie and Hermes spectrographs. Rectification, removal of residual cosmics and flaws and RV measurements of all spectra were carried out with the program SPEFO ([Horn et al. 1996](#); [Škoda 1996](#)), namely the latest version 2.63 developed by Mr. J. Krpata. SPEFO displays direct and flipped traces of the line profiles superimposed on the computer screen that the user can slide to achieve a precise overlapping of the parts of the profile of whose RV one wants to measure. Using a selection of stronger unblended lines of the cool component 2 (see Table A.1) covering the red spectral region (available for all spectra), we measured RVs of all of them to obtain a mean RV for all spectra. We also measured a selection of good telluric lines and used them for an additional fine correction of the RV zero point of

each spectrogram ([Horn et al. 1996](#)). Moreover, we measured the RVs of the steep wings of the H α emission line and of the two absorption cores of H α . We point out that although some broad and shallow lines of component 1 are seen in the spectra, their direct RV measurement is impossible because of numerous blends with the lines of component 2.

Table A.1. Spectral lines of component 2 and their air wavelengths used for the RV measurements in SPEFO.

Wavelength (Å)	Element	Wavelength (Å)	Element
6322.694	Fe I 207	6439.083	Ca I 18
6327.604	Ni I 49	6643.638	Ni I 43
6355.035	Fe I 342	6677.997	Fe I 268
6358.687	Fe I 13	6705.105	Fe I 1197
6393.612	Fe I 168	6717.687	Ca I 32
6411.658	Fe I 816	6726.673	Fe I 1197
6430.856	Fe I 62		

Notes. The numbering of the multiplets of individual ions corresponds to the one introduced by [Moore \(1945\)](#).

Table A.2. Individual SPEFO RVs of component 2.

HJD –2 400 000	RV (km s ^{–1})	Spg.	HJD –2 400 000	RV (km s ^{–1})	Spg.	HJD –2 400 000	RV (km s ^{–1})	Spg.
50 071.5415	17.71	E	54 115.5309	2.80	O	55 592.4540	–98.74	O
50 072.5331	–27.10	E	54 116.4556	–38.40	O	55 593.3881	–82.17	O
50 527.3026	–101.63	E	54 172.3849	–78.18	O	55 601.5399	–10.33	O
50 528.2947	–98.11	E	54 173.4495	–38.80	O	55 602.5009	–52.10	O
50 529.2966	–76.42	E	54 174.4208	2.48	O	55 613.5249	29.96	O
50 530.3328	–37.71	E	54 176.4755	67.45	O	55 614.4452	–7.48	O
50 842.5007	46.40	E	54 185.3680	–74.68	O	55 621.4578	6.53	O
50 843.6757	72.95	E	54 185.3914	–74.08	O	55 623.4517	67.26	O
51 565.4951	30.44	E	54 185.4381	–74.44	O	55 628.4816	–59.02	O
51 567.4662	76.03	E	54 186.3577	–39.80	O	55 644.4341	–96.59	O
52 215.6544	34.01	E	54 193.4186	–13.47	O	55 645.4161	–70.53	O
52 216.6342	–5.82	E	54 197.3561	–98.74	O	55 649.4090	70.69	O
52 217.6902	–51.60	E	54 205.3780	25.44	O	54 733.0084	74.78	D
52 220.6997	–97.73	E	54 206.4006	–15.76	O	54 939.6777	74.31	D
53 007.5331	–100.19	E	54 211.3746	–69.48	O	54 939.7269	74.40	D
53 008.5693	–101.34	E	54 222.3531	–104.84	O	54 942.6759	–11.64	D
53 009.5262	–82.21	E	54 384.5600	71.98	O	55 469.0305	74.34	D
53 010.5413	–47.46	E	54 388.6316	–71.52	O	55 471.0483	41.72	D
53 011.6043	–3.39	E	54 508.4493	–74.42	O	55 570.0131	15.43	D
53 014.4313	73.96	E	54 535.4177	–30.08	O	55 501.0092	–101.26	D
53 413.5151	50.38	E	54 569.3620	–67.56	O	55 601.9629	–29.49	D
53 414.4822	71.49	E	54 840.5091	–61.06	O	55 602.9492	–68.74	D
53 416.3923	57.77	E	54 932.3291	–98.41	O	55 858.0824	58.42	D
53 418.4050	–19.47	E	54 934.3986	–83.54	O	55 953.9157	–101.92	D
53 419.4041	–61.42	E	54 937.3221	27.71	O	55 993.7744	–84.07	D
53 420.3829	–90.60	E	55 274.4052	64.25	O	55 994.7681	–50.46	D
53 421.3983	–102.84	E	55 278.2936	0.91	O	56 031.7031	–99.73	D
53 422.4619	–93.35	E	55 280.3356	–81.24	O	56 296.0462	74.91	D
53 424.4110	–28.41	E	55 281.4343	–102.20	O	56 381.7600	–71.06	D
53 425.4095	13.94	E	55 293.3180	–82.46	O	56 382.7638	–32.61	D
53 426.4032	50.64	E	55 294.3667	–100.89	O	56 383.7508	9.30	D
53 428.4087	72.95	E	55 295.3084	–101.04	O	55 589.5585	–51.62	H
53 429.3832	55.55	E	55 296.3068	–79.51	O	55 592.5374	–98.92	H
53 430.3826	21.99	E	55 315.3200	61.49	O	55 595.4975	0.26	H
54 000.6311	–56.47	O	55 480.6300	54.66	O	55 904.7369	–34.63	H
54 017.6633	–68.43	O	55 491.5525	–24.09	O	55 906.6854	43.68	H
54 018.6197	–31.83	O	55 578.4610	–100.52	O	55 908.6513	74.17	H
54 019.5490	7.60	O	55 579.5032	–100.38	O	55 910.6683	28.73	H
54 025.5356	–17.63	O	55 590.4031	–81.03	O	55 912.7053	–58.62	H

Notes. Letters E, O, D, and H in column “Spg.” denote the Elodie, Ondřejov, DAO, and Hermes spectrographs.

Table A.3. Individual asTODCOR RVs of both components.

HJD –2 400 000	RV ₁ (km s ^{–1})	RV ₂ (km s ^{–1})	weight	HJD –2 400 000	RV ₁ (km s ^{–1})	RV ₂ (km s ^{–1})	Weight
50 071.5415	–1.160	31.356	0.538	53 416.3923	–4.494	71.609	0.424
50 072.5331	1.731	–12.346	0.842	53 418.4050	0.610	–4.722	0.968
50 527.3026	4.675	–87.466	0.840	53 419.4041	3.331	–46.735	0.765
50 528.2947	5.177	–83.880	0.655	53 420.3829	4.181	–76.069	0.988
50 529.2966	4.325	–60.928	0.706	53 421.3983	4.300	–88.491	0.915
50 530.3328	1.951	–22.894	1.333	53 422.4619	4.515	–78.451	0.426
50 842.5007	–3.226	60.359	1.302	53 424.4110	0.773	–13.666	0.688
51 565.4951	–2.191	43.976	0.503	53 425.4095	–2.012	28.347	0.680
51 567.4662	–4.117	88.335	0.440	53 426.4032	–2.985	63.936	0.511
52 215.6544	–3.967	48.493	0.858	53 428.4087	–5.194	86.918	0.872
52 216.6342	–1.243	8.344	1.335	53 429.3832	–4.271	69.230	0.318
52 217.6902	1.581	–37.213	0.781	53 430.3826	–2.161	36.197	0.850
52 220.6997	5.196	–83.691	0.497	55 589.5585	3.450	–37.172	1.578
53 007.5331	4.374	–85.632	1.310	55 592.5374	6.050	–84.350	0.840
53 008.5693	4.292	–86.321	0.761	55 595.4975	–0.645	14.860	1.345
53 009.5262	4.938	–67.760	1.824	55 904.7369	1.693	–19.898	1.590
53 010.5413	2.655	–32.753	1.185	55 906.6854	–3.181	57.918	1.406
53 011.6043	–1.166	11.645	1.440	55 908.6513	–4.222	88.134	1.124
53 014.4313	–5.432	88.287	1.501	55 910.6683	–3.695	42.479	1.566
53 413.5151	–3.674	65.533	0.359	55 912.7053	4.324	–43.761	1.270
53 414.4822	–5.642	84.895	2.866				

Notes. The weights are proportional to the square of the S/N of individual spectra.

Appendix B: Details on the photometric data reductions

Since we used photometry from various sources and photometric systems, both all-sky and differential, relative to several different comparison stars, we attempted to arrive at some homogenisation and standardisation. Special effort was made to derive improved all-sky values for the comparison stars used, employing carefully standardised *UBV* observations secured at Hvar over several decades of systematic observations. The adopted values are collected in Table B.1, together with the number of all-sky observations and the rms errors of one observation. They were added to the respective magnitude differences to obtain directly comparable standard *UBV* magnitudes for all stations. To illustrate the accuracy, with which various data sets were transformed to the standard system, we give (in Table B.2) mean differential *UBV* values for the check stars used. They were derived relatively to the Hvar values for the comparison stars HD 58187 and HD 61341.

Below, we provide some details of the individual data sets and their reductions.

- *Station 01 – Hvar*: these differential observations have been secured by HB and PZ relative to HD 58187 (the check star HD 59059 being observed as frequently as the variable) and carefully transformed to the standard *UBV* system via non-linear transformation formulae using the HEC22 reduction program – see Harmanec et al. (1994) and Harmanec & Horn (1998) for the observational strategy and

data reduction³. All observations were reduced with the latest HEC22 rel. 17 program, which allows the time variation of linear extinction coefficients to be modelled in the course of observing nights.

- *Station 11 – South African Astronomical Observatory (SAAO)*: these differential *UBV* observations were obtained by PZ with the 0.50 m reflector relative to HD 61341 (SAO 115750 being used as the check star) and also transformed to the standard Johnson system with the help of HEC22.
- *Station 37 – La Palma*: these all-sky seven-colour (7-C) observations were secured in the Geneva photometric system using the two-channel aperture photometer P7-2000 (Raskin et al. 2004) mounted on the 1.20 m Belgian *Mercator* reflector at the Observatorio de los Muchachos at La Palma.
- *Station 61 – HIPPARCOS*: these all-sky observations were reduced to the standard *V* magnitude via the transformation formulae derived by Harmanec (1998) to verify that no secular light changes in the system were observed. However, for the light-curve solution in PHOEBE, we consider the HIPPARCOS transmission curve for the H_p magnitude.
- *Station 93 – ASAS3 *V* photometry*: we extracted these all-sky observations from the ASAS3 public archive (Pojmanski 2002), using the data for diaphragm 1, having on average the lowest rms errors. We omitted all observations of grade D and observations having rms errors larger than 0^m.04. We also omitted a strongly deviating observation at HJD 2 452 662.6863.

³ The whole program suite with a detailed manual, examples of data, auxiliary data files, and results is available at <http://astro.troja.mff.cuni.cz/ftp/hect/PHOT>

Table B.1. Accurate Hvar and SAAO all-sky mean *UBV* values for all comparison stars used.

Station	Star	HD	No. of obs.	<i>V</i> (mag.)	<i>B</i> (mag.)	<i>U</i> (mag.)	(<i>B</i> − <i>V</i>) (mag.)	(<i>U</i> − <i>B</i>) (mag.)
01	1 CMi	58187	466	5.393 ± 0.010	5.493 ± 0.011	5.622 ± 0.012	0.100	0.129
01	HR 2858	59059	364	6.254 ± 0.010	6.206 ± 0.011	6.103 ± 0.013	−0.048	−0.103
01	SAO 115753	61341	39	7.991 ± 0.010	8.182 ± 0.009	8.281 ± 0.024	0.191	0.099
11	SAO 115753	61341	3	7.986 ± 0.010	8.178 ± 0.013	8.288 ± 0.015	0.192	0.110
11	SAO 115750	–	24	9.743 ± 0.011	9.883 ± 0.013	10.012 ± 0.018	0.139	0.129

Notes. These were added to the magnitude differences var.–comp. and check–comp. for data from all stations.

Table B.2. Mean *UBV* values for the check stars used at individual observing stations derived differentially relative to their respective comparison stars.

Station	Star	HD	No. of obs.	<i>V</i> (mag.)	<i>B</i> (mag.)	<i>U</i> (mag.)	(<i>B</i> − <i>V</i>) (mag.)	(<i>U</i> − <i>B</i>) (mag.)
01	HR 2858	59059	542	6.254 ± 0.010	6.206 ± 0.009	6.102 ± 0.013	−0.048	−0.104
01	SAO 115753	61341	53	7.987 ± 0.013	8.182 ± 0.011	8.278 ± 0.023	0.195	0.096
11	SAO 115750	–	28	9.747 ± 0.009	9.886 ± 0.011	10.004 ± 0.013	0.140	0.118

Notes. They illustrate how closely the data could be transformed to a comparable standard system.

Table B.3. Individual Geneva 7-C observations.

HJD −2 400 000	<i>U</i> (mag)	<i>B</i> (mag)	<i>V</i> (mag)	<i>B1</i> (mag)	<i>B2</i> (mag)	<i>V1</i> (mag)	<i>G</i> (mag)
52 307.44605	7.881	6.495	7.173	7.417	7.940	7.894	8.275
52 307.55703	7.876	6.486	7.159	7.409	7.931	7.876	8.262
52 308.45517	7.900	6.497	7.161	7.426	7.938	7.876	8.265
52 308.55777	7.881	6.472	7.130	7.404	7.904	7.846	8.233
52 309.43489	7.892	6.480	7.126	7.414	7.915	7.847	8.218
52 309.56210	7.886	6.474	7.112	7.403	7.905	7.832	8.210
52 312.45134	7.894	6.492	7.154	7.418	7.935	7.878	8.261
52 313.53300	7.907	6.503	7.171	7.426	7.945	7.890	8.275
52 317.53358	7.867	6.455	7.092	7.387	7.886	7.811	8.185
52 318.52657	7.887	6.484	7.135	7.412	7.918	7.859	8.236
52 339.42680	7.900	6.502	7.177	7.426	7.939	7.893	8.275
52 350.43584	7.881	6.475	7.130	7.400	7.913	7.851	8.221
52 351.42891	7.901	6.500	7.163	7.425	7.934	7.888	8.266
52 352.42504	7.899	6.503	7.178	7.431	7.947	7.898	8.289
52 353.41762	7.893	6.497	7.164	7.423	7.938	7.885	8.268
52 354.41404	7.888	6.481	7.133	7.418	7.918	7.856	8.235
52 355.41486	7.885	6.474	7.108	7.409	7.905	7.832	8.207
52 362.37901	7.881	6.470	7.107	7.400	7.905	7.828	8.201
52 367.39349	7.861	6.458	7.119	7.386	7.901	7.841	8.219
52 368.39548	7.880	6.461	7.095	7.396	7.895	7.818	8.191
52 369.38697	7.873	6.461	7.095	7.392	7.891	7.817	8.193
52 370.38003	7.877	6.474	7.127	7.399	7.908	7.848	8.225
52 371.39401	7.897	6.500	7.165	7.421	7.939	7.885	8.269
52 384.38727	7.890	6.486	7.152	7.411	7.925	7.869	8.264

Table B.4. Original HIPPARCOS H_p observations and their conversion to V band observations.

HJD −2 400 000	H_p (mag)	rms (mag)	V (mag)	HJD	H_p (mag)	rms (mag)	V (mag)
47 966.1374	7.2184	0.007	7.157	48 393.5983	7.2257	0.008	7.164
47 966.1517	7.2195	0.007	7.158	48 404.6932	7.1996	0.012	7.138
47 987.3742	7.1939	0.009	7.133	48 404.7075	7.2290	0.008	7.168
47 987.3885	7.2029	0.010	7.142	48 404.9599	7.2330	0.014	7.172
47 987.4630	7.1936	0.007	7.132	48 404.9742	7.2168	0.008	7.156
47 987.4774	7.2184	0.008	7.157	48 405.0487	7.2312	0.014	7.170
48 013.4952	7.1901	0.007	7.129	48 569.9541	7.1610	0.006	7.100
48 013.5095	7.1978	0.007	7.137	48 569.9684	7.1657	0.013	7.104
48 013.5840	7.2009	0.009	7.140	48 570.0573	7.1574	0.011	7.096
48 013.5984	7.1826	0.009	7.121	48 586.1305	7.2339	0.010	7.173
48 147.8756	7.2272	0.008	7.166	48 586.1449	7.2120	0.008	7.151
48 147.8900	7.2135	0.006	7.152	48 586.2194	7.2232	0.009	7.162
48 147.9646	7.2304	0.008	7.169	48 586.4115	7.2242	0.007	7.163
48 147.9789	7.2006	0.007	7.139	48 705.7530	7.1657	0.008	7.104
48 148.0534	7.2249	0.008	7.164	48 705.7673	7.1590	0.008	7.098
48 164.7628	7.2211	0.009	7.160	48 705.8418	7.1182	0.013	7.057
48 164.7771	7.1966	0.007	7.135	48 731.2523	7.1546	0.006	7.093
48 164.8517	7.1594	0.016	7.098	48 731.2666	7.1673	0.006	7.106
48 164.8660	7.2027	0.010	7.141	48 753.2881	7.2043	0.007	7.143
48 194.3522	7.1997	0.007	7.138	48 753.3025	7.1939	0.006	7.133
48 194.3665	7.1866	0.007	7.125	48 753.3770	7.2045	0.009	7.143
48 316.8239	7.2018	0.013	7.141	48 753.3913	7.1985	0.008	7.137
48 316.8382	7.1959	0.010	7.135	48 935.2322	7.2130	0.008	7.152
48 317.1794	7.1975	0.010	7.136	48 935.2465	7.2100	0.008	7.149
48 317.1937	7.1878	0.011	7.127	49 047.3806	7.1871	0.012	7.126
48 317.2683	7.1867	0.012	7.125	49 047.3949	7.1602	0.009	7.099
48 317.2826	7.1824	0.013	7.121	49 047.6431	7.1776	0.010	7.116
48 322.9710	7.2103	0.007	7.149	49 047.6575	7.1718	0.009	7.111
48 323.0455	7.1897	0.009	7.128	49 047.7320	7.1710	0.009	7.110
48 323.0598	7.2171	0.008	7.156	49 047.7463	7.1712	0.010	7.110
48 323.3122	7.2063	0.008	7.145	49 047.8209	7.1732	0.009	7.112
48 323.3265	7.2085	0.010	7.147	49 047.8352	7.1607	0.008	7.099
48 323.4011	7.1930	0.007	7.132	49 053.4135	7.1785	0.008	7.117
48 323.4154	7.1903	0.006	7.129	49 053.4279	7.2007	0.007	7.139
48 323.4900	7.2006	0.007	7.139	49 053.5024	7.1748	0.009	7.114
48 323.5043	7.2062	0.009	7.145	49 053.5167	7.1760	0.011	7.115
48 359.4706	7.2092	0.009	7.148	49 053.5913	7.1690	0.008	7.108
48 393.3316	7.2130	0.010	7.152	49 053.6056	7.1613	0.010	7.100
48 393.4062	7.2248	0.007	7.164	49 053.8561	7.1615	0.007	7.100
48 393.4205	7.2077	0.012	7.146	49 053.8704	7.1701	0.007	7.109
48 393.4951	7.2170	0.008	7.156	49 053.9450	7.1604	0.011	7.099
48 393.5094	7.2208	0.009	7.160	49 054.0339	7.1688	0.009	7.108
48 393.5840	7.2114	0.006	7.150				

Table B.5. Individual ASAS-3 V band observations from diaphragm 1 without large errors.

HJD −2 400 000	V (mag)	rms (mag)	HJD −2 400 000	V (mag)	rms (mag)	HJD −2 400 000	V (mag)	rms (mag)
52 552.8776	7.156	0.034	52 970.7859	7.118	0.037	54 107.7196	7.126	0.037
52 557.8567	7.145	0.036	52 973.8098	7.129	0.032	54 127.7145	7.114	0.037
52 559.8729	7.148	0.035	52 975.7732	7.089	0.038	54 141.7008	7.144	0.038
52 577.8040	7.143	0.036	52 979.7768	7.147	0.033	54 146.6021	7.119	0.038
52 623.7460	7.175	0.038	52 986.7882	7.143	0.039	54 152.5591	7.095	0.037
52 625.7454	7.124	0.036	52 989.7358	7.101	0.037	54 154.5939	7.160	0.037
52 637.7183	7.145	0.036	52 991.7752	7.155	0.038	54 174.6296	7.149	0.040
52 641.7108	7.132	0.036	52 996.7692	7.128	0.036	54 188.6063	7.138	0.039
52 645.7047	7.106	0.038	53 001.7538	7.084	0.031	54 201.5468	7.113	0.038
52 650.6776	7.156	0.036	53 006.6958	7.099	0.034	54 204.5454	7.101	0.039
52 652.6885	7.104	0.036	53 008.7208	7.097	0.039	54 216.5315	7.094	0.039
52 660.6893	7.120	0.035	53 016.7075	7.141	0.039	54 233.4825	7.115	0.037
52 664.6776	7.115	0.037	53 018.7030	7.140	0.040	54 235.4863	7.100	0.039
52 666.6750	7.114	0.040	53 028.7644	7.105	0.040	54 247.4538	7.102	0.039
52 670.6739	7.121	0.038	53 031.6263	7.132	0.034	54 365.8936	7.105	0.036
52 674.6623	7.153	0.036	53 035.6532	7.137	0.040	54 383.8650	7.068	0.038
52 676.6485	7.148	0.037	53 046.6032	7.082	0.036	54 412.8547	7.141	0.038
52 678.6339	7.089	0.039	53 049.6167	7.150	0.038	54 436.7788	7.100	0.039
52 681.6881	7.163	0.040	53 054.5926	7.099	0.035	54 455.7297	7.104	0.039
52 691.6242	7.104	0.039	53 058.6732	7.094	0.038	54 470.6969	7.145	0.039
52 693.6365	7.140	0.038	53 060.6989	7.103	0.039	54 479.6571	7.085	0.040
52 697.6305	7.101	0.036	53 068.5635	7.144	0.040	54 492.7149	7.086	0.039
52 699.6208	7.132	0.039	53 077.5445	7.122	0.034	54 494.7342	7.095	0.040
52 701.6187	7.164	0.036	53 102.5989	7.143	0.040	54 537.5394	7.123	0.040
52 703.6144	7.108	0.038	53 107.5350	7.144	0.040	54 558.6078	7.088	0.039
52 707.6045	7.169	0.037	53 109.5477	7.132	0.039	54 570.4912	7.088	0.040
52 718.5269	7.109	0.039	53 111.5476	7.090	0.040	54 601.4685	7.134	0.039
52 734.5519	7.138	0.039	53 113.5671	7.140	0.040	54 762.8482	7.127	0.037
52 740.5074	7.158	0.039	53 115.5672	7.140	0.035	54 774.8284	7.138	0.038
52 751.5004	7.143	0.040	53 123.4834	7.093	0.040	54 778.8182	7.075	0.038
52 760.5200	7.134	0.037	53 125.5273	7.120	0.038	54 801.7777	7.130	0.037
52 786.4622	7.134	0.038	53 133.5104	7.144	0.038	54 804.7718	7.108	0.037
52 911.8901	7.093	0.037	53 144.4748	7.096	0.034	54 807.7563	7.145	0.036
52 916.8806	7.097	0.037	53 291.8729	7.082	0.040	54 816.7776	7.087	0.040
52 926.8593	7.153	0.037	53 298.8666	7.085	0.039	54 819.7738	7.145	0.039
52 932.8498	7.150	0.034	53 333.8126	7.149	0.040	54 822.7171	7.091	0.039
52 940.8298	7.147	0.037	53 357.7288	7.114	0.038	54 825.7243	7.129	0.040
52 943.8327	7.099	0.039	53 459.5662	7.079	0.038	54 831.7039	7.138	0.037
52 949.8286	7.095	0.038	53 466.5452	7.079	0.039	54 834.6914	7.111	0.036
52 952.8292	7.148	0.040	53 469.5526	7.129	0.038	54 836.7857	7.091	0.038
52 955.8312	7.084	0.036	53 650.8382	7.162	0.040			
52 963.8062	7.104	0.037	54 091.7187	7.096	0.040			

Table B.6. Individual *UBV* band observations.

HJD –2 400 000	Weight	<i>V</i> (mag)	<i>B</i> (mag)	<i>U</i> (mag)	<i>B</i> – <i>V</i> (mag)	<i>U</i> – <i>B</i> (mag))	<i>X</i>	ΔX
Hvar								
55 574.4833	1.00	7.158	7.408	7.424	0.250	0.016	1.229	0.044
55 574.4901	1.00	7.168	7.415	7.458	0.247	0.043	1.235	0.042
55 574.4990	1.00	7.160	7.410	7.432	0.250	0.022	1.246	0.039
55 578.4494	1.00	7.121	7.399	7.447	0.278	0.048	1.225	0.052
55 578.4566	1.00	7.125	7.405	7.434	0.280	0.029	1.224	0.049
55 578.4621	1.00	7.124	7.397	7.436	0.273	0.039	1.225	0.047
55 585.4986	1.00	7.098	7.391	7.432	0.293	0.041	1.308	0.031
55 585.5069	1.00	7.101	7.371	7.403	0.270	0.032	1.335	0.029
55 585.5152	1.00	7.106	7.390	7.435	0.284	0.045	1.366	0.027
55 585.5165	1.00	7.111	7.393	7.440	0.282	0.047	1.371	0.027
55 586.4851	1.00	7.124	7.398	7.424	0.274	0.026	1.280	0.034
55 586.4948	1.00	7.131	7.399	7.433	0.268	0.034	1.306	0.032
55 586.5039	1.00	7.130	7.409	7.432	0.279	0.023	1.334	0.029
55 594.4271	1.50	7.175	7.417	7.433	0.242	0.016	1.229	0.044
55 594.4356	1.50	7.182	7.417	7.430	0.235	0.013	1.235	0.041
55 594.4444	1.50	7.184	7.426	7.435	0.242	0.009	1.246	0.039
55 596.4157	1.00	7.160	7.424	7.441	0.264	0.017	1.226	0.046
55 596.4243	1.00	7.161	7.426	7.437	0.265	0.011	1.230	0.043
55 596.4325	1.00	7.154	7.434	7.433	0.280	–0.001	1.238	0.041
55 597.3054	1.50	7.136	7.399	7.421	0.263	0.022	1.468	0.121
55 597.3134	1.50	7.133	7.397	7.440	0.264	0.043	1.425	0.111
55 597.3212	1.50	7.147	7.401	7.434	0.254	0.033	1.389	0.102
55 599.3682	0.50	7.121	7.391	7.425	0.270	0.034	1.245	0.063
55 599.3724	0.50	7.129	7.400	7.444	0.271	0.044	1.239	0.061
55 599.3754	0.50	7.125	7.395	7.431	0.270	0.036	1.236	0.059
55 645.3479	0.50	7.152	7.406	7.437	0.254	0.031	1.365	0.028
55 645.3561	0.50	7.156	7.412	7.436	0.256	0.024	1.400	0.026
55 645.3604	0.50	7.167	7.418	7.452	0.251	0.034	1.421	0.025
55 652.3121	0.50	7.147	7.392	7.409	0.245	0.017	1.310	0.031
55 652.3220	0.50	7.167	7.428	7.454	0.261	0.026	1.342	0.029
55 652.3250	0.50	7.174	7.419	7.449	0.245	0.030	1.353	0.028
55 654.3169	1.00	7.160	7.409	7.451	0.249	0.042	1.344	0.029
55 654.3253	1.00	7.163	7.410	7.434	0.247	0.024	1.377	0.027
55 654.3333	1.00	7.161	7.411	7.428	0.250	0.017	1.413	0.025
55 655.3064	1.00	7.136	7.405	7.440	0.269	0.035	1.319	0.031
55 655.3149	1.00	7.131	7.404	7.443	0.273	0.039	1.347	0.029
55 655.3230	1.00	7.123	7.396	7.430	0.273	0.034	1.379	0.027
55 657.3373	1.00	7.124	7.401	7.434	0.277	0.033	1.479	0.023
55 657.3423	1.00	7.128	7.418	7.480	0.290	0.062	1.510	0.021
55 657.3452	1.00	7.116	7.415	7.486	0.299	0.071	1.529	0.021
55 658.3436	0.50	7.173	7.424	7.458	0.251	0.034	1.537	0.021
55 658.3477	0.50	7.165	7.419	7.454	0.254	0.035	1.566	0.020
55 658.3530	0.50	7.167	7.412	7.433	0.245	0.021	1.607	0.019
55 660.3295	1.00	7.179	7.420	7.436	0.241	0.016	1.483	0.022
55 660.3307	1.00	7.185	7.421	7.437	0.236	0.016	1.490	0.022
55 660.3349	1.00	7.190	7.421	7.446	0.231	0.025	1.517	0.021
55 661.3187	1.00	7.165	7.410	7.439	0.245	0.029	1.439	0.024
55 661.3273	1.00	7.160	7.410	7.455	0.250	0.045	1.487	0.022
55 661.3359	1.00	7.154	7.409	7.454	0.255	0.045	1.543	0.020
55 662.3278	0.50	7.123	7.378	7.408	0.255	0.030	1.507	0.022
55 662.3407	0.50	7.108	7.363	7.395	0.255	0.032	1.599	0.019
55 662.3420	0.50	7.116	7.371	7.420	0.255	0.049	1.609	0.019
55 848.5816	1.00	7.145	7.415	7.480	0.270	0.065	1.690	0.175
55 848.5922	1.00	7.145	7.422	7.455	0.277	0.033	1.599	0.152
55 848.5979	1.00	7.118	7.384	7.394	0.266	0.010	1.556	0.142
55 848.6654	1.00	7.143	7.416	7.458	0.273	0.042	1.269	0.071
55 850.5676	0.50	7.097	7.369	7.406	0.272	0.037	1.779	0.198
55 850.5774	0.50	7.113	7.385	7.413	0.272	0.028	1.680	0.172
55 850.5863	0.50	7.119	7.390	7.440	0.271	0.050	1.604	0.154
55 851.5815	1.00	7.145	7.408	7.428	0.263	0.020	1.622	0.158
55 851.5899	1.00	7.149	7.413	7.442	0.264	0.029	1.557	0.142
55 851.5980	1.00	7.156	7.413	7.444	0.257	0.031	1.502	0.129

Table B.6. continued.

HJD −2 400 000	Weight	<i>V</i> (mag)	<i>B</i> (mag)	<i>U</i> (mag)	<i>B</i> − <i>V</i> (mag)	<i>U</i> − <i>B</i> (mag))	<i>X</i>	Δ <i>X</i>
55 852.6273	1.50	7.179	7.429	7.444	0.250	0.015	1.347	0.092
55 852.6355	1.50	7.175	7.423	7.443	0.248	0.020	1.319	0.085
55 852.6445	1.50	7.178	7.423	7.441	0.245	0.018	1.294	0.078
55 853.6267	1.00	7.184	7.422	7.426	0.238	0.004	1.340	0.090
55 853.6346	1.00	7.177	7.422	7.438	0.245	0.016	1.314	0.083
55 853.6426	1.00	7.185	7.431	7.442	0.246	0.011	1.292	0.077
55 858.6678	1.50	7.161	7.415	7.440	0.254	0.025	1.230	0.056
55 858.6757	1.50	7.155	7.413	7.437	0.258	0.024	1.226	0.053
55 879.5943	1.50	7.182	7.424	7.435	0.242	0.011	1.250	0.065
55 879.6022	1.50	7.183	7.436	7.444	0.253	0.008	1.240	0.061
55 879.6098	1.50	7.190	7.423	7.434	0.233	0.011	1.232	0.057
55 881.6494	1.50	7.121	7.393	7.423	0.272	0.030	1.238	0.041
55 881.6545	1.50	7.115	7.394	7.426	0.279	0.032	1.245	0.039
55 881.6579	1.50	7.118	7.401	7.432	0.283	0.031	1.250	0.038
55 938.4426	1.50	7.171	7.420	7.437	0.249	0.017	1.242	0.062
55 938.4505	1.50	7.175	7.418	7.430	0.243	0.012	1.233	0.058
55 938.4552	1.50	7.176	7.420	7.436	0.244	0.016	1.229	0.056
55 939.3829	1.50	7.133	7.402	7.430	0.269	0.028	1.398	0.104
55 939.3882	1.50	7.134	7.408	7.433	0.274	0.025	1.375	0.099
55 939.3916	1.50	7.136	7.403	7.430	0.267	0.027	1.361	0.095
55 942.4525	1.50	7.153	7.409	7.430	0.256	0.021	1.225	0.052
55 942.4592	1.50	7.160	7.413	7.436	0.253	0.023	1.224	0.050
55 942.4674	1.50	7.161	7.411	7.434	0.250	0.023	1.225	0.047
55 943.4365	1.50	7.177	7.413	7.427	0.236	0.014	1.234	0.058
55 943.4449	1.50	7.179	7.420	7.436	0.241	0.016	1.227	0.054
55 943.4499	1.50	7.178	7.418	7.431	0.240	0.013	1.225	0.052
55 945.3602	1.50	7.157	7.409	7.439	0.252	0.030	1.429	0.111
55 945.3665	1.50	7.164	7.413	7.437	0.249	0.024	1.398	0.104
55 945.3698	1.50	7.168	7.415	7.431	0.247	0.016	1.384	0.101
56 001.3240	1.50	7.177	7.421	7.430	0.244	0.009	1.241	0.040
56 001.3316	1.50	7.173	7.415	7.426	0.242	0.011	1.251	0.038
56 001.3366	1.50	7.175	7.419	7.430	0.244	0.011	1.260	0.037
56 002.3518	1.50	7.184	7.418	7.435	0.234	0.017	1.301	0.032
56 002.3596	1.50	7.176	7.415	7.434	0.239	0.019	1.324	0.030
56 002.3643	1.50	7.186	7.435	7.452	0.249	0.017	1.340	0.029
56 013.3093	0.50	7.142	7.408	7.436	0.266	0.028	1.273	0.035
56 013.3142	0.50	7.148	7.409	7.431	0.261	0.022	1.284	0.034
56 013.3203	0.50	7.146	7.396	7.424	0.250	0.028	1.299	0.032
56 015.3123	0.50	7.181	7.432	7.443	0.251	0.011	1.293	0.033
56 015.3185	0.50	7.184	7.439	7.475	0.255	0.036	1.310	0.031
56 015.3245	0.50	7.192	7.435	7.446	0.243	0.011	1.329	0.030
SAAO								
55 567.4069	1.00	7.136	7.417	7.431	0.281	0.014	1.453	0.002
55 567.4146	1.00	7.139	7.425	7.429	0.286	0.004	1.420	0.002
55 567.4217	1.00	7.144	7.420	7.427	0.276	0.007	1.394	0.002
55 570.5248	0.50	7.175	7.434	7.425	0.259	−0.009	1.415	0.004
55 573.4850	1.00	7.144	7.409	7.415	0.265	0.006	1.331	0.003
55 573.4914	1.00	7.122	7.394	7.426	0.272	0.032	1.343	0.003
55 573.4981	1.00	7.119	7.400	7.415	0.281	0.015	1.357	0.003
55 574.5248	1.00	7.180	7.428	7.462	0.248	0.034	1.461	0.004
55 574.5308	1.00	7.154	7.409	7.426	0.255	0.017	1.491	0.004
55 574.5371	1.00	7.166	7.403	7.421	0.237	0.018	1.526	0.005
55 575.5287	1.00	7.180	7.421	7.433	0.241	0.012	1.494	0.005
55 575.5345	1.00	7.169	7.429	7.415	0.260	−0.014	1.528	0.005
55 575.5408	1.00	7.191	7.440	7.426	0.249	−0.014	1.568	0.005
55 577.5457	1.50	7.135	7.415	7.412	0.280	−0.003	1.646	0.006
55 578.5443	0.50	7.130	7.401	7.420	0.271	0.019	1.657	0.006
55 578.5505	0.50	7.133	7.420	7.436	0.287	0.016	1.712	0.006
55 579.5226	1.00	7.110	7.407	7.431	0.297	0.024	1.522	0.005
55 579.5288	1.00	7.125	7.401	7.418	0.276	0.017	1.560	0.005
55 579.5345	1.00	7.118	7.382	7.422	0.264	0.040	1.601	0.005