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VARIABLE STARS IN A FIELD OF THE OLD OPEN CLUSTER M67 : PHOTOMETRIC PRECISION OF THE BOAO 1.8M TELESCOPE

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ABSTRACT

We present test results of time-series CCD photometry to investigate the photometric precision of the BOAO (Bohyunsan Optical Astronomy Observatory) 1.8m telescope. A well-known field of the old open cluster M67, which includes two pulsating blue stragglers and two W UMa type binaries, was monitored for 3.5 hours on February 22, 1996. We have collected 148 V frames and 3 B frames. Photometric noises which consist mainly of photon noise and scintillation noise, were lowered down to about 1.9 mmag for stars of $10.^m5$ in M67 with exposure time of 20 seconds. From the C-M diagram for M67, a number of observational properties were derived; E(B-V) = 0.03, $(V-M_V)_o$ = 9.6, Age = 4 Gyr. We obtained light curves for four known variable stars and confirmed their variational characteristics. The pulsating blue stragglers show a low amplitude (about 0.01 mag) of light variation.

Key Words : M67, open cluster, variable, photometry

I. INTRODUCTION

M67 (=NGC2682; $\alpha_{2000}=08^h50^m26.^s1$, $\delta_{2000}=+11°48'46''$) is one of the most famous open clusters. Many observational and theoretical studies on the object have been made by several authors. CCD photometry was done by Montgomery *et al.* (1993) over the central region of one-half degree in the cluster up to magnitude V=20. Gilliland *et al.* (1991) carried out time-resolved CCD photometry and found two oscillating blue stragglers in M67. From the high-dispersion spectra of five main sequence stars in M67, Hobbs & Thorburn (1991) derived iron abundance of [Fe/H]=−0.04±0.12. Sanders (1977) and Girard *et al.* (1989) estimated the membership probability based on relative proper motion for 1866 stars and 663 stars, respectively, in the field of M67. Demarque *et al.* (1992) and Dinescu *et al.* (1995) constructed theoretical isochrones using the OPAL opacity and derived the age of M67 as 4.0±0.5Gyr. They also obtained the distance modulus $(V-M_V)$=9.7 and deduced that the core convective overshoot parameter $D_{mix}=0.0\sim0.1H_p$ is suitable for solar abundance. Many observers have used a specific field in the old open cluster M67, mostly a region called *dipper asterism*, as an observing target to standardize their observation system (for examples, Chevalier & Ilovaisky 1991 and Anupama *et al.* 1994).

In general, physical properties of pulsating stars (rapidly oscillating Ap stars, δ Scuti stars, pulsating white dwarfs and Sun-like oscillating stars, etc.) can be obtained from their oscillation frequencies; such an approach is called *asteroseismology* (see an extensive review by Brown & Gilliland 1994). In order to resolve multi-frequency oscillations with low amplitudes, high precision photometric data over long-time base lines are needed and furthermore, international campaigns can improve the full data coverage. Gilliland *et al.* (1993) presented the results of CCD ensemble photometry for twelve stars in M67. Using six 4-m class telescopes for a week (total 156 hours of observations), they attained the detection threshold of oscillations with amplitude of about 20 μmag (only five times greater than solar oscillations) for the best stars. This may be the first good example of detecting sun-like oscillations via photometric observations.

Recently a number of observational results to search variable stars in star clusters and external galaxies were presented; for examples, variable stars in the old open cluster NGC2243 (Kaluzny *et al.* 1996) and short-period eclipsing binaries in the globular cluster M5 (Yan & Reid 1996), blue stragglers in globular clusters (Mateo 1993), δ Scuti stars in the open cluster NGC6134 (Frandsen *et al.* 1996), β Cephei type variables in the open cluster NGC6231 (Balona & Laney 1995), variable stars in the Sagittarius dwarf spheroidal galaxy (Mateo *et al.* 1995) and the dwarf galaxy IC10 (Saha *et al.* 1996) etc.

In this study, we present observational results of M67 obtained at the Bohyunsan Optical Astronomy Observatory (BOAO). The main purpose of this study is to examine the photometric accuracy of BOAO 1.8m telescope and to monitor two pulsating blue stragglers and two W UMa type binaries. From this we would like to investigate the feasibility of observational surveys for variable stars in star clusters(for examples, pulsating blue stragglers and white dwarfs in open or globular clusters). The observations and data reduction are reported in section II, discussing the photometric precision. Observational results such as the C-M diagram of M67 and light curves of four known variable stars are presented in section III. Finally, the present results are discussed and summarized in the last section.

II. OBSERVATIONS AND DATA REDUCTION

(a) Observations

Time-series CCD photometry of M67 was performed on Feburuary 22, 1996 using the 1.8m reflector at the BOAO. The observations were made with Johnson V filter and BOAO CCD #1 (AR Coated TEK1024), which has an area of 1024×1024 pixels and a pixel size of 24μm (Park *et al.* 1995). The CCD camera adopts modular dewar designed in Ifa (Institute for Astronomy at Hawaii University) and SDSU (San Diego State University) general purpose CCD controller. The CCD chip is cooled down at 173^0K to reduce thermal noises using the LN_2 (Liquid Nitrogen) cryogenic method. The readout noise and gain of the CCD are 6.4 electrons and 3.49 electrons per ADU, respectively. The size of the field of view in the CCD image is $5.'8 \times 5.'8$ (0.34 arcsec pixel^{-1}) at the f/8 Cassegrain focus of the telescope. The exposure time was 20 sec and the photometric seeing was typically $2.''0$ during the observing period. Evening twilight flat field frames were obtained to flatten raw CCD frames.

The finding chart of M67 is shown at Figure 1. We monitored 96 stars in the central region of M67, which includes two pulsating blue stragglers and two W UMa type binaries (Gilliland *et al.* 1991). We carried out the observation for 3.5 hours and obtained 148 V CCD images. The three B-filter images were also obtained in the middle(the best seeing) of the V observations to construct the C-M diagram of M67. In order to minimize external uncertainties due to pixel-to-pixel variations (Frandsen *et al.* 1989, Kjeldsen & Frandsen 1992), we made careful adjustment which makes a star be at the same spot on the CCD frame during the observing run.

(b) Data Reduction

We used the IRAF/CCDRED package to preprocess CCD images. The correction for the instrumental bias (overscan) and the trimming of unreliable subsection were applied. And then, we proceeded the corrections of zero-exposure and flat field. The PSF (point spread function) showed some variations during observing time so that we adopted the simple aperture photometry, using the IRAF/APPHOT package (Massey & Davis 1992); the aperture size was chosen as 7 pixels ($\geq$ 1.0 FWHM). The data were reduced by the procedure which is designed for handling a number of time-monitoring CCD frames (Kim & Lee 1996).

We applied the ensemble photometry to standardize instrumental magnitudes, using 11 stars brighter than $12.^m5$. These stars have been well observed by using CCDs (Gilliland *et al.* 1991, Montgomery *et al.* 1993) and they show a wide color distribution. The transformation equations for V and B magnitudes are,

$$\begin{aligned} V &= v + a_1 + a_2(B-V) + a_3X + a_4Y \\ B &= b + b_1 + b_2(B-V) + b_3X + b_4Y, \end{aligned} \tag{1}$$

where V(B) and $v(b)$ are standard magnitude and instrumental magnitude, respectively. X and Y are coordinates values of stars in CCD frames. The value of a_2 (b_2) is color coefficient of our filter system and a_3, a_4 (b_3, b_4) are used to correct position dependant terms such as the differential extinction (Gilliland & Brown 1988) and the position-

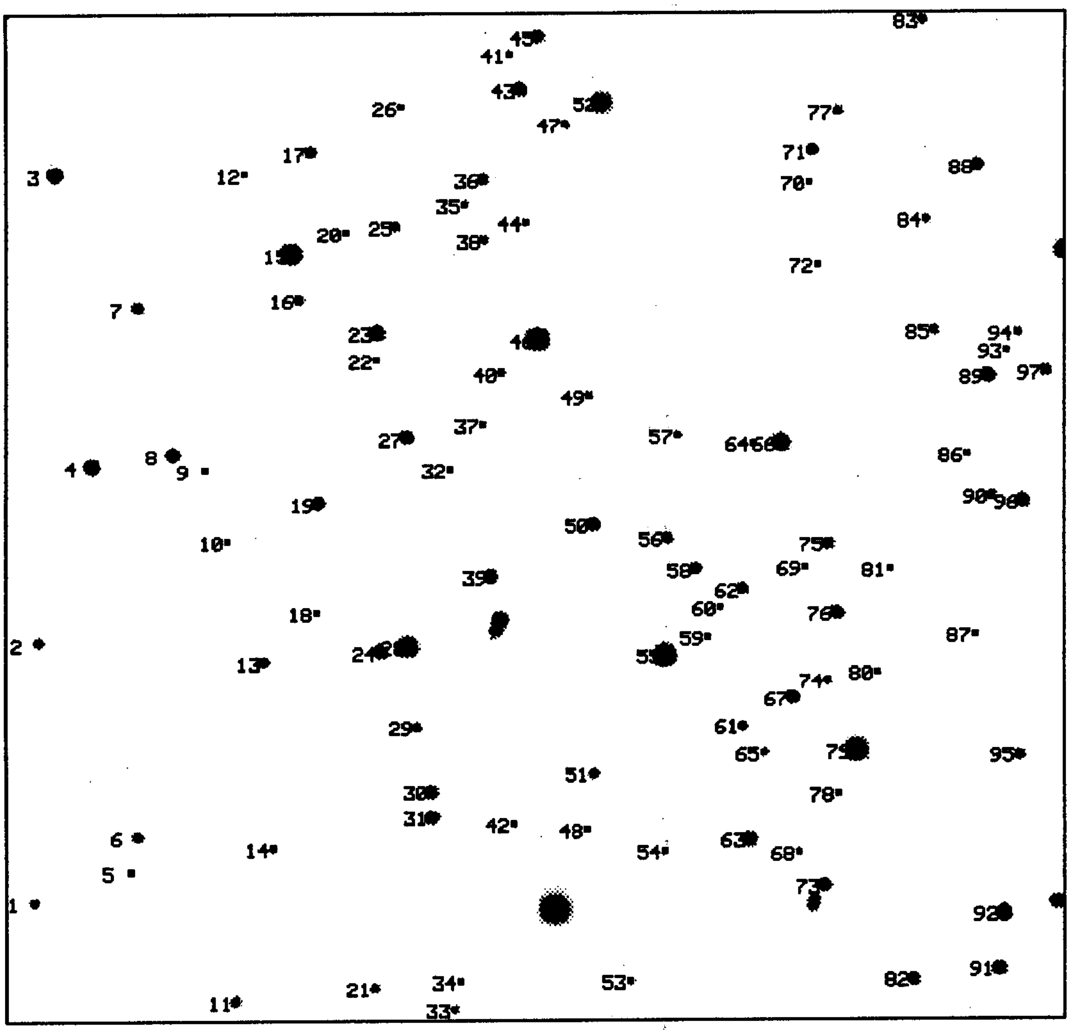

Fig. 1. Observed fields (5.′8 × 5.′8) in the central region of M67, including two pulsating blue stragglers (ID♯15, 23) and two W UMa type binaries (ID♯7, 50). Aperture photometry was performed for unsaturated, isolated stars denoted as numbers.

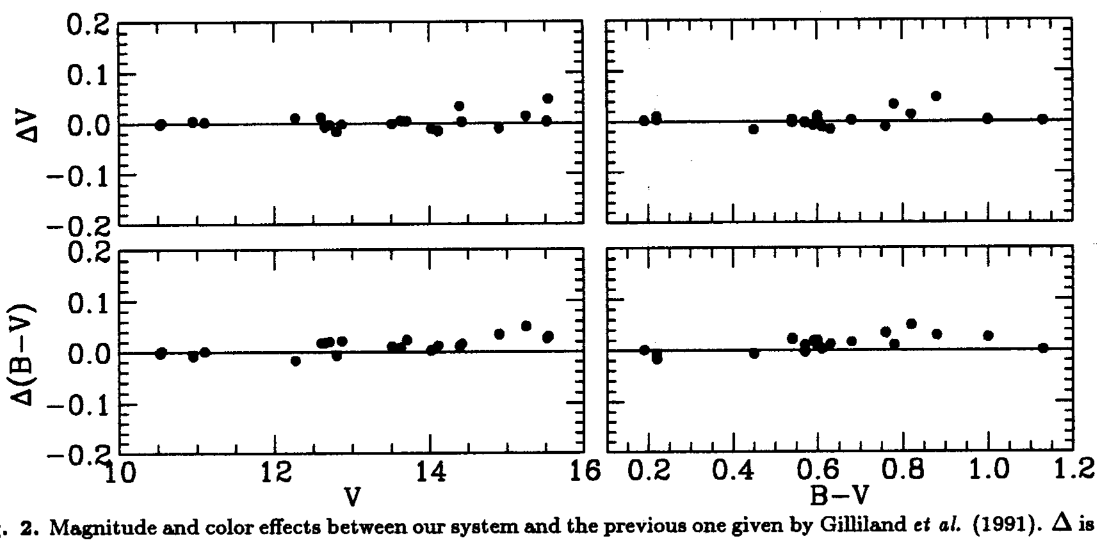

Fig. 2. Magnitude and color effects between our system and the previous one given by Gilliland *et al.* (1991). Δ is (ours - previous). V and (B-V) are the values derived in this study.

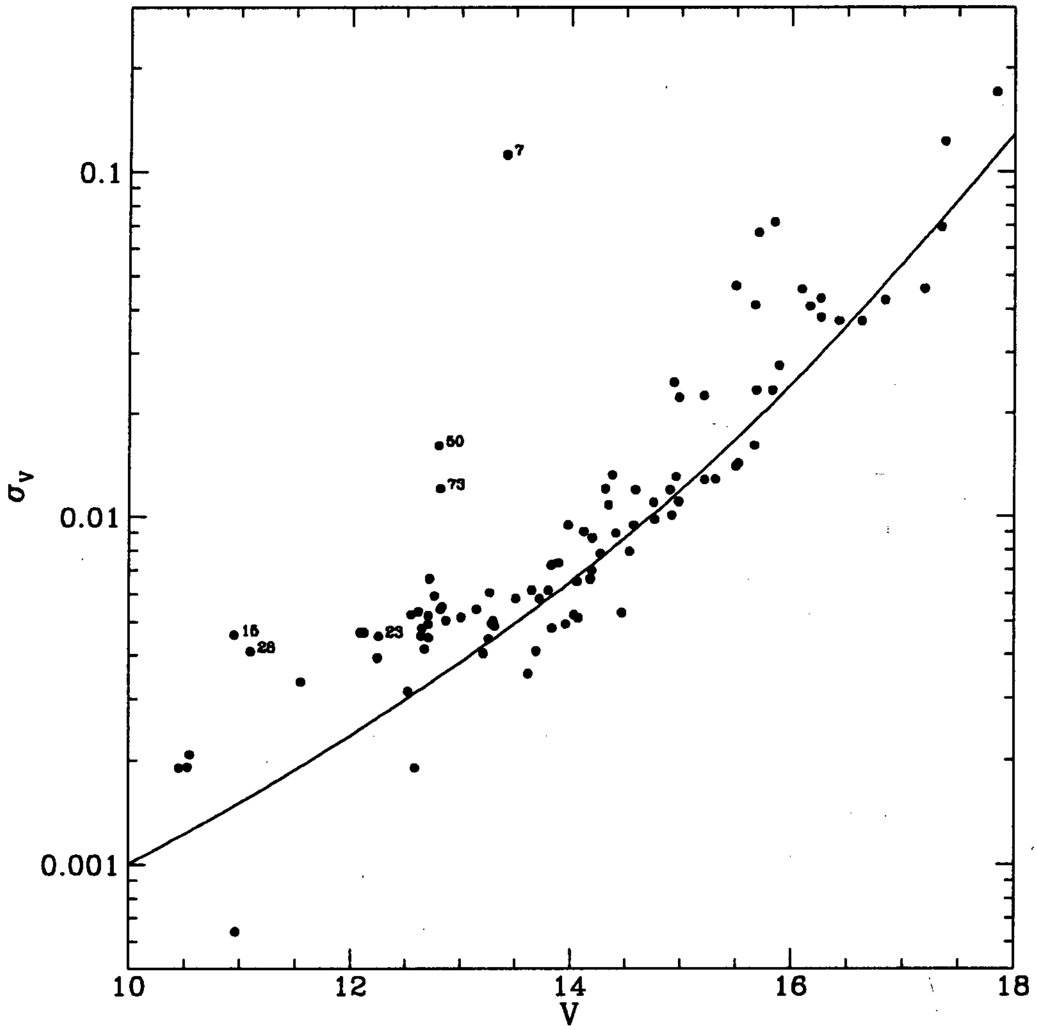

Fig. 3. Dispersion diagram of visual magnitudes for 96 stars in M67. The solid curve represents the analytic errors for single observation, including the scintillation noise and the photon noise. Four known variable stars (ID♯7, 15, 23, 50) and two stars (ID♯28, 73) having large dispersions are denoted as their identification number.

dependant variable PSF. The derived magnitude and color are compared with the previous work by Gilliland *et al.* (1991) in Fig. 2. There appear no systematic differences(Δ=ours-previous) between the two systems.

(c) Photometric Errors

The photometric precision is the most important factor in studying low-amplitude variable stars such as blue stragglers, δ Scuti variables and white dwarfs, and in searching variable stars in star clusters. According to the following formula, we calculated the standard deviation of observed magnitudes to find the noise level in our observations.

$$\sigma_V = \sqrt{\frac{\sum_{i=0}^{N}(V_i - < V_i >)^2}{N-1}}, \tag{2}$$

where N and $< V_i >$ are the observed number and the mean magnitude of each star, respectively. Variable stars are expected to have higher values due to their light variations. We plotted the standard deviation versus the average magnitude for each star in Fig. 3, where the standard deviations of 96 stars are denoted as filled circles. The solid curve represents the intrinsic error for single observation, including the scintillation noise and the photon noise. The scintillation error was estimated by adopting Young's (1967) equation;

$$\sigma_{scin} = 0.09d^{-2/3}X^{3/2}exp(-h/h_0)(\Delta t)^{-1/2} \simeq 0.^m00045, \tag{3}$$

where d=telescope diameter in cm, X=airmass (average value in this study is 1.15), h=observatory altitude in meter (1162m for BOAO), h_0=8000m and Δt=integration time in seconds. For a star with counts of 780000e$^-$ (typical for V=10.^{m}5 star), the photon noise (Howell 1992) is

$$\sigma_{photon} = \frac{1.086\sqrt{L_\star + n_{pixel}(N_{Sky} + N_{Read}^2)}}{L_\star} \simeq 0.^m00124, \tag{4}$$

where n_{pixel} is the total number of pixels used in measuring aperture. Here N_{Sky} and N_{Read} are the sky level (typical 154e$^-$/pixels) and the readout noise (6.4e$^-$ in our CCD chip), respectively.

The effects of atmospheric variations are the same for all stars in a CCD frame and the error resulted from them are negligible. The other external noises due to the instrumental drift and the offset variations (Frandsen *et al.* 1989) are difficult to estimate. The photometric noise in this study was estimated to be about 1.9 mmag for 10.^{m}5 stars, which is a little greater than the intrinsic error for a single observation. The total photometric data of 96 stars in M67 are listed in Table 1, including the identification number, coordinate value (X, Y), magnitude V, color $(B-V)$, standard deviation σ_V and observed number N.

III. RESULTS

(a) C-M Diagram for M67

The Color-Magnitude diagram for 96 observed stars in M67 is shown in Figure 4, in which the solid and dashed lines represent the best fitting ZAMS (zero-age main sequence) and theoretical isochrone of log(age)=9.6 for solar abundance (Schaller *et al.* 1992), respectively. From this, we derived two observational properties for M67; distance modulus (V-M_V)$_o$ = 9.60 and interstellar reddening E(B-V) = 0.03. These results are similar to the previous ones such as (V-M_V) = 9.7 and 4.0±0.5 Gyr by Dinescu *et al.* (1995). Several blue stragglers are shown in the brighter and bluer main sequence part than the turn-off point. The two blue stragglers (ID♯15 and 23) known as pulsating stars are located in the δ Scuti instability strip. The two W UMa type binary stars (ID♯7 and 50) are located at the region brighter by ~ 0.^{m}5 than the ZAMS in Figure 4. The characteristics of light variation of the four variable stars will be shown in the following section.

(b) Light Curves

We investigated light curves of four known variable stars and two stars with large standard deviations in Fig. 3. Figure 5 shows light variations of ten stars, including four standard stars (ID♯79, 55, 46, 52) for a comparison. The standard stars have the constant brightness and the small dispersion of $\sigma_V \simeq 0.^m002$. The two pulsating blue stragglers (ID♯15 and 23) show small-amplitude light variations (~ 0.^{m}01). They show complicated light curves, indicating the mixture of several pulsation periods. The period with the dominant pulsation power is about 1 hour. The two eclipsing binaries (ID♯7 and 50) show the typical light curves of W UMa type binary. The first one (ID♯7) is a well known binary, AH Cnc (General Catalogue of Variable Stars; Kholopov *et al.* 1988), having a period of 8.65 hours. In Fig. 5, its brightness was changed between 13.^{m}3 and 13.^{m}7 during our observing period. The characteristics of the second eclipsing binary (ID♯50) was known by Gilliland *et al.* (1991). It has a period of 10.59 hours. In this study, its light variation was shown between 12.^{m}76 and 12.^{m}83. The two stars (ID♯28 and 73) show a large dispersion in brightness as compared with the other stars of similar brightness. They are located near a bright star as seen in Fig. 1. So, the large dispersion in brightness of two stars is likely to be resulted from the light contamination of the nearest bright star through the seeing variation.

Table 1. Photometric Data of M67

ID	X	Y	V	B-V	σ_V	N	ID	X	Y	V	B-V	σ_V	N
1	26.6	120.8	14.072	0.623	0.00512	148	49	565.8	634.3	14.418	0.664	0.00893	148
2	30.5	386.0	13.806	0.575	0.00613	148	50	569.9	503.2	12.816	0.457	0.01611	148
3	46.5	861.7	12.124	1.010	0.00466	148	51	570.5	250.7	13.833	0.619	0.00724	148
4	82.2	563.5	12.248	0.563	0.00393	148	52	577.4	933.6	10.962	0.165	0.00064	148
5	120.0	151.1	17.192	1.226	0.04590	148	53	606.4	39.0	14.987	0.908	0.01108	148
6	126.5	187.4	13.719	0.656	0.00580	148	54	639.3	171.0	14.765	0.457	0.00981	148
7	126.6	725.5	13.416	0.538	0.11230	148	55	639.6	370.9	10.533	0.572	0.00191	148
8	160.4	575.4	12.589	0.583	0.00190	148	56	641.9	489.0	13.512	0.560	0.00580	148
9	191.0	560.0	15.493	0.851	0.01403	148	57	652.5	594.2	14.756	0.715	0.01102	148
10	213.0	487.2	17.373	1.515	0.06921	148	58	669.7	458.0	13.261	0.570	0.00446	148
11	220.8	20.0	13.986	0.626	0.00945	141	59	681.0	390.1	15.930	0.882	0.07150	148
12	229.6	861.2	15.297	0.797	0.01289	148	60	693.5	418.8	17.483	1.288	0.12279	148
13	248.9	365.6	13.616	0.592	0.00354	148	61	714.9	298.4	14.205	0.701	0.00866	148
14	256.9	175.4	14.465	0.686	0.00529	148	62	715.2	438.3	13.275	0.582	0.00605	148
15	274.9	779.6	10.946	0.227	0.00458	148	63	721.7	182.7	12.555	0.575	0.00524	148
16	282.0	733.0	13.696	0.517	0.00411	148	64	725.9	586.4	14.969	0.736	0.02226	148
17	293.6	883.7	13.213	0.614	0.00405	148	65	736.0	272.2	14.545	0.701	0.00792	148
18	299.7	415.9	15.517	0.974	0.01433	148	66	752.0	585.5	11.555	0.904	0.00335	148
19	301.2	525.6	12.872	0.519	0.00503	148	67	763.5	327.9	12.836	0.564	0.00551	148
20	327.0	801.1	15.236	0.770	0.02254	148	68	769.6	170.0	14.930	0.695	0.02466	148
21	355.7	33.3	14.185	0.630	0.00661	148	69	776.1	459.2	16.291	0.908	0.03791	148
22	356.8	670.7	15.731	0.684	0.06651	148	70	779.7	851.6	16.161	0.681	0.04079	148
23	358.3	699.3	12.259	0.236	0.00454	148	71	782.4	884.3	13.301	0.628	0.00502	148
24	361.5	376.0	12.713	0.550	0.00519	148	72	787.3	767.7	16.414	1.320	0.03698	148
25	376.5	807.7	14.031	0.607	0.00522	148	73	794.4	135.9	12.825	0.764	0.01209	148
26	380.7	929.0	14.913	0.768	0.01009	148	74	797.1	344.8	14.369	0.839	0.01325	148
27	387.3	592.5	12.657	0.572	0.00478	148	75	797.4	482.8	13.288	0.456	0.00493	148
28	388.4	380.8	11.098	0.189	0.00410	148	76	806.3	413.5	12.712	0.549	0.00491	148
29	397.2	298.8	14.198	0.596	0.00700	148	77	806.8	924.5	14.061	0.714	0.00651	148
30	411.1	232.3	12.769	0.806	0.00591	148	78	807.5	228.9	16.143	1.006	0.04572	148
31	411.7	206.2	12.646	0.605	0.00455	148	79	824.5	274.1	10.451	1.097	0.00190	148
32	429.0	559.6	16.614	1.255	0.03693	148	80	845.6	353.6	15.697	0.891	0.02337	148
33	433.5	10.9	14.579	0.697	0.00944	4	81	858.3	457.3	15.215	0.777	0.01282	148
34	438.6	39.7	16.268	1.022	0.04300	148	82	879.9	40.5	13.147	0.579	0.00542	148
35	443.5	830.6	14.911	0.726	0.01196	148	83	887.5	1017.4	13.893	0.764	0.00735	147
36	461.3	855.4	13.315	0.485	0.00485	148	84	892.4	813.3	14.313	0.719	0.01205	148
37	461.8	606.3	15.820	1.067	0.02339	148	85	899.5	700.2	13.956	0.613	0.00491	148
38	462.7	793.5	14.125	0.618	0.00904	148	86	931.0	572.6	15.649	0.876	0.01611	148
39	469.4	451.2	12.713	0.580	0.00450	148	87	939.8	391.6	16.802	1.073	0.04251	148
40	479.5	658.4	14.356	0.770	0.01085	148	88	941.9	868.5	13.004	0.959	0.00514	148
41	487.9	984.0	14.960	0.757	0.01308	148	89	952.3	653.5	12.526	0.598	0.00315	148
42	491.7	199.2	15.877	1.094	0.02759	148	90	955.1	531.3	13.828	0.575	0.00479	148
43	498.2	947.8	12.677	0.695	0.00416	148	91	962.6	50.7	12.722	0.549	0.00663	148
44	503.3	811.6	17.805	1.391	0.17063	148	92	966.7	106.4	12.088	0.442	0.00466	148
45	514.7	1001.4	12.823	0.610	0.00541	148	93	969.0	680.5	15.544	0.971	0.04674	148
46	514.8	692.1	10.549	1.129	0.00208	148	94	980.7	697.5	14.283	0.644	0.00781	148
47	542.3	911.2	14.592	0.725	0.01197	148	95	982.5	268.6	13.646	0.567	0.00614	148
48	564.1	193.2	15.711	0.985	0.04114	148	96	985.4	525.7	12.618	0.604	0.00534	147

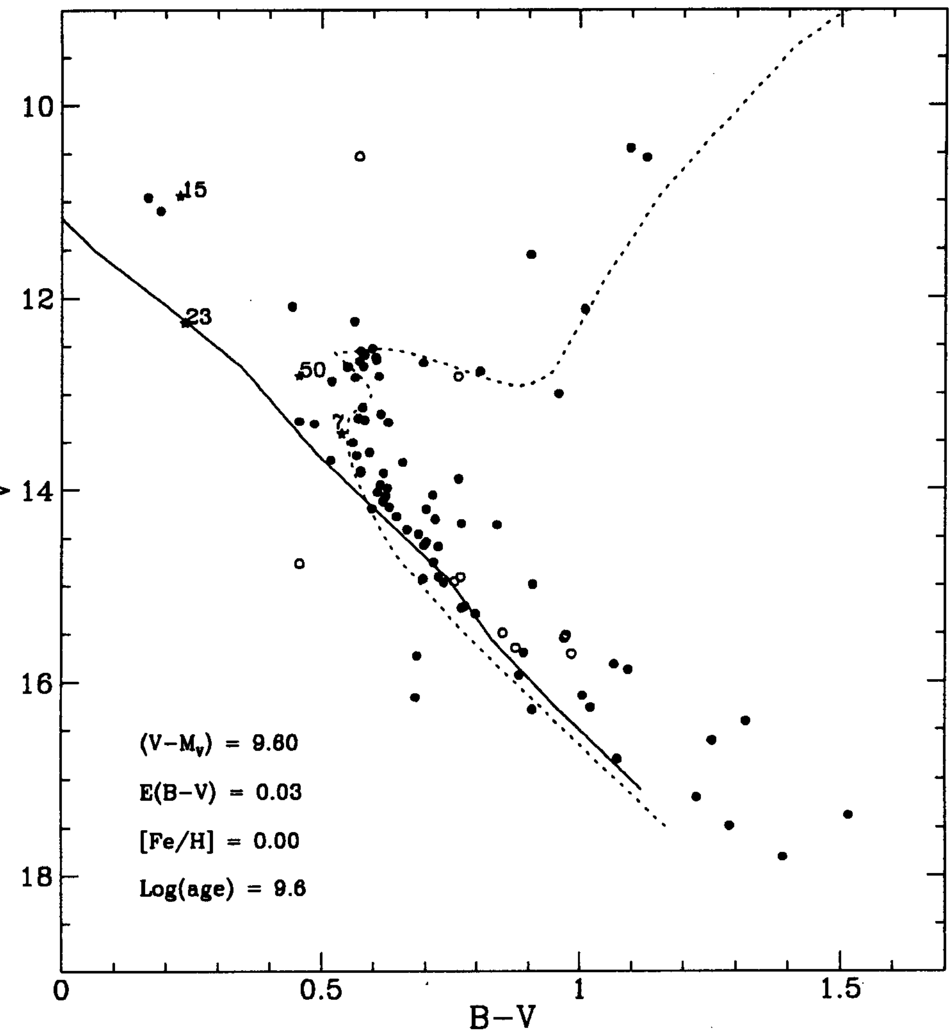

Fig. 4. C-M diagram of M67. The solid and dashed lines represent the zero-age main sequence track and the theoretical isochrone (Schaller *et al.* 1992), respectively. Open circles denote stars having a membership probability(Sanders 1977) less than 50%. Four known variable stars (ID♯7, 15, 23, 50) are denoted.

IV. SUMMARY AND DISCUSSION

We have carried out the time-series CCD photometry for 96 stars in a field of the old open cluster M67 in order to investigate the photometric accuracy of BOAO 1.8m telescope. 148 V CCD images and 3 B CCD images were collected from the observation of 3.5 hours. We applied the ensemble photometry to standardize instrumental magnitudes by using 11 standard stars. The main results obtained in this study are summarized as follows.

(1) Through the time-series CCD photometry, the photometric precision for stars of $10.^m5$ in M67 was increased up to about 1.9 mmag with exposure time of 20 seconds. This is similar to the intrinsic error which mainly consist of photon noise and scintillation noise. So, if we are obtained the data with longer exposure of a few minutes, we can get the good results for the search of light variability of white dwarfs (WD) in open clusters (for Hyades and Praesepe, $V_{WD} = 13.^m5 \sim 15.^m2$; Anthony-Twarog 1984) and blue stragglers (BS) in globular clusters (for M15, $V_{BS} = 17.^m0 \sim 18.^m0$; Guhathakurta 1993, $\Delta V_{BS} \geq 0.^m1$; Mateo 1993).

(2) From the C-M diagram for 96 observed stars in M67, we derived the distance modulus $(V\text{-}M_V)_o = 9.6$, the interstellar reddening E(B-V) = 0.03 and the age of 4 Gyr for solar abundance.

(3) The variational characteristics of four known variable stars (two pulsating blue stragglers and two W UMa

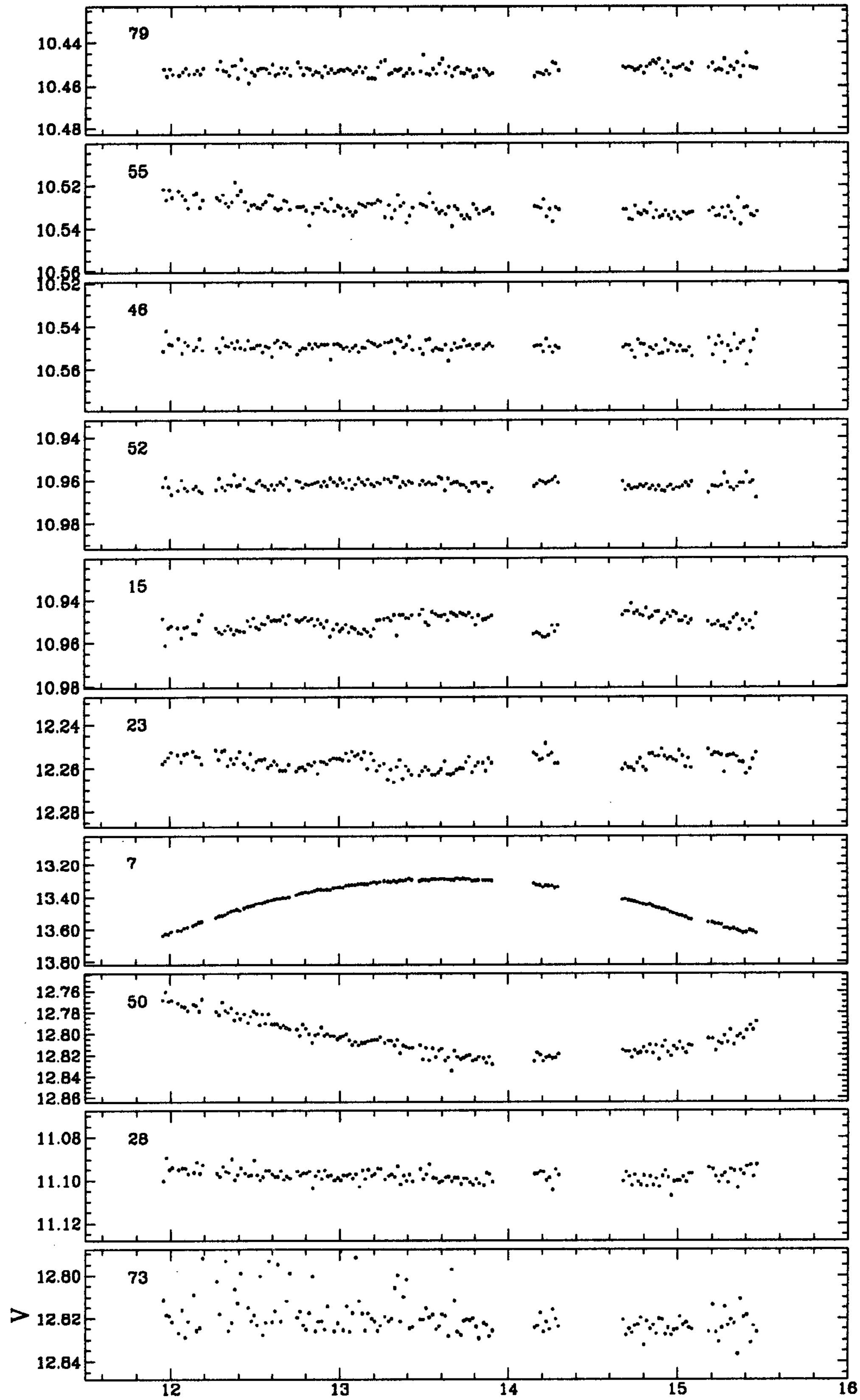

Fig. 5. Light curves of four standard stars (ID♯79, 55, 46, 52), two pulsating blue stragglers (ID♯15, 23), two W UMa type binaries (ID♯7, 50) and two stars (ID♯28, 73) with large dispersions.

type binaries) were confirmed from their light curves. The small-amplitude light variations of about 0.01 mag were detected for the two pulsating blue stragglers in M67. These are extremely small-amplitude variable stars in pulsating blue stragglers observed in old stellar systems(Mateo 1993).

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