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Absolute parameters for binary systems

II. The late-type system ZZ Ursae Majoris

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Abstract. New light curves of the late-type binary system ZZ UMa were obtained during a *uvby* and Hβ monitoring program on low mass eclipsing binaries, that has been carried out in a six year photometric observational program (Clement et al. 1997a, Paper I). The main goal of the program is to obtain accurate absolute parameters for stars in the low and intermediate mass range, in order to improve the Mass-Luminosity Relationship (MLR) at the end of the main sequence.

This paper presents a complete analysis of the first *uvby*β light curves of the late-type detached eclipsing binary ZZ UMa. This binary system has been observed during eight campaigns at the Calar Alto Observatory (Almeria, Spain).

The activity wave superposed on the eclipse light curve has been estimated, by using a new iterative fitting method (Clement et al. 1997b, Paper II). The interpretation of the wave suggests the existence of two active zones of similar intensity, separated by areas at higher temperature. Once the activity wave was subtracted from the light curves, we adjusted the geometrical solution using the EBOP code. Radiative parameters for both stars have been derived from the light curves. Combining the masses deduced from the radial velocity curves (Popper 1995), with the calculated geometrical and radiative values, we computed the absolute parameters for both components. We can conclude that the system is composed of two main sequence G-type stars with masses, radii and chemical composition similar to the Sun.

Key words: stars: binaries: eclipsing — stars: late-type — stars: individual: ZZ UMa — stars: fundamental parameters

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1. Introduction

Masses, radii, temperatures and abundances are the fundamental parameters upon which the properties and evolution of stars depend. The only source for direct determination of the mass of a star is the effect of its gravitational attraction on other stars. The most precise method to calculate the mass and the other fundamental parameters of a star (radius, temperature, and abundances) is to combine photometric and spectroscopic observations applied to eclipsing binaries.

From the spectroscopic radial velocity curve, we apportion the individual masses of the components modulated by a factor which depends on the angle of inclination of the orbit i. Once this angle is determined (from the photometric light curve), the masses of the two components can be calculated. Also, from the velocity curve, the surface gravity, eccentricity and orientation of the orbit can be deduced.

The geometric parameters (inclination angle, relative radii, etc.) can only be computed from very well-defined light curves. Specially favourable are the binary systems with total or nearly-total eclipses and soft mutual interaction between components. The radiative properties of the components (effective temperature, etc.) can be estimated from photometric calibrations and light curves.

Thus, good-quality photometric and radial velocity curves of favourable eclipsing binaries, allow us to deduce the fundamental astrophysical quantities accurately. This task has been undertaken by the astronomic community with good results, specially for early-type stars. However, more accurate astrophysical absolute parameter determinations are needed for late-type stars. In the intermediate and low mass-range, where the population of stars becomes more denser, the calibration of fundamental parameters critically depends on the values of a very small number of stars.

This paper is concerned with this particular topic. We present a detailed analysis and absolute parameters determination of the main sequence late-type detached binary system ZZ UMa, using the first available $uvby\beta$ light curves and very recent spectroscopic determination of masses.

ZZ UMa was firstly classified as eclipsing binary by Kippenhahn in Geyer et al. (1955). Its photographic light curve is of Algol type (Döppner 1962). Mallama (1980) calculated ephemerides 2441499.5953+2.2992629 E. The photoelectric curves of ZZ UMa published by Lavrona & Lavrov (1988), show that reflection and ellipticity effects are small. The secondary star was classified as G6−G8 by Janiashvili & Lavrov (1989), which is in agreement with our preliminary analysis (Clement et al. 1993).

2. Observations

$uvby\beta$ observations of the eclipsing binary ZZ UMa have been carried out during eight campaigns at Calar Alto Observatory, (Almeria, Spain). The 1.5 m telescope operated by the Spanish Observatorio Astronómico Nacional was used, equipped with a mono-channel photometer or with a four-channel photometer both using Strömgren u, v, b, y filters as well as Crawford's narrow and wide filters centred on the Hβ line. All the measurements were made within the framework of a photometric observational program of late-type eclipsing binaries. The poor atmospheric conditions in many of the observing campaigns made it necessary to observe ZZ UMa during eight campaigns to obtain the light curves (294 points) which were covered in average twice. Table 1 lists the dates of the observing campaigns, the photometer used and the amount of useful observing time.

Nightly extinction coefficients were calculated for each night, using an adequate sample of standard stars observed at least three times at an air mass range from 1 to 2. Following the procedure described by Grönbech et al. (1976), we determined the night corrections $L(n)$ for each observing period in order to obtain the magnitudes in the instrumental system. Together with the program objects we observed a selected set of standard stars from the list of Perry et al. (1987), and Olsen (1991) in order to transform the measurements into the standard Strömgren and Crawford's systems.

HD 15242 and HD 15251 were observed as comparison and check stars respectively for differential photometry, both being of similar spectral type and apparent magnitude as ZZ UMa. The constancy of the comparison was checked every night. The differences (HD 15242 − HD 15251) for consecutive measurements were calculated and the internal rms errors for the 135 points obtained were 0.004, 0.004, 0.012, 0.018 and 0.016 expressed in magnitudes for V, $(b-y)$, m_1, c_1, and β respectively. This accuracy is of the same order as that obtained for main-program stars. So, we can conclude that the comparison had constant flux during the observing periods.

Differential measurements in the standard system for ZZ UMa, with respect to HD15242 were calculated. Figure 3 shows the differential light curve of ZZ UMa in the y filter. Tables with these first $uvby\beta$ light curves have been given in Paper I.

A more detailed description of the observations, the reduction of the data, and an estimation of the accuracy of the photometry can be found in Paper I as well.

Table 1. Observing campaigns

first night	last night	photometer	% useful time
13/03/90	25/03/90	monochannel	20%
02/01/91	15/01/91	monochannel	23%
17/01/92	27/01/92	multichannel	47%
25/01/93	31/01/93	multichannel	17%
04/04/94	14/04/94	monochannel	21%
02/06/95	12/06/95	monochannel	20%
22/11/95	02/12/95	multichannel	18%
15/05/96	25/05/96	monochannel	3%

3. Reddening and radiative parameters of the comparison stars

Before analysing the geometrical and radiative properties of the system we have corrected the magnitudes and indices of the effect of interstellar extinction, by using the comparison stars as local reddening indicators. The intrinsic magnitudes and colours of the comparison stars have been computed by using the calibration for F-type stars of Crawford (1975). This calibration is based on the fact that, although β and $(b-y)$ are indices related to the effective temperature, β is free of interstellar reddening while $(b-y)$ is affected. Latterly, Reglero et al. (1990), proved that the β index can be used also for later-type star reddening estimations, in the range G5-K2 and luminosity classes V-III. We found E$(b-y)$ 0.003 and 0.010 for the comparison and check star respectively. Because the comparison stars are at close angular separation from the binary system and also at approximately the same distance, and are of similar spectral types, it is safe to assume for ZZ UMa the mean of their reddening values (0.006), that is within the calibration errors.

The intrinsic values for V, m_1, and c_1 are calculated using the equations of Crawford & Mandewewala (1976). In Table 2 we list the standard intrinsic photometric indices for the comparison stars. The magnitudes and indices listed are the mean of the values obtained in the nights where we observed standard stars (42 measurements for the comparison and 38 for the check spread over the different observational campaigns). Errors are the rms of the values to the mean.

Absolute magnitudes, M_v, visual surface brightness, $F_{\rm v}$, metal contents, [Fe/H], and effective temperatures, $T_{\rm eff}$, were derived from the semiempirical calibrations of Crawford (1975), Moon (1984), Nissen (1981) and Saxner & Hammarback (1985), respectively. Both comparisons appear to be main sequence stars with solar metal abundances. They can be classified as G0 V and G1 V. Table 3 list the radiative parameters for the comparisons. Errors in the table are the values given for the calibrations. For the distance, d, bolometric magnitude, $M_{\rm bol}$ and radius, R/R_0, the errors listed are the propagation of errors through the formula.

Table 2. Intrinsic photometric indices for the comparison stars

star	y_0	$(b-y)_0$	m_0	c_0	β
HD 15242	10.115	0.365	0.177	0.306	2.597
σ	0.013	0.005	0.010	0.021	0.014
HD 15251	9.956	0.386	0.230	0.323	2.598
σ	0.012	0.005	0.014	0.021	0.017

Table 3. Radiative parameters for the comparison stars of ZZ UMa

name	M_v	$F_{\rm v}$	[Fe/H]	$T_{\rm eff}$	d	$M_{\rm bol}$	R/R_0
HD 15242	4.53	3.754	−0.21	5837	130	4.42	1.09
σ	0.28	0.026	0.20	60	17	0.38	0.19
HD 15251	4.32	3.751	0.27	5848	135	4.16	1.22
σ	0.28	0.026	0.20	60	17	0.38	0.21

4. Discussion

4.1. Activity of ZZ UMa

One of the main problems when analysing photometric light curves for late-type binary systems is the modulation that can be seen outside eclipses, due to the effect of intrinsic surface activity phenomena in one or both components on stars of spectral type later than F. The contribution of activity mixes with the proximity effects, all of them being observed outside eclipses. The light curves of ZZ UMa show variations outside eclipses that can be attribute to this effect. So, before going into the geometrical and radiative analysis we need to clean the light curves of stellar activity contribution.

To determine the associated wave due to activity we used a new iterative method that approximates the wave at the same time that computes the EBOP solution. This method has been used in the analysis of BH Vir, a late-type binary system that shows a high level of activity which is variable with time, and proved to be very efficient, see Paper II.

For ZZ UMa this new method takes into account the fact that the modulation observed outside eclipses is produced by different physical processes: tidal distortion, mutual reflection, and the presence of spots on the surface of the stars. Quasi-synchronic rotation of the stars in evolved systems generate an overlapping of the stellar activity phenomena with the binarity effects, both having the same period.

The first step of the iterative process is to adjust a second order truncated Fourier series,

$$M(\phi) = A_0 + A_1\cos(\phi) + A_2\sin(\phi) + A_3\cos(2\phi) + A_4\sin(2\phi)$$

to the points outside eclipses, obtaining the first approximation to the wave.

The second step is to subtract this wave to the light curve and find the first binary solution for the rectified light curve of the system by using the EBOP code.

The third step is to estimate the new approximation to the activity wave by adjusting a Fourier series to the residuals of the theoretical curve, that we assumed are mainly due to activity effects.

We have iterated this cleaning process until the wave and the binary solution became stable, which happened in the fourth iteration. The coefficients found for the waves are:

coef.	u	v	b	y
A_0	0.0402	0.0391	0.0336	0.02624
A_1	−0.0144	−0.0179	−0.0132	−0.01292
A_2	0.0131	0.0107	0.0094	0.00688
A_3	−0.0167	−0.0173	−0.0156	−0.00605
A_4	0.0144	0.0087	0.0095	0.00991

Figures 1 and 2 show the results of our first estimations and final waves in the u, v, b and y filters. Both figures present differential magnitudes versus phase; continuous line corresponds to the waves in the y filter, triangules, squares, and crosses, correspond to the b, v, and u filters respectively.

We found that the variation of the waves in the iterative process was small. The mean of the differences between the coefficients of the first and the final waves was only 0.002 ± 0.001, A_3 being the coefficient that concentrated most of the variation, as expected.

The amplitude of the waves measured as the difference between the points of maximum and minimum light is 0.053, 0.048, 0.042 and 0.040 for u, v, b, and y respectively. More representative of the real contribution of the activity is the integral of the waves along one complete phase, that represents the stellar filling factor, which was found to be 0.040, 0.039, 0.033 and 0.026 for u, v, b, and y respectively. That is, assuming a black-spot model we estimate that 4% of the total area is covered by spots.

Although the activity contribution to the light curve of ZZ UMa is small and it does not show a high level of

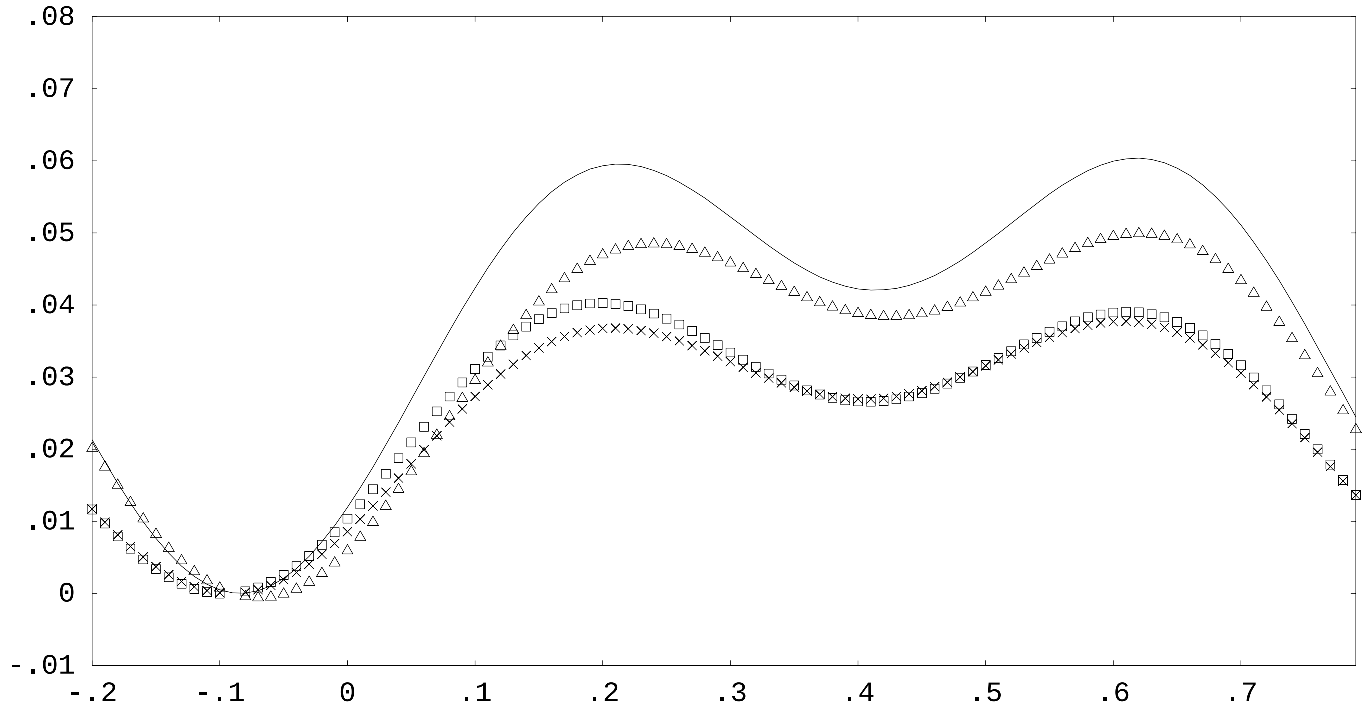

Fig. 1. Initial associated activity waves for ZZ UMa

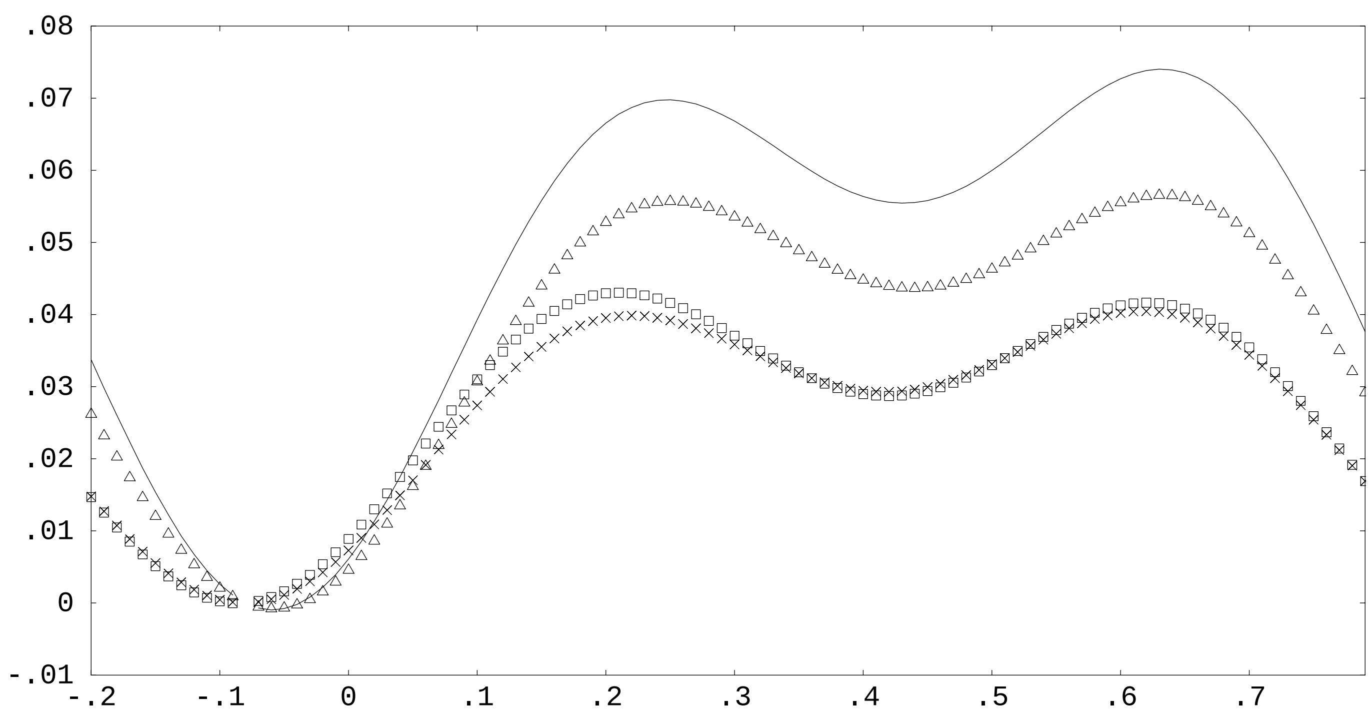

Fig. 2. Final associated activity waves for ZZ UMa

variability with time, it would have been better to estimate the activity waves independently for each period, in order to take into account the possible migration of the waves with time, but we do not have complete light curves for any of the observing campaigns.

The shape and $(b-y)$ colour of the waves suggest the existence of two active centres of similar intensity, at phase 0.2 and 0.6 isolated by a less perturbed photosphere.

4.2. Geometrical parameters of ZZ UMa

To estimate the geometrical parameters (inclination of the orbit, ratio of radii, etc.), we solved the light curve by using the EBOP code (Etzel 1975). This program is designed for the solution of detached binary systems with small side-effects due to proximity. Thus, it is adequate for ZZ UMa, for which our estimation of the radii relative to the orbit is 0.16 and 0.12 for the primary and secondary components respectively.

The process of optimisation involved in the search for the EBOP solution must always be constrained by a priori bounds imposed on the astrophysical parameters being optimised. Otherwise, as pointed out by some authors, (Popper 1984, 1993; Andersen 1991), it is possible to find different sets of solutions which fit the observed light curve with equal precision. The solution is not uniquely determined.

To get realistic first approximation to some of the values that we attempt to optimise with EBOP,(J_s/J_p and r_s/r_p), we did a photometric pre-calibration of the light curves (Clement et al. 1993). Limb darkening coefficients were taken from Claret & Giménez (1990), assuming the initial values for the effective temperatures and gravity. Gravity darkening coefficient was calculated with the black body formula of Martinov (1973) using our initial estimation of effective temperatures. For the radius of the primary star relative to the orbit, and the inclination of the orbit, we assumed $r_p = 0.16$ and $i = 88.7$ degrees as a first approximation, after a preliminary analysis. From new spectroscopy data (Popper 1995) $K_1 = 93.2 \pm 0.9$ and $K_2 = 114.5 \pm 0.9$, we quoted the mass ratio, $q = 0.81$. However, it should be noted that these values are still preliminary. The period and the initial epoch are from Mallama (1980).

In Table 5 we list the initial parameters adopted to run EBOP. "V" marks the six free parameters in every EBOP run. Those are the parameters that EBOP can optimise better. All the others remained fixed.

After subtracting the final waves from the raw data we searched for the EBOP solution following the recommendations of Etzel in the EBOP users guide (Etzel 1981).

Table 6 lists the definitive solution. Last column (σ) is the RMS dispersion of the calculated values in every filter.

The program calculates internally the mutual reflection assuming the simple case of a hemisphere uniformly illuminated (Binnendijk 1960), but taking into account the eclipse of the reflected light (Etzel 1981). The small values obtained for the reflection confirm that this simple model is good enough.

Table 4. ZZ UMa. Intrinsic magnitudes and indices

name	y_0	$(b-y)_0$	m_0	c_0	β
ZZ UMa	9.798	0.385	0.201	0.317	2.596
	0.007	0.008	0.014	0.016	0.008
Hot	10.110	0.373	0.180	0.337	2.603
	0.007	0.006	0.011	0.017	0.008
Cold	11.307	0.422	0.275	0.250	2.594
	0.035	0.054	0.065	0.085	0.016

The synthesised light curve presents total secondary eclipse (EBOP computes 10 identical values, from phase 0.494 to phase 0.501, in every filter), confirming our hypothesis. Thus, the deconvolution process from the light observed at quadrature and at the bottom of the secondary star is adequate.

So we can conclude that the binary system undergoes total eclipse and that both components have small deformation effect due to proximity.

The values for the radii and the orbit inclination obtained,

$$r_p = 0.161 \pm 0.002$$

$$r_s = 0.123 \pm 0.001$$

$$i = 88.01 \pm 0.07$$

are accurate enough to allow us to calculate the fundamental astrophysical parameters, masses and luminosities, precisely and fulfil the final objective of this work.

4.3. Radiative and absolute parameters of ZZ UMa. Evolutionary status

Following the same procedure used for BH Vir, described in Paper II, we have

1. Decoupled both stars, from the EBOP values at quadrature and at the bottom of the secondary eclipse (that is total).
2. Estimated the radiative parameters for the hot and cold components.
3. Computed the absolute parameters for both stars, combining the binary solution (J_s/J_p, r_p, r_s, i), with the photometric calibrations (F_v, T_{eff}), and the semi-amplitudes (K_1, K_2) of the radial velocity curve.

In Table 4 we list the rectified intrinsic magnitudes and indices outside eclipse (ZZ UMa), and during totality (hot component), as well as the computed values for the cold component. The errors for ZZ UMa and the hot star are the rms of the rectified observed points at quadrature (10 points), and at the bottom of the secondary eclipse

Table 5. ZZ UMa. Initial EBOP parameters (S0)

parameters	number	u	v	b	y
J_s/J_p	V−1				0.613
r_p	V−2				0.16
r_s/r_p	V−3				0.74
r_s					
prim limb dark coef	4	0.88	0.83	0.77	0.68
second limb dark coef	5	0.94	0.88	0.81	0.73
i	V−6				88.7
$e \cdot \cos(\omega)$	7				0.0
$e \cdot \sin(\omega)$	8				0.0
prim gravita dark coef	9				0.25
second gravita dark coef	10				0.25
prim reflection (internal calculation)	11				0.0
second reflection (internal calculation)	12				0.0
mass ratio	13				0.81
lead/lag ang	14				0.0
third light	15				0.0
out of phase	V−16				0.0
maximum light	V−17	−0.113	−0.177	−0.232	−0.270
integration ring	18	5			
period	19	2.29926000			
initial epoch	20	2441499.59530			

(10 points). For ZZ UMa Cold the errors are calculated through the formula used in the process of deconvolution.

Table 7 shows the absolute parameters calculated for both stars inside the system. A is the semi-mayor axis of the orbit calculated from the masses of both stars and the orbital period, using the fundamental formula given in Schmidt-Kaler et al. (1982). In the same table, $F_v(p)$ and $T_{\rm eff}(p)$ are the flux brightness and effective temperature for the primary star calculated from our photometry ($(b-y)_0$, β), using the calibrations of Moon (1984) and Saxner & Hammarbäck (1985). The flux brightnes for the cold component, $F_v(s)$, was calculated from $F_v(p)$ and J_s/J_p computed with EBOP. The effective temperature for the secondary star was deduced as well from $T_{\rm eff}(p)$ and J_s/J_p, assuming that the bolometric corrections for both stars are the same.

From the radiative parameters, the primary star can be classified as G0, while the secondary would be G5, both being main sequence stars. An estimation of their metallicity using the calibrations of Nissen (1981) gives a metal content of [Fe/H] $= -0.13 \pm 0.20$ and [Fe/H]$= 0.18 \pm 0.13$ for the hot and cold components. Both stars have solar metallicities.

The distance (172 pc) computed from the absolute magnitude, M_v, locates ZZ UMa at a distance similar to the comparisons. So the reddening estimation from the comparisons, can be assumed for the system.

We have used the evolutionary model of Claret & Giménez (1992) to estimate the age of the system. The initial parameters for the model calculations were the masses given in Table 7, and solar abundances. This model covers a wide range of masses (1 to 40 M_0), but the cold component of ZZ UMa lies out of that range and it would be necessary to extrapolate the model. For the Hot component the values predicted inside the model were:

$$\log(T_{\rm eff}) = 3.77 \pm 0.02$$

$$\log(g) = 4.17 \pm 0.04$$

$$\log(\tau) = 9.7 \pm 0.2$$

which are in good agreement with our results.

For completeness we used the evolutionary model of Schaller et al. (1992) and found that both components lie on the isochrone $\log(\tau) = 9.8$, which is in good agreement and within the uncertainty of the result given above.

Figure 4 shows the rectified light curve together with the EBOP solution. We believe that the spreading of points observed in some parts of the light curve (entrance of the primary eclipse, and phase 0.9), is due mainly to residual activity effects, coming from the mixing of data from eight different epochs.

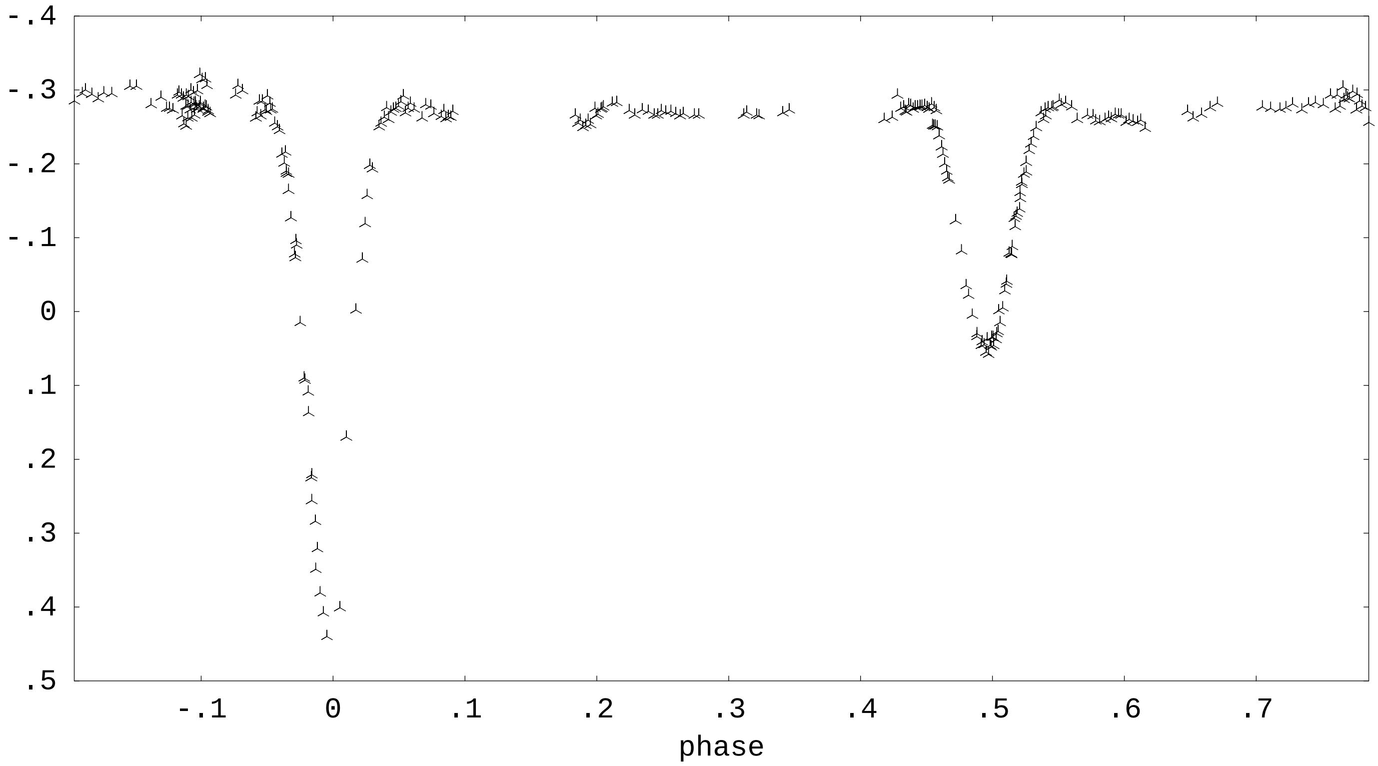

Fig. 3. Differential light curve for ZZ UMa. y filter

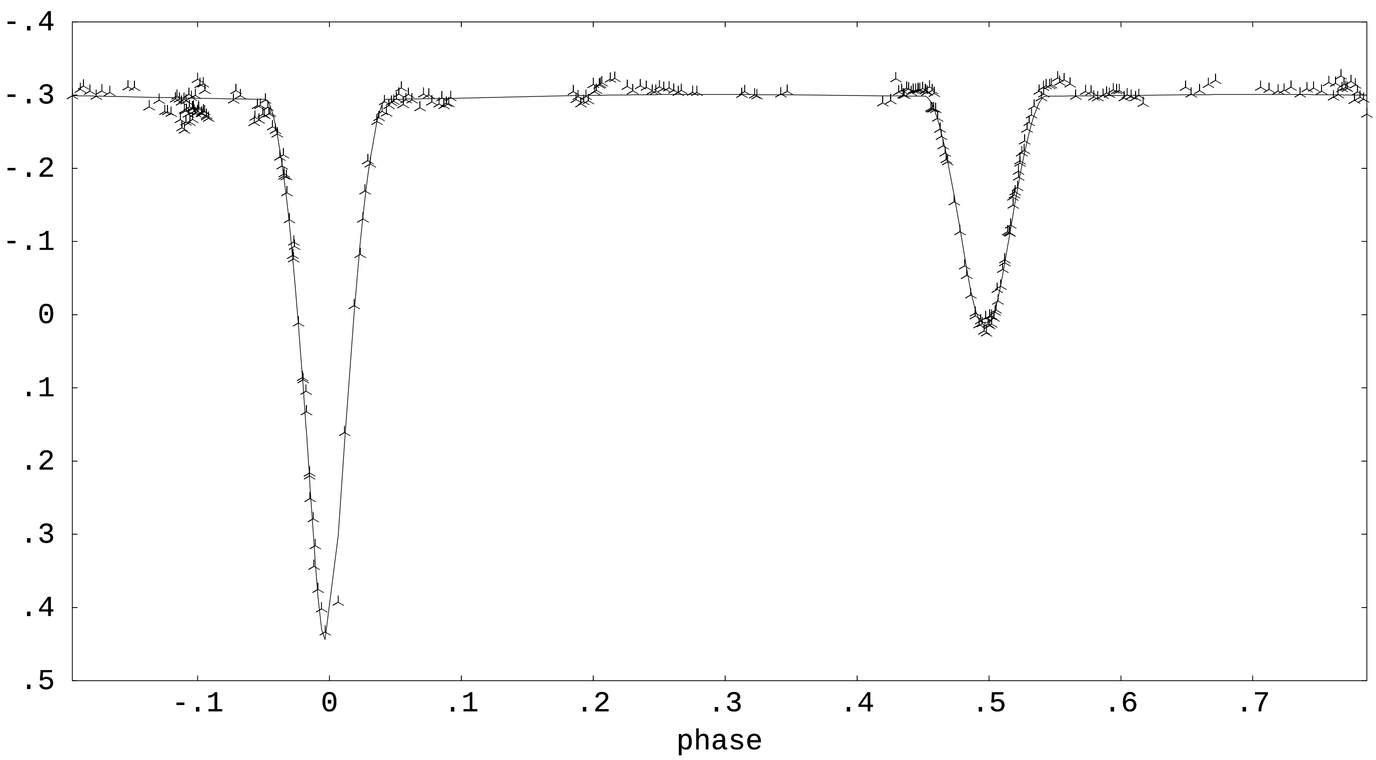

Fig. 4. ZZ UMa + EBOP definitive solution. y filter

Table 6. ZZ UMa. EBOP solution

Parameter	number	u	v	b	y	mean	σ
J_s/J_p	1	0.440	0.462	0.528	0.556		
σ	±	0.009	0.008	0.007	0.006		
r_p	2	0.158	0.161	0.164	0.160	0.161	0.002
r_s/r_p	3	0.766	0.761	0.759	0.766	0.763	0.003
r_s		0.121	0.123	0.124	0.122	0.123	0.001
prim limb dark coef	4	0.88	0.83	0.77	0.68		
second limb dark coef	5	0.94	0.88	0.81	0.73		
i	6	87.99	88.05	87.90	88.09	88.01	0.07
$e \cdot \cos(\omega)$	7	0.0					
$e \cdot \sin(\omega)$	8	0.0					
prim gravita dark coef	9	0.25					
second gravita dark coef	10	0.25					
prim reflection (internal calculation)	11	0.002	0.002	0.002	0.002		
second reflection (internal calculation)	12	0.005	0.005	0.005	0.005		
mass ratio	13	0.81					
lead/lag ang	14	0.0					
third light	15	0.0					
out of phase	16	0.002	0.002	0.003	0.003		
maximum light	17	−0.170	−0.227	−0.274	−0.297		
integration ring	18	5					
period	19	2.29926					
initial epoch	20	1499.59530					
L(primary)		0.79976	0.79395	0.79620	0.75822		
L(secondary)		0.20024	0.20605	0.23080	0.24178		
$\sigma < (\mathrm{O-C}) >$		0.018	0.016	0.014	0.012		

5. Conclusions

In this paper we have presented a precise determination of absolute parameters for the two components of the binary ZZ UMa, based on the first *uvbyβ* light curves of this system combined with recent spectroscopic determination of mass ratio.

For the cleaning of the light curve of intrinsic stellar activity, we have implemented a new iterative approach used first in the analysis of the high variable binary system BH Vir. Filling factors of 0.04 have been obtained from the activity wave analysis, that also indicate a complex geometry with at least two activity centres over the stellar surface. Due to the fact that we have mixed points from eight different observing runs, the above to referred activity centres could be a consequence of the superposition of different "instantaneous" waves more than of a real surface twin centre.

The geometric and photometric results obtained led us to conclude that ZZ UMa is composed of two main sequence stars of spectral type G0 and G5, with masses, radii and chemical compositions comparable to the Sun, that undergo total eclipse at secondary minimum.

The accuracy reached, in the determination of absolute parameters, is good enough to include ZZ UMa in the group of late-type binaries that can be used to improve the Mass-Luminosity Relationship at the end of the main sequence.

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Table 7. ZZ UMa. Absolute parameters

Literature		P	K_1	K_2		
		2.29926	93.2	114.5		
		0.0001	0.5	0.5		
Ours	EBOP	J_s	r_p	r_s	i	
		0.556	0.161	0.123	88.01	
		0.007	0.002	0.001	0.07	
Ours	photometry		redd =	0.006		
Primary	star			$(b-y)_0$	β	
				0.373	2.603	
				0.008	0.005	
Primary	star					
A	m_p	R_p	$\log(g_p)$	$F_v(p)$	$T_{eff}(p)$	
9.45	1.182	1.519	4.147	3.742	5903	
0.04	0.013	0.023	0.017	0.026	60	
d		L_p	$M_{bol}(p)$	BC		$M_v(p)$
172		2.472	3.66	−0.27		3.93
21		0.023	0.05	0.27		0.26
Secondary	Star					
	m_s	R_s	$\log(g_s)$	$F_v(s)$	$T_{eff}(s)$	
	0.962	1.159	4.293	3.678	5097	
	0.010	0.013	0.015	0.026	60	
		L_s	$M_{bol}(s)$	BC		$M_v(s)$
		0.800	4.88	−0.27		5.15
		0.023	0.06	0.27		0.26

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