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The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. VIII. Type II Cepheids in the Small Magellanic Cloud*

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ABSTRACT

The eighth part of the OGLE-III Catalog of Variable Stars (OIII-CVS) contains type II Cepheids in the Small Magellanic Cloud (SMC). The sample consists of 43 objects, including 17 BL Her, 17 W Vir and 9 RV Tau stars (first examples ever found in the SMC). Seven stars have been classified as peculiar W Vir stars – a recently identified subclass of type II Cepheids. These stars have distinctive light curves, are brighter and bluer than the ordinary W Vir variables. We confirm that a large fraction of the peculiar W Vir stars are members of binary systems.

Three type II Cepheids exhibit eclipsing variations superimposed on the pulsation light curves, and three other objects show long-period ellipsoidal variability. All stars with the indication of binarity display secondary periods which may be interpreted as amplitude and/or phase modulations of the pulsation light curves with periods equal to the orbital periods or half the orbital periods. We do not have any model for these modulations, however this phenomenon rules out a possibility of the optical blends of a pulsating star and a binary system.

For each object the multi-epoch *V*- and *I*-band photometry collected over 8 or 13 years of observations and finding charts are available to the astronomical community from the OGLE Internet archive.

Key words: *Cepheids – Stars: oscillations –Stars: Population II – Magellanic Clouds*

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

1. Introduction

Type II Cepheids (also called Population II Cepheids) are low-mass pulsating variable stars of the intermediate disk or halo population. They are divided into three groups, each one at a different evolutionary stage: BL Her with the shortest periods, W Vir with intermediate periods and RV Tau stars with the longest periods. BL Her stars are believed to evolve through the instability strip from the horizontal branch toward the asymptotic giant branch (AGB, Strom *et al.* 1970). W Vir stars loop into the instability strip as a result of the helium-shell-flash episodes which occur during the AGB stage (Schwarzschild and Härm 1970, Gingold 1976). RV Tau stars are post-AGB objects which cross the instability strip during their rapid evolution toward the white dwarf stage (Gingold 1974, Jura 1986).

To date, very few type II Cepheids have been known in the Small Magellanic Cloud (SMC). The first variable of this type was identified by Tifft (1963) in the vicinity of the globular cluster NGC 121. The catalog of variable stars in the SMC by Payne-Gaposchkin and Gaposchkin (1966) contained three type II Cepheids, of which one object – HV 206 – is now classified in the General Catalogue of Variable Stars (GCVS, Artyukhina *et al.* 1995) as a semiregular variable. Then, Geßner (1981) added XY Hyi to the list of known type II Cepheids in the SMC. This modest sample of type II Cepheids in the SMC was extended by Udalski *et al.* (1999), who studied the data collected during the second phase of the Optical Gravitational Lensing Experiment (OGLE-II). The OGLE-II catalog of Cepheids in the SMC contained a list of Cepheid-like variables which were fainter than fundamental-mode classical Cepheids. In the present study we examine this list and 11 objects classify as type II Cepheids. No RV Tau star in the SMC have been reported so far.

In this paper we increase the number of known type II Cepheids in the SMC to 43. Our investigation is based on the photometric data collected during the third phase of the OGLE project. This work is a part of the OGLE-III Catalog of Variable Stars (OIII-CVS) which is intended to include all variable sources monitored by the OGLE-III survey in the Magellanic Clouds and Galactic bulge. In the previous papers of this series we presented, among others, the sample of 203 type II Cepheids in the LMC[†] (Soszyński *et al.* 2008b, hereafter Paper I) and the catalog of 4630 classical Cepheids in the SMC (Soszyński *et al.* 2010, hereafter Paper II).

In Paper I we defined a class of peculiar W Vir stars. These objects have distinctive light curves, are brighter and bluer than the regular W Vir variables. High proportion of the peculiar W Vir stars show evidences of binarity (eclipsing or ellipsoidal variations). Matsunaga *et al.* (2009) noticed that the bright Galactic type II Cepheid, κ Pavonis, is likely to belong to this peculiar W Vir class. In this paper we confirm the classification proposed in Paper I. In the SMC seven peculiar W Vir stars are cataloged.

[†]The catalog of type II Cepheids in the LMC was extended by six objects comparing to the sample published originally.

2. Observational Data

The catalog has been prepared based on the photometric data collected in the course of the OGLE-III project with the 1.3-meter Warsaw telescope located at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution of Washington. The camera used in this stage of the OGLE project was a mosaic consisting of eight SITe 2048×4096 CCD detectors with a total field of view of about 35×35.5 arcmin. Details of the instrumentation setup can be found in Udalski (2003).

The OGLE-III fields in the SMC cover about 14 square degrees. This region was photometrically monitored from June 2001 to May 2009. Observations were obtained in two standard bands – I and V – however the sampling in the I-band is much denser (typically about 700 points) than in the V-band (50–70 points). The data were reduced using the Difference Image Analysis (DIA, Alard and Lupton 1998, Woźniak 2000). For more details of the data reductions, photometric calibrations and astrometric transformations see Udalski *et al.* (2008a).

The photometry of the stars located within the central 2.4 square degrees of the SMC was supplemented with the OGLE-II observations (Szymański 2005) obtained between 1997 and 2000. For individual objects the OGLE-II photometry was adjusted to agree with the OGLE-III light curves to account for shifts caused by different CCD pixel scales.

3. Selection and Classification of type II Cepheids

The selection process of type II Cepheids was similar to the procedure of identification of classical Cepheids in the SMC (Paper II). In brief, we performed a massive period search for over 6 million stars, *i.e.*, all objects photometrically monitored in the SMC by the OGLE-III survey (Udalski *et al.* 2008b). These computations were carried out at the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM) of the University of Warsaw. Stars with the most significant signal of periodicity (signal-to-noise ratio larger than 5) were used to construct the period–luminosity (PL) diagrams in V, I, and reddening-independent Wesenheit index $W_I = I - 1.55(V - I)$. Then, the light curves in the wide strip covering the PL relations for classical and type II Cepheids were visually examined and divided into pulsating-like, eclipsing-like and other variables.

The stars classified as possible pulsating variables were examined in detail and categorized into several groups: classical Cepheids (Paper II), type II Cepheids, RR Lyr stars, δ Sct stars and long-period variables. The final classification was based on the light curve morphology, luminosities and colors of the stars, including near-infrared data from the IRSF/SIRIUS survey (Kato et al. 2007). Objects with measurable proper motions were recognized as Galactic stars in the foreground of the SMC and removed from the sample.

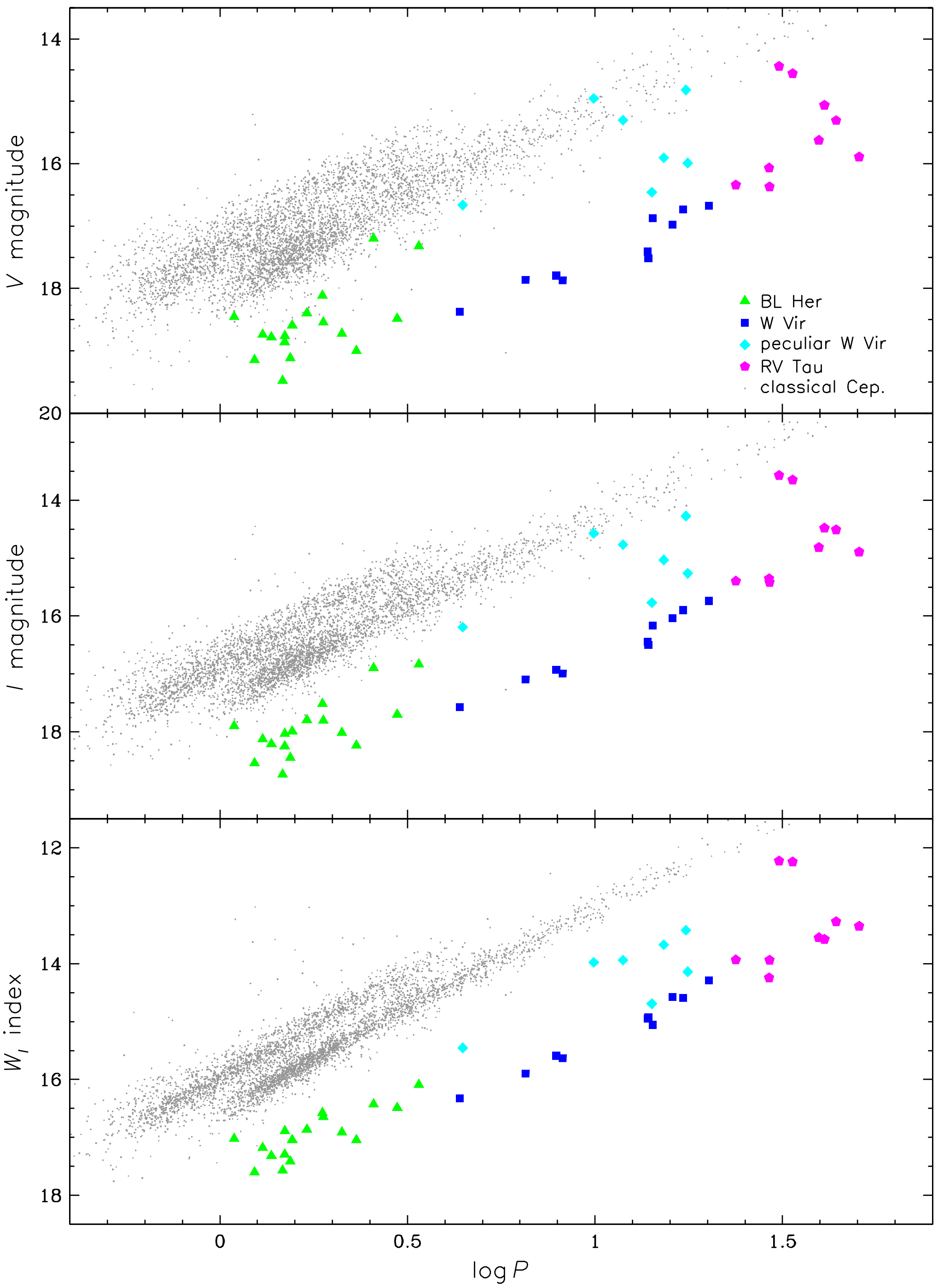

Fig. 1. Period–luminosity relations for Cepheids in the SMC. Green, blue and magenta symbols represent BL Her, W Vir and RV Tau stars, respectively. Cyan diamonds indicate peculiar W Vir stars. Small gray points show classical Cepheids cataloged in Paper II.

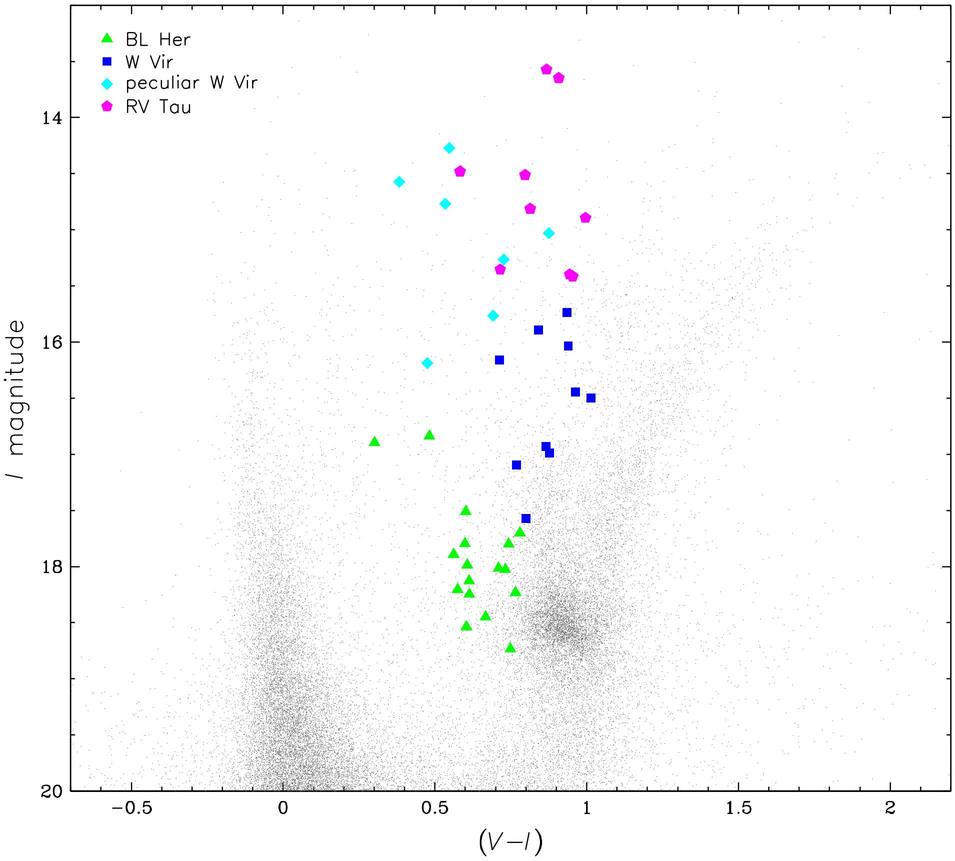

Fig. 2. Color–magnitude diagram for type II Cepheids in the SMC. Color symbols represent the same type of pulsators as in Fig. 1. The background gray points show stars from the subfield SMC100.1.

Our final list of type II Cepheids in the SMC contains 43 objects. We divided this sample into BL Her, ordinary W Vir, peculiar W Vir and RV Tau stars using generally the same criteria as in the LMC catalog (Paper I). As a boundary between RR Lyr and BL Her stars we adopted a period of 1 day. The transition between BL Her and W Vir stars was defined at $P = 4$ days and the upper boundary for W Vir stars was adopted at $P = 20$ days. The only exception was object OGLE-SMC-T2CEP-34 (with period of 20.12 days) which was classified as a W Vir star, because its light curve resembled that of W Vir rather than of RV Tau star.

Stars with longer periods were classified in our catalog as RV Tau variables, although only three of them show clear alternation of deep and shallow minima, *i.e.*, the characteristic feature of RV Tau stars. These three objects are the first definitive RV Tau stars known in the SMC. Among the other six long-period type II Cepheids, four display semiregular light curves and sometimes are referred to as SRd stars (yellow semiregulars). There is no doubt that RV Tau and SRd stars are closely related (*e.g.*, Percy and Mohammed 2004). Both classes are represented

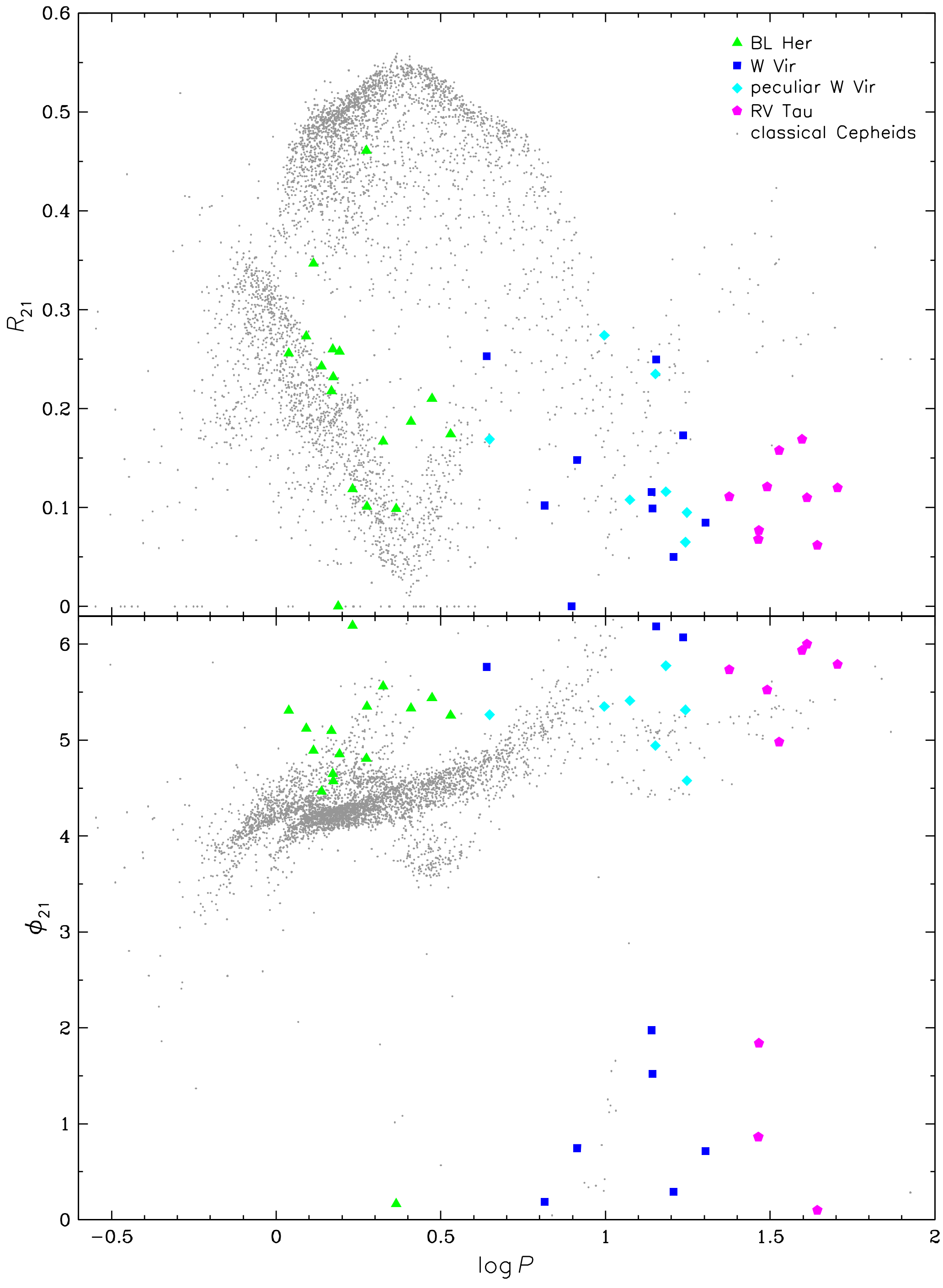

Fig. 3. Fourier parameters R_{21} and ϕ_{21} *vs.* $\log P$ for Cepheids in the SMC. Symbols represent the same type of stars as in Fig. 1.

by old, low-mass, pulsating supergiants, populating the same range of magnitudes and colors, and obeying the same PL relation. The remaining two stars are pulsating variables with eclipsing or ellipsoidal modulation (see Section 6). Their light curves, after prewhitening of the additional periodicities, are quite stable, and do not show alternations of cycles. Hereafter, all these long-period type II Cepheids are called RV Tau stars.

As in the LMC we divided W Vir stars into two groups: regular and peculiar variables. Objects of the latter class generally do not obey the PL relation of type II Cepheids (Fig. 1) – they are brighter and bluer than regular W Vir variables (Fig. 2). Peculiar W Vir stars differ from regular variables in the morphology of light curves, which is especially reflected in the Fourier coefficient ϕ_{21} (Simon and Lee 1981). In the $\log P - \phi_{21}$ diagram (Fig. 3) regular and peculiar W Vir stars are well separated. The difference between LMC and SMC peculiar W Vir stars lays in a different range of periods where these objects appear. In the LMC we did not find any peculiar W Vir star with a period longer than 10 days, while in the SMC we identified objects of that kind with periods ranging from 4.4 to 17.7 days, *i.e.*, practically in the whole range of periods covered by W Vir stars. Moreover, two type II Cepheids with periods longer than 30 days (OGLE-SMC-T2CEP-07 and OGLE-SMC-T2CEP-29), and classified as RV Tau variables, show features similar to the peculiar W Vir stars (see Section 6).

4. The Catalog

The OGLE-III catalog of type II Cepheids in the SMC comprises 43 objects: 17 BL Her, 17 W Vir (10 regular and 7 peculiar stars) and 9 RV Tau stars. Table 1 lists all the variables with their identifications in the OGLE and GCVS databases. The stars are organized in order of increasing right ascension and designated with symbols OGLE-SMC-T2CEP-NN, where NN is a two-digit consecutive number. The columns of the Table 1 are: object's designation, OGLE-III field and internal database number of the star (consistent with the photometric maps of the SMC by Udalski et al. 2008b), classification (BL Her, W Vir, peculiar W Vir, RV Tau), right ascension and declination for epoch J2000.0, cross-identifications with the OGLE-II photometric database (Szymański 2005), cross-identifications with the GCVS (Artyukhina et al. 1995), and other designations taken from the GCVS.

In Table 2 we present the basic observational parameters of the type II Cepheids from our catalog. The columns are as follows: *I*- and *V*-band intensity mean magnitudes, "single" pulsation periods (*i.e.*, intervals between successive minima) with uncertainties (derived with the TATRY code of Schwarzenberg-Czerny 1996), epochs of a maximum of light, peak-to-peak amplitudes in the *I*-band, and Fourier parameters R_{21}, ϕ_{21}, R_{31}, ϕ_{31} (Simon and Lee 1981) derived also for the *I*-band light curves.

The content of Tables 1 and 2 can be downloaded in the electronic form through

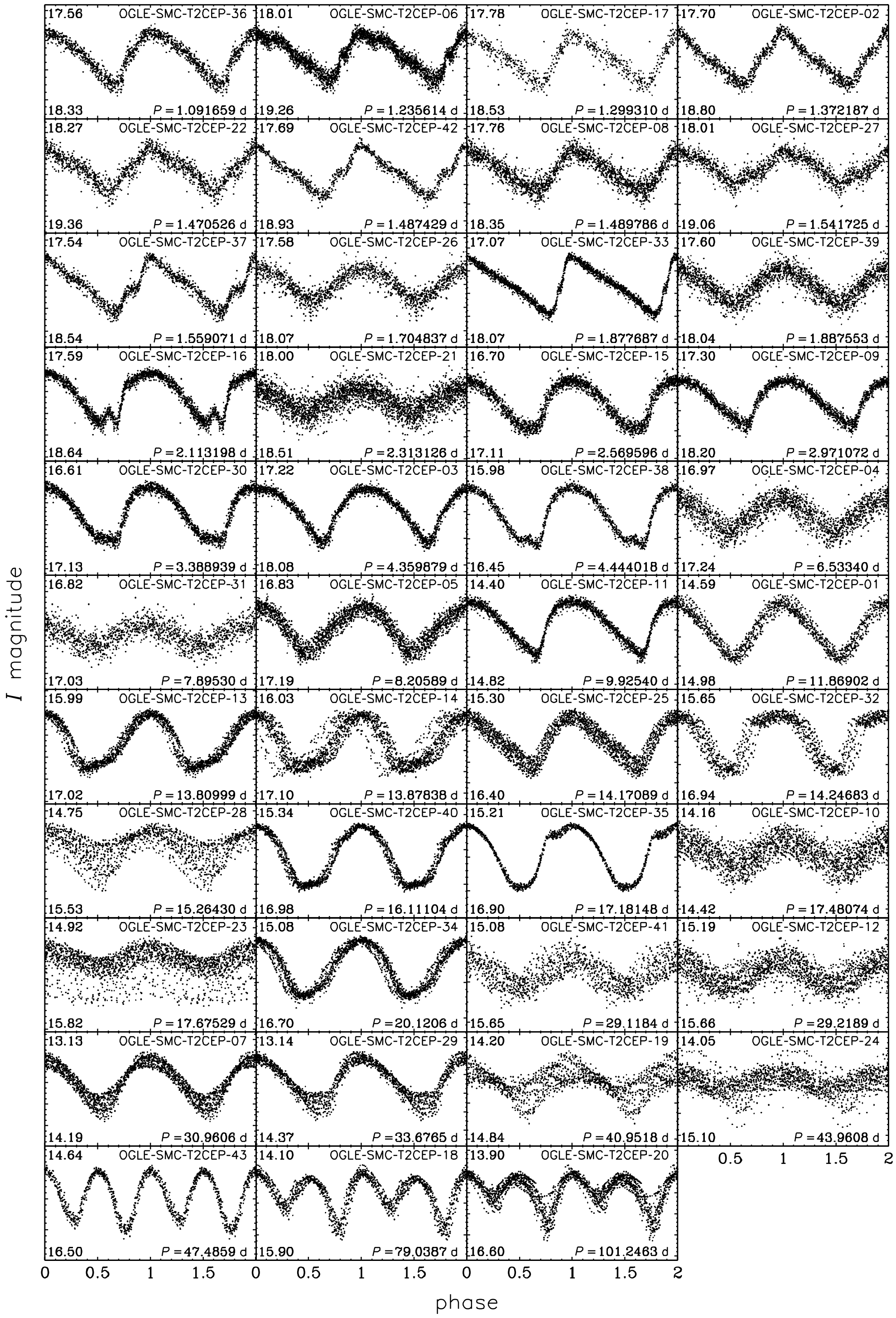

Fig. 4. Phased *I*-band light curves of type II Cepheids in the SMC. The stars are arranged with increasing periods. The range of magnitudes varies from panel to panel. Numbers in the left corners show the lower and the upper limits of magnitudes.

T a b l e 1

Type II Cepheids in the SMC

Star name	OGLE-III ID Field	No.	Type	RA [J2000.0]	DEC [J2000.0]	OGLE-II ID	GCVS SMC...	Other designation
OGLE-SMC-T2CEP-01	SMC133.6	32	pWVir	$00^{h}30^{m}02^{s}.36$	$-73^{\circ}49'07''.0$			
OGLE-SMC-T2CEP-02	SMC131.1	737	BLHer	$00^{h}34^{m}53^{s}.51$	$-72^{\circ}58'45''.9$			
OGLE-SMC-T2CEP-03	SMC133.4	9322	WVir	$00^{h}37^{m}08^{s}.35$	$-73^{\circ}43'04''.9$	SMC_SC1_33895		
OGLE-SMC-T2CEP-04	SMC125.6	89	WVir	$00^{h}38^{m}20^{s}.36$	$-73^{\circ}17'16''.4$	SMC_SC1_77980		
OGLE-SMC-T2CEP-05	SMC128.2	185	WVir	$00^{h}42^{m}03^{s}.81$	$-74^{\circ}01'24''.6$			
OGLE-SMC-T2CEP-06	SMC128.4	2107	BLHer	$00^{h}42^{m}16^{s}.01$	$-73^{\circ}39'13''.5$	SMC_SC2_81443		
OGLE-SMC-T2CEP-07	SMC125.4	2	RVTau	$00^{h}42^{m}57^{s}.49$	$-73^{\circ}07'14''.8$	SMC_SC3_31999	V0257	HV 1369
OGLE-SMC-T2CEP-08	SMC125.2	35239	BLHer	$00^{h}44^{m}00^{s}.77$	$-73^{\circ}22'54''.4$	SMC_SC3_130452		
OGLE-SMC-T2CEP-09	SMC126.1	1382	BLHer	$00^{h}44^{m}12^{s}.37$	$-72^{\circ}59'28''.5$	SMC_SC3_157235		
OGLE-SMC-T2CEP-10	SMC125.2	13188	pWVir	$00^{h}44^{m}54^{s}.66$	$-73^{\circ}28'03''.3$	SMC_SC3_184902		
OGLE-SMC-T2CEP-11	SMC125.1	37280	pWVir	$00^{h}45^{m}19^{s}.56$	$-73^{\circ}30'03''.4$	SMC_SC3_184897		
OGLE-SMC-T2CEP-12	SMC125.2	50773	RVTau	$00^{h}45^{m}19^{s}.69$	$-73^{\circ}20'13''.7$	SMC_SC3_193335		
OGLE-SMC-T2CEP-13	SMC126.1	19084	WVir	$00^{h}45^{m}41^{s}.37$	$-72^{\circ}58'35''.0$	SMC_SC4_32479		
OGLE-SMC-T2CEP-14	SMC100.8	45191	WVir	$00^{h}48^{m}02^{s}.83$	$-73^{\circ}21'17''.7$	SMC_SC4_159889		
OGLE-SMC-T2CEP-15	SMC100.7	58875	BLHer	$00^{h}49^{m}36^{s}.92$	$-73^{\circ}10'01''.4$	SMC_SC5_111664		
OGLE-SMC-T2CEP-16	SMC101.1	32853	BLHer	$00^{h}50^{m}12^{s}.58$	$-72^{\circ}43'12''.4$	SMC_SC5_235485		
OGLE-SMC-T2CEP-17	SMC102.4	258	BLHer	$00^{h}50^{m}42^{s}.03$	$-71^{\circ}39'18''.4$			
OGLE-SMC-T2CEP-18	SMC103.3	16	RVTau	$00^{h}51^{m}07^{s}.23$	$-73^{\circ}41'33''.4$			
OGLE-SMC-T2CEP-19	SMC103.3	33136	RVTau	$00^{h}53^{m}27^{s}.69$	$-73^{\circ}38'09''.5$			
OGLE-SMC-T2CEP-20	SMC101.2	48106	RVTau	$00^{h}53^{m}35^{s}.98$	$-72^{\circ}34'21''.8$	SMC_SC6_246654	V1017	HV 1586
OGLE-SMC-T2CEP-21	SMC105.7	27734	BLHer	$00^{h}53^{m}49^{s}.69$	$-72^{\circ}47'37''.4$	SMC_SC6_306714		
OGLE-SMC-T2CEP-22	SMC107.6	1433	BLHer	$00^{h}54^{m}46^{s}.72$	$-73^{\circ}48'32''.6$			
OGLE-SMC-T2CEP-23	SMC106.5	8159	pWVir	$00^{h}55^{m}01^{s}.63$	$-73^{\circ}09'47''.2$	SMC_SC7_13470		
OGLE-SMC-T2CEP-24	SMC106.7	31830	RVTau	$00^{h}55^{m}20^{s}.55$	$-73^{\circ}21'37''.9$	SMC_SC7_75158	V1193	HV 1647
OGLE-SMC-T2CEP-25	SMC106.6	34299	pWVir	$00^{h}55^{m}58^{s}.57$	$-73^{\circ}12'29''.7$	SMC_SC7_83050		
OGLE-SMC-T2CEP-26	SMC108.7	50479	BLHer	$00^{h}57^{m}24^{s}.86$	$-72^{\circ}13'17''.8$			
OGLE-SMC-T2CEP-27	SMC106.8	38983	BLHer	$00^{h}57^{m}28^{s}.64$	$-73^{\circ}31'26''.9$			
OGLE-SMC-T2CEP-28	SMC106.8	38374	pWVir	$00^{h}57^{m}31^{s}.84$	$-73^{\circ}32'11''.3$			
OGLE-SMC-T2CEP-29	SMC108.2	3	RVTau	$00^{h}57^{m}38^{s}.09$	$-72^{\circ}18'12''.2$	SMC_SC8_52799	V1372	HV 12140
OGLE-SMC-T2CEP-30	SMC106.5	51449	BLHer	$00^{h}57^{m}40^{s}.76$	$-73^{\circ}03'04''.9$	SMC_SC8_3848		
OGLE-SMC-T2CEP-31	SMC109.4	174	WVir	$00^{h}58^{m}54^{s}.15$	$-71^{\circ}22'56''.8$			
OGLE-SMC-T2CEP-32	SMC106.1	13852	WVir	$00^{h}58^{m}58^{s}.73$	$-73^{\circ}33'45''.8$			
OGLE-SMC-T2CEP-33	SMC105.4	24131	BLHer	$00^{h}59^{m}03^{s}.09$	$-72^{\circ}28'32''.2$	SMC_SC8_148923		
OGLE-SMC-T2CEP-34	SMC108.2	46300	WVir	$01^{h}00^{m}06^{s}.44$	$-72^{\circ}13'51''.7$	SMC_SC8_209984		
OGLE-SMC-T2CEP-35	SMC107.3	8878	WVir	$01^{h}00^{m}35^{s}.01$	$-73^{\circ}46'57''.9$		V1577	HV 1828
OGLE-SMC-T2CEP-36	SMC111.5	288	BLHer	$01^{h}02^{m}40^{s}.96$	$-73^{\circ}10'02''.6$			
OGLE-SMC-T2CEP-37	SMC112.8	567	BLHer	$01^{h}03^{m}46^{s}.50$	$-74^{\circ}07'28''.8$			
OGLE-SMC-T2CEP-38	SMC111.8	5979	pWVir	$01^{h}04^{m}29^{s}.00$	$-73^{\circ}33'53''.6$			
OGLE-SMC-T2CEP-39	SMC111.4	165	BLHer	$01^{h}06^{m}40^{s}.91$	$-73^{\circ}07'05''.0$	SMC_SC11_100		
OGLE-SMC-T2CEP-40	SMC119.8	119	WVir	$01^{h}08^{m}46^{s}.85$	$-71^{\circ}51'09''.4$			
OGLE-SMC-T2CEP-41	SMC116.6	11058	RVTau	$01^{h}13^{m}19^{s}.05$	$-73^{\circ}18'07''.8$			
OGLE-SMC-T2CEP-42	SMC123.3	2298	BLHer	$01^{h}23^{m}26^{s}.69$	$-72^{\circ}00'24''.3$			
OGLE-SMC-T2CEP-43	SMC123.2	2021	RVTau	$01^{h}23^{m}53^{s}.06$	$-72^{\circ}16'45''.9$			

Table 2

Observational Parameters of Type II Cepheids in the SMC

Star name	$\langle I \rangle$ [mag]	$\langle V \rangle$ [mag]	P [days]	σ_P [days]	T_{max} HJD-2450000	A_I [mag]	R_{21}	ϕ_{21}	R_{31}	ϕ_{31}
OGLE-SMC-T2CEP-01	14.768	15.303	11.8690178	0.0003296	2088.65297	0.191	0.108	5.411	0.018	5.826
OGLE-SMC-T2CEP-02	18.206	18.781	1.3721870	0.0000030	2102.59657	0.514	0.243	4.466	0.074	5.697
OGLE-SMC-T2CEP-03	17.572	18.373	4.3598789	0.0000114	627.46722	0.407	0.253	5.763	0.104	5.264
OGLE-SMC-T2CEP-04	17.093	17.862	6.5333997	0.0001285	624.25665	0.077	0.102	0.185	0.080	6.253
OGLE-SMC-T2CEP-05	16.990	17.867	8.2058890	0.0001764	2087.54105	0.140	0.148	0.746	0.036	0.596
OGLE-SMC-T2CEP-06	18.536	19.140	1.2356136	0.0000013	625.69012	0.523	0.273	5.123	0.150	3.970
OGLE-SMC-T2CEP-07	13.572	14.440	30.9606438	0.0004026	596.44583	0.415	0.121	5.524	0.020	3.670
OGLE-SMC-T2CEP-08	18.025	18.757	1.4897859	0.0000038	624.55707	0.206	0.232	4.572	0.050	2.952
OGLE-SMC-T2CEP-09	17.700	18.480	2.9710719	0.0000057	618.99334	0.356	0.210	5.440	0.123	4.397
OGLE-SMC-T2CEP-10	14.272	14.820	17.4807419	0.0005562	619.79231	0.054	0.065	5.315	0.000	–
OGLE-SMC-T2CEP-11	14.571	14.954	9.9253977	0.0000552	617.95658	0.197	0.274	5.352	0.153	4.325
OGLE-SMC-T2CEP-12	15.415	16.369	29.2189113	0.0039443	608.57963	0.103	0.077	1.840	0.022	4.392
OGLE-SMC-T2CEP-13	16.444	17.408	13.8099916	0.0001602	617.96318	0.489	0.116	1.978	0.079	2.634
OGLE-SMC-T2CEP-14	16.501	17.516	13.8783799	0.0003583	622.23967	0.456	0.099	1.521	0.073	2.624
OGLE-SMC-T2CEP-15	16.895	17.196	2.5695964	0.0000054	464.73357	0.172	0.187	5.333	0.080	3.686
OGLE-SMC-T2CEP-16	18.013	18.723	2.1131980	0.0000020	464.88124	0.461	0.167	5.564	0.076	3.589
OGLE-SMC-T2CEP-17	18.126	18.739	1.2993097	0.0000099	2540.43032	0.320	0.347	4.893	0.074	3.563
OGLE-SMC-T2CEP-18	14.813	15.627	39.5193655	0.0057005	2048.45132	0.667	0.169	5.936	0.073	5.861
OGLE-SMC-T2CEP-19	14.481	15.064	40.9118097	0.0059419	2055.86074	0.136	0.110	6.003	0.048	6.017
OGLE-SMC-T2CEP-20	14.894	15.890	50.6231456	0.0069705	439.44469	0.750	0.120	5.789	0.032	5.801
OGLE-SMC-T2CEP-21	18.233	18.999	2.3131264	0.0000203	465.02486	0.097	0.099	0.164	0.000	–
OGLE-SMC-T2CEP-22	18.731	19.480	1.4705261	0.0000067	2085.76244	0.410	0.218	5.098	0.112	0.590
OGLE-SMC-T2CEP-23	15.264	15.990	17.6752925	0.0005561	604.25442	0.121	0.095	4.576	0.000	–
OGLE-SMC-T2CEP-24	14.511	15.308	43.9607975	0.0179727	615.47093	0.154	0.062	0.101	0.127	3.929
OGLE-SMC-T2CEP-25	15.766	16.458	14.1708916	0.0001848	607.92509	0.481	0.235	4.944	0.065	4.436
OGLE-SMC-T2CEP-26	17.794	18.393	1.7048368	0.0000117	2085.92662	0.133	0.119	6.194	0.000	–
OGLE-SMC-T2CEP-27	18.446	19.113	1.5417249	0.0000080	2086.43490	0.291	0.000	–	0.160	1.387
OGLE-SMC-T2CEP-28	15.031	15.907	15.2643255	0.0003658	2093.82590	0.194	0.116	5.775	0.016	4.732
OGLE-SMC-T2CEP-29	13.648	14.556	33.6764628	0.0004650	600.72415	0.492	0.168	4.982	0.072	3.447
OGLE-SMC-T2CEP-30	16.836	17.318	3.3889388	0.0000064	620.05824	0.245	0.174	5.259	0.105	3.588
OGLE-SMC-T2CEP-31	16.929	17.794	7.8953026	0.0004850	2079.41753	0.039	0.000	–	0.000	–
OGLE-SMC-T2CEP-32	16.161	16.873	14.2468347	0.0005521	2073.05395	0.604	0.250	6.188	0.064	5.056
OGLE-SMC-T2CEP-33	17.510	18.112	1.8776865	0.0000014	620.56334	0.508	0.461	4.809	0.214	3.278
OGLE-SMC-T2CEP-34	15.737	16.672	20.1206110	0.0003603	618.98689	0.792	0.085	0.715	0.040	2.486
OGLE-SMC-T2CEP-35	15.894	16.735	17.1814841	0.0001830	2072.74556	0.909	0.173	6.069	0.071	4.216
OGLE-SMC-T2CEP-36	17.892	18.454	1.0916592	0.0000017	2104.57149	0.358	0.256	5.311	0.065	4.735
OGLE-SMC-T2CEP-37	17.986	18.593	1.5590709	0.0000030	2103.84900	0.496	0.258	4.856	0.088	1.029
OGLE-SMC-T2CEP-38	16.189	16.664	4.4440180	0.0000152	2101.74437	0.237	0.169	5.264	0.113	3.573
OGLE-SMC-T2CEP-39	17.798	18.541	1.8875529	0.0000079	625.40072	0.128	0.101	5.350	0.000	–
OGLE-SMC-T2CEP-40	16.036	16.976	16.1110373	0.0002492	2092.07312	0.873	0.050	0.291	0.053	3.043
OGLE-SMC-T2CEP-41	15.353	16.068	29.1184308	0.0069526	2089.43875	0.152	0.068	0.864	0.105	5.159
OGLE-SMC-T2CEP-42	18.246	18.860	1.4874289	0.0000032	2090.49055	0.562	0.260	4.646	0.101	0.284
OGLE-SMC-T2CEP-43	15.398	16.342	23.7429305	0.0010767	2068.62766	0.890	0.111	5.736	0.030	4.439

the WWW interface or by the anonymous FTP site:

http://ogle.astrouw.edu.pl/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/smc/t2cep/

The OGLE-II and OGLE-III *I*- and *V*-band photometry and finding charts for all stars can be downloaded from the same sites.

Phased *I*-band light curves for all the stars from our catalog are shown in Fig. 4. The stars are arranged with increasing periods to show the progression of the light curve shapes with period. The data are folded with the "single" periods with the exception of three RV Tau stars that show alternating deep and shallow minima and are presented with their formal ("double") periods. For multiperiodic stars the light curves are phased with their primary pulsation periods.

5. Cross-Identification with Other Catalogs

We cross-matched our sample of type II Cepheids in the SMC with the previously published lists of variable stars of this type. In the GCVS Vol. V (Artyukhina et al. 1995) five SMC stars have been categorized as CWA or CWB variables, *i.e.*, type II Cepheids. With the OGLE data we can confirm the classification of only one object from this list (OGLE-SMC-T2CEP-35 = HV 1828). Two of the GCVS CW stars (XY Hyi and HV 12901) lie outside the OGLE-III fields and no photometric information is available for them in our database. The two remaining stars classified in the GCVS as type II Cepheids (WS12, WS45) turned out to be classical Cepheids and were cataloged in the previous part of the OIII-CVS (Paper II). Our sample also contain several objects which had entries in the GCVS, but were not classified as type II Cepheids.

In the OGLE-II catalog of Cepheids in the SMC (Udalski *et al.* 1999) 16 stars were classified as "fainter" (FA) than fundamental-mode classical Cepheids. Most of these stars should be type II Cepheids, although the OGLE-II sample was selected based on only two seasons of observations, so the classification was rather uncertain. Our catalog includes 11 objects from the list provided by Udalski *et al.* (1999). The other five objects turned out to be other kinds of periodic stars, mainly ellipsoidal variables.

6. Discussion

In Fig. 1 we present the PL diagrams in V, I and W_I index for type II Cepheids found in the SMC. For comparison, classical Cepheids (Paper II) are plotted with small dots in the same diagrams. When neglecting peculiar W Vir stars and two RV Tau stars residing in the eclipsing systems, the scatter of the relation is rather small, especially for longer period type II Cepheids (W Vir and RV Tau stars). Similarly to the LMC (Paper I, Matsunaga *et al.* 2009), the PL relations are not linear within the entire range of periods. RV Tau stars seem to be brighter than expected from the linear extrapolation of the PL relation for the shorter-period type II Cepheids. It is worth noticing that such a non-linearity is not visible for type II Cepheids in the Galactic globular clusters (Matsunaga *et al.* 2006).

In Paper I we distinguished a new subtype of type II Cepheids – peculiar W Vir stars. From 17 stars of this kind in the LMC four objects exhibited additional eclipsing variations superimposed on the pulsation light curve. Four other peculiar W Vir stars in the LMC showed some small-amplitude long-period modulation which might be explained by the ellipsoidal variations due to binarity. If we take into account the fact that we see the binarity effects only in a fraction of systems due to random distribution of orbital inclinations, it is justified to conclude that all peculiar W Vir stars are likely to be members of binary systems.

The same conclusion can be drawn from the SMC sample presented in this study. Seven variables in our catalog have been classified as peculiar W Vir stars, of which two exhibit eclipsing variations and two others show ellipsoidal modulation. Additionally we identified two RV Tau stars with some signs of binarity – one with eclipsing and another one with ellipsoidal modulation. Tables 3 and 4 give the lists of type II Cepheids in eclipsing and ellipsoidal binary systems, respectively. The prewhitened and detrended light curves of these objects are shown in Figs. 5 and 6. Since the main pulsation period of OGLE-SMC-T2CEP-25 varied during the OGLE observations, we adjusted the periods separately in each observing season and we prewhitened the light curve independently in each chunk. Among the stars in Table 4, OGLE-SMC-T2CEP-07 and OGLE-SMC-T2CEP-25 are rather certainly the ellipsoidal variables, as their long-period components have minima alternating their depths, which is a characteristic feature of the ellipsoidal variability. For OGLE-SMC-T2CEP-10 the longest-period variability should be treated as a candidate for ellipsoidal modulation.

The most striking feature of the type II Cepheids in binary systems is that all of them exhibit multiperiodicity. In Tables 3 and 4, as well as in Figs. 5 and 6, P_p indicates the primary pulsation period, P_e is an orbital period taken from eclipsing or ellipsoidal variability, while P_s are the largest-amplitude secondary periods. Right columns of Figs. 5 and 6 show the light curves folded with only one, the strongest secondary period. For all stars but OGLE-SMC-T2CEP-10 the most significant secondary period satisfies the equation:

$$\frac{1}{P_s} = \frac{1}{P_p} - \frac{2}{P_e} \tag{1}$$

Other secondary periods are usually also a combination of the pulsation and orbital period, as given in the last column of Tables 3 and 4. In the power spectra we usually observe equidistant triplets with the main pulsational frequency at the center and two secondary peaks on both sides at the distance $2/P_e$. Generally, these two peaks have different heights. Sometimes the secondary frequencies exist at $1/P_e$

Table 3

Type II Cepheids in Eclipsing Binary Systems.

Star name	P_p [days]	A_I^p [mag]	P_e [days]	A_I^e [mag]	P_s [days]	A_I^s [mag]	$1/P_s =$
OGLE-SMC-T2CEP-23	17.6753	0.121	156.884	0.392	22.8199	0.030	$1/P_p - 2/P_e$
					15.8846	0.020	$1/P_p + 1/P_e$
OGLE-SMC-T2CEP-28	15.2643	0.194	141.835	0.202	19.4538	0.110	$1/P_p - 2/P_e$
					12.5637	0.022	$1/P_p + 2/P_e$
					17.1069	0.020	$1/P_p - 1/P_e$
					8.5526	0.016	$2/P_p - 2/P_e$
OGLE-SMC-T2CEP-29	33.6765	0.492	608.6	0.122	37.8939	0.075	$1/P_p - 2/P_e$
					30.2961	0.068	$1/P_p + 2/P_e$
					33.9861	0.049	
					33.3897	0.037	
					15.9511	0.028	$2/P_p + 2/P_e$

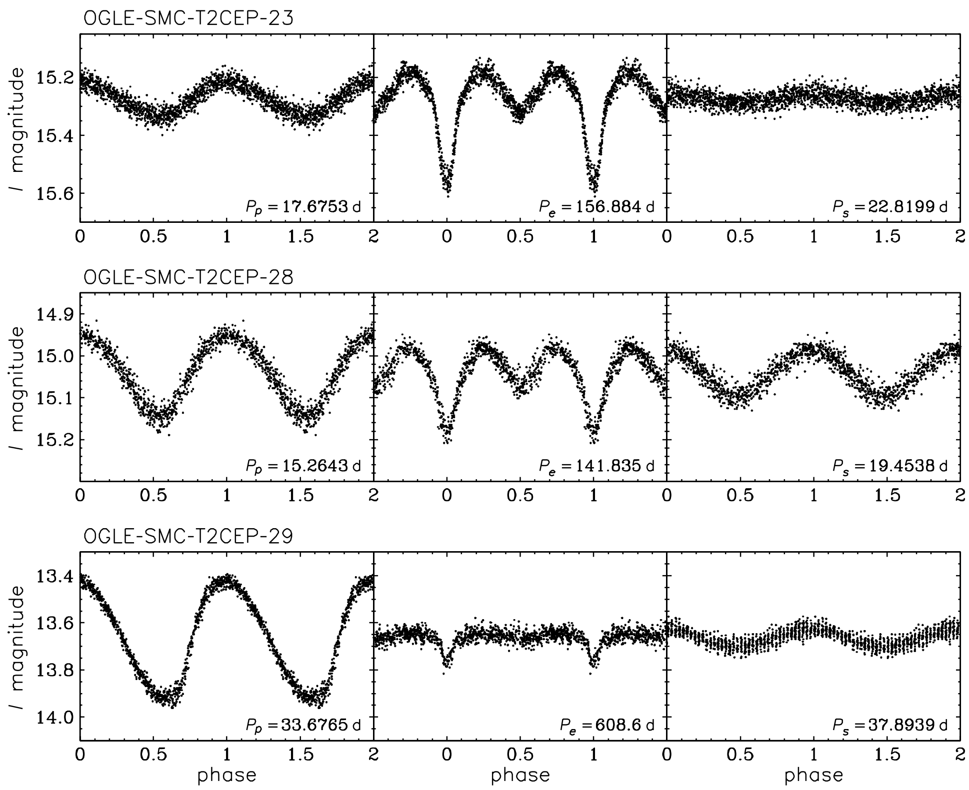

Fig. 5. Light curves of type II Cepheids in eclipsing binary systems. *Left panels* show the main pulsation light curves. *Middle panels* show the eclipsing light curves. *Right panels* show the highest-amplitude secondary components. Each light curve has been detrended and prewhitenned with all other detected periods.

Table 4

Type II Cepheids in Ellipsoidal Binary Systems.

Star name	P_p [days]	A_I^p [mag]	P_e [days]	A_I^e [mag]	P_s [days]	A_I^s [mag]	$1/P_s =$
OGLE-SMC-T2CEP-07	30.9606	0.415	392.93	0.068	36.7372	0.090	$1/P_p - 2/P_e$
					26.7370	0.034	$1/P_p + 2/P_e$
					31.1276	0.029	
					16.7994	0.024	$2/P_p - 2/P_e$
OGLE-SMC-T2CEP-10	17.4807	0.054	198.18	0.020	15.7658	0.054	
					21.2285	0.010	$1/P_p - 2/P_e$
OGLE-SMC-T2CEP-25	14.17089	0.481	174.87	0.094	16.9125	0.056	$1/P_p - 2/P_e$
					7.7105	0.014	$2/P_p - 2/P_e$
					12.1937	0.012	$1/P_p + 2/P_e$

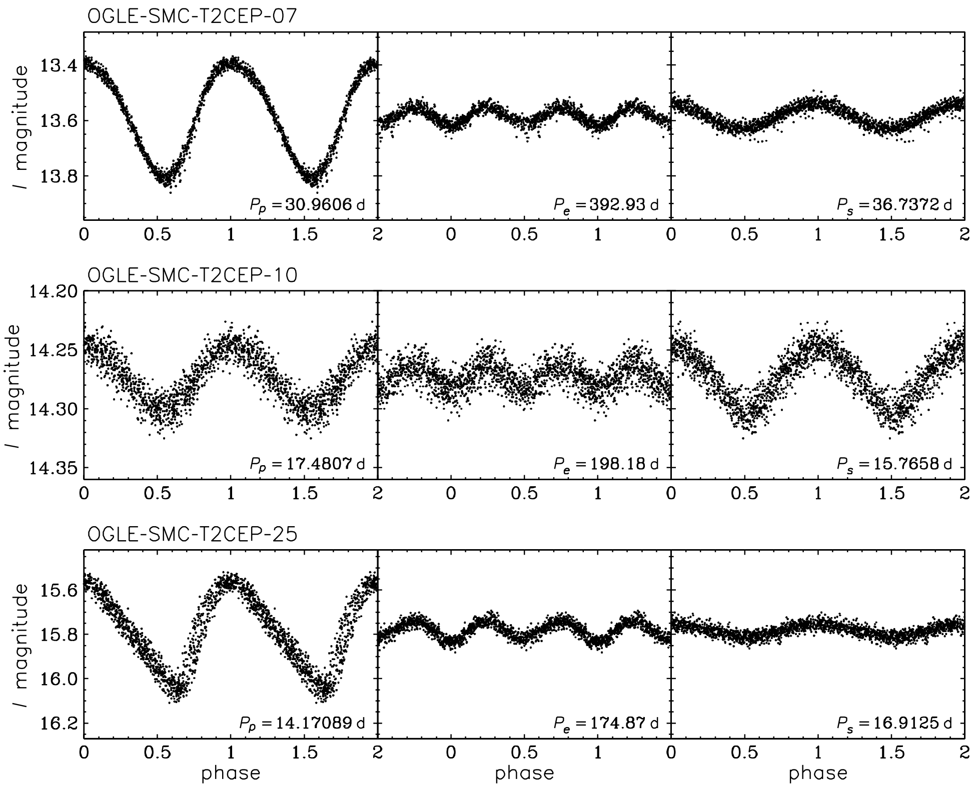

Fig. 6. Light curves of type II Cepheids with additional ellipsoidal variability. *Left panels* show the main pulsation light curves. *Middle panels* show the ellipsoidal light curves. *Right panels* show the highest-amplitude secondary components. Each light curve has been detrended and prewhitenned with all other detected periods.

from the pulsation peak. Power spectra of this kind may correspond to the modulation of amplitudes and/or phases of the pulsational light curves with periods equal to the orbital or half the orbital period.

Explanation of such behavior is beyond the scope of this paper. Detailed analysis of these cases is necessary to enhance our knowledge about the oscillations of stars which are distorted by tidal interactions from their companions. Nevertheless, we can draw one important conclusion: our Cepheids with eclipsing and ellipsoidal variations are not the optical blends of a pulsating star with a binary system, but we discovered binaries with a pulsating star as one of its components. In the case of OGLE-SMC-T2CEP-10 two main periods have almost the same amplitudes and do not obey equation (1). However, we found another small-amplitude secondary period that fulfills this rule.

The two RV Tau stars with eclipsing or ellipsoidal modulation (OGLE-SMC-T2CEP-07, OGLE-SMC-T2CEP-29) are rather untypical representatives of this type of pulsating stars. Their pulsation light curves do not show any alternations of the minima. After removing other periodicities the light curves are quite stable (contrary to a typical RV Tau star) and have shapes similar to the shorter-period peculiar W Vir stars. They are also significantly brighter than other RV Tau stars. We suggest that these two objects are the equivalents of the peculiar W Vir stars in the range of periods occupied by RV Tau stars.

7. Summary

We performed the first search dedicated exclusively to type II Cepheids in the SMC and found 43 objects of this type. Thus, we increased the number of known type II Cepheids in the SMC by several times. We also discovered first definitive RV Tau stars in this galaxy.

We found three type II Cepheids in eclipsing binary systems and three pulsators with additional ellipsoidal variations. Note that among two orders of magnitude more numerous sample of classical Cepheids in the SMC (Paper II) we identified only two pulsators with superimposed eclipsing variability. Moreover, while among the classical Cepheids it cannot be excluded that what we observe is the optical blend of a Cepheid and an eclipsing variable, in the case of type II Cepheids we are convinced that pulsating stars are actually the members of binary systems. It is evident because the amplitudes and/or phases of pulsation light curves are modulated with orbital periods or their harmonics. Such a modulation must be related to the tidal interactions between components of the binary systems, but it requires detailed studies and modeling of this phenomenon.

The huge catalogs of classical Cepheids in the LMC (Soszyński *et al.* 2008) and the SMC (Paper II) with the samples of type II Cepheids in both Clouds presented in Paper I and in this paper give an opportunity to study in detail these important distance indicators. Do both populations give consistent distance scales? This is a very important task for future investigations.

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