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NSVS 1908107, an EB-type eclipsing binary in the open cluster NGC 869

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Abstract We present a time-series BV CCD photometry for an EB-type eclipsing binary NSVS 1908107, a member of the young open cluster NGC 869. The photometric solution was obtained by using the 2003 version of the Wilson-Devinney code. It reveals that the system is a semi-detached binary with the secondary component filling its Roche lobe. The mass ratio was determined to be 0.059±0.001. With the physical parameters of the cluster, the masses, radii and luminosities of the two components of NSVS 1908107 are estimated to be $M_1 = 10.34{\pm}2.29\,M_\odot$, $R_1 = 4.65{\pm}0.34\,R_\odot$, $L_1 = 8076{\pm}371\,L_\odot$ and $M_2 = 0.61{\pm}0.13\,M_\odot$, $R_2 = 2.40{\pm}0.17\,R_\odot$, $L_2 = 1054{\pm}48\,L_\odot$ respectively. The results show that the secondary component could be a giant or subgiant star with the outer envelope being stripped.

Key words: binaries: eclipsing — binaries: semi-detached — stars: giant — stars: individual (NSVS 1908107)

1 INTRODUCTION

Eclipsing binaries in star clusters are important for the study of stellar structure and evolution. Combining photometric solutions with radial velocity observations, the mass and radii of the component stars in an eclipsing binary can be precisely determined. As members of a stellar population, the distance, age and metallicity of these stars are known from other ways. These make eclipsing binaries in star clusters an ideal test for the theories of binary structure and evolution.

NSVS 1908107 (= NGC 869 1516, RA (2000) = 02:20:02.968, DEC (2000) = +57:11:18.67) is a poorly studied early-type eclipsing binary located in the well known young open cluster NGC 869. With a proper-motion membership probability of 0.74 (Muminov 1983), it is very likely to be a member of the star cluster. Huang & Gies (2006) recognized it to be a B-type star and determined an effective temperature of 20 886±234 K for the star. Marsh Boyer et al. (2012) later updated the value to be 25 400±650 K. The variability of NSVS 1908107 was discovered by the Northern Sky Variability Survey (Hoffman et al. 2009). In the International Variable Star Index (*http://www.aavso.org/vsx/index.php?view=detail.top&oid=227491*), it is listed as a β Lyrae-type binary with a period of 1.73288182 d. So far, there has been no detailed study on this binary system in the literature.

NGC 869, also known as h Per, is a member of the Perseus double cluster with χ Per NGC 884. It is found to have similar properties with its partner. A recent study (Slesnick et al. 2002) gave a distance modulus of $(m - M)_0 = 11.85 \pm 0.05$ with a reddening of $[E(B - V)] = 0.56 \pm 0.01$ for the cluster. The age of the open cluster was determined to be 12.8±1.0 Myr. As a nearby and rich open cluster, NGC 869 was selected as a target of our ongoing variable searching program with 50BiN (Deng et al. 2013; Wang et al. 2015). Time-series photometry of NSVS 1908107 in B and V bands was collected. Based on these, a comprehensive photometric analysis of the binary system was carried out. We present the results in this paper.

2 OBSERVATIONS AND DATA REDUCTION

We observed the open cluster NGC 869 with time-series photometry from 2014 November 9 to 20 at Qinghai Station, which is administered by Purple Mountain Observatory, Chinese Academy of Sciences. Since NSVS 1908107 belongs to the cluster, the binary system was also

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Table 1 Journal of the Observations

Date	JD Start (2456900+)	Length (d)	Number of Frames (B, V)
2011 Nov 06	67.989	0.377	378, 720
2011 Nov 07	69.006	0.346	352, 659
2011 Nov 10	71.994	0.361	367, 695
2011 Nov 13	74.994	0.210	205, 384
2011 Nov 15	76.988	0.340	304, 575
2011 Nov 16	77.976	0.361	285, 690
2011 Nov 17	78.996	0.342	347, 641
2011 Nov 18	79.990	0.343	348, 644
2011 Nov 19	80.969	0.349	338, 653

observed. All the observations were carried out with the 50BiN (Zhang et al. 2014) prototype telescope equipped with an Andor 2k×2k CCD camera and two standard Johnson-Cousins-Bessel BV filters. With an image scale of 0.573 arcsec per pixel, the CCD camera provides a field of view of about $20' \times 20'$. The exposure times for each image in the B and V bands were set as 80 s and 40 s, respectively. In total, data from nine nights were obtained. The journal of observations is presented in Table 1.

The processing of the CCD frames was carried out with an automated reduction pipeline mainly based on the DAOPHOT II (Stetson 1987) package. Since photometric standard stars have not been observed during the observations, the magnitude and color calibrations for our photometry were taken using secondary standards in NGC 869 with the B and V magnitudes selected from Slesnick et al. (2002). Thirty unsaturated and isolated bright stars that were constant were used as the secondary standards. Applying a linear transformation between the 30 secondary standards and instrumental magnitudes from several images taken under photometric conditions, the standard magnitudes and colors for all stars in the field of NGC 869 were obtained. In order to normalize instrumental magnitudes of time-series BV frames, an ensemble normalization technique (Gilliland & Brown 1988) was applied. For each filter, the same 30 standard stars were used for calibration. With the following equations, the instrumental b and v data were transformed to the standard magnitudes B and V:

$$V = v + a_1 + a_2(B - V) + a_3X + a_4Y, \tag{1}$$

$$B = b + b_1 + b_2(B - V) + b_3X + b_4Y. \tag{2}$$

Here X and Y stand for the coordinate values in a CCD frame. The coefficients a_1, a_2, a_3, a_4 and b_1, b_2, b_3, b_4 were computed by applying the least-squares method. With the above equations, the photometry calibration was carried out. The mid-exposure time of each measurement was converted to HJD. In this way, we extracted the light curves of NSVS 1908107. Figure 1 shows the position of NSVS 1908107 on the color-magnitude diagram (CMD). The phased B and V band light curves with a period of 1.73288182 d are plotted in Figure 2.

3 PHOTOMETRIC SOLUTION

The Wilson-Devinney (WD) method (Wilson & Devinney 1971; Wilson 1979) was used to first obtain the photometric solution of this binary system. The light curves in B and V bands were simultaneously synthesized by means of the 2003 version of the WD code with the Kurucz atmospheres (Wilson 1990; Kallrath et al. 1998). The bolometric (X_1, Y_1, X_2, Y_2) and the monochromatic (x_1, y_1, x_2, y_2) limb-darkening coefficients in logarithmic form were taken from van Hamme (1993).

In computing the photometric solution, the values of some parameters were adopted as follows: the effective temperature of the primary star (T_1) was set as 25 400 K (Marsh Boyer et al. 2012); the gravity darkening exponents were taken as 1 for both components following Lucy (1967); the bolometric albedos were set to be 1 according to Ruciński (1969). When performing the differential correction (DC) calculation, the following parameters were adjusted: the mass ratio, q; the inclination, i; the effective temperature of the secondary star, T_2; the potentials of the two components, Ω_1 and Ω_2; and the monochromatic luminosity of the primary star, L_{1B} and L_{1V}.

In order to determine a reliable mass ratio of the system, a q-search method was used. Solutions were carried out for various values of mass ratio $q = \frac{M_2}{M_1}$ ($q = 0.01 \sim 0.1, = 0.01$ and $q = 0.1 \sim 1$, $\mathrm{step} = 0.1$). For each value of q, the calculation started at mode 2 (detached mode) and we found that the solutions usually converged at mode 5 (semi-detached configuration with the secondary star filling its Roche lobe). The relationship between the resulting weighted sum of squares, $\sum \omega(O - C)^2$, and q is displayed in Figure 3. The smallest value of $\sum$ was obtained at $q = 0.06$. Then a DC was performed until all the adjustable parameters converged. Thus, final solutions were derived. It is found that the solutions converged at $q = 0.059 \pm 0.001$ and it is a low mass ratio system. The photometric solution is listed in Table 2 and the corresponding theoretical light curves are plotted in Figure 2.

4 DISCUSSION AND CONCLUSIONS

The photometric solution reveals that NSVS 1908107 is a semi-detached binary system with the secondary component filling its Roche lobe. Combining the photometric solution listed in Table 2 with the properties of NGC 869, the physical parameters of both components were calculated. For the two components, the ratio of V-band luminosity is estimated as $\frac{L_1(V)}{L_2(V)} = 5.136$. The light curve gives the V-band magnitude of $V_{\max} = -2.5 \log(L_1(V) + L_2(V)) = 10.927$ mag at the light maxima. With the cluster distance modulus of $(m - M)_V = 13.586$ mag, the V-band absolute magnitudes M_{V1} and M_{V2} are –2.466 mag and –0.689 mag, respectively. For $T_1 = 25\,400$ K ($\log T_1 = 4.404$) and $T_2 = 21\,235$ K ($\log T_2 = 4.327$), the bolometric corrections are $BC1 = -2.562$ mag and

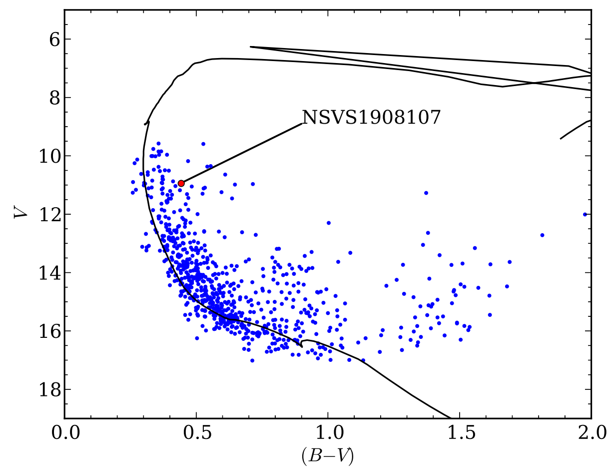

Fig. 1 Position of NSVS 1908107 (*red point*) in the CMD of NGC 869. The solid line denotes the fit of the Padova isochrones with the cluster parameters ($t = 12.8$ Myr, $Z = 0.02$, $E(B-V) = 0.56$, $(m-M)_0 = 11.85$) derived by Slesnick et al. (2002).

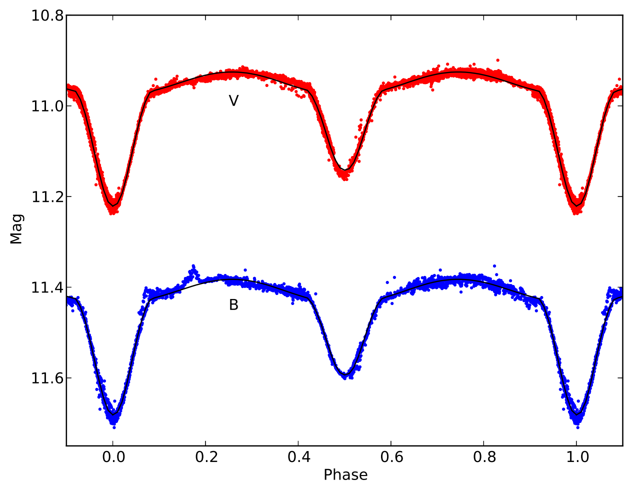

Fig. 2 Observed B (*blue points*) and V (*red points*) light curves of NSVS 1908107 and theoretical synthesis (*solid line*).

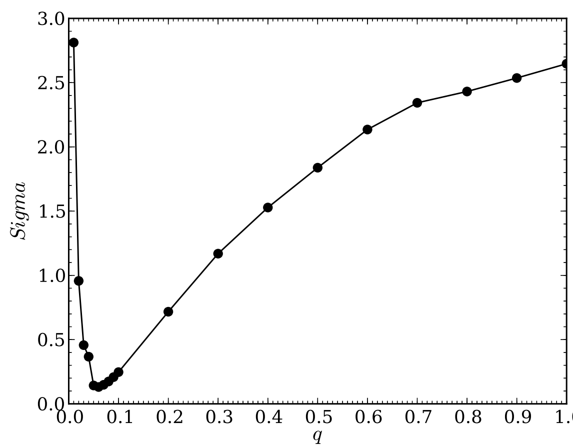

Fig. 3 The relation between $\sum$ and q for NSVS 1908107.

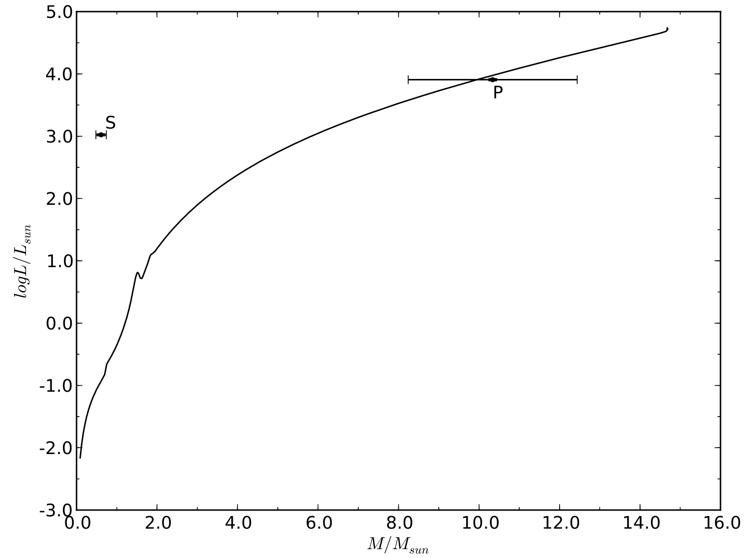

Fig. 4 The positions of primary (p) and secondary (s) components on the $M-L$ diagram. The solid line denotes the fit of the Padova stellar evolutionary track with the cluster parameters ($t = 12.8$ Myr, $Z = 0.02$, $E(B-V) = 0.56$, $(m-M)_0 = 11.85$) derived by Slesnick et al. (2002).

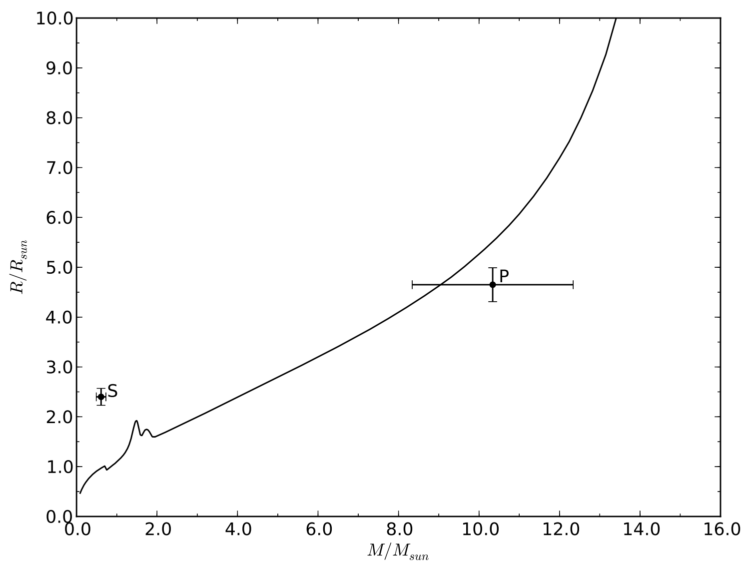

Fig. 5 The positions of primary (p) and secondary (s) components on the $M-R$ diagram. The solid line denotes the fit of the Padova stellar evolutionary track with the cluster parameters ($t = 12.8$ Myr, $Z = 0.02$, $E(B-V) = 0.56$, $(m-M)_0 = 11.85$) derived by Slesnick et al. (2002).

$BC2 = -2.128$ mag obtained by the calibration (Flower 1996), respectively. So, we get absolute bolometric magnitude $M_{\rm bol1} = -5.028$ mag and $M_{\rm bol2} = -2.81$ mag. Then, the luminosities of both components are derived to be $L_1 = 8076\,L_\odot$ and $L_2 = 1054\,L_\odot$. By applying the formula $M_{\rm bol} = 42.36 - 5\log(R) - 10\log(T_{\rm eff})$, the radii of both components are estimated to be $R_1 = 4.65\,R_\odot$ and $R_2 = 2.40\,R_\odot$. The semimajor axis (A) is calculated to be $13.49\,R_\odot$ using $r_1 = \frac{R_1}{A}$ given in Table 2, where r_1 represents the geometrical mean of the polar, side and back radii of the primary component. R_1 denotes the radius of the primary component. The total mass $(M_1 + M_2)$ is computed to be 10.95 $M_\odot$ using Kepler's third law. Using the mass ratio and the total mass, the masses of both components are calculated to be $M_1 = 10.34\,M_\odot$ and $M_2 = 0.61\,M_\odot$. The absolute parameters of NSVS 1908107 are given in

Table 2 Photometric Solution of NSVS 1908107

Parameter	Best-Fit Value	Formal Error
$i\,(^\circ)$	79.02	± 0.08
$q = \frac{M_2}{M_1}$	0.059	± 0.001
T_1 (K)	25400	
T_2 (K)	21235	± 35
Ω_1	3.0070	± 0.005
$\Omega_2 = \Omega_{\rm inner}$	1.8234	
$g_1 = g_2$	1^a	
$A_1 = A_2$	1^a	
X_1 (bolo)	0.742^a	
X_2 (bolo)	0.762^a	
Y_1 (bolo)	0.144^a	
Y_2 (bolo)	0.104^a	
$x_1\,(B)$	0.468^a	
$x_2\,(B)$	0.493^a	
$x_1\,(V)$	0.409^a	
$x_2\,(V)$	0.423^a	
$y_1\,(B)$	0.269^a	
$y_2\,(B)$	0.272^a	
$y_1\,(V)$	0.240^a	
$y_2\,(V)$	0.232^a	
$\frac{L_1}{L_1+L_2}(B)$	0.842	± 0.001
$\frac{L_1}{L_1+L_2}(V)$	0.837	± 0.001
r_1 (pole)	0.3388	± 0.0006
r_1 (side)	0.3463	± 0.0006
r_1 (back)	0.3473	± 0.0006
r_2 (pole)	0.1618	± 0.0005
r_2 (side)	0.1683	± 0.0005
r_2 (back)	0.1976	± 0.0005
$r_1 = \frac{R_1}{A}$	0.3451	

Notes: ^{a} assumed.

Table 3 Absolute Parameters for NSVS 1908107

Parameter	Primary	Secondary
Mass ($M_\odot$)	10.34 ± 2.29	0.61 ± 0.13
Radius ($R_\odot$)	4.65 ± 0.34	2.40 ± 0.17
Luminosity ($L_\odot$)	8076 ± 371	1054 ± 48

Table 3. The mass and radius of the primary component are close to the ones provided by Marsh Boyer et al. (2012) (mass= 9.9 $M_\odot$, radius = 3.7 $R_\odot$).

For the primary component, the size of its Roche lobe (R_L) can be determined by the formula (Eggleton 1983),

$$R = \frac{R_L}{A} = \frac{0.49q^{(\frac{-2}{3})}}{0.6q^{(\frac{-2}{3})} + \ln\left[1 + q^{(\frac{-1}{3})}\right]}, \tag{3}$$

where q is mass ratio ($\frac{M_2}{M_1}$) and A is semimajor axis. The fill-out factor is defined as $f = \frac{r}{R}$ (Zhai et al. 1989), where r represents the geometrical mean of the polar, side and back radii of the component. By applying the above two relations, the filling factor of the primary component is calculated to be 55.8%. These suggest that the primary star is well detached from its Roche limiting surface and the binary system is likely in the process of evolution into a near-contact binary.

In Figures 4 and 5, we plot the two components of NSVS 1908107 on the $M-L$ and $M-R$ diagrams along with the isochrones of the cluster NGC 869. The primary component appears to be an un-evolved main sequence star. The secondary is, however, obviously evolved, hotter, oversized and over-luminous compared to stars with similar mass in the cluster. The evolutionary status of the two components and the semi-detached configuration suggest that NSVS 1908107 would evolve through mass exchange after the mass-ratio is reversed. The system is now in the stage of slow mass transfer. The secondary could be a giant or subgiant star with the outer envelope being stripped. If mass transfer from the less-massive secondary component to the primary continues, it would enlarge the orbit of the binary system and possibly make the secondary separate from the Roche lobe. In this case, the secondary would be a B-type subdwarf (sdB) or a white dwarf.

In view of the subsequent evolution and final fate of the binary system, another possibility should not be excluded. Since the orbit of the binary system is very tight, and the mass of the primary is very high, it is very probable that the high-mass primary would fill its Roche lobe due to the rapid evolutionary expansion before the secondary becomes an sdB. In this case, NSVS 1908107 would suffer a common envelope evolution phase. With a mass ratio significantly smaller than the minimum value of about 0.09 (Rasio 1995), the binary system would be tidally unstable during the contact stage. Finally, it will quickly merge into a rapidly rotating star.

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