Two particular EA-type binaries in the globular cluster ω Centauri [*]

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Abstract We analyzed the B and V light curves of two EA-type binaries V211 and NV358 for the first time using the Wilson-Devinney code. Our analysis shows that V211 is a typical Algol-type binary and NV358 is a well detached binary system. As the two binaries are definite members of ω Centauri due to their proper motion, we estimated their physical parameters, obtaining $M_1 = 1.13 \pm 0.03\ M_\odot$, $R_1 = 0.98 \pm 0.01\ R_\odot$, $M_2 = 0.33 \pm 0.01\ M_\odot$ and $R_2 = 0.92 \pm 0.01\ R_\odot$ for V211; $M_1 = 1.30 \pm 0.05\ M_\odot$, $R_1 = 1.03 \pm 0.01\ R_\odot$, $M_2 = 0.58 \pm 0.02\ M_\odot$ and $R_2 = 0.78 \pm 0.01\ R_\odot$ for NV358. On the color-magnitude diagram of ω Centauri, V211 is located in the faint blue straggler region and its primary component is more massive than a star at the main-sequence turnoff. Therefore, V211 is a blue straggler and was formed by mass transfer from the secondary component to the primary. The age of NV358 is less than 1.93 Gyr, indicating that it is much younger than the first generation of stars in ω Centauri. Like NV364 in ω Centauri, NV358 should be a second-generation binary.

Key words: galaxies: globular clusters: individual (ω Centauri) — stars: binaries: close — stars: binaries: eclipsing — stars: blue stragglers — stars: individual (V211, NV358)

1 INTRODUCTION

Eclipsing binaries are very rare in globular clusters, but they play a significant role in studies of the dynamical evolution of globular clusters and stellar populations. They provide the source of energy that can oppose and avoid core collapse in globular clusters (Goodman & Hut 1989). They are also particularly interesting. Some Algol type eclipsing binaries, such as NJL5 and V239 in ω Centauri and V228 in 47 Tuc (Helt et al. 1993; Li & Qian 2012; Kaluzny et al. 2007), have been identified to be blue stragglers (BSs). They are good tools for testing the formation theories of BSs. Detached double line spectroscopic eclipsing binaries in globular clusters provide an opportunity to calculate the age of the cluster based on their well determined physical properties of mass and radius (see Thompson et al. 2001, 2010).

BS stars appear to be anomalously younger than other stars in the same population. In the color-magnitude diagrams (CMDs) of clusters, these stars are bluer and brighter than the main-sequence turnoff. They were first noticed in the globular cluster M3 by Sandage (1953). Now investigators have discovered BSs, not only in globular and open clusters and dwarf galaxies (Piotto et al. 2004; de Marchi et al. 2006; Momany et al. 2007), but also in the field (Carney et al. 2005). The formation of BSs is still controversial. Several mechanisms have been proposed to explain their formation. The two most popular BS formation mechanisms are mass transfer in close binary systems (McCrea 1964; Carney et al. 2001) and direct collision between two stars (Hills & Day 1976). Perets & Fabrycky (2009) discussed another possibility of BS formation in primordial (or dynamically) hierarchical triple star systems. By studying this type of object, one can reveal the dynamical history of a cluster and the role of dynamics in stellar evolution. Statistics on BSs can also provide some constraints for initial binary properties. The bimodal BS radial distribution in many globular clusters (e.g. Ferraro et al. 2004; Mapelli et al. 2006; Lanzoni et al. 2007; Beccari et al. 2011) has been observed. A scenario has been suggested to explain this, where BSs in the dense core were formed in collisions, whereas BSs in the low density outskirts of a cluster were formed by mass transfer in close binaries.

The traditional opinion about globular clusters is that all stars within a globular cluster are thought to share the same age and initially homogeneous chemical composition, making them simple stellar populations. This has one noticeable exception: ω Centauri, the most massive cluster in the Milky Way, whose stars show a large spread in metallicity. At present, the situation is much more complex, and researchers have identified that almost all the globular clusters so far examined in detail have at least two stellar generations. Clear evidence for multiple main sequences (Bedin et al. 2004) and giant branches (Nataf et al. 2011), as well as unusual horizontal branch (D'Antona et al. 2005) and subgiant branch (Milone et al. 2008; Moretti et al. 2009) morphologies, can all be explained in straightforward ways by the presence of multiple generations of stars. As an example, the first case of a second-generation binary, named NV364, in ω Centauri has been identified by Li et al. (2012).

ω Centauri is one of the most metal poor globular clusters in the Milky Way, with [Fe/H]= -1.53, an interstellar reddening $E(B - V) = 0.12$ and a distance modulus $(m - M)_V = 13.94$ (Harris 1996). V211, with a period of 0.576235 d, was first identified in the outskirts of the cluster by Kaluzny et al. (1996) during a search for variable stars in the central part of this globular cluster. NV358, with a period of 0.59964 d, was first discovered in the outer region of the cluster by Kaluzny et al. (2004) during a photometric survey of variable stars in the field of this cluster. On the CMD of the cluster, V211 is located in the faint BS region, while NV358 occupies a position in the bright BS domain. Light curves of several eclipsing binaries in ω Centauri have been analyzed, but light curves for these two have not. In this paper, we investigate B and V light curves of the two binaries taken from Kaluzny et al. (2004) using the Wilson-Devinney (W-D) code.

2 LIGHT CURVE ANALYSIS OF THE TWO BINARIES

ω Centauri was observed using the 1.0-m Swope telescope at Las Campanas Observatory by Kaluzny et al. (2004) under the Cluster AgeS Experiment (CASE) project during the interval from 1999 February 6/7 to 2000 August 9/10. B and V light curves of 301 variables were obtained and the photometric data are available on the VizieR webpage. Since no photometric analysis has been carried out for the two binaries V211 and NV358, which have sufficiently good photometric data and are located in the BS region on the CMD of ω Centauri, we chose to perform further analysis on them. Using the fourth version of the W-D program (Wilson & Devinney 1971; Wilson 1990, 1994; Wilson & Van Hamme 2003), which is a good tool for modeling eclipsing binaries using real photometric and spectroscopic (radial velocity) data, we analyzed the B and V light curves of the two binaries taken from Kaluzny et al. (2004) for the first time. Some of the photometric data that have serious

deviations from the phased light curves (mostly in the B band) were deleted. The ephemerides used to calculate the phases of the two binaries were

$$\text{Min.}I = 2451283.7791 + 0.576235E, \tag{1}$$

$$\text{Min.}I = 2451284.1098 + 0.599640E. \tag{2}$$

During the process of deriving our solutions, the effective temperature of the primary component, T_1, was determined based on the values of dereddened $B - V$ at the secondary minimum of the two binaries described below. The gravity-darkening coefficients of the components were taken to be 1.0 for a radiative atmosphere ($T \geq 7200$ K) from von Zeipel (1924) and 0.32 for a convective atmosphere ($T < 7200$ K) from Lucy (1967). The bolometric albedo coefficients of the components were fixed at 1.0 and 0.5 for radiative and convective atmospheres respectively following Ruciński (1969). The bolometric and bandpass limb-darkening coefficients of the components were also fixed (van Hamme 1993). Starting with the solutions derived by mode 2, we found that the solutions of V211 usually converged when the secondary component filled its Roche lobe and that of NV358 quickly converged. So, the final iterations of V211 were made in mode 5, which corresponds to the semi-detached configuration, while that of NV358 was made in mode 2. The quantities that varied in the solutions of the two stars were the mass ratio q, the effective temperature of the secondary component T_2, the monochromatic luminosity of the primary component in the B and V bands L_1, the orbital inclination i and the dimensionless potential of the primary component Ω_1. The dimensionless potential of the secondary component Ω_2 was also a variable for NV358.

2.1 V211

The temperature of the primary component, T_1, was determined from the dereddened color index $(B-V)_1$ using the program provided by Worthey & Lee (2011). Bellini et al. (2009) determined the membership probability of V211 to be 90%. We adopted an interstellar reddening of $E(B - V) = 0.12$ and a metallicity value of [Fe/H]$= -1.53$ (Harris 1996) for ω Centauri. The color index at the secondary minimum is a good approximation to the color index of the primary star. Based on the phased data, the color index at the secondary minimum is measured to be $(B-V)_1 = 0.393$, leading to $T_1 = 7035$ K. The bolometric albedo and the gravity-darkening coefficients of the components are respectively set as $A_1 = A_2 = 0.5$ and $g_1 = g_2 = 0.32$ for a convective atmosphere. Bolometric and bandpass square-root limb-darkening parameters of the components were taken from van Hamme (1993) and are listed in Table 1. A q-search method was used to determine the mass ratio of V211. Solutions were carried out for a series of values of the mass ratio (0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7). The relation between the resulting sum Σ of weighted square deviations and q is plotted in Figure 1. The minimum value was obtained at $q = 0.30$. Therefore, we fixed the initial value of mass ratio q at 0.30 and made it an adjustable parameter. Then, we executed a differential correction until it converged and final solutions were derived. The final photometric solutions are listed in Table 1. The comparison between the observed and theoretical light curves is shown in Figure 1.

2.2 NV358

The color index of NV358 at the secondary minimum is 0.142. Bellini et al. (2009) determined that the membership probability of NV358 is 99%. The $(B - V)_{1,0}$ of the primary, which represents the color index after correcting for reddening, was fixed at 0.022. Using the same method that was applied to V211, we fixed the effective temperature of the primary component of NV358 at $T_1 = 9239$ K. The bolometric albedo and the gravity-darkening coefficients of the components were respectively set to $A_1 = A_2 = 1.0$ and $g_1 = g_2 = 1.0$ for a radiative atmosphere. Bolometric and bandpass square-root limb-darkening parameters of the components were taken from van Hamme (1993) and are listed in Table 2. A q-search method was also used to determine the mass ratio of
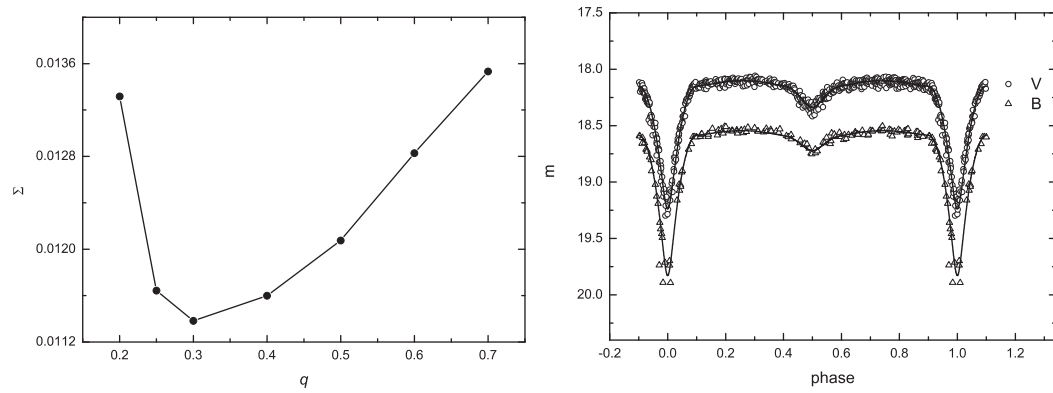
Fig. 1 Left panel shows the q-search for V211. Right panel displays the observed (*open symbols*) and theoretical (*solid lines*) light curves of V211 in the BV passbands.
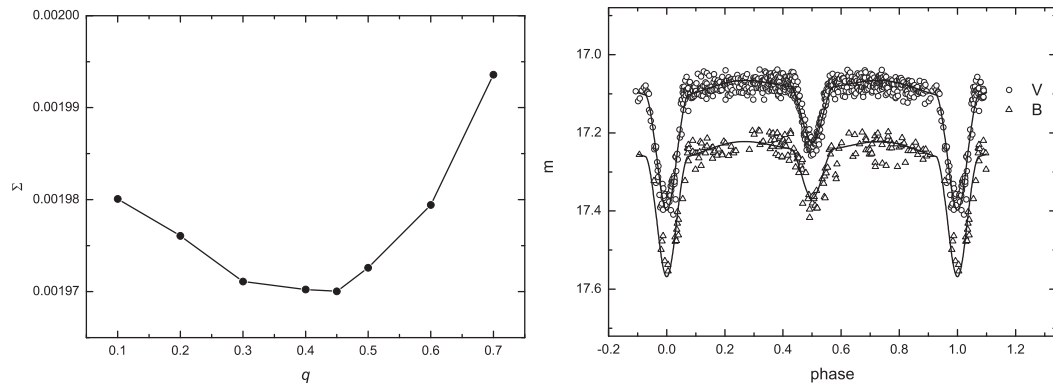

Fig. 2 Left panel shows the q-search for NV358. Right panel displays the observed (*open symbols*) and theoretical (*solid lines*) light curves of NV358 in the BV passbands.

NV358. The final photometric solutions are listed in Table 2. Figure 2 shows a comparison between the observed and theoretical light curves.

Because Johnson et al. (2009) found a large metallicity spread for stars in the cluster ω Centauri, a metallicity value of [Fe/H]$= -1.0$ was also used to determine the effective temperature of the primary component, and $T_1 = 7104$ K for V211 and $T_1 = 8923$ K for NV358 were obtained. The solutions based on the metallicity of [Fe/H]$= -1.0$ are listed in Tables 1 and 2. We find that the additional results of this metallicity value agree with previous values. Therefore, the results using [Fe/H]$= -1.53$ are adopted to be the final solution.

3 RESULTS AND DISCUSSIONS

Based on the B and V light curves, photometric solutions for the two EA-type binaries, V211 and NV358, have been derived. It is shown that V211 is a typical Algol-type binary and NV358 is a well detached binary system. The primary and secondary components of NV358 fill 68.3% and 81.4% of their critical Roche lobes, respectively. Using the fractional luminosities of the components from the B and V light-curve solutions, quoted above, and adopting the observed B and V magnitudes of the two binaries at maximum light, we found the following visual magnitudes of the components

Table 1 Photometric Solutions for V211 in the Globular Cluster ω Centauri

Parameters	[Fe/H] $= -1.53$	Errors	[Fe/H]$= -1.0$	Errors
$g_1 = g_2$	0.32	Assumed	0.32	Assumed
$A_1 = A_2$	0.5	Assumed	0.5	Assumed
$x_{1\mathrm{bol}}$	0.093	Assumed	0.093	Assumed
$x_{2\mathrm{bol}}$	0.265	Assumed	0.265	Assumed
$y_{1\mathrm{bol}}$	0.632	Assumed	0.632	Assumed
$y_{2\mathrm{bol}}$	0.441	Assumed	0.441	Assumed
x_{1B}	0.173	Assumed	0.173	Assumed
x_{2B}	0.757	Assumed	0.757	Assumed
y_{1B}	0.706	Assumed	0.706	Assumed
y_{2B}	0.109	Assumed	0.109	Assumed
x_{1V}	0.059	Assumed	0.059	Assumed
x_{2V}	0.445	Assumed	0.445	Assumed
y_{1V}	0.726	Assumed	0.726	Assumed
y_{2V}	0.398	Assumed	0.398	Assumed
$T_1(\mathrm{K})$	7035	Assumed	7104	Assumed
$q(M_2/M_1)$	0.2941	±0.0094	0.2942	±0.0093
$T_2(\mathrm{K})$	5219	±24	5257	±24
i	85.166	±0.416	85.172	±0.415
$L_1/(L_1 + L_2)(B)$	0.8739	±0.0008	0.8737	±0.0008
$L_1/(L_1 + L_2)(V)$	0.8160	±0.0013	0.8160	±0.0013
Ω_1	3.7041	±0.0562	3.7055	±0.0566
Ω_2	2.4532	Assumed	2.4534	Assumed
$r_1(\mathrm{pole})$	0.2922	±0.0048	0.2921	±0.0049
$r_1(\mathrm{side})$	0.2972	±0.0052	0.2971	±0.0052
$r_1(\mathrm{back})$	0.3002	±0.0054	0.3001	±0.0054
$r_2(\mathrm{pole})$	0.2597	±0.0023	0.2596	±0.0023
$r_2(\mathrm{side})$	0.2704	±0.0024	0.2704	±0.0024
$r_2(\mathrm{back})$	0.3031	±0.0024	0.3031	±0.0024

of the two binaries: $V_1 = 18.331 \pm 0.002$, $B_1 = 18.686 \pm 0.001$, $V_2 = 19.948 \pm 0.008$ and $B_2 = 20.788 \pm 0.007$ for V211, $V_1 = 17.330 \pm 0.003$, $B_1 = 17.449 \pm 0.002$, $V_2 = 18.751 \pm 0.010$ and $B_2 = 19.131 \pm 0.010$ for NV358. The main source of errors is the respective uncertainties in the solutions. Figure 3 shows the positions of the individual eclipsing components on the CMD (Noble et al. 1991) of ω Centauri. V211 is located in the faint BS region, while NV358 occupies a position in the bright BS domain.

3.1 Physical Parameters of the Two Binaries

According to the WFI@2.2m proper motion catalog of globular cluster ω Centauri compiled by Bellini et al. (2009), V211 (designation 298164) and NV358 (designation 129801) are definite members of the cluster due to their proper motions, with respective membership probabilities of 90% and 99%. Using the same method as Liu et al. (2011), we estimated the physical parameters of the two binaries by the light-curve program of the W-D code. First, we calculated the absolute bolometric magnitudes of the two binaries based on their V-band absolute magnitudes. Second, using the light-curve program of the W-D code, we could also obtain the absolute bolometric magnitudes of the two binaries, which can be compared to the results in the previous step. When the results of the two steps are consistent with each other, the physical parameters of the two binaries are obtained. The physical parameters of the two binaries are listed in Table 3, where the errors represent the uncertainty of q. The mean physical parameters of the two binaries are as follows: for V211, $M_1 = 1.13 \pm 0.03\ M_\odot$, $R_1 = 0.98 \pm 0.01\ R_\odot$, $M_2 = 0.33 \pm 0.01\ M_\odot$ and $R_2 = 0.92 \pm 0.01\ R_\odot$; for NV358, $M_1 = 1.30 \pm 0.05\ M_\odot$, $R_1 = 1.03 \pm 0.01\ R_\odot$, $M_2 = 0.58 \pm 0.02\ M_\odot$ and $R_2 = 0.78 \pm 0.01\ R_\odot$.

Table 2 Photometric Solutions for NV358 in the Globular Cluster ω Centauri

Parameters	[Fe/H] $= -1.53$	Errors	[Fe/H]$= -1.0$	Errors
$g_1 = g_2$	1.0	Assumed	1.0	Assumed
$A_1 = A_2$	1.0	Assumed	1.0	Assumed
x_{1bol}	0.435	Assumed	0.435	Assumed
x_{2bol}	0.082	Assumed	0.082	Assumed
y_{1bol}	0.254	Assumed	0.254	Assumed
y_{2bol}	0.646	Assumed	0.646	Assumed
x_{1B}	0.061	Assumed	0.061	Assumed
x_{2B}	0.125	Assumed	0.125	Assumed
y_{1B}	0.792	Assumed	0.792	Assumed
y_{2B}	0.753	Assumed	0.753	Assumed
x_{1V}	0.039	Assumed	0.039	Assumed
x_{2V}	0.036	Assumed	0.036	Assumed
y_{1V}	0.701	Assumed	0.701	Assumed
y_{2V}	0.743	Assumed	0.743	Assumed
$T_1(\mathrm{K})$	8918	Assumed	8923	Assumed
$q(M_2/M_1)$	0.4442	±0.0125	0.4443	±0.0125
$T_2(\mathrm{K})$	7249	±47	7255	±48
i	76.033	±0.272	76.037	±0.272
$L_1/(L_1+L_2)(B)$	0.8247	±0.0016	0.8248	±0.0016
$L_1/(L_1+L_2)(V)$	0.7873	±0.0019	0.7875	±0.0020
Ω_{crit}	2.7669	Assumed	2.7672	Assumed
Ω_1	4.0500	±0.0447	4.0463	±0.0448
Ω_2	3.4006	±0.0607	3.4027	±0.0607
$r_1(\mathrm{pole})$	0.2761	±0.0035	0.2764	±0.0035
$r_1(\mathrm{point})$	0.2861	±0.0041	0.2864	±0.0041
$r_1(\mathrm{side})$	0.2805	±0.0037	0.2808	±0.0038
$r_1(\mathrm{back})$	0.2841	±0.0039	0.2845	±0.0040
$r_2(\mathrm{pole})$	0.2072	±0.0063	0.2071	±0.0063
$r_2(\mathrm{point})$	0.2192	±0.0082	0.2190	±0.0082
$r_2(\mathrm{side})$	0.2103	±0.0067	0.2101	±0.0067
$r_2(\mathrm{back})$	0.2166	±0.0077	0.2165	±0.0077

Table 3 Physical Parameters of V211 and NV358

Parameters	Values	Errors	Values	Errors
	V211		NV358	
$M_1\,(M_\odot)$	1.13	±0.03	1.30	±0.05
$M_2\,(M_\odot)$	0.33	±0.01	0.58	±0.02
$R_1\,(R_\odot)$	0.98	±0.01	1.03	±0.01
$R_2\,(R_\odot)$	0.92	±0.01	0.78	±0.01
$A\,(R_\odot)$	3.30	±0.02	3.68	±0.04
$L_{bol1}\,(L_\odot)$	2.03	±0.05	5.86	±0.13
$L_{bol2}\,(L_\odot)$	0.54	±0.01	1.46	±0.13
$\log g_1$ (cgs)	4.51	±0.01	4.52	±0.01
$\log g_2$ (cgs)	4.03	±0.01	4.42	±0.02
M_{bol1} (mag)	3.98	±0.01	2.83	±0.01
M_{bol2} (mag)	5.41	±0.01	4.34	±0.04
M_{bol} (mag)	3.722	±0.010	2.589	±0.016
$m_{v_{max}}$ (mag)	18.11	Assumed	17.07	Assumed

3.2 The Particularity of the Two Binaries

Both of the binaries are very interesting targets. V211 is located in the faint BS region on the CMD of ω Centauri and is a definite member star of this cluster. Therefore, V211 is an eclipsing BS. The mass of the primary component of V211 is $1.13\,M_\odot$, which is larger than that of a star at the main
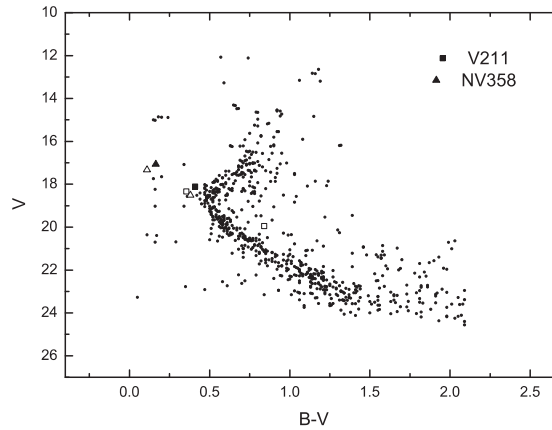
Fig. 3 Positions of the two binaries in the CMD of ω Centauri. The solid square gives the position of V211 and the solid triangle shows the position of NV358. Here open symbols represent the positions of the primary and secondary components of the two binaries.

sequence turnoff ($M_{\rm TO} = 0.8\ M_\odot$). Like other eclipsing Algol BS cases, such as NJL5 and V239 in ω Centauri and V228 in 47 Tuc (Helt et al. 1993; Li & Qian 2012; Kaluzny et al. 2007), V211 should have been formed by mass transfer from the secondary component to the primary, inducing a reversal of the original mass ratio so that the current primary was originally the less massive component. NV358 occupies a position in the bright BS domain of the CMD of ω Centauri, and the two components of NV358 are also located in the BS region. Both are bluer than the main-sequence stars in ω Centauri, indicating that they are younger and more metal rich. We have derived the surface gravity of the primary component as $\log g = 4.52$ cgs, suggesting that it is a main-sequence star. Then, we can estimate its age using the equation

$$t_{\rm MS} = \frac{3.37 \times 10^9}{(M/M_\odot)^{2.122}}, \tag{3}$$

derived from Yıldız (2011). An age of $T_a \leq 1.93$ Gyr is obtained for the primary component. It is believed that short period binary systems are formed by a fragmentation process and are unlikely to be formed from a capture process. Therefore, the components of NV358 should be the same age. We adopt a value of 1.93 Gyr for the age of NV358. The age of ω Centauri is 16 ± 3 Gyr (Noble et al. 1991), and almost at the same time the first generation of stars formed in ω Centauri. Therefore, NV358 is much younger than the first-generation stars there. Like NV364 in ω Centauri (Li et al. 2012), we deduce that NV358 is also a second-generation binary.

In summary, V211 is an eclipsing BS, making it an important object to test the hypothesis that BSs are formed by mass transfer in close binaries. At the same time, V211 was discovered in the outer region of ω Centauri, so it can verify the scenario that BSs in the outskirts of a low density cluster were formed by mass transfer in close binaries. NV358 is a second-generation binary, contributing evidence of multiple populations in ω Centauri. NV358 was discovered in the outer region but not in the center of ω Centauri, supporting the result that ω Centauri was previously the nucleus of a nucleated dwarf galaxy, but later it was completely destroyed by a gravitational interaction between the Milky Way and the nucleated dwarf galaxy, so that only its nucleus is now observed (Li et al. 2012). In the future, we hope to obtain related spectroscopic data, making it possible to evaluate more accurate physical parameters of the two binaries. This will provide further evidence to verify our results.

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