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Search for variable stars in the open cluster NGC 7654

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Abstract. Time-series CCD photometry of the open cluster NGC 7654 was performed over five nights from October 2nd to 18th, 1997 U.T., in order to search for new variable stars. We also carried out UBV photometric observations to obtain physical parameters of variable stars in the cluster.

We have derived the distance modulus of $(V - M_V)_\circ$ = 10.9 ± 0.2 and the interstellar reddening of $E(B - V)$ = 0.62 ± 0.05 by fitting the ZAMS to the observed color-color and color-magnitude diagrams of the cluster. Using the theoretical isochrones with solar metal abundance by Bertelli et al. (1994), an age of the cluster, $log\, t$ = 8.0, was estimated.

Applying the ensemble normalization technique to the observed 1215 time-series data, light variations of 284 stars, fainter than $11\overset{\mathrm{m}}{.}0$ in the observed field, were carefully examined. As a result, three slowly pulsating B stars and one eclipsing binary were discovered in the cluster. We also confirmed the light variation of a low amplitude δ Sct star which has been recently discovered by Viskum et al. (1997).

Key words: Galaxy: open clusters and associations: individual: NGC 7654 – stars: variables: general – stars: binaries: eclipsing

1. Introduction

Slowly pulsating B stars (hereafter, called SPBs) are main sequence stars with spectral types ranging from B3 to B9. They have pulsation periods of $0\overset{\mathrm{d}}{.}4 \sim 5\overset{\mathrm{d}}{.}0$ and low amplitudes less than $0\overset{\mathrm{m}}{.}1$. These pulsational characteristics make the observational study of SPBs very difficult. So far about 100 SPBs have been known, of which 72 stars were recently discovered by Hipparcos satellite (Waelkens et al. 1998). Their pulsations are recognized as excitation of g-mode oscillations, because the observed periods are longer than the expected value for a radial fundamental mode. These facts are very important from an asteroseismological point of view since the g-mode oscillations penetrate deep into the stellar interior providing valuable information on the stellar internal structure.

Among ∼100 SPBs, only 3 stars were identified to be members of open clusters (Choi 1997; Waelkens 1991; Waelkens et al. 1990, 1998). The Balona group (Balona 1994; Balona & Koen 1994; Balona & Laney 1995) observed the young open clusters NGC 3293, NGC 4755 and NGC 6231, in order to detect new SPBs in open clusters. However, they found no SPBs although many β Cephei stars were discovered in these open clusters. Because of this scarcity, it would be worthy of notice if one finds SPBs in open clusters. Furthermore, they are very useful to study the pulsational characteristics of SPBs and the stellar structure of B-type stars since we can estimate physical parameters of stars (distance, age and chemical abundance, etc.) in open clusters more accurately than any field stars.

The young open cluster NGC 7654 ($\alpha = 23^h24^m12^s$, $\delta = 61^\circ35'$, J2000.0) is located in the Cassiopeia constellation and has a field size of about 12 arcmin. Its interstellar reddening, distance modulus and age have been known as about $0\overset{\mathrm{m}}{.}57$, $11\overset{\mathrm{m}}{.}0$ and 10^8 year, respectively, from several UBV and uvbyβ photometric results (Pesch 1960; Schmidt 1977; Danford & Thomas 1981; Kaltcheva 1990). From the CCD time-series observation during only one night, Viskum et al. (1997) discovered two δ Scuti variable star candidates in the cluster.

Most stars in the field of NGC 7654 are strongly concentrated (Trumpler type is I 2 r) within about 6 arcmin. Therefore, it would be a very suitable object for a CCD photometric observation. We have chosen this cluster for detecting new SPBs from a CCD photometry, because it contains many bright B-type stars as indicated from its color-magnitude diagram (e.g. Hoag et al. 1961).

2. Observation and data reduction

UBV CCD photometry and time-series observation of NGC 7654 were done at Bohyunsan Optical Astronomy Observatory (BOAO) over five nights during the period of Oct. 2nd to 18th, 1997 U.T. The observation log is listed in Table 1. We carried out the observations with a TEK 1024 CCD camera attached to the BOAO 1.8m optical telescope. The CCD has 1024×1024 pixels and a pixel size of 24μm. The field of view of the CCD image is $5\overset{'}{.}8 \times 5\overset{'}{.}8$ ($0\overset{''}{.}34$ per pixel) at the f/8 Cassegrain focus of the telescope. The CCD chip cooling was maintained down to 173K to reduce thermal noise using the LN_2 (Liquid Nitrogen) cryogenic method. The readout noise and gain of the CCD are 6.4e$^-$ and 3.49e$^-$/ADU (Park et al. 1995), respectively.

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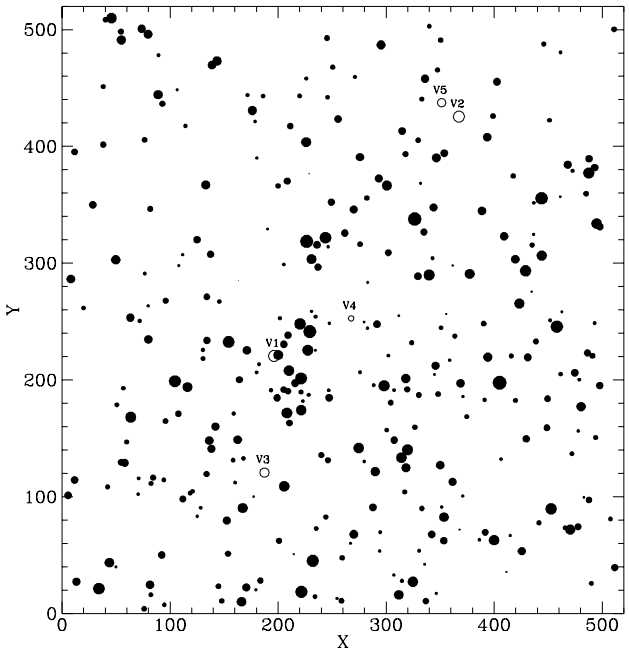

Fig. 1. Observed CCD field ($5'.8 \times 5'.8$) of the open cluster NGC 7654. Five variable stars (V1,V2,V3,V4 and V5) are marked by open circles. North is up and east is to the left.

Table 1. Observation Log.

Start HJD	Running time	N_{obs}	Filter	Seeing	Remark
2450724.16	$4^h.8$	116	B	$1''.2$	clear
725.16	$4^h.5$	127	B	$1''.5$	clear
738.05	$6^h.9$	314	B	$1''.8$	cirrus
739.03	$3^h.8$	209	B	$1''.7$	cirrus
740.08	$6^h.8$	449	UBV	$1''.3$	clear

In Fig. 1, the observed 320 stars in the central region of NGC 7654 are shown. We carried out CCD time-series observation for 26.8 hours in order to search for new variable stars, particularly B-type variables, and obtained 1215 B filter CCD images. Exposure times were chosen in a range of 30 sec to 50 sec, depending on the seeing and the transparency. In order to minimize external uncertainties such as the pixel-to-pixel variations (see Frandsen et al. 1989), we carefully adjusted the telescope pointing at the same spots on CCD frames during the observing run. The UBV CCD photometry was also performed to obtain the color-magnitude diagram of the cluster. We used the nearby well-observed open cluster NGC 7790 as a standard field.

The CCD pre-processings (bias subtraction and flat fielding etc.) were performed with the IRAF/CCDRED package. We applied the point-spread function (PSF) photometry to get instrumental magnitudes using the IRAF/ DAOPHOT package (Massey & Davis 1992).

Transformation of the instrumental magnitudes to the standard system was done with well-defined 19 stars in the open cluster NGC 7790. The standard magnitudes and colors of stars in the open cluster NGC 7654 were obtained using the typical transformation equations (e.g., Massey & Davis 1992) as follows,

$$U = u + 19.643 + 0.133(U-B) - 0.698X, \sigma_U = 0^m.065$$
$$B = b + 21.819 + 0.048(B-V) - 0.483X, \sigma_B = 0^m.039$$
$$V = v + 21.928 - 0.116(V-I) - 0.318X, \sigma_V = 0^m.042$$

where U, B and V are the standard magnitudes, and u, b and v are the instrumental magnitudes. X denotes the airmass.

The derived magnitudes and colors were compared with those by Hoag et al. (1961) and Pesch (1960). Our CCD photometric results are in good accord with the previous photoelectric ones (Fig. 2).

The ensemble normalization technique introduced by Gilliland & Brown (1988) was applied to the instrumental magnitudes of all time-series CCD frames for standardization, using a few tens of stars ranging from $12^m.5$ to $15^m.0$ except for variable stars. The transformation equation is

$$B = b + c1 + c2(B-V) + c3Px + c4Py$$

where B and b are the standard magnitude and instrumental magnitude, respectively. c1 is the zero point and c2 is the color coefficient. c3 and c4 are used to correct position dependent terms such as the atmospheric differential extinction and the position-dependent variable PSF.

3. Physical parameters of NGC 7654

We obtained the color-color and color-magnitude diagrams (Fig. 3) of NGC 7654 from UBV CCD photometry. The solid and dashed lines represent the ZAMS given by Lee & Sung (1995) for solar metal abundance and the theoretical isochrones by Bertelli et al. (1994). Three isochrones with Z = 0.02 are superimposed in the right panel of Fig. 3. From the upper left to the lower right, the dashed and solid lines represent the isochrones for $log\,t$ = 7.7, 8.0 and 8.3, respectively.

The best ZAMS fit in the color-color diagram gives the reddening value of E(B−V) = 0.62 ± 0.05 with E(U−B)/ E(B−V) = 0.72. We derived the distance modulus $(V-M_V)_\circ$ = 10.9 ± 0.2 and the age $log\,t$ = 8.0 by fitting the ZAMS and theoretical isochrone in the color-magnitude diagram, assuming R_V = 3.1. These values are consistent with the previous ones (e.g., Pesch 1960; Kaltcheva 1990), within observational errors.

4. Variable stars

In order to search for variable stars in the cluster, we examined light variations of 284 stars among total 320 stars in the observed field. We excluded the saturated stars brighter than B $\simeq 12^m$ and the stars located within 20 pixels from the edge of the time-series CCD frames. Four variable stars were discovered. We also confirmed light variations for one of the two δ Scuti star candidates (♯ 501) recently detected by Viskum et al. (1997); the variability of the other star (♯ 215) could not be examined because it was located near the edge of our CCD frames. The finding chart of five variable stars is shown in Fig. 1.

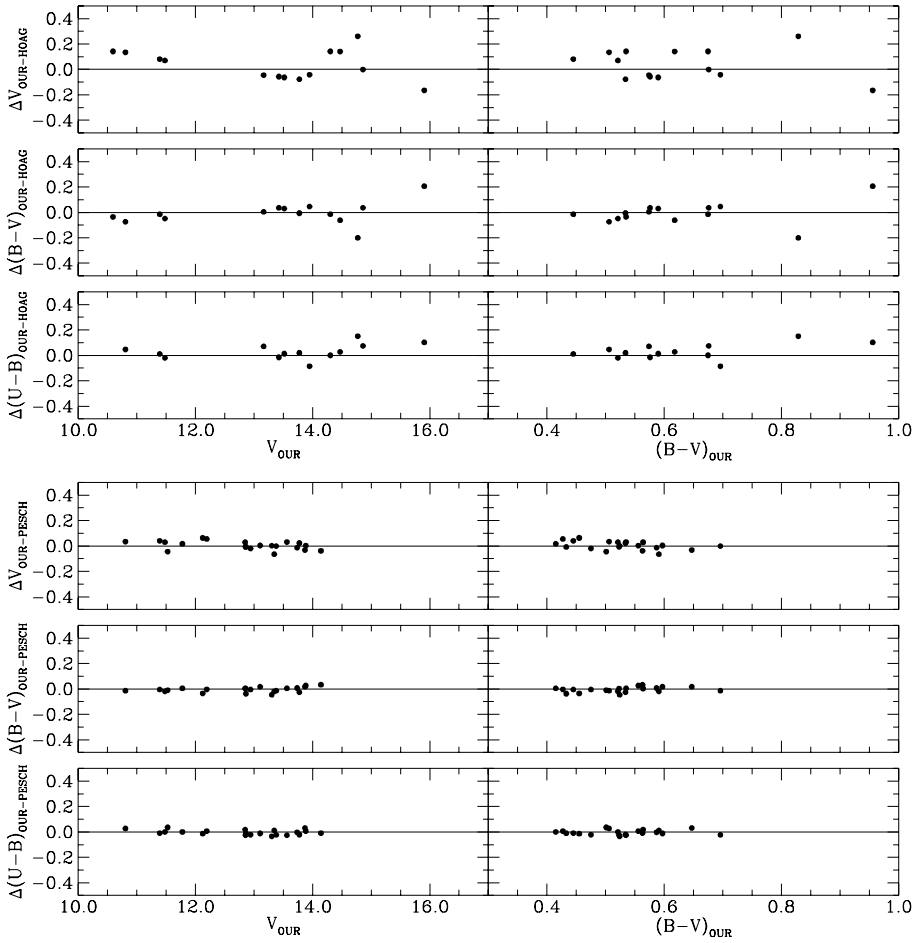

Fig. 2. Comparison between our photometric data and other data (Hoag et al. 1961, Pesch 1960) for stars in the open cluster NGC 7654.

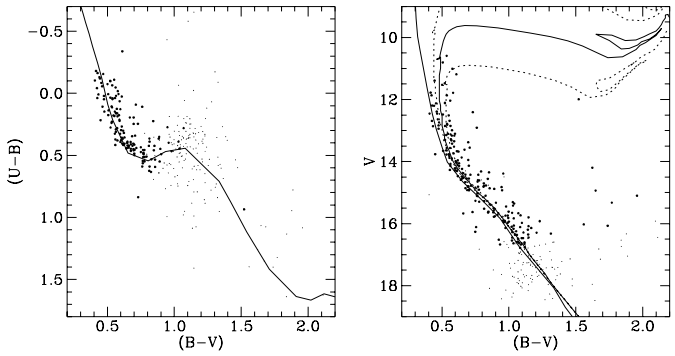

Fig. 3. Color-color diagram and color-magnitude diagram of the open cluster NGC 7654. Small dots denote stars with observation errors larger than $0\overset{m}{.}05$. We adopted the ZAMS estimated by Lee & Sung (1995) for solar metal abundance. Three isochrones with Z = 0.02 by Bertelli et al. (1994) are superimposed in the right panel. From the upper left to the lower right, the dashed and solid lines represent the isochrones for $log\, t$ = 7.7, 8.0 and 8.3, respectively.

Fig. 4 shows brightness changes of the variable stars (V1, V2, V3, V4 and V5) in the open cluster NGC 7654. Light variations of a non-variable star (C) are also plotted for comparison in the top panel. The brightness of star V4 steeply increased by about $0\overset{m}{.}3$ near HJD 2450724.16 and remained nearly constant at other times in spite of large dispersion due to its faintness.

We show five variable stars on the color-magnitude diagram of NGC 7654 in Fig. 5, where the interstellar reddening and distance modulus estimated by us are used. Three variable stars V1, V2 and V3 are located within or near SPBs instability strip (Dziembowski et al. 1993). A known δ Scuti star candidate (V5) is located near the blue edge of δ Scuti instability strip.

Using the Fourier analysis and/or phase-match technique, we obtained the pulsation periods of four pulsating variable stars. The light curves of V1, V2, V3 and V5 are shown in Fig. 6. Data points are differently marked for each observation night. The results are summarized in Table 2. Note that abnormal features, steep maximum and poor fit at minimum, are shown at the phase diagram of V2. If we rule out the poor quality data (i.e., dots at the phase diagram), we can obtain a well-defined sinusoidal light curve of V2 with pulsation period of $0\overset{d}{.}816$. Additional observations would be required to confirm the period of V2. From the light curves, periods, amplitudes and positions in the color-magnitude diagram, we propose that three pulsating variable stars V1, V2 and V3 are new SPBs. The period and amplitude of V5 are in good accord with those by Viskum et al. (1997).

The light curve of V4 is shown in Fig. 7, where V magnitudes are scaled up by $1\overset{m}{.}3$ to match B magnitudes. The brightness increased by $\sim 0\overset{m}{.}3$ from HJD 2450724.16 to HJD 2450724.22 in two passbands and there were no noticeable brightness changes

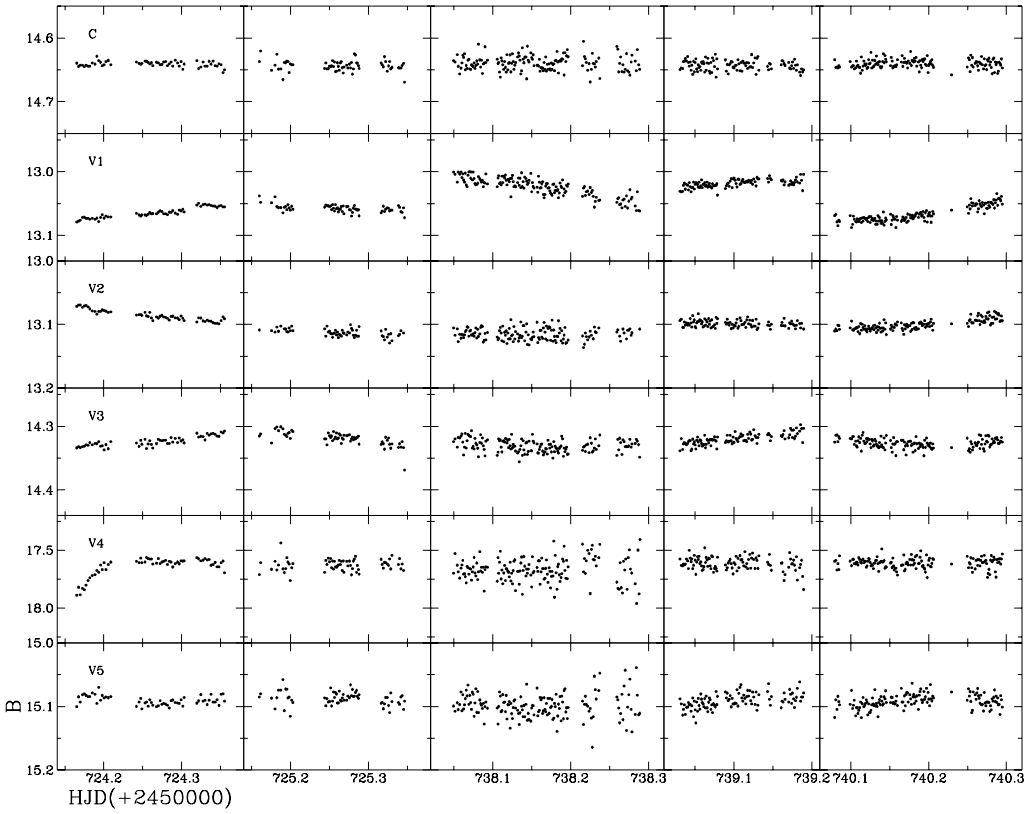

Fig. 4. Light variations of the variable stars (V1, V2, V3, V4 and V5) in the open cluster NGC 7654. The brightness of a non-variable star (C) is also plotted for comparison.

during the other observing period. The light curve of V4 is similar to that of an Algol-type eclipsing binary.

5. Conclusion and discussion

UBV CCD photometry and time-series observation of the young open cluster NGC 7654 have been performed to obtain physical parameters of the cluster and to search for variable stars.

We obtained the interstellar reddening E(B−V) = 0.62 ± 0.05, the distance modulus $(V-M_V)_\circ$ = 10.9 ± 0.2 and the age $log\, t$ = 8.0, from the ZAMS and theoretical isochrone fitting to the color-color and color-magnitude diagrams of the cluster. These values are in good agreement with the previous observational results.

Using CCD time-series data, we examined light variations of 284 stars in the observed field and discovered three SPBs and one long period Algol-type eclipsing binary. We also confirmed light variations of a δ Scuti star recently detected by Viskum et al. (1997).

Considering the fact that so far only three stars among about 100 SPBs have been reported as members of open clusters (IC 2391, NGC 6025 and NGC 6405; Waelkens 1991), the discovery of three SPBs in the open cluster NGC 7654 is quite noteworthy. We examined light variations of total 42 stars within SPBs instability strip and detected three SPBs. Therefore, the incidence of SPBs is estimated to be about 7%.

The SPBs in open clusters are very useful for a study of their pulsational characteristics and the stellar structure of B-type stars because their physical parameters can be estimated

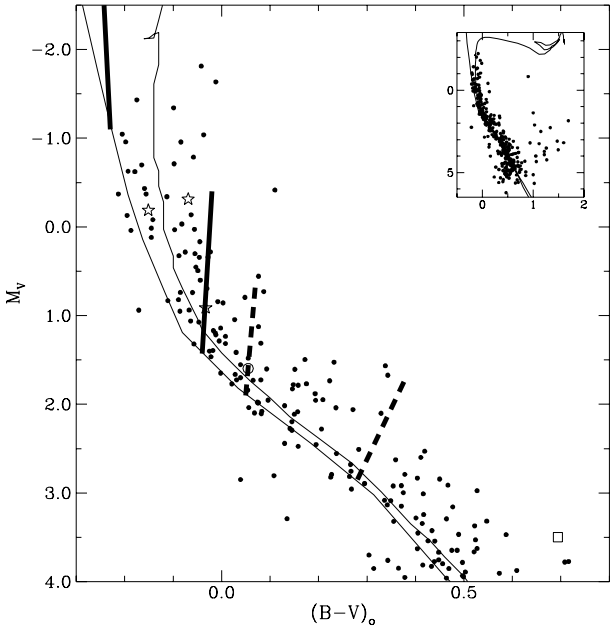

Fig. 5. Position of five variable stars in the color-magnitude diagram of NGC 7654. The upper solid line denotes a theoretical isochrone of $log\, t$=8.0 (Bertelli et al. 1994), and the lower line the ZAMS (Lee & Sung 1995). The thick solid bars represent SPBs instability strip (Dziembowski et al. 1993) and the thick dashed bars δ Scuti instability strip (Breger 1979). V1, V2 and V3 are marked with star symbols. V4 and V5 are denoted as open square and open circle, respectively.

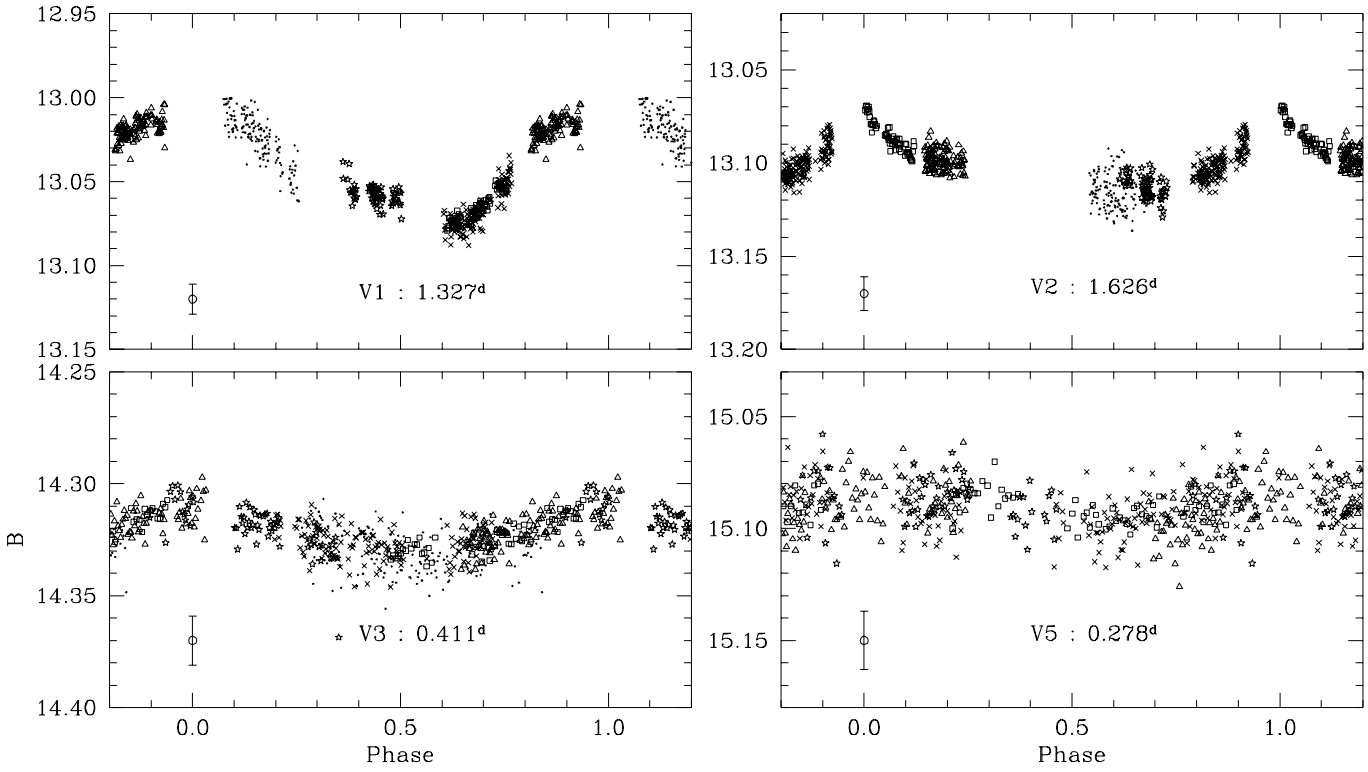

Fig. 6. Phase diagrams of four pulsating variable stars. Data points are differently marked for each observation night. Typical observation errors were represented by error bars.

Table 2. Main observational results of five variable stars in the open cluster NGC 7654.

ID	RA(2000)	DEC(2000)	V	B-V	Period	ΔB	Epoch	Type
V1†	$23^h24^m52\overset{s}{.}2$	$61°36'30''$	$12\overset{m}{.}51$	$0\overset{m}{.}55$	$1\overset{d}{.}327$	$\sim 0\overset{m}{.}07$	2450737.95	SPBs
V2†	$23^h24^m35\overset{s}{.}9$	$61°38'49''$	$12\overset{m}{.}64$	$0\overset{m}{.}47$	$1\overset{d}{.}626^*$	$\sim 0\overset{m}{.}05$	2450724.16	SPBs
V3†	$23^h24^m53\overset{s}{.}1$	$61°35'22''$	$13\overset{m}{.}74$	$0\overset{m}{.}59$	$0\overset{d}{.}411$	$\sim 0\overset{m}{.}02$	2450724.38	SPBs
V4†	$23^h24^m45\overset{s}{.}4$	$61°36'52''$	$16\overset{m}{.}32$	$1\overset{m}{.}31$		$\sim 0\overset{m}{.}3$		EA
V5‡	$23^h24^m37\overset{s}{.}4$	$61°38'57''$	$14\overset{m}{.}42$	$0\overset{m}{.}68$	$0\overset{d}{.}278$	$\sim 0\overset{m}{.}016$	2450740.23	δ Scuti

†: discovered in this study, ‡: discovered by Viskum et al. (1997), *: could be $0\overset{d}{.}816$ (see text).

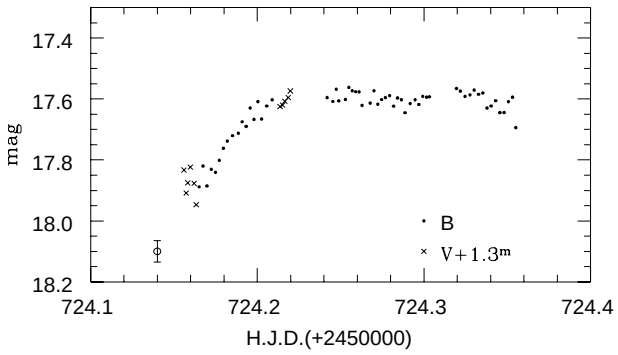

Fig. 7. Light curve of V4 in B and V passbands observed on Oct. 2, 1997. B magnitudes are denoted as dots and V magnitudes crosses. The brightness increased by $\sim 0\overset{m}{.}3$ from HJD 2450724.16 to HJD 2450724.22 in two passbands.

more accurately than any field SPBs. Furthermore, statistical studies on the incidence of variability within SPBs instability strip enable us to give an important clue as to what physical parameters (rotation etc., Gautschy & Saio 1996) might affect on the stability of pulsation modes.

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