The Optical Gravitational Lensing Experiment. Cepheids in the Magellanic Clouds. II. Single-Mode Second Overtone Cepheids in the Small Magellanic Cloud*

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ABSTRACT

We present a sample of 13 candidates for single-mode second overtone Cepheids discovered in the 2.4 square degree area of the SMC bar during the OGLE microlensing search. All candidates passed four photometric tests: analysis of Fourier parameters of the light curve, R_{21} and ϕ_{21}, position in the period-luminosity diagram and location in the color-magnitude diagram.

The stars form a very homogeneous group of objects with very similar light curves of low amplitude and almost sinusoidal shape. Their color indices $B-V$ and $V-I$ are also very similar and the objects determine the observational blue edge of the instability strip of the first overtone Cepheids. This is the first firm sample of the single-mode second overtone Cepheids detected so far.

1 Introduction

The existence of second overtone pulsations in the Cepheid variable stars was predicted by Stobie (1969). For years this was only a theoretical possibility as no such object has been found. The first indication of existence of second mode pulsations was the discovery of double-mode Cepheid CO Aur (Mantegazza 1983) which is believed to pulsate simultaneously in the first

*Based on observations obtained with the 1.3 m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington.

and second overtones. This is the only Galactic object of that kind. Another Galactic object, HR 7308, was proposed to be a single-mode second overtone Cepheid candidate (Burki *et al.* 1986).

The major breakthrough in this field occurred when huge photometric databases collected during the microlensing search programs were analyzed. Two targets of microlensing searches, the Large and Small Magellanic Clouds are ideal objects for Cepheid study possessing huge population of these stars, additionally located at approximately the same distance.

The MACHO team reported discovery of 45 double-mode Cepheids pulsating in the first and second overtones in the LMC (Alcock *et al.* 1999) and 20 such objects in the SMC (Alcock *et al.* 1997). The EROS team discovered additional sample of 7 such objects in the SMC (Beaulieu *et al.* 1997).

The MACHO team also undertook a search for Cepheids pulsating solely in the second overtone (Alcock *et al.* 1999). Based on Fourier decomposition of light curves of double-mode Cepheids pulsating in the first and second overtones they characterized properties of second overtone pulsations and provided constraints on Fourier parameters allowing separation of the second overtone pulsators from Cepheids of other type. They found one potential candidate for single-mode second overtone Cepheid in their sample of about 1400 Cepheids in the LMC. Also theoretical modeling of second overtone pulsations in Cepheids by Antonello and Kanbur (1997) confirmed qualitatively the MACHO team results.

The large amount of BVI photometric data of the SMC collected during the Optical Gravitational Lensing Experiment (OGLE) provides an unique material for analysis of variable stars in this galaxy. Lower metallicity of the SMC as compared to the LMC makes this object particularly attractive for searching for second overtone pulsating Cepheids because such stars should be more numerous in low metallicity environment (Antonello and Kanbur 1997). Indeed, the largest sample of double-mode Cepheids (23 pulsating in the fundamental mode and first overtone and 70 pulsating in the first and second overtones) discovered so far in one galaxy was reported by the OGLE team (Udalski *et al.* 1999).

In this paper we describe the search for pure second overtone pulsations, *i.e.*, single-mode second overtone Cepheids. The search among about 2300 Cepheids detected in the 2.4 square degree area in the central bar of the SMC led to discovery of 13 candidates – the first firm sample of single-mode second overtone pulsating Cepheids.

2 Observations

All observations presented in this paper were carried out during the second phase of the OGLE experiment with the 1.3-m Warsaw telescope at the Las Campanas Observatory, Chile, which is operated by the Carnegie Institution of Washington. The telescope was equipped with the "first generation" camera with a SITe 2048×2048 CCD detector working in the drift-scan mode. The pixel size was 24 μm giving the 0.417 arcsec/pixel scale. Observations of the SMC were performed in the "slow" reading mode of the CCD detector with the gain 3.8 e^-/ADU and readout noise about 5.4 e^-. Details of the instrumentation setup can be found in Udalski, Kubiak and Szymański (1997).

Observations of the SMC started on June 26, 1997. As the microlensing search is planned to last for a few years, observations of selected fields will be continued during the following seasons. In this paper we present data collected up to March 4, 1998. Observations were obtained in the standard BVI-bands with majority of measurements made in the I-band.

Photometric data collected during the first observing season of the SMC for 11 fields (SMC_SC1–SMC_SC11) covered about 2.4 square degree of the central parts of the SMC and were used to construct the BVI photometric maps of the SMC (Udalski *et al.* 1998). The reader is referred to that paper for more details about methods of data reduction, tests on quality of photometric data, astrometry, location of observed fields etc.

3 Search for Second Overtone Cepheids

In a search for single-mode second overtone Cepheid candidates in our sample of SMC Cepheids we followed strategy outlined by the MACHO group (Alcock *et al.* 1999), who used the double-mode Cepheids pulsating in the first and second overtones to characterize the most important properties of second overtone pulsations. Based on analysis of parameters R_{21} and ϕ_{21} of Fourier decomposition of light curves of double-mode Cepheids they concluded that the second overtone pulsations should be small amplitude, almost sinusoidal light variations. They constrained area in the R_{21} *vs.* $\log P$ and ϕ_{21} *vs.* $\log P$ diagrams where the second overtone pulsations could be distinguishable from the first overtone and fundamental mode Cepheids and found one possible candidate for second overtone Cepheid in their sample of about 1400 LMC Cepheids. Similar conclusions on properties of second overtone single-mode pulsations were drawn by Antonello and Kanbur (1997) from theoretical models.

With larger sample of double-mode Cepheids found by the OGLE team in the SMC (Udalski *et al.* 1999), we were in position to perform independent analysis of properties of second overtone pulsations in double-mode Cepheids. Appendix C in Udalski *et al.* (1999) presents light curves of double-mode Cepheids decomposed to both pulsation modes (column 3 – second overtone pulsations, column 4 – first overtone pulsations). It is striking that the light curves of the second overtone pulsations look almost identical – they are indeed small amplitude, almost sinusoidal light variations. More quantitative conclusions can be drawn from Fig. 4 of Udalski *et al.* (1999) which presents R_{21} *vs.* $\log P$ and ϕ_{21} *vs.* $\log P$ diagrams for Cepheids in the SMC with positions of double-mode first and second overtone Cepheids. It is clear that in most cases the R_{21} values of the second overtone pulsations are small ($R_{21} < 0.2$; if this parameter is not statistically significant R_{21} is shown as zero, meaning sinusoidal light curve). The area limited by $R_{21} < 0.2$ and $\log P < 0$ is the best region where the second overtone pulsations can be distinguished from the first overtone Cepheids which practically do not populate that area. Similarly, the ϕ_{21} values of the second overtone Cepheids mostly populate regions above the sequence of the first overtone Cepheids in the ϕ_{21} *vs.* $\log P$ diagram. This is another way of distinguishing objects pulsating in these modes. Thus, our results are in good agreement with Alcock *et al.* (1999) study of LMC double-mode Cepheids. R_{21} and ϕ_{21} parameters of the Fourier decomposition of the Cepheid light curve provide two important constraints which single-mode second overtone Cepheid candidates should fulfill.

The shape of the light curve is not sufficient to make sound identification of the potential single-mode second overtone Cepheids. It is well known that many variable objects reveal small amplitude almost sinusoidal light variations. The best example are ellipsoidal binary variable stars in which changing aspects during orbital motion of distorted components result in low amplitude sinusoidal variations. Another examples are binary stars with reflex effect, spotted stars etc. Fortunately, the Cepheid variable stars occupy a well defined region in the color-magnitude diagram (CMD), practically not populated by stars of other type. Thus, by constraining colors and luminosities of potential candidates in the CMD diagram one can get rid of most of contaminating stars: ellipsoidal variable stars which are usually hot main sequence objects, spotted stars – usually late type giants or main sequence stars of low luminosity etc.

Another constraint can be imposed by analyzing the period of variability and the mean luminosity of candidates. It is well known that the period of the first overtone pulsations is in double-mode Cepheids by factor of 0.74 shorter than that of the fundamental mode. Thus, the single mode first overtone pulsators should be shifted by $|\log 0.74| = 0.131$ to the left in the period-luminosity (PL) diagram (I *vs.* $\log P$). Indeed, clear separation of the first overtone and fundamental mode Cepheids is observed in PL diagrams of Cepheids from the LMC (Alcock *et al.* 1999) and SMC (see below).

By analogy the period of the second overtone Cepheids is by factor of 0.805 shorter than the period of the first overtone variations in double-mode Cepheids. Therefore one can expect that the single-mode second overtone Cepheids should be shifted by $|\log 0.805| = 0.094$ to the left from the first overtone Cepheid sequence in the PL diagram. The shift is smaller than in the case of the fundamental mode and first overtone Cepheids. Natural width of the sequence of first overtone Cepheids, additionally broadened by differential reddening and observational errors, makes this constraint not very strong, if considered alone. Nevertheless, it is an important part of the multi-constraint test described above.

4 Results of Search

We started our search from the analysis of Fourier parameters of light curve decomposition of all 2300 Cepheids detected in the SMC. We selected candidates with R_{21} in the regions of R_{21} *vs.* $\log P$ diagram where the second overtone pulsations in double-mode Cepheids are located. Then we eliminated all objects for which ϕ_{21} parameter fell in the first overtone pulsation sequence in the ϕ_{21} *vs.* $\log P$ diagram.

In the next step we limited ourselves to the analysis of Cepheids for which *VI*-band observations were available. Only stars from the following part of the CMD diagram were considered: $I < 18.5$ mag, $0.25 < (V - I) < 1.3$ mag. Finally, we checked positions of our all second overtone Cepheid candidates in the PL diagram. Some of them were located in the first overtone PL sequence and as such they were rejected from the final list.

As a test we performed similar Fourier analysis of the remaining variable star candidates discovered in the OGLE variable stars search. Some candidates passed R_{21} and ϕ_{21} criteria but, as we expected, they turned out to be ellipsoidal variable stars located in the upper part of the main sequence with $V - I < 0.2$.

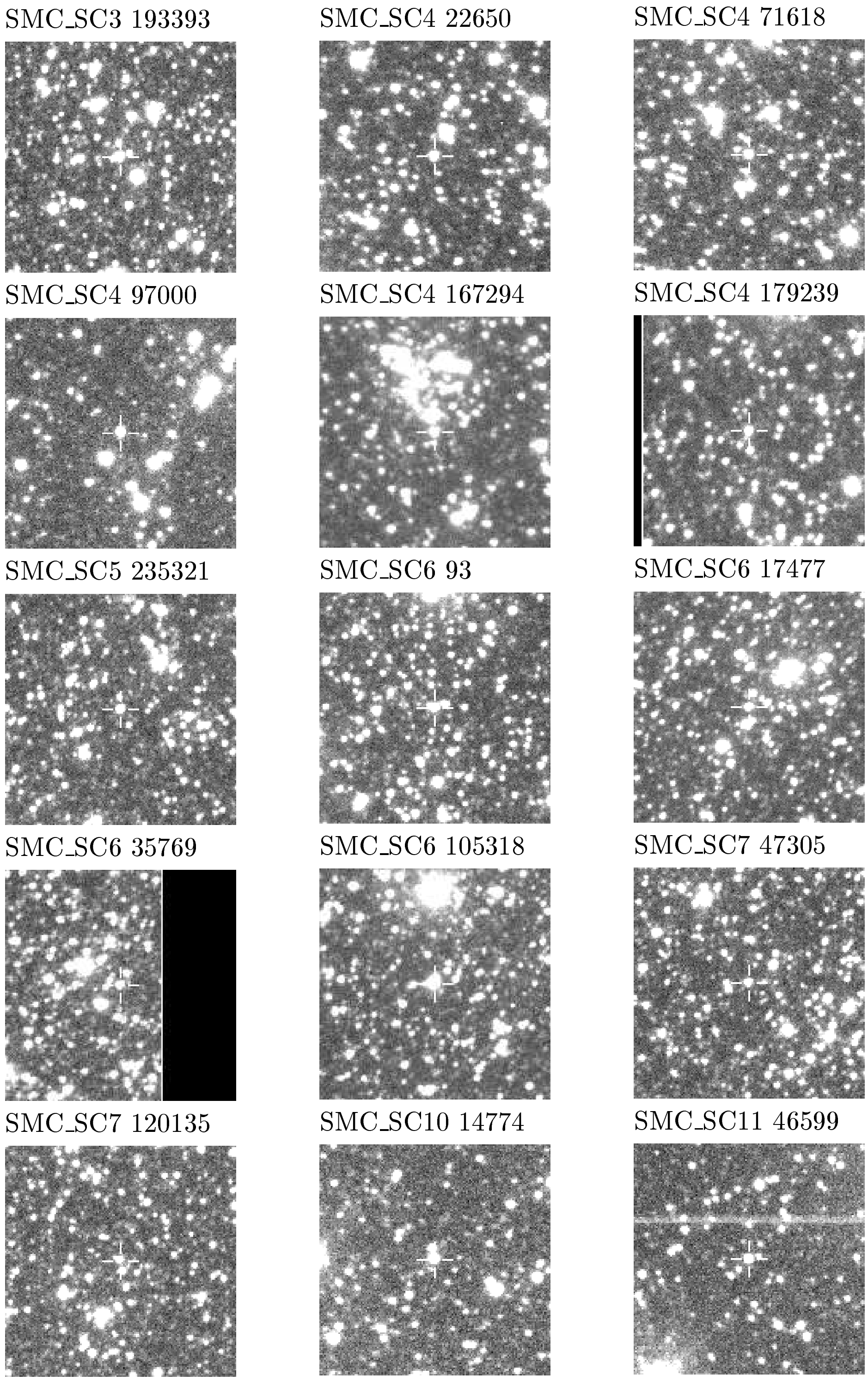

Fig. 1. Finding charts for single-mode second overtone Cepheid candidates.

Table 1

Single-mode second overtone Cepheid candidates in the SMC

Field	Star No.	RA(J2000)	DEC(J2000)	P [days]	R_{21}	ϕ_{21}	I [mag]	$B-V$ [mag]	$V-I$ [mag]	Remarks
SMC_SC3	193393	$0^h44^m56.^s96$	$-73°19'37.''9$	0.63056	0.000	–	15.946	0.115	0.362	uncertain
SMC_SC4	22650	$0^h46^m00.^s23$	$-73°10'32.''3$	0.78255	0.195	4.581	16.535	0.328	0.452	
SMC_SC4	71618	$0^h46^m33.^s19$	$-73°07'45.''4$	0.70772	0.116	4.753	16.682	0.279	0.432	
SMC_SC4	97000	$0^h46^m32.^s54$	$-72°40'31.''0$	0.70837	0.145	4.787	16.762	0.311	0.467	
SMC_SC4	167294	$0^h47^m51.^s99$	$-73°13'33.''2$	1.12408	0.000	–	15.982	0.221	0.536	
SMC_SC4	179239	$0^h48^m29.^s24$	$-73°01'16.''1$	0.63053	0.000	–	16.838	0.242	0.423	
SMC_SC5	235321	$0^h50^m10.^s09$	$-72°41'51.''1$	0.73759	0.124	2.063	16.743	0.284	0.433	
SMC_SC6	93	$0^h52^m04.^s47$	$-73°24'43.''2$	0.92159	0.000	–	16.176	0.250	0.344	
SMC_SC6	17477	$0^h51^m57.^s62$	$-73°14'47.''9$	0.57225	0.133	2.414	16.756	0.113	0.416	
SMC_SC6	35769	$0^h51^m26.^s26$	$-73°02'58.''0$	0.59371	0.274	2.976	16.878	0.261	0.447	
SMC_SC6	105318	$0^h52^m30.^s84$	$-73°13'38.''4$	1.34489	0.061	5.893	14.598	0.077	0.337	uncertain
SMC_SC7	47305	$0^h54^m55.^s60$	$-72°44'04.''1$	0.65083	0.000	–	16.939	0.300	0.469	
SMC_SC7	120135	$0^h55^m14.^s35$	$-72°45'26.''8$	0.51687	0.000	–	17.267	0.267	0.441	
SMC_SC10	14774	$1^h03^m37.^s13$	$-72°32'22.''7$	0.73343	0.000	–	16.335	0.282	0.452	
SMC_SC11	46599	$1^h07^m30.^s54$	$-72°38'41.''2$	0.70284	0.000	–	16.772	0.291	0.469	

We were left with a list of 15 candidates for single-mode second overtone Cepheids which passed all four constraints: R_{21} and ϕ_{21} values, CMD location and PL position. Table 1 contains basic parameters of these stars: ID, equatorial coordinates (J2000), period in days, R_{21} and ϕ_{21} Fourier parameters and intensity-mean BVI photometry. Finding charts for all candidates are presented in Fig. 1. The size of the I-band subframes is 60×60 arcsec; North is up and East to the left. Fig. 2 shows the phased light curves of all stars. BVI photometry of all objects will be available from the OGLE Internet archive when the catalog of Cepheids in the SMC is released.

Fig. 3 shows R_{21} *vs.* $\log P$ and ϕ_{21} *vs.* $\log P$ diagrams with positions of candidates marked by open circles. $R_{21}=0$ means non-significant value of this parameter, *i.e.*, sinusoidal light curve. In this case ϕ_{21} is not defined.

Fig. 4 presents PL diagrams with positions of candidates marked by star symbols. Abscissa in the upper panel of Fig. 4 is the intensity-mean I-band magnitude while in the lower panel the extinction insensitive magnitude $W_I=I-1.55\times(V-I)$. This parameter, W_I, removes effects of interstellar extinction and partially color term of the more general period-luminosity-color relation for Cepheids. The diagrams might still be slightly contam-

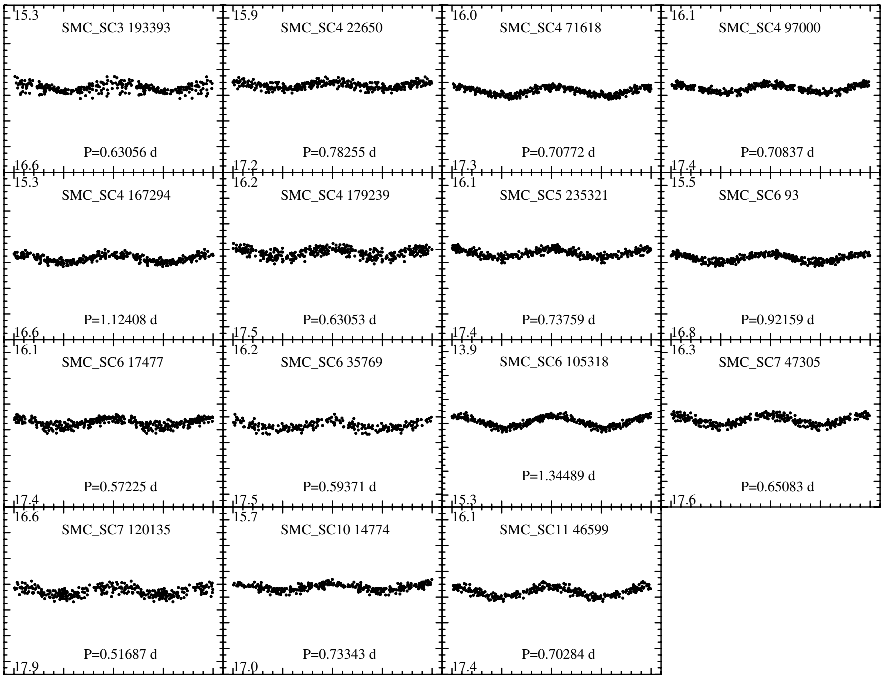

Fig. 2. Light curves of single-mode second overtone Cepheid candidates.

inated by non-Cepheids as the data come from the preliminary version of the OGLE catalog of Cepheids in the SMC. Nevertheless, the diagrams, in particular that presented in the lower panel of Fig. 4, are the most tight and most complete PL diagrams for classical Cepheids obtained so far.

It is difficult to assess completeness of the sample of second overtone candidates. The 16-17th mag objects with amplitude of 0.1 mag or below are close to the detection limit of the main OGLE variable star search. The best example are two candidates: SMC_SC4 179239 and SMC_SC6 35769 which are located close to the edge of appropriate fields. Therefore they should be also detected in the overlapping fields but they were not. In the case of SMC_SC4 179239 no periodicity was detected in the counterpart photometry due to somewhat larger errors of measurements. In the second case – the standard deviation of measurements of the counterpart of SMC_SC6 35769 was slightly below the limit separating variable and non-variable stars and this object was not checked for variability. Nevertheless light curves of both counterpart stars look almost identical like those of detected objects. We may conclude that more detailed reanalysis of the OGLE data of all

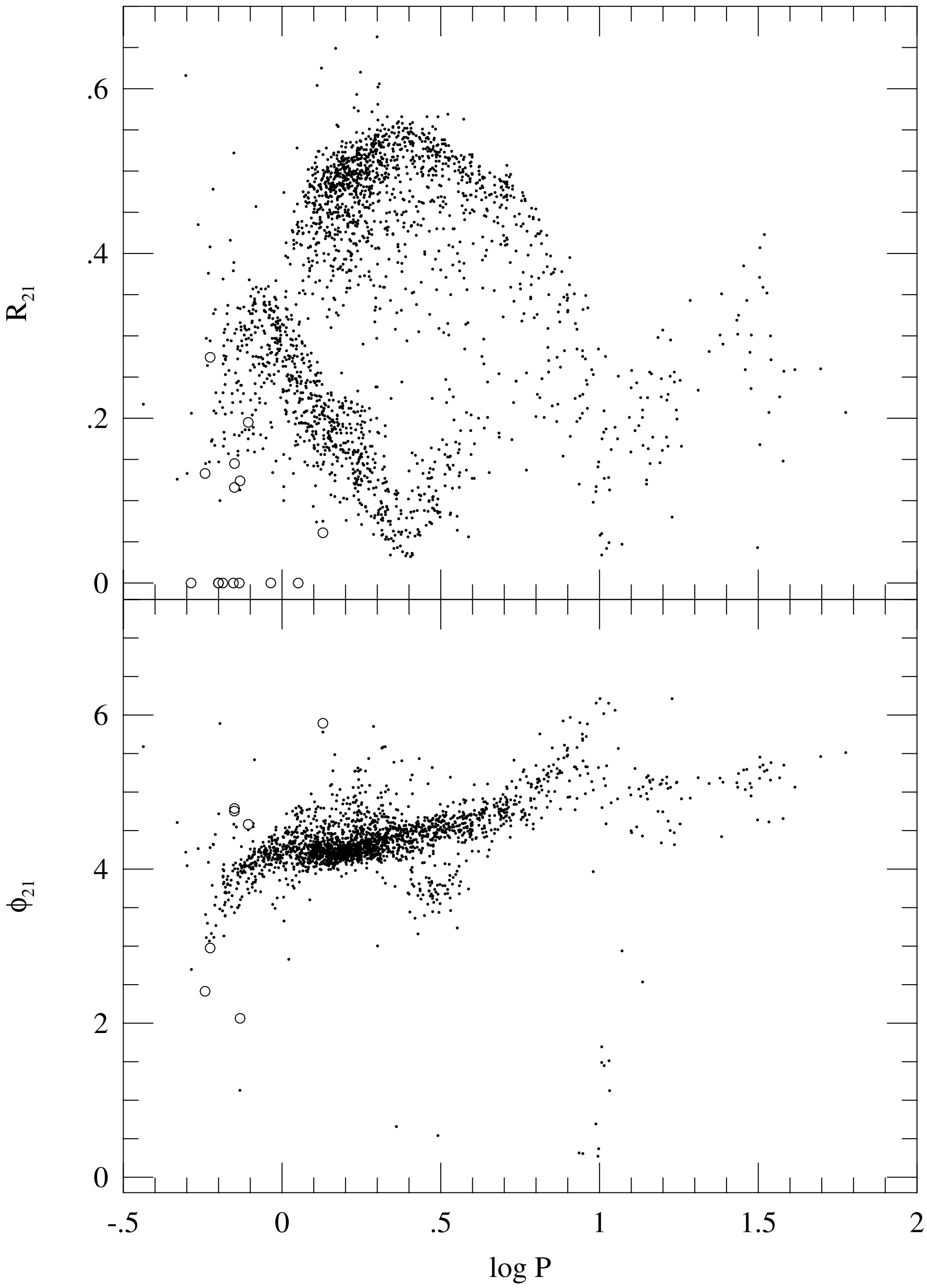

Fig. 3. R_{21} and ϕ_{21} *vs.* $\log P$ diagrams for single-mode Cepheids from the SMC (small dots). Large open circles mark values of the second overtone Cepheid candidates.

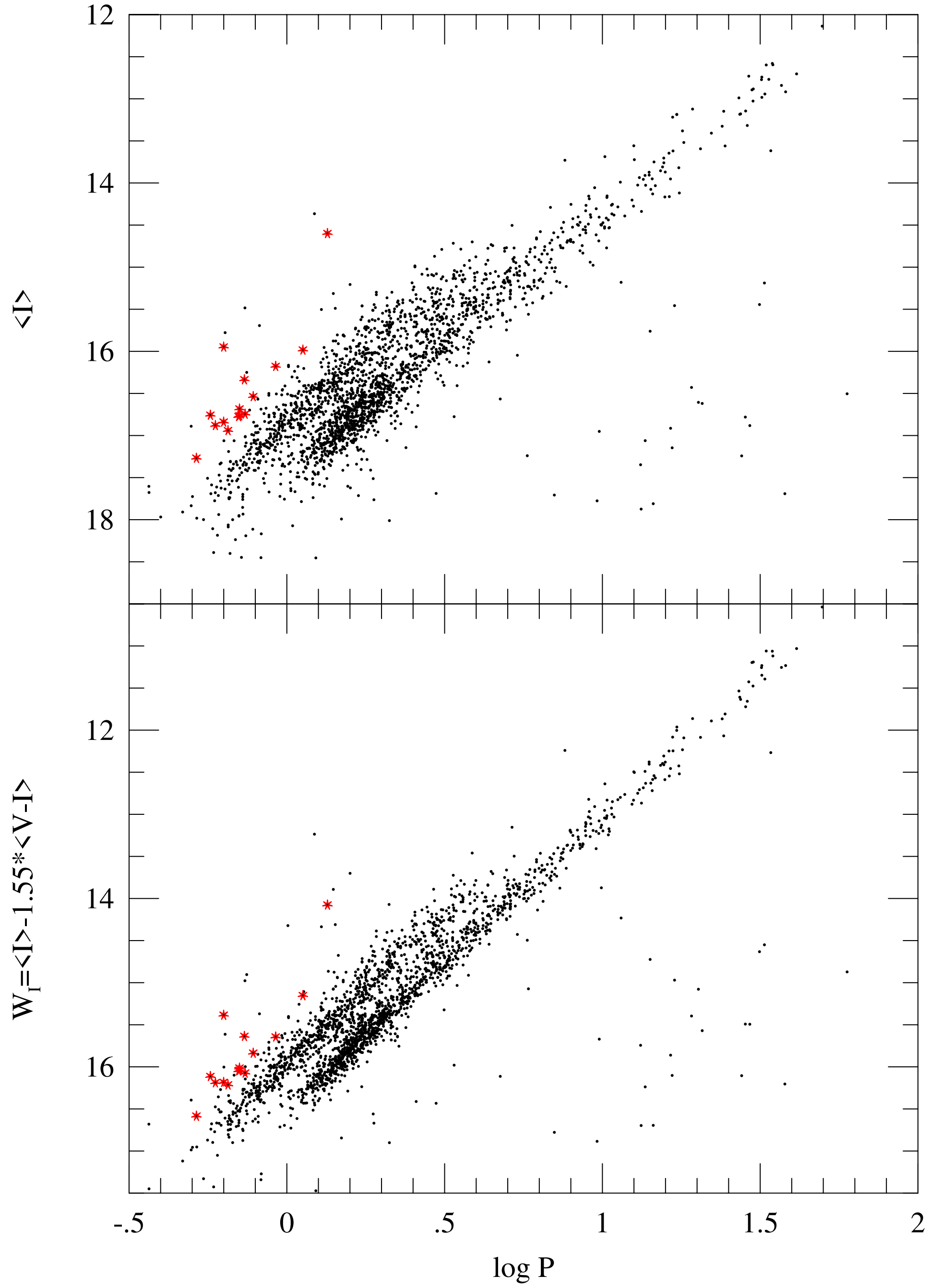

Fig. 4. Period-luminosity diagrams for Cepheids from the SMC. Star symbols mark positions of single-mode second overtone Cepheid candidates.

stars in the Cepheid range of the CMD diagram, focused on low amplitude variations can lead to discovery of a few more candidates for single-mode second overtone Cepheids.

5 Discussion

15 candidates for single-mode second overtone Cepheids were found among the variable stars detected in the 2.4 square degree field in the central part of the SMC. This is the first so numerous sample of such rare objects. Larger population of the second overtone Cepheids was predicted in lower metallicity environment by theory and it seems that this is indeed the case. Metallicity of the SMC is smaller than that of the LMC and Galaxy where only single candidates were proposed.

Are the selected objects indeed second overtone pulsators? The light curves of candidates presented in Fig. 2 show striking resemblance to the light curves of the second overtone pulsations in double-mode Cepheids (*cf.* Appendix C, column 3 Udalski *et al.* 1999). In most cases their light curves are almost sinusoidal, the amplitude in the I-band is about 0.1 mag. For many candidates the R_{21} parameter of Fourier decomposition of the light curve is statistically non-significant indicating sinusoidal light curve (ϕ_{21} is not defined). For the remaining objects R_{21} and ϕ_{21} values fall in similar regions where second overtone pulsation values in double-mode Cepheids can be found (Fig. 3 and Fig. 4 of Udalski *et al.* 1999).

Location of majority of objects in the PL diagrams (Fig. 4) is consistent with the expected location of the second overtone pulsators induced from the second to the first overtone period ratio in double-mode Cepheids. Two objects, however, namely SMC_SC3 193393 and SMC_SC6 105318, seem to be too bright and therefore they are uncertain candidates. The remaining candidates form a sequence parallel to the sequences of the first overtone and fundamental mode Cepheids, but more quantitative approximation of the PL relation for these objects would be premature due to limited number of candidates.

Fig. 5 shows the color-magnitude diagram of the field SMC_SC1. Only about 20% of stars from this field are plotted with tiny dots for clarity. Larger dots indicate positions of the first overtone (lighter points) and fundamental mode (darker points) Cepheids detected during the OGLE search in 11 fields in the SMC bar. The sample is corrected for difference of the mean reddening between SMC_SC1 and other fields as described in Udal-

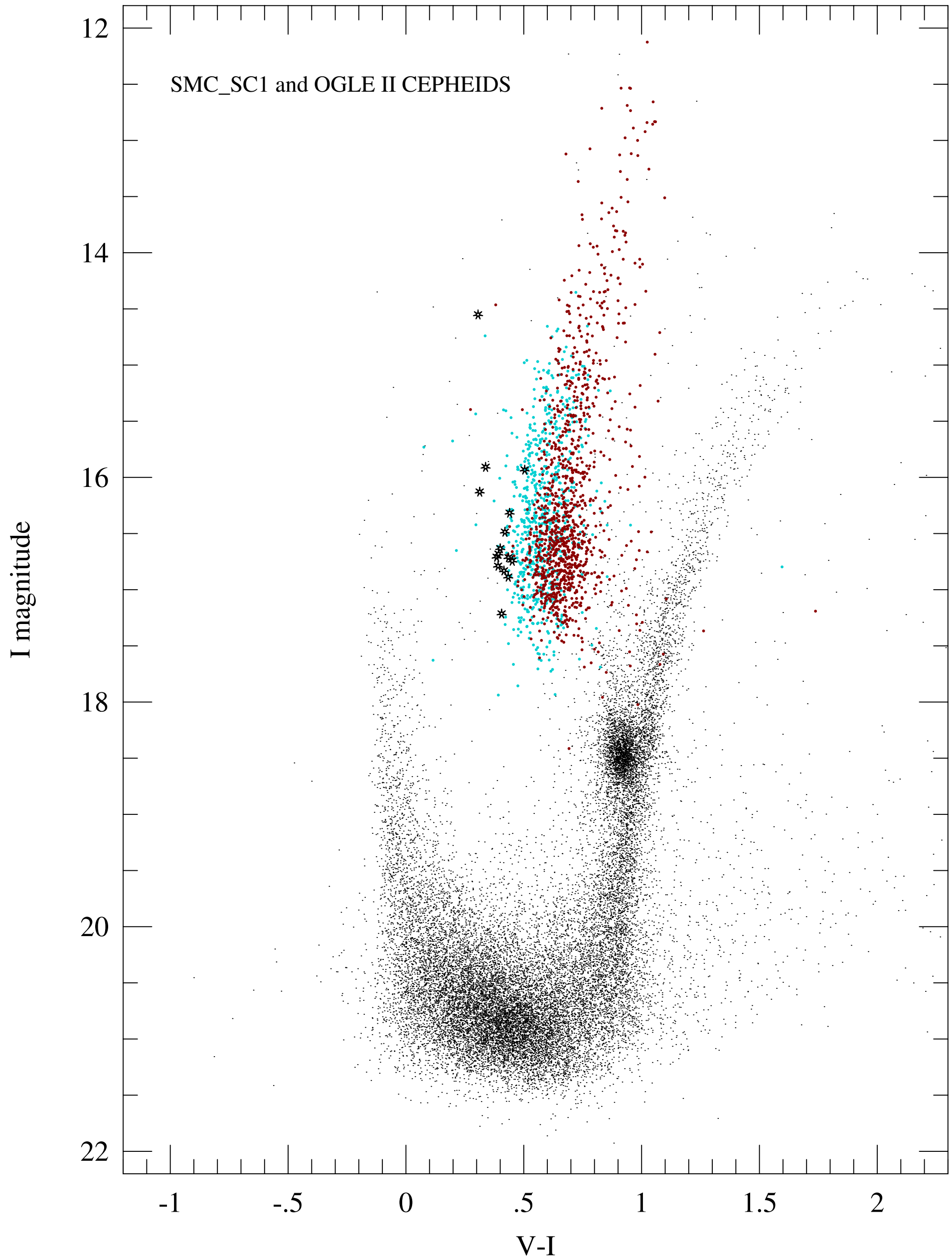

Fig. 5. Color-magnitude diagram of the SMC_SC1 field. Only about 20% of field stars are plotted by tiny dots. Larger dots show positions of single-mode fundamental type Cepheids (darker dots) and first overtone stars (lighter dots). Star symbols mark positions of the single-mode second overtone Cepheid candidates.

ski *et al.* (1999). The reddening to the SMC_SC1 field is estimated to be $E(V-I)=0.08$ (Udalski *et al.* 1999).

Star symbols show positions of the single-mode second overtone Cepheid candidates in the CMD diagram. Magnitudes and colors of all these stars were also corrected for the mean difference of reddening between fields and the reference SMC_SC1 field in the same way as for the remaining Cepheids.

One can notice that the second overtone Cepheid candidates form a very homogeneous group as far as not only morphology of the light curves but also photometric properties are concerned. Except for three objects, all the remaining candidates have very similar colors and they determine the observational blue edge of the instability strip of the first overtone Cepheids. This is exactly the location where one would expect second overtone objects. The mean $V-I$ color of this group is 0.414, thus the stars would be located at the end of the blue wing of the distribution of $V-I$ color indices of the first overtone Cepheids in the SMC (*cf.* Fig. 6 Udalski *et al.* 1999).

Two of three deviating objects in Fig. 5, namely SMC_SC3 193393 and SMC_SC6 105318, are the same stars which also deviate in the PL diagram. Their colors, in particular $B-V$, are too blue. Moreover, the mean level of brightness of both stars is changing by a few hundredths of magnitude in the time scale of months. Therefore variability of these objects is very likely of other origin, not related to pulsations. The third deviating object SMC_SC6 93 passes well the remaining tests. Also its $B-V$ color is close to the colors of other stars. Therefore we keep it in the list of single-mode second overtone Cepheids candidates.

Summarizing, the search for single-mode second overtone Cepheids in the SMC resulted in discovery of 13 firm candidates for the second overtone pulsators. They passed four photometric tests based on the Fourier decomposition of the light curve, location in the PL diagram and location in the CMD diagram. Selected stars form a very homogeneous group with very similar light curves of almost sinusoidal shape and small amplitude. They have very similar color indices and they determine the observational blue edge of the instability strip of the first overtone Cepheids. All these facts strongly support the hypothesis that the stars are indeed the Cepheids pulsating solely in the second overtone. This is the first firm sample of such objects detected so far.

Spectroscopic observations could provide additional information necessary to prove that the objects from the presented sample are indeed second overtone pulsating Cepheids. All stars are relatively bright and with the new large telescopes in southern hemisphere starting operation in the coming years, obtaining good resolution spectroscopy of candidates should be feasible in the near future.

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