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Variable stars in the open cluster Mel 71

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Abstract. The UBVI and time-series CCD photometric observations of the intermediate-age open cluster Mel 71 were carried out to search for variable stars and obtain their physical parameters. By fitting the ZAMS to the observed color-color and color-magnitude diagrams, we estimated a reddening value of the cluster E(B$-$V) = 0.20 $\pm$ 0.05 and a distance modulus $(\mathrm{V}-\mathrm{M}_V)_\circ$ = 11.6 $\pm$ 0.2. We also found its age of about *log t* = 9.0 from an isochrone fitting method for Z = 0.008.

Using the observed time-series data, we carefully examined light variations of 358 stars, fainter than $13\overset{\mathrm{m}}{.}0$. Four δ Sct stars and one eclipsing binary were discovered. They are located in the δ Sct instability strip of the color-magnitude diagram. Incidence of variability within the instability strip is about 7%. Newly found δ Sct stars show complex light variations, implying that they have multiple pulsation frequencies. The period of the binary star is estimated to be about $0\overset{\mathrm{d}}{.}678$.

Key words: Galaxy: open clusters and associations: individual: Mel 71 – stars: variables: δ Sct – stars: binaries: eclipsing

1. Introduction

One of the most effective and productive usage of 1 m class telescope may be CCD time-series photometry of variable stars in star clusters. Simultaneous photometry of all stars in the cluster with a CCD enables us to do the efficient observation. Moreover, one can obtain precise time-series data, by observing the stars under the same weather conditions. It would be very important for observational studies of multi-periodic pulsating variable stars such as δ Sct stars, γ Dor stars and SPBs (Slowly Pulsating B stars) *etc.*, because they require many accurate time-series data to analyze their complicated light curves. Since all of the stars in the cluster are assumed to have the same reddening, distance, age and chemical abundance, from a theoretical point, we can also set the strong constraints on these physical parameters required for pulsation mode identification and model calculation of the variable stars. Recently, from time-series CCD photometry of open clusters, a number of multi-periodic pulsating variable stars have been discovered (for examples, Frandsen et al. 1996; Viskum et al. 1997; Choi et al. 1998). In this paper, we carried out time-series CCD photometry of the open cluster Mel 71 in order to search new δ Sct stars.

δ Sct stars are located at the classical instability strip on and above the main sequence of spectral types from A to F. These variables are known to have short pulsation periods of 0.5$\sim$5 hours and small pulsation amplitudes less than 0.1 magnitude (Rodríguez et al. 1994; García et al. 1995). Since the last several years, δ Sct stars have been an important target in studying stellar structure and testing evolution theory (called asteroseismology, see Brown & Gilliland 1994 for an extensive review), because most δ Sct stars pulsate in a number of radial and nonradial modes at the same time; thus, they provide us with useful seismic information.

The intermediate-age open cluster Mel 71 is a very suitable object for detecting new δ Sct stars, because the large populated turn-off point in its color-magnitude diagram is nearly the same as δ Sct instability strip. Furthermore, since most of probable member stars in the cluster are moderately concentrated (Trumpler type is II 1 m) within just $\sim$6 arcmin, it is very easy to observe them with a CCD. Pound & Janes (1986) observed 631 stars fainter than 14^m and combined them with photometric data of bright stars by Hassan (1976). They derived the reddening E(B$-V$) = 0.10 $\pm$ 0.05 and the distance $(\mathrm{V}-\mathrm{M}_V)_\circ$ = 11.88 $\pm$ 0.20 from fitting the ZAMS and red giant clump of the Hyades cluster. The abundance of the cluster was found to be [Fe/H] = $-$0.57 $\pm$ 0.18 by Washington photometry for 16 red giant stars (Geisler et al. 1992) and [Fe/H] = $-$0.32 $\pm$ 0.16 by high dispersion echelle spectra for 2 red giants (Brown et al. 1996). The membership of individual star has not been examined yet, except for 24 red giants investigated by Mermilliod et al. (1997).

2. Observation and data reduction

Time-series CCD observations of Mel 71 were made at Bohyunsan Optical Astronomy Observatory (BOAO). The 1.8m telescope with the TeK 1024$\times$1024 CCD was used. The CCD gives a scale of $0\overset{\prime\prime}{.}34$ per pixel and a field of view of $5\overset{\prime}{.}8\times5\overset{\prime}{.}8$. We have obtained a total of 160 V frames over four nights from February 1st to 16th, 1997. The photometric seeing (FWHM) was typically $2\overset{\prime\prime}{.}0$. Exposure times were chosen in a range of 3 min to 5 min, depending on the seeing and the transparency. Unfortunately, reflection efficiency of the telescope mirrors was very low, because the mirrors had not been re-aluminized for

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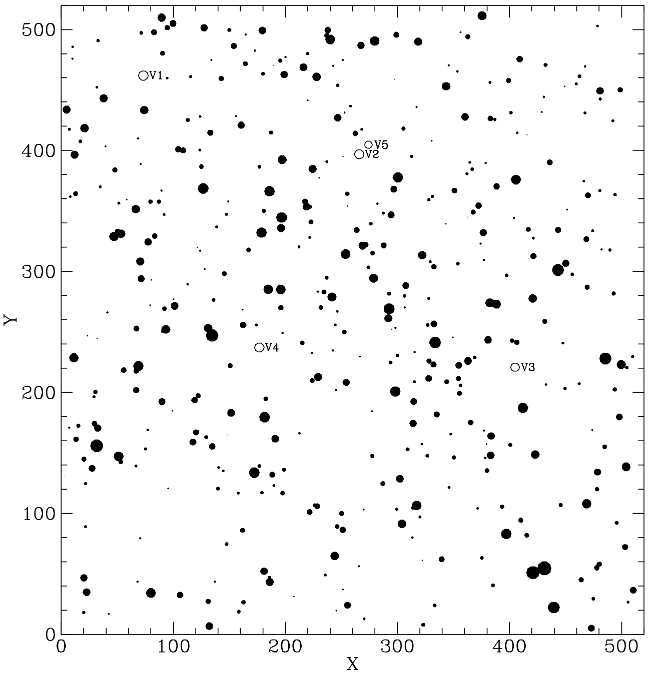

Fig. 1. Observed CCD field (5.′8×5.′8) of the open cluster Mel 71. North is upward and east is the left. Five new variable stars marked by open circles are denoted by their ID numbers.

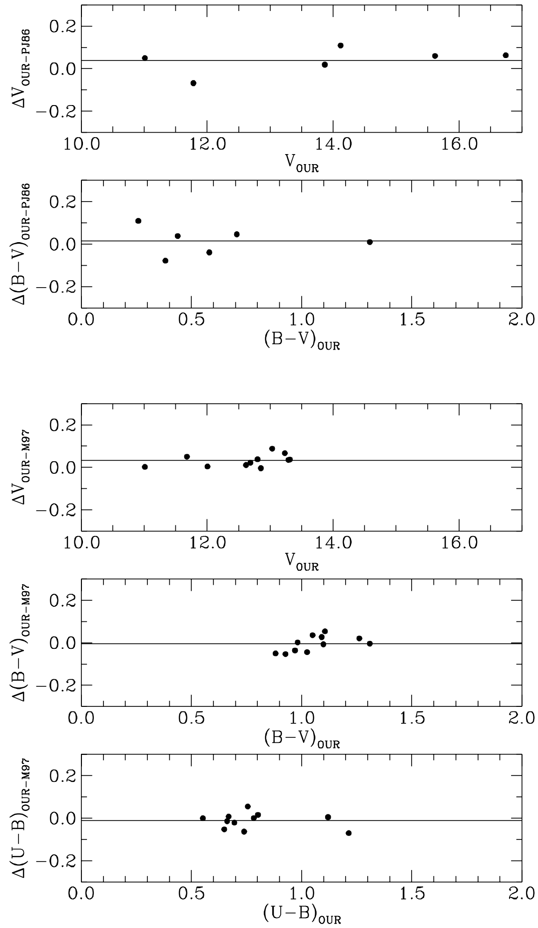

Fig. 2. Magnitude and color differences between our data and the previous data by Pound & Janes (1986, PJ86) and Mermilliod et al. (1997, M97).

about 3 years. After the re-aluminization on June, 1998, the zero point of the transformation equation in the next paragraph increased by about 2.5 mag in V. In order to minimize external uncertainties, we carefully controlled the telescope pointing at the same spot on CCD frames during the observing run (see Frandsen et al. 1989). In addition to the time-series observations, we carried out UBVI photometry on a very clear night (Feb. 3) to estimate the physical parameters of the cluster. The Johnson UBV and Cousin I filters were used. Several tens of UBVRI standard stars by Landolt (1992) were also observed to transform instrumental magnitudes and colors to the standard system.

Using the IRAF/CCDRED package, we processed CCD images to correct overscan regions, trim unreliable subsections, subtract bias frames and correct inhomogeneous quantum efficiency between the CCD pixels (flat fielding). Instrumental magnitudes were obtained via the PSF (Point Spread Function) photometric routine in the IRAF/ DAOPHOT package (Massey & Davis 1992).

From the magnitudes of the standard stars, we obtained the following transformation equations;

$$
\begin{aligned}
U &= u + 19.083 + 0.228(U-B) - 0.632X, \sigma_U = 0\stackrel{\mathrm{m}}{.}059 \\
B &= b + 20.866 + 0.158(B-V) - 0.410X, \sigma_B = 0\stackrel{\mathrm{m}}{.}052 \\
V &= v + 20.594 + 0.011(B-V) - 0.248X, \sigma_V = 0\stackrel{\mathrm{m}}{.}037 \\
I &= i + 21.327 + 0.051(V-I) - 0.124X, \sigma_I = 0\stackrel{\mathrm{m}}{.}051
\end{aligned}
$$

where U, B, V and I are the standard magnitudes, and u, b, v and i are the instrumental magnitudes. The airmass is denoted as X.

After correcting the difference of aperture size between the standard stars and stars in the cluster, we obtained the standard magnitudes and colors of the stars in the observed field of Mel 71, using the above equations. The observed 429 stars in the cluster are shown in Fig. 1. Our UBVI CCD photometric results agree with the previous photoelectric ones by Pound & Janes (1986) and Mermilliod et al. (1997), although our magnitudes are slightly fainter (Fig. 2); $\Delta V_{OUR-PJ86}$ = 0.039 ± 0.060, $\Delta(B-V)_{OUR-PJ86}$ = 0.014 ± 0.066, $\Delta V_{OUR-M97}$ = 0.032 ± 0.029, $\Delta(B-V)_{OUR-M97}$ = −0.005 ± 0.037, $\Delta(U-B)_{OUR-M97}$ = −0.012 ± 0.037.

We applied the ensemble normalization technique (Gilliland & Brown 1988) to standardize instrumental magnitudes of the time-series CCD frames, using a few tens of stars ranging from $13\stackrel{\mathrm{m}}{.}0$ to $14\stackrel{\mathrm{m}}{.}0$ except for variable stars. The transformation equation is,

$$V = v + a_1 + a_2(B-V) + a_3X + a_4Y,$$

where V and v are standard magnitude and instrumental magnitude, respectively. X and Y are coordinate values of stars in a CCD frame. Using this equation, we corrected for color (a_2)

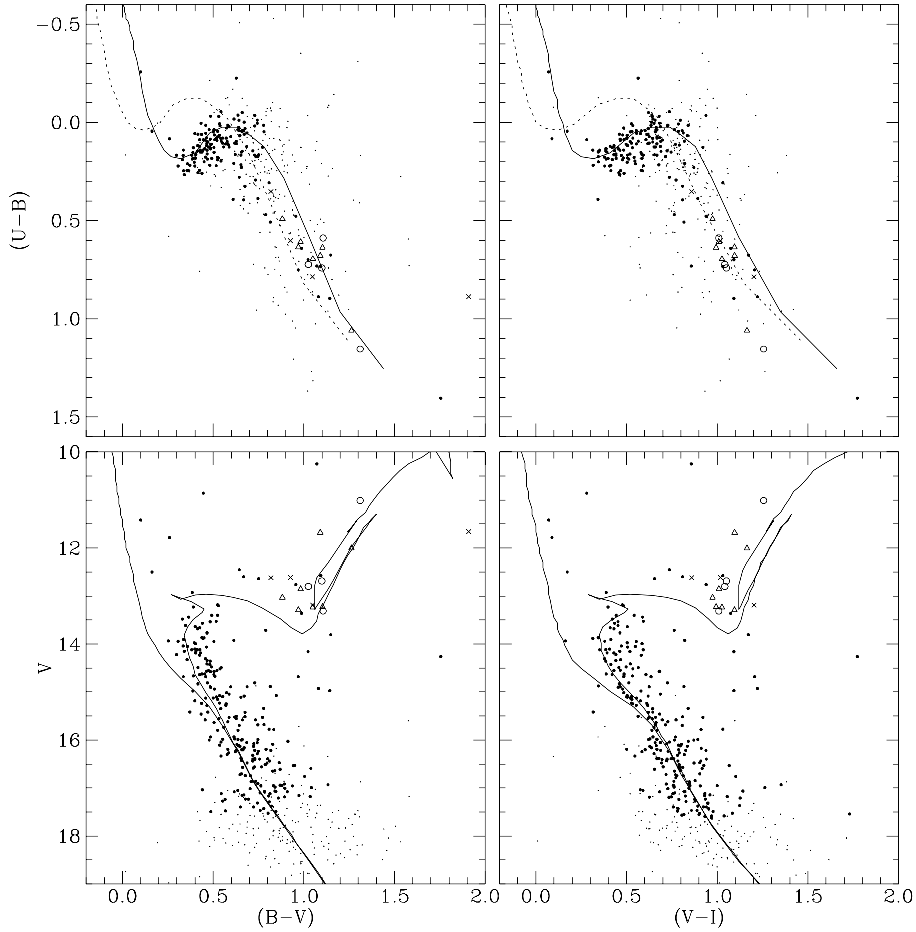

Fig. 3. Color-color and color-magnitude diagrams of Mel 71. The dashed line represents the unreddened ZAMS. The solid lines denote the ZAMS and the theoretical isochrone for *log t* = 9.0 and Z = 0.008 model by Bertelli et al. (1994). Stars with observation errors larger than $0.^{m}05$ are marked with small dots. Crosses: non-members, open circles: red giant members and open triangles: spectroscopic binary red giant members, identified by Mermilliod et al. (1997).

and position (a_3 and a_4) dependent terms of the observation system and/or atmospheric extinction.

3. Physical parameters

The color-color and color-magnitude diagrams of Mel 71 are shown in Fig. 3. Considering the observed value of [Fe/H] = −0.57 (Geisler et al. 1992) and [Fe/H] = −0.32 (Brown et al. 1996), the theoretical isochrone with Z = 0.008 ([Fe/H] = −0.40) by Bertelli et al. (1994) was adopted. The isochrone had been derived from stellar models with convective overshooting. We used the youngest isochrone of *log t* = 6.6 as the ZAMS.

The best fit of the ZAMS in the color-color diagram gives the reddening value of E(B−V) = 0.20 ± 0.05 and E(V−I) = 0.20 ± 0.05, with a value of E(U−B)/E(B−V) = 0.72. This is slightly larger than the previous estimate of E(B−V) = 0.10 ± 0.05 (Pound & Janes 1986). The latter was derived from a fitting of the ZAMS and red giant clump of the Hyades cluster to the color-magnitude diagram of Mel 71. This difference may be caused by uncertainty of the position of the clump and the difference of metallicity between the Hyades cluster and Mel 71. The derived value of E(V−I) = 0.20 is slightly smaller than E(V−I) = 0.25 estimated by E(V−I)/E(B−V) = 1.25 (Dean et al. 1978). However, since the reddening value is not large, the difference of about $0.^{m}05$ is perhaps expected or may result from observation errors and/or some problems in the (V−I) isochrone for Z = 0.008 model (see Phelps 1997).

We obtained the distance modulus of $(V-M_V)_\circ = 11.6 \pm 0.2$ and the age of *log t* = 9.0, from the ZAMS and isochrone fit in a color-magnitude diagram, assuming $R_V = 3.1$. The distance is somewhat closer than the previous estimates of $(V-M_V)_\circ = 11.88 \pm 0.20$ (Pound & Janes 1986) and $(V-M_V)_\circ = 12.13$ (Mermilliod et al. 1997), perhaps resulting from the adopted different reddening values. In the (B−V) color-magnitude diagram, the isochrone fits well to the observed red giant members. If the magnitudes and colors of spectroscopic binaries separate into those of two components (primary and secondary), the location of spectroscopic binary red giant members would move red-ward (see Mermilliod et al. 1997) and also match well with the isochrone. However, in the (V−I) color-magnitude diagram, the isochrone does not fit well to the red giant stars. This discrepancy is also seen in the well-known open cluster M 67 (Montgomery et al. 1993) and the old open cluster Be 17 (Phelps 1997), suggesting that the (V−I) isochrone may have some errors.

4. Variable stars

In order to search variable stars, we examined light variations of 358 stars among 429 stars in the observed field. We discarded the saturated stars brighter than 13^m and the stars located within

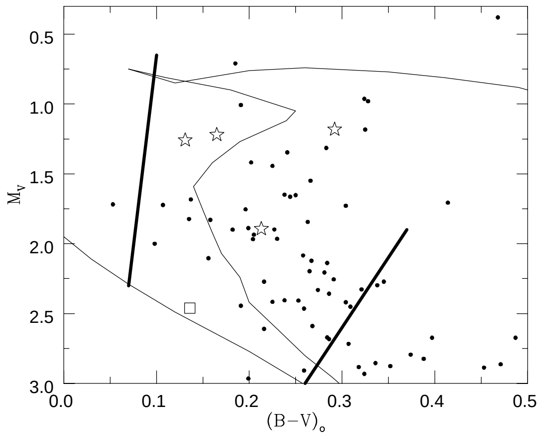

Fig. 4. Position of new variable stars in the color-magnitude diagram of Mel 71. Four δ Sct stars denote star symbols and one eclipsing binary, open square. Solid lines represent the ZAMS and the theoretical isochrone for *log t* = 9.0 and Z = 0.008 (Bertelli et al. 1994). Thick lines are the borders of the empirical δ Sct instability strip (Breger 1979). The reddening and distance modulus derived in this study were used.

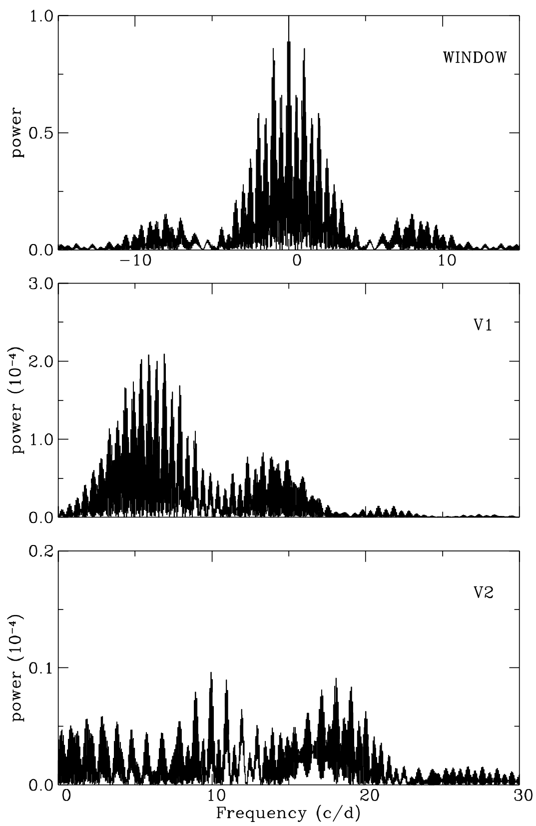

Fig. 5. Power spectra of two new δ Sct stars (V1 and V2). The spectral window is shown in the top panel.

20 pixels from the edge of the time-series CCD frames. Four short-period small-amplitude pulsating stars and one eclipsing binary have been discovered. The finding chart of new variable stars in the open cluster Mel 71 is shown in Fig. 1.

Four new pulsating stars are located near the turn-off point and within δ Sct instability strip in the color-magnitude diagram (Fig. 4). In order to estimate their pulsation frequencies, we performed the multiple frequency analysis, using the Fourier method and linear least square fitting (see Kim & Lee 1996). In Fig. 5, we present the power spectrum of two variable stars, V1 and V2, clearly showing the presence of pulsations. The result of Fourier analysis for these pulsating stars are summarized in Table 1, where the uncertain frequencies with the signal to noise amplitude ratio (S/N) of smaller than 4.0 (Breger et al. 1993) are involved. Light variations of four pulsating stars are shown in Fig. 6. Obvious brightness changes of V1 and V2 are noticed. We also found the brightness changes of V3 and V4, although their pulsation amplitudes are small; their power spectrum may be uncertain because of our limited data set. Considering the position in the color-magnitude diagram, light curves and pulsation frequencies, these four pulsating stars can be classified as δ Sct stars.

Table 1. Results of Fourier analysis for new δ Sct stars

ID	V	B−V	Frequency (μHz)	S/N	Amplitude (mmag)
V1	13.439	0.365	79.8	19.9	29.5
			154.2	9.7	14.1
			111.4	3.5	6.0
V2	13.478	0.331	115.0	3.9	6.8
V3	14.113	0.413	170.8	3.8	5.7
V4	13.401	0.492	148.2	3.5	3.8

The brightness of the other stars within δ Sct instability strip is constant at a detection level of about 3 mmag. We examined light variations of total 56 stars within the instability strip and found 4 δ Sct stars. Therefore, the incidence of δ Sct stars for Mel 71 is estimated to be about 7%. It is much lower than ∼30% for field stars with amplitudes of $0\overset{m}{.}01$ (Breger 1979) and ∼20% for the open cluster NGC 6134 at a detection level of 1 mmag (Frandsen et al. 1996). However, it is higher than those in several other open clusters investigated by Viskum et al. (1997).

We also found one eclipsing binary (V5), which is located within δ Sct instability strip. Its light curve is shown in Fig. 7. Maximum V magnitude variation is about $0\overset{m}{.}2$ and the period is estimated to be about 0.678 day (epoch at primary minimum is HJD 2450483.05). The light curve is similar to that of a β Lyrae type eclipsing binary star (Hoffmeister et al. 1985).

5. Conclusion

From the UBVI CCD photometry, we estimated the reddening, distance modulus and age of the open cluster Mel 71. The reddening value and distance modulus are slightly different from the previous estimates by Pound & Janes (1986). It may result from uncertainty of the position of the red giant clump and the difference of metallicity between the Hyades cluster and Mel 71.

Using the time-series data obtained from total 160 V CCD frames, we examined light variations of 358 stars in the observed field. Four δ Sct stars and one eclipsing binary were discovered.

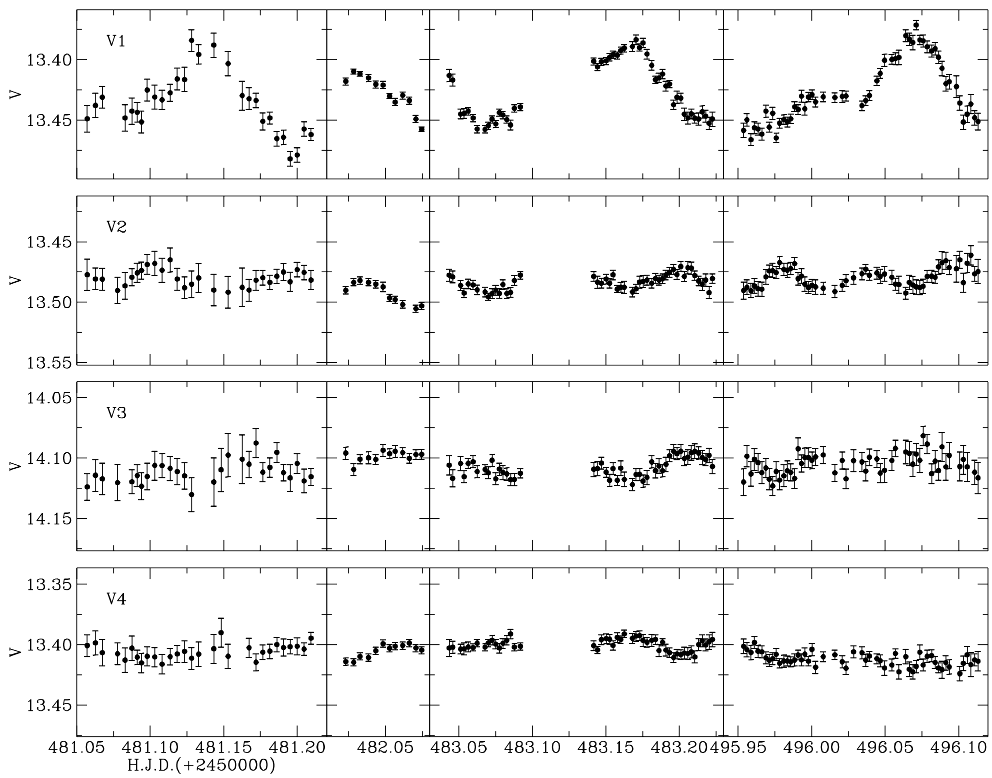

Fig. 6. Light variations of four new δ Sct stars.

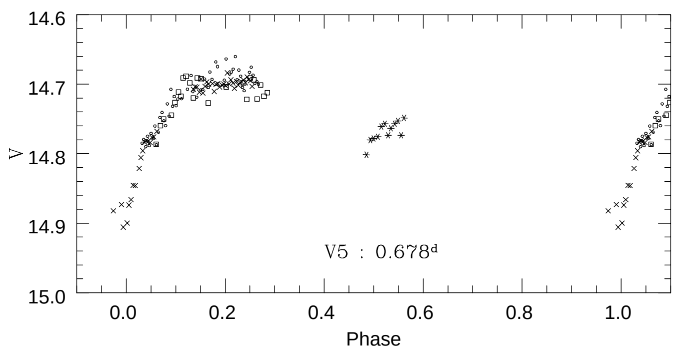

Fig. 7. Light curves of a new eclipsing binary. Data points obtained over four nights are differently marked for each observation night.

All of them are located near the turn-off point in the color-magnitude diagram of the cluster.

The incidence of variability within δ Sct instability strip is estimated to be about 7%. For field stars, the corresponding value is larger than 30% (Breger 1979). However, it may strongly depend on open clusters, e.g. from about 40% for the Hyades cluster to ∼2% for NGC 7245 with a similar detection level (Viskum et al. 1997). More systematic studies to search δ Sct stars in open clusters would be necessary in order to understand as to which physical parameters can control pulsation phenomena.

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