R Coronae Borealis stars in the Magellanic Clouds

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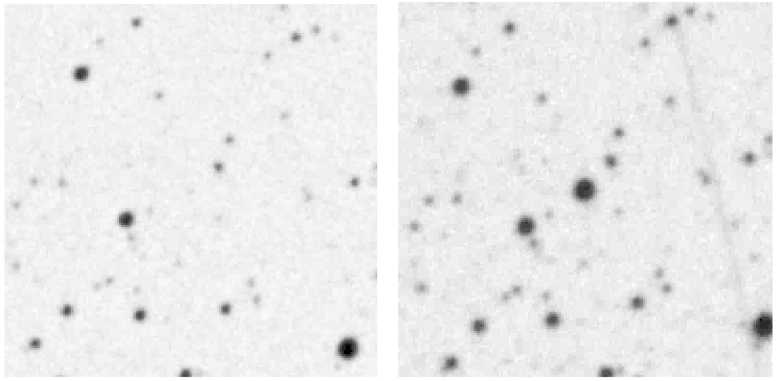
ABSTRACT

R Coronae Borealis (RCB) stars are a rare and enigmatic class of irregular variable star whose variation is driven by the formation of dust clouds in the stellar atmosphere. Since the discovery of the first extragalactic RCB star in the Large Magellanic Cloud in 1927, 26 have now been identified in the LMC and SMC. Observations of RCB stars in these galaxies allow accurate luminosity determinations, a quantity which is ill-determined for galactic RCB stars and vital in constraining their evolutionary status. This project reviews recent efforts to identify RCB stars in the Magellanic Clouds and also presents new OGLE–III photometry of currently known Magellanic RCB stars.

1. Introduction

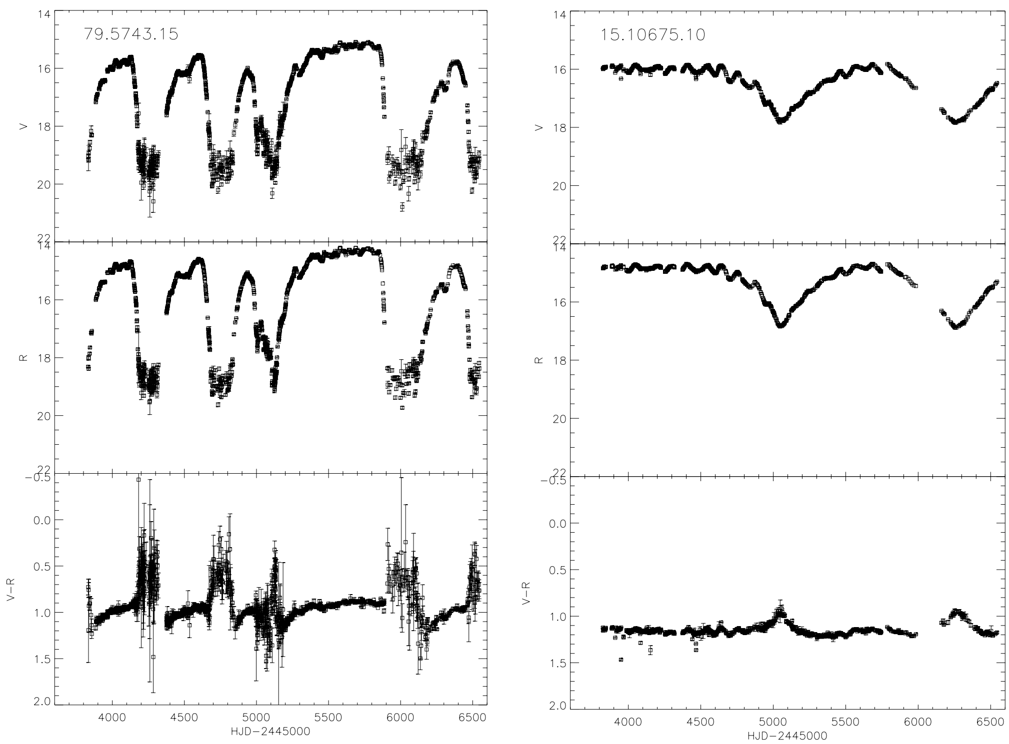
R Coronae Borealis (RCB) stars are carbon-rich, hydrogen-deficient supergiant stars which undergo rapid and extreme variations in brightness, sometimes by as much as 8 magnitudes (see Clayton 1996, for a review). The mechanism responsible for these irregular and unpredictable variations is the formation of dust clouds in the outer atmosphere of the star (de Laverny & Mékarnia 2004). When a cloud lies along the line-of-sight, a decline is observed. As the dust moves away from the star and dissipates the star recovers to its original brightness. Figure 1 illustrates the dramatic nature of an RCB decline and a typical light curve is shown in Figure 2(a). There is a large variation in light curve shape between RCB stars, and the initial development of the decline usually shows different development from decline to decline in the same star.

Around 50 galactic RCB stars have been identified, but distances to these objects and hence their absolute magnitudes are ill-defined at present. In constrast, distances to the Magellanic Clouds (MC) are known with some precision, hence observations of RCB stars in these galaxies can provide accurate measurements of absolute magnitudes and other distance-dependent quantities. From such studies it has been shown that RCB stars possess a range of absolute visual magnitudes; $-5 < M_V < -2.5$ (Alcock et al. 2001). Such information is essential to further understand the formation mechanism and evolutionary status of RCB stars. We are also interested in the physical and chemical processes occurring when RCB stars enter a decline and subsequent recovery. The metal–poor chemical environment of the Magellanic Clouds provides an ideal new site to investigate



(a) 29 January 1985 (b) 28 November 1987

Fig. 1.— R–band SuperCOSMOS images of the RCB star KDM 7101 (centre of field) in the LMC. The star is reddened and has an I-band excess in the earlier image, consistent with optically thick dust clouds obscuring the star. Deep declines such as this ($\Delta I \approx 2^m.5$) are typical of RCB variables.



(a) RCB star MACHO 79.5743.15 (b) DY Per star MACHO 15.10675.10

Fig. 2.— Magnitude and colour changes in two of the stars observed by Alcock et al. (2001). Compare the deeper and rapid declines of the RCB star to the slower and more symmetric development of the cooler DY Per–type star.

these processes. To this end the long–term goal of this project is to acquire $UBVRI$ photometry, spectroscopy and polarimetry of Magellanic RCB stars as they enter declines using Target-of-Opportunity time on the newly comissioned Southern African Large Telescope (SALT). In any case however, to obtain robust statistics the current sample size of 26 objects must be greatly increased.

This report provides a review of recent efforts to identify RCB stars in the Magellanic Clouds as well as introducing newly extracted OGLE photometry of these stars. It is outlined as follows: In §2 we briefly comment on all 26 currently known RCB stars in the LMC and SMC. We have obtained OGLE–III I–band photometry for most of these stars and this is presented in §3, along with historical photometry from other studies. In §4 we review recent developments in the field, particularly the work of Kraemer et al. (2005) in the SMC. We conclude with a brief discussion of future avenues along which this research may progress.

2. Known RCB stars in the Magellanic Clouds

The first extragalactic RCB star, W Mensae (HV 966), was discovered by Luyten in the LMC in 1927. This was followed by HV 5637 (Hodge & Wright 1969) and soon after by HV 12842 (Payne-Gaposchkin 1971), both of which were also in the LMC. All of these stars have since been spectroscopically confirmed as being carbon-rich and hydrogen-deficient. With the advent of large scale photometric microlensing surveys such as MACHO and EROS, samples of all types of variable stars have increased dramatically. Using the MACHO dataset Alcock et al. (1996) initially discovered 2 RCB stars in the LMC, then a further 12, including 4 rare DY Per–type stars (Alcock et al. 2001). DY Per–type RCB stars are cooler and fainter than traditional RCB stars and present slower and more symmetric declines (Keenan & Barnbaum 1997). Although they have similar light curves and spectroscopic properties it is not yet clear if DY Per stars are related to RCB stars, or are another class entirely. Figure 2(b) shows a typical DY Per light curve.

Contrary to cited literature, Cieslinski et al. (2003) identified the first candidate RCB star in the SMC on the basis of its I–band OGLE–II light curve during their search for Eruptive Cataclysmic Variables. This tally was soon increased by Morgan et al. (2003), who discovered another SMC candidate and an additional 3 RCB stars in the LMC, from their spectra of $\sim$2300 carbon stars. EROS2 light curves lead Tisserand et al. (2004) to confirm the RCB status of the Cieslinski et al. and Morgan et al. candidates, while also identifying another 3 SMC candidates, two of which show DY Per–type variations. In the latest developments Kraemer et al. (2005) spectroscopically confirmed the carbon–rich nature of one of Tisserand et al.'s RCB candidates and suggested, based on its IR spectrum and magnitudes, that it is actually a cool DY Per star. They also identified another candidate RCB star, based solely on its similar mid–IR spectrum, although we claim that a Mira or similar variable can also explain the observations, including a recently acquired OGLE-III light curve (see §4). Table 1 lists various identifiers and positions of all 26 currently known RCB and DY Per variables in the Magellanic Clouds.

RA	DEC	TYPE	OGLE-II	OGLE-III	NAME	OTHER	SOURCE
SMALL MAGELLANIC CLOUD							
00 37 47.07	-73 39 02.1	RCB	-	SMC133.4 11928	RAW 21	J003747-733902(sm0102l20592b)	Mo03, Ts04
00 40 14.65	-74 11 21.2	DYPER	-	SMC128.8 5816	[MH75] 431	J004014-741121(sm0106m19412b)	Ts04
00 44 07.45	-72 44 16.3	DYPER	SMC_SC3 172361	edge of chip	RAW 233	J004407-724416(sm0077k11497b)	Ts04
00 46 16.33	-74 11 13.6	RCB	-	SMC104.6 3030	MSX SMC 014	-	Kr05
00 48 22.87	-73 41 04.7	RCB	-	SMC103.6 8671	RAW 476	J004822-734104(sm0014k11612b)	Ts04
00 57 18.12	-72 42 35.3	DYPER	SMC_SC7 252741	SMC105.6 22488	MSX SMC 155	J005718-724235(sm0067m28134b)	Ts04, Cs03, Kr05
LARGE MAGELLANIC CLOUD							
05 01 00.299	-69 03 43.5	RCB	LMC_SC15 85515	overexposed	MACHO*05:01:00.269:03:43	HV 12524, SP 31-38	Al01
05 03 44.790	-69 38 12.73	DYPER	-	LMC120.5 6851	MACHO*05:03:44.769:38:12	10.3800.35	Al01
05 10 28.50	-69 47 04.3	RCB	-	LMC112.6 8722	--	KDM 2373, SP 39-12, HC 182	Mo03
05 11 31.402	-67 55 52.34	RCB	-	LMC109.6 21921	MACHO*05:11:31.467:55:52	HV 5637, SP 37-16	HW69, Mo03
05 14 46.177	-67 55 48.07	RCB	x overexposed	LMC109.3 5316	MACHO*05:14:46.267:55:4	16.5641.22, HV 2379	Al01
05 15 51.834	-69 10 08.99	RCB	LMC_SC8 151063	LMC100.6 48589	MACHO*05:15:51.869:10:08	79.5743.15, PMN J0515-6910	Al01
05 16 51.890	-68 45 17.81	DYPER	-	LMC101.7 8114	MACHO*05:16:51.868:45:17	2.5871.1759	Al01
05 19 56.050	-69 48 06.44	DYPER	LMC_SC7 363932	LMC103.3 15150	MACHO*05:19:56.069:48:06	78.6460.7	Al01
05 20 48.244	-70 12 12.51	RCB	x in decline	LMC104.4 56018	MACHO*05:20:48.270:12:12	6.6575.13	Al01
05 21 47.997	-70 09 57.41	RCB	LMC_SC21 136130	LMC104.4 60857	MACHO*05:21:47.970:09:57	6.6696.60, HV 942	Al01
05 22 56.944	-68 58 16.87	RCB	x -	-	MACHO*05:22:56.968:58:16	80.6956.207, SHV 0523154-690100	Al01
05 26 24.761	-71 11 13.32	RCB	-	LMC164.1 16431	MACHO*05:26:24.771:11:13	W Men, HV 966, R102	Ly27
05 26 33.853	-69 07 33.21	RCB	-	LMC161.3 45704	MACHO*05:26:33.869:07:33	80.7559.28, SHV 0526537-690959	Al01
05 32 13.263	-69 55 59.23	RCB	LMC_SC2 365505	LMC169.7 40649	MACHO*05:32:13.369:55:59	81.8394.1358	Al96
05 33 49.126	-70 13 22.49	RCB	LMC_SC1 206923	LMC170.4 12337	MACHO*05:33:49.170:13:22	11.8632.2507, HV 2671	Al96
05 41 23.49	-70 58 01.8	RCB	-	LMC178.3 5808	--	KDM 5651, SP 55-17, HC 119	Mo03
05 45 02.92	-64 24 23.2	RCB	Outside OGLE fields		Outside MACHO field	HV 12842, F05447-6425	PG71
05 46 13.045	-71 07 40.6	DYPER	LMC_SC20 60162	LMC186.7 11588	MACHO*05:46:13.071:07:40	SHV 0546548-710843, SP 55-23	Al01
05 46 46.211	-70 38 12.7	RCB	x -	-	MACHO*05:46:46.270:38:12	12.10803.56	Al01
06 04 05.53	-72 51 23.1	RCB	-	LMC203.2 3	Outside MACHO field	KDM 7101, SP 65-2	Mo03

Table 1: All currently known RCB and DY Per variables in the Magellanic Clouds. Crosses indicate stars for which we do not yet have OGLE photometry. Source column gives discovery paper and any substantial follow-up studies (see text for references to abbreviations).

3. Photometry

We have obtained I–band photometry for all 6 SMC objects and 15 of the 20 known LMC objects from the OGLE-III microlensing survey of the Magellanic Clouds and Galactic Bulge (Udalski 2003). The extracted light curves are shown in Figures A1 and A2. The data covers the period early–2001 to late–2005, extending to mid–December 2005 in many cases. Of the 5 stars for which photometry was not able to be obtained, one was outside observed OGLE fields and the remaining 4 were not found in the standard database, possibly due to position errors or being in decline when the field reference image was constructed. MACHO light curves reveal one such star, LMC104.4 56818, has been in decline at $V \approx 21$ since mid–1998 so it is highly likely that it was missed when the reference images were made. We are still awaiting these remaining I–band light curves and any available V–band data so that the $V - I$ colour may be constructed. Publically available photometry from the literature has also been sought, including the MACHO photometry of Alcock et al. (2001) and EROS2 data of Tisserand et al. (2004). The MACHO data give the Kron-Cousins R and V standard magnitudes and cover the period early–1992 to late–1999. Tisserand et al.'s EROS2 data span mid–1996 to early–2003 and have V_E and R_E magnitudes which overlap the standard V and R bands for V_E and approximately follow the standard I–band for R_E.

4. Discussion

4.1. Recent developments

All RCB stars have previously been identified on the basis of their strong and irregular variability at optical wavelengths. Kraemer et al. (2005) however have confirmed one RCB candidate in the SMC and identified a further candidate on the basis of their IR spectral properties using the *Spitzer Space Telescope*. Figure 3 shows that both stars have near–featureless mid–IR spectra, similar to that of the prototype R CrB. This implies the stars have hydrogen–deficient atmospheres, which leads to the formation of amorphous carbon dust instead of the hydrogen–rich Polycyclic Aromatic Hydrocarbons (PAHs) and C_2H_2 molecules which have strong IR features not present in the spectra. During their search of the EROS2 database Tisserand et al. previously identified one of the stars, MSX SMC 155[1], as an RCB candidate requiring further investigation. From visual spectra, Kraemer et al. confirm the star is carbon–rich and from IR observations and dust models suggest it is a very cool DY Per–type star of surface temperature ∼2000–2500 K. To date 6 DY Per candidates have now been found in the Magellanic Clouds; 4 by Alcock et al. (2001) in the LMC and a further two by Tisserand et al. (2004) in the SMC, but interestingly not MSX SMC 155.

The EROS2 and MACHO light curves of MSX SMC 155 are not typical of known DY Per stars (see for example Figure 2 in Alcock et al. (2001) and Figures 2 & 3 in Tisserand et al.).

[1] MSX SMC 155 = sm0067m28134b in Tisserand et al. (2004)

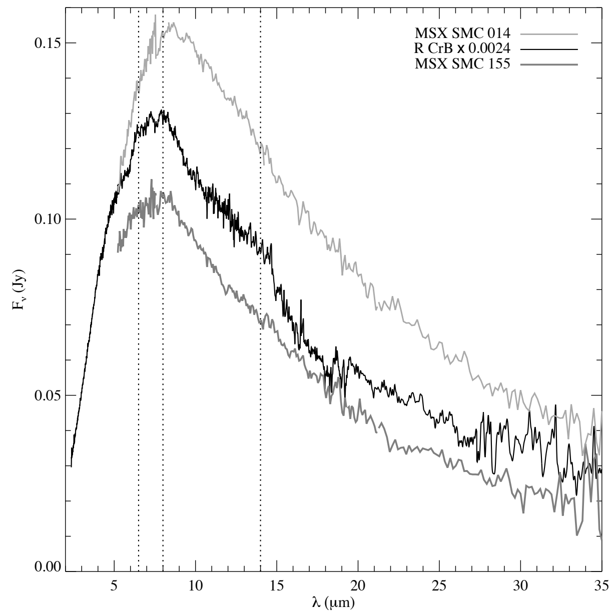


Fig. 3.— IRS spectra of MSX SMC 155 (bottom trace) and the other RCB star found by Kraemer et al., MSX SMC 014 (top trace). Both stars have similar spectra to the prototype R CrB (middle trace). Dotted lines denote spectral features: amorphous carbon at 6 and 14 μm in R CrB and a possible, unidentified feature near 8 μm in all three stars. Figure 2 in Kraemer et al. (2005).

Our OGLE data, which overlaps EROS2 and continues until 2005 December reveal variations of order 5-6 magnitudes, which although slow, appear more like RCB variations than DY Per. The position of MSX SMC 155 (and indeed the other 2 SMC DY Per candidates) on the 2MASS K versus $H - K$ colour–magnitude diagram of Tisserand et al. (their Figure 9) is also inconsistent with the 4 spectroscopically confirmed DY Per stars of Alcock et al. (2001). Furthermore, from its EROS2 lightcurve Tisserand et al. estimate an absolute visual magnitude for MSX SMC 155 of $M_V = -1.3$, far fainter than the other SMC and LMC DY Per candidates at $M_V \sim -2.1$ and $M_V \sim -2.5$ respectively. Given these factors it is perhaps premature to classify MSX SMC 155 as a DY Per star until a more thorough spectroscopic investigation and longer–term photometry are carried out.

The other RCB candidate identified by Kraemer et al., MSX SMC 014, has the same featureless mid–IR spectrum and K–band variability as MSX SMC 155. This was sufficient for Kraemer et al. to claim that MSX SMC 014 is the sixth and newest RCB star in the SMC. They could not obtain any detailed time series photometry because the star does not appear in either of the MACHO, EROS or OGLE–II databases. We have however located the object in the OGLE-III database and extracted historical I–band photometry of the star from 2001 March to 2005 December, which is shown in Figure 4.

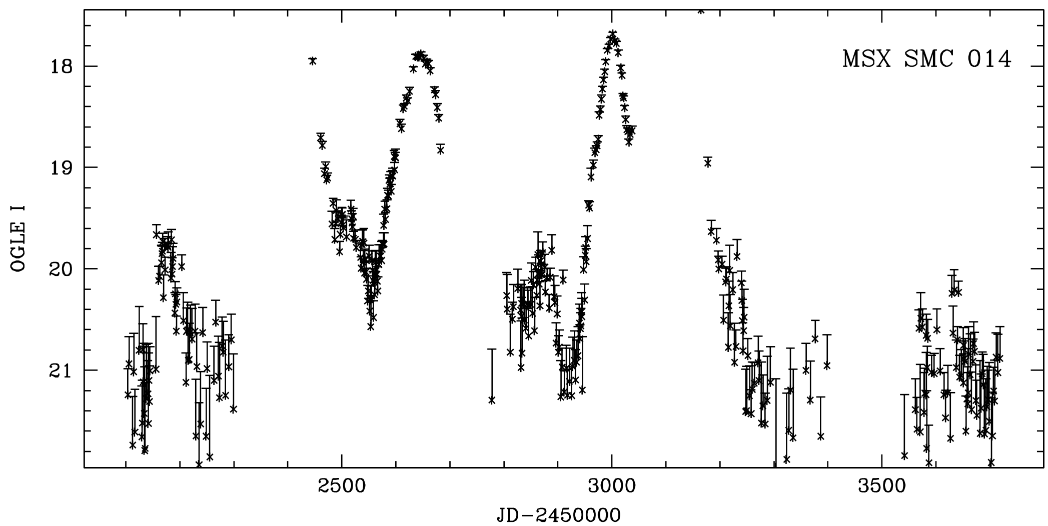


Fig. 4.— OGLE–III I–band light curve for MSX SMC 014.

The light curve is not typical of RCB or DY Per stars. Instead, the regularity and amplitude of the variation between days 2500 and 3000 is suggestive of a Long Period Variable such as a Mira. Inspecting the light curve visually gives a rough period of $\sim 360^d$ and applying the 'string-length' period–finding technique of Dworetsky (1983) gives the two most likely periods to be 347^d and 383^d, with a mean of 365^d. A period of $\sim$ 1 year is consistent with Mira–type variables, whose periods generally range from $100 - 1000^d$. The seasonal gaps in the OGLE data prevent a conclusive identification of periodicity, but further observations should elucidate this.

A subclass of Miras are known to be carbon–rich and possess large variations in visual and IR brightness on time scales which are substantially longer than their pulsational periods. Such variations may be similar to the declines of RCB stars (Feast 2001). Kraemer et al. had insufficient near–IR data to constrain the surface temperature of MSX SMC 014 but we note that Miras have surface temperatures close to that of DY Per stars ($T_{eff} \sim 3500$ K; Keenan & Barnbaum 1997). The large bolometric luminosity suggested by Kraemer et al. for MSX SMC 014 of $L \approx 9700\ L_{\odot}$ and the SED peak at $\sim 10\mu m$ are also characteristic of a dusty AGB star like a Mira. We therefore claim that as well as an RCB star, a hydrogen–deficient Mira also explains the full set of observations, but as in the case of MSX SMC 155, further photometric and spectroscopic data are necessary before any firm conclusions can be drawn. The large light–gathering capacity and location of SALT make it ideal to undertake such studies.

4.2. Future work

The primary focus of future work in this project is to obtain *UBVRI* photometry, polarimetry and medium to high resolution spectroscopy of Magellanic RCB stars as they enter into declines to further investigate the physical and chemical processes occuring in the decline phase. We will be applying for Target-of-Opportunity time on SALT to conduct these observations. Therefore in collaboration with the OGLE team we have added all 26 RCB and DY–Per stars to the OGLE Early Warning System for rapid notification should they enter a decline. As mentioned above, SALT and its instrument suite are ideally suited to not only this decline work, but to also investigate and confirm the properties of some of the fainter candidates, for example those of Kraemer et al.

Due to the unpredictability and rarity of RCB declines, long–term microlensing surveys such as MACHO, EROS and OGLE have obviously played an important role in the discovery of most of the known RCB stars in the Magellanic Clouds. Of relevance to local astronomers is the Microlensing Observations in Astrophysics (MOA, e.g. Hearnshaw et al. 2000) program currently underway at Mt John Observatory which has already been used to successfully identify a range of variable stars in the Magellanic Clouds, including Eclipsing Binaries and Long Period Variables (Bayne et al. 2002; Noda et al. 2002). The MOA database can potentially be mined for new RCB candidates or used to supplement existing photometry by providing additional wavebands and temporal baselines.

4.3. Conclusions

Because of their known distance, observations of RCB and DY Per stars in the Large and Small Magellanic Clouds can offer great insight into the evolutionary status, formation mechanism and physical and chemical processes occuring in these rare and poorly–understood class of variable star. In this project we have collated results from recent searches for RCB stars in the Magellanic Clouds and produced a catalogue of the 26 known objects with associated OGLE-III *I*–band photometry. This should serve as a foundation for further aspects of this project, particularly observations of the decline phases of the stars using SALT in the coming months and years. We have also critically reviewed the work of Kraemer et al. (2005) and suggest that based on our newly obtained OGLE-III data, their classification of two stars in the SMC, MSX SMC 155 and MSX SMX 014, as DY Per and RCB candidates respectively is premature. We claim in particular that a hydrogen-deficient Mira for instance can explain the observations of MSX SMC 014 as well as the current RCB classification.

REFERENCES

Alcock, C., Allsman, R. A., Alves, D. R., Axelrod, T. S., Becker, A., et al. 1996, ApJ, 470, 583

—. 2001, ApJ, 554, 298

Bayne, G., Tobin, W., Pritchard, J. D., Bond, I., Pollard, K. R., et al. 2002, MNRAS, 331, 609

Cieslinski, D., Diaz, M. P., Mennickent, R. E., & Pietrzyński, G. 2003, PASP, 115, 193

Clayton, G. C. 1996, PASP, 108, 225

de Laverny, P. & Mékarnia, D. 2004, A&A, 428, L13

Dworetsky, M. M. 1983, MNRAS, 203, 917

Feast, M. 2001, Encyclopedia of Astronomy & Astrophysics, Vol. 2 (IOP Publishing), 1748–1754

Hearnshaw, J. B., Bond, I. A., Rattenbury, N. J., Noda, S., Takeuti, M., et al. 2000, in ASP Conf. Ser. 203: IAU Colloq. 176: The Impact of Large-Scale Surveys on Pulsating Star Research, 31–37

Hodge, P. W. & Wright, F. W. 1969, ApJS, 17, 467

Keenan, P. C. & Barnbaum, C. 1997, PASP, 109, 969

Kraemer, K. E., Sloan, G. C., Wood, P. R., Price, S. D., & Egan, M. P. 2005, ApJ, 631, L147

Luyten, W. J. 1927, Harvard College Observatory Bulletin, 846, 33

Morgan, D. H., Hatzidimitriou, D., Cannon, R. D., & Croke, B. F. W. 2003, MNRAS, 344, 325

Noda, S., Takeuti, M., Abe, F., Bond, I. A., Dodd, R. J., et al. 2002, MNRAS, 330, 137

Payne-Gaposchkin, C. H. 1971, The variable stars of the Large Magellanic Cloud (Smithsonian Contributions to Astrophysics, Washington: Smithsonian Institution Press, —c1971)

Skuljan, L., Cottrell, P. L., Gilmore, A. C., & Kilmartin, P. M. 2003, PASA, 20, 159

Tisserand, P., Marquette, J. B., Beaulieu, J. P., de Laverny, P., et al. 2004, A&A, 424, 245

Udalski, A. 2003, Acta Astronomica, 53, 291

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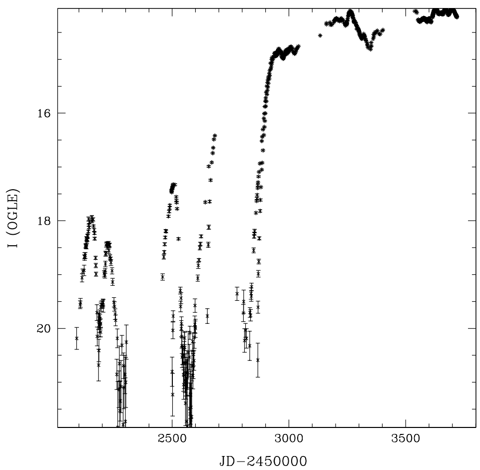
A. OGLE light curves

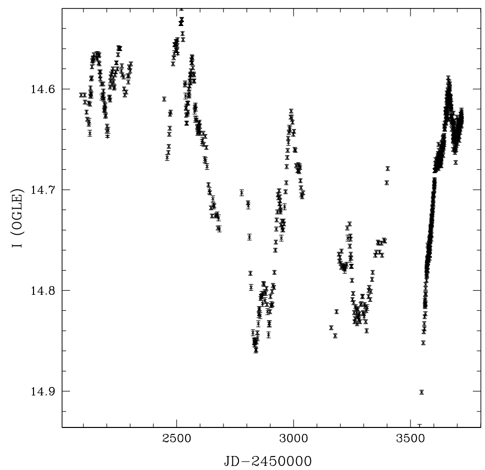
Figures A1 and A2 show I–band OGLE-III photometry of all RCB and DY Per candidates in the SMC and 15 of the 20 known LMC candidates. One LMC candidate is outside the OGLE fields and we are currently expecting photometry on the remaining four. Data points with errors exceeding one magnitude are excluded to aid clarity.

B. Finding charts

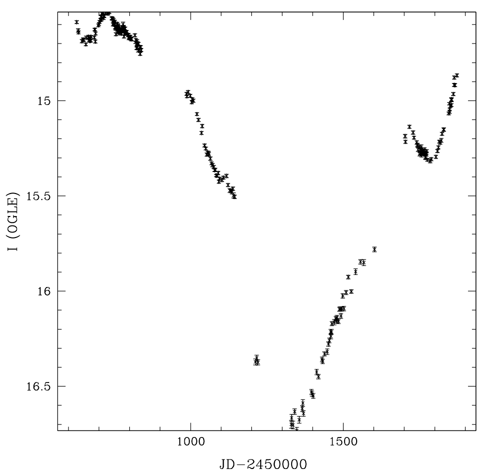
We also present multi-epoch R–band finding charts for all currently known RCB and DY Per candidates in the Magellanic Clouds. Images are $120''$ across and are taken from the SuperCOSMOS Sky Survey, available online at `http://www-wfau.roe.ac.uk/sss`. North is at the top of each field, east on the left.



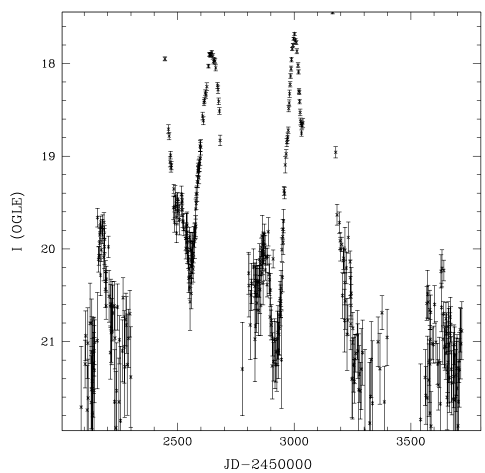
(a) RAW 21 (RCB)



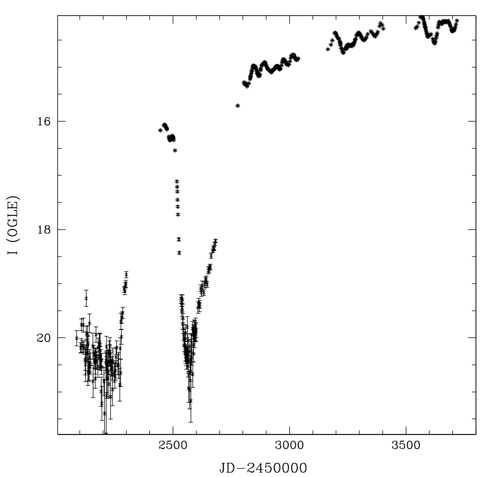
(b) MH75 431 (DY Per)



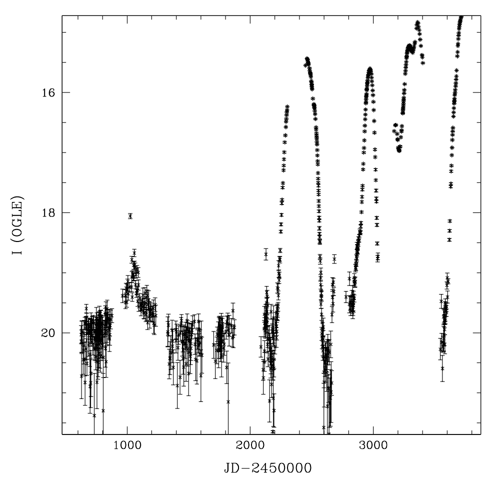
(c) RAW 233 (DY Per)



(d) MSX SMC 014 (RCB?)

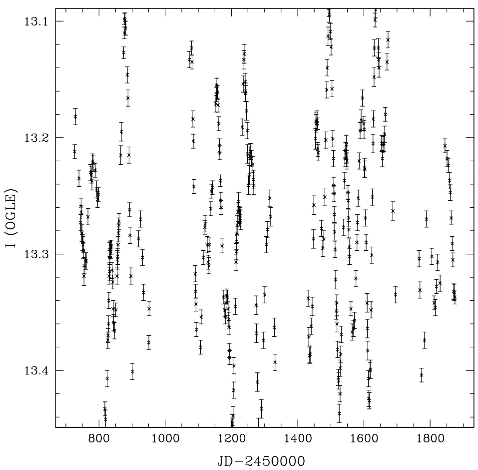


(e) RAW 476 (RCB)

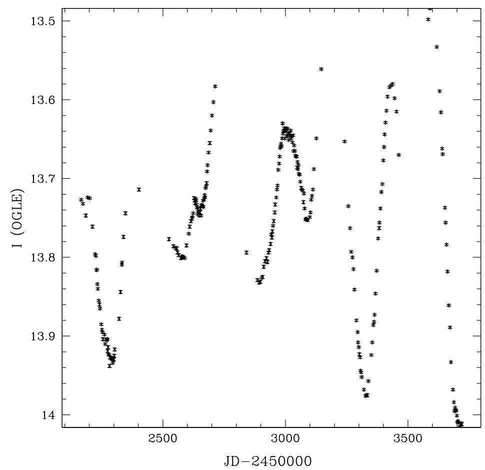


(f) MSX SMC 155 (DY Per?)

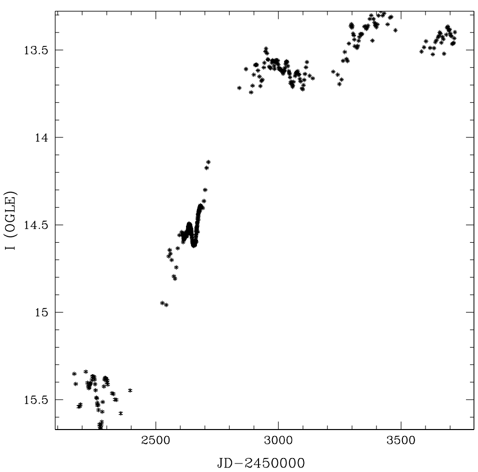
Fig. A1. — OGLE *I*–band light curves for SMC candidates.



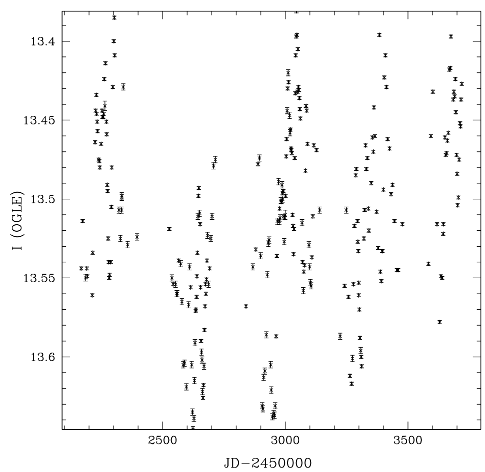
(g) HV 12524 (RCB))



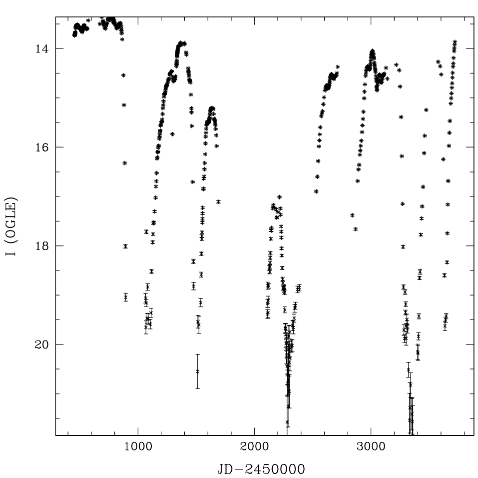
(h) 10.3800.35 (DY Per)



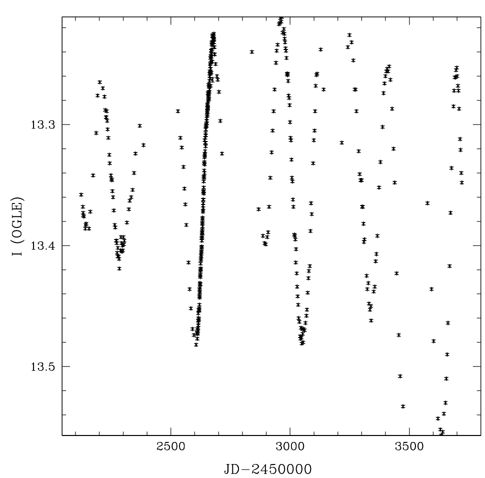
(i) KDM 2373 (RCB)



(j) HV 5637 (RCB)

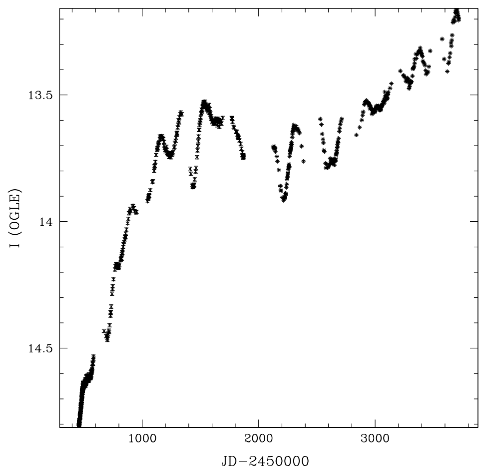


(k) 79.5743.15 (RCB)

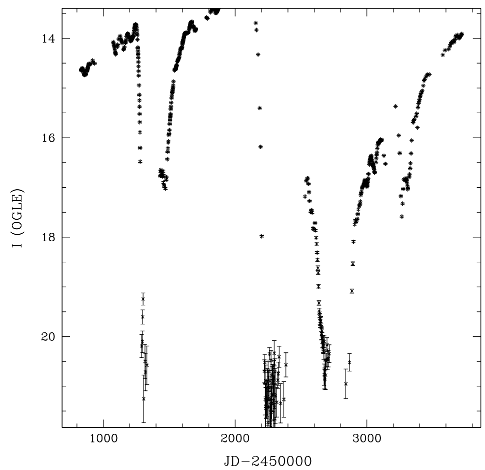


(l) 2.5871.1759 (DY Per)

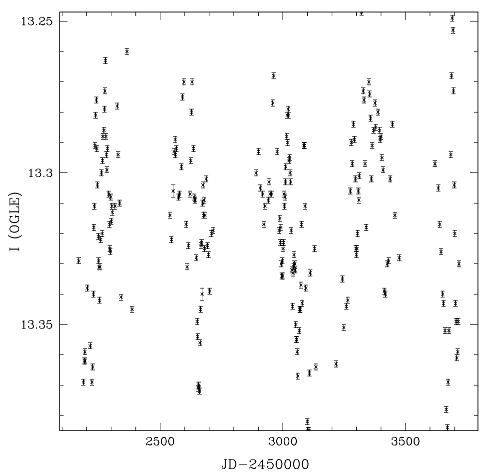
Fig. A2. — OGLE *I*–band light curves for LMC candidates.



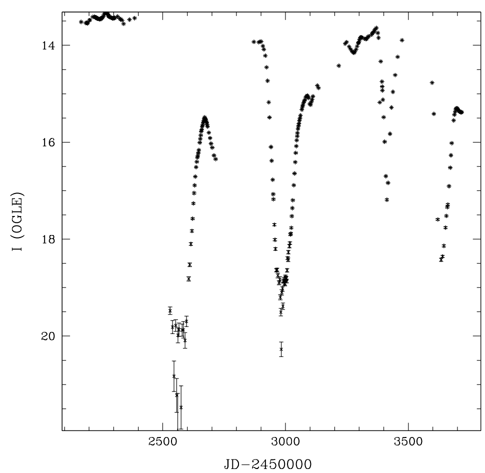
(m) 78.6460.7 (DY Per)



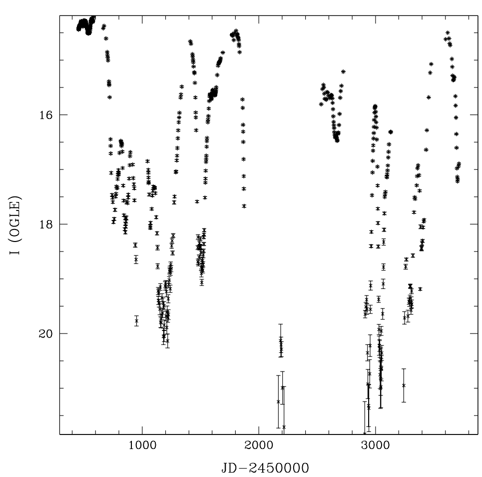
(n) HV 942 (RCB)



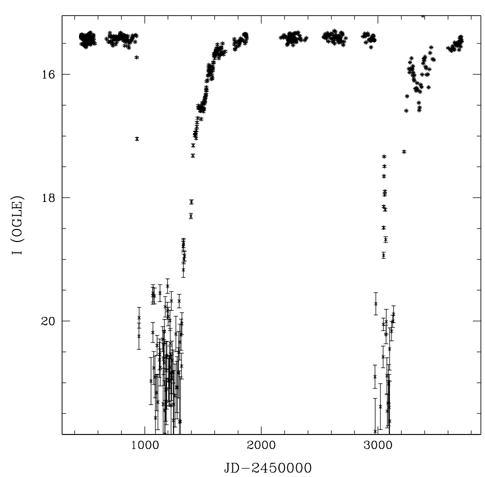
(o) W Men (RCB)



(p) 80.7559.28 (RCB)

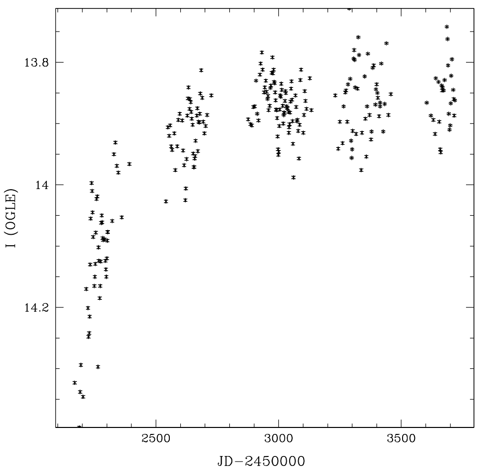


(q) 81.8394.1358 (RCB)

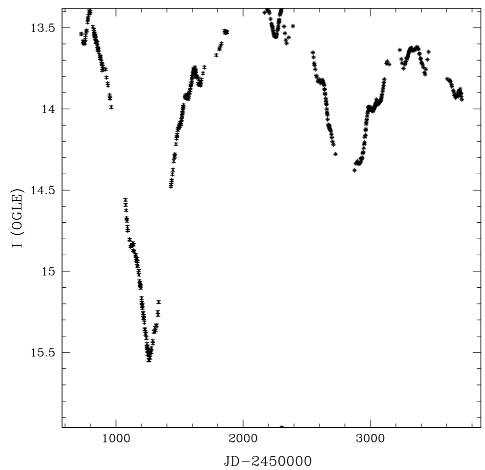


(r) HV 2671 (RCB)

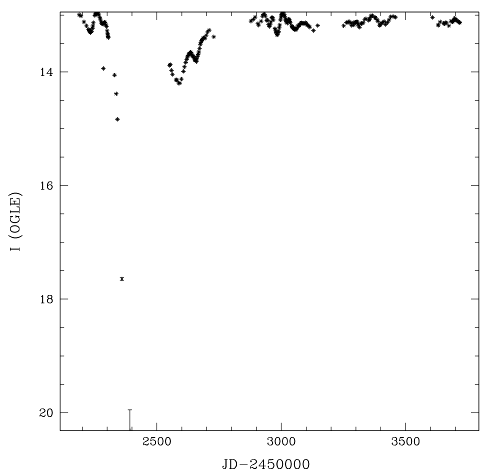
Fig. A2. — *cont.*



(s) KDM 5651 (RCB)



(t) SP 55–23 (DY Per)



(u) KDM 7101 (RCB)

Fig. A2. — *cont.*