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Variable stars in the open cluster NGC 2141 *

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Abstract We report the results of a search for variable stars in the open cluster NGC 2141. Ten variable stars are detected, among which nine are new variable stars and they are classified as three short-period W UMa-type eclipsing binaries, two EA-type eclipsing binaries, one EB-type eclipsing binary, one very short-period RS CVn-type eclipsing binary, one d-type RR Lyrae variable star, and one unknown type of variable star. The membership and physical properties are discussed, based on their light curves, positions in the color magnitude diagrams, spatial locations and periods. A known EB-type eclipsing binary is also identified as a blue straggler candidate in the cluster. Furthermore, we find that all eclipsing contact binaries have prominent asymmetric eclipses and display the O'Connell effect, which increases with a decrease in orbital periods. This suggests that the O'Connell effect is probably related to the evolution of the orbital period in short period eclipsing binary systems.

Key words: stars: binaries: general — open clusters and associations: individual (NGC 2141) — variables: general

1 INTRODUCTION

This paper is a contribution from our ongoing program that searches for variable stars in open clusters (Zhang et al. 2002, 2004; Luo et al. 2009, 2012b). One of our main goals is to study stellar evolution via a census of variable stars in open clusters. Stars in an open cluster have approximately the same age and chemical abundances. Exploiting these facts, the statistical properties of variable stars can be used to apply constraints to stellar theoretical models (Kim et al. 2000) and unresolved physical processes like mass transfer, common-envelope ejection, mass loss, angular momentum loss, etc (Jiang et al. 2009; Pietrzyński et al. 2009, 2013; Ivanova et al. 2013). In addition, these properties have also been used to measure the age and distance of the host clusters and provide some hints about the dynamical evolution of the cluster (Meibom et al. 2009).

NGC 2141 is an old open cluster near the direction of the Galactic anticenter. The coordinates of the cluster center are RA(J2000)=$06^{\rm h}02^{\rm m}58.2^{\rm s}$ and Dec(J2000)=$+10°26'39''$ ($l = 198.75°$, $b = -5.79°$) (Carraro et al. 2001). Burkhead et al. (1972) presented the first photoelectric and photographic observations and concluded that NGC 2141 has a late intermediate age, a mean color excess of $E(B-V) = 0.30$ and a distance modulus of $m - M = 14.1$. Rosvick (1995) then collected new

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optical VI and near-infrared JH photometry. By comparing with theoretical isochrones, the age and metallicity were estimated to be $t = 2.5$ Gyr and $Z = 0.006$ respectively. The corresponding color excess and distance modulus were $E(B-V) = 0.35 \pm 0.07$ and $m - M = 14.16 \pm 0.16$ respectively. Carraro et al. (2001) acquired deeper BV and JK photometry in a small area around the cluster center, from which they derived a slightly larger reddening ($E(B-V) = 0.4$) and a slightly shorter distance (~ 3.8 kpc). The latest photometric data for this cluster have been presented by Donati et al. (2014), who concluded that NGC 2141 is an old open cluster with age in the range 1.25 and 1.9 Gyr, $E(B-V)$ between 0.36 and 0.45, $(m-M)_0$ between 11.95 and 12.21 and subsolar metallicity. NGC 2141 is still an interesting target for the study of variable stars. Much deeper photometry has shown that the cluster contains a very rich binary population and mass segregation is apparent (Carraro et al. 2001; Donati et al. 2014). Although many variable candidates in NGC 2141 have been reported, detailed information is not yet known (Kissinger & Kafka 2005; Widhalm & Kafka 2006). Therefore, we measured new time-series photometry for the open cluster NGC 2141 to detect possible variable stars. Observations and data reductions are described in Section 2; identification of variable stars is presented in Section 3; their physical properties are discussed in Section 4; and a summary follows in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

All photometric observations of the open cluster NGC 2141 were carried out over four nights, 2011 January 4–7, using the Lijiang 2.4 m telescope administered by Yunnan Astronomical Observatories, Chinese Academy of Sciences. We used the Yunnan Faint Object Spectrograph and Camera (YFOSC) to take the data. This facility is equipped with a 4096×2048 CCD camera and two filter systems: standard Johnson-Cousin-Bessel $UBVRI$ and SDSS $ugriz$. It provides two observational modes: recording spectra and imaging. We utilized the imaging mode, under which the effective number of pixels is 2048×2048 and the field of view is about $10' \times 10'$. The standard Johnson-Cousin-Bessel V filter was chosen and the exposure times were set to be 360 seconds. In total, we acquired 230 V-band frames. An additional set of $BVRI$ photometry data for the cluster was obtained on 2011 January 6, when photometric sky conditions were available. Two Landolt standard fields: SA 95 and SA 98 (Landolt 1992), and a Stetson photometric standard field: open cluster M67 (Stetson 2000), were also observed to construct photometric standards.

The raw images were de-biased and flat-fielded with the IRAF-CCDPROC package. The instrumental magnitudes of stars in the CCD images were then extracted using the point-spread function fitting program in the IRAF-DAOPHOT package. The instrumental magnitudes in $BVRI$ bands were corrected by using the IRAF-DAOGROW package and converted to the standard system with the following transformation equations:

$$B = b - 1.277 \pm 0.025 + (0.031 \pm 0.004)(b - v) - (0.233 \pm 0.019)X\,, \quad (1)$$

$$V = v - 1.052 \pm 0.013 - (0.073 \pm 0.002)(b - v) - (0.119 \pm 0.010)X\,, \quad (2)$$

$$R = r - 0.991 \pm 0.009 - (0.103 \pm 0.004)(v - r) - (0.095 \pm 0.007)X\,, \quad (3)$$

$$I = i - 0.624 \pm 0.024 + (0.019 \pm 0.005)(v - i) - (0.065 \pm 0.018)X\,, \quad (4)$$

where b, v, r and i are the instrumental magnitudes, B, V, R and I denote the standard magnitudes, and X is the air mass.

3 IDENTIFICATION OF VARIABLE STARS

For the purpose of searching for variable stars, we applied differential photometry to each star detected in the V-band images. Following Zhang et al. (2002), an image with the best seeing and

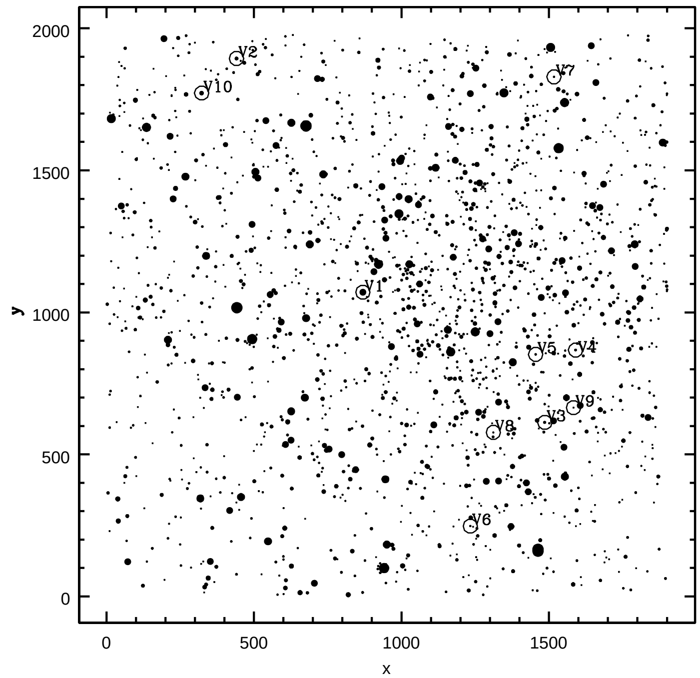

Fig. 1 Observed CCD field of the open cluster NGC 2141 and locations of variable stars.

highest signal to noise ratio was chosen to be the reference frame, from which we then iteratively selected about one hundred non-variable bright stars as the reference stars. With these reference stars, the magnitudes of all stars in the images were corrected with respect to the reference frame.

We then used two selection methods to identify variable candidates from the above differential light curves. Firstly, we selected stars as candidates whose light curves show larger deviations than those with similar brightness. Then, we calculated the Stetson J-indexes (Stetson 1996) of stars and identified stars with a large J-index as candidates. Finally, we visually inspected the light curves of variable candidates and rejected spurious variables and those showing small variability or chaotic light variations. In total, we identified ten new variable stars in the field of NGC 2141. In this paper, They are named V1–V10.

Figure 1 displays their spatial locations in the observed CCD field and Table 1 gives their coordinates and physical parameters derived from the color magnitude diagrams (CMDs) and light curves.

4 PHYSICAL PROPERTIES OF VARIABLE STARS

4.1 Cluster Membership

In general, the determination of cluster membership mainly depends on the proper motions and radial velocities. However, these values have not been reported for the variables that we identified. In this paper, we discuss their cluster memberships only according to their spatial locations in the cluster field and positions in the CMDs.

To derive the cluster memberships of variable stars from the spatial locations, we derived the physical parameters of the cluster. First of all, we determined the center of the cluster by finding the maximum surface number density of stars in the cluster field. Here, only stars with $V \leq 20$ were considered. The cluster center was roughly determined to be the pixel coordinate (1234, 1080) in our

Table 1 Parameters Describing Variable Stars in the Field of NGC 2141

Star ID	RA (J2000)	Dec (J2000)	$V_{\max}$ (mag)	$B-V$ (mag)	$V-R$ (mag)	$V-I$ (mag)	Radius (′)	Period (d)	T_0 (d)	Type	Memb
V1	06:03:03.85	10:27:15.68	15.046	0.604	0.408	0.924	1.78	0.6233	68.1022	EB	likely
V2	06:03:12:33	10:31:09:82	16.857	0.820	0.528	1.049	5.42	0.3984	70.1991	RRd	unlikely
V3	06:02:51.90	10:25:07.05	17.230	0.894	0.561	1.084	2.52	1.3665	68.2472	EA	likely
V4	06:02:49.37	10:26:14.71	17.981	0.872	0.536	1.054	1.95	4.9878	70.3432	EA	likely
V5	06:02:52.54	10:26:15.50	18.213	0.987	0.589	1.157	1.49	0.3261	67.3106	EW	likely
V6	06:02:55.28	10:24:58.06	18.264	0.924	0.579	1.193	3.98	0.3112	67.1370	EW	likely
V7	06:02:51.52	10:30:54.07	19.031	0.975	0.663	1.275	3.79	0.5529	70.1531	EB	likely
V8	06:02:56.72	10:23:22.77	19.111	1.134	0.723	1.466	2.44	0.2305	70.1278	RS CVn	likely
V9	06:02:50.20	10:25:22.10	19.231	1.362	0.943	1.712	2.59	0.2432	70.0987	EW	unlikely
V10	06:03:14.57	10:30:34.05	16.120	1.056	0.663	1.329	5.48				likely

Notes: $T_0(\mathrm{HJD}-2455500)$ denotes the phase zero epoch.

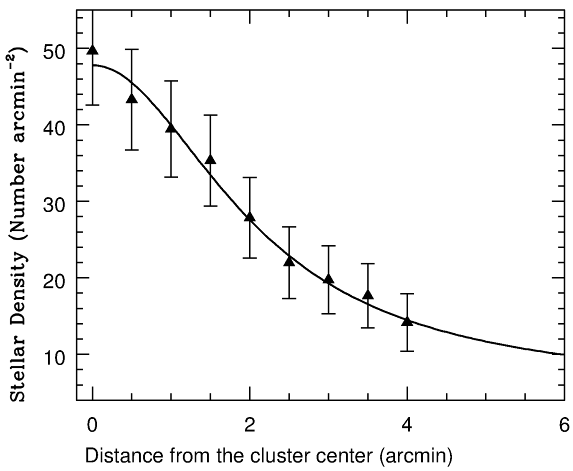

Fig. 2 The stellar radial density profile for stars brighter than 20.0 mag in the field of NGC 2141. The solid line denotes the King profile.

reference CCD frame. Then, we defined a series of concentric rings around the center. The width of the rings was set to be 106 pixels ($\sim 30''$). The stellar radial density profile was derived by counting the number of stars per area in each concentric ring and is shown in Figure 2. The error bars were determined on the assumption that the number of stars in each ring statistically follows a Poisson distribution. We adopted a two-parameter King model (King 1966) to fit the radial density profile

$$\sigma(r) = \sigma_{\rm bg} + \frac{\sigma_0}{1+(\frac{r}{r_{\rm c}})^2}\,, \tag{5}$$

where $\sigma_{\rm bg}$ is the background field density, σ_0 the central density of stars, and $r_{\rm c}$ the core radius of the cluster. A best fitting model is shown by the solid line in Figure 2 and yields $\sigma_{\rm bg} = 5.3 \pm 3.2$ stars arcmin^{-2}, $\sigma_0 = 42.5 \pm 3.5$ stars arcmin^{-2} and $r_{\rm c} = 2.1 \pm 0.3$ arcmin. The distances of variable stars from the center are given in Table 1. We could deduce from Figure 2 that our observed field is inside the cluster, which implies that all variable stars are probably cluster members at different spatial locations.

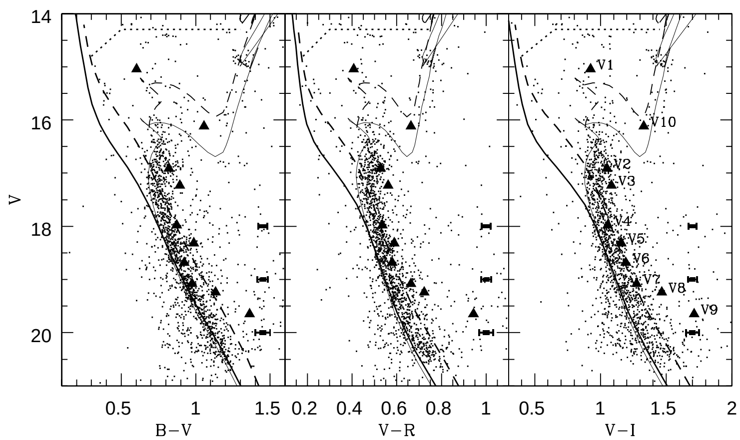

Fig. 3 CMDs of NGC 2141 and positions of variable stars in the CMDs. The thin solid lines denote the fit of the Padova theoretical isochrones with an age of $t = 1.9$ Gyr, a metallicity of $Z = 0.008$, a reddening of $E(B - V) = 0.36$ mag, and a distance modulus of $(m - M)_0 = 13.20$ mag (Donati et al. 2014) and the thick solid lines are the zero age main sequences. The dashed lines are the corresponding binary sequences. The dotted lines approximately indicate the upper edge of blue stragglers (Lu et al. 2010).

In addition, CMDs can also provide some very important constraints on the cluster membership of variable stars. CMDs of NGC 2141 were constructed with $BVRI$ multi-color photometric data and are displayed in Figure 3. We mark their positions on the CMDs and plot the Padova theoretical isochrones (Girardi et al. 2002) with the physical parameters of the cluster (age: $t = 1.9$ Gyr, metallicity: $Z = 0.008$, reddening: $E(B - V) = 0.36$ mag, distance modulus: $(m - M)_0 = 13.20$ mag) derived by Donati et al. (2014). Generally, stars in the open cluster are distributed along the isochrones. Two variable stars (V1 and V9) are far from the isochrones. However, it is noted that the position of V1 in the CMDs is located in the main sequence but is brighter than the turn-off stars. The current observations and binary evolution theories (Bailyn 1995;Lu et al. 2010;Geller & Mathieu 2011) have shown that the cluster members can be located in the area of V1. As a result, we concluded that all variable stars except for V9 are probably cluster members.

4.2 Periodicity Analysis

We used the PDM program in the IRAF-ASTUTIL package to determine the periods of variable stars, which is based on the phase dispersion minimization method (Stellingwerf 1978). To do this, we set the range of the period to be 0.01–8 d. Then, we used the PDM program to estimate a few possible periods in the range and derive the corresponding phase-folded light curves. After visually inspecting the phase-folded light curves, we determined the best ones. Nine stars (V1–V9) were found to be periodic variable stars and their periods and phase zero points are given in Table 1. The phase-folded light curves are shown in Figure 4. The light curves of V10 are shown in Figure 5. However, periodical variability is not found in our observations of V10.

4.3 Classification and Discussion

We classified the variable stars with criteria mainly based on the shapes of light curves, the detected periods and the positions in the CMDs. The classification and characterization of the variable stars in our study are discussed as follows.

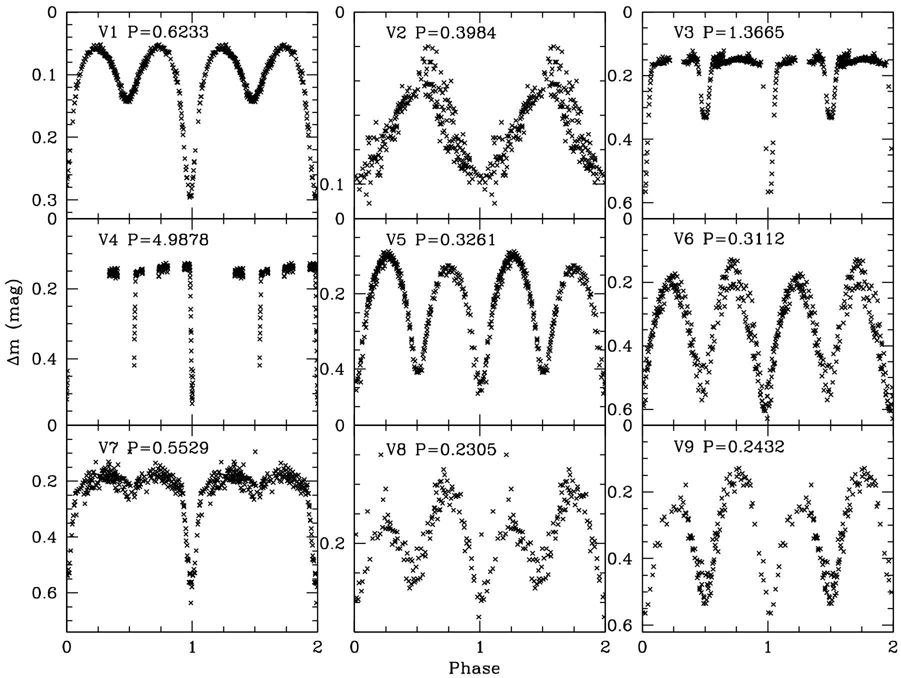

Fig. 4 Phased light curves of nine periodic variable stars in the field of NGC 2141.

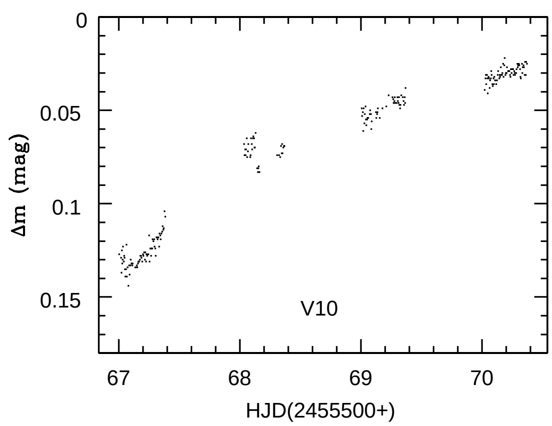

Fig. 5 Light curves of V10, an unknown type of variable star in the field of NGC 2141.

V1 has been classified as an EB-type eclipsing binary star by Licchelli (2011) and was named VSX J060303.8+102715 by the American Association of Variable Star Observers (AAVSO)[1]. It is a likely cluster member and the period was updated to be 0.6233 d. It is very interesting that, among stars we observed in the cluster, V1 is the most likely to be a blue straggler candidate. The position of V1 in the CMDs is just in the region where the formation of blue stragglers via mass transfer has been predicted (Chen & Han 2008; Lu et al. 2010) and observationally many blue stragglers have

[1] *http://www.aavso.org.*

been found (Geller & Mathieu 2011). Our detailed photometric solution (Luo et al. 2012a) showed that V1 is a semi-detached binary with a less massive component that is filling the Roche Lobe and it displays super-luminance. Here, the discovery of V1 supports the conclusion that blue stragglers in an open cluster originate from the mass transfer of binary stars (Geller & Mathieu 2011). Moreover, V1 is a rare eclipsing blue straggler binary system in the cluster that is transferring mass from the less massive component to the more massive one (Luo et al. 2012a). Therefore, follow-up observations are important for investigating the physical process involved in mass transfer during the formation of blue stragglers in an open cluster. The light curve of V7 is similar to V1. It is identified as an EB-type eclipsing binary star and the period was determined to be 0.5529 d. In the CMDs, this star is located on the main sequence defined by cluster binary stars. This star is also a likely cluster member.

V2 shows a peculiar light curve with slowly descending and quickly ascending sections. The shape of the light curves are similar to those of an RR Lyrae variable star. The most probable period was determined to be 0.3984 d, which is too long for a normal δ Scuti star. Therefore, it is reasonable that V2 is classified as an RR Lyrae variable star. From Figure 4, we can clearly see that the light curve obviously appears to exhibit high asymmetry and rapid changes from one period to another. The period modulations can also be seen in phased light curves. These characteristics suggest that V2 is a d-type RR Lyrae star. The position in the CMDs is just on the main sequence, therefore, we can conclude that V2 is not a cluster member but rather a background field star.

V3 and V4 have flat light maxima and are identified as EA-type eclipsing binaries. They are probable cluster members. The period of V3 is estimated to be 1.3665 d. However, the light curve of V4 is incomplete and the period is roughly determined to be 4.9878 d. Further observations are needed to ascertain the exact nature.

There are four short period eclipsing contact binary systems (V5, V6, V8 and V9) with orbital periods of $0.23 \sim 0.33$ d. The characteristics of their light curves are very similar. The light curves have a clear difference in depths of the eclipses, in which the primary eclipses are deeper than the secondary ones. Moreover, the light curves show the O'Connell effect (O'Connell 1951). The secondary light maxima are larger than the primary ones for V6, V8 and V9, but not for V5. The characteristic parameters of the light curves are given in Table 2, from which we can see that the O'Connell effect increases with the decrease in orbital period. This shows that the O'Connell effect is probably related to the evolution of the orbital period in short period eclipsing binary systems. The O'Connell effect shown by V8 is stronger than the others, accounting for even more than 63% of the amplitude of the light curve. Therefore, it is identified as an RS CVn-type eclipsing binary system. The others (V5, V6 and V9) have the general nature of a W Uma-type eclipsing binary system and are classified as W Uma binaries. However, whether the O'Connell effect exists in short period eclipsing binary systems is still uncertain. Many different theories have been proposed to explain this effect, but no one theory has been successfully applied to more than a handful of binary systems (Wilsey & Beaky 2009). Further multi-color photometric and spectroscopic observations may provide some insight into the nature of the O'Connell effect in eclipsing binary systems.

Table 2 Characteristic Parameters of the Light Curves of Four Eclipsing Contact Binaries

Star	$\Delta(\mathrm{Min\,I} - \mathrm{Min\,II})$ (mag)	$\Delta(\mathrm{Max\,I} - \mathrm{Max\,II})$ (mag)	$A \times 2$ (mag)	$\Delta(\mathrm{Max\,I} - \mathrm{Max\,II})/A$ (%)	Period (d)
V5	0.06	0.04	0.38	21.1	0.3261
V6	0.06	0.05	0.47	21.3	0.3112
V8	0.03	0.07	0.22	63.6	0.2305
V9	0.02	0.09	0.23	41.9	0.2432

Notes: $\Delta(\mathrm{Min\,I} - \mathrm{Min\,II})$ is the difference between primary and secondary eclipses, $\Delta(\mathrm{Max\,I} - \mathrm{Max\,II})$ is the difference between primary and secondary light maxima and A is the amplitude of the light curve.

V10 is classified as an unknown type of variable star. The time-series light curves do not show any periodical variability in our observations. Further observations will help us determine its period and physical properties.

5 SUMMARY

In this paper, we have presented time-series V band and multi-color $BVRI$ CCD photometry of the open cluster NGC 2141, as part of an effort undertaken in 2011 to detect variable stars. The following conclusions can be drawn:

(1) Ten variable stars have been detected in the field of the old open cluster NGC 2141, among which nine are newly discovered. We discussed their memberships on the basis of their spatial locations, positions in the CMDs and physical properties. Eight stars (V1, V3, V4, V5, V6, V7, V8 and V10) are probable members of the cluster, but the others (V2 and V9) are not likely cluster members. We found that nine stars are periodic variable stars and their periods were determined with the phase dispersion minimization method.

(2) We assessed the classifications of variable stars and discussed their physical properties, primarily based on the shape of the light curve, the detected period and the position in the CMDs. They are categorized as three W UMa-type eclipsing binaries, two EA-type eclipsing binaries, two EB-type eclipsing binaries, one d-type RR Lyrae star, one RS CVn-type eclipsing binary and one unknown type of variable star. A known EB-type eclipsing binary, V1, is located in the area of the CMD defined by blue stragglers in the cluster and it is identified as a blue straggler candidate.

(3) In this study, we found that all four short period eclipsing contact binaries show a clear difference in depths of eclipses and exhibit the O'Connell effect which increases with a decrease in the orbital period. This illustrates that the O'Connell effect is probably related to the evolution of the orbital period in short period eclipsing binary systems.

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References

Bailyn, C. D. 1995, ARA&A, 33, 133
Burkhead, M. S., Burgess, R. D., & Haisch, B. M. 1972, AJ, 77, 661
Carraro, G., Hassan, S. M., Ortolani, S., & Vallenari, A. 2001, A&A, 372, 879
Chen, X., & Han, Z. 2008, MNRAS, 384, 1263
Donati, P., Beccari, G., Bragaglia, A., Cignoni, M., & Tosi, M. 2014, MNRAS, 437, 1241
Geller, A. M., & Mathieu, R. D. 2011, Nature, 478, 356
Girardi, L., Bertelli, G., Bressan, A., et al. 2002, A&A, 391, 195
Ivanova, N., Justham, S., Chen, X., et al. 2013, A&A Rev., 21, 59
Jiang, D., Han, Z., Jiang, T., & Li, L. 2009, MNRAS, 396, 2176
Kim, S.-L., Park, B.-G., Chun, M.-Y., et al. 2000, in Astronomical Society of the Pacific Conference Series, 203, IAU Colloq. 176: The Impact of Large-Scale Surveys on Pulsating Star Research, eds. L. Szabados, & D. Kurtz, 457
King, I. R. 1966, AJ, 71, 64
Kissinger, J., & Kafka, S. 2005, in Bulletin of the American Astronomical Society, 37, American Astronomical Society Meeting Abstracts, 1278
Landolt, A. U. 1992, AJ, 104, 340

Licchelli, D. 2011, *http://www.aavso.org/vsx/*
Lu, P., Deng, L. C., & Zhang, X. B. 2010, MNRAS, 409, 1013
Luo, Y. P., Zhang, X. B., Luo, C. Q., Deng, L. C., & Luo, Z. Q. 2009, New Astron., 14, 584
Luo, Y., Wang, B., Chen, H., Zhang, X., & Han, Z. 2012a, Science China Physics, Mechanics, and Astronomy, 55, 1500
Luo, Y. P., Zhang, X. B., Deng, L. C., & Han, Z. W. 2012b, ApJ, 746, L7
Meibom, S., Grundahl, F., Clausen, J. V., et al. 2009, AJ, 137, 5086
O'Connell, D. J. K. 1951, Publications of the Riverview College Observatory, 2, 85
Pietrzyński, G., Thompson, I. B., Graczyk, D., et al. 2009, ApJ, 697, 862
Pietrzyński, G., Graczyk, D., Gieren, W., et al. 2013, Nature, 495, 76
Rosvick, J. M. 1995, MNRAS, 277, 1379
Stellingwerf, R. F. 1978, ApJ, 224, 953
Stetson, P. B. 1996, PASP, 108, 851
Stetson, P. B. 2000, PASP, 112, 925
Widhalm, A. M., & Kafka, S. 2006, in Bulletin of the American Astronomical Society, 38, American Astronomical Society Meeting Abstracts, 1128
Wilsey, N. J., & Beaky, M. M. 2009, Society for Astronomical Sciences Annual Symposium, 28, 107
Zhang, X. B., Deng, L., Tian, B., & Zhou, X. 2002, AJ, 123, 1548
Zhang, X. B., Deng, L., Zhou, X., & Xin, Y. 2004, MNRAS, 355, 1369