Variable Stars in the Open Cluster M11 (NGC 6705)

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ABSTRACT. V-band time-series CCD photometric observations of the intermediate-age open cluster M11 were performed to search for variable stars. Using these time-series data, we carefully examined light variations of all stars in the observing field. A total of 82 variable stars were discovered, of which 39 stars had been detected recently by Hargis et al. On the basis of observational properties such as variable period, light-curve shape, and position on a color-magnitude diagram, we classified their variable types as 11 δ Scuti–type pulsating stars, two γ Doradus–type pulsating stars, 40 W UMa–type contact eclipsing binaries, 13 Algol-type detached eclipsing binaries, and 16 eclipsing binaries with long period. Cluster membership for each variable star was deduced from the previous proper-motion results and position on the color-magnitude diagram. Many pulsating stars and eclipsing binaries in the region of M11 are probable members of the cluster.

Online material: color figures

1. INTRODUCTION

A number of pulsating variable stars are found in stellar clusters. Population I variables such as δ Scuti–type stars and β Cephei–type stars are populous in open clusters, and Population II variables such as RR Lyrae–type stars and SX Phoenicis–type stars are rich in globular clusters. Pulsating stars in clusters are important targets for investigating stellar internal structure and evolution (so-called asteroseismology) because physical parameters such as age and absolute magnitude that impose constraints on the stellar pulsation model can be determined independently from the properties of the clusters (see a recent excellent review by Pigulski 2006). One can get high-precision photometric results for open clusters because stars in open clusters are less crowded than those in globular clusters. Therefore, open clusters are very important targets for studying low-amplitude pulsating stars (e.g., Stello et al. 2006).

Δ Scuti–type variable stars are A3–F0 type main-sequence or subgiant stars in the lower part of the classical instability strip. They have short pulsating periods from 0.02 to 0.3 days and amplitudes less than 1.0 mag (Breger 1979). Most of them have amplitudes less than 0.1 mag (Rodríguez & Breger 2001). Many δ Scuti–type stars are discovered in intermediate-age open clusters because the main-sequence turnoff point of the clusters overlaps the δ Scuti instability strip.
For example, Arentoft et al. (2005) discovered 11 δ Scuti–type stars in the intermediate-age open cluster NGC 1817.

Eclipsing binary stars are found in open clusters as well. They are located above the single-star main sequence in the color-magnitude diagram of the clusters. Detached eclipsing binaries offer an opportunity to directly measure the stellar parameters such as mass, luminosity, and radius. Therefore, eclipsing binaries in open clusters can be used as distance indicators and to check stellar evolution theory (Paczyński & Sasselov 1997). The age of the cluster versus relative incidence between long-period detached eclipsing binaries and short-period contact binaries gives us a very important constraint on the dynamical evolution of binary systems (Rucinski et al. 1996). According to the most popular binary evolution model by Huang (1967) and Vilhu (1982) W UMa–type binaries evolve into a contact configuration from initially detached systems by angular momentum loss via magnetic torque. Detached binaries with initial periods as long as 5–10 days may evolve into a contact configuration with orbital periods shorter than 1 day on a timescale of a few gigayears. Observational results support the model; i.e., W UMa–type contact binaries are observed to be present in old open clusters of about 4–5 Gyr (Kaluzny et al. 1993) but have not been observed to be present in open clusters younger than about 1 Gyr (Hargis et al. 2005, hereafter HSB05; Rucinski 1998).

As part of our long-term project to survey variable stars in...
open clusters, extensive time-series CCD observations have been performed for intermediate-age open clusters using a 1.0 m telescope at the Mount Lemmon Optical Astronomy Observatory (LOAO) in Arizona. The primary goal of this project is to search for eclipsing binaries and short-period (less than a few days) pulsating variables and to study their physical properties in detail. From the extensive list of variable stars in the cluster, we can examine the possible relevance of characteristics of variable stars to cluster parameters. Kang et al. (2007) detected a total of 41 variable stars in the intermediate-age open cluster NGC 2099, which was the first observing target of our project.

We selected M11 (NGC 6705; R.A., = 18h51m04s, decl., = −06°16′30″) as the second target. This cluster is one of the well-established open clusters with intermediate age of about 200–250 Myr (Mermilliod 1992; Sung et al. 1999 and references therein). It is a rich and large cluster located at a low Galactic latitude (b = −2.8°). The most comprehensive study of variable stars in this cluster was recently performed by HSB05. They surveyed the cluster center with a field of view of 13.7′ × 13.7′ and detected 39 variable stars. In view of the large radius of this cluster (16′; Sung et al. 1999), however, more extensive observations with wider area are needed to secure a complete list of variable stars. In this paper, we
present results of variable stars detected from our time-series observations with a wider field of view and relatively long time span.

In § 2, we present our observations and data analysis. Section 3 describes the physical properties of the pulsating variables and eclipsing binary stars detected from our observations. We discuss the cluster membership of the variable stars in § 4. A summary and conclusion are given in § 5.

2. OBSERVATIONS AND DATA REDUCTION

We carried out time-series observations of M11 on 18 nights in 2004 June using a 2K × 2K CCD camera attached to the LOAO 1.0 m telescope in Arizona. The field of view of a CCD image is about 22.2 × 22.2 arcmin², given a CCD plate scale of 0.64° pixel⁻¹ at the f/7.5 Cassegrain focus of the telescope. A total of 1001 time-series images, i.e., 406 images with a long exposure of 600 s and 595 images with a short exposure of 60 s, were obtained with a V-band filter to secure faint objects, as well as bright ones. In order to minimize position-dependent external errors (Frandsen et al. 1989), we carefully controlled the telescope to keep the stars at fixed pixel positions on the CCD during our observing run. For the purpose of constructing a BV color-magnitude diagram of M11, additional B-band observations were made on one night of 2004 October: two frames with exposure times of 1000 and 100 s. During the whole observing run, the typical seeing disk of a star (FWHM)
was about 2.2". Figure 1 displays the observing CCD field of M11.

Instrumental signatures of each CCD frame were removed and calibrated using the bias, dark, and flat-field frames, with the aid of the IRAF package \textit{ccdred}. We obtained instrumental magnitudes of stars from the empirical point-spread function (PSF) fitting method in the IRAF package \textit{DAOPHOT} (Stetson 1987; Massey & Davis 1992).

We applied an ensemble normalization technique (Gilliland & Brown 1988) in order to normalize instrumental magnitudes of CCD frames, following the same procedure used by Kim et al. (2001). Using this technique, we corrected for the color- and position-dependent effects of the observation system and atmospheric differential extinction for all CCD frames. A few tens of bright stars with wide color range, selected from Sung et al. (1999), were used as the secondary standard stars.

### 3. VARIABLE STARS

We carefully examined the light variations of about 32,000 stars by visual inspection. Saturated stars and the stars located...
at the edge of CCD frames were excluded. A total of 82 variable stars were discovered: 13 pulsating stars and 69 eclipsing binaries. A finding chart of the variable stars is shown in Figure 1, and their observational properties are presented in Tables 1 and 2. We derived the periods of pulsating variable stars using the discrete Fourier analysis (Scargle 1989; Kim et al. 2001). Table 3 summarizes results of the multiple-frequency analysis. The phase-matching method (Hoffmeister & Kholopov 1985) was applied for eclipsing binaries to estimate their orbital periods.

### 3.1. Previously Known Variable Stars

Six variable stars had been known in the open cluster M11 before HSB05’s study. BS Scuti was located outside our observing field, and a bright variable, V369 Scuti ($V = 9.35$ mag), was saturated in our data. IT Scuti has been known to be a slow irregular variable, but we could not detect its light variations. We could not find any light variations for the other three suspected variables, NSV 11410, NSV 11402, and NSV 24615. HSB05 detected a total of 39 variable stars including six δ Scuti–type stars (HV 1–HV 6), 17 W UMa–type variables (HV 8, HV 10–HV 25), 14 detached eclipsing binaries (HV 26–HV 39), one irregular variable (HV 7), and one unclassified candidate variable (HV 9). We were able to identify all of these variable stars in our observations.

Power spectra of six δ Scuti–type pulsating stars are shown in Figure 2. Two stars, HV 2 and HV 6, show a dominant frequency with relatively large power: $f_1 = 18.271$ cycles day$^{-1}$.

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**TABLE 3**

**RESULTS OF FREQUENCY ANALYSIS FOR δ SCUTI–TYPE STARS**

| ID   | Frequency (cycles day$^{-1}$) | $A_i^a$ (mmag) | $\Phi_i^a$ | S/N$^b$ |
|------|-------------------------------|-----------------|------------|---------|
| HV 1 | $f_1 = 22.200$                | $7.1 \pm 0.8$   | $3.11 \pm 0.11$ | 4.7     |
|     | $f_2 = 9.632$                | $5.4 \pm 0.8$   | $1.67 \pm 0.14$ | 3.8     |
| HV 2 | $f_1 = 18.271$                | $9.5 \pm 0.5$   | $4.49 \pm 0.05$ | 9.9     |
| HV 3 | $f_1 = 23.758$                | $6.6 \pm 1.4$   | $2.74 \pm 0.22$ | 3.1     |
| HV 4 | $f_1 = 21.723$                | $6.1 \pm 0.8$   | $1.12 \pm 0.13$ | 4.6     |
|     | $f_2 = 4.881$                | $4.9 \pm 0.8$   | $2.28 \pm 0.16$ | 3.9     |
| HV 5 | $f_1 = 4.179$                | $8.1 \pm 1.2$   | $0.44 \pm 0.16$ | 3.4     |
|     | $f_2 = 27.961$                | $6.0 \pm 1.2$   | $1.99 \pm 0.21$ | 3.0     |
| HV 6 | $f_1 = 12.373$                | $179.4 \pm 9.8$ | $1.04 \pm 0.06$ | 10.2    |
| KV 1 | $f_1 = 6.433$                | $15.1 \pm 0.7$  | $3.33 \pm 0.05$ | 6.5     |
|     | $f_2 = 10.417$                | $6.6 \pm 0.7$   | $0.54 \pm 0.11$ | 4.6     |
|     | $f_3 (\approx p_3) = 3.003$  | $7.3 \pm 0.7$   | $-0.16 \pm 0.12$ | 4.6     |
|     | $f_4 = 19.388$                | $89.8 \pm 2.1$  | $1.20 \pm 0.02$ | 21.0    |
| KV 2 | $f_1 = 19.388$                | $89.8 \pm 2.1$  | $1.20 \pm 0.02$ | 21.0    |
|     | $f_2 = 24.835$                | $19.1 \pm 2.1$  | $-0.86 \pm 0.11$ | 5.3     |
| KV 3 | $f_1 = 21.015$                | $12.7 \pm 1.6$  | $-0.74 \pm 0.13$ | 5.3     |
|     | $f_2 = 18.435$                | $10.6 \pm 1.6$  | $3.04 \pm 0.15$ | 4.7     |
| KV 4 | $f_1 = 11.384$                | $13.5 \pm 1.2$  | $4.64 \pm 0.09$ | 4.9     |
|     | $f_2 = 16.056$                | $116.2 \pm 4.4$ | $-0.61 \pm 0.04$ | 16.4    |

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$^a V = V_0 + \sum A_i \cos [2\pi(t - t_0) + \Phi_i],$ $t_0 = HJD + 2,453,000.00.$

$^b S/N = \text{(power for each frequency/mean power after prewhitening for all frequencies)}^{1/2}.$

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**Fig. 3.—Phase diagrams of two γ Doradus–type stars.**
for HV 2 and $f_1 = 12.373$ cycles day$^{-1}$ for HV 6. In particular, the large power of HV 6 is characteristic of high-amplitude $\delta$ Scuti-type variable stars, as noted by HSB05, which differ from most $\delta$ Scuti-type pulsators with small amplitudes (see Rodríguez et al. 1996; Rodríguez 2004 and references therein). The pulsation periods of the four variables HV 1, HV 2, HV 3, and HV 6 are coincident with those of HSB05. However, our periods for HV 4 and HV 5 are different from HSB05’s results, probably due to the low amplitudes and multiple periodicities; our data show a weak signal near 24 cycles day$^{-1}$ for HV 5, which corresponds to the period of 0.04154 days by HSB05. Low frequencies less than 5 cycles day$^{-1}$ with low amplitudes about 5–8 mmag ($f_1$ for HV 4 and $f_1$ for HV 5) may originate from the slow variations of our observation system and/or atmospheric conditions.

HSB05 has classified HV 7 (their ID 220) as an irregular variable having both long- and short-timescale light variations. As shown in Figure 3, we confirmed the long-timescale variations of about 0.633 days but failed to detect the very short timescale variations of about 10 minutes. In comparison with the other variables with similar brightness such as HV 8, the phase diagram of HV 7 shows rather large scatter over the whole phase, implying the existence of multiple frequencies. HSB05 also noted that HV 7 showed different light variations...
Fig. 5.—Light curves of seven previously reported long-period eclipsing binary systems in Hargis et al. (2005).

from night to night. On the basis of the variable period, multiple
periodicities, light-curve shape, and the position on a color-
magnitude diagram located within the δ Scuti instability strip
(see Fig. 9), we suggest that HV 7 is a γ Doradus–type pulsating
star. In order to confirm the γ Doradus–type pulsation and rule
out the possibility of the binary or rotation effect, high-reso-
lution time-series spectroscopic observations of HV 7 would
be required.

We confirmed all 17 W UMa–type binary stars detected
by HSB05. Orbital periods obtained in our study are in good
agreement with HSB05’s results, except for HV 21. The pe-
riod difference of HV 21 may result from the well-known
1.0 cycles day$^{-1}$ alias effect for the data obtained at a single
observatory. In addition to these binaries, our data showed very
clearly that HV 9 (their ID 708) is a W UMa–type binary.

HSB05 could not classify the variable type of HV 9 because
it was near the edge of the CCD frame and then they had
obtained data on only two nights. Figure 4 displays phase di-
agrams of these 18 W UMa–type binary stars.

HSB05 identified 14 detached eclipsing binary stars. Among
these binaries, they detected multiple eclipses for six systems
(HV 26, HV 27, HV 28, HV 29, HV 31, and HV 32) and then
were able to determine their orbital periods. From our more
extensive data set with longer time span, we obtained full light
curves (Fig. 7, left) for these six binaries and determined more
accurate periods and epochs (listed in Table 1). In the case of
HV 29, HSB05 determined the orbital period of 5.62050 days.
However, based on our complete light curve, we obtained a
half-orbital period (2.8060 days) for this system.

HSB05 detected only one or two eclipses for the remain-
ing eight systems (HV 30, HV 33, HV 34, HV 35, HV 36, HV 37, HV 38, and HV 39) and so could not determine their orbital periods. Among these eight systems, we could determine the period of 4.460 days and epoch for HV 30. For four systems (HV 33, HV 34, HV 35, and HV 38), only one or two eclipsing features were detected in our data. We tried to determine their orbital periods by combining HSB05’s epochs and ours but failed due to the large separation of epochs. For two systems,
HV 36 and HV 39, our data did not show an eclipsing feature. HV 37 (their ID 4804) showed slow variations, the same as HSB05, but we could not determine its variable type. Figure 5 displays light variations of these seven eclipsing binaries for which we could not estimate orbital periods.

3.2. New Pulsating Variables

We discovered six new pulsating variable stars in our observing field. On the basis of pulsation periods and positions on the color-magnitude diagram of the cluster, we classified five $\delta$ Scuti–type stars (KV 1–KV 5) and one $\gamma$ Doradus–type star (KV 6). The signal-to-noise amplitude ratio (S/N) greater than 4.0 (Breger et al. 1993) was used as a detection criterion for pulsation frequency. The results of the frequency analysis for these pulsating stars are listed in Table 3.

As shown in Figure 2 (right), KV 2 and KV 5 are high-amplitude pulsating variables with large powers. We checked the period ratio for these high-amplitude $\delta$ Scuti–type stars and found that the ratio of $f_i/f_p$ is similar to that of the theoretical radial modes $P_i/P_p = 0.761$ (for a model with $Y = 0.28$, $Z = 0.02$, $M = 1.7 M_\odot$, $T_{\text{eff}} = 7000$ K, and $L = 15 L_\odot$; Breger 1979). This indicates that
KV 2 may be excited in two radial modes, i.e., fundamental ($P_0$ for $f$) and first-overtone radial modes ($P_1$ for $f$). KV 5 seems to be a monoperiodic high-amplitude δ Scuti–type star.

The other three stars (KV 1, KV 3, and KV 4) show a few weak powers. They are inside or near the δ Scuti–type instability strip. We detected five frequencies for KV 1. Its period ratios of $f_1/f_0 = 0.617 \pm 0.001$ and $f_2/f_0 = 0.520 \pm 0.001$ are nearly the same as those of theoretical radial modes $P_2/P_0 = 0.616$ and $P_1/P_0 = 0.521$ (Breger 1979), respectively, indicating that KV 1 is excited in fundamental ($P_0$ for $f$), second-overtone

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Fig. 8.—Light curves of nine new long-period eclipsing binary systems detected in our study.
(P$_2$ for $f_2$) and third-overtone (P$_3$ for $f_3$) radial modes. The frequency $f_3 = 3.003$ cycles day$^{-1}$ seems to be the 1.0 cycles day$^{-1}$ alias effect of a combination frequency, $f_2 - f_1 = 1.0 = 2.984$ cycles day$^{-1}$, and the other frequency $f_2$ may be a nonradial mode. We detected two frequencies for KV 3 and only one frequency for KV 4.

KV 6 has a long period of 0.9079 days, which is comparable to that of γ Doradus–type pulsating stars (Kaye et al. 1999). On the color-magnitude diagram (Fig. 9), it is located outside the red edge of the δ Scuti instability strip and near the red edge of the γ Doradus instability strip (Handler & Shobbrook 2002). Therefore, we suggest that KV 6 is a γ Doradus–type pulsating star. The phase diagram of KV 6 is displayed in the right panel of Figure 3.

3.3. New Eclipsing Binaries

We discovered 22 new W UMa–type binary stars (KV 7–KV 28). We obtained complete phase coverage for these binary systems, except for KV 21, which shows an incomplete secondary minimum due to its orbital period of about 0.5 days. Figure 6 shows various shapes of the light curves of these systems with different amplitudes. Two systems, KV 15 and KV 16, show slightly different brightness between two maxima,
which gives a hint of the existence of spots on the stellar surface (Wilson 1994). In several systems (e.g., KV 10), the depths of the two minima seem to be different, meaning significant temperature differences between primary and secondary stars.

We discovered six new detached eclipsing binaries (KV 29–KV 34) in our observing field. Phase diagrams of these systems are presented in the right panels of Figure 7 (see also Table 2). Most of these systems have flat maxima to show a shape typical of detached binaries. Two systems, KV 32 and KV 33, show slightly round maxima in their phase diagrams, indicating that they have a relatively small separation between component stars and one of the components fills its Roche lobe. This is supported by their short orbital periods of about 0.65 days.

We also detected nine new eclipsing binary systems, KV 35–KV 43 (see Fig. 8 and Table 2), but could not determine their ephemerides due to our limited data set. They seem to have long orbital periods. From the repeated occurrence of the minima in their light curves, we estimate that the orbital periods are about 6 days for KV 36 and about 2 days for KV 35 and KV 43.

4. COLOR-MAGNITUDE DIAGRAM AND MEMBERSHIP

The \(BV\) color-magnitude diagram of M11 is shown in Figure 9. The thick solid line represents the empirical zero-age main sequence (ZAMS) from Sung & Bessell (1999). The thin solid line is the theoretical isochrone of Girardi et al. (2000) with a solar metal abundance \((Z = 0.019)\) and an age of \(\log t_{\text{age}} = 8.35\), adopting the \(E(B-V) = 0.428\) and \((V-\text{H}11002)_{0} = 11.55\) from Sung et al. (1999). The dashed line is the possible equal-mass binary sequence to the isochrone as a guide to the membership of detected eclipsing binaries. Solid bars, nearly perpendicular to the ZAMS, represent the \(\delta\) Scuti instability strip (Breger 1979).

In Figure 9, we show the positions of 72 variable stars with different symbols for different types of variables: pulsating stars (stars), \(\delta\) Scuti–type binaries (circles), and detached systems (triangles). In the figure, nine faint variables and one star (KV 32) near the edge of the CCD chip are excluded because we could not obtain their \(B\) magnitudes. Since the color-magnitude diagram of M11 has very large contamination by field stars (Mathieu 1984; Brocato et al. 1993; Sung et al. 1999), it is not easy to distinguish cluster member stars from the field population. The sequence of the “blue” field star population \((B - V < 1.2\) mag) is overlapped by the cluster main sequence at about \(V > 15\) mag (see Figs. 3 and 6 of Sung et al. 1999), which severely hampers the identification of member variable stars detected in our study. The “red” field population is also a main contaminant of membership estimation for the faint and red variable stars with \(V > 17\) mag and \(B - V > 1.2\) mag. McNamara et al. (1977) and Su et al. (1998) provided probabilities of membership for bright stars in the field of M11 based on the relative proper motions.

4. SUMMARY AND CONCLUSION

All 13 pulsating stars, except for two fainter ones, KV 5 and KV 6, are located inside or near the \(\delta\) Scuti instability strip, suggesting that they may be probable member stars in the cluster. Available membership probability information of five \(\delta\) Scuti–type stars (KV 1: 99%, HV 2: 98%, HV 3: 96%, HV 4: 83%, and HV 5: 80%) from McNamara et al. (1977) supports the possible membership of these stars. On the other hand, McNamara et al. (1977) found a zero membership probability for two \(\delta\) Scuti–type stars (HV 1 and KV 2) and a \(\gamma\) Doradus–type star (HV 7). In the case of two faint variables, KV 5 and HV 6, although membership probabilities are not available from McNamara et al. (1977), their faintness implies that they are field \(\delta\) Scuti–type variable stars.

According to the membership information of McNamara et al. (1977) three bright \((V < 14.0\) mag) binary stars (KV 29, KV 35, and KV 37) show high \(P_{m} > 97\%\) membership probabilities. However, some other bright binary stars have low membership probabilities: 0% for HV 8 and 5% for KV 36. Although many fainter \((V > 15.0\) mag) binary stars are located in the region between the empirical ZAMS and the equal-mass binary sequence, it is difficult to say with certainty whether these stars are cluster members due to the large contamination of the field star population. Binary stars fainter than the main sequence or brighter than the equal-mass binary sequence are likely nonmembers of the cluster. Furthermore, as displayed in Figure 1, most contact binaries are located outside the cluster half-mass radius \((r = 4.5';\) Mathieu 1984) and thus seem to be nonmembers (Hargis et al. 2005).

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color-magnitude diagram. Four of them (HV 33, KV 29, KV 35, and KV 37) have high membership probability of $P \geq 80\%$. We found two W UMa-type contact binaries (HV 10 and HV 16) to be possible cluster members; i.e., they are inside the cluster half-mass radius and are located between the ZAMS and the binary sequence. However, since the membership information of HV 10 and HV 16 is not available, we could not be sure whether the open cluster M11 with intermediate age (~200 Myr) can contain contact binaries. It is of importance to discover the existence of contact binaries in intermediate-age open clusters to advance the understanding of the dynamical evolution of binary systems. Therefore, a further proper-motion and/or radial velocity survey for contact binaries in the field of M11 should be required to secure their cluster memberships. In conclusion, because many pulsating stars and eclipsing binaries in the region of M11 are probable members of the cluster, we believe that the cluster M11 is one of the best observing targets for asteroseismology studies, as well as for investigating the dynamical evolution of binary systems.

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