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Identification of a deep contact binary in the field of the globular cluster 47 Tuc ☆

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HIGHLIGHTS

- The masses and the radii of each component are determined.
- The age and distance of V95 are determined.
- Different metal abundance conditions are discussed.

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ABSTRACT

Three light curves of the eclipsing binary V95–47 Tuc were obtained in serval nights from December, 2010 to November, 2011. By analyzing the light curves with the 2010 version of the W-D code, the mass-ratio and the fill-out factor of V95 are determined as 0.164 and 53.8%, respectively. It is sure that this contact binary is a foreground object of the globular cluster 47 Tuc. By comparing to the Dartmouth model isochrones, the masses and the radii of the component stars are estimated, as well as the age and the distance. They are, $M_1 = 0.97M_\odot$, $M_2 = 0.16M_\odot$, $R_1 = 1.05R_\odot$, $R_2 = 0.49R_\odot$, Age = 7.0 Gyr and Dist = 1570 pc. The cool spots model is introduced in the BV-band photometric solutions because of the observed O'Connell effect. We compare the two modeling cool spots in size, temperature and position, thinking that they could be the same one. It can be explained as that a cool spot, which is on the surface of the more massive component, shifted 126 degrees along the latitude line from west to east in a year. This phenomenon may be called as starspot migration.

1. Introduction

A contact binary, especially for a W UMa type, usually consists of two main sequence component stars. The main sequence stars always lie in a narrow range of the H-R diagram, in which masses and radii are related to temperatures and luminosities. Thus, one can estimate the luminosity (or absolute magnitude) of a main sequence star via its even a crude estimated mass, because the estimated error in mass is always larger than that in magnitude. For an instance, consider a star with a mass of $1M_\odot$ and with an absolute magnitude of 4.64 mag; if the estimated mass deviated from the true value for $0.1M_\odot$, the absolute magnitude would deviate from the true value for 0.07 mag. The former error is 10%, while the later error is 2%. It means that even if a higher departure occurred in the mass estimate, a lower departure would happen in the absolute magnitude estimate. Thus, it is a safe way that we derived the absolute magnitudes of the components from their masses. Then, we can compute the distance from Earth to the binary system. Hence, for some special contact binaries (e.g., totally eclipsing systems), the photometric solutions are close to the spectroscopic solutions so that the photometric observation data are helpful enough to obtain the acceptable fundamental parameters, as well as the distance. The contact binary V95–47 Tuc is one of them. Although V95 is a foreground star of the globular cluster 47 Tuc according to the estimated distance in this paper, we will still introduce the cluster first.

47 Tuc (NGC 104) is a big and bright globular cluster in the southern sky region. Recently, Thompson et al. (2010) (hereafter Th10) via an analysis of the detached binary V69–47 Tuc, which is a member of the cluster, updated the cluster parameters. The

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measurements of the masses and radii for the V69 components are high accuracy, which is better than 1%. After they compared the observations to Dartmouth model isochrones (Dotter et al., 2008), the most caring parameters, the age and the apparent distance modulus ($(m-M)_V$), are $11.25 \pm 0.21 \pm 0.45$ Gyr and 13.35 ± 0.08, respectively. Generally, such an old and crowded globular cluster should generate many binary systems because of a long evolutional time and a high frequency of star collisions. Through two surveys (Kaluzny et al., 1998, hereafter K98; Weldrake et al., 2004, hereafter W04), more than 100 variable stars were found in 47 Tuc area. To determine fundamental parameters of contact binary systems within the cluster that have EW type light curves and that present a flat bottom around their minima is our initial goal, because the systems with these typical characters are usually totally eclipsing systems. V95 has a such light curve.

V95 was discovered by Kaluzny et al. (1998) with the OGLE program. They obtained its orbital period (0.2789 day) and color index ($(V-I) = 0.69$), naming it as OGLEGC 245. Wekdrake et al. (W04) surveyed this cluster again. V95 is the ninety-fifth variables in this survey. They obtained a new light curve but they did not analyze it. O'Connell effects (O'Connell, 1951) were found in both light curves of K98 and W04. This effect is an observational fact in light curves of the eclipsing binaries. Ordinarily, the two maxima of a contact binary should have same brightness because the two components should be axial symmetric in geometry. However, actually, the maximum I is brighter than the maximum II in some cases, which are called as positive O'Connell effect, while the maximum I is fainter than the maximum II in other contrary cases, which are called as negative O'Connell effect. (The maximum I is the maximum at phase 0.25 of a light curve, while the maximum II is the maximum at phase 0.75 of a light curve.) The star spots model is the most popular explanation for this effect.

2. Observations

The observations of 47 Tuc field in B, V and R-bands were carried out with the 2.15-m Jorge Sahade (JS) reflector telescope (f/15 Cassegrain) at Complejo Astronómico El Leoncito Observatory (CASLEO), San Juan, Argentina. (The V-band data were obtained on December 2 and 3, 2010, while the R-band data were obtained on November 23, 24, 2011 and the B-band data were obtained on November 25, 26 and 27, 2011, respectively.) The charge-coupled device (CCD) type is Versarray 1300B. A focal reducer was only used in V-band. Conditions of the nights were clear with a seeing of $\leqslant 3''.5$. The field of view for the CCD photometric system is 9 arcmin × 9 arcmin and the scale of picture is $0''.6/pixels$ with the focal reducer, while the field of view is 5 arcmin × 5 arcmin and the scale of picture is $0''.33/pixels$ without it. Exposure times were 90 s for the V filter, 15 s for the R filter and 45 s for the B filter. The comparison star is CL*NGC104 LEE 1618 ($00^h22^m49^s.506, -72^\circ13'58''.6$), of which the brightness is close to our target. The PSF (point spread function) method is used to reduce the observed images with IRAF. At least five isolated bright stars in each image are chosen as PSF stars. Every observed image derives a PSF image, by using the AUTO profile; and then, the photometric magnitudes of the targets are corrected by these PSF images. The photometric uncertainties in these tables are read out from the IRAF program. They depend on, as we known, the correct input parameters, such as the FWHMPSF, the standard deviation of background in counts, the readout noise, etc. They also depend on the fitting methods themselves. Most of photometric uncertainties are about less than 0.01 magnitudes in these observations. The least-squares parabolic fitting method was used to obtain the times of minima because the minima are ought to symmetric. New times of minima are listed in Table 1. We used these minima to modify the period of V95. The new ephemeris is,

Table 1
Times of minima for V95 in the field of 47 Tuc.

HJD (Hel.)	Error (days)	Type	Filters	Reference
2449947.8794	±0.0014	II	V	From K98'data
2449948.8527	±0.0013	I	V	From K98'data
2449949.8188	±0.0014	II	V	From K98'data
2455533.65519	±0.0026	I	V	The present paper
2455534.63250	±0.0024	II	V	The present paper
2455888.55769	±0.0010	II	R	The present paper
2455888.69720	±0.0013	I	R	The present paper
2455890.64896	±0.0025	I	B	The present paper
2455891.62556	±0.0026	II	B	The present paper

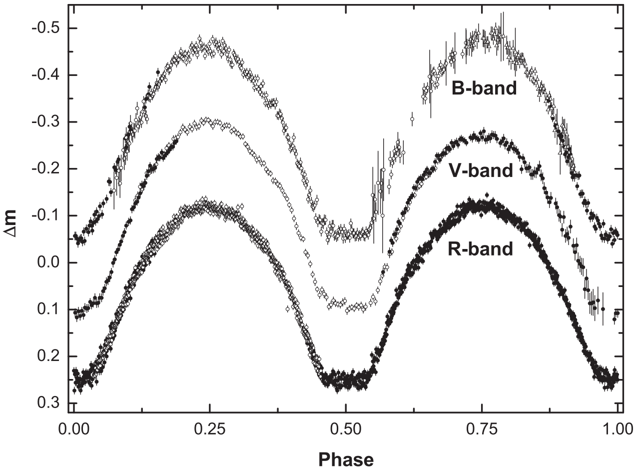

Fig. 1. Observed B, V and R-band light curves of V95 in the globular cluster 47 Tuc. Solid circles denote the data obtained in 2010-12-02 for V-band, 2011-11-23 for R-band and 2011-11-25 for B-band, respectively; open ones denote the data obtained in 2010-12-03 for V-band, 2011-11-24 for R-band and 2011-11-26 for B-band. Particulary, open triangles denote the B-band data obtained in 2011-11-27. The error bars show the uncertainties of the photometric measurements, which are mentioned in Section 2.

$$24555888.6961 \pm 0.0010 + 0^d.27889875 \pm 0.00000008 \times E. \quad (1)$$

The ephemeris $2455888.69724 + 0^d.27889875 \times E$ was used to calculate the phases. The light curves with error bars are displayed in Fig. 1. A remarkable O'Connell effect can be seen in the V and B-band light curves. However, it nearly disappeared in the R-band light curve. We will discuss this in Section 4.

3. Photometric solution

We derive the photometric elements with the 2010 version of the W-D program (Wilson and Devinney, 1971; Wilson, 1979; Wilson, 1990; Wilson, 2008; Van Hamme and Wilson, 2007). The most important step is to estimate the effective temperature of star 1. To do this, a color index and the metal abundance of V95 are necessary. The point is whether V95 is a member of the cluster 47 Tuc. Assuming case A that it is a field contact binary according to the study of W04, we adopt the color index of $(V-I) = 0.69$ given by K98 and a typical metal abundance value ([M/H] = 0) of sun-like field contact binary. Using the program provided by Worthey and Lee (2011), we compute the temperature as 5800 K and the bolometric correction coefficient as $BC_V = -0.085$ for star 1. In case B, we considered an interstellar extinction. The corrected color index $(V-I)$ would be 0.63 by using the reddening value of

$E(V-I)=0.06$ (Th10). And then we obtain the corresponding temperature and bolometric correction coefficient as 6035 K and −0.032, respectively. While in case C, we assumed V95 is a member of 47 Tuc. So, the corrected color index $(V-I)$ is 0.63 and the metal abundance is −0.7 (according to Th10). The computed temperature and bolometric correction coefficient are 6055 K and −0.099, respectively. In all cases, the bolometric albedo $A_1=A_2=0.5$ (Rucinski, 1969) and the values of the gravity-darkening coefficient $g_1=g_2=0.32$ (Lucy, 1967) are used, for a convective equilibrium shell model and a common convective envelope of both components. Square root limb-darkening coefficients are used, taken from Claret and Gimenez (1990). We adjust the orbital inclination (i); the mean temperature of star 2 (T_2); the monochromatic luminosity of star 1 (L_1), and the dimensionless potential of star 1 ($\Omega_1=\Omega_2$, mode 3 for contact configuration). The O'Connell effects in the light curves can not be ignored. Since V95 is a later-type sun-like star, star spots model should be applicable to it. A cool spot is introduced on the more massive component. The final photometric solutions for each case are listed in Tables 2–4. Only the fitting of case A is shown (Fig. 2), because the fittings of the three cases are not so different (Fig. 3).

Table 2
Case A photometric solutions for V95 in the field of 47 Tuc, with $T_1=5800$ K, [M/H] = 0.0.

Parameters	2010 V-Band	2011 B-band	2011 R-band
$g_1=g_2$	0.32	0.32	0.32
$A_1=A_2$	0.50	0.50	0.50
$x_{1bolo}=x_{2bolo}$	0.193	0.193	0.193
$y_{1bolo}=y_{2bolo}$	0.526	0.526	0.526
$x_{1B}=x_{2B}$	–	0.465	–
$y_{1B}=y_{2B}$	–	0.343	–
$x_{1V}=x_{2V}$	0.246	–	–
$y_{1V}=y_{2V}$	0.562	–	–
$x_{1R}=x_{2R}$	–	–	0.117
$y_{1R}=y_{2R}$	–	–	0.634
Phaseshift	-0.0025 ± 0.0004	0.0047 ± 0.0003	0.0037 ± 0.0001
T_1 (K)	5800	5800	5800
T_2 (K)	5707 ± 18	5935 ± 10	5963 ± 7
q (M_2/M_1)	0.165 ± 0.002	0.150 ± 0.002	0.164 ± 0.001
i (°)	79.6 ± 1.0	75.5 ± 0.5	78.4 ± 0.2
$L_1/(L_1+L_2)(B)$	–	0.8069 ± 0.0027	–
$L_1/(L_1+L_2)(V)$	0.8297 ± 0.0031	–	–
$L_1/(L_1+L_2)(R)$	–	–	0.8107 ± 0.0009
$\Omega_1=\Omega_2$	2.0643 ± 0.0044	2.0200 ± 0.0069	2.0837 ± 0.0031
Ω_{in}	2.1431	2.1031	2.1405
Ω_{out}	2.0370	2.0063	2.0350
θ (°)	85.9	85.9	–
ψ (°)	126.1	252.1	–
Ω (sr)	0.17845	0.13845	–
T_s/T_*	0.605	0.633	–
f (%)	74.3 ± 4.1	85.8 ± 7.1	53.8 ± 2.9

Table 3
Case B photometric solutions for V95 in the field of 47 Tuc, with $T_1=6035$ K, [M/H] = 0.0.

Parameters	2010 V-Band	2011 B-band	2011 R-band
$g_1=g_2$	0.32	0.32	0.32
$A_1=A_2$	0.50	0.50	0.50
$x_{1bolo}=x_{2bolo}$	0.162	0.162	0.162
$y_{1bolo}=y_{2bolo}$	0.558	0.558	0.558
$x_{1B}=x_{2B}$	–	0.360	–
$y_{1B}=y_{2B}$	–	0.479	–
$x_{1V}=x_{2V}$	0.180	–	–
$y_{1V}=y_{2V}$	0.547	–	–
$x_{1R}=x_{2R}$	–	–	0.067
$y_{1R}=y_{2R}$	–	–	0.672
Phaseshift	-0.0024 ± 0.0004	0.0043 ± 0.0003	0.0037 ± 0.0001
T_1 (K)	6055	6055	6055
T_2 (K)	5961 ± 20	6190 ± 12	6226 ± 7
q (M_2/M_1)	0.165 ± 0.002	0.161 ± 0.002	0.165 ± 0.001
i (°)	79.5 ± 0.9	76.4 ± 0.5	78.6 ± 0.2
$L_1/(L_1+L_2)(B)$	–	0.8020 ± 0.0026	–
$L_1/(L_1+L_2)(V)$	0.8282 ± 0.0031	–	–
$L_1/(L_1+L_2)(R)$	–	–	0.8100 ± 0.0009
$\Omega_1=\Omega_2$	2.0617 ± 0.004	2.0497 ± 0.0087	2.0838 ± 0.0032
Ω_{in}	2.1431	2.1326	2.1431
Ω_{out}	2.0370	2.0289	2.0370
θ (°)	85.9	85.9	–
ψ (°)	126.1	257.8	–
Ω (sr)	0.17845	0.15845	–
T_s/T_*	0.605	0.633	–
f (%)	76.7 ± 4.0	79.9 ± 8.0	55.9 ± 3.0

Table 4
Case C photometric solutions for V95 in the field of 47 Tuc, with $T_1=6055$ K, [M/H] = −0.7.

Parameters	2010 V-Band	2011 B-band	2011 R-band
$g_1=g_2$	0.32	0.32	0.32
$A_1=A_2$	0.50	0.50	0.50
$x_{1bolo}=x_{2bolo}$	0.164	0.164	0.164
$y_{1bolo}=y_{2bolo}$	0.556	0.556	0.556
$x_{1B}=x_{2B}$	–	0.360	–
$y_{1B}=y_{2B}$	–	0.473	–
$x_{1V}=x_{2V}$	0.184	–	–
$y_{1V}=y_{2V}$	0.645	–	–
$x_{1R}=x_{2R}$	–	–	0.070
$y_{1R}=y_{2R}$	–	–	0.670
Phaseshift	-0.0024 ± 0.0004	0.0044 ± 0.0003	0.0037 ± 0.0001
T_1 (K)	6035	6035	6035
T_2 (K)	5942 ± 20	6163 ± 12	6205 ± 7
q (M_2/M_1)	0.165 ± 0.002	0.161 ± 0.003	0.166 ± 0.001
i (°)	79.7 ± 0.9	76.3 ± 0.5	78.7 ± 0.2
$L_1/(L_1+L_2)(B)$	–	0.8016 ± 0.0026	–
$L_1/(L_1+L_2)(V)$	0.8293 ± 0.0031	–	–
$L_1/(L_1+L_2)(R)$	–	–	0.8094 ± 0.0009
$\Omega_1=\Omega_2$	2.0656 ± 0.0044	2.0490 ± 0.0098	2.0862 ± 0.0033
Ω_{in}	2.1431	2.1326	2.1458
Ω_{out}	2.0370	2.0289	2.0390
θ (°)	85.9	85.9	–
ψ (°)	126.1	257.8	–
Ω (sr)	0.17845	0.15845	–
T_s/T_*	0.605	0.633	–
f (%)	73.0 ± 4.1	80.6 ± 9.0	55.8 ± 3.1

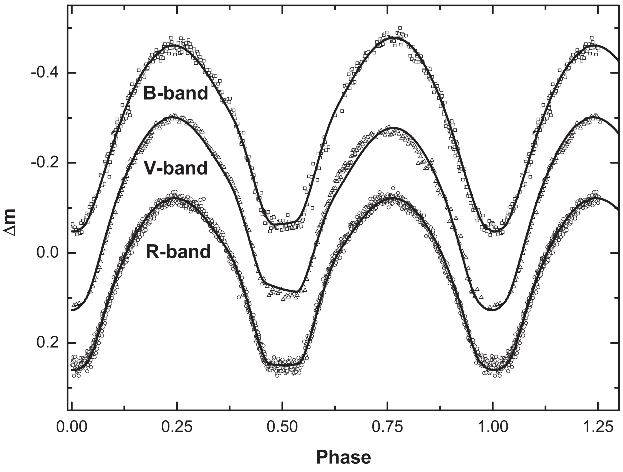

Fig. 2. Observed (symbols) and theoretical (solid line, in case A) light curves in the B, V and R-band for V95 in the field of 47 Tuc. These light curves are obtained in different observations. The obvious O'Connell effect is explained by presence of a cool spot on the primary component.

4. Discussion and conclusion

It is not a doubt that the light curves of V95 present a short-time-scale variation. This variation is reflected in the type-chang-

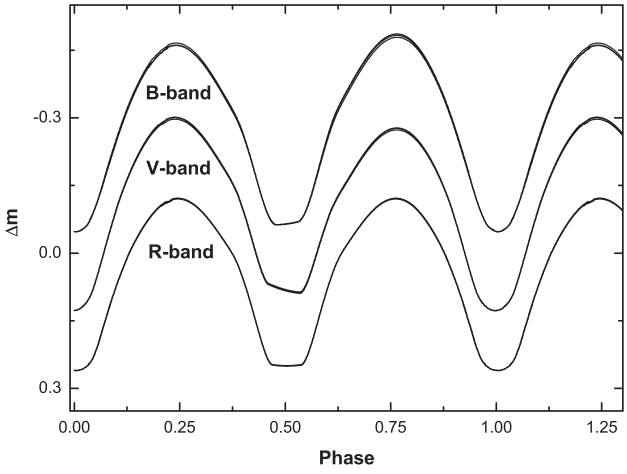

Fig. 3. Comparison of light curves for the three cases. They are almost the same.

ing of the O'Connell effects. It is not caused by mixing the primary minima and the secondary minima because V95 is a totally eclipsing contact binary system in which the light curves show a flat bottom when secondary minimum occurred, but it is caused by star spots. When a star possesses a strength magnetic field, the matter in the convection zone will be frozen by magnetic lines. Therefore the convection becomes tranquil, which leads to that the heat generated from the star center cannot be transported to the surface effectively so that the local surface temperature is lower than the surrounding temperature. This low temperature area is the cool star spot as people known. Conclusively, to generate a cool spot has two preconditions. First, the heat transport in the star depends on convection. Second, the magnetic field is strong enough to freeze the convection. V95 satisfies these two preconditions. The effective temperature of V95 is about 6000 K so that its primary component should consist of a radiation equilibrium core and a convection equilibrium shell. The rotational period of the components are 0.27889875 day (this paper). That is the same value as the orbital period of V95, according to the synchronous rotation hypothesis. The rotational angle velocities of the components are about 100 times larger than that of the Sun. Thus, the components of V95 should have much stronger magnetic fields than the Sun has. This could answer the question whether the cool spots can exist.

Although the two modeled cool spots presented in different years, their sizes and temperatures are almost the same values, only except for the positions. (Please see the Fig. 4.) It can be easily understood that the cool star spot migrates on the surface of the primary component just like the behavior of sunspots. If it is true, the spot migrated 126 degrees from west to east in a year, which followed the same direction as the rotational direction.

The R-band observations were obtained 1 or 2 days' earlier than the B-band observations. Normally, the cool spot cannot vanish in such short time, why did we not find its tracks in the R-band observations? It might be a result of Wien's displacement law. Consider that the cool spot is an ideal black-body. So its radiation follows the formula of $\lambda_m T = b$, where λ_m is the wave length in which the spot has the strongest radiation; T is the temperature of the spot; b is the Wien's displacement coefficient with a value of 2.897756×10^{-3} m· K. The temperature of the present spot should be 4000 K. Consequently, λ_m is computed as 700 nm, which is close to the center wave length of the R-band. It means that the spot is bright in R-band. While the center wave length of the B and V-band are 440 nm and 550 nm, respectively. The spot is truly dark in these two bands so that the corresponding light curves became asymmetric. If a hot spot presents here, the situation inverts.

Since the opacity of a W UMa type contact binary is dominated by the bound-free absorption process, the metal abundance impacts the color index obviously. Hence, it is necessary to discuss the metal abundance of V95. By providing that V95 is a foreground star of the cluster 47 Tuc, and that it is not affected by the interstellar extinction, the metal abundance of V95 should be a typical value of a main sequence star, namely [M/H]=0; of course, its color index does not need correcting. This is the case A. If the V95 is still a foreground star of the cluster 47 Tuc but it is affected by the interstellar extinction, the metal abundance will keep zero but the color index will be modified with an extinction value. Here, we assume that its interstellar extinction is the same as that of the cluster 47 Tuc. Adopting the color excess value of $E(V-I) = 0.06$, we obtain a corrected color index as $(V-I) = 0.63$. This is the case B. On condition that V95 is a member of 47 Tuc, the situations of its metal abundance and its inter-

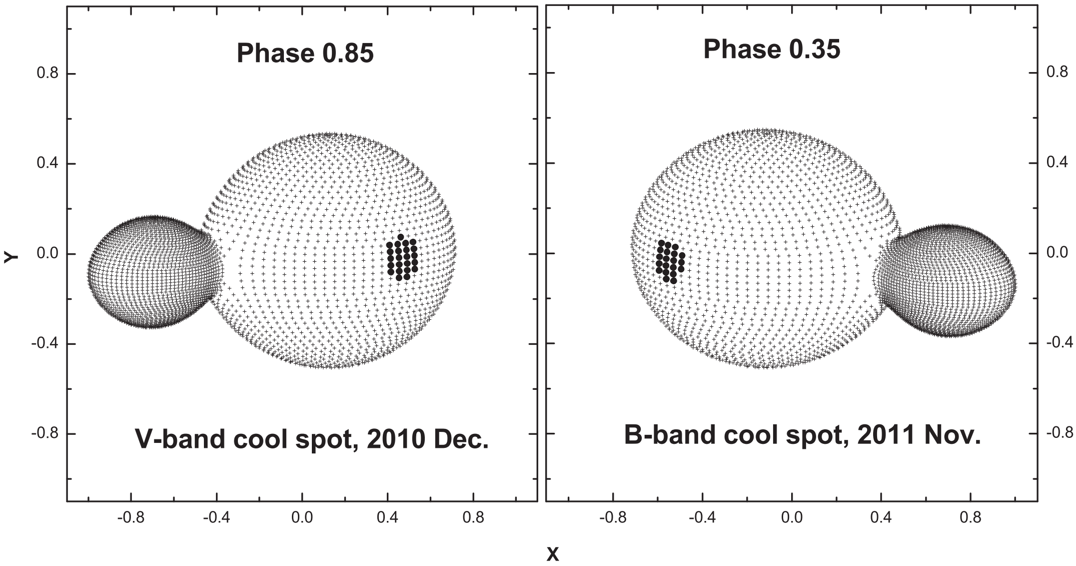

Fig. 4. Geometrical structure of the high fill-out factor, extreme mass-ratio contact binary V95 with the changed cool spot. The spot is assumed on the more massive component.

Table 5
Physical parameters of V95 in different cases.

	CaseA T = 5800 K, [M/H]=0	CaseB T = 6035 K, [M/H]=0	CaseC T = 6055 K, [M/H]=-0.7
$M_1(M_\odot)$	0.97	1.05	0.90
$M_2(M_\odot)$	0.16	0.17	0.15
$R_1(R_\odot)$	1.05	1.08	1.02
$R_2(R_\odot)$	0.49	0.51	0.48
$A(R_\odot)$	1.87	1.92	1.82
$\log g_1$	4.38	4.39	4.37
$\log g_2$	4.26	4.27	4.24
M_{bol1}	4.66	4.43	4.53
M_{bol2}	6.19	5.95	6.05
$M_{bol_{max}}$	4.426	4.194	4.295
BCv.	−0.085	−0.032	−0.099
Distance (pc)	1570	1790	1657
Age (Gyr)	7.0	3.9	7.5

stellar extinction should depend on those of the mother cluster 47 Tuc, namely [M/H]=-0.7 and $(V - I) = 0.63$. This is the case C. The photometric solutions were done under the three cases in Section 3. Comparing the solutions to Dartmouth model isochrones (Dotter et al., 2008), we obtain the masses and the radii for each component, and compute the distance (from the Earth to the binary) and the age of V95. Only the R-band solution is used to estimate these parameters because the results in this band are less affected. Some detail information of the compute progress can be read in some recent papers (e.g., Liu et al., 2011a; Liu et al., 2011b; Li et al., 2012). The results of parameters are listed in Table 5. The M_{bolmax}, which is presented in Table 5, occurs in 0.25 phase or in 0.75 phase, the phases when the two components completely do not cover each other.

Before a further discussion of Table 5, we contrast the three-case-solutions with each other. Look at case B and case C. The primary's temperature difference is only 20 K and the metal abundance difference is 0.7 while the age difference is as large as 3.6 Gyr. This implies that the metal abundance impacts the age estimation of the contact binary sensitively. Then look at case A and case B. They have the same metal abundance; however, the temperature difference is 235 K. Then the age difference is 3.1 Gyr. This indicates that the temperature also affects the age estimation greatly. Which case is the truest? Case C is primarily excluded, because the distance of V95 is 1657 pc in this case, while the distance of 47 Tuc is 4677 pc according to the result of Thompson et al. (2010), which is in contradiction to the assumption. Then we discuss the case B. Having analyzed the kinematic data of 129 W UMa type contact binary systems, Bilir et al. (2005) found when the mass ratios of the systems are less than or equal to 0.32 ($q \leqslant 0.32$), their average kinematic age is about 5.53 Gyr; when the contact factors are greater than 0.2 ($f > 0.2$), the age is 5.24 Gyr; when the orbital periods are greater than 0.2 day and less than or equal to 0.4 day ($0.2 < P \leqslant 0.4$), the age is 6.18 Gyr; when the total masses of the systems are less or equal to 1.6 solar mass ($M_{tol} \leqslant 1.6$), the age is 7.87 Gyr. According to these results, the age of V95 should be greater than 5.24 Gyr. A further study was given by Li et al. (2007). They analyzed the 97 field contact binaries mentioned in Bilir et al. (2005), obtaining an average value of ln P for each group. The period of V95 is modified as 0.27889875 day so that the $\ln P = -1.2769$. This value falls between the group with the age of 7.14 Gyr and the group with the age of 8.89 Gyr. The age of 3.9 Gyr, the result of case B, is too small, more or less. Hence the case B can be excluded, too. The remaining case A, which seems reasonable both in its assumption and its results, may be the truth.

In conclusion, V95 is a small mass ratio ($q \leqslant 0.164 \pm 0.001$), deep contact ($f \geqslant 53.8\% \pm 2.9\%$) binary system, with a migrating cool spot on the massive component. It is a foreground star of 47 Tuc, with a distance of 1570 pc from us. The primary component has 0.97 solar mass while the secondary component has 0.16 solar mass. Its age might be 7.0 Gyr.

Of course, the estimations are purely based on single stellar structure and evolution theory. Due to some interactions between the two components such as mass transfer, the evolutional progresses of W UMa type contact binaries should be different from these single stars. Thus, to obtain more accurate parameters still needs spectroscopic observations.

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