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CCD PHOTOMETRY OF FAINT VARIABLE STARS IN THE FIELD OF THE GLOBULAR CLUSTER M4[1]

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ABSTRACT

We present the results of a photometric survey for faint variable stars in the nearby globular cluster M4. Twelve variables were discovered. Seven of the twelve are W Ursa Majoris stars that are probable members of the cluster. Another variable is a faint blue degenerate star with a period of about 60 minutes. While the magnitude and colors of this star are consistent with those of a cataclysmic variable in M4, a spectrum shows no emission lines. © *1997 American Astronomical Society.* [S0004-6256(97)01906-7]

1. INTRODUCTION

Binary stars are known to play an important role in the evolution of globular clusters. An extensive review of observational and theoretical aspects of this topic was published by Hut *et al.* (1992). Over the past decade several eclipsing binaries have been discovered in globular clusters. Mateo (1996) lists 8 clusters in which a total of about 30 variables have been discovered.

Recently, this list has been extended significantly by the identification of 33 eclipsing binaries in ω Cen by the OGLE group (Kaluzny *et al.* 1996). It is believed that blue stragglers (BS), which have been detected in practically all carefully observed globulars, are formed either through merging of close binaries (Zinn & Searle 1976), or through direct stellar collisions (Hoffer 1983).

In fact most of the binaries discovered so far in globular clusters are BS. In addition to eclipsing binaries some fraction of BS are pulsating variables of the SX Phe type (see Nemec *et al.* (1994) and Bailyn (1995) for recent reviews). The relative frequency of variable BS is known to vary significantly from cluster to cluster. For example about 30% of BS in NGC 5053 are short period variables (Nemec *et al.* 1995) while no single variable could be identified among about 27 BS in NGC 6366 (Harris 1993). In addition to the nature of BS stars, binary stars are of interest in measuring the distances to globular clusters and the masses of the component stars (e.g., Paczyński 1996). Very few clusters have been monitored in detail, and we have begun a survey of the southern, nearby globular clusters to locate faint variables for further study.

In this paper we present results of a photometric survey for faint variables in the field of the globular cluster M4 =NGC 6121 ($l^{II}=351.0$, $b^{II}=+16.0$), one of the two nearest globular clusters. It has been the object of numerous photometric, spectroscopic, and astrometric studies (Richer & Fahlman 1984; Cudworth & Rees 1990; Kanatas *et al.* 1995; Cote & Fischer 1996; Richer *et al.* 1996; Alcaino *et al.* 1988 and references therein). The cluster is relatively sparse making it a good candidate for photometric studies, but it is located on the sky near the galactic bulge. Its reddening is estimated at $E(B-V)=0.40$, with some evidence for variability of the reddening across cluster face (Alcaino & Liller 1984; Cudworth & Rees 1990).

2. OBSERVATIONS AND DATA REDUCTION

An 8.8×8.8 arcmin^2 field centered on the cluster was monitored during six nights spanning the period from 1995 June 1 to June 6 (UT). All observations were made using the 2.5-m du Pont telescope at Las Campanas Observatory. A thinned 2048×2048 Tektronix CCD with a scale of 0.26 arcsec/pixel was used as the detector. Observations were made using Johnson UBV filters, and most of the frames were collected in the B-band. The exposure times varied slightly from night to night depending on the observing conditions, with typical values of 120 s and 60 s for B and V filters, respectively. In addition, four 900-second U-band frames were taken on June 4 UT. A condensed log of the observations is listed in Table 1. Columns 2 and 3 in that table give the number of frames collected on a given night

[1]Based on observations collected at the Las Campanas Observatory of the Carnegie Institution of Washington.

TABLE 1. Observing log.

Date UT	N_B	N_V	Δt hours	⟨FWHM⟩ arcsec
June 1	83	21	8.0	1.04
June 2	48	14	5.8	1.14
June 3	11	5	1.7	1.12
June 4	16	11	2.9	1.05
June 5	10	4	3.5	1.16
June 6	26	27	5.3	2.26

for the B and V filters. The total duration of the monitoring (in hours) is listed in the fourth column. The last column gives the median value of the seeing. The observing conditions were generally good with the exception of the last night when the seeing was poor. Preliminary processing of the CCD frames was done with the standard routines in the IRAF-CCDPROC[2] package. The flatfield frames were prepared by combining ''dome flats'' and exposures of the twilight sky.

Profile photometry was measured with DoPHOT (Schechter *et al.* 1993). We used the program in the fixed-position mode, with stellar positions measured from an average of the two V frames with the best image quality. The images suffered from some systematic positional variability of the point spread function, and to cope with this effect we applied a procedure similar to that described in Kaluzny *et al.* (1995). Each frame was divided into a 5×5 grid of overlapping sub-frames, and instrumental photometry for a given sub-frame was transformed to the common instrumental system of the ''template'' image. The final data bases for the B and V filters contained ''light curves'' for 13425 and 14650 stars, respectively.

3. VARIABLE STARS

3.1 Search for Variability

The search for variables was conducted by separately analyzing light curves for stars in the B and V data bases. To select potential variables we employed three methods, all described in detail in Kaluzny *et al.* (1996). The first method is based on selecting stars exhibiting ''noisy'' light curves. A χ^2 test is applied to the light curves to identify such stars. In the second method the light curves are scanned with a filter designed to detect eclipse-like events. A star is flagged as a possible eclipsing variable if the light curve shows three consecutive measurements significantly below the mean brightness level. Finally, we used the CLEAN algorithm (Roberts *et al.* 1987) to calculate power spectra for all well sampled light curves. The light curves showing possible periodic signals were selected for further examination. To illustrate the overall quality of the photometry, we present in Fig. 1 a plot of the rms deviation versus average B magnitude for 11680 ''light curves'' containing at least 75 data points and with $\langle B\rangle<22.0$.

[2]IRAF is distributed by the National Optical Astronomical Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation

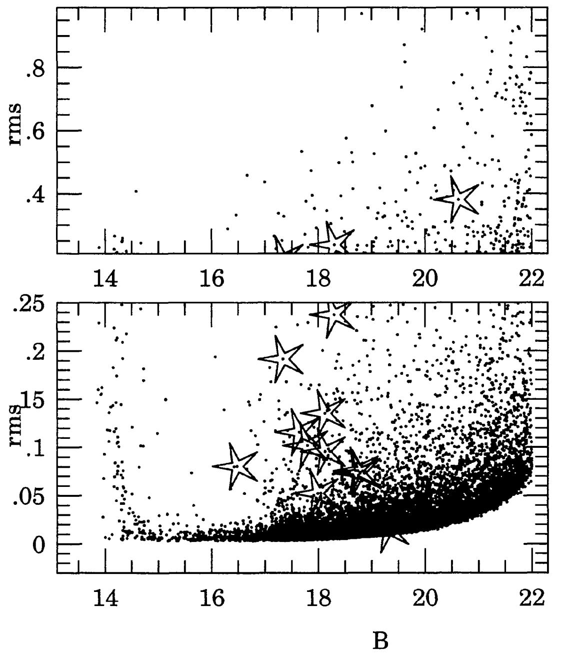

FIG. 1. Standard deviation vs average B magnitude for stars measured on at least 75 out of 168 frames obtained on the nights of 1995 June 1–5. The 12 newly identified variables are marked with asterisks.

Twelve certain variables were identified this way. Hogg (1973) lists 43 variables in M4 and so we have assigned the 12 newly identified variables identifications running from V44 to V55. Several RR Lyr stars were also detected, but since images of these variables were over-exposed in a large fraction of the images we do not discuss these stars in this paper. The equatorial coordinates of the newly discovered variables are given in columns 2 and 3 in Table 2. These coordinates were derived from the positions of 87 stars from Cudworth & Rees (1990). The residuals from the adopted transformation rarely exceed 0.25 arcsec. Finding charts for the 12 variables are given in Fig. 2.

3.2 Properties of the Variables

The observations of the newly identified variables were transformed to the standard UBV system using the following relations:

$$v=\text{const}+V-0.016\times(B-V), \quad (1)$$

$$b=\text{const}+B-0.076\times(B-V), \quad (2)$$

$$u-b=\text{const}+0.947\times(U-B), \quad (3)$$

$$b-v=\text{const}+0.944\times(B-V). \quad (4)$$

The color terms of the transformation were derived from observations of several Landolt (1992) fields. The zero points were calculated using independently calibrated UBV photometry of M4 obtained in 1996 with the 40-inch Swope telescope at Las Campanas Observatory (Kaluzny & Thompson, in preparation).

The photometric properties of the newly identified variables are given in Table 2. In this table, ΔB is the full amplitude of the variations in the B-band. It was possible to

TABLE 2. Parameters for M4 variables.

ID	RA(1950)	Dec(1950)	Type	Period (day)	$T_0(HJD)$ 2449869+	V_{max}	B_{max}	ΔB	$(B-V)$ (max)	Member?
44	16:20:16.89	−26:26:27.6	EW	0.26369(3)	0.5671(2)	17.69	18.69	0.23	0.99	Y
45	16:20:10.96	−26:23:21.5	RR	0.60334	0.715	19.37	19.86	1.20	0.49	N
46	16:20:43.05	−26:25:00.9	?	0.04357	0.5469	18.51	18.81	0.07:	0.30	?
47	16:20:21.49	−26:22:14.7	EW	0.26997(2)	0.5364(1)	16.85	17.67	0.29	0.82	Y
48	16:20:32.67	−26:24:47.8	EW	0.28252(14)	0.5638(6)	16.42	17.12:	0.22:	0.70	Y
49	16:20:30.21	−26:25:05.4	EW/EB	0.29762(10)	0.6290(3)	16.95	18.13	1.02	1.18	N
50	16:20:27.21	−26:24:51.8	EW/EB	0.26651(17)	0.6797(3)	17.17:	18.00	0.44	0.83	Y
51	16:20:29.10	−26:24:12.5	EW	0.30311(15)	0.4331(2)	17.03	17.97	0.42	0.94	Y
52	16:20:27.38	−26:24:01.1	Ell,RS?	–	–	16.95:	17.92	0.14:	0.97:	?
53	16:20:34.36	−26:25:14.6	EW	0.30851(9)	0.4311(3)	15.75	16.34	0.25	0.59	Y
54	16:20:46.76	−26:27:46.7	EB	0.25265(2)	0.4580(2)	17.74	18.67	0.32	0.93	?
55	16:20:41.66	−26:24:20.9	EW/EB	0.31077(3)	0.6354(2)	16.70	17.51	0.49	0.81	Y

Notes to TABLE 2

EW—W Ursae Majoris; EB—eclipsing binary with β Lyrae type light curve; RR—RR Lyrae; Ell—Ellipsoidal variable; RS—RS Canum Venaticorum variable.

derive periods for 11 out of the 12 stars, and phased B-band light curves for these stars are shown in Fig. 3. Nine of the variables are eclipsing binaries. Moments of the individual minima measured from the B-band light curves of these eclipsing systems are listed in Table 3.

Photometry extracted from 99 images in the B band and from 45 images in the V band was averaged to produce a color magnitude diagram (CMD) for the monitored field. Images with poor seeing were not used in the average. Only stars measured on at least 33 B images and at least 22 V images were retained in the final CMD which is shown in Fig. 4. Positions and identifications of the 12 detected variables are also marked in this figure.

The periods and light curves of variables V44 and V47-53 and V55 indicate that these stars are W UMa contact binaries. Stars V50 and V55 exhibit light curves with distinctly different depths of primary and secondary eclipses. We note also that V47 and V53 exhibit total eclipses. This should

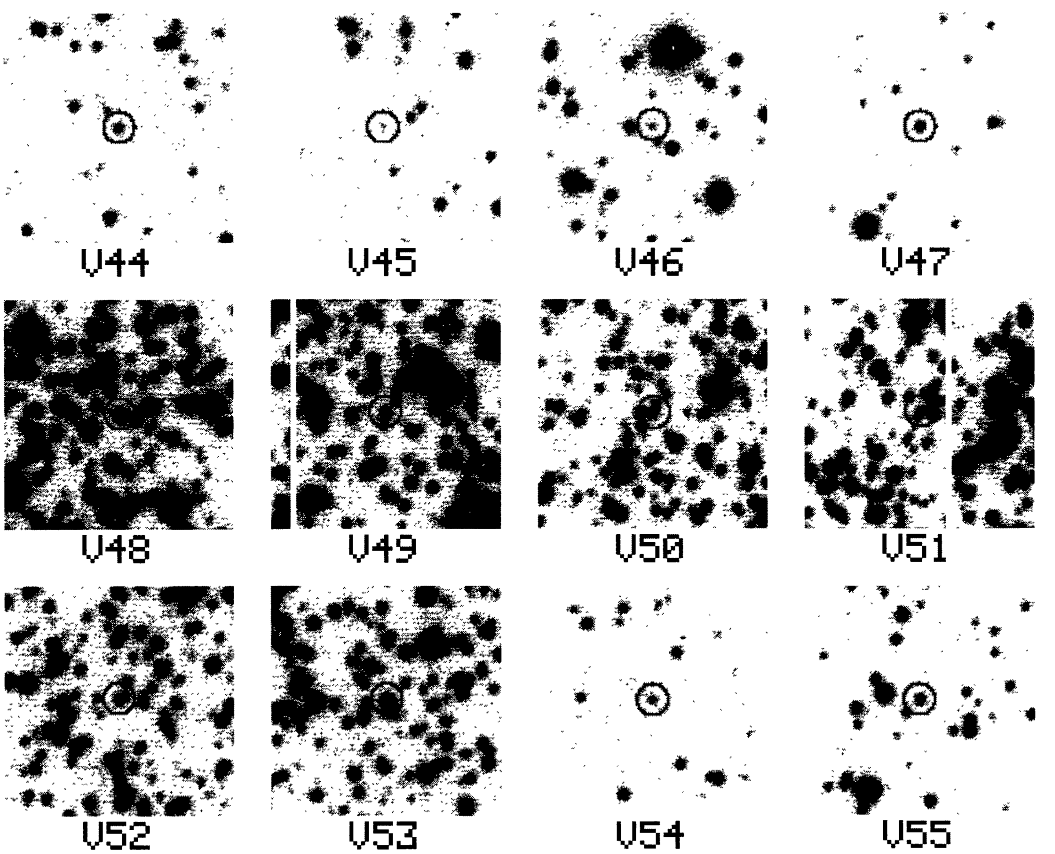

FIG. 2. Finder charts for the 12 newly discovered variables. Each chart is 30 arcsec on a side with north up and east to the right.

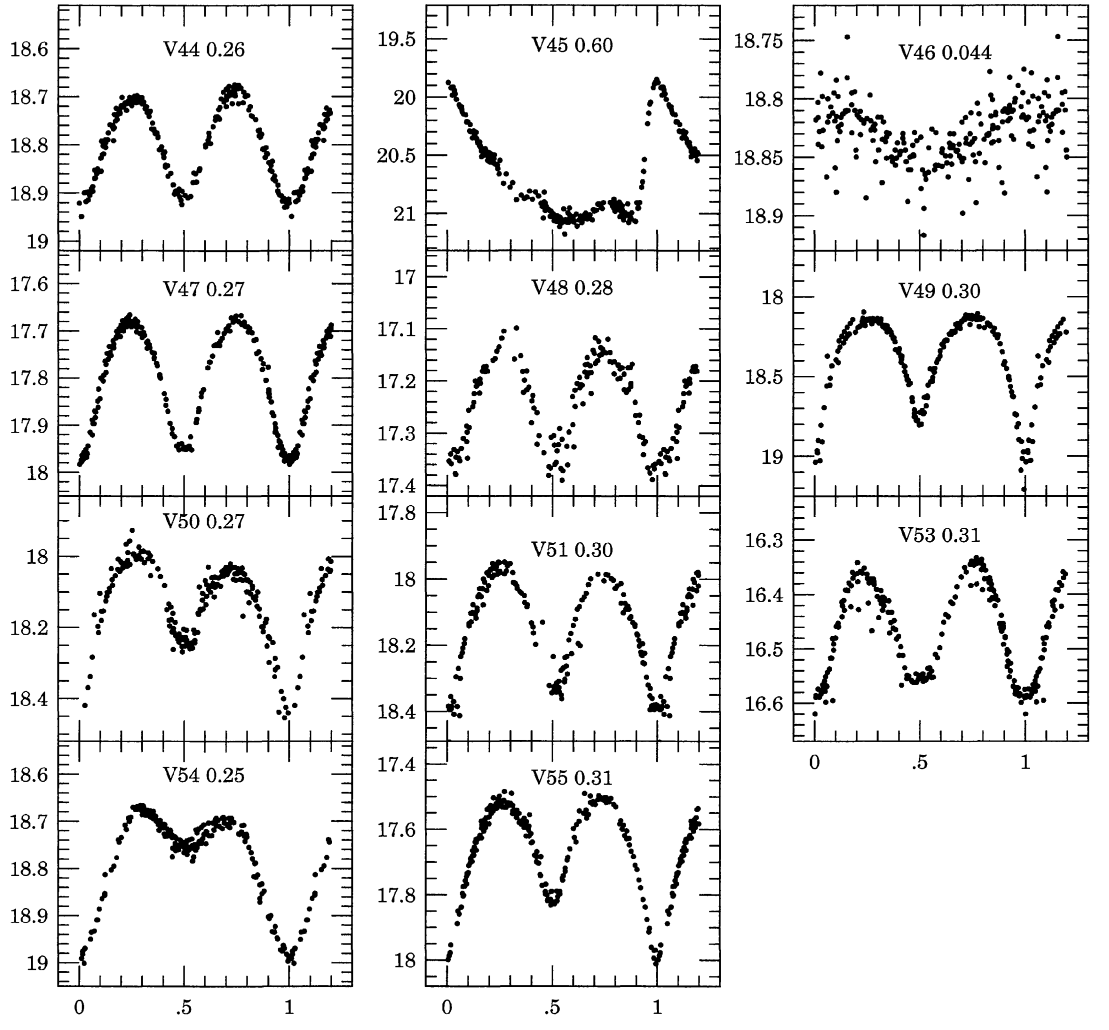

FIG. 3. Phased B-band light curves for 11 out of the 12 newly identified variables in the field of M4.

allow an accurate determination of the geometrical parameters for these systems. Two eclipsing binaries—V48 and V53—are candidate blue stragglers. Three systems are found at the cluster turnoff while another three are located slightly to the red of the upper main sequence. Variable V49 is observed to be about 0.3 mag to the red of the main sequence. We show below that it is likely to be a field star.

The light curve of V54 is very unusual considering the very short period of this variable, $P=0.25$ d. Apparently the components of this binary are in very poor thermal contact or the system is even in a detached configuration. Among the few hundred non-degenerate eclipsing binaries with $P<0.4$ day listed in the General Catalogue of Variable Stars (Kholopov *et al.* 1985) almost all show EW-type light curves. One of the very few exceptions is V361 Lyr (Kaluzny 1990) which shows a light curve similar to that of V54.

Variable V45 is a field RR Lyr star of type RRab. The position marked in Fig. 4 corresponds to an average color and magnitude of $\langle B\rangle=20.67$ and $\langle V\rangle=20.00$. The star is located in the cluster background at a heliocentric distance of about 35 kpc.

The light curve of V46 shows a coherent modulation with a period of 0.04357 d. The phased light curve of this variable is rather noisy due to the presence of flickering. The light curves for the 2 nights with best temporal coverage are presented in Fig. 5 and the cleaned power spectrum of V46 is shown in Fig. 6. The observed average colors of V46 are $(B-V)=0.28$ and $(U-B)=-0.04$. Assuming a reddening and a distance modulus for M4 of $E(B-V)=0.40$ and $(m-M)_V=12.75$, respectively (e.g., Cudworth & Rees 1990), we obtain $M_V=5.8$, $(B-V)_0=-0.12$, and $(U-B)_0=-0.33$ for V46 assuming that it is a cluster member. Such parameters are consistent with the classification of V46 as a cataclysmic variable. However, this is ruled out by spectroscopic observations. A medium-resolution spectrum of the variable was taken with the 3.6-m telescope at ESO in 1996 April by H. Duerbeck and J. Kaluzny. This spectrum does not show any emission lines which are the signatures of cataclysmic variables. The absorption lines of the Balmer series are very strong and wide. In fact the spectrum of V46 resembles the spectra of sdB type subdwarfs as well as spectra of some detached pairs of white and red dwarfs. The observed colors of V46 are consistent with this star being a composite system. Clearly more detailed spectroscopic ob-

TABLE 3. Moments of minimum light derived for eclipsing binaries in M4.

ID	Min HJD 2449800+	σ	E	ID	Min HJD 2449800+	σ	E
44	69.5671	0.0004	0	50	69.6793	0.0003	0
44	69.6981	0.0004	0.5	50	69.8187	0.0011	0.5
44	69.8314	0.0006	1.0	50	70.6123	0.0005	3.5
44	70.6222	0.0003	4.0				
44	74.7088	0.0006	19.5	51	69.5849	0.0002	0.5
				51	69.7351	0.0004	1.0
47	69.6703	0.0003	0.5	51	70.6458	0.0005	4.0
47	69.8075	0.0002	1.0				
47	70.6154	0.0002	4.0	53	69.5857	0.0005	0.5
47	74.6661	0.0003	19.0	53	69.7396	0.0004	1.0
				53	70.6650	0.0002	4.0
48	69.7051	0.0008	0.5	53	74.6777	0.0021	17.0
48	70.6939	0.0004	4.0				
48	74.6491	0.0026	18.0	54	69.5930	0.0008	0.5
				54	69.7101	0.0002	1.0
49	69.6294	0.0004	0	54	74.7637	0.0004	21.0
49	69.7776	0.0003	0.5				
49	70.6708	0.0002	3.5	55	69.6355	0.0002	0
49	70.8040	0.0029	4.0	55	69.7905	0.0003	0.5
				55	74.7632	0.0005	16.5

servations are needed to settle the nature of this variable.

In Fig. 7 we show light curves obtained for V52 on the night of 1995 June 01 and June 02. The available data do not allow a determination of the period of this variable. It is located about 0.1 mag to the red of the cluster turnoff on the CMD. The possible classes of variables to which V52 may belong include spotted variables (RS CVn or BY Dra stars) and ellipsoidal variables.

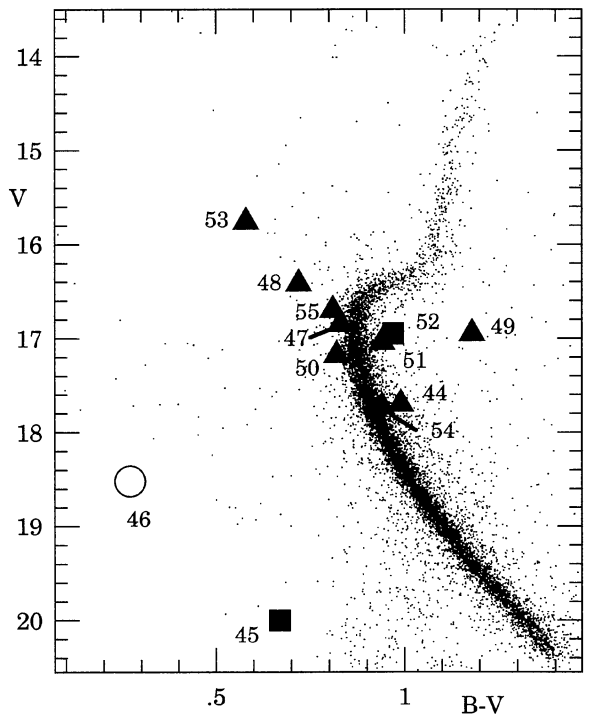

FIG. 4. A $B-V$ color-magnitude diagram of M4 with the positions of the variables marked: triangles—eclipsing binaries; open circle—probable degenerate binary V46; squares—variables V45 and V52.

3.3 *Cluster Membership of the W UMa Variables*

We have used the absolute brightness calibration of W UMa type binaries established by Rucinski (1995) to calculate M_V for the newly discovered contact binaries in M4. Rucinski's calibration gives M_V at maximum light as a function of period, unreddened color $(B-V)_0$ and metallicity:

$$M_V^{cal} = -2.38 \log(P) + 4.26(B-V)_0 + 0.28 - 0.3[\mathrm{Fe/H}]. \quad (5)$$

We adopted [Fe/H] = −1.28 for all systems (Zinn 1985). The apparent distance modulus for each system was calcu-

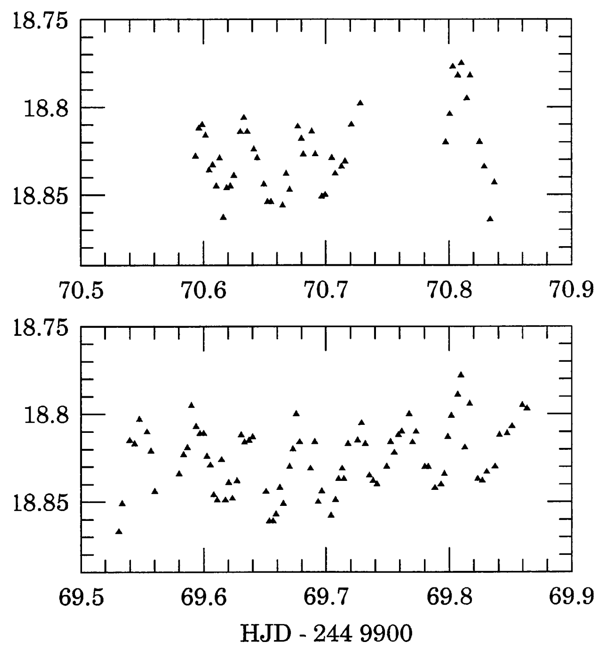

FIG. 5. The B-band light curves of variable V46 obtained on the nights of 1995 June 1 and 2.

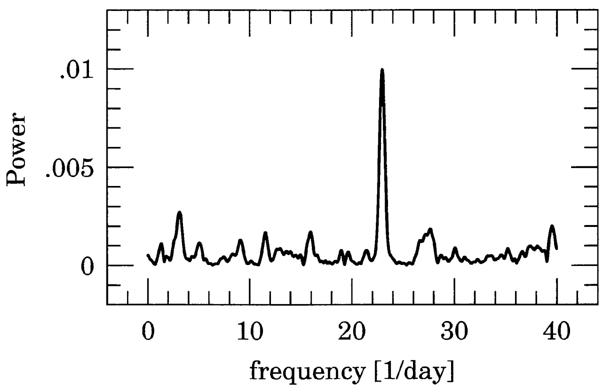

FIG. 6. The power spectrum for the B-band light curve of V46.

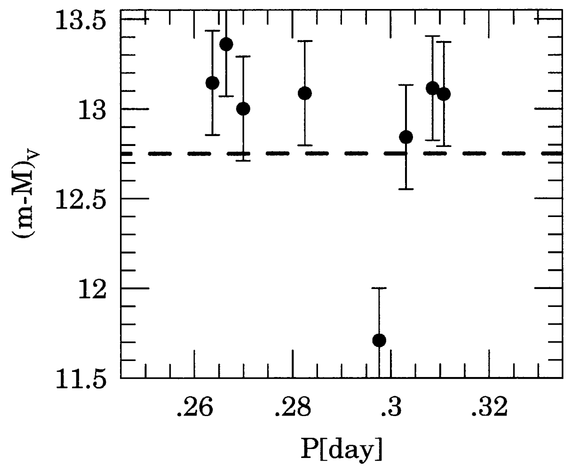

FIG. 8. Period, apparent distance modulus diagram for contact binaries from the field of M4. A horizontal line at $(m-M)_V=12.75$ corresponds to the distance modulus of the cluster (Cudworth & Rees 1990). The error bars correspond to expected random errors of the derived distance moduli.

lated as the difference between its V_{max} magnitude and M_V^{cal}. Figure 8 shows the period versus apparent distance moduli diagram for the contact binaries in Table 2. Variable V54 was excluded from consideration as it does not show a typical W UMa-type light curve. The apparent distance modulus of M4 is $(m-M)_V=12.75\pm0.2$ (Cudworth & Rees 1990). The system with the most discrepant value of $(m-M)_V$ is V49. It is most likely a foreground variable. For the remaining contact binaries the calculated distance moduli are grouped around $(m-M)_V\approx13.1$. Apparently these 7 systems are located at similar distances, and, considering the preliminary character of Rucinski's calibration and the relatively large uncertainty of $(m-M)_V$ for M4, we may conclude that variables V44, V47-48, V50-51, V53, and V55 are all members of the cluster.

It is interesting to note that the cluster member W UMa stars seem to be concentrated near the upper main sequence in the CMD, with no variables found more than one magnitude below the turnoff. A similar distribution of cluster W UMa stars is also observed in M71 (Yan & Mateo 1994). We performed tests to determine the completeness of the detection of W UMa stars as a function of magnitude in the data base of B "light curves." First, two hundred stars were randomly selected from each of four half-magnitude bins from $B=19.0$ to $B=21.0$, corresponding to $V=18.05$ to $V=19.73$. Then two sets of model light curves were generated from the prescription given by Rucinski (1993): (a) inclination $i=60.0$ degrees, mass ratio $q=0.10$, and degree of contact $f=0.5$, and (b) inclination $i=70.0$ degrees, mass ratio $q=0.20$, and degree of contact $f=0.5$. The resulting full amplitudes of the light curves are 0.153 mag for the first case, and 0.323 for the second. Note that the full amplitudes for the EW stars in Table 2 are all greater than 0.323 mag. These artificial light curves are then added to the 200 observed light curves in each of the four magnitude bins after randomly selecting a period (uniformly on the interval 0.2 to 0.4 days) and a phase for the first data point in the light curve (uniformly on the interval 0 to 1). The resulting 800 light curves for each of the two cases were then analysed with the χ^2 test described in Sec. *3.1*. The results are given in Table

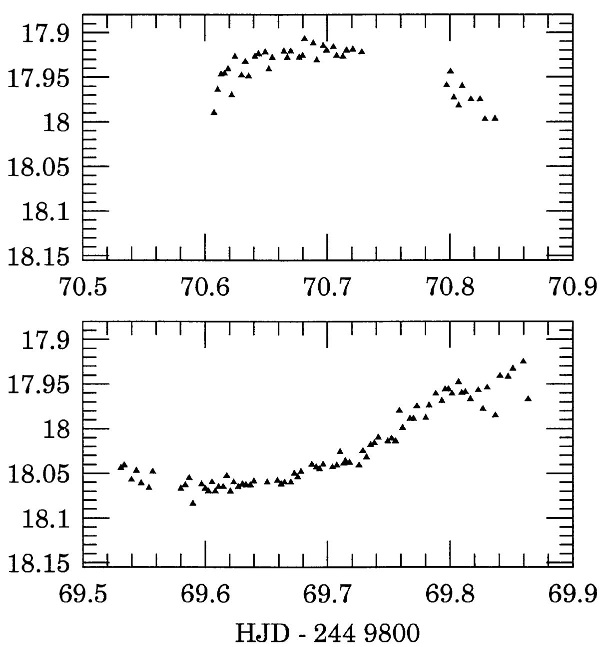

FIG. 7. The B-band light curves of variable V52 obtained on the nights of 1995 June 1 and June 2.

TABLE 4. Recovered variables.

B_{min}	B_{max}	completeness case (a)	completeness case (b)
19.0	19.5	0.95	0.99
19.5	20.0	0.95	1.00
20.0	21.5	0.96	1.00
21.5	22.0	0.90	0.99

Notes to TABLE 4

Parameters for artificial light curves: case (a) inclination $i=60.0$ degrees, mass ratio $q=0.10$, degree of contact $f=0.5$; case (b) inclination $i=70.0$ degrees, mass ratio $q=0.20$, degree of contact $f=0.50$.

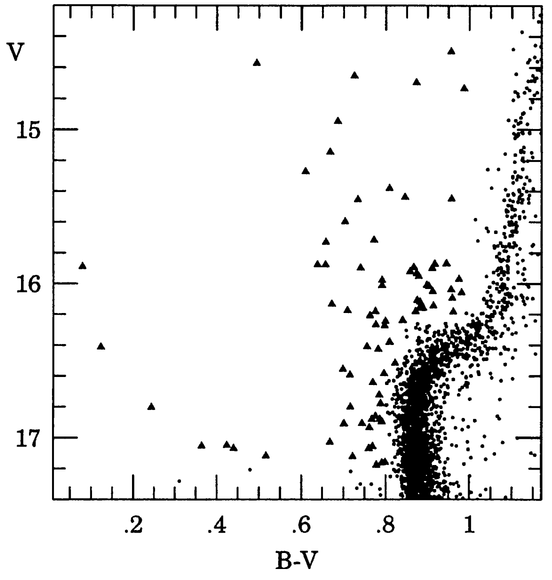

FIG. 9. The turnoff region of the CMD shown in full in Fig. 3. Stars selected as potential blue/yellow stragglers are marked with triangles.

4. The measured completeness for each magnitude bin is equal to (*number of recovered variables*)/200. From these tests we can conclude that there are no missed W UMa stars in our sample with full amplitudes greater than 0.323 mag between $V=18.05$ and $V=19.7$. The measurements are also essentially complete for the case of W UMa stars with full amplitudes of 0.153 mag over the same magnitude range. Note that no such stars are found even at brighter magnitudes in this cluster, in M71 (Yan & Mateo 1994), or in ω Cen (Kaluzny *et al.* 1996). A more complete discussion will be presented in Kaluzny & Thompson (in preparation).

3.4 Blue Stragglers

As we have noted above, only two of the newly detected variables are located in the blue straggler region in the cluster CMD. Both of them—V48 and V53—are contact binaries. No SX Phe stars were detected. SX Phe stars can exhibit photometric variability with very small amplitudes. Variables with full amplitudes of 0.05 mag were recently identified in ω Cen (Kaluzny *et al.* 1996). We therefore examined in detail the light curves of a sample of stars located in the blue/yellow straggler region of the CMD. In Fig. 9 we present an expanded view of the cluster CMD for the turnoff region. Stars whose light curves were selected for additional examination are marked with triangles. Light curves were examined visually as well as with a CLEAN (Roberts *et al.* 1987) algorithm to search for any possible periodic variability. Of the 82 selected objects, 4 show noisy but nonperiodic light curves with full amplitudes exceeding 0.05 mag. Two other stars are already identified variables (V48 and V53). For the remaining 78 stars we can exclude any periodic variability on a time scale of hours and with full amplitudes exceeding 0.03 mag.

4. SUMMARY

We have used CCD observations obtained over a six night period to identify twelve new faint variable stars in the direction of the globular cluster M4. Seven of these variables are W Uma binaries which are likely to be cluster members. One variable appears to be a binary, including an sdB type subdwarf.

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