Variable stars in the field of open cluster NGC 2126 [*]

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Abstract We report the results of a time-series CCD photometric survey of variable stars in the field of open cluster NGC 2126. In about a one square degree field covering the cluster, a total of 21 variable candidates are detected during this survey, of which 16 are newly found. The periods, classifications and spectral types of 14 newly discovered variables are discussed, which consist of six eclipsing binary systems, three pulsating variable stars, three long period variables, one RS CVn star, and one W UMa or δ Scuti star. In addition, there are two variable candidates, the properties of which cannot be determined. By a method based on fitting observed spectral energy distributions of stars with theoretical ones, the membership probabilities and the fundamental parameters of this cluster are determined. As a result, five variables are probably members of NGC 2126. The fundamental parameters of this cluster are determined as: metallicity to be $0.008 \, Z_{\odot}$, age $\log(t) = 8.95$, distance modulus $(m - M)_0 = 10.34$ and reddening value $E(B - V) = 0.55$ mag.

Key words: open clusters: individual (NGC 2126) — stars: variables (general) — binaries: general

1 INTRODUCTION

Studies of variable stars in star clusters are crucial tools for the understanding of stellar evolution and the nature of the host clusters. Recent works on variable stars in clusters can be found in Frandsen & Arentoft (1998); Park & Nemec (2000) and Zloczewski et al. (2007). Population I pulsating variables such as delta Scuti stars, γ Dor stars and slow pulsating B stars are populous in open clusters, and Population II pulsating variables such as RR Lyr-type stars and SX Phoenicis-type stars are rich in globular clusters. Stars in open clusters are not as crowded as globular clusters, so high-precision photometric results for open clusters can be obtained. Therefore, open clusters are very important targets for investigating pulsating variables. Eclipsing binary stars are also found in open clusters. For example, 45 short-period eclipsing binaries were discovered in the open cluster Collinder 61 (Mazur et al. 1995), seven eclipsing binaries were detected in the open cluster NGC 2099 (Kang et al. 2007), and sixty-one eclipsing systems were detected in the open cluster NGC 6791 (De Marchi et al. 2007).

The Beijing-Arizona-Taiwan-Connecticut (BATC) photometric system is a multicolor sky survey. The system has shown advantages for open cluster studies (Fan et al. 1996; Wu et al. 2005, 2007). This system has also contributed to the search for variable stars in clusters. For instance, seventeen pulsating

stars and ten eclipsing systems were found in the open cluster NGC 188 (Zhang et al. 2002, 2004). Three pulsating variable stars were discovered in the direction of NGC 4565 (Li et al. 2004), and six eclipsing binaries and seven pulsating variables in the field of open cluster 2168 (Hu et al. 2005). In this paper, we search for variable stars in the field of NGC 2126.

NGC 2126 ($\alpha_{2000} = 06^{\mathrm{h}}02^{\mathrm{m}}.55$, $\delta_{2000} = +49°52'$; $l = 163.23885$, $b = 13.13066°$) is a moderately rich typical open cluster with several dozens of members scattered in a region of $5' \sim 6'$ in the constellation Auriga (Lyngå 1987). The first photometry was made in blue and red ($\lambda\lambda 4300 - 6200$ Å) photographic observation by Cuffey (1943), who estimated the distance to NGC 2126 as 950 pc. Sixty years later, the first CCD $VR_c\,I_c$ photometric observation was performed by Gáspár et al. (2003). They found 6 variable stars in the cluster field, of which three could be members. They also obtained the fundamental parameters of the cluster: the age is $9.0 < \log(t) < 9.4$, the reddening value $E(B - V) = 0^{\mathrm{m}}.2 \pm 0.^{\mathrm{m}}15$, and the distance $d \leq 1.3 \pm 0.6$ kpc. To search for more cluster variable stars in the open cluster NGC 2126, we performed a dedicated CCD survey with the BATC system. In this paper, observations and data reduction are described in Section 2. The search for variable stars is reported in Section 3. The physical parameters and the CMD of the cluster are described in Section 4. Results and discussions are presented in Section 5. A brief summary is given in Section 6.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Observations

We observed NGC 2126 from 2004 December 4 to 2005 March 24. The observations were conducted with the 60/90 cm f/3 Schmidt telescope, which is located at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC), with a 2K×2K CCD camera at its main focus. The field of view of the CCD covers about 1 deg^2, with an image scale of 1.7 arcsec per pixel. The filter system consists of 15 intermediate-band filters with bandwidths 350–490 Å, covering a spectral range of 3000–10 000 Å, which are specifically designed to avoid most of the known bright and variable night-sky emission lines. In searching for variable star observations, f (5270 Å) and i (6660 Å) band filters were employed. The exposure times were set at 300 seconds in the f-band and 120 s in the i-band for each observation. In total, we got 487 frames of NGC 2126, 243 in the f-band and 244 in the i-band, respectively.

2.2 Data Reduction

Reduction of the CCD data including bias substraction and flat-fielding with dome flats was performed with an automatic procedure called PIPELINE I, which has been developed as a standard program for the BATC multicolor Sky Survey (Fan et al. 1996). The dome flat-field images were taken by using a diffuser plate in front of the corrector plate of the Schmidt telescope; the flat fielding technique has been verified (Wu et al. 2002; Zhou et al. 2004). The instrumental magnitudes of point sources in CCD frames were measured by the PIPELINE II program, which is based on the DAOPHOT stellar photometric reduction package of Stetson (1987). The PIPELINE II program was applied to each single CCD frame to get the magnitude of each point source by PSF (point spread function) fitting and the aperture photometries with different apertures. As a result, a list of PSF and aperture magnitudes in various filter bands was obtained for all the detected objects.

2.3 Flux Calibration

In order to give the spectral types of the variables (see Sect. 3.1), we observed NGC 2126 with another 13 BATC filter bands (from c to p) in one night with semi-photometric conditions. Due to there not being enough nights with photometric conditions, the flux calibrations of NGC 2126 are only defined in the f-band and the i-band by the four standard stars (Oke & Gunn 1983) (BD+174708, BD+262606, HD19445 and HD849373). The fluxes of the four stars have been recalibrated by Fukugita et al. (1996). In this paper, the standard stars were observed between air masses of 1.0 and 2.0. The details of the
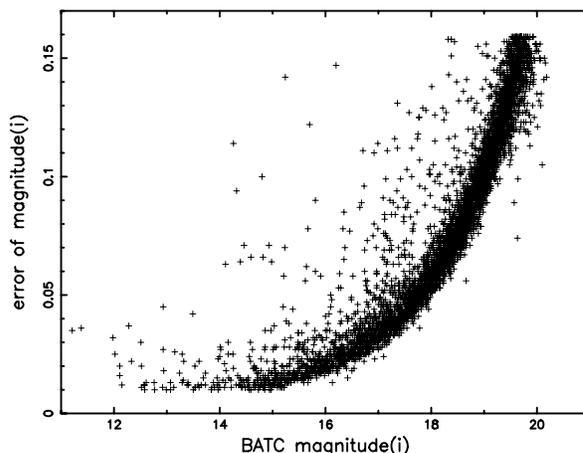
Fig. 1 Plot of the rms scatter of the i-band for BATC observation in the field of NGC 2126. The dense parts are normal stars, which are intrinsically stable.

flux calibration were described by Zhou et al. (2001). Since the flux calibrations of NGC 2126 in the f-band and the i-band have been defined by the four standard stars as described above, we can perform flux calibration of NGC 2126 in the other 11 bands based on the method called model calibration as presented by Zhou et al. (1999).

3 SEARCHING FOR VARIABLES

In the frames, about 4416 stars are detected in the field of NGC 2126. To search for variable stars, we sum the magnitude scatter of each measurement. The magnitude scatter of all stars in the i-band is shown in Figure 1. The abscissa is the mean magnitude of each star. The dense parts are normal stars which are intrinsically stable in Figure 1. A star is selected as a variable candidate if 1) it presents a large deviation (> 3 rms) compared with that of other stars of similar magnitude; 2) it has been measured on at least 100 frames. Based on these conditions, hundreds of possible variable candidates were selected. Then, we checked the real-time light curves and the suspect time-series data of all candidates. The candidates showing noisy chaotic light variations were rejected from the variable sample. After that, the number of variable candidates decreased to about fifty. Furthermore, we checked the frames, and got rid of the stars that were located at the image edge, or were saturated or contaminated by bright stars. Ultimately, a total of 19 certain variable stars were identified from the candidates. Among these 19 stars, 5 variables, named V1-V2,V4-V6 are known variables from Gáspár et al. (2003), with the remaining 14 objects, named V7-V20 being newly discovered. A known variable star named V3 in Gáspár et al. (2003) was not detected as a variable candidate in this paper. We then checked the data, and found that its variable amplitudes were too low to be detected. In addition, there are two candidates, the properties of which cannot be determined in this paper. The positions of all 21 variable candidates in the field of NGC 2126 are marked in Figure 2, and the newly found variables are marked in sequence of distance away from the center of the cluster.

Analysis of the light-curves was done with the phase dispersion minimization (PDM) method (Stellingwerf 1978). In this method, the main characteristics of light curves such as the periods and amplitudes of light variations are given.

According to the periods, spectral types and behaviors of the light curves, the variable stars are classified: seven binary systems, five pulsating variable stars, an RS CVn star, a W UMa star or δ Scuti star, one eclipsing binary with a pulsating component, three long period variables, and three objects that
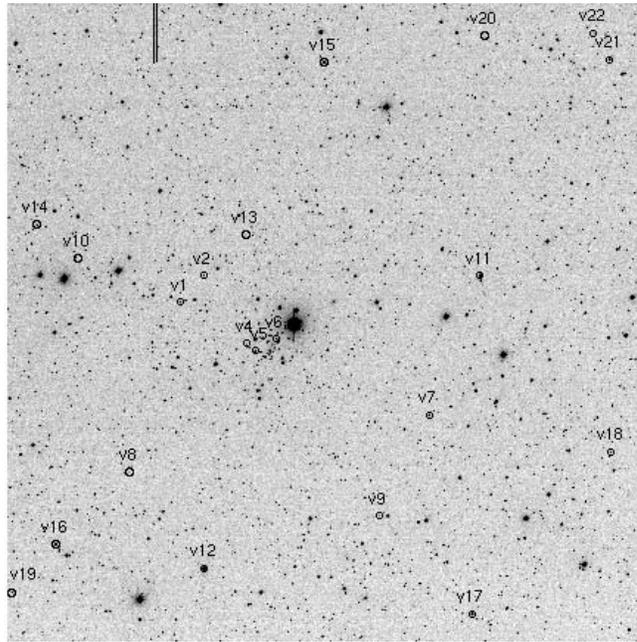
Fig. 2 Observed CCD field ($58' \times 58'$) of the open cluster NGC 2126. Identification of variable stars is also marked. North is up and east is to the left.

Table 1 Observation Summary of 21 Variable Stars in Open Cluster NGC 2126

| ID	Period	α_{2000}	δ_{2000}	$\bar{m}(i)$	error	Δamp(i)	Spec	Variable Type	Member
V1	1.64444 or 0.82222	06:01:44.09	+49:56:30.3	13.868	0.02	0.198	A	γ Dor	0.91
V2	-	06:01:57.36	+49:58:54.8	14.356	0.025	0.117	A	-	0.65
V4	1.0966	06:02:21.28	+49:52:37.0	15.507	0.091	0.637	F	EA	0.00
V5	0.0827	06:02:26.38	+49:51:56.5	12.930	0.05	0.104	A	δ Sct	0.30
V6	1.1732 or 0.129572	06:02:37.99	+49:53:02.5	14.211	0.045	0.479	F	EA+δSct	0.00
V7	0.395	06:04:04.14	+49:45:53.4	12.671	0.066	0.240	A	W UMa or δ Scuti	-
V8	0.28448	06:01:14.33	+49:40:58.9	16.364	0.184	0.808	-	eclipsing binaries	0.00
V9	0.444462	06:03:34.89	+49:36:45.0	15.626	0.083	0.454	F	W UMa	0.00
V10	0.47743	06:00:46.04	+50:00:34.9	17.032	0.163	0.728	-	eclipsing binaries	0.00
V11	38.5	06:04:34.69	+49:58:33.4	11.032	0.045	0.170	M	LPV	0.00
V12	-	06:01:55.94	+49:32:08.5	10.122	0.024	0.134	-	uncertain	0.00
V13	-	06:02:21.61	+50:02:35.5	11.007	0.018	0.090	M	LPV	0.46
V14	0.80042	06:00:22.78	+50:03:40.4	14.013	0.058	0.392	-	EA	-
V15	-	06:03:07.49	+50:18:13.8	11.395	0.017	0.111	M	LPV	0.00
V16	-	06:00:32.51	+49:34:27.4	11.692	0.012	0.085	-	uncertain	-
V17	0.0636	06:04:26.43	+49:27:39.5	11.494	0.012	0.093	A	δ Scuti	0.00
V18	0.2004	06:05:46.45	+49:42:11.0	16.084	0.160	0.721	K	eclipsing binaries	-
V19	0.5375	06:00:07.54	+49:30:07.5	14.640	0.042	0.279	-	RRa Lyr	-
V20	0.30215	06:04:39.65	+50:20:25.8	15.228	0.111	0.709	F	δ Scuti	-
V21	0.956	06:05:50.90	+50:18:01.8	12.961	0.022	0.169	G	RS CVn	0.02
V22	0.22356 or 0.447124	06:05:42.28	+50:20:27.0	16.642	0.201	1.158	-	eclipsing system	0.00
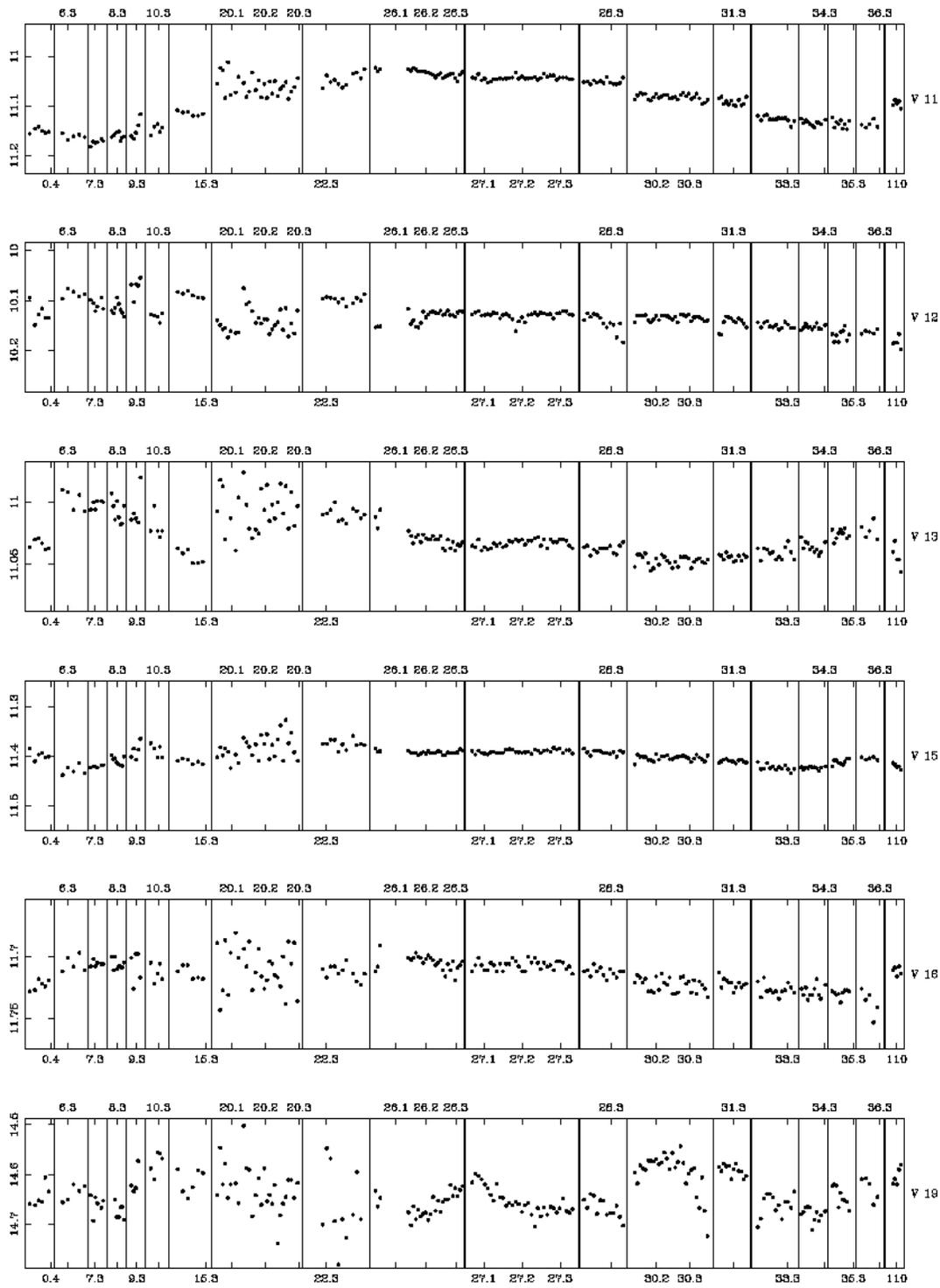
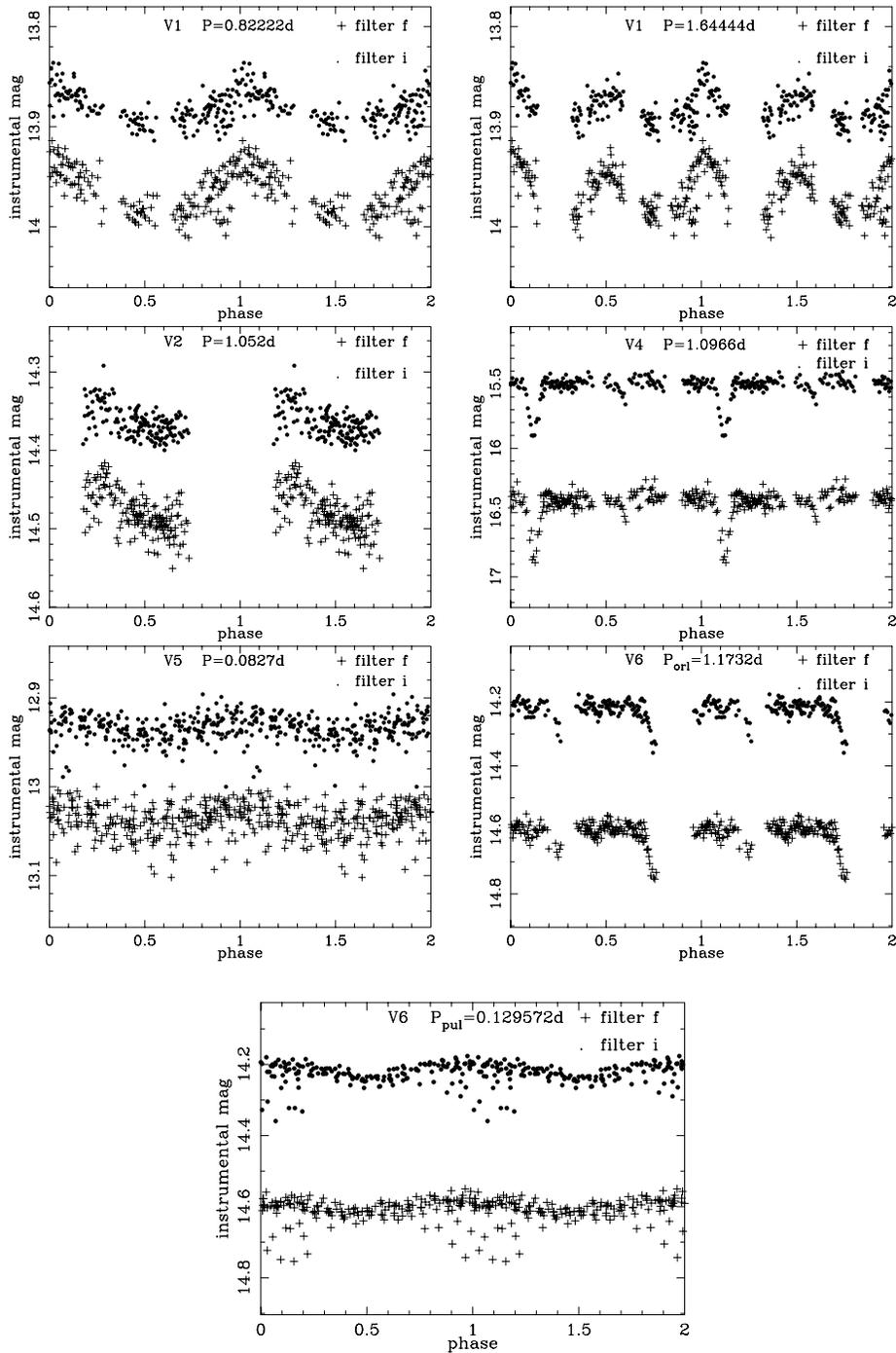**Fig. 3** Real-time light curves for six variable stars.

Fig. 4 Light curves for 5 known variable stars in the f- and i-bands, respectively, with the periods marked in each frame.
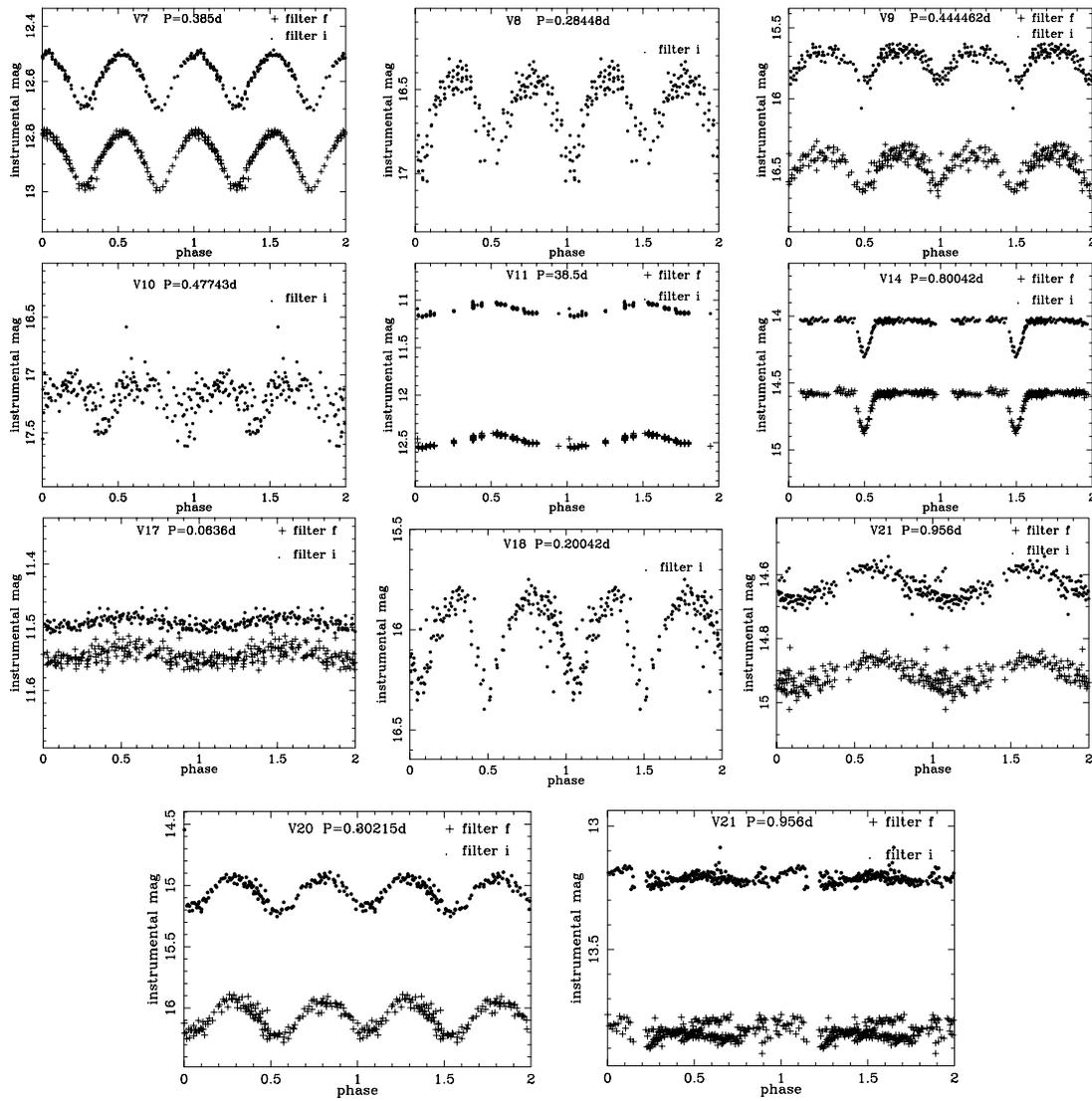
Fig. 5 Light curves for new variable stars in the f- and i-bands, respectively, with the periods marked in each frame.
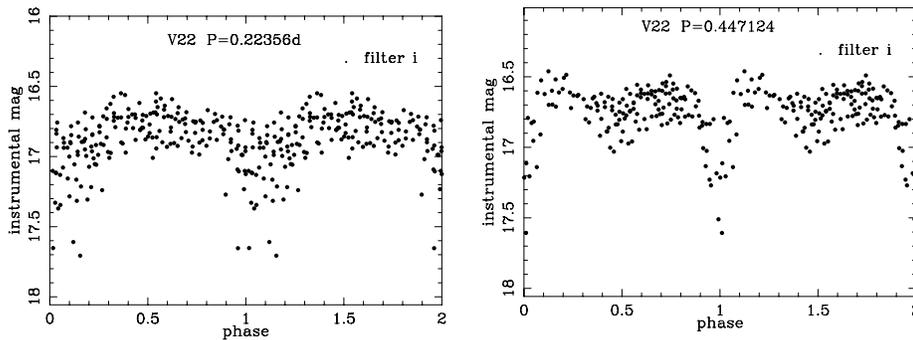

Fig. 6 Light curves for V22 with two possible periods in the i-band.

cannot be confirmed based on the PDM method. The analyzed results, including their periods, variable amplitudes, mean magnitudes and spectral types, are also listed in Table 1. The real-time light curves of 6 variables are shown in Figure 3. The phased light curves of V1, V2, V4, V5 and V6 are presented in Figure 4. The phased light curves of 11 new variables are shown in Figure 5. The phased light curves of V22 are shown in Figure 6.

4 THE PHYSICAL PARAMETERS AND CMD OF THE CLUSTER

Based on the photometric data in the BATC 13 filter bands, the fundamental parameters of the open cluster NGC 2126 are determined by fitting the spectral energy distributions (SEDs) of stars in the cluster field with theoretical SEDs of Padova stellar evolutionary models (Girardi et al. 2000, 2002; Wu et al. 2005). At the same time, the membership probabilities of the stars, including the variable stars studied in this paper, were determined based on the method of Wu et al. (2006). The best-fitting theoretical results of the cluster NGC 2126 are: metallicity $Z = 0.008 \, Z_\odot$, age $\log(t)$=8.95, distance modulus $(m - M)_0$=10.34 and reddening value $E(B - V) = 0.55$ mag. The derived reddening is much larger than that derived by Gáspár et al. (2003).

Malkov & Kilpio (2002) used various observational data for common interstellar extinction models. They recommended using the model proposed by Arenou et al. (1992) to calculate the extinction for objects with distances greater than 1 kpc and with galactic latitudes $|d| = 30°$. Adopting the distance 1.170 kpc for NGC 2126 calculated from the above derived $(m - M)_0 = 10.34$, the visual extinction $A_v = 1.467 \pm 0.369$ is determined based on the model of Arenou et al. (1992). Adopting $R_v = 3.3$, the extinction of NGC 2126 is estimated to be $E(B - V) = 0.45 \pm 0.11$, which is consistent with that derived in this study within the errors.

Also based on the photometric data in the BATC 13 filter bands, the spectral types of the stars including the variable stars studied in this paper, can be given by fitting the BATC SEDs with the module SEDs of Gunn & Stryker (1983), in which 74 spectral types from O to M6 and luminosities from main sequence to giant are included.

The results of membership probabilities are shown in the last column in Table 1. In this table, "-" denotes that we did not obtain the parameter of this variable in this paper. The CMD of the observed field is shown in Figure 7. The filled circles denote the stars whose membership probabilities are more than 70 percent. The black squares denote the variable stars. In addition, because V10, V14, V16 and V19 do not lie in the e-band in the image, they are not plotted in the CMD diagram. The thick solid line denotes theoretical isochrones with $\log(t) = 8.95$. The theoretical isochrones with parameters derived by the SED-fitting can fit star distributions in the CMD very well. The membership probabilities of V1 and V2 are 0.91 and 0.65, respectively. They are on the main sequence of the cluster NGC 2126. Therefore, V1 and V2 should be members of NGC 2126. Considering the characteristics of variable stars and the positions in the CMD (Fig. 7), V5 and V13 may be members of NGC 2126, although their membership probabilities are only 0.30 and 0.46, respectively. V7 is located near the turn-off, and should be a member of NGC 2126.

5 RESULTS AND DISCUSSIONS

5.1 The Known Variables in NGC 2126

There are a total of five known variable stars (Gáspár et al. 2003) in the field of NGC 2126. Their basic parameters are listed in Table 1. During this observation, good light curves for V1, V2, V4 ,V5 and V6 were recorded.

V1: Being similar to the previous work, we obtained two periods of V1, 0.82222 d and 1.64444 d compared with 0.822235 d and 1.6447 d from Gáspár (2003). Gáspár (2003) suggested that V1 could be a γ Dor or RS CVn star. The double-peak of the phase diagram is clear with a period of 1.64444 d (Fig. 4). In our observation, we classified V1 as an A-type. However, the RS CVn criteria, which were defined by Hall 1976 and are widely used, suggest that the spectral type of an RS CVn star is
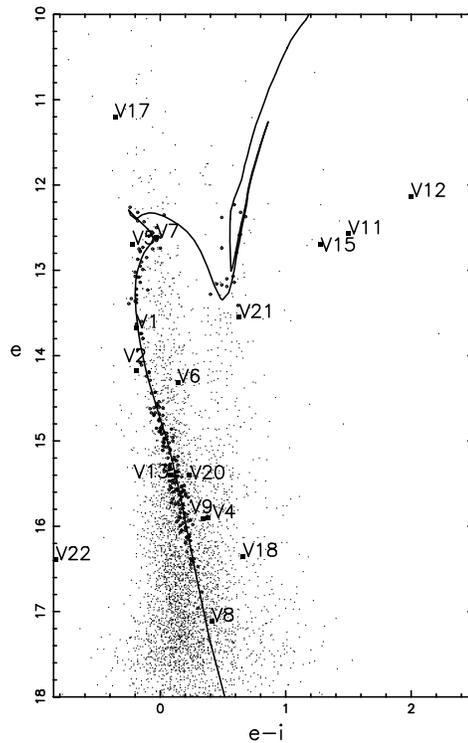
Fig. 7 Color-magnitude diagrams of NGC 2126. The solid line shows the $\log(t) = 8.96$ theoretical isochrone (Girardi et al. 2000). The filled circles denote stars observed whose probabilities of being members are more than 70 percent. The black squares denote variable stars.

F$\sim$K type. Kaye et al. (1999) defined the γ Dor phenomenon that consists of variable stars with an implied range in spectral type A7-F5 and in luminosity class IV, IV-V or V. Therefore, V1 may be a γ Dor star rather than an RS CVn.

V2: This was discovered by Gáspár (2003), and periods around 0.5 d and 1 d were given; however neither period can give a continuous phase diagram with no gap. So, Gáspár (2003) did not determine the cause of the low amplitude. In this paper, its spectral type is determined to be A-type. The phased light curves of Figure 4 show that V2 is becoming faint and its period may be longer than 2 d.

V4: This is an Algol-type eclipsing binary. Gáspár (2003) observed only one minimum for this star and failed to determine its period. During our observations, we recorded three eclipse events. Using the PDM code, a probable period of 1.0966 d is derived. In addition, we determined its spectral type to be F-type.

V5: Gáspár (2003) analyzed the frequencies of this star with Fourier analysis, and determined two frequencies $f_1 = 11.43\,\mathrm{d}^{-1}$ and $f_2 = 12.14\,\mathrm{d}^{-1}$ and $f_1/f_2 = 0.94$. So, they suggested V5 was a multiply periodic oscillation δ Scuti star with non-radial modes. In this study, its spectral type is classified as A-type. Based on the PDM code, we derive a probable period to be 0.0827 d which is close to f_1, and the amplitude is 0.104 mag, which is very low. Combining the results of Gáspár (2003) and of this paper, V5 may be confirmed to be a δ Scuti star.

V6: Gáspár (2003) showed that V6 was an eclipsing binary system with a δ Sct-type pulsation with $P_{\mathrm{pul}} = 0.129\,\mathrm{d}$ and $P_{\mathrm{orb}} = 1.1732\,\mathrm{d}$, and it might have a $f_{\mathrm{pul}}{:}f_{\mathrm{orb}} = 1{:}9$ resonance between the orbital motion and pulsation. Our results of $P_{\mathrm{pul}} = 0.12957\,\mathrm{d}$ and $P_{\mathrm{orb}} = 1.1732\,\mathrm{d}$ are consistent

with Gáspár (2003). Considering its spectral type of F-type determined in this paper, V6 may be a δ Scuti star in an eclipsing binary.

5.2 The Newly Discovered Variables

In this paper, sixteen new variables were discovered in the field of NGC 2126. According to the behaviors of the light curves, the spectral types and the period analysis, classifications were made. Among the sixteen new variables, four were classified as eclipsing systems, one as a W UMa type star, one as an EA star, one as a W UMa star or δ Scuti star, three as pulsating variable stars (one RR Lyr and two δ Scuti), one RS CVn star, three long period variables, and two variable candidates that are not confirmed in this paper. Their basic parameters are listed in Table 1. The real-time light curves of V11-V13, V15-V16 and V19 are shown in Figure 3. The phased light curves of V7-V11, V14, V17-V21 are shown in Figure 5. The phased light curves of V22 are plotted in Figure 6.

V7: Its position in the CMD, i.e. near the turn-off, shows that it is a member of this cluster. It is difficult to determine its variable type. From the period of 0.395 d and the behaviors of the light curves, it looks like a W UMa binary system, which has a type of G or K and periods of 0.22 to 0.8 d (Binnendijk 1965). However, according to the spectral type of A-type, and the light curves of sinusoidal variations, V7 may be a high amplitude δ Scuti star. The spectral types of δ Scuti stars are from A to F with short periods of 0.02 to 0.3 d (Breger 1991).

V8: This is likely to be an eclipsing binary system with a period of 0.28448 d. The phased light curves are plotted in Figure 5.

V9: This possesses typical W UMa-type light curves, and its spectral type is classified as an F-type, which is consistent with the W UMa type, i.e. F∼G. Therefore, V9 should be a W UMa eclipsing system with a period of 0.444462 d.

V10: This star may be a field eclipsing system, the period of which is 0.47743 d. The phased light curves are shown in Figure 5.

V11, V13 and V15: These may be field long period variable stars. As we know, the spectral types of red giants and supergiants are M, R, N or S, and the periods are up to 600 d. In our observations, V11, V13 and V15 are all classified as M-types. Their real-time light curves also have long time variations (Fig. 3). Based on PDM code analysis, we obtained a probable period of V11 to be 38.5 d. The phase diagrams are plotted in Figure 5. The periods of V13 and V15 cannot be obtained in this paper.

V14: This is a field Algol-type eclipsing system. Its light curves have deep primary minima and flat bright parts. A period of 0.80042 d is obtained.

V17: This is classified as an A-type in this paper. The light curves suggest that it is likely a δ Scuti variable with a period of 0.1272 d.

V18: About V18, its spectral type is classified as a K-type in this study. Analysis of the light curves reveals that it is likely to be an eclipsing binary system with a period of 0.20042 d.

V19: Its real-time light curve possesses the character of RR Lyra: asymmetrical, and increasing rapidly and decreasing slowly. So, V19 may be an RR Lyra system with $P = 0.5375$ d.

V20: This is classified as an F-type star in this paper. From its light curves (Fig. 5), it may be a δ Scuti star with $P = 0.30315$ d.

V21: The spectral type of V21 is classified as a G-type in this paper. From Section 5.1, we know that RS CVn is a later G ∼ K type. So, V21 may be an RS CVn variable with a period of 0.956 d. In the i-band, the light curves show that it is likely to be an RS CVn. However, in the f-band, they are very distorted.

V22: The most confusing object in this paper is V22. The analysis of light curves gives two periods: one is 0.22356 d and the other is 0.447124 d (Fig. 6). From the phased diagram of the period 0.22356 d, V22 is most likely an eclipsing contact binary system. On the other hand, the light curves of the period 0.447124 d have deep primary minima and secondary minima. So, V22 may be a field eclipsing binary system.

6 CONCLUSIONS

In this paper, we have presented a time-series CCD photometric survey of variable stars in the field of the open cluster NGC 2126. In this survey, 21 variables were discovered, including five previous ones (Gáspár et al. 2003). Based on SED fitting between the theoretical isochrones and the photometry, the membership probabilities of stars and the fundamental parameters of NGC 2126 were determined. The important results of this study are the following:

1. We discovered 16 new variable stars in this survey: six were classified as eclipsing systems with four eclipsing binary systems (V8, V10, V18 and V22), a W UMa type star (V9), an EA star (V14), three long period variables (V11, V13 and V15), three pulsating variable stars with an RR Lyr (V19) and two δ Scuti (V17 and V20), and an RS CVn star (V21). About V7, its light curves show that it is most likely a W UMa type star. However, its spectral type is classified as A-type. So, it is very difficult to confirm whether it is a W UMa star or a δ Scuti star. More information will be needed in future observations. In addition, two variable candidates (V12 and V16) were not confirmed in this paper. Among the 16 newly discovered variable stars, two (V7 and V13) may be members of the open cluster NGC 2126.
2. We also determined the mass of each variable star belonging to members of cluster NGC 2126, and the physical parameters of this cluster. The masses of V1, V2, V5 and V13 are 1.1312, 0.9131, 1.4808 and $0.4754 M_\odot$, respectively. The mass of V1 suggests that it may be located at the blue edge of the instability strip; and its pulsations are driven by modulation of the radiative flux from the interior of the star that is a relatively deep envelop convection zone (Guzik et al. 2000; Warner et al. 2003). As a γ Dor, the variations of V1 are consistent with the model of high order (n) and low spherical degree (l), nonradial, gravity (g)-mode oscillations (Kaye et al. 1999). Because we cannot determine the pulsating class of V2, the cause of its pulsation is unknown. Although the spectral type of V13 is known, the real-light curves are only a part of the whole, and the driving mechanism is not known.
3. The physical parameters of the open cluster NGC 2126 are: metallicity $Z = 0.008\,Z_\odot$, age $\log(t) = 8.95$, distance modulus $(m - M)_0 = 10.34$ and $E(B - V) = 0.55$ mag.

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