ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **136**, 27–33 (1999)

UBVR photometry of pre-catacylismic binaries: HW Virginis

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Received May 25; accepted November 17, 1998

Abstract. New *UBVR* light curves of the eclipsing binary HW Vir have been obtained. All the published times of primary and secondary eclipses have been collected. By adding the new times of the eclipses obtained by us, the general behavior of the O–C changes has been revealed. The updated O–C change seems to show a cyclic character. This behavior may be the result of whether rotation of the apsis connecting the star's centers or revolution of the couple around a third body. The former has been excluded due to the fact that the O–C values of primary and secondary eclipses show similar variation, i.e., not 180° out of phase. Therefore the O–C changes have been analysed under the assumption of the light–time effect. The period of revolution around the third body was found to be 19 years. The time span following the discovery of eclipsing nature of the system covers 69 percent of the period predicted. The B, V and R light curves have been analysed by the WD code and the physical parameters of the components were obtained. The hotter, primary component is an sdB star with a temperature of about 36 000 K, and the cooler one is a late–type main sequence star with a temperature of 3300 K. The physical parameters derived for the secondary component are in accordance with the parameters of the theoretical models. This analysis indicates that the low mass, cooler secondary does not fill its critical Roche lobe. Therefore, mass accretion from the cool main sequence star to the hot sdB primary is not yet expected.

Key words: stars: HW Vir — binaries: eclipsing — cataclysmic variables

1. Introduction

The eclipsing nature of the UV – bright object BD – 7° 3477 was discovered by Menzies & Marang (1986). The star, named as HW Vir in the variable stars catalogue, has been observed spectroscopically by Berger & Fringant (1980) and classified as an sdB star. The first *UBVRI* light curves were obtained by Menzies & Marang (1986). They analysed the light curves to obtain the physical and geometric properties of the component stars. Using the velocities of the primary component Menzies & Marang (1986) derived the semi–amplitude of the orbit 87.9 km s^{-1}, a mass function of 0.0082 $M_\odot$ and a projected semi–major axis of 1.4 10^5 km. They suggested the plausible masses of the components to be 0.25 $M_\odot$ and 0.12 $M_\odot$. Later on, Wood et al. (1993) obtained simultaneous *UBVR* photometry of the short period eclipsing binary HW Vir. Their analyses indicated that the mass of the primary is about 0.50 $M_\odot$, which corresponds to sdB stars. Assuming the secondary component is a main sequence star they derived the mass ratio between 0.30 and 0.48. They have also assumed a temperature of T_2 = 3700 K for the secondary star because it contributes very little light to the total brightness of the system and it fits for a wide range of the mass ratio. Their analyses showed that the system HW Vir consists of an ordinary sdB star with a mass near 0.50 $M_\odot$ and a main sequence star with a mass near 0.15 $M_\odot$. They have also proposed that the orbital period of the system will decrease as the system loses its angular momentum. Then, the secondary component will fill its own critical Roche lobe and a mass transfer to the sdB component will begin. Therefore the system is the progenitor of a cataclysmic variable. Later on Kilkenny et al. (1994) discussed the period decrease in the sdB eclipsing binary HW Vir based on the data gathered over a nine-year baseline. They concluded that the most plausible mechanism of this decrement in the orbital period was the angular momentum loss via magnetic braking in a weak stellar wind. Hilditch et al. (1996) searched the reflection effect in the system HW Vir. As it is known that the most conspicuous feature of the light curves of the eclipsing binaries, including a sub-dwarf and a low-mass companion, is the reflection effect which is seen outside the primary eclipse, they obtained the radial velocities of the hot sdB primary by means of an echelle spectrograph. Combining the results yielded by the radial velocity curve with that of the light curve solutions (e.g. Wood et al. 1993) they derived the astrophysical parameters of the components of HW Vir. Because the system HW Vir is a single–lined eclipsing binary they have assumed the mass of hot primary as 0.50 $M_{\odot}$, and obtained a mass of 0.14 $M_{\odot}$ for the low-mass secondary star. However, the temperature of $T_2 = 3700$ K derived for this low-mass companion is rather higher than those expected from theoretical models, as acted by Hilditch et al. (1996).

In this study we present the new times of minima and the new *UBVR* light curves of the exotic binary HW Vir. The main purposes of this paper are to reveal the most plausible mechanism of the orbital period decrease and to obtain geometric and physical parameters of the components which constitute the system.

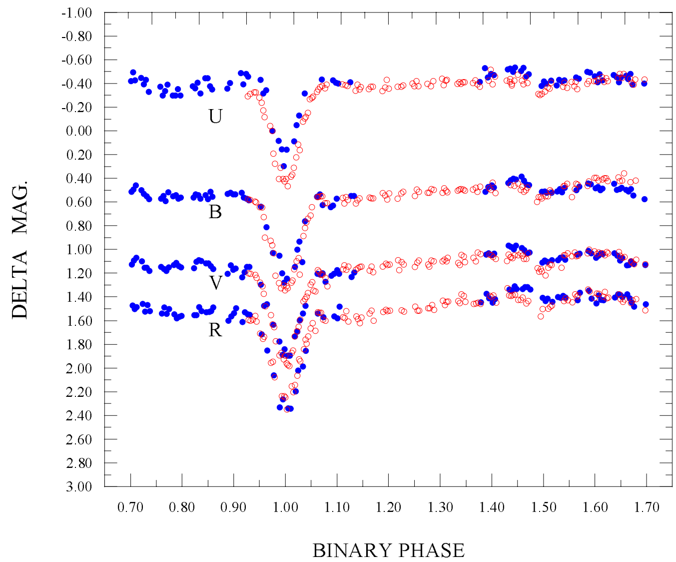

Fig. 1. U, B, V and R light curves of HW Vir. Filled circles represent the magnitudes obtained on May 26, and open circles for May 27, 1997

2. Observations

The system HW Vir was observed on two nights, namely 26/27 and 27/28 May 1997. The observations were obtained with the 40 cm Cassegrain reflector of the TUBITAK Turkish National Observatory. The observatory is at an altitude of 2500 m and had seen the first light on January 1997. An SSP5A type photometer was attached to the telescope. The Johnson's wide − band U, B, V and R filters were used. Each measurement is a mean of the two 10 seconds integrations. In this study we measured the sky background before and after the measurements of the comparison and variable, but not during the eclipse. The main comparison star was BD − 8° 3411. The differential observations, variable minus comparison, were corrected for atmospheric extinction. The extinction coefficients were obtained for each night using the observations of the main comparison star. The times were also reduced to the Sun's center.The orbital phases were calculated using the light elements given by Gürol & Selam (1994) as,

$$\text{Min I} = \text{JD Hel. } 2448\,294.88647 + 0\overset{\text{d}}{.}\,11671953\, E.$$

The differential magnitudes for each band were plotted against the orbital phase and are shown in Fig. 1. The observations obtained on two nights agree well in B, V and R bands; but there are some differences in U filter. These differences in U band arise mainly from the fact that the photometer we used is more sensitive to the longer wavelengths.

3. Period analysis

Using the data gathered over a period of nine years, Kilkenny et al. (1994) showed that the orbital period of HW Vir was decreasing. Although they reviewed the possible mechanisms that would cause period decrease, they could not reach a conclusion as to which one was the most likely candidate. Among the probable mechanisms, the gravitational radiation effect, apsidal motion and mass transfer were ruled out. The remaining causes like the existence of a third body, mass loss through stellar winds and angular momentum loss through magnetic braking have been thoroughly studied. Of all these mechanisms, a period decrease through angular momentum loss has been given the highest probability. As stated previously, the final decision would be reached only after new observations.

In the present study, we obtained two primary minimum times and one secondary minimum time. Minimum times that have been obtained ever since the system was found to be an eclipsing binary are given in Table 1. O–C (I) deviations are obtained by using the light elements given by Menzies & Marang (1986),

$$\text{Min I} = \text{JD Hel. } 2445\,730.55607 + 0\overset{\text{d}}{.}1167196311\, E.$$

O–C (I) deviations are plotted in Fig. 2. As it is seen from the figure, there is no significant deviation until $E = 23\,000$. For $E > 23\,000$ it is obvious that O–C (I) deviations decrease continuously. Assuming that O–C (I) varies linearly with E we recalculated the light elements. The new elements are,

$$\begin{array}{lll} \text{Min I} = \text{JD Hel. } 2445\,730.556503 & + & 0\overset{\text{d}}{.}1167195820\, E \\ \qquad\qquad\qquad\qquad\quad \pm 13 & & \qquad\quad \pm\, 42. \end{array}$$

O–C deviations show a sine-like scattering around the linear fit. This sine-like curve, although it has not shown a complete cycle yet, seems to be nearing its one cycle completion.

Such a variation could be accounted for in three different ways:

1. Mass transfer. Components of HW Vir are sdB and low mass main sequence stars. It is known that in such a system, where mass accretion occurs from a low

Table 1. Times of minima of HW Vir. References: (1) Menzies & Marang (unpublished); (2) Kilkenny et al. (1994); (3) Marang & Kilkenny (1989); (4) Wood et al. (1993); (5) Selam et al. (IBVS4109); (6) This study

Min (JD Hel.)	E	O–C (I)	O–C (II)	Ref.	Min (JD Hel.)	E	O–C (I)	O–C(II)	Ref.
45730.55607	0	0	−0.00043	1	48365.3852	22574	0.0002	0.00085	2
45731.60654	9	0.00001	−0.00044	1	48371.4546	22626	0.0002	0.00083	2
45732.54029	17	0.00002	−0.00045	1	48404.3695	22908	0.0001	0.00081	2
45733.5323	25.5	−0.0001	−0.00055	2	48406.3538	22925	0.0002	0.00088	2
45733.59079	26	−0.0001	−0.00042	1	48410.3222	22959	0.0001	0.00081	2
45734.42455	34	−0.0001	−0.00042	1	48682.5123	25291	0.0001	0.00085	2
45734.5829	34.5	0	−0.00043	2	48684.4965	25308	0.0001	0.00082	2
45735.57495	43	0.00007	−0.00050	1	48703.5218	25471	0.0001	0.00082	2
45736.50862	51	0.00016	−0.00058	1	48704.4556	25479	0.0001	0.00087	2
45740.47730	85	−0.00006	−0.00037	1	48705.5060	25488	0.0001	0.00079	2
45740.59396	86	0	−0.00043	1	48776.3548	26095	0.0001	0.00080	5
45741.52774	94	−0.00002	−0.00040	1	48776.3550	26095	0.0002	0.00100	5
45742.46164	102	−0.00016	−0.00026	1	48776.3553	26095	0.0005	0.00130	5
45744.44585	119	−0.00014	−0.00028	1	48803.3170	26326	−0.0001	0.00078	2
45773.50883	368	0.00007	−0.00048	1	49104.4533	28906	−0.0004	0.00056	2
45773.62559	369	0.00003	−0.00044	1	49122.3113	29059	−0.0005	0.00046	2
45774.44253	376	0.00013	−0.00054	1	49137.3681	29188	−0.0006	0.00044	2
45774.55928	377	0.00009	−0.00051	1	49139.3524	29205	−0.0005	0.00050	2
45775.37632	384	0.00009	−0.00050	1	49149.3318	29290.5	−0.0006	0.00038	5
45775.60982	386	0.00003	−0.00044	1	49149.3323	29290.5	−0.0001	0.00088	5
45776.42691	393	−0.00002	−0.00039	1	49149.3325	29290.5	0.0001	0.00108	5
45776.4853	393.5	0.00010	−0.00036	2	49189.25	29632.5	−0.0005	0.00048	2
45776.54358	394	0.00003	−0.00044	1	49393.5095	31382.5	−0.0004	0.00072	5
45819.37975	761	−0.00004	−0.00036	1	49393.5671	31383	−0.0012	−0.00004	5
46098.57312	3153	−0.00005	−0.00023	1	49393.5672	31383	−0.0011	0.00006	5
46100.55736	3170	−0.00006	−0.00022	1	49400.5114	31442.5	−0.0017	−0.00056	5
46101.60776	3179	0.00002	−0.00029	1	49400.5119	31442.5	−0.0012	−0.00006	5
46164.4030	3717	−0.00006	−0.00019	1	49400.5125	31442.5	−0.0006	0.00054	5
46164.51976	3718	−0.00010	−0.00015	1	49427.4739	31673.5	−0.0014	−0.00028	5
46223.2881	4221.5	0.00010	−0.00012	2	49427.475	31673.5	−0.0003	0.00082	5
46223.34645	4222	−0.00009	−0.00013	1	49427.5327	31674	−0.0009	0.00016	5
47684.32597	16739	0.00001	0.00038	1	49427.5327	31674	−0.0009	0.00016	5
47684.3260	16739	0	0.00041	3	49511.3372	32392	−0.0012	0	5
47687.24396	16764	0.00001	0.00038	1	49511.3373	32392	−0.0011	0.00010	5
47687.2440	16764	0.0001	0.00042	3	49518.3407	32452	−0.0008	0.00032	5
47688.2944	16773	0.0001	0.00035	3	50595.4270	41680	−0.0033	−0.00168	6
47689.2282	16781	0.0001	0.00039	3	50595.4272	41680	−0.0031	−0.00148	6
47968.5384	19174	0.0001	0.00063	2	50595.4272	41680	−0.0031	−0.00148	6
47972.5068	19208	0.0001	0.00057	2	50595.4274	41680	−0.0029	−0.00128	6
48267.5741	21736	0.0001	0.00076	2	50596.3608	41688	−0.0033	−0.00164	6
48294.8865	21970	0.0001	0.00078	4	50596.3608	41688	−0.0033	−0.00164	6
48295.0033	21971	0.0002	0.00086	4	50596.3608	41688	−0.0033	−0.00164	6
48295.937	21979	0.0002	0.00080	4	50596.3607	41688	−0.0034	−0.00174	6
48307.6089	22079	0.0001	0.00075	2	50596.3019	41687.5	−0.0038	−0.00218	6
48311.5774	22113	0.0001	0.00078	2	50596.3025	41687.5	−0.0032	−0.00158	6
48313.5617	22130	0.0002	0.00085	2					

mass star to a high mass one, the orbital period increases. Nevertheless, it is also known from the light curve analysis that in the HW Vir system, the low mass star has not filled its Roche lobe yet (see Sect. 4). For this reason it is not reasonable to account for the O–C deviations in terms of mass transfer.

2. Magnetic braking. It was stated by Patterson (1984) that no matter how small the rate of mass-loss is, magnetic braking would eventually cause a decrease in period. However, in the HW Vir system, since the low mass star is very much smaller than its own Roche lobe it becomes unrealistic to expect that the low mass star will lose mass through stellar wind. Besides, the variation of the orbital period of HW Vir shows an uniform decreasing pattern which would have shown increasing and decreasing

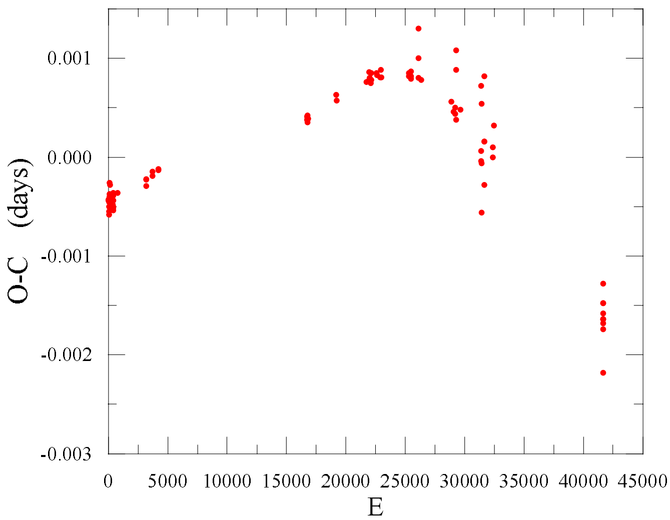

Fig. 2. The deviations between the observed and calculated times of minima

Table 2. The parameters of the third-body orbit

Element	Units	Value
Long Period P	year	19.28 ± 26
$a \sin i$	km	30.72 10^6 ± 63
Eccentricity e		0.508 ± 20
Longitude of Periastron ω	deg	341.7918 ± 2.44
Time of Periastron	JD	24 28434.0016 ± 276
$f(M_3)$	$M_\odot$	0.000023

portions otherwise. Therefore, neither magnetic braking is the likely mechanism that causes O–C deviations in the system.

3. A third body. Sinusoidal variations in O–C may be attributable either to an orbital motion around a third body or to apsidal motion. But the observational facts such as circular orbit inferred from the radial velocities (Hilditch et al. 1996) are the strongest evidence that would compel one to rule out the apsidal motion as a possible mechanism for period change. What remains behind is the possibility of orbital motion around a third body.

The additional time delay of any observed eclipse due to orbiting around a third–body can be represented by,

$$\Delta T = \frac{a \sin i}{c}[(1-e^2)\sin(v+\omega)/(1+e\cos v)+e\sin\omega]\,,$$

$c = 2.590\ 10^{10}$ km d^{-1} is the velocity of light. In this case the resulting eclipse ephemeris is given by, $t_{\rm ec} = t_0 + EP' + \Delta T$ where t_0 is the starting epoch, E is the integer eclipse cycle number. We have chosen Irwin's (1952, 1959) definition for the zero of the light-time effect. The linear least squares solution was applied in order to obtain the best fit and the standard deviations of the parameters calculated. The results are given in Table 2.

The final parameters, given in Table 2, were used to obtain the calculated light-time values and the computed

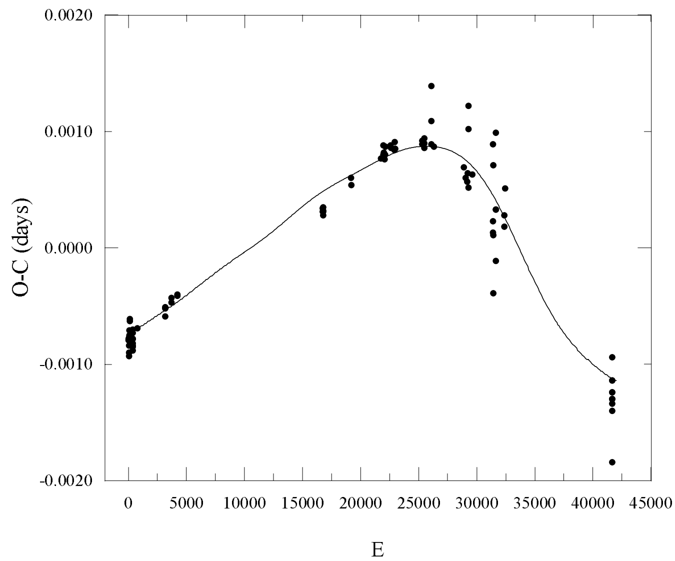

Fig. 3. O–C diagram for HW Vir

light-times were plotted in Fig. 3 along with the observed values. The fit seems to be quite good. The present analysis see to cover the 69 per cent of the whole cycle of the orbital motion. Further observations will justify or falsify the third body hypothesis.

Using the $a$sini value given in Table 2, the mass function has been computed to be 0.000023 $M_\odot$. Assuming a combined mass of 0.5 $M_\odot$ + 0.14 $M_\odot$ for the eclipsing pair the mass of the third body can be evaluated from the mass function depending on the inclination of the third-body orbit with respect to the plane of the sky. The mass of the third component was found to be 0.022 $M_\odot$ for inclination 90°, and 0.025 $M_\odot$ for the inclination 60°. For the inclination above 17° the mass computed by us would lead to a sub-stellar mass. Therefore, such a low mass of tertiary component would make it too faint for direct detection. If we assume the inclination is about 17° the mass of the third body would be 0.008 $M_\odot$. The visual magnitude of such a body would be $20^{\rm m}$ for the distance of 141 pc.

4. Light curve analysis

The first light curve of the system was obtained by Menzies & Marang (1986). Assuming that the temperature of the primary star is $T_1 = 26\ 000$ K they found that T_2 = 4500 K, r_1 = 0.203 and r_2 = 0.207. In the light curve analysis they used the Wilson Devinney (1971) differential correction programme. Using mass function they predicted the masses of components to be 0.25 $M_\odot$ and 0.12 $M_\odot$. Later, Wood et al. (1993) observed the system in *UBVR* and analyzed the light curves with the Wilson Devinney Code. In their analysis, although the radii of the components were consistent with the previous results, the temperatures of the primary star and the secondary one were predicted as 29 000 < T_1 < 36 000 K and $T_2 \sim 3700$ K, respectively. In the same analysis, the masses of the components were given as $M_1 = 0.50\ M_\odot$ and $M_2 = 0.15\ M_\odot$.

Although it has already been stated, we feel compelled to repeat again that since the system is very faint and the photometer we used is insensitive to short wavelengths, our observations in U band were scattered, as we expected.

In the analysis of the light curves the normal points were performed in each band. The $B(\lambda\ 4200)$, $V(\lambda\ 5400)$ and $R(\lambda\ 7000)$ light curves were represented by 51, 65 and 69 normal points, respectively.

The mass of sdB stars is given as $0.50\ M_\odot$ by Saffer et al. (1994). If we use this value in the mass function obtained by Hilditch et al. (1996), the mass of the companion star is found to be around $0.14\ M_\odot$ as noted earlier by Hilditch et al. For this reason we adopt the value of 0.28 for the mass ratio. Limb darkening coefficients play a very important role in light curve analysis. These coefficients depending on the temperatures of the stars are theoretically evaluated for the stars hotter than 5500 K. To the best knowledge of the authors of the present study there is no reference giving those coefficients for stars cooler than 5500 K. In the previous analysis of HW Vir, limb darkening coefficients of the cooler component are taken as those of a star with an effective temperature of 5500 K. In the present paper, limb darkening coefficients of sdB star for B, V and R colour are taken from Rucinski (1985) as 0.240, 0.199 and 0.162, respectively. Corresponding values for cooler low mass star are derived from light curve analysis. Gravity darkening coefficients for hotter star for all three colours are taken as 1.0 and for cooler star as 0.32. Bolometric albedo for hotter star for all three colours is assumed to be 1.0. If the mass of the cooler component is taken as $M_1 = 0.14\ M_\odot$ then its effective temperature should be 3300 K (Dorman et al. 1989). In the solution the above values are kept fixed.

The initial values of the parameters were performed by means of LC (Light Curve) program till a good approach to the observational data was obtained. Then the DC (Differential Corrections) was run iteratively until an acceptable stability of the solution was reached. The adjustable parameters were: orbital inclination (i), surface temperature of the hotter component (T_1), nondimensional potentials $\Omega_{1,2}$ of both components, luminosity of hotter star, the limb darkening coefficient and the albedo of the cooler star. The results are given in Table 3. The computed light curves using the parameters given in Table 3 were plotted in Fig. 4 with those of the normal points. The computed curves seem to fit well with the observed normal points.

Using the results of the radial velocity curve analysis we obtained the radius of the orbit as $0.89\ R_\odot$. The three – colour light curves were analysed simultaneously to obtain the radii of the components. The mean fractional radius of hotter and cooler component stars are 0.218 and 0.201,

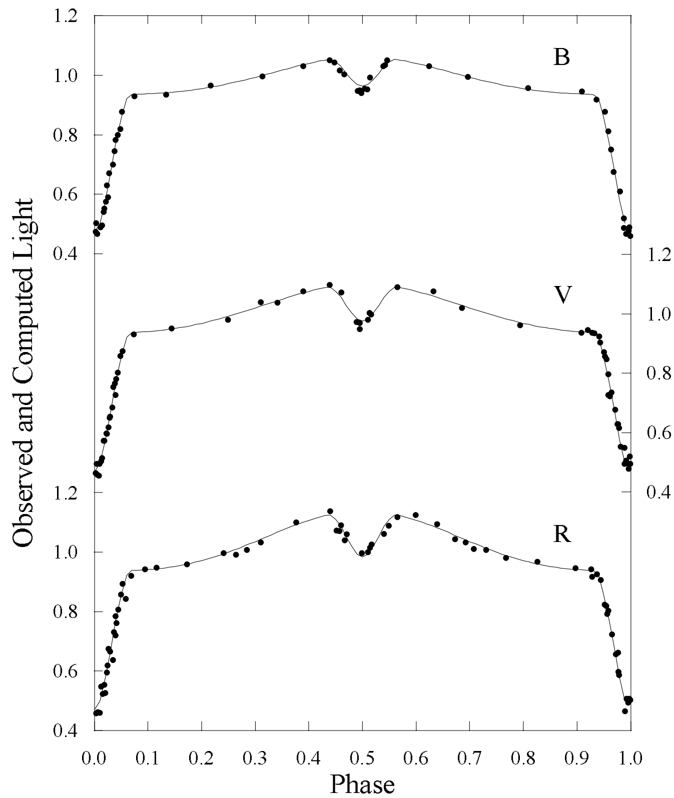

Fig. 4. The observed normal points in B, V and R are plotted against the orbital phase and compared with the computed curves. Note that the ordinate is intensity

respectively. The mass, radius and luminosity of the hotter primary star were calculated as 0.50, 0.21 and 55.628 solar units, whilst these parameters are 0.14, 0.20 and 0.0003 for the cooler secondary star. The critical Roche lobes of the components were calculated using the mass ratio of 0.28 and are shown in Fig. 5. As it is seen from this figure, both of the components are smaller than those of the corresponding Roche lobes. However the cooler secondary star is closer to its Roche lobe than is the primary star.

5. Conclusion and discussion

It is known that sdB stars represent part of the final stage of stellar evolution. As is already stated before, HW Vir is the progenitor of cataclysmic binary stars. As soon as the low mass main sequence component fills its Roche lobe the system is expected to become a cataclysmic binary star. HW Vir and the similar eclipsing binaries play a very important role in understanding the latest stages of stellar evolution. In Menzies & Marang (1986) the mass and the temperature of the sdB are $M_1 = 0.25\ M_\odot$ and 26 000 K, respectively. In the same paper, the luminosity of the primary is given as $6.53\ L_\odot$. However, Saffer et al. (1994) showed that the mass of a sdB star should be around $0.50\ \pm\ 0.01\ M_\odot$. For this reason we adopted the mass of sdB component in HW Vir as $0.50\ M_\odot$. Using the mass

Table 3. The results of the light curve analysis with WD Code

Parameters	B λ4200	V λ5400	R λ7000
a	0.89 $R_\odot$	0.89 $R_\odot$	0.89 $R_\odot$
i	81°.62 $\pm$ 0°.49	81°.02 $\pm$ 0°.11	82°.04 $\pm$ 0°.33
X_1	0.24	0.199	0.162
X_2	0.97	0.904 $\pm$ 0.024	0.887 $\pm$ 0.003
g_1	1.0	1.0	1.0
g_2	0.32	0.32	0.32
T_1	36320 $\pm$ 20 K	36411 $\pm$ 15 K	36900 $\pm$ 13 K
T_2	3300 K	3300 K	3300 K
A_1	1.0	1.0	1.0
A_2	0.755 $\pm$ 0.004	0.968 $\pm$ 0.007	0.968 $\pm$ 0.007
Ω_1	4.8443 $\pm$ 0.0023	4.8943 $\pm$ 0.0018	4.8943 $\pm$ 0.0016
Ω_2	3.2407	3.2407	3.2407
q	0.28	0.28	0.28
L_1	11.859 $\pm$ .0.031	11.859 $\pm$ .0.031	11.859 $\pm$ 0.031
L_2	0.0005	0.0032	0.0142
$r_{1(\mathrm{pole})}$	0.2211	0.2211	0.2211
$r_{1(\mathrm{point})}$	0.2245	0.2245	0.2245
$r_{1(\mathrm{side})}$	0.2228	0.2228	0.2228
$r_{1(\mathrm{back})}$	0.2240	0.2240	0.2240
$r_{2(\mathrm{pole})}$	0.1950	0.1950	0.1950
$r_{2(\mathrm{point})}$	0.2056	0.2056	0.2056
$r_{2(\mathrm{side})}$	0.1976	0.1976	0.1976
$r_{2(\mathrm{back})}$	0.2035	0.2035	0.2035
σ	0.0006	0.0004	0.0007

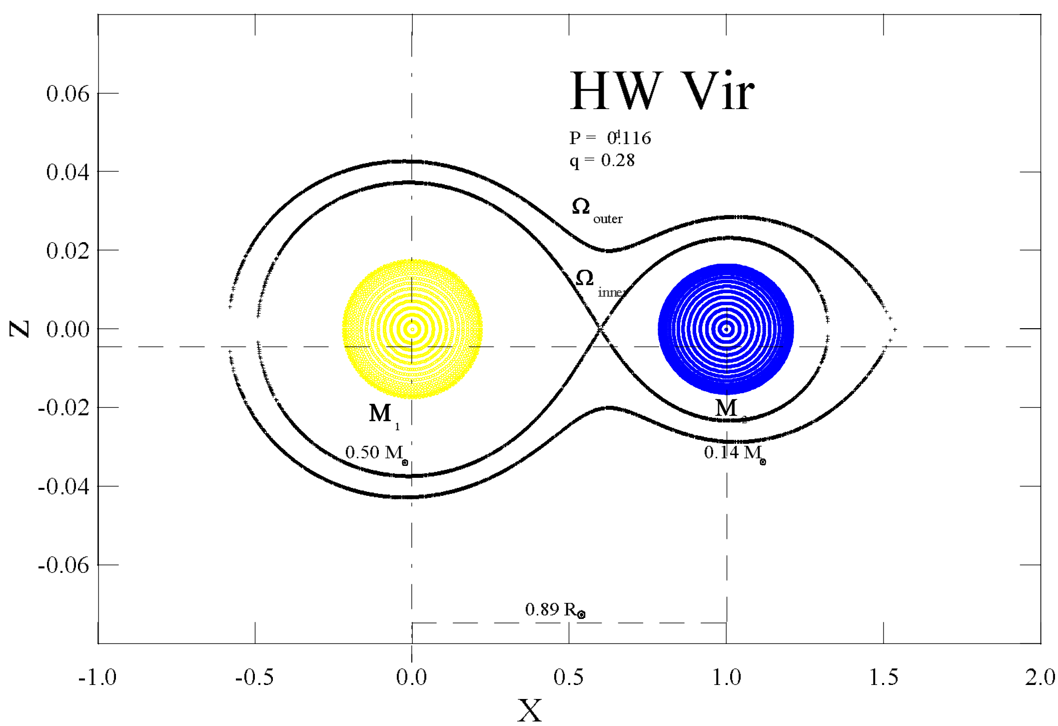

Fig. 5. Roche model geometry of the HW Virginis system from our data. The quantities presented are based on the orbital parameters (DC solutions) and the assumed absolute dimension of this system. The radii correspond to spheres of equal volume

function of Hilditch et al. (1996) we found the mass of the companion as 0.14 $M_{\odot}$. The values we calculated indicate that the luminosity of the hotter component of HW Vir should be as high as 55.6 $L_{\odot}$. In the diagram developed by Iben & Tutukov (1993) showing the latest stages of low mass stars, the hotter component of HW Vir falls between the evolutionary tracks of stars of 0.38 $M_{\odot}$ and 0.52 $M_{\odot}$. On the other hand temperature, radius and luminosity values of the low-mass component are consistent with the corresponding theoretical values that are calculated on the basis of assumed masses (Dorman et al. 1989), as shown also by Hilditch et al. (1996).

O–C variations of HW Vir obtained from data covering a 19 year period are assumed to be caused by orbital motion about a third body in the system. Based on this assumption, the analysis of the system implies that it is revolving around a third body on an elliptic orbit of the radius of 30.72 10^6 km with a period of 7040 days. The data that is gathered between the period 1984-1997 indicated that the system has completed 69 per cent of one whole cycle of the orbital motion. Observations of the system in the following years will test the justifiability of the third body hypothesis. The light curve analysis of the system indicates that the low mass component has just filled 80 per cent of its own Roche Lobe.

Acknowledgements. Our sincere thanks go to Dr. C. İbanoğlu; without his unsparing support this work would have not possibly come to its completion. We also thank Dr. R. Pekünlü who carefully read the manuscript. This study was partly supported by Ege University Science Foundation. This is part of the M.Sc. thesis presented by Ömür Çakırlı.

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