The optical gravitational lensing experiment. Variable stars in globular clusters

IV. Fields 104A-E in 47 Tucanae[*]

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Abstract. Five fields located close to the center of the globular cluster NGC 104 = 47 Tuc were surveyed in a search for variable stars. We present V-band light curves for 42 variables. This sample includes 13 RR Lyr stars – 12 of them belong to the Small Magellanic Cloud (SMC) and 1 is a background object from the galactic halo. Twelve eclipsing binaries were identified – 9 contact systems and 3 detached/semi-detached systems. Seven eclipsing binaries are located in the blue straggler region on the cluster color-magnitude diagram (CMD) and four binaries can be considered main-sequence systems. One binary is probably a member of the SMC. Eight contact binaries are likely members of the cluster and one is most probably a foreground star. We show that for the surveyed region of 47 Tuc, the relative frequency of contact binaries is very low as compared with other recently surveyed globular clusters. The sample of identified variables also includes 15 red variables with periods ranging from about 2 days to several weeks. A large fraction of these 15 variables probably belong to the SMC but a few stars are likely to be red giants in 47 Tuc. VI photometry for about 50 000 stars from the cluster fields was obtained as a by product of our survey[1].

1. Introduction

The Optical Gravitational Lensing Experiment (OGLE) is a long term project with the main goal of searching for dark matter in our Galaxy by identifying microlensing events toward the galactic bulge (Udalski et al. 1992, 1994). At times the bulge is unobservable we conduct other long-term photometric programs. A complete list of side-projects attempted by the OGLE team can be found in Paczyński et al. (1995). In particular, during the observing seasons 1993, 1994 and 1995 we monitored globular clusters NGC 104 = 47 Tuc and NGC 5139 = ω Cen in a search for variable stars of various types. Of primary interest was the detection of detached eclipsing binaries. In Papers I, II & III (Kaluzny et al. 1996, 1997a,b) we presented results for ω Cen. Here we report on variables discovered in the field of 47 Tuc.

2. Observations and data reduction

The OGLE[2] project was conducted using the 1-m Swope telescope at Las Campanas Observatory. A single 2048 ×

2048 pixels Loral CCD chip, giving a scale of 0.435 arcsec/pixel was used as the detector. The initial processing of the raw frames was done automatically in near-real time. Details of the standard OGLE processing techniques were described by Udalski et al. (1992).

In 1993 we monitored fields 104A and 104B located west and east of the cluster center, respectively. In 1994 we monitored field 104C located north of the cluster center. In 1995 we monitored fields 104D and 104E covering southern part of the cluster. A condensed summary of the data used in this paper is given in Table 1. Detailed logs of the observations can be found in Udalski et al. (1993, 1995, 1997). The equatorial coordinates of centers of fields 104A-E are given in Table 2. A schematic chart with marked locations of all of the monitored fields is shown in Fig. 1. Most of the monitoring was performed through the Johnson V filter. Some exposures in the Kron-Cousins I band were also obtained. Most of observations in the V-band were collected with an exposure time ranging from 300 to 600 seconds (420 seconds was the most common value). The I-band exposures lasted 300 seconds. For the majority of the analyzed frames the seeing was better than 1.6 arcsec. The reduction techniques as well as the algorithms used for selecting potential variables are described in Paper I. Profile photometry was extracted with the help of DoPHOT (Schechter et al. 1993). The total number of stars contained in data bases with V band photometry ranged from 18397 to 33014. Table 3 gives condensed information about the numbers of stars analyzed for variability and about the quality of the derived photometry. The useful data were obtained for stars with $14.0 < V < 20.25$.

Table 1. Summary of observations collected for fields 104A-E. N_V is the number of V-band images included in the data bases

Field	N_V	Dates of observations
104A	286	Jun. 17 - Sep. 7, 1993
104B	270	Jun. 17 - Sep. 7, 1993
104C	288	Jun. 16 - Sep. 15, 1994
104D	125	Jun. 8 - Aug. 22, 1995
104E	120	Jun. 8 - Aug. 22, 1995

3. Variable stars

In this paper we present results for 42 variables identified in the five observed fields. All of them are new discoveries and were assigned names OGLEGC212 − 216, OGLEGC218 − 223 and OGLEGC225 − 255. Names OGLEGC217 and OGLEGC224 were given to previously known variables $V9$ and $V3$ (e.g. Hogg 1973). Photometry

Table 2. Equatorial coordinates for the centers of fields 104A-E

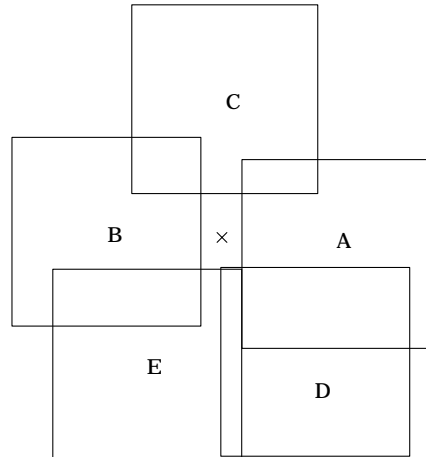| Field	RA(1950) h:m:s	DEC(1950) deg:′ : ″
104A	0:19:52.7	−72:22:45
104B	0:23:53.1	−72:21:01
104C	0:21:47.9	−72:10:35
104D	0:20:14.7	−72:31:14
104E	0:23:10.4	−72:31:22

Fig. 1. A schematic chart showing location of fields 104A-E. The cluster center is marked with a cross. Each field covers 14.7×14.7 armin^2. North is up and east is to the left

obtained for these two stars was poor because their images were badly overexposed on most of analyzed frames. Therefore, we decided to drop OGLEGC217 = $V9$ and OGLEGC224 = $V3$ from our list of variables. Our survey did not cover the central part of the cluster which was invesigated recently by Edmonds et al. (1996).

The rectangular and equatorial coordinates of the 42 newly identified variables are listed in Table 4[3]. The rectangular coordinates correspond to positions of variables on the V-band "template" images. These images allow easy identification of all objects listed in Table 4. The name of the field in which a given variable can be identified is given in the 6th column. All frames collected by the OGLE team were deposited at the NASA NSS Data

[3]   In fact variability of OGLEGC212, 213, 214, 216, 243, 245 and 246 was reported recently by Kaluzny et al. (1997c). These authors surveyed a western part of the cluster covering a region overlapping with fields 104A and 104C. It is encouraging that all but one variable from Kaluzny et al. (1997c) were recovered in the current study. We missed variable $V8$ which is very faint and was not included on the list of template stars for the field 104A.
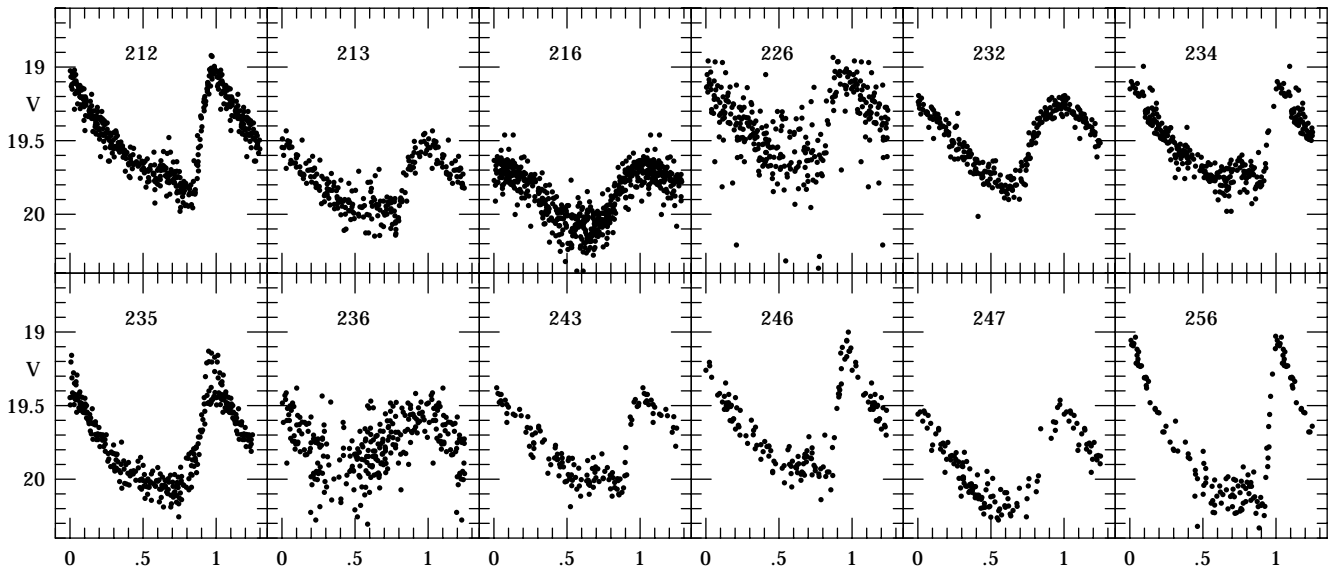
Fig. 2. Phased *V* light curves for RR Lyr stars from the SMC. Inserted labels give the names of variables

Center[4]. Frames mr5228, mr5227, mr7890, mr14597 and mr14595 were used as templates for fields 104A, 104B, 104C, 104D and 104E, respectively. The transformation from rectangular to equatorial coordinates was derived from positions of stars which could be matched with objects from the astrometric list kindly provided by Kyle Cudworth. The number of "transformation stars" identified in a given field ranged from 55 to 100. The adopted frame solutions reproduce equatorial coordinates of these stars with residuals rarely exceeding 0.5 arcsec. According to Cudworth the absolute accuracy of equatorial coordinates for stars from his table is not worse than 2″.

Our sample of variables includes 13 RR Lyr stars. Table 5 lists basic characteristics of the light curves of these stars. The mean *V* magnitudes were calculated by numerically integrating the phased light curves after converting them into an intensity scale. Photometric data for the remaining variables are given in Table 6. The *V − I* colors listed in Tables 5 and 6 were measured at random phases. For each of fields we used a single exposure in the *I* band bracketed by two exposures in the *V* band. To determine the periods of identified variables we used an *aov* statistic (Schwarzenberg-Czerny 1989, 1991). This statistic allows – in particular – reliable determination of

periods for variables with non-sinusoidal light curves (eg. eclipsing binaries). Phased light curves of RR Lyr stars are shown in Figs. 2 and 3 while Fig. 4 presents phased light curves for the remaining variables with determined periods. Time domain light curves for these variables for which we were unable to determine periods are shown in Fig. 5.

Figure 6 shows the location of all variables with known colors on the cluster color-magnitude diagram (CMD). For the RR Lyr stars marked positions correspond to the intensity-averaged magnitudes. For the remaining variables we marked positions corresponding to the magnitude at maximum light. All but one RR Lyr stars are grouped around $V \approx 19.5$ indicating that they belong to the SMC. RR Lyr variable OGLEGC223 is a background object in the galactic halo.

There are 12 certain eclipsing binaries in our sample of variables. This group of stars is dominated by contact binaries with EW-type light curves and periods shorter than 0.4 day. The only 3 stars whose light curves indicate a detached or semi-detached configuration are OGLEGC228, OGLEGC240 and OGLEGC253. OGLEGC240 is a detached binary with an EA-type light curve. The light curve of this variable is relatively noisy due to the faintness of the object. None the less examination of the individual frames leaves no doubts about the reality of the observed changes. The blue color and apparent magnitude of OGLEGC240 indicates that it is an A spectral type binary in the SMC.
OGLEGC228 shows a light curve typical of semi-detached binaries. This star is located among candidate blue-stragglers on the cluster CMD. OGLEGC253 is also a potential blue straggler. Its light curve shows two minima of very different depth but we cannot exclude possibility

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[4] The OGLE data (FITS images) are accessible to astronomical community from the NASA NSS Data Center. Send e-mail to: archives@nssdc.gfc.nasa.gov with the subject line: REQUEST OGLE ALL and put requested frame numbers (in the form MR00NNNN where NNNN stands for frame number according to OGLE notation), one per line, in the body of the message. Requested frames will be available using an "anonymous ftp" service from nssdc.gfc.nasa.gov host in location shown in the return e-mail message from archives@nssdc.gsfc.nasa.gov

Table 3. Basic statistical data for stars in fields 104A-E examined for variability. The data are given in bins 0.5 mag wide. Columns 2, 4, 6, 8 and 10 give *median* value of *rms* for a given bin. Columns 3, 5, 7, 9 and 11 give the numbers of stars examined for variability

| | 104A | | 104B | | 104C | | 104D | | 104E | |
V	$< \text{rms} >$	N	$< \text{rms} >$	N	$< \text{rms} >$	N	$< \text{rms} >$	N	$< \text{rms} >$	N
14.25	0.014	214	0.014	196	0.021	100	0.016	112	0.012	86
14.75	0.017	118	0.015	112	0.014	65	0.012	54	0.011	69
15.25	0.016	109	0.015	115	0.014	62	0.012	63	0.013	57
15.75	0.015	153	0.016	165	0.012	117	0.017	93	0.012	67
16.25	0.018	240	0.019	244	0.016	152	0.018	122	0.017	111
16.75	0.026	434	0.023	499	0.018	261	0.019	222	0.020	213
17.25	0.027	2057	0.027	2181	0.022	1273	0.023	1064	0.022	1017
17.75	0.032	3149	0.032	3248	0.025	1922	0.026	1734	0.026	1584
18.25	0.041	3973	0.039	4089	0.031	2486	0.034	2292	0.033	2179
18.75	0.052	4574	0.054	4884	0.042	3193	0.044	2697	0.044	2622
19.25	0.072	4515	0.071	5000	0.055	3746	0.058	3029	0.061	2984
19.75	0.102	3803	0.100	4248	0.076	3727	0.081	2537	0.086	2930
20.25	0.148	2986	0.144	3029	0.114	3456	0.119	2118	0.127	2579

that the components of this binary are in geometrical contact. Several systems with light curves similar to the light curve of OGLEGC253 were analyzed during last decade (e.g. Hilditch et al. 1989). Although most of detected binaries are candidate blue stragglers, there are four contact systems located slightly to the red of the cluster main sequence. These four binaries are potential main sequence systems belonging to 47 Tuc. We shall return below to the question about membership of identified contact binaries.

Variables which could not be classified as either RR Lyr stars or eclipsing binaries are generally red stars with periods ranging from 2 days to several weeks. Six red variables which are located on or near the subgiant branch of 47 Tuc can be considered candidates for cluster members. Recently Edmonds & Gilliland (1996) reported discovery of low amplitude variability among a large fraction of K giants in 47 Tuc. Using the data collected with the HST they estimated that most of variable giants have periods between 2 and 4 days and V amplitudes in the range $5 - 25$ mmag. Edmonds & Gilliliand (1996) argue that the observed variability of K giants from 47 Tuc is caused by low-overtone pulsations. The variable K giants from our sample have periods ranging from 2 to 36 days and show full amplitudes in the V band ranging from 0.08 to 0.18 mag. Based on the quality of our data we estimate conservatively that we should be able to detect any periodic variables among cluster giants with periods up to 2 weeks and full amplitudes exceeding 0.05 mag. We note that six candidates for variable K giants identified by us can easily be studied spectroscopically. Such observations would answer the question about the mechanism of observed photometric variability. Observed light variations are sufficiently large to imply detectable changes of $V_{\rm rad}$ if the variability is indeed due to pulsations.

Variables with $V - I > 1.1$ and $V > 15.5$ are likely to be evolved stars on the AGB in the SMC. We note

that SMC stars can be easily distinguished from 47 Tuc members based on their radial velocities (heliocentric radial velocities of SMC and 47 Tuc are $+175$ km/s and -18.7 km/s, respectively).

We consider some of our period determinations as preliminary. Particularly, for OGLEGC229 we adopted $P = 8.38$ d because the light curve seems to show two distinct minima. However, we cannot exclude the possibility that the correct period is in fact half this value. Also the period of OGLEGC240 can be half the adopted value of $P = 4.32$ d. For $P = 2.16$ d our light curve of OGLEGC240 would show just one detectable eclipse.
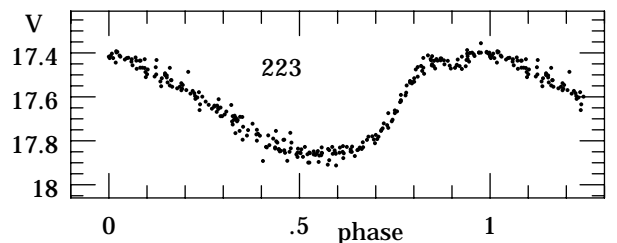

Fig. 3. Phased V light curve for the halo RR Lyr star OGLEGC223

3.1. Cluster membership of the contact binaries

The 47 Tuc cluster is located at a hight galactic latitude of $b = -45$ deg. However, we cannot assume that all eclipsing binaries listed in Table 6 are cluster members. In particular, faint contact binaries with $V > 16$ are known to occur at high galactic latitudes (e.g. Saha 1984). We have applied the absolute brightness calibration established by Rucinski (1995) to calculate M_V for the newly discovered contact binaries. Rucinski's calibration gives M_V as
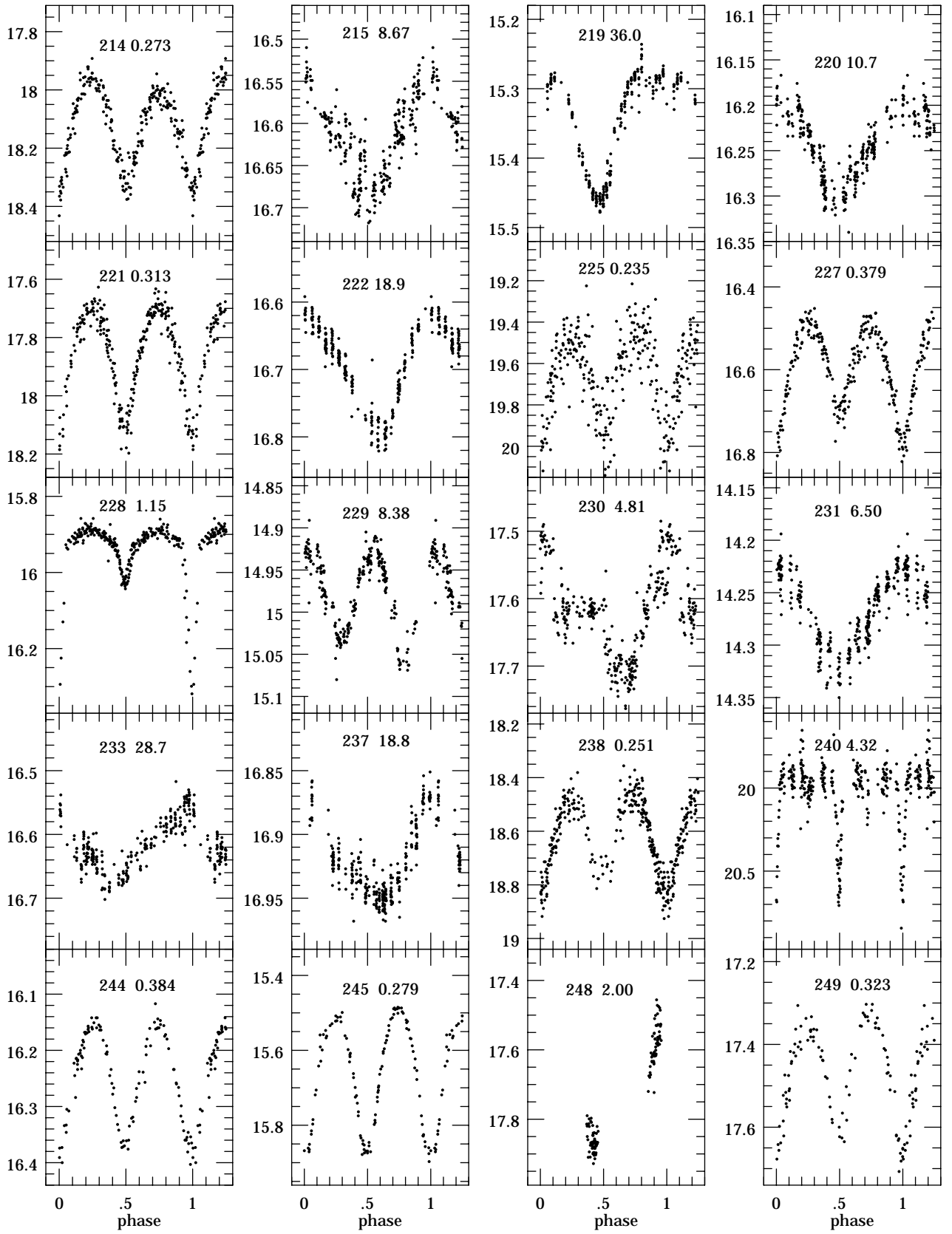
Fig. 4. Phased *V* light curves for the variables listed in Table 6. Inserted labels give the names of variables and their periods in days
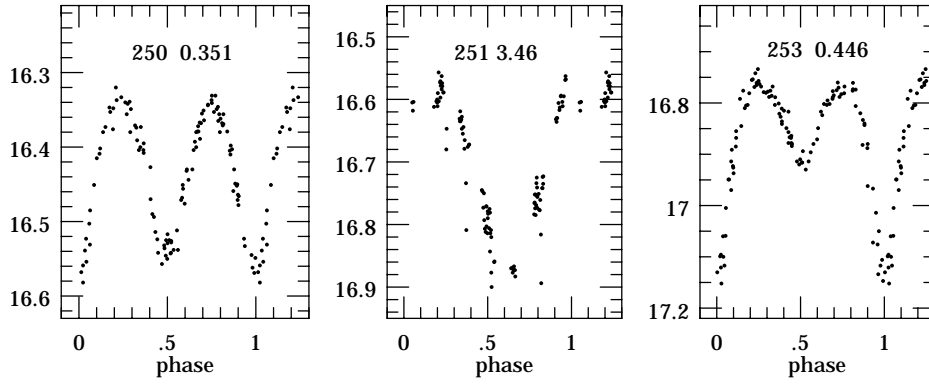
Fig. 4. continued

Table 4. Rectangular and equatorial coordinates for variables identified in the field of 47 Tuc. The X and Y coordinates give positions of the variables on the template images (see text for details)

Name	X	Y	RA(1950) h:m:s	Dec(1950) deg:′ : ″	Field
OGLEGC212	220.9	254.7	0:18:41.83	−72:28:44.7	A
OGLEGC213	226.8	1488.2	0:18:33.61	−72:19:49.3	A
OGLEGC214	993.9	1581.3	0:19:45.95	−72:18:42.8	A
OGLEGC215	1338.7	541.9	0:20:26.80	−72:26:01.4	A
OGLEGC216	1364.1	1905.1	0:20:18.63	−72:16:09.3	A
OGLEGC218	1706.3	1622.4	0:20:53.31	−72:17:59.4	A
OGLEGC219	344.5	244.3	0:22:54.32	−72:27:00.8	B
OGLEGC220	206.5	1776.8	0:22:30.21	−72:16:00.3	B
OGLEGC221	390.8	1673.4	0:22:48.44	−72:16:39.2	B
OGLEGC222	643.2	280.3	0:23:22.66	−72:26:35.0	B
OGLEGC223	768.9	816.9	0:23:30.69	−72:22:37.9	B
OGLEGC225	709.6	1398.1	0:23:20.72	−72:18:27.9	B
OGLEGC226	931.0	1853.5	0:23:38.38	−72:15:02.5	B
OGLEGC227	1014.1	90.7	0:23:59.63	−72:27:44.3	B
OGLEGC228	1041.4	657.1	0:23:57.90	−72:23:37.6	B
OGLEGC229	1023.4	1208.5	0:23:52.00	−72:19:39.2	B
OGLEGC230	1131.5	1315.2	0:24:01.46	−72:18:49.1	B
OGLEGC231	1070.9	1853.6	0:23:51.64	−72:14:57.5	B
OGLEGC232	1512.2	176.1	0:24:46.64	−72:26:49.3	B
OGLEGC233	1784.4	591.1	0:25:09.02	−72:23:39.6	B
OGLEGC234	163.2	618.6	0:20:29.83	−72:13:58.7	C
OGLEGC235	223.1	1394.6	0:20:30.00	−72:08:20.0	C
OGLEGC236	800.0	337.9	0:21:32.23	−72:15:38.6	C
OGLEGC237	1403.4	1232.5	0:22:22.42	−72:08:48.9	C
OGLEGC238	1800.1	661.7	0:23:04.39	−72:12:41.6	C
OGLEGC239	1359.7	528.5	0:22:23.80	−72:13:55.8	C
OGLEGC240	1552.8	1853.8	0:22:31.56	−72:04:13.9	C
OGLEGC241	1649.5	992.6	0:22:47.51	−72:10:23.8	C
OGLEGC242	130.6	969.0	0:18:49.43	−72:32:03.6	D
OGLEGC243	328.9	931.3	0:19:08.78	−72:32:14.1	D
OGLEGC244	1467.4	389.3	0:21:02.32	−72:35:33.2	D
OGLEGC245	1227.3	1183.7	0:20:33.52	−72:29:56.4	D
OGLEGC246	1074.1	1119.8	0:20:19.25	−72:30:29.1	D
OGLEGC247	1559.2	285.6	0:21:11.95	−72:36:15.1	D
OGLEGC248	1604.9	520.4	0:21:14.64	−72:34:31.7	D
OGLEGC249	698.3	12.0	0:22:46.26	−72:38:49.3	E
OGLEGC250	930.6	1371.6	0:22:59.38	−72:28:51.8	E
OGLEGC251	542.1	1778.9	0:22:19.39	−72:26:07.2	E
OGLEGC252	1171.0	909.6	0:23:25.73	−72:32:04.6	E
OGLEGC253	1863.2	873.3	0:24:32.62	−72:31:57.2	E
OGLEGC254	1629.1	1072.4	0:24:08.63	−72:30:38.8	E
OGLEGC255	1540.6	1294.4	0:23:58.50	−72:29:05.4	E

Table 5. Light curve parameters for RR Lyr stars from the field of 47 Tuc. A_V is the full range of variability

Name OGLEGC	P day	$V − I$	V mean	A_V
212	0.6946	0.63	19.5	0.8
213	0.6329	0.56	19.8	0.4
216	0.3617	0.47	19.9	0.4
223	0.2971	0.33	17.6	0.45
226	0.6474	?	19.4	0.45
232	0.3635	0.53	19.5	0.5
234	0.6159	0.79	19.55	0.6
235	0.5317	0.42	19.8	0.6
236	0.5083	0.77	19.8	0.3
243	0.6255	0.56	19.8	0.55
246	0.5719	0.80	19.65	0.8
247	0.5115	0.51	19.9	0.65
255	0.5251	0.50	19.8	1.0

a function of period, unreddened color $(V−I)_0$ and metallicity:

$$M_V^{\mathrm{cal}} = -4.43 \log(P) + 3.63(V − I)_0 − 0.31 − 0.12 \times [\mathrm{Fe/H}]. \qquad (1)$$

We adopted for all systems $[\mathrm{Fe/H}] = −0.76$ and $E(V − I) = 0.05$ (Harris 1996). Figure 7 shows the period versus an apparent distance modulus diagram for contact binaries identified in fields 104A-E. An apparent distance modulus was calculated for each system as a difference between its V_{max} magnitude and M_V^{cal}. An apparent distance modulus for 47 Tuc is estimated at $(m − M)_V = 13.21$ (Harris 1996). The only system with significantly deviating value of $(m−M)_V$ is OGLEGC245. This binary is most probably a foreground variable. The remaining 8 systems plotted in Fig. 7 are likely members of the cluster.

3.2. Completeness of the survey for contact binaries

Our survey resulted in the identification of 8 contact binaries which are likely members of the cluster and 2

Table 6. Light-curve parameters for eclipsing binaries and red variables identified in the field of 47 Tuc. Certain eclipsing systems and likely K giants belonging to the cluster are marked in the second column

Name OGLEGC	Type	Period days	$V - I$	V_{max}	V_{min}
214	Ecl	0.2737	0.82	17.96	18.34
215		8.666	1.14	16.56	16.68
218		?	1.69	15.80	16.17
219	K	36.05	1.08	15.28	15.46
220	K	10.69	1.03	16.265	16.34
221	Ecl	0.3135	0.79	17.78	18.22
222	K	18.93	0.95	16.62	16.80
225	Ecl	0.2346	1.04	19.47	20.0
227	Ecl	0.3788	0.52	16.49	16.77
228	Ecl	1.1504	0.34	15.90	16.30
229	K	8.378	1.06	14.92	15.05
230		4.814	1.23	17.51	17.71
231	K	6.498	0.93	14.225	14.325
233		28.69	1.45	16.55	16.72
237	K	18.80	0.85	16.87	16.95
238	Ecl	0.2506	0.77	18.46	18.80
239		?	1.53	16.58	16.67
240	Ecl	4.3158	0.00	19.93	20.65
241		?	1.67	16.72	16.83
242		?	2.48	16.55	17.42
244	Ecl	0.3837	0.51	16.16	16.38
245	Ecl	0.2789	0.69	15.49	15.87
248		1.9967?	1.26	17.55:	?
249	Ecl	0.3226	0.64	17.33	17.66
250	Ecl	0.3514	0.43	16.34	16.56
251		3.4629	1.12	16.56	16.87
252		?	2.90	17.04	16.68
253	Ecl	0.4462	0.57	16.77	17.12
254		?	1.81	16.47	16.62

Table 7. Results of a test with artificial variables. Columns 2-5 give numbers of recovered variables. See text for details

Range of V	Field 104B Case-I	Field 104B Case-II	Field 104E Case-I	Field 104E Case-II
$16.0 - 17.0$	89	90	99	99
$17.0 - 18.0$	88	94	90	94
$18.0 - 18.5$	81	96	89	94
$18.5 - 19.0$	74	89	73	92
$19.0 - 19.5$	52	88	35	88

Table 8. List of frames used for construction of CMD's for fields 104A-E

Frame	Field	T_{exp} s	Filter	FWHM arcsec
mr5228	104A	420	V	1.1
mr5176	104A	120	V	1.2
mr8181	104A	60	V	1.05
mr5382	104A	400	I	1.2
mr5381	104A	120	I	1.25
mr8182	104A	10	I	1.35
mr5227	104B	420	V	1.0
mr5177	104B	120	V	1.4
mr8184	104B	60	V	1.0
mr5385	104B	400	I	1.3
mr5386	104B	120	I	1.45
mr8183	104B	10	V	1.0
mr7889	104C	500	V	1.0
mr7902	104C	50	V	1.0
mr7903	104C	500	I	1.0
mr7904	104C	50	I	1.05
mr14597	104D	420	V	1.05
mr14589	104D	61	V	1.05
mr14592	104D	420	I	1.20
mr14591	104D	60	I	1.15
mr14595	104E	420	V	1.1
mr14596	104E	60	V	1.0
mr14593	104E	420	I	1.1
mr14594	104E	60	I	1.1

exhibiting eclipses deeper than about 0.3 mag (see Tables 1 and 3).

A hint that our survey is quite complete with respect to faint short period variables comes from the fact that we detected 12 RR Lyr stars from the SMC. Graham (1975) searched for variables a field covering an area 1 deg ×1.3 deg. His field was centered north of 47 Tuc and included a small part of the cluster. Graham identified 76 RR Lyr stars, with surface density of 0.016 variables per arcmin^2. The effective area covered by our survey was 935 arcmin^2 yelding surface density of RR Lyr stars of about 0.013 variables per arcmin^2. Apparently we did not miss in our survey too many RR Lyr stars from the SMC.

The relative frequency of occurrence of *detectable* contact binaries in our sample is $f_c = 8/76119 \approx 1.0E - 4$. This frequency is more than an order of magnitude lower than the binary frequency observed for fields containing galactic open clusters (Kaluzny & Rucinski 1993; Mazur et al. 1995) and for fields located near the galactic center which were monitored by OGLE (Rucinski 1997). Recent surveys of globular clusters M 71 (Yan & Mateo 1994) and M 5 (Yan & Reed 1996) gave $f_c = 4/5300 \approx 7.5E - 4$ and $f_c = 5/3600 \approx 1.4E - 3$, respectively.

To get a quantitative estimate of the completeness of our sample we performed tests with artificial variables for fields 104B and 104E. Results of test for field 104B should apply also to the fields 104A and 104C because all three fields contain similar numbers of measurable stars and were observed with comparable frequency. Similarly,
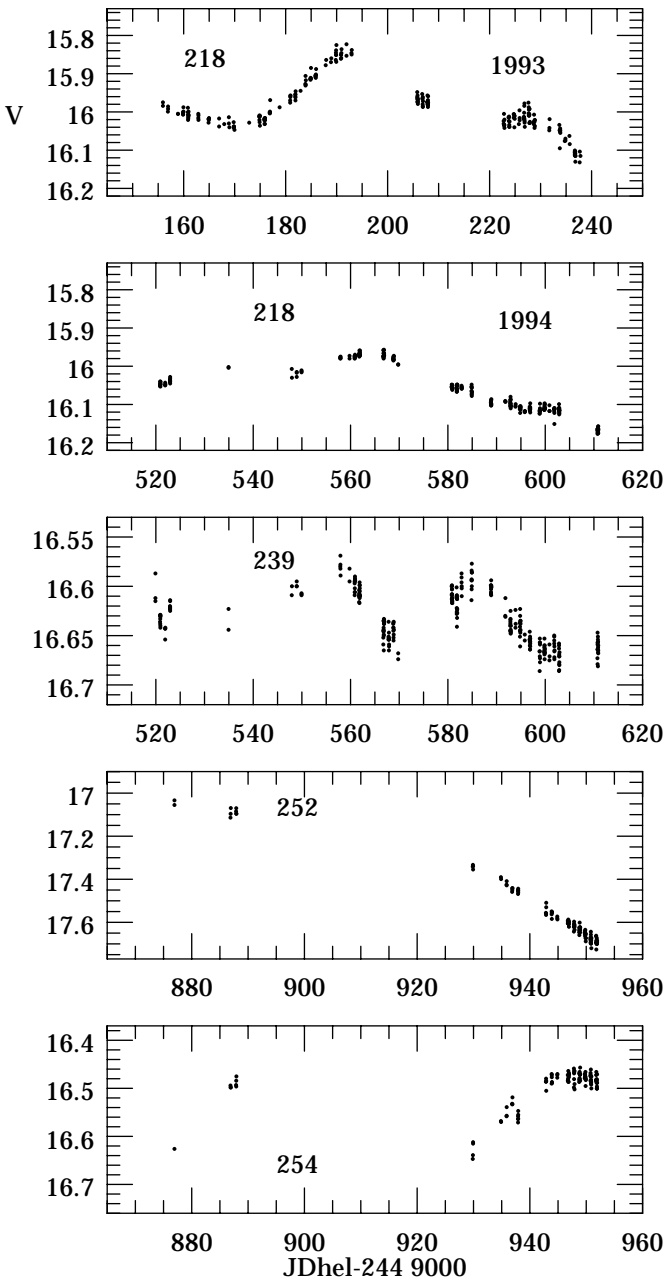
detached/semidetached binaries which are possible blue stragglers belonging to the cluster. Only 4 contact systems were identified below the cluster turnoff. These numbers are surprisingly small considering that we analyzed the light curves of 76119 stars with average magnitudes $V < 19.5$, mostly main sequence stars belonging to the cluster. For the clusters members the limiting magnitude $V = 19.5$ corresponds to $M_V = 6.1$. We adopted here $(m - M)_V = 13.4$ for the apparent distance modulus of 47 Tuc (Hesser et al. 1987). The quality and quantity of photometry was sufficient to allow the detection of potential eclipsing binaries with periods shorter than 1 day and

Fig. 5. Time domain light curves for variables with unknown periods. Light curves for 1993 and 1994 seasons are shown for OGLEGC218

rate cases were considered. Case I – a contact binary with the inclination $i = 60$ deg and the mass ratio $q = 0.10$. Case II – a contact binary with the inclination $i = 70$ deg and the mass ratio $q = 0.30$. In both cases the so called "fill-out-parameter" was set to $f = 0.5$. The light curves corresponding to Case-I and Case-II show depths of primary eclipses equal to 0.15 and 0.32 mag, respectively. For each of the artificially generated light curves a period was drawn in a random way from the range $0.2 - 0.45$ d. Also the phase for the first point of the given light curve was randomly selected. The simulated light curves were then analysed in the manner as the observed light curves. Specifically, we applied a procedure based on the χ^2 test. The number of artificial variables which were "recovered" for Cases I-II and 5 magnitude ranges is given in Table 7. It may be concluded that the completeness of our sample of contact binaries is better than 88% for systems with $V < 19.5$ and depth of eclipses higher than 0.32 mag. For systems with full amplitudes as small as 0.15 mag the completeness is higher than 73% for $V < 19.0$.

It has been noted by Kaluzny et al. (1997c) that the frequency of occurrence of contact binaries in 47 Tuc is very low in comparison with open clusters and with several globular clusters which have been recently surveyed for eclipsing binaries by various groups. However, results presented here are based on a larger sample of stars than the sample analyzed by Kaluzny et al. (1997c). A more extended discussion of this topic is given in Kaluzny et al. (1997c). It is appropriate to note at this point that the low frequency of occurrence of contact binaries among 47 Tuc stars was first suggested by Shara et al. (1988).

4. The color-magnitude diagrams

As a by product of our survey we obtained V vs. $V - I$ CMD's for all 5 monitored fields. In Fig. 8 we show the CMD's for fields 104A and 104E. For each field the final photometry was obtained by merging measurements extracted from "long" and "short" exposures. Photometry obtained for fields 104A-B extends to brighter magnitudes than photometry obtained for fields 104C-E. The frames used for construction of CMD's of monitored fields are listed in Table 8. Any detailed analysis of these data is beyond the scope of this paper. We note only that our data can be used to select candidates for cluster blue stragglers.

All photometry presented in this section was submitted in tabular form to the editors of A&A and is available in electronic form to all interested readers (see Appendix A). The potential users of this photometry should be aware about possibility of some systematic errors of the photometry. These errors are most likely to be significant for relatively faint stars. The CCD chip used for observations by the OGLE suffers from some nonlinearity. More details on this subject can be found in Paper I.
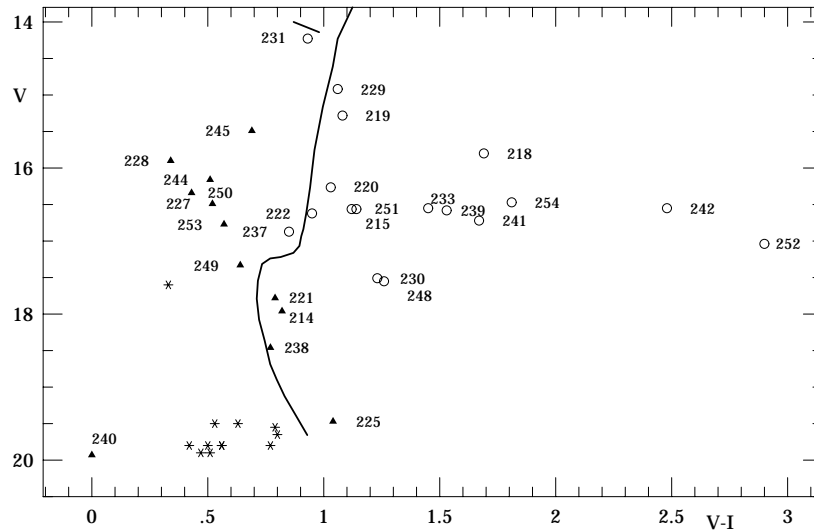
results for field 104E should apply to field 104D. For both fields we selected 5 samples of objects from sets of stars whose light curves were examined for variability. The brightest sample included stars with $16.0 < V < 17.0$ and the faintest sample included stars with $19.0 < V < 19.5$. a total of 100 stars were selected at random from each sample. The observed light curves of these stars were then interlaced with the synthetic light curves of model contact binaries. The synthetic light curves were generated using a simple prescription given by Rucinski (1993). Two sepa-

Fig. 6. A schematic CMD for 47 Tuc with the positions of the variables from fields A-E marked. The triangles represent certain eclipsing binaries, the asterisks RR Lyr stars and the open circles the remaining variables. Positions of stars from Table 6 are labeled
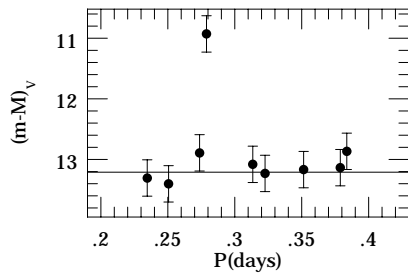

Fig. 7. Period vs. apparent distance modulus diagram for contact binaries from the field of 47 Tuc. A horizontal line at $(m - M)_V = 13.21$ corresponds to the distance modulus of the cluster. Error bars correspond to the formal uncertainty in the absolute magnitudes derived using Rucinski's (1995) calibration

5. Summary

The main result of our survey is the identification of 8 contact binaries which are likely members of 47 Tuc and 2 detached/semidetached binaries which are possible blue stragglers. Particularly interesting is the bright binary OGLEGC228. By combining radial velocity curves with photometry one would be able to determine an accurate distance to this system. That would in turn give distance to the cluster if the binary is indeed member of 47 Tuc. We failed to identify any detached eclipsing systems among cluster turnoff stars. Three such systems with periods ranging from 1.5 to 4.6 day were identified in our survey of ω Cen (Papers I and II).

We identified 6 variables which are likely to be red giants belonging to the cluster. These stars exhibit mod-

ulation of luminosity with periods ranging from 2 to 36 days and full amplitudes in the V band ranging from 0.08 to 0.18 mag. They may represent high-amplitude counterparts of low-amplitude variable K giants identified in the central region of 47 Tuc by Edmonds & Gilliland (1996).

6. Appendix A

Tables containing light curves of all variables discussed in this paper as well as tables with VI photometry for the surveyed fields are published by A&A at the centre de Données de Strasbourg, where they are available in electronic form: See the Editorial in A&A 1993, Vol. 280, page E1.

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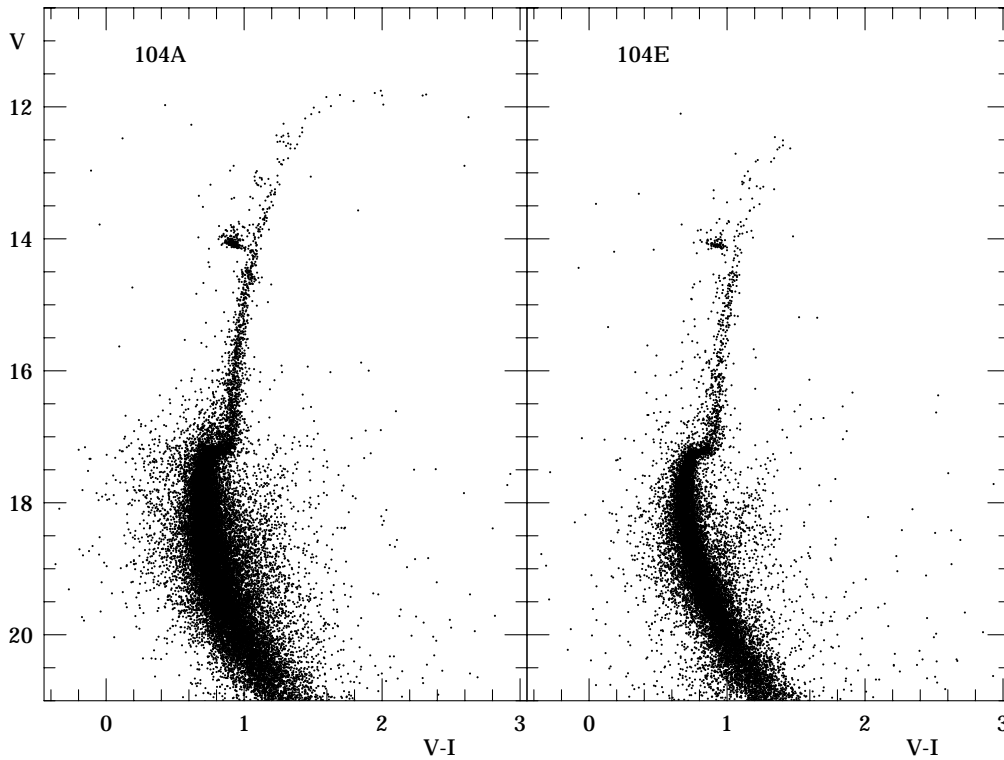Kaluzny J., Rucinski S.M., 1993, in Blue Stragglers, Saffer R.A. (ed.). San Francisco, ASP Conf. Ser. 53, 164

Fig. 8. The CMDs for fields 104A (left) and 104E (right)

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