ACTA ASTRONOMICA
Vol. **59** (2009) pp. 335–347

The Optical Gravitational Lensing Experiment. The OGLE-III Catalog of Variable Stars. V. R Coronae Borealis Stars in the Large Magellanic Cloud*

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Received November 20, 2009

ABSTRACT

The fifth part of the OGLE-III Catalog of Variable Stars presents 23 R CrB (RCB) stars in the Large Magellanic Cloud (LMC). 17 of these objects have been spectroscopically confirmed by previous studies, while 6 stars are new candidates for RCB variables. We publish the *VI* multi-epoch OGLE photometry for all objects.

We use the sample of carbon-rich long-period variables released in the previous part of this catalog to select objects with severe drops in luminosity, *i.e.*, with the DY-Per-like light curves. DY Per stars are often related to R CrB variables. We detect at least 600 candidates for DY Per stars, mostly among dust enshrouded giants. We notice that our candidate DY Per stars form a continuity with other carbon-rich long-period variables, so it seems that DY Per stars do not constitute a separate group of variable stars.

Key words: *Stars: AGB and post-AGB – Stars: carbon – Magellanic Clouds*

1. Introduction

R CrB (RCB) stars are hydrogen-deficient, carbon-rich supergiants which undergo sudden and severe declines in brightness due to the formation of carbon dust at irregular intervals. This is a very rare type of variable stars, with only about

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

50 known representatives in the Galaxy (Clayton 1996, Zaniewski *et al.* 2005, Tisserand *et al.* 2008) and 22 RCB stars known in the Magellanic Clouds. The evolutionary status of these objects is not yet well understood, with two proposed scenarios for the origin of the RCB stars (*e.g.*, Iben *et al.* 1996): the amalgamation of a binary white dwarf system or the expansion of a pre-white dwarf to supergiant size through the final helium shell flash.

RCB stars can be divided into three sub-classes: hot (≈ 20000 K), warm (≈ 7000 K) and cool (≈ 5000 K) stars. Additionally, there is a group of very cool objects (≈ 3500 K), called DY Per stars. This last class of variables also undergoes irregular declines in brightness, but the fading episodes are much slower than in classical RCB stars and with symmetric recoveries. It is not clear whether DY Per stars are related to RCB variables, or they represent extreme cases of classical carbon-rich (C-rich) asymptotic giant branch (AGB) stars.

The first RCB star in the Large Magellanic Cloud (LMC) – W Men (HV 966) – was discovered by Luyten (1927). Before the era of large microlensing surveys only two more variables of that type have been identified in the LMC: HV 5637 (Hodge and Wright 1969) and HV 12842 (Payne-Gaposchkin 1971). Both stars were confirmed spectroscopically by Feast (1972). The MACHO microlensing project increased to 13 the number of known classical RCB stars in the LMC (Alcock *et al.* 1996, 2001). They also discovered four DY Per stars in the LMC. The EROS-2 survey yielded additional six RCB stars and six DY Per variables (Tisserand *et al.* 2009). They also listed two unconfirmed candidates for RCB variables and eleven candidates for DY Per stars in this galaxy. Thus, at present 19 ordinary RCB stars and ten DY Per variables in the LMC have spectroscopically confirmed status. The Optical Gravitational Lensing Experiment (OGLE) made available a real time monitoring system of the known RCB variables in the Magellanic Clouds and Galactic Bulge (the RCOM system, Udalski 2008).

In this paper we describe the OGLE-III catalog of RCB stars in the LMC. This is a part of the OGLE-III Catalog of Variable Stars (OIII-CVS) which is intended to include all variable sources detectable in the OGLE-III fields. In the previous part of the OIII-CVS (Soszyński *et al.* 2009) we presented the sample of almost 92 000 long-period variables (LPVs) in the LMC, including about 9500 C-rich stars. All the confirmed and candidate DY Per stars described in this paper can be found in the OGLE-III catalog of LPVs.

2. Observational Data

All observations provided in this catalog were obtained with the 1.3-meter Warsaw telescope located at Las Campanas Observatory in Chile. The observatory is operated by the Carnegie Institution of Washington. The telescope was equipped with the CCD mosaic camera consisting of eight detectors with 2048×4096 pixels each, with the total field of view of about 35×35.5 arcmin.

The third phase of the OGLE project (OGLE-III) lasted from 2001 to 2009. During this period about 40 square degrees in the LMC were photometrically monitored for stellar variability. We collected typically 400–600 observing points per star in the *I* photometric band and 40–60 measurements in the *V*-band. For the central 4.5 square degrees of the LMC the OGLE-III photometry has been supplemented by the OGLE-II data collected between 1997 and 2000, which gives the total time span of observations of over 12 years. For more information on the instrumentation setup and the photometric reduction techniques see Udalski (2003), Udalski *et al.* (2008) and the previous papers of this series.

The near- and middle-infrared single-epoch photometric measurements used in this study were originated in the 2MASS point source catalog (Cutri *et al.* 2003) and the SAGE Spitzer survey (Meixner *et al.* 2006). The search radius of $1''$ was used to match the visual and infrared data.

3. Identification of Variable Stars

3.1. RCB Stars

The majority of RCB stars presented in this catalog were identified by visual inspection of light curves during the selection of LPVs in the LMC (Soszyński *et al.* 2009). The light curves with distinct, irregular drops in brightness were retained in a separate list and then cross-identified with the most recent catalog of RCB and DY Per stars in the LMC by Tisserand *et al.* (2009). From 19 spectroscopically confirmed RCB stars in the LMC two objects (HV 12842 and EROS2-LMC-RCB-6) are located outside the OGLE-III fields, so there are no OGLE light curves for these stars. Further two RCB stars (HV 5637, EROS2-LMC-RCB-3) do not show any significant magnitude declines during the time span covered by the OGLE survey. The same behavior for HV 5637 was noticed by Alcock *et al.* (2001) and Tisserand *et al.* (2009). Even so, both stars are included in our catalog, because it is well-known that some RCB stars may go for long intervals without minima (*e.g.*, XX Cam, Diethelm 1994).

Thus, this catalog includes 17 of the 19 confirmed RCB stars in the LMC. Their 2MASS and SAGE infrared magnitudes were used to plot the color–color diagrams presented in Fig. 1. We also show here the C-rich Miras and semiregular variables (SRVs) in the LMC from the previous part of the OIII-CVS (Soszyński *et al.* 2009). In these planes classical RCB stars are well separated from the majority of AGB stars (*e.g.*, Morgan *et al.* 2003), so the infrared colors can be used as a tool for selecting candidates for RCB stars.

In the list of irregular stars compiled on the basis of the light curve inspection we found six other objects with the infrared colors similar to the confirmed RCB stars. These stars are marked in Fig. 1 with cyan crosses and their OGLE-III *I*-band light curves are shown in Fig. 2. As can be seen, these stars exhibit irregular fading episodes, however usually not so deep and not so sudden as for typical RCB stars.

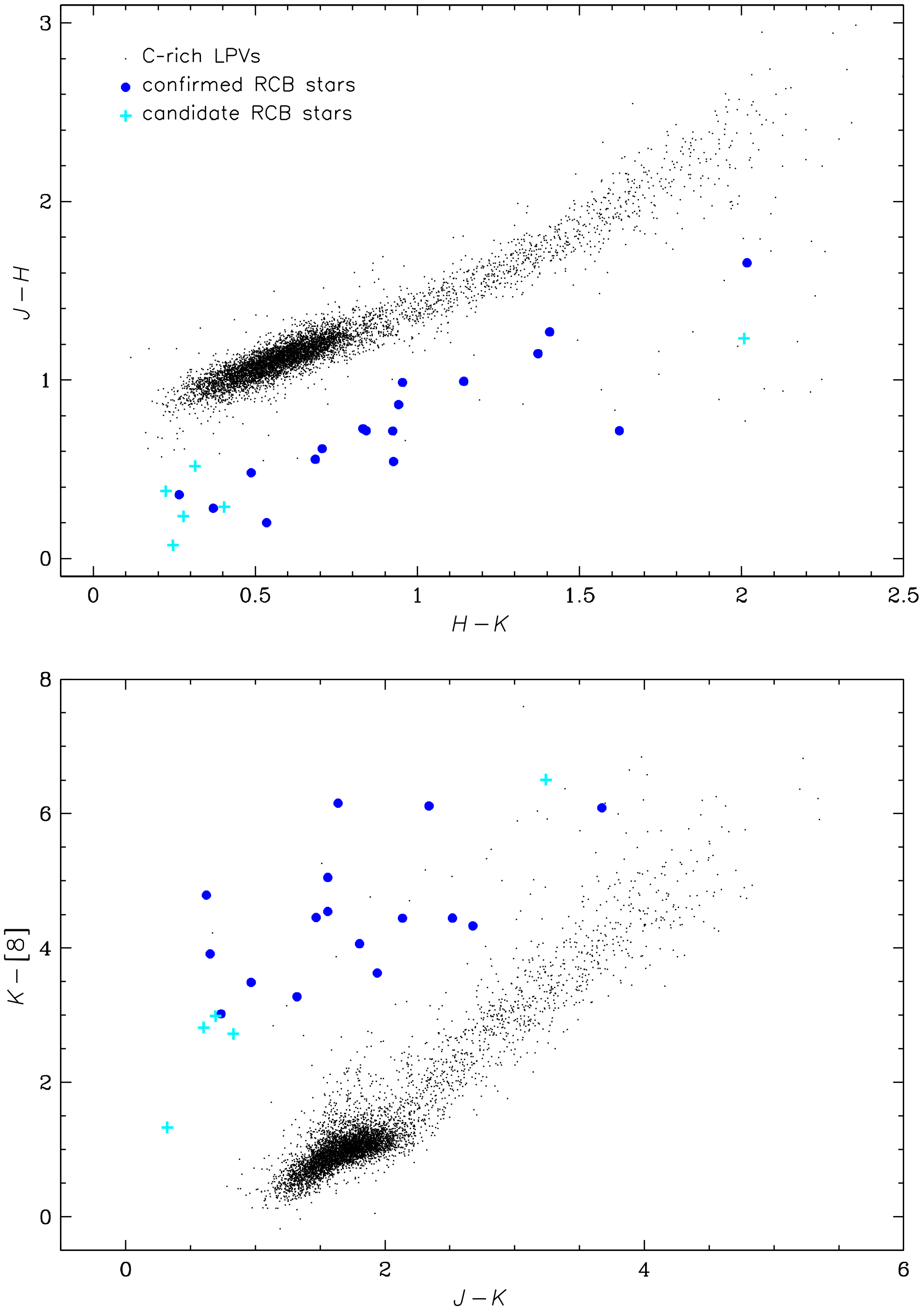

Fig. 1. Color–color diagrams for the confirmed (blue dots) and candidate (cyan crosses) RCB stars in the LMC. Small black dots mark C-rich AGB stars from Soszyński *et al.* (2009).

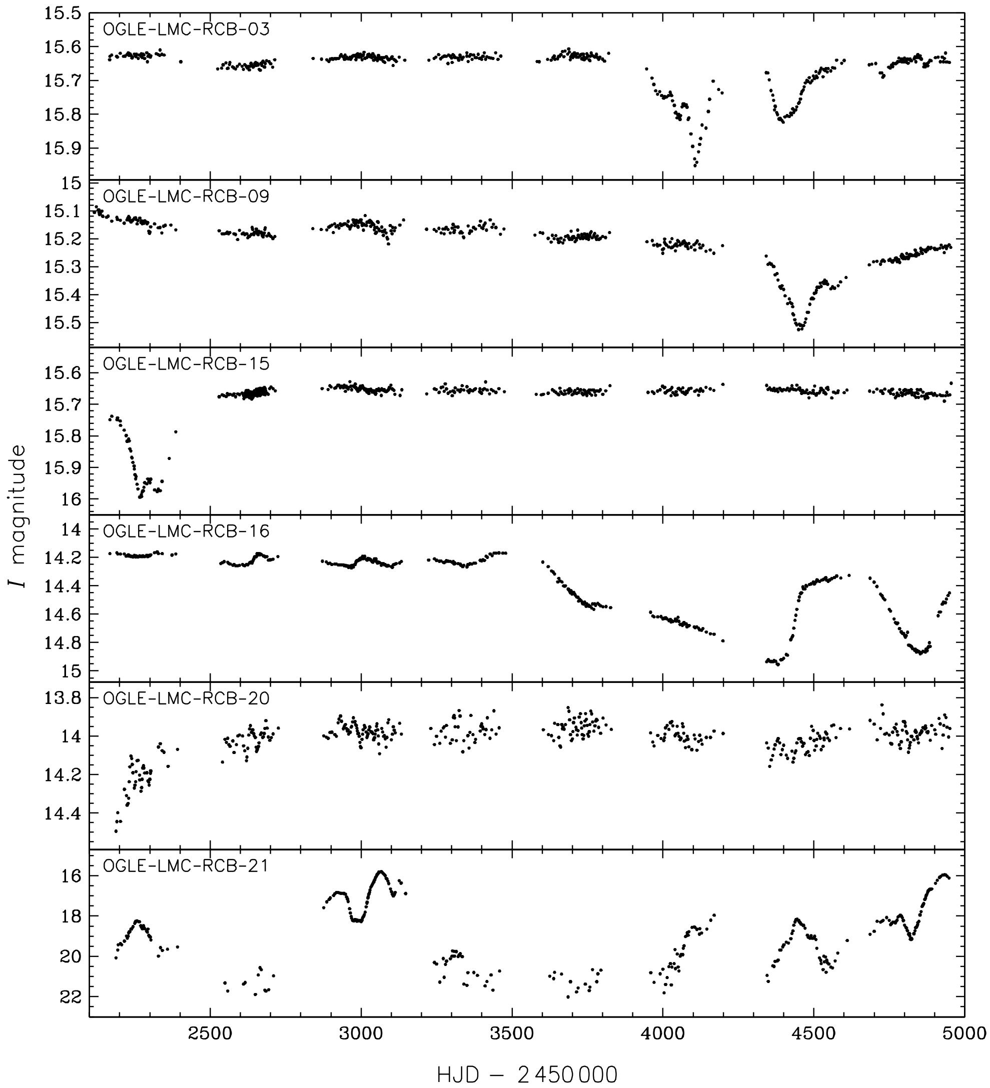

Fig. 2. The OGLE-III *I*-band light curves of candidates for RCB stars in the LMC.

The only exception is OGLE-LMC-RCB-21 with the light decline up to 5.7 mag. It looks that virtually all *bona fide* RCB stars in the region covered by the OGLE-III fields in the LMC have been already cataloged by the MACHO and EROS-2 projects. Our six new candidates are likely low-active RCB stars, but obviously, their status has to be confirmed spectroscopically.

3.2. DY Per stars

From ten confirmed DY Per stars (Alcock *et al.* 2001, Tisserand *et al.* 2009) our catalog includes eight objects. EROS2-LMC-DYPer-2 and EROS2-LMC-DYPer-3 lie out of the OGLE-III fields. We marked these eight stars with red dots in the

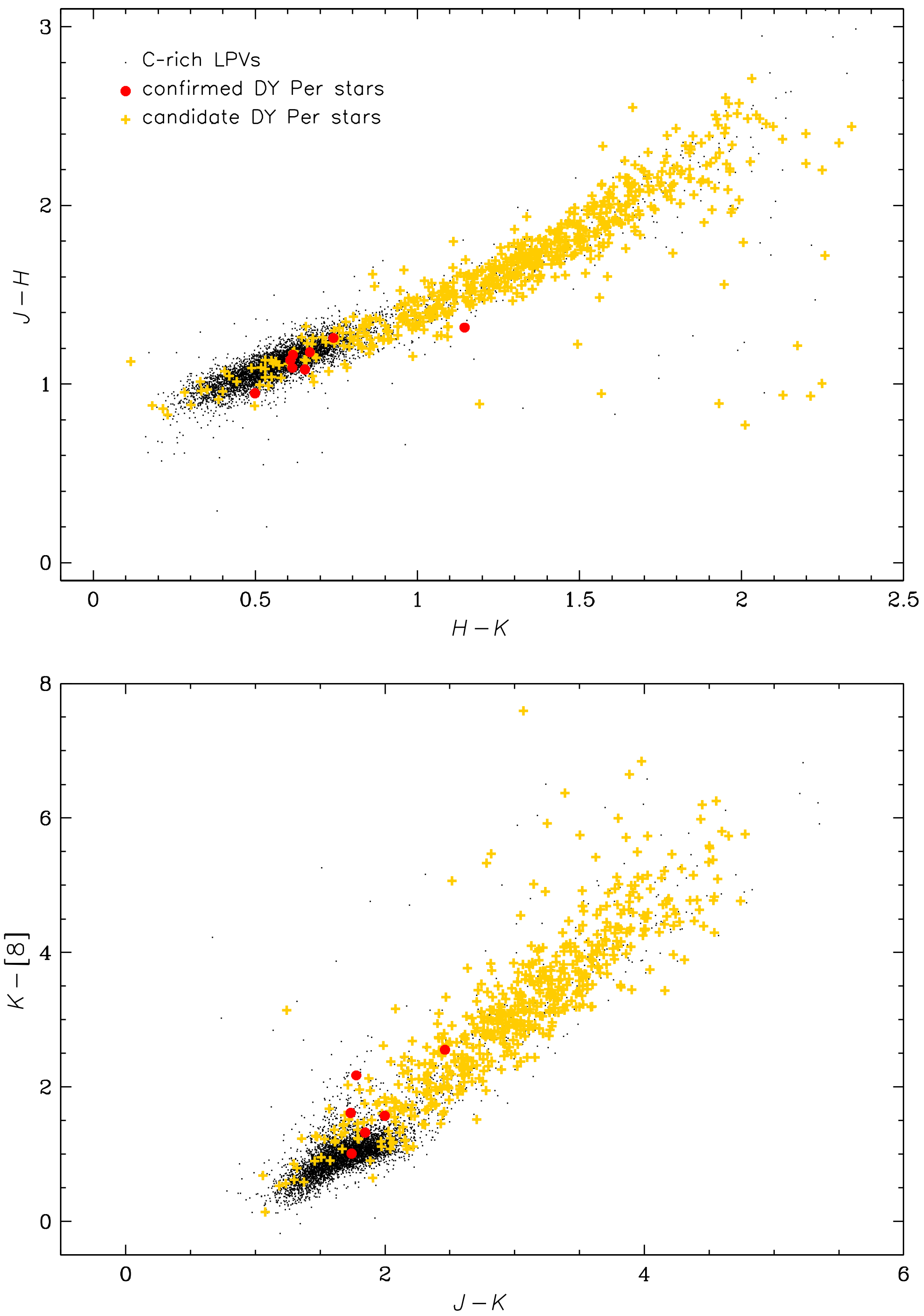

Fig. 3. Color–color diagrams for the confirmed (red dots) and candidate (yellow crosses) DY Per stars in the LMC. Small black dots mark C-rich AGB stars from Soszyński *et al.* (2009).

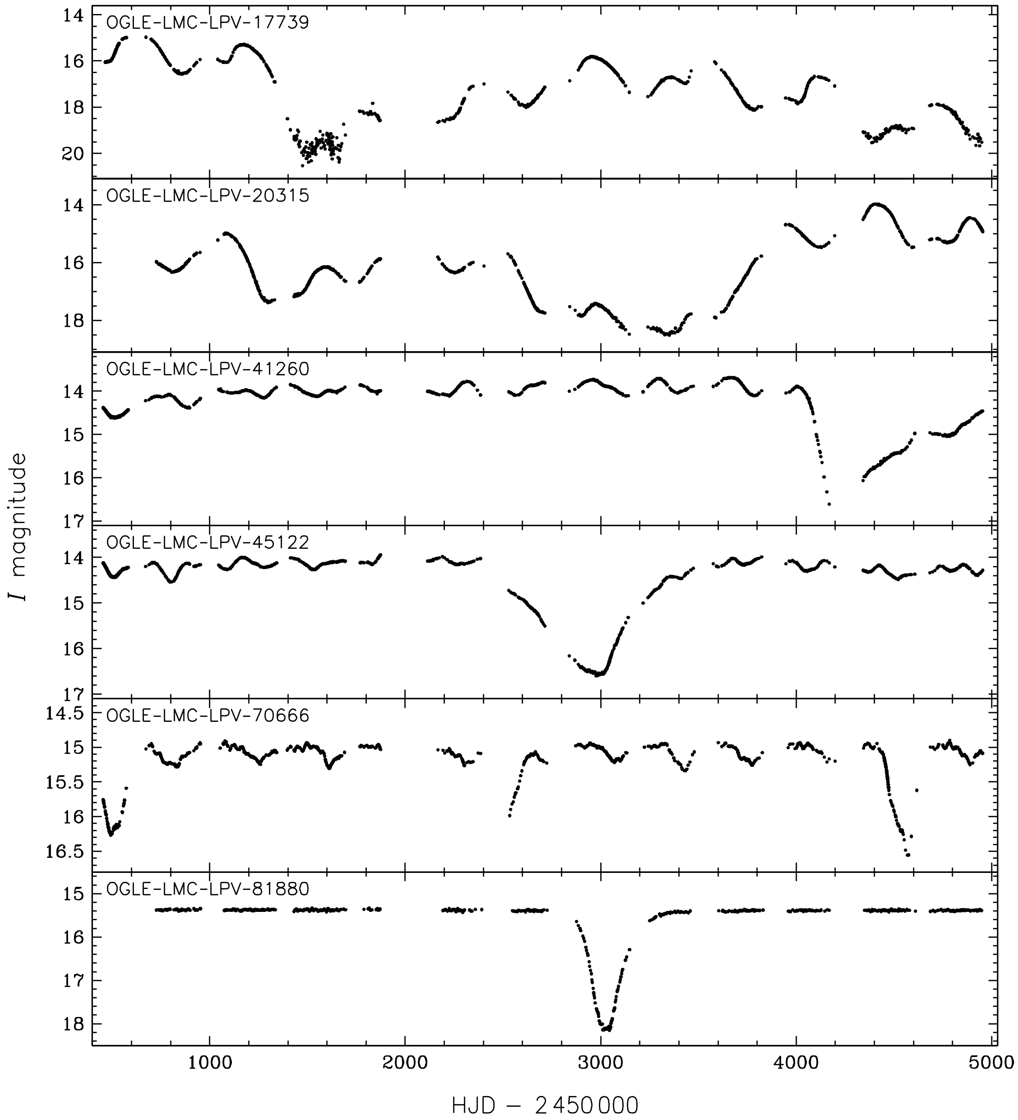

Fig. 4. The OGLE-II and OGLE-III *I*-band light curves of six selected candidates for DY Per stars in the LMC.

infrared color–color diagrams (Fig. 3). As noticed by Alcock *et al.* (2001) and Tisserand *et al.* (2009), DY Per stars occupy the same region in the color–color diagrams as other C-rich AGB stars. Actually, the light curves of DY Per stars are typical for C-rich LPVs and all of them were included in our catalog of LPVs in the LMC (Soszyński *et al.* 2009). The irregular variations of brightness superimposed on the periodic, pulsational changes are very common among C-rich SRVs and Miras, especially among dust-enshrouded objects.

We looked through the light curves of AGB LPVs in the LMC from the OGLE-

III catalog and detected 600 objects with similar features as possessed by the confirmed DY Per stars, *i.e.*, with significant irregular declines of brightness (>1.5 mag). We marked these stars in Fig. 3 with yellow crosses. Most of the DY-Per-like stars occupy the area of the dust obscured AGB stars, *i.e.*, $(J-K)\gtrsim 2$ mag and $(K-[8])\gtrsim 1.5$ mag.

In Fig. 4 we show the OGLE-II and OGLE-III light curves of six selected candidates for DY Per variables. These data show a wide variety of light curves, with various time scales and amplitudes of the fading episodes and different behavior in the maximum brightness. We emphasize that we did not detect any qualitative feature that separates stars with the luminosity drops and other C-rich stars. Both groups constitute a continuity.

4. The Catalog of RCB Stars

In Table 1 we present the full list of confirmed and candidate RCB stars identified in the OGLE-III fields in the LMC. The stars are sorted by increasing right ascension and designated with symbols OGLE-LMC-RCB-NN, where NN is a two-digit consecutive number. Table 1 provides information about the equinox J2000.0 RA/DEC coordinates of stars and their identifications in the OGLE-III, OGLE-II, MACHO and EROS-2 databases, as well as in the General Catalogue of Variable Stars (Artyukhina *et al.* 1995). In the case of OGLE-LMC-RCB-02 there is no OGLE-III identification, because the star is too bright and saturates profile in the regular OGLE-III photometry. However, we publish the DoPhot profile photometry for this object.

Table 2 contains the basic parameters of the objects in the catalog: *I*- and *V*-band magnitudes at maximum light, pulsation periods, amplitudes of pulsation, and the maximum drop amplitudes in the *I*-band. Several very active RCB stars have not fully recovered at all during the OGLE observations and for these objects we provide just the maximum of measured brightness. The periods and amplitudes of pulsation are given only for stars that have spent outside the declines enough time to determine periods. In some cases we used the MACHO light curves to improve the periods. Note that RCB stars usually show semiregular and multi-periodic variations, but we provide only one, the primary period.

The content of Tables 1 and 2 can be downloaded in the electronic form through the WWW interface or *via* the anonymous FTP site:

http://ogle.astrouw.edu.pl/
ftp://ftp.astrouw.edu.pl/ogle/ogle3/OIII-CVS/lmc/rcb/

The multi-epoch *VI* photometry and finding charts for all stars are also available in the OGLE Internet Archive.

T a b l e 1

The identifications of RCB stars in the LMC

Star name	OGLE-III ID Field	No	Status	RA [J2000.0]	DEC [J2000.0]	OGLE-II ID	MACHO ID	EROS-2 ID	GCVS ID LMC...	Other designation
OGLE-LMC-RCB-01	LMC126.5	51348	conf.	$04^h59^m35.^s84$	$-68°24'44.''7$			EROS2-LMC-RCB-3		
OGLE-LMC-RCB-02	LMC127.4		conf.	$05^h00^m59.^s95$	$-69°03'44.''9$	LMC_SC15_85955	18.3325.148		V0635	LMV1365, HV12524
OGLE-LMC-RCB-03	LMC115.8	119	cand.	$05^h04^m40.^s52$	$-67°03'11.''8$					
OGLE-LMC-RCB-04	LMC112.6	10912	conf.	$05^h10^m28.^s52$	$-69°47'04.''4$		5.4887.14	EROS2-LMC-RCB-2		
OGLE-LMC-RCB-05	LMC109.6	29164	conf.	$05^h11^m31.^s37$	$-67°55'50.''7$		20.5036.12		V1394	HV5637
OGLE-LMC-RCB-06	LMC112.2	21869	conf.	$05^h14^m40.^s22$	$-69°58'39.''9$		5.5489.623	EROS2-LMC-RCB-1		
OGLE-LMC-RCB-07	LMC109.3	26874	conf.	$05^h14^m46.^s44$	$-67°55'46.''7$		16.5641.22		V1667	LMV282, HV2379
OGLE-LMC-RCB-08	LMC100.6	66625	conf.	$05^h15^m51.^s80$	$-69°10'08.''6$	LMC_SC8_151063	79.5743.15			
OGLE-LMC-RCB-09	LMC100.7	17279	cand.	$05^h16^m48.^s11$	$-69°22'22.''0$	LMC_SC8_224909				
OGLE-LMC-RCB-10	LMC104.4	59502	conf.	$05^h20^m48.^s20$	$-70°12'12.''6$	LMC_SC21_243519	6.6575.13			
OGLE-LMC-RCB-11	LMC104.4	79389	conf.	$05^h21^m47.^s97$	$-70°09'57.''0$	LMC_SC21_136130	6.6696.60		V2242	HV942
OGLE-LMC-RCB-12	LMC161.5	46026	conf.	$05^h22^m57.^s38$	$-68°58'18.''7$		80.6956.207		V2314	SHV0523154
OGLE-LMC-RCB-13	LMC164.1	18389	conf.	$05^h26^m24.^s52$	$-71°11'11.''8$		21.7407.7		V2643	HV966, W Men
OGLE-LMC-RCB-14	LMC161.3	58668	conf.	$05^h26^m33.^s90$	$-69°07'33.''3$		80.7559.28		V2629	SHV0526537
OGLE-LMC-RCB-15	LMC160.1	57260	cand.	$05^h28^m07.^s68$	$-68°52'54.''3$					
OGLE-LMC-RCB-16	LMC172.8	11923	cand.	$05^h31^m54.^s25$	$-71°53'49.''7$					
OGLE-LMC-RCB-17	LMC169.7	62497	conf.	$05^h32^m13.^s35$	$-69°55'57.''8$	LMC_SC2_365505	81.8394.1358			
OGLE-LMC-RCB-18	LMC170.4	17112	conf.	$05^h33^m48.^s94$	$-70°13'23.''5$	LMC_SC1_206923	11.8632.2507		V3334	LMV535, HV2671
OGLE-LMC-RCB-19	LMC180.5	22569	conf.	$05^h39^m36.^s99$	$-71°55'46.''8$		27.9574.93	EROS2-LMC-RCB-4		
OGLE-LMC-RCB-20	LMC178.3	7948	cand.	$05^h41^m23.^s51$	$-70°58'01.''7$		15.9830.5			
OGLE-LMC-RCB-21	LMC183.5	614	cand.	$05^h42^m21.^s92$	$-69°02'59.''3$					
OGLE-LMC-RCB-22	LMC185.1	39955	conf.	$05^h46^m47.^s74$	$-70°38'13.''6$	LMC_SC20_138270	12.10803.56			
OGLE-LMC-RCB-23	LMC203.2	5	conf.	$06^h04^m05.^s47$	$-72°51'22.''7$			EROS2-LMC-RCB-5		

T a b l e 2

Parameters of the RCB stars in the LMC

Star name	I_{max} [mag]	V_{max} [mag]	P_{puls} [days]	$A_{puls}(I)$ [mag]	$A_{drop}(I)$ [mag]
OGLE-LMC-RCB-01	13.143	14.333	39.216	0.067	0.18
OGLE-LMC-RCB-02	13.324	14.580	84.679	0.117	7.36
OGLE-LMC-RCB-03	15.627	16.566	18.839	0.004	0.32
OGLE-LMC-RCB-04	13.265	14.483	42.723	0.056	2.43
OGLE-LMC-RCB-05	13.528	14.798	39.377	0.051	0.27
OGLE-LMC-RCB-06	13.570	15.239	53.426	0.188	6.16
OGLE-LMC-RCB-07	13.427	15.200	45.472	0.089	7.63
OGLE-LMC-RCB-08	13.583	15.390	53.840	0.136	9.14
OGLE-LMC-RCB-09	15.102	15.563	20.770	0.011	0.42
OGLE-LMC-RCB-10	14.943	17.912	–	–	6.63
OGLE-LMC-RCB-11	13.520	14.490	57.690	0.156	7.09
OGLE-LMC-RCB-12	14.223	16.140	–	–	6.75
OGLE-LMC-RCB-13	13.323	13.797	66.957	0.033	2.98
OGLE-LMC-RCB-14	13.667	15.690	58.116	0.106	5.64
OGLE-LMC-RCB-15	15.656	16.645	–	–	0.34
OGLE-LMC-RCB-16	14.179	14.437	–	–	0.81
OGLE-LMC-RCB-17	14.440	16.580	128.139	0.114	6.82
OGLE-LMC-RCB-18	15.391	15.758	46.272	0.038	5.80
OGLE-LMC-RCB-19	13.378	15.142	54.993	0.151	5.47
OGLE-LMC-RCB-20	13.976	15.173	18.857	0.041	0.52
OGLE-LMC-RCB-21	15.793	–	–	–	5.72
OGLE-LMC-RCB-22	13.410	15.087	46.435	0.142	7.44
OGLE-LMC-RCB-23	13.249	14.380	84.717	0.124	1.80

All the confirmed and candidate DY Per stars are included in the OGLE-III catalog of LPVs (Soszyński *et al.* 2009), so we decided not to prepare the separate list of these objects. We flagged these stars in the remarks of the previous part of the OIII-CVS. The spatial distribution of the RCB and DY Per stars from our catalog is shown in Fig. 5.

5. Discussion

We performed an independent search for RCB in the LMC and found no undoubted new objects of that type. It suggests that the catalogs of RCB stars in the LMC prepared on the basis of the MACHO and EROS-2 data are close to being complete. The six new candidates for RCB stars identified among the OGLE light curves have infrared colors similar to the confirmed RCB stars, and their *I*-band light curves exhibit declines, however not so deep as for typical RCB stars. We propose to consider these new candidates as low-active RCB stars, similar to the

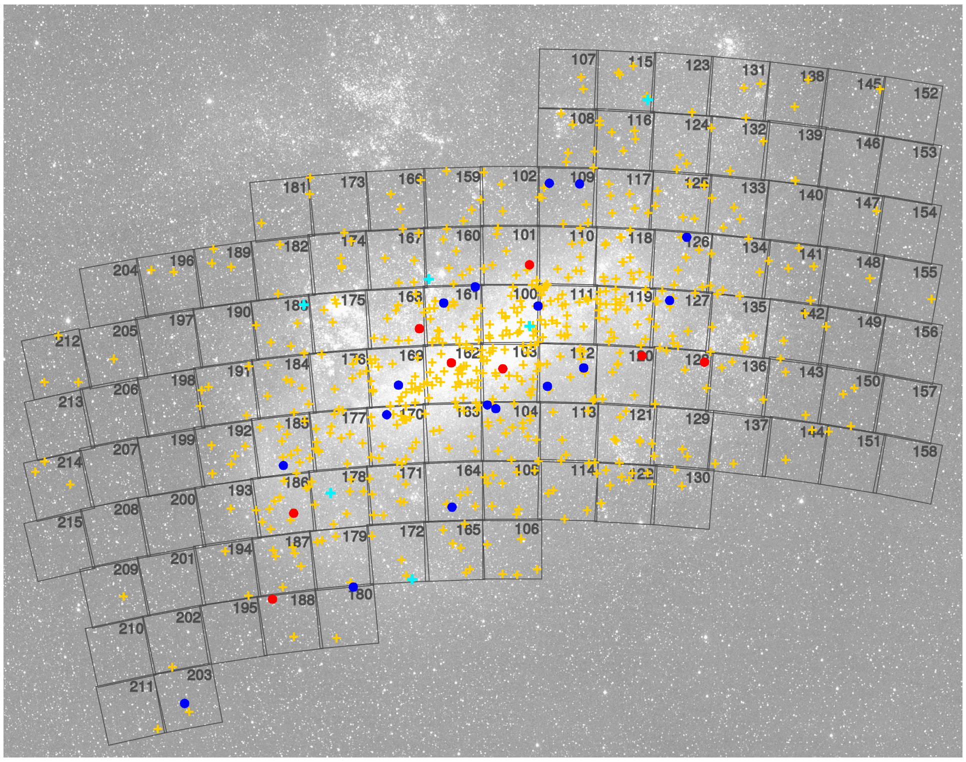

Fig. 5. Spatial distribution of RCB and DY Per stars in the LMC. Color symbols represent the same types of stars as in Figs. 1 and 3. The background image of the LMC is originated from the ASAS wide field sky survey (Pojmański 1997).

confirmed HV 5637 and EROS2-LMC-RCB-3. Only one candidate RCB variable – OGLE-LMC-RCB-21 – undergoes large brightness variations (>5 mag), but this star have not reached flat maximum during the OGLE coverage, so its resemblance to RCB stars is not firm (it may be also a DY Per star). The status of all candidate RCB stars must be confirmed spectroscopically.

Among these six new candidates, one object (OGLE-LMC-RCB-20 = KDM5651) was placed by Morgan *et al.* (2003) in the list of the suspected RCB stars on the basis of its spectral characteristics. We also checked two candidate RCB stars selected by Tisserand *et al.* (2009). EROS2-LMC-RCB-7 seems to be a highly-obscured star with the *I*-band luminosity varying between 19 mag and 20 mag. A sign of periodicity of about 700 days and the infrared colors of this object suggest that this is a C-rich Mira. The other EROS candidate for RCB stars – EROS-LMC-RCB-8 – lies outside the OGLE-III fields. The object MSX050825.4–685359, considered by Wood and Cohen (2001) as a possible RCB star, seems to be a DY Per variable.

Eight of ten DY Per stars identified and spectroscopically confirmed by Alcock *et al.* (2001) and Tisserand *et al.* (2009) can be detected in the LMC OGLE-III fields. All these stars are included in the OGLE-III catalog of LPVs in the LMC

(Soszyński *et al.* 2009) and classified as SRVs. Larger or smaller declines occur in all these objects with exception of EROS2-LMC-DYPer-1 (=OGLE-LMC-LPV-07762) which in the OGLE data shows only small variations (≈ 0.2 mag) of the mean luminosity.

Our photometry of C-rich AGB stars shows that severe variations of light at irregular intervals are quite common among C-rich red giants. We selected 600 stars with DY Per-like curves. Most of them have $(J-K) > 2$ mag, *i.e.*, they are thought to be AGB stars with thick circumstellar envelopes. We stress that the selected objects do not constitute any separate group of variable stars, but they form a continuity with other C-rich AGB stars. Thus, it should be considered that DY Per stars are just the extreme cases of dust-enshrouded AGB stars, and they are not separate type of variables.

The vast majority of our DY Per candidates are Miras or SRVs, but a number of objects were categorized as OGLE Small Amplitude Red Giants (OSARGs). Some of these stars exhibit Long Secondary Periods (LSPs), just like OGLE-LMC-LPV-70666 presented in Fig. 4 with the LSP equal to ≈ 1 year. Recently, Wood and Nicholls (2009) showed that the LSP phenomenon is associated with increased mass loss from red giants and the circumstellar dust is likely in a clumpy or a disk-like configuration. OGLE-LMC-LPV-70666 is a special case, because the three deep minima recorded by OGLE seem to happen periodically, with the time interval of about 2010 days. It is possible that we detected eclipses by a compact cloud of dust orbiting the red giant. Another light curve which draws particular attention is OGLE-LMC-LPV-81880 (also shown in Fig. 4). This is likely an OSARG variable which exhibited a single, nearly symmetric dip of almost 3 mag. It is unclear if this event was caused by a dust ejection, or by another phenomenon.

Acknowledgements. We are grateful to P. Tisserand for pointing out errors in Figs. 1 and 3. We thank G. Pojmański and J. Skowron for providing software and data which enabled us to prepare this study.

This work has been supported by the Foundation for Polish Science through the Homing (Powroty) Program and by MNiSW grants: NN203293533 to IS and N20303032/4275 to AU.

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