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# A SOLAR-TYPE STELLAR COMPANION TO A DEEP CONTACT BINARY IN A QUADRUPLE SYSTEM

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## ABSTRACT

The four-color ($B$, $V$, $R_c$, $I_c$) light curves of V776 Cas are presented and analyzed using the Wilson–Devinney method. It is discovered that V776 Cas is an early F-type (F2V) overcontact binary with a very high contact degree ($f = 64.6\%$) and an extremely low-mass ratio ($q = 0.130$), which indicate that it is at the final evolutionary stage of cool short-period binaries. The mass of the primary and secondary stars are calculated to be $M_1 = 1.55$ $(\pm0.04)\,M_\odot$, $M_2 = 0.20(\pm0.01)\,M_\odot$. V776 Cas is supposed to be formed from an initially detached binary system via the loss of angular momentum due to the magnetic wind. The initial masses of the present primary and secondary components are calculated to be $M_{1i} = 0.86(\pm0.10)\,M_\odot$ and $M_{2i} = 2.13(\pm0.04)\,M_\odot$. The observed–calculated curve exhibits a cyclic period variation, which is due to the light-travel time effect caused by the presence of a third component with a period of 23.7 years. The mass of the third component is estimated to be $M_3 = 1.04(\pm0.03)\,M_\odot$ and the orbital inclination of the third component is calculated to be $i' = 33\overset{\circ}{.}1$. The distance of the binary system to the mass center of the triple system is calculated to be $a'_{12} = 3.45$ AU. The presence of the close-in tertiary component may play an important role in the formation and evolution of this binary system by drawing angular momentum from the central system.

*Key words:* binaries: close – binaries: eclipsing – stars: evolution – stars: individual (V776 Cas)

## 1. INTRODUCTION

V776 Cas (BD+69 0121, HIP 8821, $V = 9\overset{m}{.}09$) is the brighter member of the visual binary ADS 1485. The companion, at a separation of $5\overset{''}{.}38$, is 2 mag fainter than the contact binary. V776 Cas was discovered as an eclipsing binary with a small amplitude by the *Hipparcos* mission (Lindegren 1997). Duerbeck (1997) classified its spectral type as F0, its color index as $B - V = 0.525$ mag, and its variability to range from 8.943 to 9.090 mag in the $V$-band, but also found the period of the binary system to be $P = 0.8808$ days, which was nearly twice that of the actual period ($P = 0.44041574$ days). The binary star was observed photometrically by Gomez-Forrellad et al. (1999), who assumed the star to be an EW-type undergoing marginal eclipses or an ellipsoidal variable. Their $V$-band light curve observed by using a 14-cm telescope at the Piera Observatory showed that the primary minimum was 0.019 mag deeper than the secondary one. Rucinski et al. (2001) obtained the first spectroscopic elements of the system: mass ratio $q = 0.130 \pm 0.004$, $V_\gamma = -24.71 \pm 0.69\ \mathrm{km\,s^{-1}}$, $(M_1 + M_2)\sin^3 i = 0.975 \pm 0.026\,M_\odot$. They pointed out that V776 Cas was an A-subtype W UMa binary system with a spectral type of F2V. After that, photometric analysis of V776 Cas was carried out by Djurašević et al. (2004), Elmasli et al. (2004), Zola et al. (2005), and Oh et al. (2007). D'Angelo et al. (2006) discovered that V776 Cas was a triple system with a solar-type tertiary component, and the spectroscopic observations gave the fitted temperature to be $T_3 = 6100$ K. They also gave the mass ratio to be $M_3/M_1 = 0.67$. Ghaderi et al. (2012) also analyzed the radial velocity curves of V776 Cas and obtained its orbital parameters, which were almost consistent with those obtained by Rucinski et al. (2001).

There are many different types of close binaries and there is not a single formation scenario for all types. Two evolutionary mechanisms are proposed for this problem: nuclear evolution and angular momentum evolution (Hilditch et al. 1988). Webbink's (1976) model suggested that the primary component in the binary system expanded first and filled the Roche lobe on its way to the red giant branch, then the mass transfer occurred and led the initially detached binary system to be a contact one via a case a mass transfer. However, angular momentum evolution via magnetic braking (Schatzman 1962; Mestel 1968) was thought to be the main mechanism for the formation and evolution of W UMa-type contact binaries by Okamoto & Sato (1970), vant Veer (1979), and Vilhu (1982). A possible scenario is that W UMa-type binaries are formed from low-mass detached close binaries through the loss of angular momentum due to the magnetic wind, and the binary systems finally merged, thus forming blue stragglers (Tutukov et al. 2004). A new method was established to compute the initial mass and orbital evolution of W UMa-type contact binaries (Yıldız & Doğan 2013; Yıldız 2014). The results suggested that binary systems with an initial mass (the initially more massive one) higher than 1.8 $M_\odot$ evolved to be A-subtype systems while systems with an initial mass lower than this became W-subtype systems. For the binary systems with an initial mass higher than 1.8 $M_\odot$, the nuclear evolution is the principal mechanism responsible for the Roche lobe filling process, while the binary systems with an initial mass less than 1.8 $M_\odot$ evolve into the contact phase mainly due to the rapid angular momentum evolution. More detailed analyses of W UMa-type binary systems are needed to test the theory in the future.

V776 Cas is a typical A-subtype W UMa-type overcontact binary system with a close-in stellar component and a distant visual component. Orbital properties of the close-in tertiary component will provide valuable information on the formation of close binaries and stellar dynamical interaction. However,

**Table 1**
Coordinates of V776 Cas, the Comparison, and the Check Stars

| Targets | Name | $\alpha_{2000}$ | $\delta_{2000}$ | $V_{mag}$ |
|---|---|---|---|---|
| Variable | V776 Cas | $01^h53^m23^s.4$ | $+70°02'33''.4$ | 9.09 |
| The comparison | GSC 04314-00961 | $01^h52^m32^s.2$ | $+70°04'01''.7$ | 11.12 |
| The check | GSC 04314-00473 | $01^h52^m57^s.7$ | $+70°04'29''.5$ | 12.49 |

the orbital period variations of V776 Cas have been neglected since it was discovered, which is a very important part of the research of contact binary stars. As discussed by Liao & Qian (2010), the most plausible explanation of the cyclic period changes in close binaries is the light-travel time effect (LTTE) caused by the presence of the tertiary component around the binary system. And the survey of Tokovinin et al. (2006) implied that the close-in tertiary around the close binary may play an important role in the formation and evolution of a close binary by shortening the orbital period of the binary system through transferring angular momentum from the central binary system. In the present paper, four-color ($B$ $V$ $R_c$ $I_c$) light curves of V776 Cas are obtained and analyzed. All available times of light minimum are collected and the observed times of light minimum-calculated times of a light minimum observed–calculated (O–C) curve are presented for the first time. Based on the spectroscopic elements, photometric analyses, and the O–C fitting results, the absolute physical parameters of the close binary system and the close-in tertiary component are obtained. It will give us a comprehensive understanding of this close binary system and be an excellent target to test the formation scenario of W UMa-type contact binaries.

## 2. OBSERVATIONS

The $B$-, $V$-, $R_c$-, and $I_c$-band light curves of V776 Cas were carried out in three nights on January 10 and 16, and February 27, 2013 with an Andor DW436 1K CCD camera attached to the 85cm reflecting telescope at the Xinglong Observation Base. The coordinates of the variable star, the comparison star, and the check star are listed in Table 1. The integration times were 15s for the $B$-band, 10s for the $V$-band, 6s for the $R_c$-band, and 5s for the $I_c$-band, respectively. The light curves of those observations are displayed in Figure 1.

During the observations, the broadband Johnson–Cousins $B$ $V$ $R_c$ $I_c$ filters were used. PHOT (measured magnitudes for a list of stars) of the aperture photometry package in the IRAF [6] was used to reduce the observed images.

Times of light minimum of V776 Cas were also observed and determined, which were listed in Table 2.

## 3. ORBITAL PERIOD INVESTIGATION OF V776 CAS

The study of orbital period change is a very important part of understanding contact binary systems. However, the period change investigation of V776 Cas has been neglected since it was discovered. In the present work, all available times of light minimum are collected. Minimum times with the same epoch have been averaged, and only the mean values are listed in Table 3. Using the following linear ephemeris,

$$\mathrm{Min.I(HJD)} = 2456249.2172 + 0^{\mathrm{d}}.44041574 \times E, \quad (1)$$

the O–C values are calculated and listed in the fourth column of Table 3 and plotted in the upper panel of Figure 2. Based on the least-square method, the new ephemeris is

$$\begin{aligned}\mathrm{Min.I} = {} & 2456249.2107(\pm 0.0001) \\ & + 0.440416842(\pm 0.000000009) \times E \\ & + 0.0109(\pm 0.0001)\sin[0^{\circ}.01829 \\ & \times E + 130^{\circ}.9(\pm 0^{\circ}.6)]. \quad (2)\end{aligned}$$

The sinusoidal term reveals a cyclic change with a period of 23.7 years and an amplitude of 0.0109 days. The residuals from Equation (2) are displayed in the bottom panel of Figure 2.

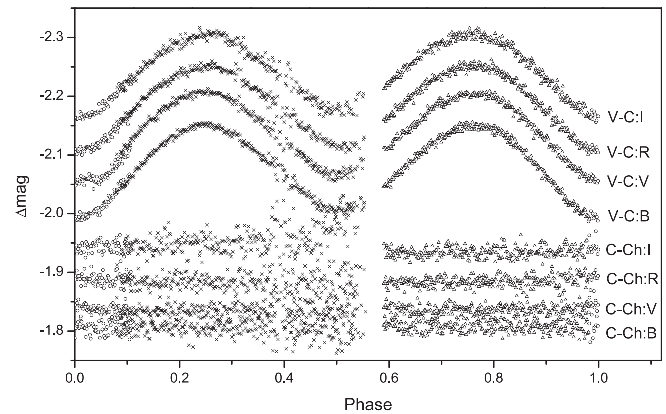


**Figure 1.** CCD photometric light curves in the $B$-, $V$-, $R_c$-, and $I_c$-bands. The magnitude difference between the comparison and the check stars is presented. The standard deviations of the comparison-check observations are 0.012 mag for the $B$-band, 0.010 mag for the $V$-band, 0.012 mag for the $R_c$-band and 0.019 mag for the $I_c$-band. Crosses, triangles, and open circles correspond to the data observed on January 10, January 16, and February 27, respectively.

**Table 2**
New CCD Times of Light Minimum for V776 Cas

| JD (Hel.) | Error (days) | Min. | Filter | Method | Telescopes |
|---|---|---|---|---|---|
| 2454781.3140 | ±0.0003 | I | $V$ | CCD | 85 cm |
| 2454816.9898 | ±0.0003 | I | $V$ | CCD | 50 cm |
| 2456243.0517 | ±0.0042 | I | $N$ | CCD | 1 m |
| 2456249.2172 | ±0.0004 | I | $N$ | CCD | 60 cm |
| 2456253.1826 | ±0.0021 | I | $VR_cI_c$ | CCD | 60 cm |
| 2456350.9589 | ±0.0066 | I | $BVR_cI_c$ | CCD | 85 cm |

**Note.** 60 cm and 1 m correspond to the 60 cm and 1 m reflecting telescope of the Yunnan Observatories. 50 and 85 cm correspond to the 50 and 85 cm reflecting telescope at the Xinglong Observation Base.

## 4. PHOTOMETRIC SOLUTIONS OF V776 CAS

As shown in Figure 1, the variations of light curves in four colors are continuous and have very small magnitude differences between the depth of the primary minimum and the secondary one, which indicates that V776 Cas is a typical EW-type contact binary. In Figure 1, the light curves have been shifted vertically, which will make no difference to the results of Wilson–Devinney (W–D) program, as differential photometry method is used. The phases are calculated with the

[6] The Image Reduction and Analysis Facility is hosted by the National Optical Astronomy Observatories in Tucson, Arizona (iraf.noao.edu).

**Table 3**
(O–C) Values of Light Minima for V776 Cas

| JD (Hel.) (2400000+) | Min | Epoch | (O–C) | Error | Method | Reference |
|---|---|---|---|---|---|---|
| 47941.2021 | I | −18864 | −0.0126 | ⋯ | CCD | 1 |
| 48025.0820 | II | −18673.5 | −0.0319 | ⋯ | CCD | 1 |
| 48072.4360 | I | −18566 | −0.0226 | ⋯ | CCD | 1 |
| 48160.7468 | II | −18365.5 | −0.0151 | ⋯ | CCD | 1 |
| 48226.1370 | I | −18217 | −0.0267 | ⋯ | CCD | 1 |
| 48370.8188 | II | −17888.5 | −0.0214 | 0.0011 | CCD | 1 |
| 48371.0347 | I | −17888 | −0.0257 | 0.0011 | CCD | 1 |
| 48433.3500 | II | −17746.5 | −0.0293 | ⋯ | CCD | 1 |
| 48500.0850 | I | −17595 | −0.0173 | 0.0001 | CCD | 2 |
| 48611.5045 | I | −17342 | −0.0229 | ⋯ | CCD | 1 |
| 50814.8957 | I | −12339 | −0.0317 | ⋯ | CCD | 3 |
| 51788.2184 | I | −10129 | −0.0278 | 0.0008 | CCD | 3 |
| 52556.3107 | I | −8385 | −0.0205 | 0.0005 | CCD | 4 |
| 52556.5306 | II | −8384.5 | −0.0208 | 0.0004 | CCD | 4 |
| 52932.4331 | I | −7531 | −0.0132 | ⋯ | CCD | 1 |
| 52937.4908 | II | −7519.5 | −0.0202 | ⋯ | CCD | 1 |
| 53086.1374 | I | −7182 | −0.0140 | 0.0001 | CCD | 5 |
| 53351.7116 | I | −6579 | −0.0105 | 0.0001 | CCD | 6 |
| 53966.5385 | I | −5183 | −0.0040 | 0.0007 | CCD | 7 |
| 54039.4274 | II | −5017.5 | −0.0038 | 0.0004 | CCD | 8 |
| 54093.6015 | II | −4894.5 | −0.0009 | 0.0003 | CCD | 9 |
| 54700.4962 | II | −3516.5 | −0.0009 | 0.0004 | CCD | 10 |
| 54781.3140 | I | −3333 | 0.0025 | 0.0003 | CCD | 22 |
| 54788.3554 | I | −3317 | −0.0028 | 0.0002 | CCD | 11 |
| 54816.9898 | I | −3252 | 0.0046 | 0.0003 | CCD | 22 |
| 54819.6290 | I | −3246 | 0.0013 | 0.0002 | CCD | 12 |
| 55154.3451 | I | −2486 | 0.0014 | 0.0028 | CCD | 13 |
| 55202.5705 | II | −2376.5 | 0.0013 | 0.0005 | CCD | 14 |
| 55223.2688 | II | −2329.5 | 0.0001 | 0.0003 | CCD | 15 |
| 55397.4509 | I | −1934 | −0.0023 | 0.0008 | CCD | 15 |
| 55421.4527 | II | −1879.5 | −0.0031 | 0.0006 | CCD | 15 |
| 55475.4078 | I | −1757 | 0.0011 | 0.0006 | CCD | 15 |
| 55779.5150 | II | −1066.5 | 0.0012 | 0.0006 | CCD | 16 |
| 55804.3990 | I | −1010 | 0.0017 | 0.0163 | CCD | 17 |
| 55872.6655 | I | −855 | 0.0038 | 0.0004 | CCD | 18 |
| 56155.4089 | I | −213 | 0.0003 | 0.0003 | CCD | 19 |
| 56156.5120 | II | −210.5 | 0.0023 | 0.0008 | CCD | 16 |
| 56220.3713 | II | −65.5 | 0.0013 | 0.0139 | CCD | 20 |
| 56221.2511 | II | −63.5 | 0.0003 | 0.0007 | CCD | 16 |
| 56221.4725 | I | −63 | 0.0015 | 0.0003 | CCD | 16 |
| 56243.0517 | I | −14 | 0.0003 | 0.0040 | CCD | 22 |
| 56249.2172 | I | 0 | 0 | 0.0004 | CCD | 22 |
| 56253.1826 | I | 9 | 0.0017 | 0.0021 | CCD | 22 |
| 56350.9589 | I | 231 | 0.0057 | 0.0070 | CCD | 22 |
| 56500.4830 | II | 570.5 | 0.0086 | 0.0004 | CCD | 19 |
| 56542.5356 | I | 666 | 0.0015 | 0.0003 | CCD | 19 |
| 56638.5450 | I | 884 | 0.0003 | 0.0002 | CCD | 21 |

**References:** (1) Private provision, (2) Gomez-Forrellad et al. (1999), (3) Rucinski et al. (2001), (4) Tanriverdi et al. (2003), (5) Krajci (2005), (6) Nelson (2005), (7) Parimucha et al. (2007), (8) Csizmadia et al. (2006), (9) Nelson (2007), (10) Parimucha et al. (2009), (11) Yilmaz et al. (2009), (12) Nelson (2009), (13) Hubscher et al. (2010), (14) Nelson (2011), (15) Parimucha et al. (2011), (16) Parimucha et al. (2013), (17) Hubscher & Lehmann (2012), (18) Hoňková et al. (2013), (19) Zasche et al. (2014), (20) Hubscher & Lehmann (2013), (21) Basturk et al. (2014), (22) present work.

following linear ephemeris:

$$\mathrm{Min.I(HJD)} = 2456249.2172 + 0\overset{\mathrm{d}}{.}44041574 \times E. \quad (3)$$

To understand its geometrical structure and evolutionary state, the $B$-, $V$-, $R_c$-, and $I_c$-band light curves shown in Figure 1 are analyzed using the 2013 version of the W–D program (Wilson & Devinney 1971; Wilson 1979, 1990, 2008, 2012; Van Hamme & Wilson 2007; Wilson et al. 2010). The numbers of observed data points used in the W–D program are 624 in the $B$-band, 616 in the $V$-band, 610 in the $R_c$-band, and 603 in the $I_c$-band, respectively.

During the W–D processing, the effective temperature of star 1 is chosen as $T_1 = 7000$ K according to the spectral type determined (Cox 2000). Convective outer envelopes for both components are assumed. The bolometric albedo $A_1 = A_2 = 0.5$ (Ruciński 1969) and the values of the gravity-darkening coefficients $g_1 = g_2 = 0.32$ (Lucy 1967)

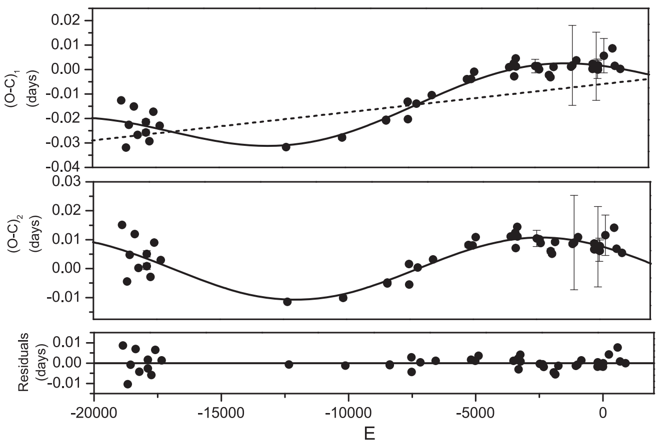


**Figure 2.** The (O–C)$_1$ values of V776 Cas from the linear ephemeris of Equation (1) are presented in the upper panel. The solid line in the panel refers to the combination of a new linear ephemeris and a cyclic variation. The dashed line represents the new linear ephemeris. In the middle panel of Figure 2, (O–C)$_2$ values calculated from the new linear ephemeris in Equation (2) are displayed. The solid line refers to a theoretical light-travel time effect (LTTE) orbit of the tertiary component in the system. The residuals from the whole effect are displayed in the bottom panel.

are used. To account for the limb-darkening in detail, logarithmic functions are used. The corresponding bolometric and passband-specific limb-darkening coefficients are chosen from Van Hamme's (1993) table. During the calculating it is found that the solution converges at mode 3, and the adjustable parameters are: the orbital inclination $i$; the mean surface temperature of star 2 ($T_2$); the monochromatic luminosity of star 1 ($L_{1B}$, $L_{1V}$, $L_{1R}$ and $L_{1I}$); the dimensionless potential of star 1 ($\Omega_1 = \Omega_2$ in mode 3 for overcontact configuration) and the third light $l_3$. The final photometric solutions are listed in Table 4 and the theoretical light curves are displayed in Figure 3. The theoretical light curves that have not been contaminated by the third light are also plotted in Figure 3 using dashed lines. The contact configuration of V776 Cas is displayed in Figure 4.

It has to be mentioned that the mass ratio q ($M_2/M_1$ ) and the effective temperature of the primary star ($T_1$) are very important input parameters when the W–D calculations are carried out. The newly obtained mass ratio of V776 Cas was $q = 0.1306 \pm 0.0046$, with a very high accuracy (Ghaderi et al. 2012), which was consistent with that of Rucinski et al. (2001), so we chose $q = 0.130$ in our calculations. And another solution of $T_1 = 6890$ K is also obtained and listed in Table 4. We can conclude that it makes almost no difference to the results when the the effective temperatures are set as $T_1 = 7000$ K and $T_1 = 6890$ K. Therefore, hereafter we use the solution of $T_1 = 7000$ K as our final results in the paper.

## 5. DISCUSSIONS AND CONCLUSIONS

The light curve solutions indicate that V776 Cas is an A-subtype overcontact binary system with a very high contact degree ($f = 64.6\%$) and an extremely low-mass ratio ($q = 0.130$), which indicate that it is at the final evolutionary stage of a cool short-period binary. It may merge into a single rapid-rotation star, which may be the progenitor of a blue straggler or a FK Com-type star (Zhou et al. 2015). The two components have nearly the same surface temperature ($\Delta T = 80$ K) in spite of their quite different masses and radii. This suggests that the system is under thermal contact. Considering our orbital inclination ($i = 55\overset{\circ}{.}4$) and the mass function given by Rucinski et al. (2001): $(M_1 + M_2)\sin^3 i = 0.975 \pm 0.026\, M_\odot$, we can easily calculate the mass of the two components to be $M_1 = 1.55(\pm 0.04)\, M_\odot$, $M_2 = 0.20(\pm 0.01)\, M_\odot$. The absolute physical parameters of the two components in V776 Cas are listed in Table 5.

As the spectroscopic search carried out by D'Angelo et al. (2006) confirmed, V776 Cas is a triple system with a solar-type tertiary component ($T_3 = 6100$ K); the third light ($l_3$) is also included as an adjustable parameter during the photometric processing. The results suggest that the third light contributes nearly 15% of the total luminosity and it apparently reduces the depths of the primary and secondary minimum, as shown in Figure 3. The third component mainly radiates in the $R_c$ and $I_c$ bands. According to the third light values in the $R_c$ and $I_c$ filters listed in Table 4, the color index of the tertiary component is calculated to be $R_c - I_c = 0.32$, which corresponds to a spectral type of G0V. It is consistent with the result of spectroscopic fitting. The mass of the third component is estimated to be $M_3 = 1.04(\pm 0.03)\, M_\odot$ according to the mass ratio ($M_3/M_1 = 0.67$) obtained by D'Angelo et al. (2006). By assuming a circular orbit ($e = 0.0$), the projected radius of the orbit that the eclipsing binary rotates around at the barycenter of the triple system is calculated with the equation

$$a'_{12} \sin i' = A_3 \times c, \tag{4}$$

where $A_3$ is the amplitude of the O–C oscillation and $c$ is the speed of light, i.e., $a'_{12} \sin i' = 1.88(\pm 0.02)$ AU. The mass function and the mass of the tertiary companion are computed with

$$f(m) = \frac{4\pi^2}{GP_3^2} \times (a'_{12} \sin i')^3 = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2}, \tag{5}$$

where $G$ and $P_3$ are the gravitational constant and the period of the (O–C)$_2$ oscillation. The orbital inclination of the third component is calculated to be $i' = 33\overset{\circ}{.}1$. The distance of the binary system to the barycenter of the triple system is calculated to be $a'_{12} = 3.45$ AU.

Over the past decade, light curve solutions of V776 Cas have been achieved by Djurašević et al. (2004), Elmasli et al. (2004), Zola et al. (2005), and Oh et al. (2007). Their results are listed in Table 6. Our results are consistent with those of Djurašević et al. (2004)'s. The solutions of Zola et al. (2005) and Oh et al. (2007) gave consistent results. Compared with our results, they obtained a lower orbital inclination and a higher contact degree. The effective temperatures of the two components were very close to each other and the third light ($l_3$) was almost negligible. These may be caused by the different mass ratio used in the W–D calculation or they could be due to the effect of a different third light contamination. However, magnetic activities and mass transfer between the two components may also respond to the difference among the solutions since there is a late-type component in the overcontact binary system and Oh et al. (2007) used a spot model to modeling the light curves. As both spectroscopic observation and O–C curve analysis confirm the existence of a solar-type close-in tertiary in the close binary system, our results with a contribution of third light may be much more acceptable.

The formation and evolutionary scenario of W UMa-type binaries are still an unsolved problem in astrophysics.

**Table 4**
Photometric Solutions of V776 Cas

| Parameters | Without $l_3$ | With $l_3$ | Without $l_3$ | With $l_3$ |
|---|---|---|---|---|
| $T_1(K)$ | 7000(fixed) | 7000(fixed) | 6890(fixed) | 6890(fixed) |
| $g_1$ | 0.32(fixed) | 0.32(fixed) | 0.32(fixed) | 0.32(fixed) |
| $g_2$ | 0.32(fixed) | 0.32(fixed) | 0.32(fixed) | 0.32(fixed) |
| $A_1$ | 0.50(fixed) | 0.50(fixed) | 0.50(fixed) | 0.50(fixed) |
| $A_2$ | 0.50(fixed) | 0.50(fixed) | 0.50(fixed) | 0.50(fixed) |
| $q(M_2/M_1)$ | 0.130(fixed) | 0.130(fixed) | 0.130(fixed) | 0.130(fixed) |
| $i(°)$ | 54.2(±0.1) | 55.4(±0.1) | 54.3(±0.1) | 55.4(±0.1) |
| $\Omega_{in}$ | 2.0476 | 2.0476 | 2.0476 | 2.0476 |
| $\Omega_{out}$ | 1.9633 | 1.9633 | 1.9633 | 1.9633 |
| $\Omega_1 = \Omega_2$ | 2.0124(±0.0009) | 1.9932(±0.0007) | 2.0128(±0.0009) | 1.9932(±0.0007) |
| $T_2(K)$ | 6865(±10) | 6920(±2) | 6749(±11) | 6796(±2) |
| $\Delta\ T(K)$ | 135 | 80 | 141 | 94 |
| $T_2/T_1$ | 0.9807(±0.0014) | 0.9886(±0.0003) | 0.9795(±0.0016) | 0.9863(±0.0003) |
| $L_1/L_T$ $(B)$ | 0.8671(±0.0002) | 0.8573(±0.0019) | 0.8682(±0.0002) | 0.8587(±0.0019) |
| $L_1/L_T$ $(V)$ | 0.8647(±0.0002) | 0.8560(±0.0018) | 0.8656(±0.0002) | 0.8570(±0.0018) |
| $L_1/L_T$ $(R_c)$ | 0.8633(±0.0002) | 0.8552(±0.0020) | 0.8640(±0.0002) | 0.8560(±0.0020) |
| $L_1/L_T$ $(I_c)$ | 0.8620(±0.0002) | 0.8544(±0.0028) | 0.8626(±0.0002) | 0.8551(±0.0028) |
| $L_3/L_T'$ $(B)$ | ⋯ | 0.1423(±0.0099) | ⋯ | 0.1452(±0.0100) |
| $L_3/L_T'$ $(V)$ | ⋯ | 0.1338(±0.0099) | ⋯ | 0.1358(±0.0100) |
| $L_3/L_T'$ $(R_c)$ | ⋯ | 0.1531(±0.0109) | ⋯ | 0.1553(±0.0110) |
| $L_3/L_T'$ $(I_c)$ | ⋯ | 0.1675(±0.0152) | ⋯ | 0.1699(±0.0152) |
| $r_1$(pole) | 0.5270(±0.0003) | 0.5324(±0.0007) | 0.5269(±0.0003) | 0.5325(±0.0007) |
| $r_1$(side) | 0.5861(±0.0004) | 0.5948(±0.0011) | 0.5860(±0.0004) | 0.5949(±0.0011) |
| $r_1$(back) | 0.6086(±0.0005) | 0.6189(±0.0013) | 0.6084(±0.0005) | 0.6191(±0.0013) |
| $r_2$(pole) | 0.2167(±0.0003) | 0.2233(±0.0009) | 0.2165(±0.0003) | 0.2235(±0.0009) |
| $r_2$(side) | 0.2269(±0.0004) | 0.2349(±0.0011) | 0.2269(±0.0004) | 0.2352(±0.0011) |
| $r_2$(back) | 0.2725(±0.0009) | 0.2935(±0.0031) | 0.2721(±0.0009) | 0.2944(±0.0032) |
| $f$ | 41.8%(±1.1%) | 64.6%(±2.9%) | 41.4%(±1.1%) | 65.4%(±2.9%) |
| $\Sigma\omega(O–C)^2$ | 0.049755 | 0.042135 | 0.049924 | 0.042369 |

**Note.** $L_T = L_1 + L_2$, $L_T' = L_1 + L_2 + L_3$.

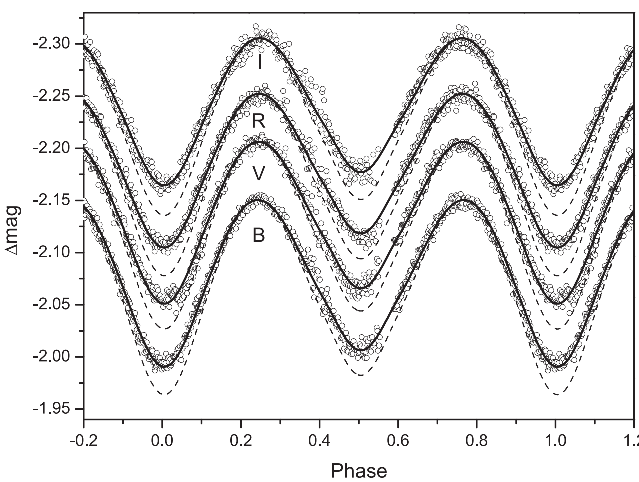


**Figure 3.** Observed (open circles) and theoretical (solid lines) light curves in the $B$-, $V$-, $R_c$-, and $I_c$-bands for V776 Cas. The standard deviation of the fitting residuals are 0.005 mag for the $B$-band, 0.006 mag for the $V$-band, 0.006 mag for *the* $R_c$-band, and 0.006 mag for the $I_c$-band, respectively. The dashed lines represent the theoretical light curves without the third light.

According to the method established by Yıldız & Doğan (2013), the initial masses of the two components in V776 Cas are calculated to be $M_{2i} = 2.13(\pm0.04)\,M_\odot$ and $M_{1i} = 0.86$ $(\pm0.10)\,M_\odot$. The initial mass of the present less massive one ($M_{2i}$) is within the mass range pertaining to A-subtype close

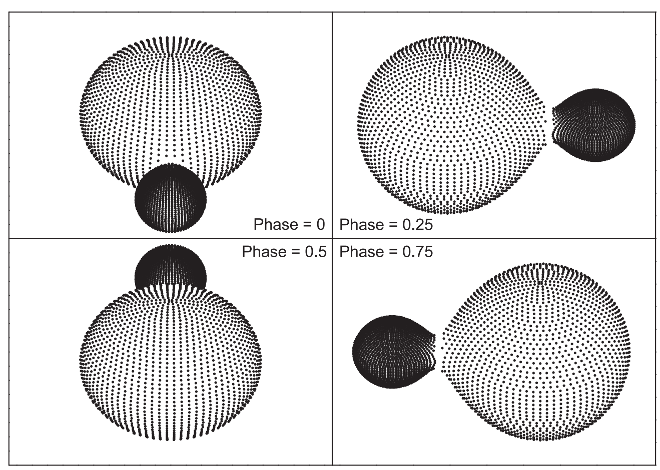


**Figure 4.** Contact configurations of V776 Cas at phases 0.0, 0.25, 0.5, and 0.75.

**Table 5**
Absolute Parameters of the Two Components in V776 Cas

| Parameters | Primary | Secondary |
|---|---|---|
| $M$ | $1.55(\pm0.04)\ M_\odot$ | $0.20(\pm0.01)\ M_\odot$ |
| $R$ | $1.71(\pm0.15)R_\odot$ | $0.73(\pm0.06)R_\odot$ |
| $L$ | $6.93(\pm0.72)L_\odot$ | $1.17(\pm0.12)L_\odot$ |

**Table 6**
Photometric Solutions of V776 Cas for the Past Decade

| Parameters | Djurašević et al. (2004) | Zola et al. (2005) | Oh et al. (2007) | The Present Work |
|---|---|---|---|---|
| $T_1(K)$ | 6890 | 6700 | 7047 | 7000 |
| $q(M_2/M_1)$ | 0.130 | 0.138 | 0.145(±0.001) | 0.130 |
| $i(°)$ | 55.8(±0.2) | 52.5(±0.9) | 53.584(±0.134) | 55.4(±0.1) |
| $\Omega_1 = \Omega_2$ | 1.9984 | 2.001(±0.008) | 2.0127(±0.0019) | 1.9932(±0.0007) |
| $f$ | 58.39% | 77% | 81.9% | 64.6%(±2.9%) |
| $T_2(K)$ | 6620(±46) | 6725(±90) | 7004(±39) | 6920(±2) |
| $\Delta T(K)$ | 270 | 25 | 43 | 80 |
| $T_2/T_1$ | 0.9608(±0.0067) | 1.0037(±0.0134) | 0.9939(±0.0055) | 0.9886(±0.0003) |
| $L_1/L_T$ (U) | … | 0.8386(±0.0053) | … | … |
| $L_1/L_T$ (B) | … | 0.8380(±0.0059) | 0.8362 | 0.8573(±0.0019) |
| $L_1/L_T$ (V) | 0.866 | 0.8390(±0.0056) | 0.8357 | 0.8560(±0.0018) |
| $L_1/L_T$ ($R_c$) | … | 0.8392(±0.0052) | 0.8354 | 0.8552(±0.0020) |
| $L_1/L_T$ ($I_c$) | … | … | … | 0.8544(±0.0028) |
| $L_3/L'_T$ (U) | … | 0.0071(±0.0031) | … | … |
| $L_3/L'_T$ (B) | … | 0.0074(±0.0032) | 0.0174 | 0.1423(±0.0099) |
| $L_3/L'_T$ (V) | 0.136 | 0.0061(±0.0033) | 0.0162 | 0.1338(±0.0099) |
| $L_3/L'_T$ ($R_c$) | … | 0.0041(±0.0031) | 0.0152 | 0.1531(±0.0109) |
| $L_3/L'_T$ ($I_c$) | … | … | … | 0.1675(±0.0152) |
| $\theta(°)$ | … | … | 90 | … |
| $\psi(°)$ | … | … | 274.90(±0.62) | … |
| $r$(rad) | … | … | 10 | … |
| $T_f$ | … | … | 0.980(±0.010) | … |
| $M_1(M_\odot)$ | 1.63 | 1.750(±0.040) | 1.71 | 1.55(±0.04) |
| $M_2(M_\odot)$ | 0.21 | 0.242(±0.017) | 0.25 | 0.20(±0.01) |
| $R_1(R_\odot)$ | 1.73 | 1.821(±0.017) | 1.77 | 1.71(±0.15) |
| $R_2(R_\odot)$ | 0.74 | 0.748(±0.012) | 0.81 | 0.73(±0.06) |
| $L_1(L_\odot)$ | … | 5.90(±0.11) | 6.83 | 6.93(±0.72) |
| $L_2(L_\odot)$ | … | 1.01(±0.06) | 1.39 | 1.17(±0.12) |
| $a_{\rm orb}(R_\odot)$ | 2.985 | 3.07(±0.03) | 3.05 | 2.94(±0.03) |

**Note.** $L_T = L_1 + L_2$, $L'_T = L_1 + L_2 + L_3$.

binaries. The initial mass of the present primary one ($M_{1i}$) indicates that it is a late-type star, which has played a very important role for the early angular momentum evolution of close binaries, as magnetic braking is supposed to be the main mechanism for such stars with convective envelopes. For V776 Cas, the mass loss of the secondary star is calculated to be $1.93\,M_\odot$ and the mass gained by the primary component is $0.69\,M_\odot$, which also confirms the conclusion that only one-third of the mass lost by the secondary component is transferred to the primary component (Yıldız & Doğan 2013).

V776 Cas is the brighter member of the visual binary ADS 1485. The close binary system is even confirmed to be a triple system with a solar-type third component orbiting around the close binary system. Thus, it is actually a quadruple system. Tokovinin et al. (2006) surveyed a sample of 165 solar-type spectroscopic binaries and found that the fraction of spectroscopic binaries with additional companions is 63% ± 5%. The fraction had a strong correlation with the periods ($P$) of binary systems, which reached 96% for $P < 3$ days and dropped to 34% for $P > 12$ days. Qian et al. (2013, 2014) thought that the existence of an additional stellar component in the binary system might play an important role for the formation and evolution by removing angular momentum from the central binary system during the early dynamical interaction or late evolution. It is possible that third-body interactions in the birth environment may help to accelerate the orbital evolution of the central binary system. Angular momentum is drained from the inner close pair either by the ejection of the tertiary companion (Goodwin et al. 2004) or through the Kozai mechanism (Kozai 1962; Fabrycky & Tremaine 2007). The angular momentum and orbital period of the binary system will decrease, and the initially detached binary system evolves into the contact configuration during their main sequence evolutionary stage. V776 Cas is an important target for testing theories of W UMa-type binaries' formation and stellar dynamical interaction and evolution.

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