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Discovery of 13 New Variable Stars in the Field of the Open Cluster NGC 2168 (M35)

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Abstract A wide-field time-series CCD photometric survey of variable stars in the field of the open cluster NGC 2168 was carried out using the BATC Schmidt telescope. In total 13 new variable stars are discovered with three W UMa systems, one EA type and two EB type eclipsing binaries (one of them could be a W UMa system), and seven pulsating stars including three candidates of δ Scuti stars.

Key words: open clusters: individual (NGC 2168) – stars: variables (general) – binaries: general

1 INTRODUCTION

Because of its wide field of view, the 60/90 Schmidt telescope equipped with a 2k×2k CCD of the BATC (Beijing-Arizona-Taiwan-Connecticut Multicolor Sky Survey) program has been used to study the structure and dynamics of star clusters. Combined with time-series photometric measurements, the 60/90 Schmidt telescope could be a very useful instrument in the discovery and detailed investigation of variable stars of different types of star clusters. In previous work, Zhang et al. (2002, 2003) have detected eight and 28 new variable stars in the old open clusters NGC 188 and NGC 7789, respectively.

NGC 2168 (M35), one of the richest, compact and nearby open clusters with a total mass $\sim$ 1600–3200 $M\odot$ (Leonard & Merrott 1989), is located in the direction of the Galactic anti-center ($\alpha = 6^{\rm h}8^{\rm m}56.5^{\rm s}, \delta = 24^\circ 21.6'$, J2000.0). It is an intermediate-age open cluster with an age of about 100 Myr (von Hippel et al. 2000) to 200 Myr (Sung & Bessell 1999), metallic abundance of [Fe/H] ~ -0.3 and $E(B-V) = 0.255 \pm 0.024$ mag according to the *UBVI* CCD photometry of Sung & Lee (1992) and Sung & Bessell (1999). It has been well-studied by astrometric measurements (McNamara & Sekigushi 1986a, b) since intermediate-age open clusters can provide a wealth of information on the evolution of intermediate-mass stars and white dwarfs (Williams et al. 2004) and the dynamical evolution of clusters (Perryman et al. 1998).

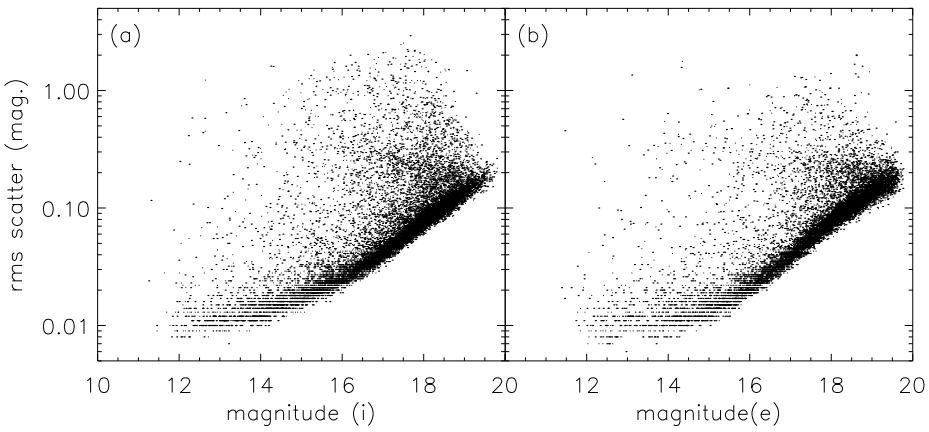

Fig. 1 Plots of the rms scatter in the e-band (a) and in the i-band (b) for the BATC observations of the field of NGC 2168.

Finally, Barrado y Navascués et al. (2001) made detailed multi-fiber spectroscopic measurements of this cluster using the WIYN/HYDRA instrument. They reported the identification of 13 spectroscopic binaries in NGC 2168. More recently, Kim et al. (2004) reported a detection of two variable stars. In this paper, we report the discovery of 13 new variable star candidates in this open cluster field. The observations and data reduction are described in Section 2. The search for variable stars and the determination of periods are described in Section 3. Results and a discussion are given in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

The present data set was obtained from observations between 2002 November 25 and 29, using the 60/90 cm Schmidt telescope at the Xinglong Station of the National Astronomical Observatories, CAS (NAOC). A description of the photometric system consisting of 15 intermediate-band filters (350–490 Å) covering a spectral range of 3000–10000 Å in the BATC multicolor sky color survey can be found in Fan et al. (1996). The field of view of the 60/90 Schmidt telescope is about 1 deg, hence yielding an image scale of 1.67″ per pixel. In the observations of NGC 2168, the e (6656 Å) and i (4925 Å) filters were used. The exposure times were 120 s for the i band and 300 s for the e band. The average dead time between two image frames was 10 minutes. The rms scatter in the i-band and e-band measurements are shown in Figure 1.

We followed the data reduction process and photometry extracting procedure of Zhou et al. (2001) and Zhang et al. (2002). There are in total 114 e-band images and 112 i-band images. An image with the best seeing condition was chosen to provide the calibration standard. We selected 100 bright stars in this image to serve as standard stars. On this basis, we are able to compute the relative magnitudes of all stars on the same reference scales. The light curves of all objects observed in the field can be derived by this approach. The magnitudes in this paper we provided are all instrumental magnitudes.

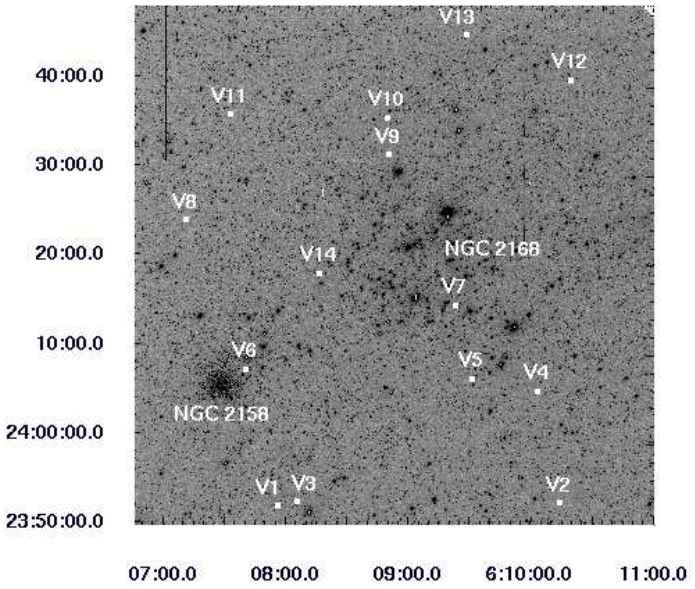

Fig. 2 Observed CCD field ($55.7' \times 55.7'$) of the open cluster NGC 2168. The star cluster near the bottom of the left-hand side is NGC 2158. The positions of the 14 variable stars are indicated with numbers.

3 SEARCHING FOR VARIABLE STARS AND PERIOD DETERMINATION

There are about 15 000 stars in the field of NGC 2168. To search for variable stars, we selected 670 stars with peak-to-peak magnitude variations $> 3\sigma$ in their light curves for further analysis. We applied the method of phase dispersion minimization (PDM, Stellingwerf 1978) to analyze the light curves. After visual inspection, 14 variable candidates have been identified. One of them has been reported by Kim et al. (2004). Figure 2 shows the positions of all 14 variable candidates in this field. We note that none of the 13 spectroscopic binaries found by Barrado y Navascués et al. (2001) coincides with our list.

The coordinates, magnitudes and the photometric errors in the e- and i-bands of the new variables are summarized in Table 1. Table 2 presents the amplitudes of variable variations, best estimated periods and their possible types. The finding charts and phase diagrams of these variable stars are given in Figures 3 and 4.

4 RESULTS AND DISCUSSION

A systematic study of the BATC time-series photometric observations of NGC 2168 has produced 13 new variable stars. Their properties and classifications on the basis of their light curves are summarized in the following. All of the phase zero epochs were based on the i filter data.

V1 A δ Scuti star with an orbital period of 0.1783 days or, less likely, a W UMa system with the double period. The phase diagram in Figure 1 is presented as a W UMa system with

[1] V14 is the same as V1 in Kim et al. (2004).

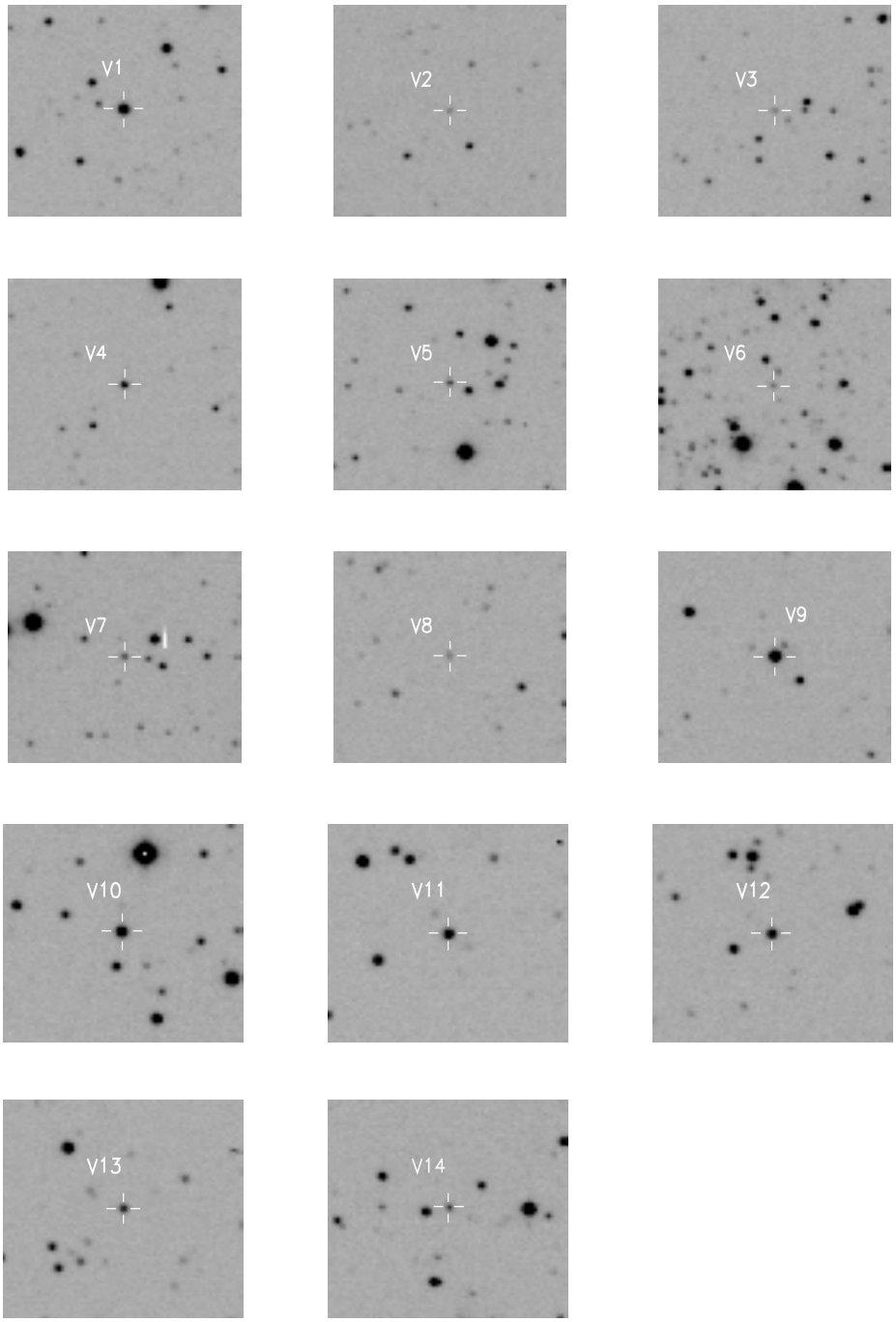

Fig. 3 Finding charts of the 14 variable stars in the field of NGC 2168. Field of views of each one panel is about $2' \times 2'$.

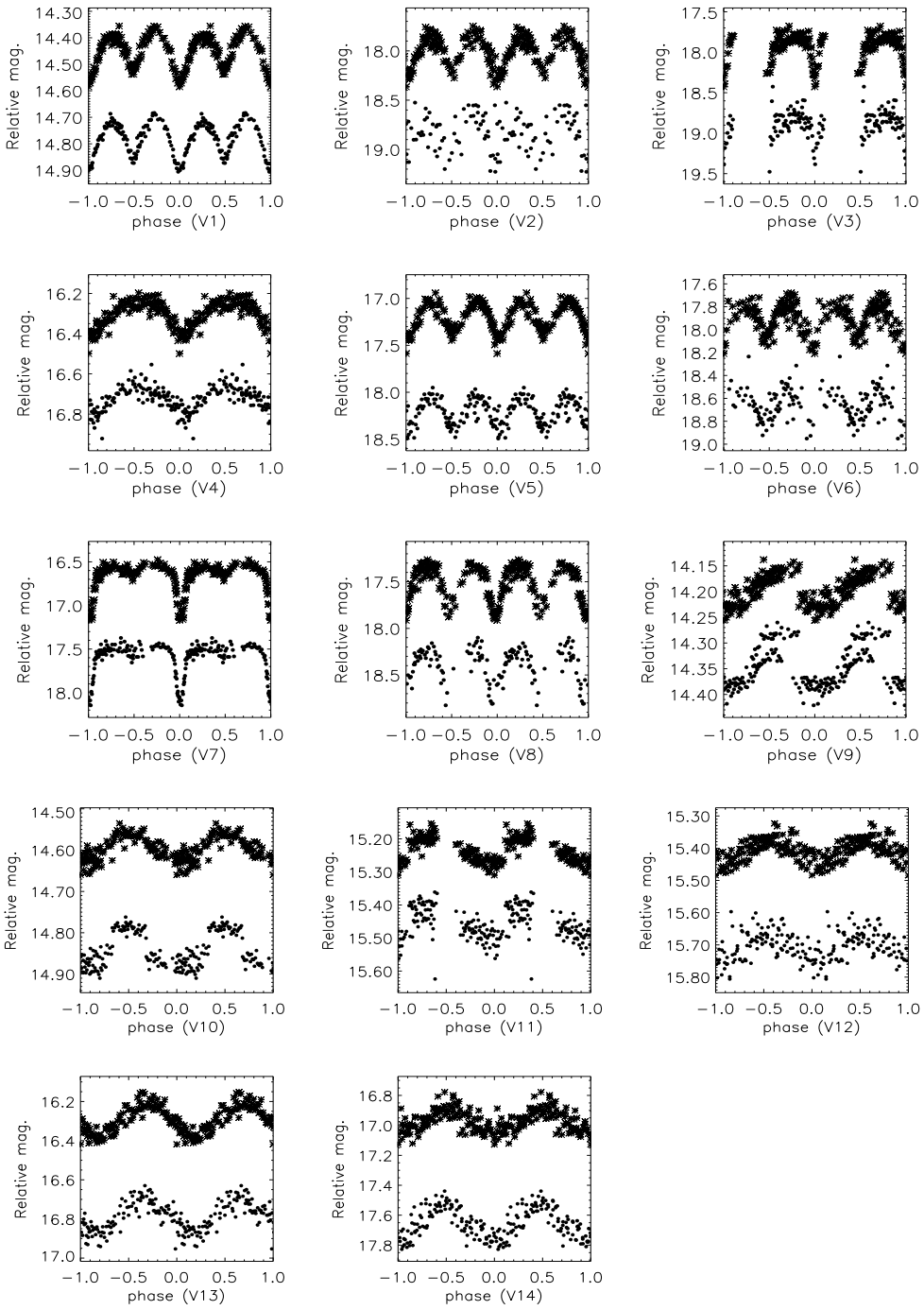

Fig. 4 Phase period diagrams of 14 variable stars in the field of NGC 2168. The cross signs show data points in i filter and fill circles present the e filter data.

Table 1 Variables in the Field of NGC 2168

ID	RA (J2000)	DEC (J2000)	mag_{min} (i)	error (i)	mag_{min} (e)	error (e)
V1	06:07:55.75	23:52:18.30	14.35	0.01	14.91	0.01
V2	06:10:13.94	23:53:23.50	17.74	0.08	18.95	0.14
V3	06:08:05.32	23:52:50.20	17.67	0.09	18.37	0.11
V4	06:10:01.85	24:05:50.00	16.19	0.03	16.47	0.04
V5	06:09:29.27	24:07:03.00	16.94	0.07	18.17	0.10
V6	06:07:37.99	24:07:25.30	17.67	0.08	15.90	0.03
V7	06:09:20.42	24:15:15.70	16.47	0.04	17.04	0.04
V8	06:07:07.03	24:24:04.40	17.26	0.06	15.27	0.04
V9	06:08:45.63	24:31:56.90	14.13	0.01	17.69	0.07
V10	06:08:44.97	24:36:06.60	14.53	0.01	17.88	0.08
V11	06:07:27.57	24:35:58.90	15.15	0.02	16.88	0.04
V12	06:10:14.45	24:40:43.50	15.32	0.02	17.65	0.07
V13	06:09:23.05	24:45:30.90	16.15	0.03	17.75	0.09
V14 [1]	06:08:13.21	24:18:30.80	16.77	0.06	16.97	0.04

Table 2 Data for the Variables in the Field of NGC 2168

ID	Amp. (i)	Amp. (e)	Period (day)	Type
V1	0.229	0.222	0.1783 (0.3566)	δ Scuti or W UMa
V2	0.672	0.542	0.2725	EB or W UMa
V3	0.750	1.052	0.7320	EA
V4	0.302	0.239	0.1581	δ Scuti
V5	0.646	0.831	0.3975	W UMa
V6	0.529	0.716	0.3416	W UMa
V7	0.696	0.772	0.5290	EB
V8	0.650	0.977	0.3260	W UMa
V9	0.118	0.160	0.4548	pulsating
V10	0.125	0.148	0.6882	pulsating
V11	0.157	0.263	0.5929	pulsating
V12	0.160	0.209	0.1336	δ Scuti
V13	0.266	0.323	0.3890	pulsating
V14	0.350	0.389	0.0647	pulsating

the period of 0.3566 days. The difference between the two local minima of the light curve is about 0.03 mag. It could be a W UMa type with a small amplitude or a δ Scuti star, instead. The phase zero epoch was obtained at $T_0 = 2,452,604.280$.

V2 An EB or a W UMa system with an orbital period of 0.6879 days. The difference between the two local minima of the light curve is about 0.1 mag. The phase zero epoch was obtained at $T_0 = 2,452,607.290$. It is the faintest object in the present list of variable stars.

V3 An EA system with an orbital period of 0.6326 days at $T_0 = 2,452,608.314$.

V4 Most likely a δ Scuti star with an orbital period of 0.1581 days at $T_0 = 2,452,607.269$.

V5 A W UMa system with an orbital period of 0.3975 days at $T_0 = 2,452,604.394$.

V6 A W UMa system with an orbital period of 0.3426 days at $T_0 = 2,452,605.394$.

V7 An EB system with an orbital period of 0.3530 days at $T_0 = 2,452,607.253$. It is also the one with an identification number of 192 in Sung & Bessell (1999) and 5291 in Barrado y Navascués et al. (2001).

V8 A W UMa system with an orbital period of 0.3257 days at $T_0 = 2,452,60604.315$.
V9 The brightest object in the present list of variable stars. Probably a pulsating star with a period of 0.4515 days at $T_0 = 2,452,607.297$. It is also the star with the identification number of 5011 in Barrado y Navascués et al. (2001).
V10 A pulsating star with a period of 0.6877 days at $T_0 = 2,452,607.232$.
V11 A pulsating star with a period of 0.5919 days at $T_0 = 2,452,608.337$.
V12 Most likely a δ Scuti star with an orbital period of 0.1336 days at $T_0 = 2,452,607.304$.
V13 A pulsating star with a period of 0.3886 days at $T_0 = 2,452,604.373$.
V14 A pulsating star with a period of 0.0647 days at $T_0 = 2,452,607.318$. Found previously by Kim et al. (2004) with ID given as V1.

Note that, of these new variable candidates, the three W UMa systems detected might not be associated with NGC 2168. This is consistent with the fact that NGC 2168 is relatively young ($\approx$ 100–200 Myr) while contact binaries like W UMa must have formed from detached systems through angular momentum loss (AML) or some other ways.

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