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Searching for Variable Stars in the Field of NGC 7789 *

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Abstract We present the results of a time-series CCD photometric survey of variable stars in the field of the open cluster NGC 7789. In a field of about one degree centering on the cluster, a total of 28 new variable stars are discovered (14 W UMa systems, nine EA-type eclipsing binaries, one RR Lyr star, and four unclassified). In addition, we recovered 11 old variables previously discovered by other authors. Preliminary parameters are given for some of these variables.

Key words: open clusters: individual (NGC 7789) — stars: variables (general) — binaries: general

1 INTRODUCTION

NGC 7789 is a rich, intermediate-age open cluster. Since the first extensive photometry by Burbidge & Sandage (1958), many follow-up observational studies have been made on it by several authors. Burbidge & Sandage (1958) provided magnitudes and colors for nearly 700 stars within a field of 450 arcsec of the cluster center. They also determined the apparent distance modulus, reddening and metallicity: $(m-M)_v = 12.0$, $E(B-V) = 0.24$ and $[\mathrm{Fe/H}] = -0.26 \pm 0.06$. The distance modulus was determined again to be $(m-M)_v = 12.3$ by Jahn et al. (1995) based on the lower limit of the red-giant clump in the color-magnitude diagram. The cluster's age is about 1.6 Gyr as recently estimated by Gim et al. (1998). A proper motion study made by McNamara & Solomon (1981) yielded 679 probable member stars of NGC 7789.

NGC 7789 has been the target of several previous searches for variable stars. Jahn et al. (1995) made the first time-resolved CCD photometry which resulted in the discovery of 15 variables in the central part of the cluster. Later Kim & Park (1999) detected 16 variables, including eight suspected variables and three old objects previously discovered by Jahn et al. (1995). The very recent CCD photometric monitoring on NGC 7789 was carried out by Mochejska & Kaluzny (1999, hereafter MK). A total of 45 variables were found in two $23 \times 23\,\mathrm{arcmin}^2$ fields, 31 in the central part ($\alpha = 23.952^{\mathrm{h}}, \delta = 56.71^\circ$) and 14 in the extended area ($\alpha = 23.988^{\mathrm{h}}, \delta = 56.64^\circ$).

As the second target of the BATC variable searching program (Zhang et al. 2002), the open cluster NGC 7789 was observed in 2000 based on time resolved CCD photometry. The main

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goal is to discover more interacting binaries as well as other types of variable stars through observations of a wider field than in the previous works mentioned above. In the present paper we report the results of the observations.

2 OBSERVATIONS AND DATA REDUCTION

The observations were carried out at the Xinglong station of Beijing Astronomical Observatory on three nights between 2000 Sept 23 and Sept 25. The data were collected using the 60/90cm Schmidt telescope equipped with a 2k×2k Aerospace Ford CCD camera. The field of view was about 1 arc-degree, and the scale was 1.67 arcsec/pixel. A BATC[9], i filter was used: it is centered at 6600Å and has a bandwidth of 490Å. The cluster center was positioned at the center of the field. Useful data were collected during 6–8 hours on each night, amounting to a total of 20.5 hours of monitoring. The exposure time was 120 seconds. A total of 102 frames of NGC 7789 were obtained with an average dead time of 10–15 minutes. The preliminary data processing and photometry extracting were made following Zhou et al. (2001) and Zhang et al. (2002). No absolute calibration was done: the magnitudes in our dataset are instrumental magnitudes .

3 SEARCHING FOR VARIABLE STARS

There are many ways to identify variables from a large sample of stars in a time series dataset. In the case of NGC 7789, a very rich cluster, there are more than 30 000 stars in each of the frames of our dataset. In order to make the identification of variable stars on an objective base, we applied Stetson's variability index (Steson 1996). For a time-resolved observed star, the variability index can be defined as

$$J = \frac{\sum_{k=1}^{n} w_k sgn(P_k)\sqrt{|P_k|}}{\sum_{k=1}^{n} w_k}, \tag{1}$$

where the user has assigned, to each of the n pairs of observations considered, a weight w_k, and

$$P_k = \begin{cases} \delta_{i(k)}\delta_{j(k)} & if i(k) \neq j(k) \\ \delta_{i(k)}^2 - 1 & if i(k) = j(k) \end{cases} \tag{2}$$

is the product of the normalized residuals of the two paired observations i and j, and

$$\delta = \sqrt{\frac{n}{n-1}}\frac{v - \bar{v}}{\sigma_v} \tag{3}$$

is the magnitude residual of a given observation from the average normalized by the standard error. Thus all the residuals are compared on an equal basis.

The variability index is very robust for long-term surveys (Stetson 1996; Kaluzny et al. 1998). In our case, the observing strategy was designed to search for variables by time-series monitoring, each star was usually measured 4–6 times within 1 hour in one single filter. Thus we simply take every two subsequent measurements to be a pair, i.e., m1 and m2, m3 and m4 and so on. Here, the weight for each pair should be redefined. For our observations, we think that the main factor affecting the J index is the time interval between the two measurements in each pair. The shorter the time interval is, the larger the weight should be. Accordingly, we define the weight as follows:

$$w_k = e^{\frac{\Delta t_k}{\overline{\Delta t}}}, \tag{4}$$

where Δt_k is the time interval for a given pair and $\overline{\Delta t}$ is the mean value of Δt_k for the n pairs. Thus pairs with normal time intervals have weights close to unity, and those with long time intervals (for example, the last measurement of one night and the first of the next night) are given very low weights. This way, we avoid possible large negative contributions to the J index. In addition, we redefined σ as the average deviation for each star, so that the value of the J index for all the stars are comparable.

In this way, the J indexes for the stars in our database are computed. In Figure 1 we plot the variability index J vs. the average i magnitude. Also shown is the deviation vs. average i for all the stars. Most of the stars have values of J close to zero, as is expected. Then we picked out the stars with large J values and large deviations as the variable candidates. Using a cutoff $J_{\rm min} = 0.4$, we obtained a total of 290 variable candidates. The light curves of all the candidates were then examined in detail. After rejecting spurious variables and stars with noisy and chaotic light curves, we arrived at a total of 39 variables, including 11 variables in the MK catalogue. In addition, we searched for light variations in each of the variables previously discovered by Jahn et al. (1995), Kim & Park and MK, but no more objects could be added to our list of variables. In Table 1, the frequency of variable detection in various range of the J index is shown. It implies that with the cutoff $J_{\rm min} = 0.4$, almost all the variables confirmed in our database are included in our list of variables.

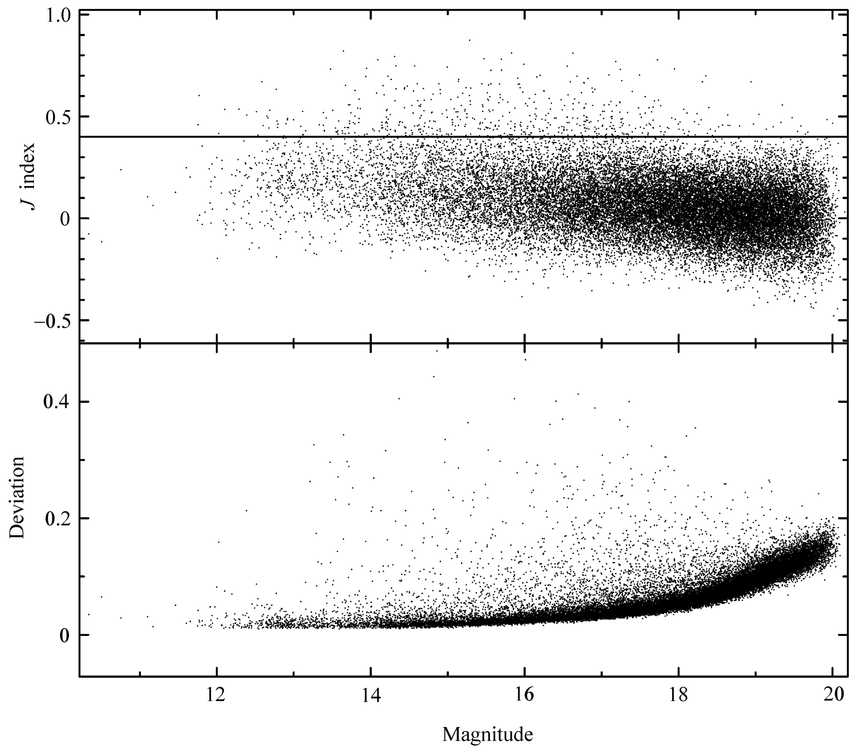


Fig. 1 Diagrams of J index and deviations vs. average i magnitude.

Table 1 Searching for Variables with the J Index

J index	Candidates	Variables	Frequency
0.75–0.80	9	5	0.56
0.70–0.75	11	4	0.36
0.65–0.70	14	4	0.29
0.60–0.65	35	10	0.29
0.55–0.60	50	7	0.14
0.50–0.55	54	4	0.07
0.45–0.50	70	4	0.06
0.40–0.45	47	1	0.02

The rectangular equatorial coordinates for the all the 39 variables are listed in Table 2. The J index as well as the average light deviations are also shown. In this table, the variables are labeled with the lower-case prefix v to avoid confusion with MK's and Kim & Park's catalogues. The 11 old variables are labelled v1 to v11, their names quoted from MK's catalogue are also given for cross identification. The 28 newly discovered variables are arbitrarily labelled v12 to v39. Figure 2 shows a rough finding chart which may simplify the identification of the variables. For comparison, the regions monitored by the previous authors are also indicated. The X and Y coordinates in this chart correspond to the coordinates in Table 2.

Table 2 The Variables Identified in the Field of NGC 7789

ID	ID_{MK}	α (2000)	δ (2000)	X	Y	mag	σ	J Index
v1	V1	23:57:09.92	56:42:17.9	1074.40	753.88	14.61	0.04	0.48
v2	V8	23:57:25.70	56:43:33.0	1151.27	796.15	15.55	0.08	0.58
v3	V22	23:56:38.70	56:43:58.6	925.54	816.35	17.26	0.24	0.68
v4	V27	23:59:40.96	56:43:07.3	1801.92	769.66	17.48	0.22	0.57
v5	V29	23:56:35.87	56:44:29.9	912.36	834.95	18.31	0.24	0.60
v6	V30	23:59:50.86	56:44:55.4	1850.41	832.22	15.33	0.05	0.51
v7	V34	23:59:33.52	56:43:23.6	1766.27	779.67	17.49	0.22	0.77
v8	V35	23:56:56.39	56:48:34.6	1014.44	975.72	17.67	0.14	0.52
v9	V36	23:56:09.04	56:33:42.9	773.30	459.92	15.88	0.05	0.41
v10	V37	23:56:32.15	56:44:17.4	894.30	828.13	14.33	0.10	0.75
v11	V42	23:58:22.92	56:32:09.8	1419.22	391.03	17.18	0.11	0.62
v12	-	23:58:16.38	56:31:20.5	1387.09	362.77	13.65	0.16	0.70
v13	-	23:54:38.66	56:36:22.4	339.63	565.91	16.20	0.16	0.63
v14	-	23:56:53.75	56:21:49.1	979.41	37.06	14.57	0.15	0.70
v15	-	23:57:59.66	56:29:52.7	1305.17	313.00	15.83	0.13	0.61
v16	-	23:57:22.56	56:59:35.4	1148.61	1359.31	16.82	0.13	0.59
v17	-	23:58:56.71	57:03:36.4	1600.70	1491.68	16.78	0.13	0.64
v18	-	23:59:02.75	57:05:37.1	1630.68	1561.83	16.63	0.18	0.75
v19	-	23:54:20.94	57:06:47.5	289.47	1635.77	18.35	0.20	0.68
v20	-	23:53:42.48	57:07:06.8	106.76	1653.29	17.09	0.20	0.57
v21	-	23:58:24.38	57:09:14.7	1450.12	1692.21	15.47	0.10	0.65
v22	-	23:55:08.20	57:10:12.1	518.06	1748.27	16.88	0.12	0.58
v23	-	23:56:47.90	57:12:54.4	994.34	1830.37	17.73	0.15	0.64
v24	-	23:53:37.39	57:13:02.8	90.03	1862.27	18.94	0.19	0.53
v25	-	23:55:48.50	57:04:51.8	704.47	1555.46	15.70	0.16	0.73
v26	-	23:54:05.16	56:56:11.4	201.67	1266.38	15.67	0.16	0.73
v27	-	23:53:57.42	56:39:47.2	144.80	692.25	16.59	0.14	0.77
v28	-	23:58:54.51	56:47:41.6	1581.03	933.38	15.99	0.19	0.78
v29	-	23:56:42.38	56:22:15.3	924.53	53.75	13.48	0.15	0.68
v30	-	23:58:43.93	56:51:02.3	1532.24	1051.65	14.15	0.08	0.48
v31	-	23:58:38.61	56:59:09.7	1511.66	1337.16	17.57	0.15	0.61
v32	-	23:58:25.00	57:11:04.6	1454.25	1756.47	17.94	0.14	0.57
v33	-	23:54:37.04	57:10:37.0	370.46	1767.48	15.94	0.13	0.62
v34	-	23:55:27.09	56:28:17.5	565.11	275.25	18.24	0.25	0.49
v35	-	23:59:34.44	56:45:16.9	1771.65	845.84	15.14	0.30	0.51
v36	-	23:56:33.24	56:26:00.3	883.45	186.37	14.31	0.05	0.63
v37	-	23:58:29.91	56:28:01.0	1450.46	244.93	18.21	0.18	0.46
v38	-	23:54:12.78	56:29:48.9	207.04	339.94	17.24	0.09	0.63
v39	-	23:54:45.94	56:43:44.4	382.89	823.22	15.70	0.08	0.55

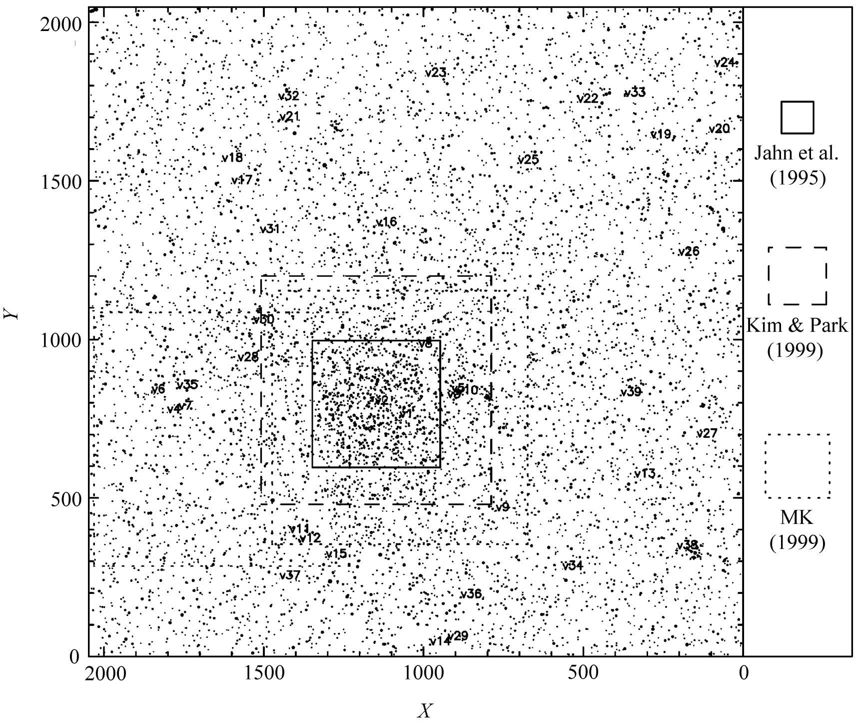


Fig. 2 A rough finding chart for the variables in NGC 7789 identified in this program. The square frames mark the regions previously monitored by Jahn et al. (1995), Kim & Park (1999) and MK (1999), respectively.

4 RESULTS AND DISCUSSION

In this Section we present the light curves of the variables observed in the program field. Our analysis of the light curves was made with the PDM code as described by Zhang et al. (2002). The light curves are shown in Figures 3–5. Detailed finding charts for the 28 new variables are provided in Figure 6, each with field of view about $2 \times 2\,\mathrm{arcmin}^2$. In Table 3 we present the basic data for all the new and part of the old variables.

4.1 The 11 Old Variables

A total of 11 old variables are detected in our observations. They are MK's V1, V8, V22, V27, V29, V30, V34, V35, V36, V37 and V42. Their phased light curves are presented in Figure 3. With the PDM method, revised periods are determined from our data for 5 of the 11 old variables. The parameters of these 5 variables (V22, V29, V34, V36 and V42) are given in Table 3. As for the other six stars, we did not try to determine the periods with the PDM code because of the poor data coverage, the values of periods used for phasing the light curves are simply taken from MK. It is seen that our light curves are somehow noisier than those presented by MK. It may partly due to the under-sampling of our large field image.

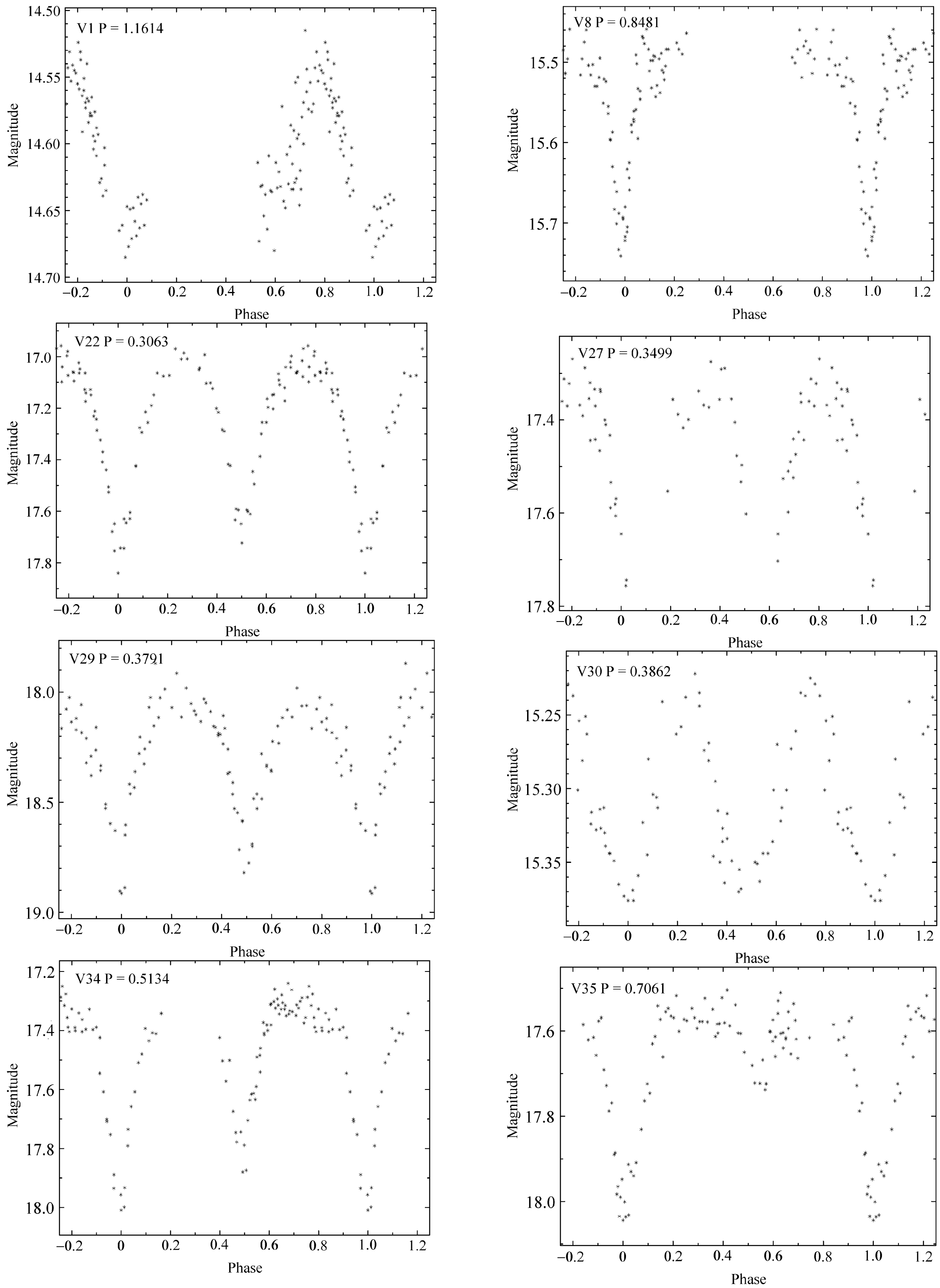


Fig. 3 Phased light curves of the 11 old variables in field of NGC 7789.

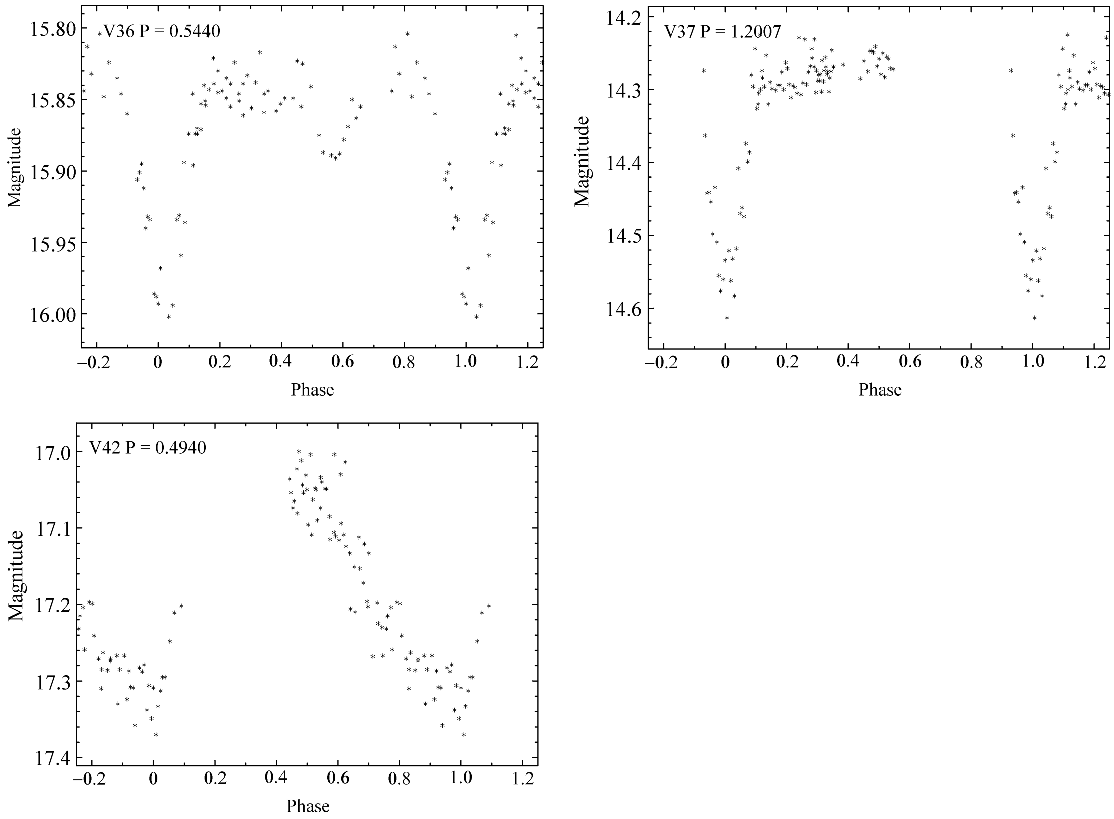


Fig. 3 Continued

Table 3 Main Data for the 28 Newly Discovered Variables

ID	P (day)	Amp.	Type	T_0 (2,451,000+)	ID	P (day)	Amp.	Type	T_0 (2,451,000+)
v3	0.3061	0.82	EW	812.290	v23	0.3893	0.53	EW	811.272
v5	0.3792	0.95	EW	812.055	v24	0.3182	0.58	EW	812.202
v7	0.5129	0.73	EW	811.259	v25	0.4520	0.58	RR Lyr	812.235
v9	0.5440	0.18	EA	813.147	v37	0.3304	0.45	EW	812.15
v11	0.4951	0.33	pulsating	-	v27	0.6562	0.45	EA	812.05
					v26	-	>0.8	EA	-
v12	0.3917	0.51	EW	812.146	v28	-	0.70	EA	812.094
v13	0.2719	0.52	EW	811.260	v29	-	0.60	EA	811.215
v14	0.3447	0.52	EW	811.144	v30	-	0.26	EA	811.088
v15	0.3776	0.39	EW	812.197	v31	-	0.60	EA	812.206
v16	0.3243	0.45	EW	813.126	v32	-	0.50	EA	811.252
v17	0.3998	0.51	EW	813.168	v33	-	0.50	EA	811.230
v18	0.3956	0.58	EW	813.101	v34	-	1.00	EA	811.252
v19	0.3556	0.69	EW	812.178	v35	-	>1.0	-	
v20	0.7632	0.51	EW	811.261	v36	-	0.16	-	
v21	0.8442	0.31	EW	812.163	v38	-	0.30	-	
v22	0.2801	0.40	EW	811.285	v39	-	0.22	-	

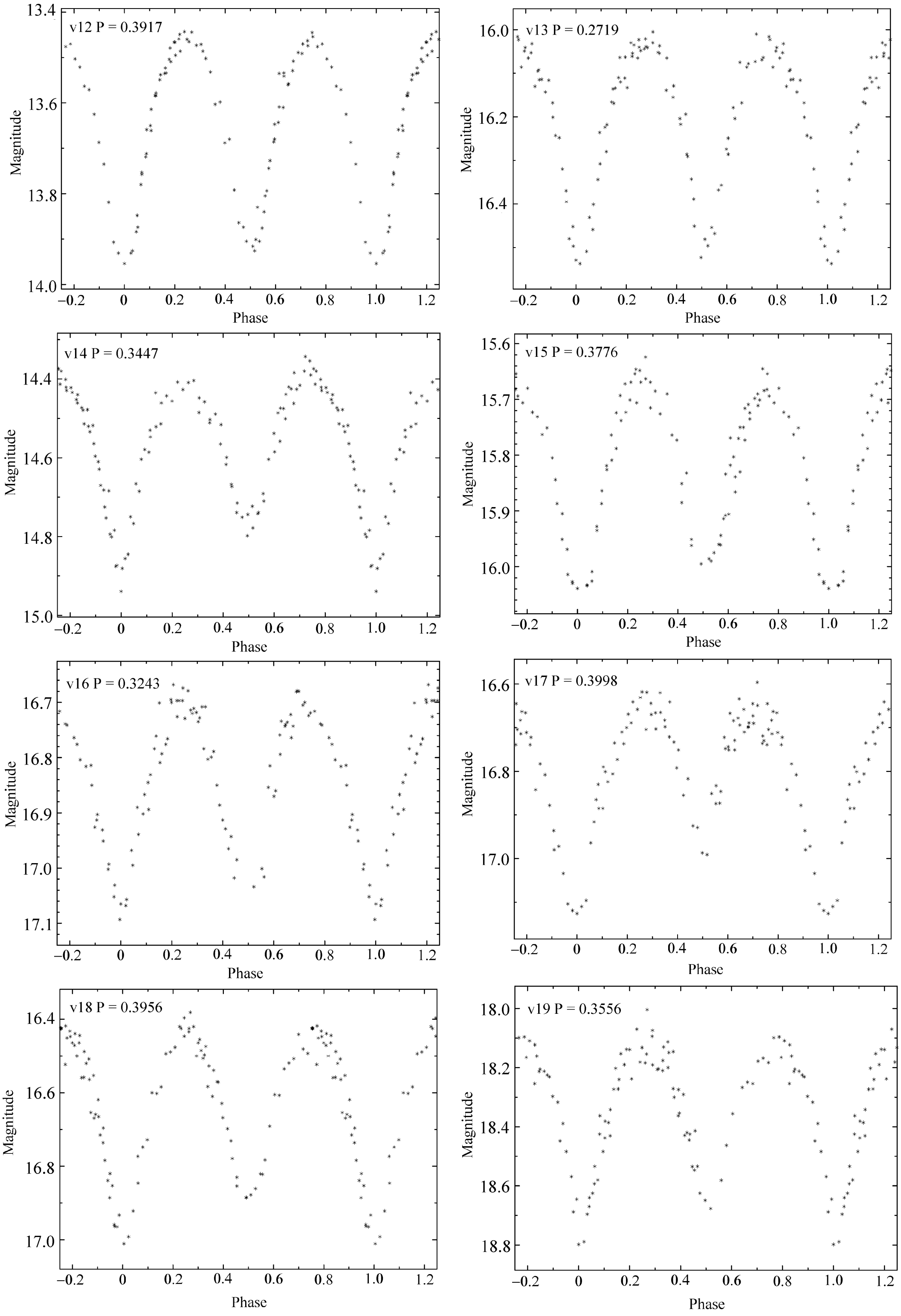
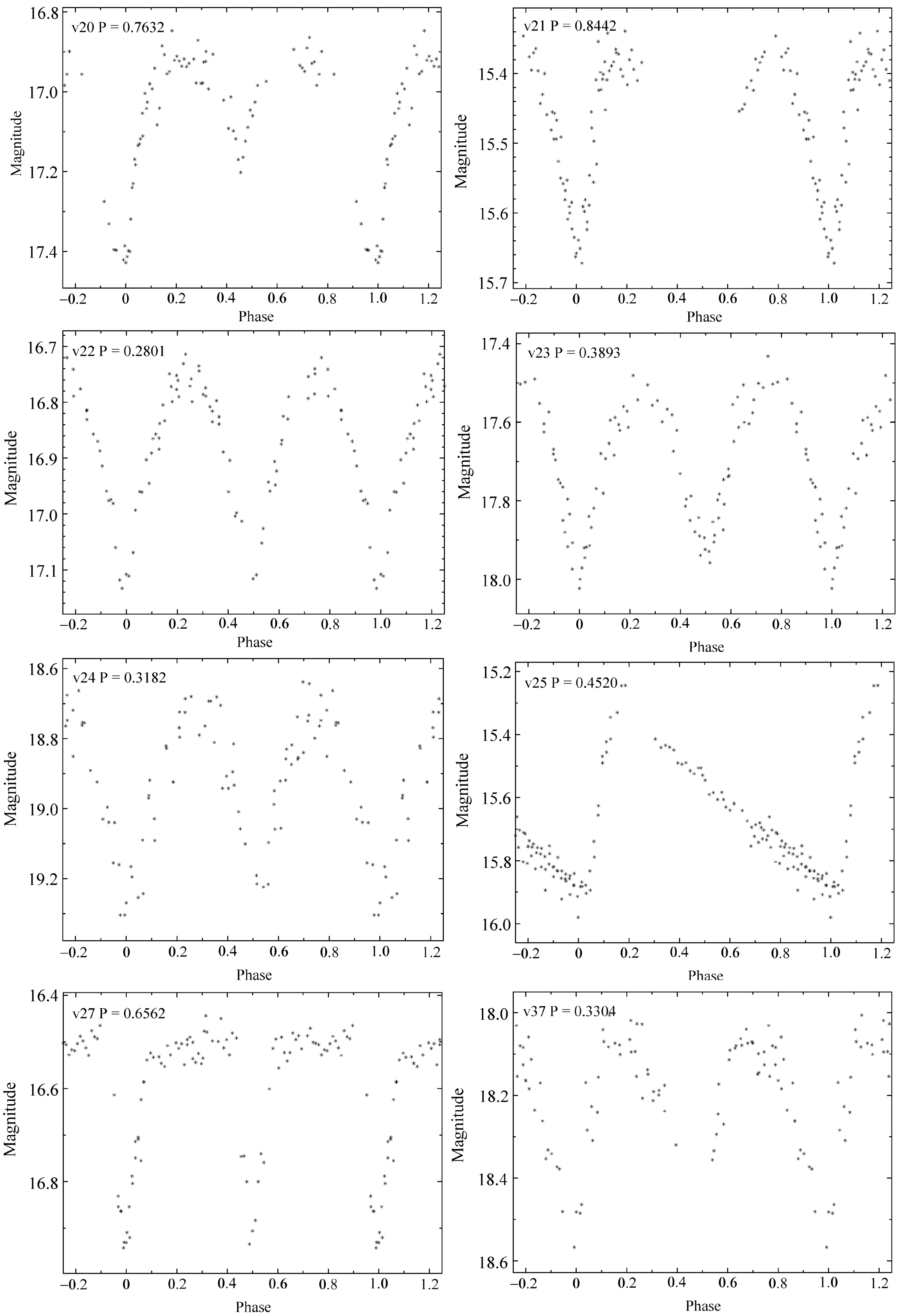


Fig. 4 Phased light curves of 16 of



the newly discovered variables.

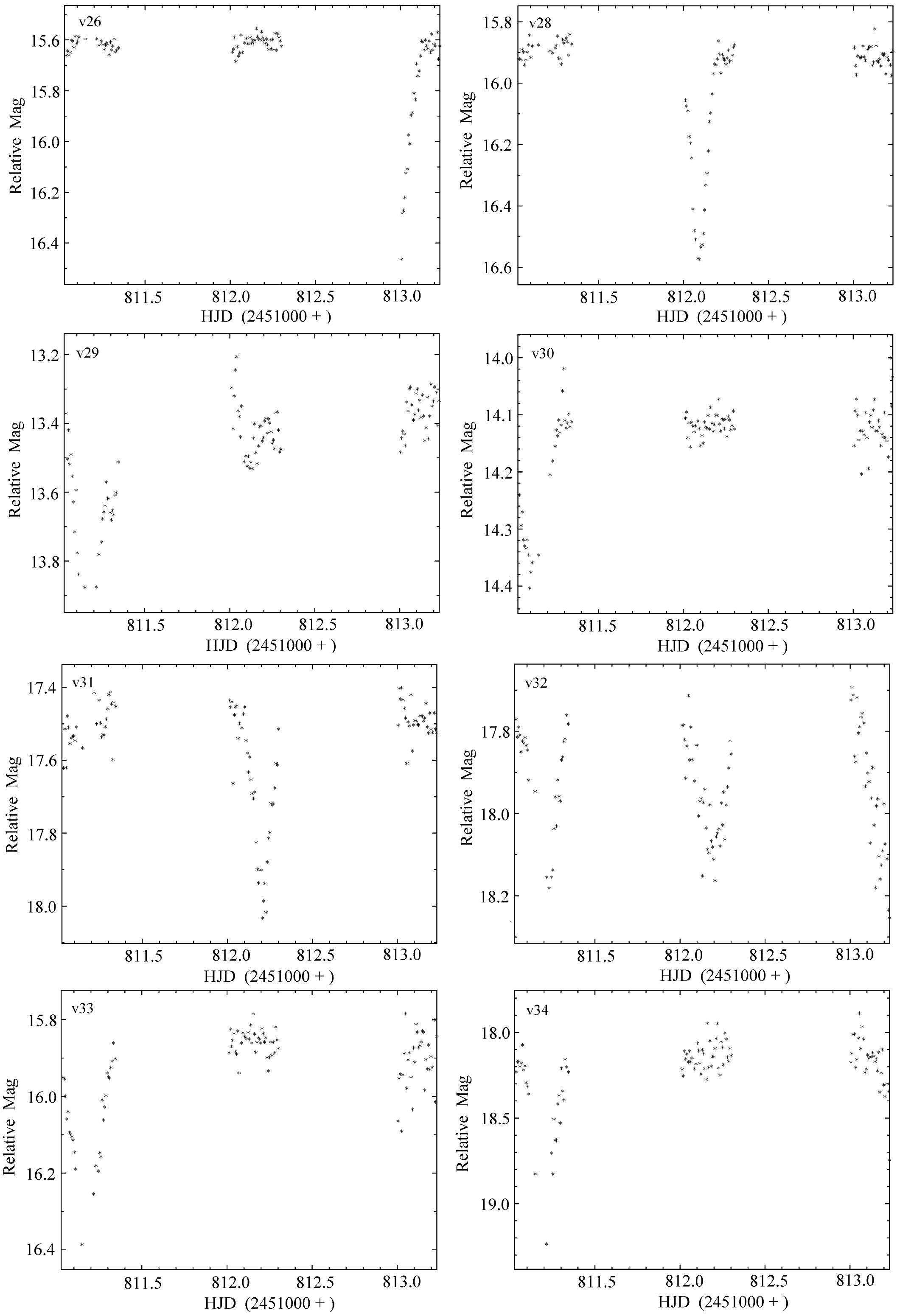


Fig. 5 Real-time light curves of 12 of the new variables.

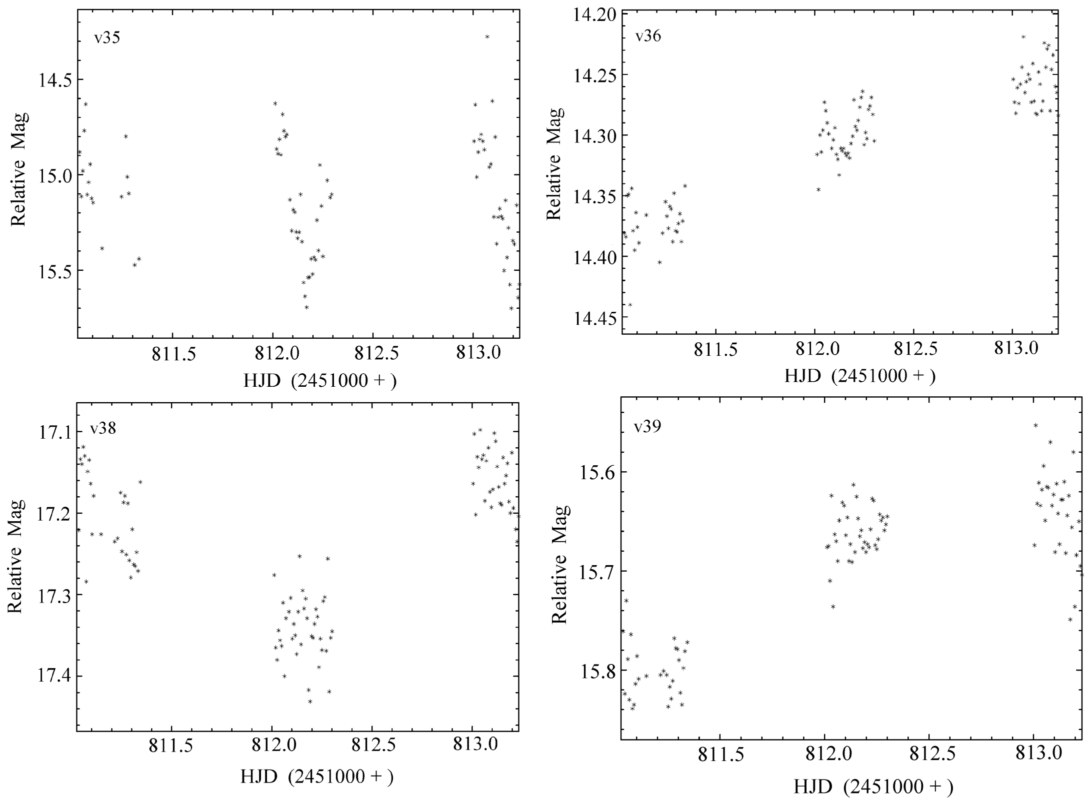


Fig. 5 Continued

The periods determined for the old variables from our data are all very close to those given by MK, all within 0.001 days except that of V34.

For V36, MK gave a period of 1.0896 days. However, if we phase with this period, we obtain a featureless light curve. Using the PDM code, we could determine a new period of 0.5440 days. It is just about half the MK value. Another interesting object among the 11 detected old variables is V42. It was classified as a pulsating star by MK with a period of 0.4940 days. This period is confirmed by our observations. Our survey gives a more obvious light curve with an amplitude of light variation as large as 0.33 mag. It looks like an RR Lyr variable from the shape of its light curve, but the color index of $B - V = 1.22$ given by MK suggests a late K-type star. This spectral type is rather late for RR Lyr and δ Scuti stars. More observations are needed for this variable.

4.2 The New Variables

In total, 28 new variable stars are discovered in this survey. Using the PDM code, it is possible to determine the period for 16 of these variables. Phased light curves for these 16 variables are shown in Figure 4. Figure 5 presents the real-time light curves for the other 12 new variables. Basic parameters for all the 28 newly discovered variables are given in Table 3, in which the times of light minima (T_0, in JD(hel)) are determined with the KW method (Kwee & van Woerden 1956).

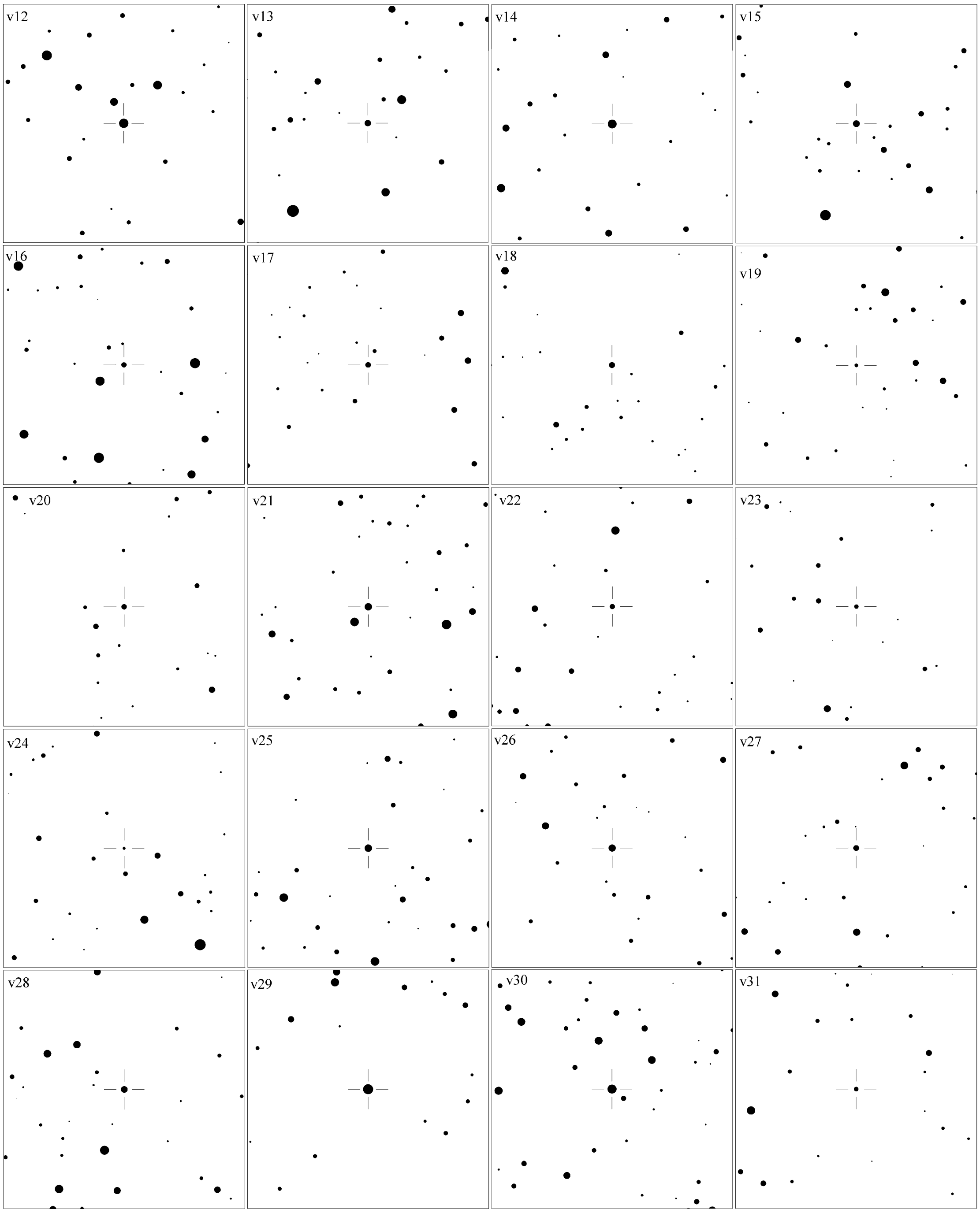


Fig. 6 Detailed finding charts for the 28 newly discovered variables in NGC 7789. Each panel has a size of 2×2 min.

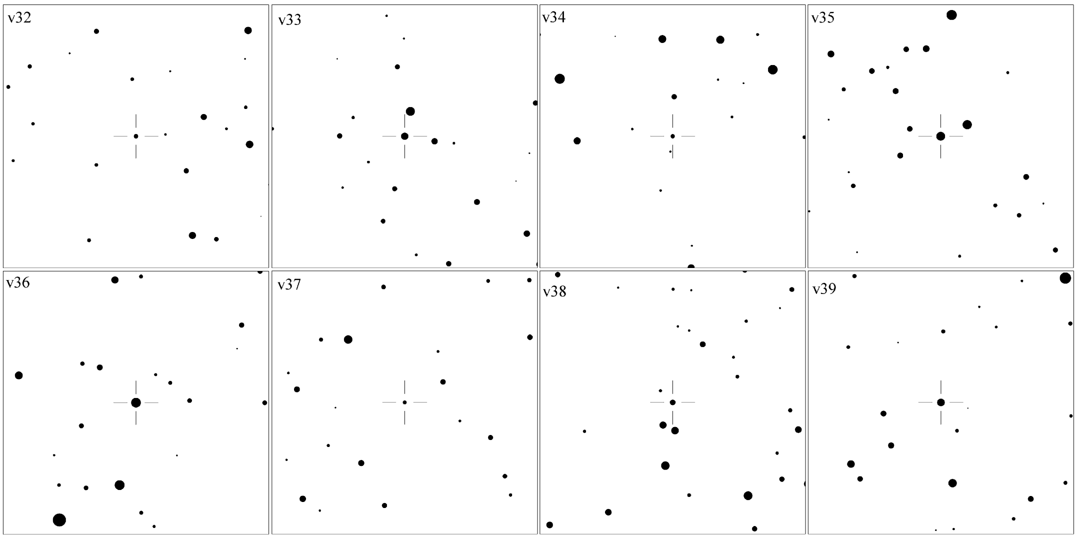


Fig. 6 Continued

23 out of the 28 newly discovered variables are shown to be eclipsing binaries. Among which, 14 have periods shorter than one day and exhibit EW type light curves, they are classified as W UMa stars, the other nine binaries show EA-type light curves. In addition, we have detected one definite pulsating stars and four variables with uncertain classifications.

v12: A bright eclipsing binary. Its light curve is of the EW-type with almost equal eclipsing minima. The variable is a typical W UMa binary. Our best estimate of the orbital period is 0.3917 days, with primary minimum $T_0 = 2,451,812.146$.

v13: A certain W UMa eclipsing binary with a very short period of 0.2719 days. A primary minimum was obtained at $T_0 = 2,451,811.260$.

v14: A definite eclipsing binary with an EW-type light curve. The orbital period is about 0.3447 days. A minimum time is derived, $T_0 = 2,451,812.144$. It is classified as a W UMa star.

v15: A W UMa system with an orbital period of 0.3776 days and a primary minimum time of 2,451,812.197.

v16: A W UMa binary, relatively faint, the period is determined to be 0.3243 days. A primary minimum time is derived at $T_0 = 2,451,813.126$.

v17: An eclipsing binary with an EW light curve. The minima Min. I and Min. II differ very much. It belongs to the A-subtype of W UMa stars. Its orbital period is derived as 0.3998 days with a primary minimum time of $T_0 = 2,451,813.168$.

v18: An E UMa eclipsing binary with a period of 0.3956 days and a primary minimum time at $T_0 = 2,451,813.101$.

v19: A very faint eclipsing binary star. The light curve presents the EW type with a very large amplitude of eclipse of about 0.69 mag. Its period is about 0.3556 days with a primary minimum time at $T_0 = 2,451,812.178$.

v20: A faint variable with an EB-type light curve. The period is about 0.7632 days with a minimum time at $T_0 = 2,451,811.261$.

v21: An eclipsing binary star with a relative long period of 0.8442 days. The light curve is not completely covered, and is of EB or EW type. The classification of the binary is therefore uncertain. A primary minimum time is obtained at $T_0 = 2,451,812.163$.

v22: A certain W UMa binary with a short orbital period of 0.2801 days. A minimum time of $T_0 = 2,451,811.285$ is obtained.

v23: Definite W UMa type star. An orbital period of 0.3893 days along with a primary minimum time $T_0 = 2,451,811.272$ are determined.

v24: The faintest variable identified during this program. It is definitely a W UMa binary star. The best estimate of the orbital period is about 0.3182 days. A primary minimum time is derived at $T_0 = 2,451,812.202$.

v25: A bright variable located about half a degree north of the cluster center. The light curve shows that it is definitely a pulsating variable. A period of 0.4520 days is determined with a large light variation amplitude of 0.58 mag. It is classified as a RR Lyr star. Its membership to the cluster is unknown. More observations for this star are recommended.

v27: A eclipsing binary with an EA-type light curve. The light curve presents two almost equal eclipses with an amplitude of 0.45 mag. The orbital period is estimated to be 0.6562 days. It is an interesting object for future observations.

v37: A faint eclipsing binary found very close to the cluster center. The light curve is somewhat noisy and is of EW or EB type. A period of 0.3304 days is assigned.

Stars v26, v28, v29, v30, v31, v32, v33 and v34 are all obviously eclipsing binaries. Their orbital periods cannot be determined because of incompletely covered data: we recorded only some single eclipses in our observations. Their times of minima are given in Table 3. These eight variables are all likely to be EA-type eclipsing binaries with relative long periods, when we note their behavior in the real-time light curves. The other four stars, v35, v36, v38 and v39 show definite light variations, but no conclusions can be drawn.

5 SUMMARY

We have presented a time-series CCD photometry survey in an 1 arc degree field centered on the open cluster NGC 7789. Using Steston's variability index, our search has resulted in the discovery of 28 new variables: including 23 eclipsing binaries (of which 14 are W UMa stars), one RR Lyr star and four miscellaneous variables of unclear nature. In addition, 11 old variables discovered by previous authors were observed during this survey. With the new data, revised parameters for some of these variables are given.

Only 11 out of some 45 previously known variables (Jahn et al. 1995; MK 1999; Kim & Park 1999) are detected in this program. This is partly due to the low photometry precision for the large field survey. At the same time, in the regions monitored by the previous works we find five new variables (Figure 2). They are all relatively faint variables with large amplitudes. This shows the advantages of the BATC system in the study of open clusters.

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References

Burbridge E. M., Sandage A., 1958, ApJ, 128, 174
Gim M., VandenBerg D. A., Stetson P. B., Hesser J. E., Zurek D. R., 1998, PASP, 110, 1318
Jahn K., Kaluzny J., Rucinski S. M., 1995, A&A, 295, 101
Kaluzny J., Stanek K. Z., Krockenberger M., Sasselov D. D., Tonry J. L., Mateo M., 1998, AJ, 115, 1016
Kim C., Park N.-K., 1999, ApSS, 268, 287
Kwee K. K., van Woerden H., 1956, BAN, 12, 327
McNamara B. J., Solomom S., 1981, A&AS, 43, 337
Mochejska B. J., Kaluzny J., 1999, Acta Astro., 49, 351
Stetson P. B., 1996, PASP, 108, 851
Zhang X. B., Deng L., Tian B., Zhou X., 2002, AJ, 123, 1548
Zhou X., Jiang Z. J., Xue S. J. et al., 2001, Chin. J. Astron. Astrophys. (ChJAA), 1, 372