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An analysis of the light curves of the overcontact binary system V2388 Ophiuchi

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Abstract. We present four seasons' (2000–2003) ground-based photometry of the short-period contact binary V2388 Oph. The system is the brighter component of visual binary HIP 87655. The magnitude difference between the visual companion and the eclipsing pair was estimated to be $1\overset{m}{.}19$, $1\overset{m}{.}09$ and $1\overset{m}{.}09$ in B, V and R bandpasses, respectively. The light curves in BVR are solved by the WD code. Combining the parameters found by the light curve analysis with those of the radial velocity solution we derived the masses and radii of the star components as: $M_1 = 1.80(2)\ M_\odot$, $M_2 = 0.34(1)\ M_\odot$, $R_1 = 2.60(2)\ R_\odot$, $R_2 = 1.30(1)\ R_\odot$. The primary component appears to be more evolved in the mass-radius, mass-luminosity planes and also in the HR diagram. It lies near the terminal-age main-sequence, which agrees well with the position of deeper-contact A-type systems. The large fill-out factor of 0.65 does also support this classification.

Key words. stars: binaries: eclipsing – stars: binaries: visual – stars: fundamental parameters – stars: individual: V2388 Oph – techniques: photometric

1. Introduction

V2388 Oph (HIP 87655, $V_{\max} = 6\overset{m}{.}13$, $P = 0\overset{d}{.}80$) is a W UMa-type eclipsing binary system and the brighter component of the very close visual binary star CCDM J17542+1108 (Fin 381). Fin 381 is a 6th magnitude, close visual binary which has been the subject of many speckle-interferometry investigations. Hartkopf et al. (1996) obtained the first speckle orbit. Söderhjelm (1999) improved the orbital parameters of the visual system by combining ground-based data with the partly reduced Hipparcos data. Söderhjelm (1999) gives the revised orbital elements as $P = 8.9$ years, $a = 0\overset{''}{.}088$, $e = 0.32$, $i = 157°$, $\omega = 233°$ and $\Omega = 169°$. He also estimated the absolute magnitude difference between components as 1.80 mag. The variability of V2388 Oph (HD 163151) was discovered by Rodriguez et al. (1998) during the course of a photometric and multicolor multisite campaign on the γ Dor variable HD 164615. The star HD 163151 was used as one of the check stars. Its differential magnitudes with respect to the comparison and second check star were found to be variable and to show light curves similar to those of close binary systems. They determined the orbital period to be $0\overset{d}{.}8023$ and classified it as a W UMa-type eclipsing binary. The variability of HD 163151 was also discovered independently by the Hipparcos satellite mission (ESA 1997). Yakut & İbanoğlu (2000) observed this visual binary photometrically and obtained ground-based wide-band BVR light curves. Rucinski et al. (2002) has already published first and good radial velocity curves of the system.

The aim of this paper is to present and analyze new light curves of V2388 Oph and combine them with RV solution to derive the basic physical properties of the components.

2. New photometry and times of minimum light

The observations of V2388 Oph in Johnson U, B, V and R bands were carried out on 25 nights from May 5, 2000 to August 17, 2003 with the 48 cm Cassegrain and 30 cm Schmidt-Cassegrain telescopes of Ege University Observatory (EUO). We collected the data with $UBVR$ photometry using an uncooled single channel SSP-5 type photometer including the Hamamatsu R4457 detector attached to both telescopes. The aperture of the SSP-5 photometer is unchangeable and has a diameter of 1 mm which corresponds to about 67 arcsec for the 30 cm telescope and 33 arcsec for the 48 cm one. The standard observing sequence is s–c–v–v–s–v–v–c–s, where s is the sky background, c is the comparison star (HD 166095) and v is the variable star. An integration time of 10 s was used for each measurement in each filter. The journal of the observations is summarized in Table 1. The comparison star, also used by Rodriguez et al. (1998), was HD 166095. Since the constancy of the brightness for this star was already assured by Rodriguez et al., no additional check stars were observed. The differential observations, in the sense variable minus comparison, were corrected for atmospheric extinction

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Table 1. Date of the observations.

Year	Month, day	Telescope	Photometer, detector
2000	May, 7 June, 4, 10, 27 July, 8, 18, 23 August, 2, 3, 8, 9, 12, 23	48 cm, Cassegrain	SSP-5, Hamamatsu R4457
2001	May, 15, 27, 29, 31 June, 5, 15 July, 12, 16, 24	30 cm, Schmidt-Cassegrain	SSP-5, Hamamatsu R4457
2002	May, 5, 12	30 cm, Schmidt-Cassegrain	SSP-5, Hamamatsu R4457
2003	August, 17	30 cm, Schmidt-Cassegrain	SSP-5, Hamamatsu R4457

Table 2. Times of the primary and secondary minima in $\mathrm{JD_{hel}}$. The second column indicates rms of the mid-eclipses in the last decimal.

Times of min HJD 2 400 000+	Error	Epoch	O–C [day]	Ref.
49 878.4682	–	−15	−0.0018	Rodriguez et al. (1998)
49 886.4919	–	−5	−0.0011	Rodriguez et al. (1998)
49 890.5045	–	0	0.0000	Rodriguez et al. (1998)
51 569.7076	6	2093	−0.0108	This study
51 700.4852	9	2256	−0.0081	This study
51 749.430	1	2317	−0.0036	This study
51 780.320	2	2355.5	−0.0022	This study
52 400.515	2	3128.5	+0.0150	This study
52 869.436	1	3713	−0.0084	This study

using the extinction coefficients obtained for each night from the brightness variation of the comparison star. The standard deviations for each differential observation are estimated to be $0\overset{\mathrm{m}}{.}023$, $0\overset{\mathrm{m}}{.}013$, $0\overset{\mathrm{m}}{.}008$ and $0\overset{\mathrm{m}}{.}011$ for the U, B, V and R bands, respectively. The complete light curves of the system were obtained in three bandpasses in the year 2000 and four bandpasses in the year 2001. The light curves obtained in the year 2000 have already been published by Yakut & İbanoğlu (2000). The light and color changes with respect to the comparison star are shown in Figs. 1 and 2. The observations made in 2002 and 2003 were only used for determining new times of minimum light.

The phases were calculated using the following ephemeris given by Rodriguez et al. (1998),

$$\mathrm{HJD\,min}I = 2\,449\,890.5045 + 0\overset{\mathrm{d}}{.}8023 \times E. \quad (1)$$

Six times of minimum light were derived using the method of Kwee & van Woerden (1956). These are listed in Table 2 together with the previously obtained timings. The O–C residuals indicate the difference between observed and calculated times using the ephemeris given by Rodriguez et al. (1998).

3. Analysis of the O–C curve

Since the eclipsing pair is the brighter component of a very close visual binary, it should revolve around the center of mass with a visual companion. The parameters of the third-body orbit were determined by Söderhjelm (1999). The additional time delay of any observed eclipse due to orbiting around a third body is given by Mayer (1990)

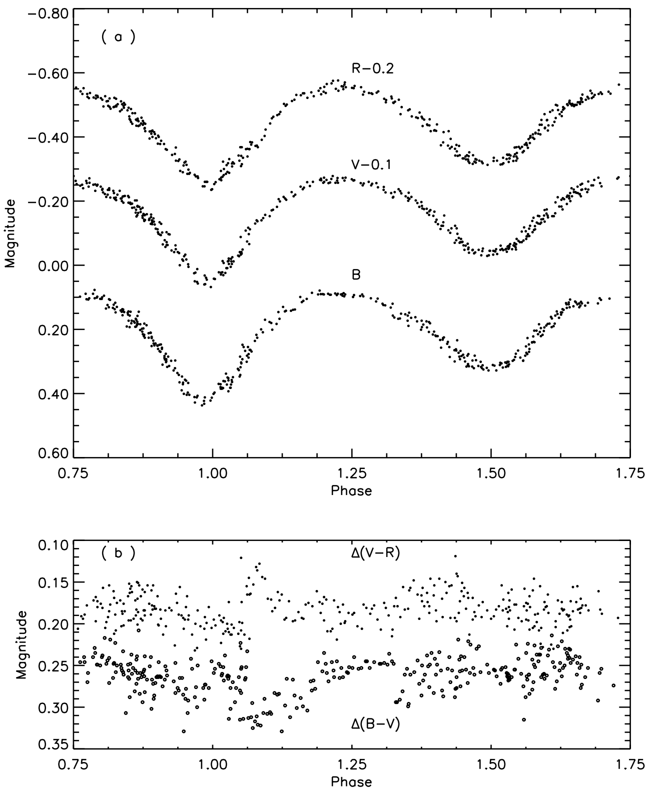

Fig. 1. a) The B, V and R light curves of V2388 Oph in 2000, and **b)** color changes against orbital phase.

$$\Delta T = \frac{A}{\sqrt{1-e^2\cos^2 w}}\left[\frac{1-e^2}{1+e\cos v}\sin(v+\omega)+e\sin\omega\right] \quad (2)$$

where A is the semi-amplitude of the light-time effect. In this case the resulting eclipse ephemeris is,

$$T_{\mathrm{ecl}} = T_1 + EP_1 + \Delta T \quad (3)$$

where T_1 is the starting epoch, E is the integer eclipse cycle number and P_1 is the orbital period of the contact binary. Taking $\omega_{12} = \omega_3 + 180°$ and the parameters listed by Söderhjelm (1999) we calculated ΔT values for each timings. The light-time effect was compared in Fig. 3 with the residuals for times of minimum light with respect to the linear light

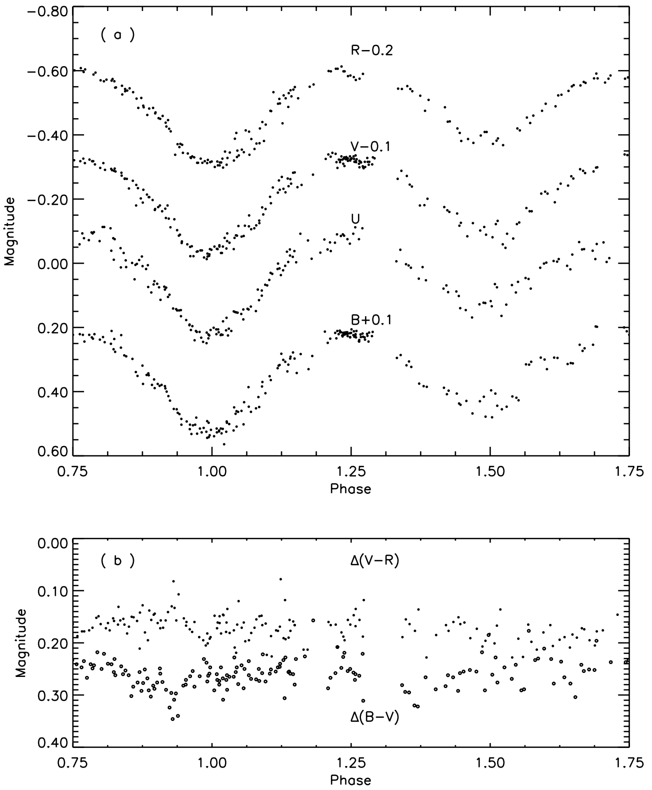

Fig. 2. a) The U, B, V and R light curves of V2388 Oph obtained in 2001, and **b)** color changes against orbital phase.

elements. Neither the available O–C data nor the baseline is adequate for the determination of the parameters of the third body. Therefore, by taking the parameters of the third-body orbit given by Soderhjelm (1999) as constant we revised the light elements of the contact binary. We find the light elements of the system as,

$$\mathrm{HJD\,min}I = 2\,449\,890.5110(4) + 0.8022981(2) \times E. \qquad (4)$$

The orbital period of the eclipsing pair, we find, is very close to that obtained by Rodriguez et al. (1998). Since the system is a contact binary, continuing mass-transfer between the components should affect the O–C variation. If the mass transfer is large enough, a parabolic O–C change is expected. This variation will be parabolic in shape superimposed on the variation due to a third body as in the case of XY Leo (Yakut et al. 2003). However, the observational data base is not yet adequate to draw any conclusion at the present time.

4. Light-curve analysis

The light curve of V2388 Oph shows the following peculiarities: a) the secondary eclipse is asymmetric and distorted, b) the maxima are asymmetric and this seems to be more apparent towards the longer wavelengths and c) there are narrow light depressions.

The secondary minimum is a grazing total eclipse of which the egress is steeper than the ingress. The unequal height of the maxima is one of the main characteristics of contact systems.

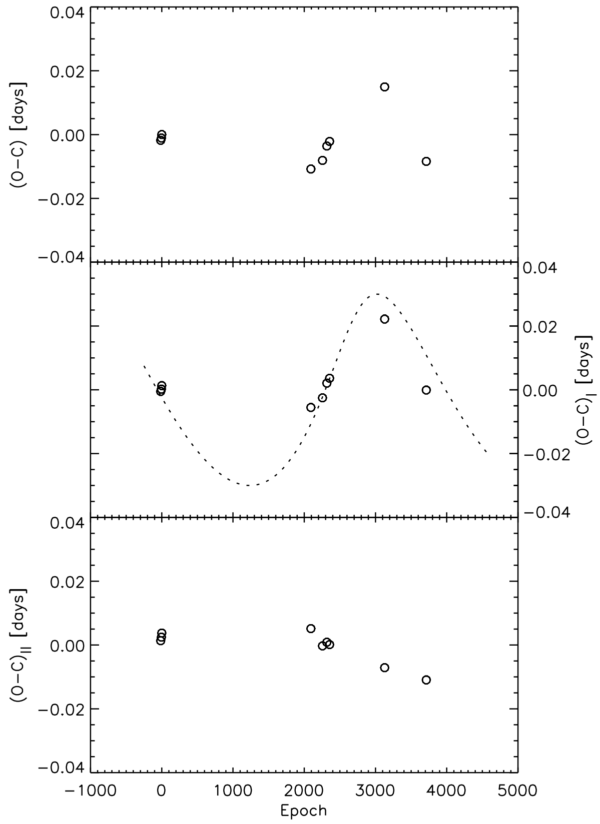

Fig. 3. a) The (O–C) diagram for V2388 Oph. **b)** The (O–C)$_I$ diagram obtained with the new light elements given in Eq. (4). The dashed curve represents a light-time effect for the third-body orbit with a period of 8.9 years and an amplitude of about 0.06 days. **c)** The (O–C)$_{II}$ diagram after subtraction of the light-time effect.

This difference between the maxima could originate either from mass transfer between the components or from surface inhomogeneities in one or both components. Such an asymmetry could be reproduced by both hot and cool spots, if it originates from surface inhomogeneities. The narrow light depression is seen at about phase 0.1 in the light curve obtained in the year 2000. At this phase the $B-V$ colour gets redder while the $V-R$ is bluer. Such a variation has been seen just before mid-primary eclipse, i.e. at phase ~0.9 in the light curve obtained in the year 2001. Although this feature is near the limit of detection, there are sufficient data points in the feature, and the depression in phase 0.1 was observed on two different nights, indicating repeatability. When these events were observed the star was fairly far from the horizon which indicates that it may not be related to atmospheric effects. In addition no variation in the brightness of the comparison star was observed at these phases. The width of the feature is small when compared with the main eclipses, which suggests that a compact volume is occulting or being occulted by one of the two components. Since its phase is displaced from the primary minimum, this volume would need to be separate from the stellar components. Localized cool occulting material orbiting the more massive star seems to be more plausible because the light contribution of the more massive component to the total light exceeds 80%. Such narrow features are typical for semi-detached

Algol-type binaries (Walter 1973; Arevalo et al. 1995). Similar photometric depressions were also detected in the short-period chromospherically active stars: CG Cyg by Bedford et al. (1987), XY UMa by Kjurkchieva et al. (2000a), SV Cam by Kjurkchieva et al. (2000b) and RT And by Kjurkchieva et al. (2001). These photometric depressions in the light of some detached, semi-detached and also contact binaries were usually attributed to the presence of a gas stream between the component stars or to a circum-binary shell of cool material. Further high quality photometry is necessary to reveal whether it may be attributed to systematic effects or is intrinsic to the binary system.

We computed the ΔT value in Eq. (3) for each measurement and subtracted it from the original observing times. Then, we recalculated orbital phases for each measurement. Combining all differential magnitudes in each filter in 2000 and 2001 we solved for the orbital parameters. Since the U-band light curve was obtained only in the year 2001, and the available data seem to be insufficient for analysis we excluded it from analysis. The 1998 version of the Wilson–Devinney code (Wilson & Devinney 1971; Wilson 1994) was employed for our light curve analysis. Mode 3 was used, which assumes that both of the components filled their Roche lobes. The following values are adopted for the light-curve analysis: the temperature of the primary component was set at $T_1 = 6900$ K according to Drilling & Landolt (2000) which corresponds to spectral type of an F3V star (Rucinski et al. 2002), the mass ratio $q = 0.186$ is taken from Rucinski et al. (2002), the values of the gravity darkening coefficients $g_1 = g_2 = 0.32$ (Lucy 1967), the limb darkening coefficients $x_1 = x_2 = 0.727$ for B, 0.623 for V and 0.548 for R band (Claret 2000) and the values of the albedo $A_1 = A_2 = 0.5$ (Rucinski 1969). The adjustable parameters are inclination i, the temperature of the secondary component T_2, the luminosity L_1, the surface potential Ω and the phase shift ϕ_0. As was stated in the introduction, V2388 Oph is the bright component of the visual binary system. Therefore, the light curves were analyzed by assuming that there was a third-light in the system and the last adjustable parameter was the third light for B, V and R colors. Initial values of l_3 were taken from Rodriguez et al. (1998). We combined all the observations obtained in 2000 and 2001 and solved B, V and R light curves simultaneously. The differential correction code was run until the corrections to the input parameters were lower than their errors. The program rapidly and robustly converged to the final orbital values as well as the component parameters. The results are given in Table 3. The derived value of Ω and spectroscopic mass ratio q confirm that V2388 Oph has a high degree of overcontact with a contact parameter of $f = 0.65$. The values of Ω and q also imply that the eclipses would be partial if $i < 74\overset{\circ}{.}4$, confirming that V2388 Oph is on the limit of total secondary and annular primary eclipse. We also analyzed the BV light curves of the system obtained by Rodriguez et al. We assumed the same initial parameters and followed the same procedure. In the third column of Table 3 the results of this solution are also presented for comparison. The parameters seem to comparable within 3σ. However, the results obtained from the intermediate ubvy light curves are too different. They assumed slightly different input parameters than those used in our analysis. Moreover, Rodriguez et al. put a hot spot on the primary component. Such a spot distorts the light curves, so one obtains different parameters.

Table 3. Photometric elements of V2388 Oph and their standard deviations σ. The last column indicates the results of previous light curves obtained by Rodriguez et al. TS: this study, R: Rodriguez et al.

Parameter		$(BVR)_{\rm TS}$	$(BV)_{\rm R}$
i (°)		74.7(7)	76.6(1.5)
T_2 (K)		6349(23)	6505(53)
$\Omega_1 = \Omega_2$		2.120(5)	2.114(13)
ϕ		−0.0085(3)	−0.001(1)
$(\frac{L_1}{L_1+L_2})$	B	0.859(17)	0.843(35)
	V	0.848(16)	0.834(31)
	R	0.844(15)	–
$(\frac{L_2}{L_1+L_2})$	B	0.141	0.157
	V	0.152	0.166
	R	0.156	–
l_3	B	0.249(12)	0.284(24)
	V	0.265(13)	0.292(22)
	R	0.265(12)	–
$r_{1_{\rm pole}}$		0.511(1)	0.513(1)
$r_{1_{\rm side}}$		0.565(2)	0.568(2)
$r_{1_{\rm back}}$		0.593(2)	0.597(2)
$r_{2_{\rm pole}}$		0.250(1)	0.252(2)
$r_{2_{\rm side}}$		0.264(1)	0.266(2)
$r_{2_{\rm back}}$		0.326(5)	0.233(6)

The temperature of V2388 Oph falls within the transition region of about 7000 K which separates the hotter stars with radiative envelopes ($g = 1.0$, $A = 1.0$) from the cooler stars with convective envelopes ($g = 0.32$, $A = 0.5$) according to Rafert & Twigg (1980). However, current WD models do not take into account the star-to-star convection necessary for energy balance. So the light curves were re-analyzed under the hypothesis of radiative envelopes. The results are almost the same as those of the convective-envelope solution except small fluctuations in some parameters. The LC program was used to create the synthetic light curve shown in Fig. 4. Figure 5 shows a three-dimensional representation of the binary system.

Wilson (1992) clarified the meaning of the third light. As he stated, many papers have listed values of the third light, with no indication of what the number means. His suggestion about the unit of l_3 was to express it in the light curve of the triple star system at a definite phase. Thus the value of l_3 in units of total triple system light were found to be 0.251(4), 0.267(13) and 0.267(12) in B, V and R bandpasses, respectively at the reference phase 0.25. Knowing the light contributions of the stars to the total light, the ratios of l_3/l_1, l_3/l_2 and $l_3/(l_1 + l_2)$ were simply calculated to be 0.399, 2.112 and 0.335 for the B band; 0.437, 2.189 and 0.365 for the V band; 0.440, 2.131 and 0.365 for the R band. Using the ratios given above we found the magnitude difference between the third star and the eclipsing pair as $1\overset{\rm m}{.}19(6)$, $1\overset{\rm m}{.}09(5)$ and $1\overset{\rm m}{.}09(4)$ for the B, V and R bandpasses, respectively. Söderhjelm (1999) estimated the absolute magnitude difference to be $1\overset{\rm m}{.}80$ by combining the Hipparcos astrometry with existing ground-based observations. On the other

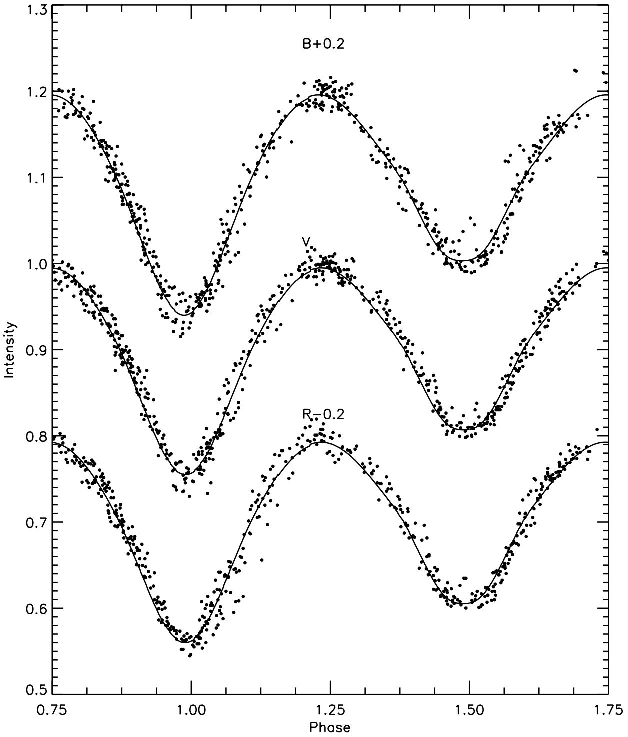

Fig. 4. A comparison of the observed (dots) and computed (solid line) *B*, *V* and *R* light curves of V2388 Oph obtained in the year 2000 and 2001. The curves in *B* and *R* bands are moved by +0.2 and −0.2 in intensity for a good visibility.

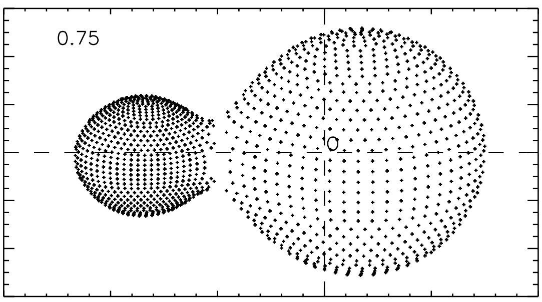

Fig. 5. 3-D representation of the V2388 Oph at phase 0.75.

hand, Rucinski et al. (2002) estimated a magnitude difference of $1\overset{\mathrm{m}}{.}75$ based on the broadening function. We calculated the total visual magnitude of the triple system as $6\overset{\mathrm{m}}{.}16(1)$ using the *V*-magnitude of the comparison taken from SIMBAD as $6\overset{\mathrm{m}}{.}328$. Since the parallax of the system was given by Hipparcos as 14.72 mas, we estimate the absolute visual magnitude of the triple system as $M_{\rm V} = 1\overset{\mathrm{m}}{.}20(1)$ ignoring the interstellar extinction. Hence, we find the absolute visual magnitude of the contact system to be $2\overset{\mathrm{m}}{.}33(6)$. The absolute visual magnitude of the system was also calculated using the calibration of Rucinski & Duerbeck (1997, their Eq. (1)) for $(B-V)_0 = 0.41$ and found to be $2\overset{\mathrm{m}}{.}25$ which is in good agreement with our estimate. These values put the system among the most luminous contact systems. This result is in agreement with that suggested independently by Rucinski et al. (1997).

Table 4. Absolute parameters for V2388 Oph. Errors in the table expressed in units of last decimal places are given in parentheses after each value.

Parameter		Primary	Secondary
Mass	$[M_\odot]$	1.80 (2)	0.34 (1)
Radius	$[R_\odot]$	2.60 (2)	1.30 (1)
Effective temperature	[K]	6900 (fixed)	6349 (23)
Luminosity	$[L_\odot]$	13.5 (1.9)	2.43 (7)
Surface gravity (log *g*)	cm s^{-2}	3.86	3.74
Absolute visual magnitude	mag	$1\overset{\mathrm{m}}{.}95$ (13)	$3\overset{\mathrm{m}}{.}82$ (13)
Distance	pc	68 (4)	

5. Basic physical properties of the system

The radial-velocity study made recently by Rucinski et al. (2002) gives $K_1 = 44.62$ km s^{-1}, $K_2 = 240.22$ km s^{-1} and $q_{\rm sp} = 0.186$. Combining these values with the orbital period of the system we find $a \sin i = 4.51\ R_\odot$ and $(m_1 + m_2)\sin^3 i = 1.921\ M_\odot$. Since the inclination of the orbit with respect to the plane of the sky was derived by the light curve analysis one can derive the absolute parameters of the system listed in Table 4. The standard errors of the parameters in Table 4 are expressed in units of last decimal places quoted. The primary component of V2388 Oph appears to be among the largest and more luminous primaries of contact binaries in the mass-radius and mass-luminosity diagrams given by Hilditch et al. (1988).

6. Discussion and conclusions

We have obtained a model for V2388 Oph using the Wilson-Devinney code for computing light curves of a binary system. The light curve of this overcontact binary is almost symmetrical despite a small difference between the height of the maxima. The deeper primary eclipse is the transit but the secondary eclipse is the occultation. Solutions with a hot spot on the primary component were also considered but did not change the parameters of the system appreciably. Since V2388 Oph is the brighter component of the visual binary HIP 87655 we derived the magnitude difference between visual companion and the eclipsing pair to be $1\overset{\mathrm{m}}{.}19$, $1\overset{\mathrm{m}}{.}09$ and $1\overset{\mathrm{m}}{.}09$ in *B*, *V* and *R* bandpasses, respectively.

The fill-out factor of 0.65 was found to be in agreement with those for W UMa A-type binaries (see Rucinski 1985). The primary component of the V2388 Oph system appears to be more evolved in the mass-radius and mass-luminosity planes and in the HR diagram. Since the derived mass and radius do not significantly depend upon the adopted effective temperature the principal indicator of the evolutionary state of the primary was considered to be its location on the mass-radius diagram. The primary component lies near the terminal-age main-sequence, which agrees well with the position of deeper-contact A-type systems: they all have substantially larger radii than expected for zero-age main-sequence masses. The larger radius for the secondary of the V2388 Oph also supports this conclusion. According to its mass the secondary is more over-luminous in the mass-luminosity diagram, which is in agreement again for the A-type contact systems. However, the specific angular momentum of V2388 Oph seems to be somewhat higher than the contact systems (see Hilditch et al. 1988, their Fig. 3). This overcontact system appears to be one of the most luminous among known contact binaries.

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