A&A 372, 588–593 (2001)
DOI: 10.1051/0004-6361:20010532

Astronomy & Astrophysics

uvby light curves of the eclipsing binary system V2154 Cyg⋆

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Received 29 September 2000 / Accepted 6 April 2001

Abstract. This paper presents complete *uvby* light curves for the recently discovered eclipsing binary system V2154 Cyg. Additional Crawford H_β data were also obtained. Three times of primary minima and two secondary minima are determined. An improved orbital period is found to be $2\overset{\mathrm{d}}{.}6306312$. A detailed photometric analysis is made using the EBOP code. This eclipsing binary is probably one of the components of a much wider double star, forming altogether a triple system. The results show that the eclipsing pair is a detached system with two late-type stars very different in size. Masses of about $M_1 = 1.4\ M_\odot$ and $M_2 = 0.8\ M_\odot$ are inferred for the components by using stellar evolution models. The total mass of the probable triple system is estimated to be of about 3.5 $M_\odot$, leading to a minimum orbital period of about 140 yr for the visual pair.

Key words. stars: binaries: eclipsing – stars: individual: V2154 Cyg – stars: fundamental parameters – techniques: photometric

1. Introduction

V2154 Cyg (HD 203839, Hip 105584) was discovered as an eclipsing binary system by the Hipparcos satellite (ESA, 1997) with a period of $P = 2\overset{\mathrm{d}}{.}63060$ and eclipses depths in the primary and secondary minima of about $\Delta V \sim 0\overset{\mathrm{m}}{.}3$ and $0\overset{\mathrm{m}}{.}05$, respectively. Although this remarkable primary depth and being moderate bright ($V = 7\overset{\mathrm{m}}{.}8$), it had never been reported as photometric variable. Hipparcos catalogue reports V2154 Cyg as also a double visual star (components A and B). Fabricius & Makarov (2000) give a separation of $0\overset{\prime\prime}{.}47$ between these two components and magnitude differences of $2\overset{\mathrm{m}}{.}18$ and $2\overset{\mathrm{m}}{.}15$ in the Tycho B_T and V_T passbands.

The eclipsing nature of V2154 Cyg was also discovered, in an independent way and using *uvby* photometry, in the year 1996 by Martín et al. (2001) during the course of a survey for γ Dor variables carried out on the open cluster M 39. V2154 Cyg is not a member of this cluster, but it was used as a check star during these observations. New observations were collected during 1998 in order to complete the light curves using Strömgren *uvby* photometry. Based on these new observations, together with the old ones obtained in 1996, a photometric study is presented in this paper using the EBOP code. Section 2 is dedicated to describe the observations itself while Sect. 3 is devoted to analyse the light curves. Some conclusions are summarised in Sect. 4.

2. Observations

The observations were carried out during 1998, July to November, using the 90 cm telescope at the Sierra Nevada Observatory, Spain. The photometer attached to this telescope is a six-channel *uvbyβ* spectrograph photometer for simultaneous measurements in *uvby* or in the narrow and wide H_β channels, respectively, using uncooled EMI photomultipliers type 9789 QA (Nielsen 1983). Twenty-eight nights were devoted to measuring V2154 Cyg using the four *uvby* filters. In addition, a few measures were collected in H_β around the phase 0.25 of the orbital period.

For these observations, HD 204626 was used as the main comparison star with HD 204977 as check star. The sequence was, generally, C1, C2, Var, C1, C2, Var. Sky measurements were made every 2 or 3 cycles depending of the position of the Moon in the sky. 852 *uvby* measurements were collected for the variable, about 800 for C1 and 650 for C2. Each integration consisted of 35 s for the variable and C1 and 40 s for C2. This means, for any of the stars, an internal error in each observation better than $0\overset{\mathrm{m}}{.}003$ in the u filter for C2, namely the worst case. The extinction corrections were based on nightly coefficients determined from the main comparison star. Then, magnitude differences of each object relative to C1 were calculated by means of linear interpolation.

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⋆ Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/372/588

During the observations reported here, neither of the comparison stars showed any sign of variability. Each night, the standard deviations for C2–C1 differences were always better than $0\overset{m}{.}010$, $0\overset{m}{.}005$, $0\overset{m}{.}004$ and $0\overset{m}{.}006$ for u, v, b and y, respectively. In addition, the mean values obtained for the C2–C1 differences on each of the nights were always the same within $0\overset{m}{.}002$, as standard deviation, for any of the filters. Moreover, when we consider the full sample, the standard deviations of C2–C1 were found to be of $0\overset{m}{.}0085$, $0\overset{m}{.}0035$, $0\overset{m}{.}0032$ and $0\overset{m}{.}0043$ for u, v, b and y, respectively. Furthermore, a frequency analysis was performed to these data in order to investigate the existence of possible small variabilities in any of the comparison stars. When a Fourier analysis was applied (using the method described in Rodríguez et al. 1998) to the v filter, we obtain C2 and C1 not showing any sign of variability within about $0\overset{m}{.}001$, in the range from 0 to 30 cd^{-1}. Similar results were obtained for the other two b and y filters. Hence, C1 and C2 can be considered as constant stars.

To transform our data into the standard $uvby\beta$ system, we have used the same procedure described in Rodríguez et al. (1997). The data obtained, as magnitude differences variable minus C1 in the standard system versus Heliocentric Julian Day, are listed in Table 1. This table is available via *ftp* at the CDS and can also be requested from the authors. The data have also been deposited in the Commission 27 IAU Archives of Unpublished Observations, file 343E. These standard data, together with those obtained on 9 nights during 1996 (Martín et al. 2001), are used in the following section to analyse the light curves of V2154 Cyg. In total, 976 data in each of the four $uvby$ are used. Nearly all phases have been covered at least twice.

Derived standard $uvby\beta$ indices for V2154 Cyg and the two comparison stars are given in Table 2 together with relevant catalogue information on these stars. These derived Strömgren values are in very good agreement with those found in the bibliography (e.g. Hauck & Mermilliod 1998) and also with those published in Martín et al. (2001).

Table 2. Data for V2154 Cyg (photometry at phase 0.25) and the comparison stars.

	Variable	Comp. 1	Comp. 2
HD no.	203839	204626	204977
SAO no.	50783	50910	50959
α_{2000}	$21^h23^m8^s$	$21^h28^m24^s$	$21^h30^m46^s$
δ_{2000}	$48°\ 31'8''$	$48°26'4''$	$47°51'44''$
l	91°	92°	92°
b	−1°	−2°	−3°
Sp. type	F0	A0III	B9V
V	$7\overset{m}{.}773$	$7\overset{m}{.}568$	$8\overset{m}{.}510$
	±3	±4	±5
$b-y$	$0\overset{m}{.}274$	$0\overset{m}{.}035$	$0\overset{m}{.}010$
	±4	±4	±4
m_1	$0\overset{m}{.}143$	$0\overset{m}{.}128$	$0\overset{m}{.}136$
	±4	±4	±4
c_1	$0\overset{m}{.}488$	$1\overset{m}{.}113$	$0\overset{m}{.}991$
	±8	±10	±11
β	$2\overset{m}{.}660$	$2\overset{m}{.}828$	$2\overset{m}{.}845$
	±6	±5	±9

Table 3. Times of minima for V2154 Cyg.

HJD 2400000.+	Type
51031.5184	Sec
51048.6170	Pri
51060.4547	Sec
51098.5991	Pri
51106.4905	Pri

3. Results

3.1. Period

Three times of light minima were obtained for the primary minimum and other two for the secondary one during the observations collected in 1998. They are the only times of minima available for this binary system up to date and are listed in Table 3. These times of minima were determined using the method described in Rodríguez et al. (1990) where each light minimum is derived as average of the four $uvby$ bands. The estimated uncertainties in determining a time of minimum is of about $0\overset{d}{.}0005$ and $0\overset{d}{.}0015$ for the primary and secondary eclipses, respectively.

In order to improve the period determination of this binary system, a frequency analysis was utilised making use of least-squares algorithms better than the classical O-C method, because of the short baseline in time available from the times of minima. In this way, a period of $P_1 = 2\overset{d}{.}63068$ was found as the best solution for our data with a baseline of 2.3 years. This derived period is slightly longer than that of $P_2 = 2\overset{d}{.}63060$ given by the Hipparcos catalogue (ESA 1997). To verify the reliability of these determinations, the Hipparcos data were corrected to make compatible with our data in the y filter. Consequently, the baseline of the full sample is much longer (8.9 years). When all the data are phased using linear ephemeris with origin in time $T_0 = 2451048\overset{d}{.}6170$ (our first time of primary minimum) and periods of P_1 or P_2, we obtained that P_1 is slightly long while P_2 is slightly short. Then, a new frequency analysis was performed for the full sample and a new best solution was found as $P_3 = 2\overset{d}{.}6306312$ with an errorbar of 20×10^{-7}. The Hipparcos data are reconciled with the ones collected by us when altogether are phased using a new linear ephemeris with T_0 and P_3. Assuming this linear ephemeris, our $uvby$ data were phased and plotted in Fig. 1. The bottom panels in each graph show the corresponding magnitude differences of C2–C1.

3.2. Analysis of the light curves

The light curves of V2154 Cyg do not show notable distortions outside the eclipses and the bottom of the secondary

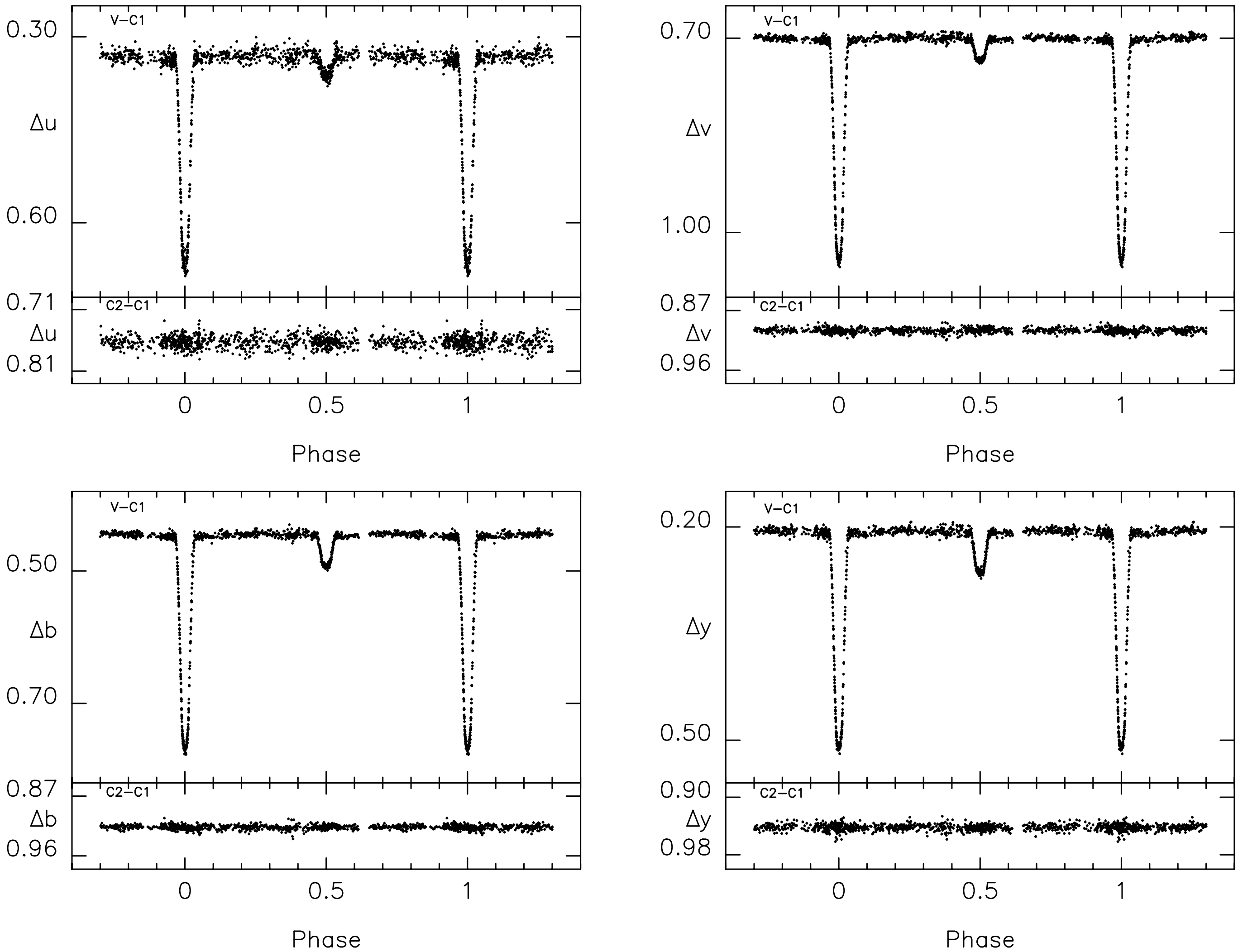

Fig. 1. *uvby* light curves of V2154 Cyg relative to C1 = HD 204626. The bottom panels in each graph show the corresponding light curves of C2–C1.

minimum appears flat, being this eclipse relatively shallow although clearly defined at phase 0.5. This appearance indicates that the eclipses are complete, primary being annular and secondary being total, and seems to be originated by two well-detached components with very different surface brightnesses.

The photometric analysis of the *uvby* light curves has been carried out with the EBOP code (Etzel 1981) which is based in the Nelson-Davis-Etzel (NDE) model (Popper & Etzel 1981). This model has proved to yield reliable photometric elements for detached binaries, like V2154 Cyg, where the proximity effects are not very important. The last version, named EBOPC, which permits the treatment for systems showing apsidal motion (Giménez & Quintana 1992, Giménez & Díaz-Cordovés 1993) was used throughout, although apsidal motion is not relevant for the present analysis.

Several basic assumptions were made for solving the four light curves of V2154 Cyg. Theoretical limb darkening coefficients (x), as derived by Díaz-Cordovés et al. (1995), for *uvby* bands were adopted. Gravity darkening coefficients (y) for convective atmospheres (Lucy 1967; Kitamura & Nakamura 1983) have been used. These values are lower than those corresponding to radiative envelopes frequently obtained with the formulae by Martynov (1973). We have verified that the use of either of these values has negligible effects on the final elements derived for V2154 Cyg. After some preliminary trial solutions, circular orbit was assumed. The amount of third light L_3 is not negligible because the visual component B is at $0\farcs47$ and therefore is unresolved in our photometric measurements. From the magnitude differences between the visual components derived from the Hipparcos data (Fabricius & Makarov 2000), we obtained a L_3 contribution of $\sim$11% in terms of the total light of the system (0.119 in y and 0.116 in b). L_3 was included as a free parameter in some of the computations and in the analysis of the v and u curves.

In absence of a spectroscopic mass ratio, q, we made several attempts to derive a wise value for this parameter. Residuals become slightly lower in the y filter for $q = 0.68$, but the values pointed out are different for the other colours, the shorter the wavelength the smaller the mass ratio ($q = 0.58$, 0.52 and 0.44 for b, v and u, respectively). This is somehow expected because the light curves of V2154 Cyg do not contain enough information to discriminate the q parameter. We have finally chosen $q = 0.55$, obtained as the ratio of the individual masses of the components calculated from the mass-effective temperature empirical relation for main sequence stars given by Habets & Heitnze (1981).

This rough estimation is sufficient for the photometric analysis of V2154 Cyg, in view of the fact that changing q by 0.1, does not significantly affect the geometrical elements derived. The assumption is no longer valid when the objective is to establish reliable absolute dimensions for the system. The relevant parameters to be determined from the fits are: the radius of the primary component, r_1, the ratio of radii, $k = r_2/r_1$, the orbital inclination, i, and the ratio of central surface brightnesses, J_2/J_1. Phase shifts and the photometric scale factor were always left as free parameters. Light curves have been analysed separately for each of the four $uvby$ filters. When solved with k as free parameter, the convergence indicates an average value $k \simeq 0.49$, but clearly correlated with the amount of third light L_3 and the orbital inclination i. Values of k ranging from 0.47 to 0.53, coupled with the appropriate i and L_3 values, provide equally good (minimum) residuals between the synthetic and observed light curves.

After computing several grid solutions for fixed values of k and L_3, we have used the observed L_3 values for y and b colours to constrain the acceptable range in k. We found $k = 0.498$ and 0.500 for y and b filters, respectively, so we have finally adopted $k = 0.499$ as the best solution. L_3 for v and y bands are obtained through the convergence process with k fixed in that value. Inferred photometric elements for each passband are presented in Table 4. Good interagreement is found for the solutions in all colours. Table 5 lists the adopted mean photometric elements for the eclipsing binary. Flux and luminosity ratios given there correspond to the mean geometrical elements. Quoted errors correspond to a realistic estimation of the uncertainties caused by slight changes on the adopted input parameters. The size of the secondary component is about half of the primary, while the luminosity ratio indicates very dissimilar components. The fractional radii are small, meaning in practice that both stars have little oblateness (0.0025 for the primary and 0.00095 for the secondary) and that this binary can be considered as a detached system.

Figure 2 shows the observed and calculated y light curve together with the corresponding (O–C) residuals plotted against the orbital phase. The $(b - y)$ and $(u - b)$ colour index variations are also shown. No systematic trends are appreciable in the (O–C) plots and the residuals correspond to the expected values from the observational scatter typical of each colour. Individual photometric $uvby$ indices for each component, listed in Table 6, are derived by using the joint indices out of eclipses and the luminosity ratios at each bandpass as given in Table 5. We must point out that these indices, particularly m_1 and c_1, may have some systematic effects due to the adopted third light and its correlation with the other photometric elements. The indices listed for the component 1 are compatible with those obtained directly from observations at phase 0.5, during the total secondary eclipse, where the combined light of L_3 and the primary eclipsing component is measured.

Table 4. EBOP solutions for the $uvby$ light curves of V2154 Cyg.

parameter	u	v	b	y
J_2/J_1	0.122	0.129	0.194	0.249
	4	3	3	4
r_1	0.1448	0.1443	0.1437	0.1433
	10	8	8	12
$k(= r_2/r_1)$	0.499	0.499	0.499	0.499
$i(°)$	88.65	88.83	88.70	88.50
	18	15	10	10
u_1	0.70	0.73	0.67	0.59
u_2	0.95	0.90	0.85	0.76
y_1	0.49	0.42	0.37	0.32
y_2	0.66	0.56	0.49	0.42
Phase shift (10^{-5})	−41	−59	−59	−58
mag. quad.	0.330	0.699	0.444	0.205
L_1	0.974	0.971	0.957	0.946
L_2	0.026	0.029	0.043	0.054
L_3	0.101	0.100	0.116	0.119
σ(mag)	0.0080	0.0034	0.0032	0.0038

Table 5. Adopted mean photometric elements for V2154 Cyg.

parameter	u	v	b	y	mean
r_1					0.1440
					20
$k(= r_2/r_1)$					0.499
					20
$i(°)$					88.6
					0.5
J_2/J_1	0.119	0.125	0.191	0.251	
L_2/L_1	0.026	0.029	0.044	0.058	

A β value of $2\overset{\mathrm{m}}{.}678$ can be determined for the primary component of the eclipsing pair assuming that the corresponding variation in $(b - y)$ and β are identical. This assumption is not valid for the secondary. By using the Smalley & Kupka (1997) calibration, an effective temperature value of $T_1 = 6700$ K is found for the hotter component. Assuming a null reddening (which is valid for the primary), a value of about $T_2 = 5000$ K is derived for the secondary component making use of the Kurucz (1993) and Bell & Gustafsson (1989) calibrations. This is consistent with a temperature difference of about 1800 K derived from the surface flux ratios J_2/J_1 and the flux scale given by Popper (1980).

As for the visual companion V2154 Cyg B, the small separation ($0\overset{\prime\prime}{.}47$) and the common proper motions reported (Dommanget & Nys 2000) may indicate that is

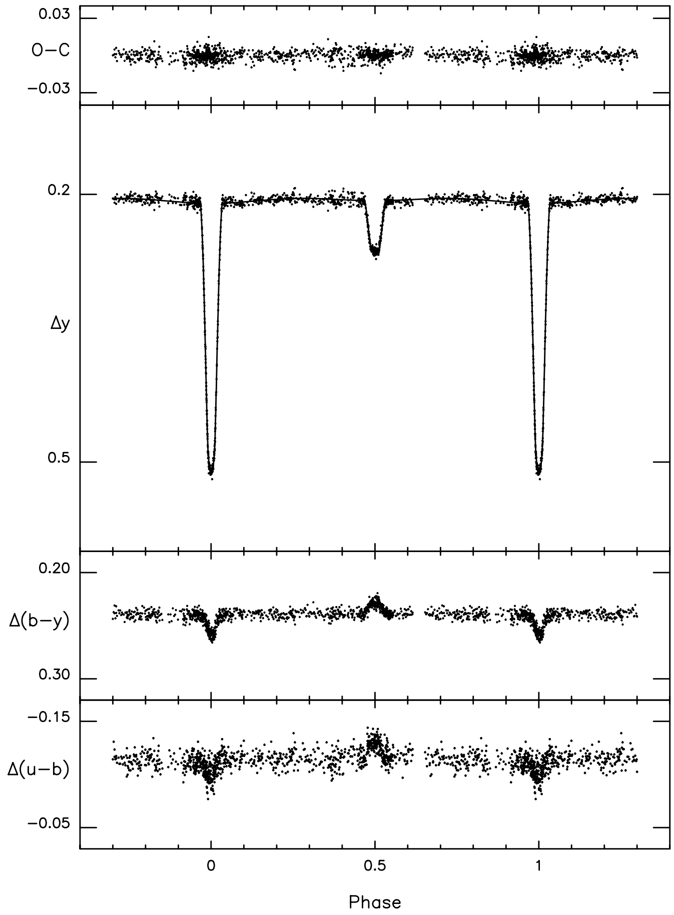

Fig. 2. y light curve and $(b-y)$ and $(u-b)$ colour index variations of V2154 Cyg-C1 together with the synthetic y light curve and residuals.

gravitationally bound to the A star, forming a wide binary system. Then V2154 Cyg could be a triple system. This is not an unusual configuration and several cases of eclipsing binaries being members of triple or multiple systems have been described in the literature (e.g., Andersen et al. 1990; Van Leeuwen & Van Genderen 1997).

This association is however not fully confirmed because the distance modulus derived from $B-V$ index of the B component, assuming null reddening, is not compatible with the distance to the system of ~88 pc measured by the Hipparcos satellite (ESA 1997). Information about its radial velocity will help to better solve this contradiction. Although the luminosity ratio of the components of the eclipsing pair is rather low, it might be detected also as a double-lined spectroscopic binary by using high resolution and S/N ratio instrumentation. In fact, the system may show three sets of lines due to the unavoidable inclusion of the (also faint) B component within the slit of the spectrograph.

If we consider that A and B constitute a wide pair at a distance of 88 pc, the separation of $0''.47$ is equivalent to a minimum separation of 41 AU. Assuming a total mass of about 3.5 $M_\odot$ for the triple system and a circular orbit, we can obtain a minimum orbital period of ~140 yr for

Table 6. Colour indices for the components of V2154 Cyg.

	System (A+B)	Comp. 1	Comp. 2	Star B
V	$7^{\mathrm{m}}.773$	$7^{\mathrm{m}}.971$	$11^{\mathrm{m}}.070$	$10^{\mathrm{m}}.084$
$b-y$	$0^{\mathrm{m}}.274$	$0^{\mathrm{m}}.256$	$0^{\mathrm{m}}.553$	$0^{\mathrm{m}}.302$
m_1	$0^{\mathrm{m}}.143$	$0^{\mathrm{m}}.126$	$0^{\mathrm{m}}.285$	$0^{\mathrm{m}}.276$
c_1	$0^{\mathrm{m}}.488$	$0^{\mathrm{m}}.522$	$0^{\mathrm{m}}.157$	$0^{\mathrm{m}}.316$
β	$2^{\mathrm{m}}.660$	$2^{\mathrm{m}}.678$	-	-

the possible wide pair. With such a period, no third light-time effect is noticeable within the span of our photometric observations, but a long term monitoring of minima might allow to measure it. Less straightforward, also long term optical interferometric observations should provide the basic parameters of this wide orbit.

Since the radial velocity curves of V2154 Cyg are not available yet, its absolute dimensions cannot be derived and the system cannot be used as a reliable test to the evolution theory. However, it is interesting to investigate the capability of prediction of stellar models when only a few observational constraints are available. In this way, we have used the stellar evolution code by Claret (1995) assuming the solar chemical composition and a mixing-length parameter of 1.52. The computations were carried out without mass loss. By using as indicators the derived effective temperature of the primary, mass ratio q and ratio of radii k we have computed a series of couple of models. The results indicate that both components are not too much evolved with masses of about 1.4 and 0.8 $M_\odot$ for the primary and secondary, respectively. The inferred surface gravities are consistent, within the present uncertainties, with the derived values of q and k.

The above numerical experiment, though instructive, is not definitive of course. Even considering the severe limitations to interpret the evolutionary history of V2154 Cyg one interesting aspect should be remarked: the mass range we are dealing. Clausen et al. (1999) pointed out that the two components of a sample of eclipsing binary systems in the mass range of 0.7–1.0 $M_\odot$ with accurate absolute dimensions were not fitted by a single isochrone. The "theoretical" mass of the secondary falls just in this problematic interval. It would be very interesting to obtain through spectroscopic studies the absolute dimensions not only to test the evolutionary models but also to check if the discrepancy in age is also present in this system.

4. Conclusions

We present for the first time complete *uvby* light curves for the recently discovered eclipsing binary system V2154 Cyg based in simultaneous measurements collected in the four filters. Times of primary and secondary minima are determined and an improved orbital period of $2^{\mathrm{d}}.6306312$ is found by means of frequency analysis. They are the only times of minima available for this binary system up to date. The behaviour of the light curves indicates that the eclipses are complete, annular for the primary and total for the secondary, being originated by two well-detached components with very different surface brightnesses.

An analysis of the photometric elements was carried out using the EBOP code. The results show that V2154 Cyg is a detached system with two late-type components very different in size ($k = 0.499$) and mass ratio of $q = 0.55$ with $T_1 = 6700$ K and $T_2 = 5000$ K. Stellar evolution models have been also used to gain some more insight about this system. The results indicate that both components are not too much evolved with masses of about $M_1 = 1.4\ M_\odot$ and $M_2 = 0.8\ M_\odot$.

In order to obtain reliable absolute dimensions for the components of the system, the photometric elements determined in this paper should be supplemented by accurate spectroscopic parameters from radial velocity observations. Spectroscopic observations will provide basic information on this possible triple system and, in particular, on the interesting eclipsing binary formed by two late-type components, being the secondary a low-mass star, which light curves do not show significant evidences of wave-type distortions normally associated to stellar activity. Spectroscopic data would also be very interesting in order to check if a discrepancy in age is also present in this system.

Acknowledgements. This research was supported by the Junta de Andalucía and the Dirección General de Enseñanza Superior e Investigación Científica (DGESIC) under project PB98-0499. This research has made use of the Simbad database, operated at CDS, Strasbourg, France. We like to thank the referee for very helpful remarks.

References

Andersen, J., Nordstrom, B., & Clausen, J. V. 1990, A&A, 228, 365
Bell, R. A., & Gustafsson, B. 1989, MNRAS, 236, 653
Claret, A. 1995, A&AS, 109, 441
Clausen, J. V., Baraffe, I., Claret, A., & VandenBerg, D. A. 1999, PASPC, 173, 265
Dommanget, J., & Nys, O. 2000, A&A, 363, 991
Díaz-Cordovés, J., Claret, A., & Giménez, A. 1995, A&AS, 110, 329
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Etzel, P. B. 1981, in Photometric and Spectroscopic Binary Systems, ed. E. B. Carling, & Z. Kopal (Reidel, Dordrecht), 111
Fabricius, C., & Makarov, V. V. 2000, A&A, 356, 141
Giménez, A., & Quintana, J. M. 1992, A&A, 260, 227
Giménez, A., & Díaz-Cordovés, J. 1993, in Light Curve Modelling of Eclipsing Binary Stars, ed. E. F. Milone (Springer-Verlag, New York), 125
Habets, G. M. H., & Heitnze, J. R. W. 1981, A&AS, 46, 193
Hauck, B., & Mermilliod, M. 1998, A&AS, 129, 431
Kitamura, M., & Nakamura, Y. 1983, Ann. Tokyo Astron. Obs. 2nd Ser., 19, 413
Kurucz, R. L. 1993, CD-ROM 13: ATLAS 9, SAO (Cambridge)
Lucy, L. B. 1967, Z. Astrophys., 65, 89
Martín, S., et al. 2001, in preparation
Martynov, D. Ya. 1973, in Eclipsing Binary Stars, ed. V. P. Tsesevich (Jerusalem), 148
Nielsen, R. F. 1983, Inst. Theor. Astrophys. Oslo Report No. 59, ed. O. Hauge, 141
Popper, D. M. 1980, ARA&A, 18, 115
Popper, D. M., & Etzel, P. E. 1981, AJ, 86, 102
Rodríguez, E., López de Coca, P., Rolland, R., & Garrido, R. 1990, Rev. Mex. Astron. Astrofís., 20, 37
Rodríguez, E., González-Bedolla, S. F., Rolland, A., Costa, V., & López de Coca, P. 1997, A&A, 324, 959
Rodríguez, E., Rolland, A., López-González, M. J., & Costa, V. 1998, A&A, 338, 905
Smalley, B., & Kupka, F. 1997, A&A, 328, 349
Van Leeuwen, F., & Van Genderen, A. M. 1997, A&A, 327, 1070