



Photometric investigation of two contact binaries in the young open cluster NGC 957



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HIGHLIGHTS

- The multi-color CCD photometry of the open cluster NGC 957 are presented.
- Two contact binaries V4 and V5 were discovered and analyzed using the W-D method.
- V4 and V5 are A-subtype system and V5 presents the O'Connell effect.
- The member of the two contact binaries V4 and V5 are discussed.

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ABSTRACT

We present V- and R- band time-series CCD photometry of two contact binaries in the region of the young open cluster NGC 957. The two eclipsing binaries were discovered by Bukowiecki et al., 2009. OEJV 112, 1 and named as V4 and V5, respectively. In the present paper, the first detailed studies of the two contact binary systems are carried out. Firstly, based on the light curves, 28 times of minimum light were detected for V4 and 21 times of minimum light for V5, respectively. Secondly, the orbital periods of V4 and V5 were redetermined as $P_{V4} = 0.40032(5)$ days and $P_{V5} = 0.30752(4)$ days, respectively. The photometric solutions were analyzed by using Wilson Decinny Code. The results reveal that both V4 and V5 are W UMa-type contact binaries with a degree of $f_{V4} = 31(\pm 1)\%$ and $f_{V5} = 65(\pm 1)\%$. The mass ratios were determined to be $q_{V4} = 0.30$ and $q_{V5} = 0.19$. For V5, the well known O'Connell effect was detected in the dataset, which effect can be explained by employing a dark spot placed on the more massive primary component. Finally, based on the distances of the two contact binaries, which were calculated by using a relation given by Gettel et al., the two contact binaries are judged to be foreground stars in the open cluster NGC 957.

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1. Introduction

NGC 957 (RA = $02^h33^m21^s$, Dec = $57^\circ33'36''$) is a young open cluster located in Perseus spiral arm of our Galaxy. Ruprecht (1966) reported that it is a loose and not rich stellar ensemble of type III2p. Gimenez and Garcia-Pelayo (1980) described it as a young star cluster at a distance of 1.8 kpc. This cluster was further investigated by Gerasimenko (1991) using Johnson UBV photoelectric and photographic photometry, which resulted the reddening of $E(B - V) = 0.90$ mag, the distance of 2.1 kpc and the age of about 4 Myr. These parameters also were reported by Dias et al. (2002), reddening of $E(B - V) = 0.842$ mag, distance of 1815 pc

and $\log(\text{age}) = 7.042$. More recently, the first UBVR CCD photometry for NGC 957 was carried out by Yadav et al. (2008). They derived the cluster's basic parameters, the reddening of $E(B - V) = 0.71 \pm 0.05$ mag, the distance of 2.2 ± 0.2 kpc and the age of 10 ± 5 Myr ($\log(\text{age}) = 7.0$). Then, Bukowiecki et al. (2009) carried out the BV CCD photometric observation for searching the variable stars in this open cluster. 14 variables were discovered, including 10 eclipsing binaries. 3 W UMa type binaries were found with periods shorter than a day. Meanwhile, they derived the reddening $E(B - V) = 0.81 \pm 0.05$ mag, the distance modulus of 13.8 ± 0.1 , the distance of 1890 ± 50 pc and the age of $\log(\text{age}) = 7.10 \pm 0.05$.

W UMa-type variable stars are interacting binary systems with short-period (usually $P < 1$ day) where both of the two components overflow their critical Roche lobe and share a common convective envelope. There are many unsolved problems for these type

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binary systems, such as the formation and evolution, the deep, low mass ratio over contact binary et al. Photometric investigation of totally eclipsing contact binary systems in stellar clusters is very important to understand these problems. Recently, many studies of contact binaries have been carried out in open cluster and many W UMa-type binaries were detected. In NGC 188, at least 9 W UMa-type binaries were reported (Zhang et al., 2002; 2004). In M67 and Tombaugh 2, there are 4 and 5 W UMa-type binaries (Gilliland, 1991; Sandquist and Shetrone, 2003; Kubiak et al., 1992). Berkely 39 and Cr 261, were known to possess 12 and at least 28 contact binaries, respectively (Kaluzny et al., 1993; Mazur et al., 1995). In NGC 2301, one contact binary was detected by Wang et al. (2015). In NGC 957, 10 eclipsing binaries (V1, V2, V3, V4, V5, V9, V10, V12, V13, V14) have been found, including 3 contact binaries (V1, V3, V5) (Bukowiecki et al., 2009). The period and the type of the eclipsing binaries were determined by Bukowiecki et al. (2009). In this paper, new CCD photometric observations are presented for NGC 957. Two contact binaries are observed in our field. One is V4, classified as EB type by Bukowiecki et al. in 2009 initially, which maybe presented as EW type in our light curve, the other is V5, which shows EW type. The first detailed studies of the two contact binaries are carried out in this work. The observation and data reduction are described in Section 2. The period analysis and determination of ephemeris are shown in Section 3. The light curve analysis by using Wilson-Decinny Code are given in Section 4. Finally, the discussion and conclusion are shown in Section 5.

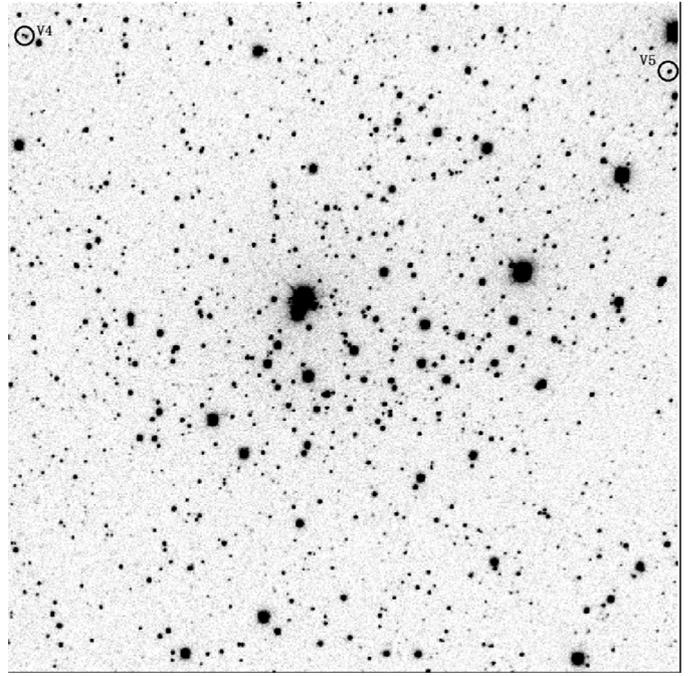


Fig. 1. A 16.5×16.5 finding chart for the two W UMa-type contact binaries V4 and V5 in the field of open cluster NGC 957.

2. Photometric observations, data reduction and analysis

The new time-series VR CCD photometric observations of young open cluster NGC 957 were carried out on November 12, 14, 16, 17, 18, 19, 20 and 21, 2013 from 85 cm reflecting telescope at Xinglong station of the National Astronomical Observatory, Chinese Academy of Sciences (NAOC). One 1024×1024 PI CCD camera and a standard Johnson - Cousins - Bessel multicolor filter system were used during the observation (Zhou et al., 2009). The effective field of view is 16.5×16.5 . The twilight sky flat, bias and dark frames were taken on each observing day, which were processed with the standard routines of CCDPROC in the IRAF package at first. Then, the instrumental magnitudes of stars detected in the program field were obtained by PHOT from the aperture photometry package of IRAF. The star NGC 957 86 ($\alpha_{J2000} = 02^h33^m18.0^s$, $\delta_{J2000} = 57^{\circ}31'36.0''$) are used as the comparison star and the star NGC 957 156 ($\alpha_{J2000} = 02^h33^m33.5^s$, $\delta_{J2000} = 57^{\circ}37'45.7''$) are used as the check star, respectively. The standard deviation of the differential magnitude between the comparisons and check stars are about 0.03 mag in V band and about 0.08 mag in R band.

At last, from these observations, we detected two W UMa binaries which named as V4 and V5 (Bukowiecki et al., 2009) and carried out a detailed photometric study in the first time in this paper. In the beginning, we just want to investigate the contact binaries in NGC957 and the center of the field put in the center of the cluster, so that the two contact binaries V4 and V5 are located in the edge of the field which are shown in Fig. 1. Therefore, sometimes they will move out the field. Because of the position and weather effect for the two systems, only the data on last day (on November 21, 2013) can cover the complete curve and have the best S/N for the two contact binaries. So all of the photometric analyses below for the two contact binaries are derived by using these data of the day. A total number of 376 and 363 data points were accumulated from this day for V4 in V and R bands, respectively. For V5, 321 and 314 data points were obtained in V and R bands, respectively. The corresponding light curves of the two contact binaries are displayed in Figs. 2 and 3.

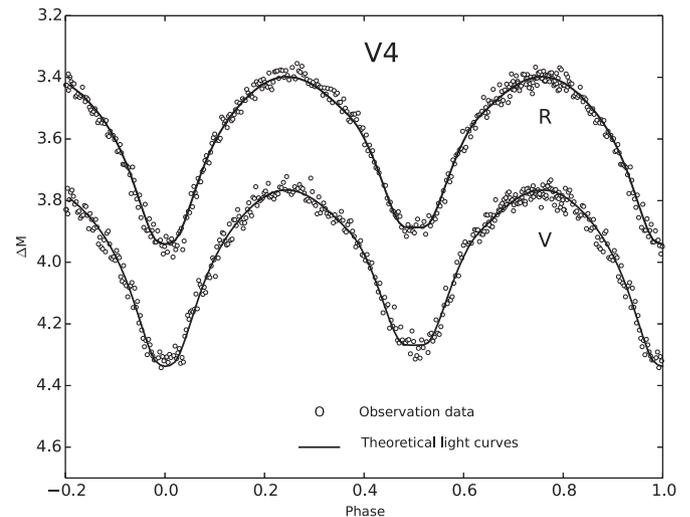


Fig. 2. CCD photometric light curve of V4 in open cluster NGC 957 observed on November 21, 2013 with V- and R- bands. Open circles is for the observational data in V, R bands. The solid line is the theoretical light curves, which was calculated using the W-D method in Section 4.

3. Period analysis and determination of ephemeris

We derive the period of the two contact binaries using Period04 package (Lenz and Breger, 2005) at first. Then the final periods for the two systems are obtained by using their times of minima by means of the linear least-squares method. The times of minima are obtained by using K-W method (Kwee and van Woerden, 1956). During our observation, 28 times of minimum light are detected for V4 and 21 times of minimum light for V5, respectively. All of the eclipse times for V4 and V5 at VR band are listed in Tables 1 and 2, respectively. The orbital period of the two contact binaries are calculated as $P_{V4} = 0.40032(5)$ days and $P_{V5} = 0.30752(4)$ days. For V4, based on the primary minimum time of 2456618.0974 (7) and the period of 0.40032(5) days, we determined the following

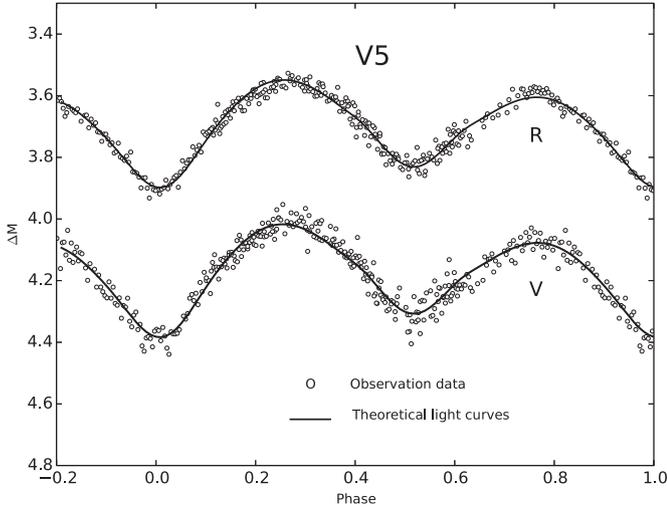


Fig. 3. The light curve of V5 observed on November 21, 2013 with V- and R- bands. Symbols are the same as those in Fig. 2.

Table 1

New times of light minimum for V5 in open cluster NGC 957.

HJD	Error	Min.	Filter	E	O-C
2456609.08526	0.00013	I	V	-22.5	-0.0044
2456609.08685	0.00035	I	R	-22.5	-0.0028
2456609.29223	0.00035	II	V	-22.0	0.0023
2456609.29956	0.00082	II	R	-22.0	0.0098
2456611.08801	0.00013	I	V	-17.5	-0.0031
2456611.09002	0.00015	I	R	-17.5	-0.0011
2456611.28863	0.00050	II	V	-17.0	-0.0027
2456611.28918	0.00031	II	R	-17.0	-0.0021
2456613.09289	0.00060	I	V	-12.5	-0.0001
2456613.09204	0.00019	I	R	-12.5	-0.0008
2456613.29705	0.00040	II	V	-12.0	-0.0013
2456613.29168	0.00027	II	R	-12.0	0.0041
2456614.10211	0.00033	I	V	-10	0.0084
2456614.08978	0.00020	I	R	-10	-0.0039
2456615.09497	0.00038	I	V	-7.5	0.0004
2456615.09057	0.00094	I	R	-7.5	-0.0040
2456615.29394	0.00042	II	V	-7.0	0.0008
2456615.29156	0.00033	II	R	-7.0	-0.0031
2456616.09570	0.00020	I	V	-5.0	0.0003
2456616.09625	0.00040	I	R	-5.0	0.0009
2456616.29572	0.00018	II	V	-4.5	0.0001
2456616.29578	0.00014	II	R	-4.5	0.0002
2456617.29595	0.00036	II	V	-2.0	-0.0005
2456617.29663	0.00014	II	R	-2.0	0.0001
2456618.09686	0.00019	I	V	0.0	-0.0003
2456618.09741	0.00017	I	R	0.0	0.0002
2456618.29834	0.00026	II	V	0.5	0.0010
2456618.29895	0.00021	II	R	0.5	0.0016

linear ephemeris:

$$\text{Min.}I = 2456618.0974(7) + 0.40032(5)\text{days} \times E. \quad (1)$$

With the same method, we determine the linear ephemeris for V5 based on the primary minimum time of 2456618.2368 (8) and the period of 0.30752(4) days as following:

$$\text{Min.}I = 2456618.2368(8) + 0.30752(4)\text{days} \times E. \quad (2)$$

Base on the above ephemeris formulae, we fold their light curve in orbital phase(see Fig. 2 and 3) and calculate the corresponding O - C values for these two contact binaries. The values of Epoch (E) and O-C are listed in the last two columns of Tables 1 and 2.

4. Photometric solutions with the W-D method

In the present paper, the photometric solutions of V4 and V5 were detailed analyzed at the first time by using the W-D program

Table 2

New times of light minimum for V5 in open cluster NGC 957.

HJD	Error	Min.	Filter	E	O - C
2456609.00769	0.00017	II	V	-30	-0.0038
2456609.00915	0.00028	II	R	-30	-0.0023
2456609.17077	0.00035	I	V	-29.5	0.0055
2456609.16424	0.00017	I	R	-29.5	-0.0011
2456611.01068	0.00027	II	V	-23.5	0.0003
2456611.01214	0.00031	II	R	-23.5	0.0017
2456611.15996	0.00018	I	V	-23	-0.0044
2456611.16442	0.00030	I	R	-23	0.0003
2456611.32109	0.00072	II	R	-22.5	0.0023
2456615.01385	0.00042	II	V	-10.5	0.0059
2456615.00903	0.00034	II	R	-10.5	0.0010
2456615.15539	0.00058	I	V	-10	-0.0064
2456615.15942	0.00044	I	R	-10	-0.0024
2456615.31793	0.00047	II	V	-9.5	0.0024
2456615.31945	0.00061	II	R	-9.5	0.0040
2456618.08404	0.00019	II	V	-0.5	0.0009
2456618.08783	0.00012	II	R	-0.5	0.0047
2456618.23248	0.00018	I	V	0.0	-0.0044
2456618.23266	0.00017	I	R	0.0	-0.0042
2456618.38891	0.00029	II	V	0.5	-0.0018
2456618.39245	0.00021	II	R	0.5	0.0018

(Wilson and Devinney, 1971; Wilson, 1979, 1990, 1994; Wilson and Van Hamme, 2003). The light curves of V4 and V5 are displayed in Fig. 2 and Fig. 3. As shown in the two figures, the light curve are typical EW type, where the brightness varies continuously and the depths of both light minima are nearly the same.

During the analysis, we give the effective temperatures to be $T_1 = 5338(288)$ K and $4929(198)$ K for the primary component of V4 and V5, respectively. They are averaged from 2MASS J and H magnitudes that using the following relation obtained by Collier Cameron et al. (2007),

$$T_{eff} = -4369.5(J - H) + 7188.2, 4000 K < T_{eff} < 7000K. \quad (3)$$

The basic information for the two contact binaries in 2MASS are showed in Table 3. V4 and V5 are named as 2MASS J02342291+5725468 and 2MASS J02322600+5726420 in 2MASS, respectively. In order to check our results of the parameters of temperatures, we analyse period - color diagram of the two contact binaries. In general, W UMA-type contact binaries have a well defined region in the period - color diagram (Eggen, 1967); the observed systems are found within a broad strip (Kaeher and Fehlbeg, 1991) defined by

$$1.5\text{Log}T_{eff} - \text{Log}P = 5.975...6.15, \quad (4)$$

where P is the period in days. Here, we plot the color - period diagram of the two contact systems, which is shown in Fig. 4. We can see that both of the two contact binaries are located in the strip.

From the effective temperature, it suggests that these two contact binaries are late G spectral type binaries. For the two contact binary systems, the gravity-darkening coefficients $g_1 = g_2 = 0.32$ (Lucy, 1967) and the bolometric albedos $A_1 = A_2 = 0.5$ (Rucinski, 1969) were used, which correspond to the common convective envelope of both components. A nonlinear limb-darkening law with a logarithmic form was applied in the light-curves synthesis. The initial bolometric (X_1, X_2, Y_1, Y_2) and monochromatic limb-darkening coefficients (x_1, x_2, y_1, y_2) of the components were taken from Van Hamme (1993), which are listed in Tables 4 and 5. During the computation, we find that solutions converged at mode 3, and the adjustable parameters are as follows: the inclination, i , the mean temperature of star 2, T_2 , the monochromatic luminosity of star 1, L_{1V} and L_{1R} , and the dimensionless potentials of star 1 and star 2 ($\Omega_1 = \Omega_2$ for mode 3). However, no mass ratios for the two contact binaries were obtained in previous literature, we fixed the

Table 3

Basic information for the two contact binaries in the field of open cluster NGC 957.

Name	R.A. (J2000) (d:m:s)	Dec. (J2000) (d:m:s)	J (mag)	ΔJ (mag)	H (mag)	ΔH (mag)	K_s (mag)	ΔK_s (mag)	T_{eff} (K)
2MASS J02342291 + 5725468(V4)	02:34:22.917	+57:25:46.89	13.828	0.043	13.416	0.05	13.284	0.046	5388(288)
2MASS J02322600 + 5726420(V5)	02:32:26.007	+57:26:42.04	13.539	0.025	13.021	0.038	12.868	0.034	4925(198)

Notes: The magnitudes of J, H, K_s are from the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003), and the temperatures (T_{eff}) are derived from the colors given by (J - H). The corresponding errors are propagated from uncertainties in the J and H magnitude.

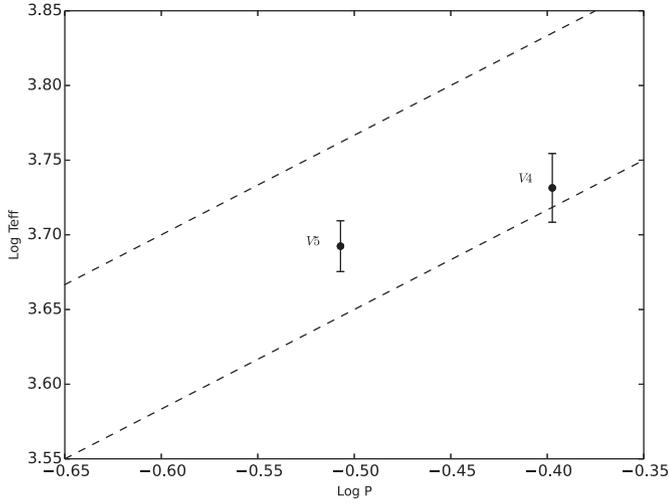


Fig. 4. The period vs. effective temperatures of the two contact binaries V4 and V5 in open cluster NGC 957. Note that the error bars refer to the temperature errors (the last column of Table 3). The dashed lines denote the relation between period and temperature described by Kaehler and Fehlbeg (1991).

Table 4

Photometric solutions for V4.

Parameters	Best-fit value(model 3)	
	Primary	Secondary
$g1 = g2$ (deg)	0.32	
$A1 = A2$ (deg)	0.50	
X_{bolo}	0.649	0.647
Y_{bolo}	0.193	0.176
x_V	0.786	0.787
y_V	0.177	0.172
x_R	0.696	0.698
y_R	0.214	0.211
i (deg)	81.40(56)	
$q = M_2/M_1$	0.30(1)	
$T(K)$	5388	5302(13)
$\Omega_1 = \Omega_2$	2.408(2)	
$L_1/(L_1 + L_2)_V$	0.749(1)	
$L_1/(L_1 + L_2)_R$	0.748(2)	
$r(\text{pole})$	0.4679(9)	0.2741(10)
$r(\text{side})$	0.5065(13)	0.2873(12)
$r(\text{back})$	0.5360(16)	0.3315(23)
$f(\%)$	31(1)	

Table 5

Photometric solutions for V5.

Parameters	Best-fit value(model 3)	
	Primary	Secondary
$g1 = g2$ (deg)	0.32	
$A1 = A2$ (deg)	0.50	
X_{bolo}	0.643	0.643
Y_{bolo}	0.160	0.160
x_V	0.797	0.799
y_V	0.094	0.064
x_R	0.717	0.723
y_R	0.164	0.146
i (deg)	65.15(71)	
$q = M_2/M_1$	0.19(1)	
$T(K)$	4925	4770(12)
$\Omega_1 = \Omega_2$	2.146(2)	
$L_1/(L_1 + L_2)_V$	0.837(1)	
$L_1/(L_1 + L_2)_R$	0.830(2)	
$r(\text{pole})$	0.5052(4)	0.2465(4)
$r(\text{side})$	0.5559(6)	0.2589(6)
$r(\text{back})$	0.5828(7)	0.3115(9)
$\text{Latitude}_{spot}(\text{deg})$	89.9(2)	
$\text{Longitude}_{spot}(\text{deg})$	39.1(5)	
$\text{Radius}_{spot}(\text{deg})$	63.3(1)	
T_{spot}/T_2	0.36(5)	
$f(\%)$	65(1)	

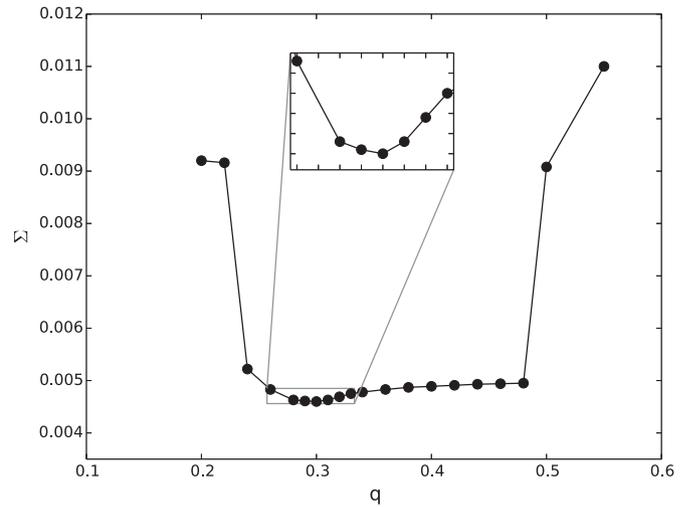


Fig. 5. Relation between Σ and q of V4.

mass ratio by a q -search method with different values from 0.1 to 5. the solution were carried out for a series of values of the mass ratio. During the fixed, we found that it is hard to reach a converged solution when $q > 0.6$ and 0.4 for V4 and V5, which implies that the two binaries could be contact systems of A subtype. The relation between the resulting sum Σ of the weighted square deviations and q are plotted in Fig. 5 and 6 for V4 and V5, respectively. We found that the best mass ratios are $q = 0.30$ and $q = 0.19$ for V4 and V5, respectively.

The detailed photometric solutions of V4 are listed in Table 4 and the theoretical light curves are displayed in Fig. 2 (The

observed data is marked with open circles and the theoretical light curves are marked with solid lines). For V5, the light curves show clear O'Connell effects (different heights of the two light maxima) in Fig. 3. Therefore, the spot models were adopted to explain the asymmetry of the light curves. After considering all possible spot models (hot and dark spots on the primary and secondary components), a dark spot located on the primary components was adopted in the solution of the W-D program. There are four spot parameters for each spot in the W-D program: the spot temperature ($T_s = T_d/T_0$, T_s is the ratio between the spot temperature T_d

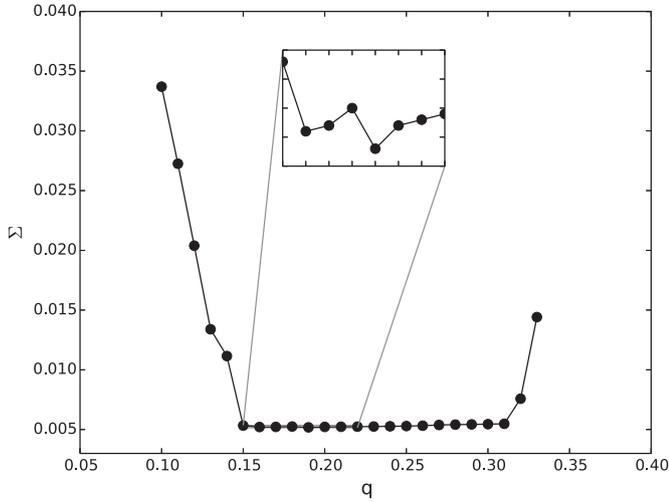


Fig. 6. Relation between Σ and q of V5.

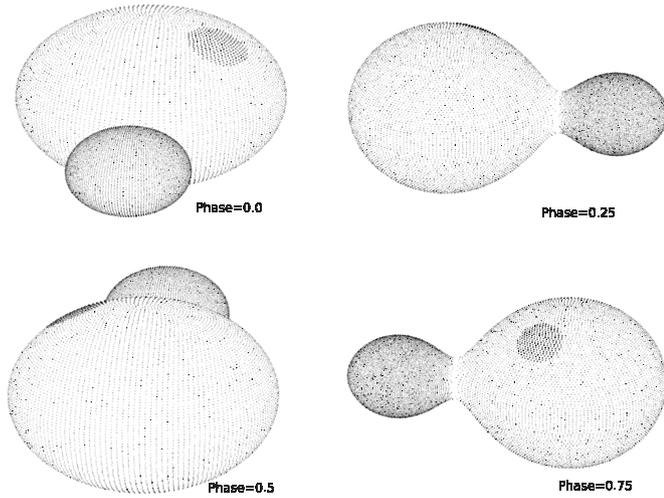


Fig. 7. Geometrical structure of V5 at phases of 0.0, 0.25, 0.5, and 0.75, respectively.

and the photosphere surface temperature T_0 of the star), the spot angular radius (r_s) in radians, the co-latitude of the spot center (θ) in degrees and longitude of the spot center (ϕ) in degrees. Finally, the best fitting of the photometric solutions are obtained with a dark spot. The observed data (marked with open circles) and the theoretical light curves (marked with solid lines) as V4 are shown in Fig. 3. The results and parameters of the dark spot are shown in Table 5. In order to investigate the variability of the O'Connell effects of V5, the relatively good data of four days (on November 12, 14, 18, 21, 2013) are analysed. But they do not display any obvious changes, which shows that the activities of the dark spot on the contact binary V5 is too weak to see in the light curves. Additionally, the corresponding geometric structure of the system V5 is displayed with dark spot in Fig. 7.

5. Discussions and conclusions

We performed V- and R- band time-series CCD photometry of two contact binaries in the open cluster NGC 957. The two systems were discovered by Bukowiecki et al. in 2009 and named as V4 and V5. In this paper, we carried out detailed photometric analysis for the two contact binaries at the first time and obtained the photometric parameters based on the light curves. The results of two contact binary systems are concluded below:

V4: 28 minimum light times of V4 were obtained in our observation data. The period is redetermined as 0.40032(5) days, and its (J-H) color corresponds to a late G spectral type binary. The results of the detailed photometric solution show that this system is a typical W UMa-type contact binaries with a degree of $f = 31(\pm 1)\%$. The effective temperatures of the components show that it is a contact binary with a very small difference temperature of $\Delta(T_1 - T_2) = 66\text{K}$. From our analysis, the mass ratio of $q \sim 0.30$ and the primary component has a higher temperature, which imply that this binary could be contact system of A-subtype.

V5: There are 21 minimum light times for V5 in total. The period is around 0.30752(4) days, and its (J-H) color also corresponds to a late G spectral type binary as V4. Its light curves exhibit cases of the O'Connell effect like many contact binaries (Li et al., 2014; Liu et al., 2012; Qian et al., 2012; Luo et al., 2015) and the common phenomenon due to magnetic activities on the surface. Therefore, a dark spot was introduced in our theoretical light curve. In the light curve analysis, a good fit was obtained with binary mode 3 under a dark spot on the primary component. The results reveal that it is a W UMa-type contact binaries with a degree of $f = 65(\pm 1)\%$ and a very low mass ratio of $q \sim 0.19$. The effective temperatures of the components show that it is a contact binary with a small difference temperature of $\Delta(T_1 - T_2) = 155\text{K}$. The results show that large mass corresponding to a higher temperature in this system, so V5 could be a A-subtype contact binaries like V4.

We also estimated the distance of the two contact binaries base on the empirical relation

$$\log D = 0.2V_{\max} - 0.18 \log(P) - 1.60(J - H) + 0.56, \quad (5)$$

which relation was derived based on a sample of contact binaries by Gettel et al. (2006). For V4 and V5, the V_{\max} equal 15.7 and 16.1 mag based on our observation data, respectively. Then, the distances for the two systems were obtained as 1295 and 1105 pc based on Eq. (5), respectively. Comparing with the distance $1890 \pm 50\text{ pc}$ of the open cluster NGC 957 (Bukowiecki et al., 2009), both of the two contact binaries are more likely to be foreground stars in the cluster.

In summary, (a) we have presented new V- and R- bands CCD photometric of two contact binaries in the field of the open cluster NGC 957. The period was recalculated using the minimum times of the two contact binaries and the mass ratio were re-estimated in this work. (b) We report the detailed photometric solution of two contact binaries V4 and V5 in open cluster NGC 957 at the first time. The results reveal that both the binary systems are A-subtype W UMa-type contact binaries, and V5 has a O'Connell effect which can be explained by a dark spot placed on the massive primary component. (c) The distances of the two systems were estimated using the empirical relation. Based on the results, both of the two contact binaries are more likely to be foreground stars in the open cluster NGC957.

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