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THE MACHO PROJECT LMC VARIABLE STAR INVENTORY. X. THE R CORONAE BOREALIS STARS

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ABSTRACT

We report the discovery of eight new R Coronae Borealis (RCB) stars in the Large Magellanic Cloud (LMC) using the MACHO project photometry database. The discovery of these new stars increases the number of known RCB stars in the LMC to thirteen. We have also discovered four stars similar to the Galactic variable DY Per. These stars decline much more slowly and are cooler than the RCB stars. The absolute luminosities of the Galactic RCB stars are unknown since there is no direct measurement of the distance to any Galactic RCB star. Hence, the importance of the LMC RCB stars. We find a much larger range of absolute magnitudes ($M_V = -2.5$ to -5 mag) than inferred from the small pre-MACHO sample of LMC RCB stars. It is likely that there is a temperature-M_V relationship with the cooler stars being intrinsically fainter. Cool ($\sim$5000 K) RCB stars are much more common than previously thought based on the Galactic RCB star sample. Using the fairly complete sample of RCB stars discovered in the MACHO fields, we have estimated the likely number of RCB stars in the Galaxy to be $\sim$3200. The SMC MACHO fields were also searched for RCB stars, but none were found.

Subject headings: Magellanic Clouds — stars: evolution — stars: variables: other

On-line material: machine-readable tables, color figure

1. INTRODUCTION

The R Coronae Borealis (RCB) stars are rare, hydrogen-deficient, carbon-rich supergiants which undergo spectacular declines in brightness of up to 8 mag at irregular intervals as dust forms along the line of sight (Clayton 1996). Their rarity may stem from the fact that they are in an extremely rapid phase of evolution toward white dwarfs. So understanding the RCB stars is a key test for any theory which aims to explain hydrogen deficiency in post–asymptotic giant branch (AGB) stars. AGB and post-AGB stars are the dominant formation sites for refractory grains subsequently injected into the interstellar medium, and therefore they play an important role in any theory of dust condensation.

There are two major evolutionary models for the origin of RCB stars: the Double Degenerate and the Final Helium Shell Flash (Iben, Tutukov, & Yungleson 1996a). The former involves the merger of two white dwarfs, and the latter involves a white dwarf/evolved planetary nebula (PN) central star which is blown up to supergiant size by a final helium shell flash. In the final flash model, there is a close relationship between RCB stars and PN. The connection between RCB stars and PN has recently become stronger, since the central stars of three old PNe (Sakurai's Object, V605 Aql, and FG Sge) have had observed outbursts that transformed them from hot evolved central stars into cool giants with the spectral properties of a RCB star (Kerber et al. 1999; Asplund et al. 1999; Clayton & De Marco 1997; Gonzalez et al. 1998).

However, the absolute luminosities of the RCB stars are unknown. There is no direct measurement of the distance to any Galactic RCB star (Alcock et al. 1996 and references therein). A group of RCB stars were measured by HIPPARCOS but the data provided only lower limits on their

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distances (Cottrell & Lawson 1998; Trimble & Kundu 1997). So the only source of distances and absolute luminosities for the RCB stars is the LMC. The distance to the LMC is fairly well determined, $m-M = 18.4$ mag (e.g., Nelson et al. 2000). Until recently, only three RCB stars were known in the LMC (Feast 1972). On the basis of this small sample of stars, an absolute magnitude range of $M_V = -4$ to -5 is inferred. Alcock et al. (1996) reported the discovery of two additional LMC RCB stars. These two stars were both fainter, $M_V \sim -3.5$ but one of the two is a member of the subclass of hot RCB stars and may not be comparable to the cooler stars.

This paper reports the results of a more extensive search of the MACHO database for new RCB stars.

2. OBSERVATIONAL DATA

2.1. *MACHO Photometry*

The MACHO Project (Alcock et al. 1992) is an astronomical survey experiment designed to obtain multiepoch, two-color CCD photometry of millions of stars in the LMC (also, the Galactic bulge and SMC). The survey makes use of a dedicated 1.27 m telescope at Mount Stromlo, Australia, and because of its southerly latitude it is able to obtain observations of the LMC year round (Hart et al. 1996). The camera built specifically for this project (Stubbs et al. 1993) has a field of view of 0.5 deg^2, which is achieved by imaging at prime focus. Observations are obtained in two bandpasses simultaneously, using a dichroic beam splitter to direct the "blue" ($\sim$4400–5900 Å) and "red" ($\sim$5900–7800 Å) light onto 2×2 mosaics of 2048×2048 Loral CCDs. These bandpasses are referred to as $V_{\rm MACHO}$ and $R_{\rm MACHO}$, respectively. Images are obtained and read out simultaneously. The 15 μm pixel size maps to 0".63 on the sky. The data were reduced using a profile-fitting photometry routine known as SODOPHOT, derived from DoPHOT (Schecter, Mateo, & Saha 1993). This implementation employs a single starlist generated from frames obtained in good seeing. The results reported in this survey comprise only a fraction of the planned data acquisition of the MACHO project. The MACHO data were acquired for 82 LMC fields covering approximately 40 deg^2 and were monitored for about 7 years from 1992 to 1999. Most of the data come from the top-22 fields which contain approximately 9 million stars (Alcock et al. 1997a, 1999). These data have been searched for variable stars and microlensing candidates and over 40,000 variables have been found, most newly discovered. The great majority of these fall into four well-known classes: there are approximately 25,000 very red semiregular or irregular variables, 1500 Cepheids, 8000 RR Lyraes, and 1200 eclipsing binaries (Cook et al. 1995). Typically, the data set for a given star covers a timespan of about 2700 days and contains up to 1500 photometric measurements (multiple observations are obtained on a given night whenever conditions allow). The output photometry contains flags indicating suspicion of errors due to crowding, seeing, array defects, and radiation events.

The MACHO light curves for the RCB candidate stars, including all available data, are shown in Figure 1. Tables containing all the MACHO photometric data for these stars are given in the Appendix. HV 12842 lies outside the MACHO fields and so has no light curve. Only data free from suspected errors are plotted and included in the tables. Typical photometric uncertainties are in the range 1.5%–2%. The $V_{\rm MACHO}$ and $R_{\rm MACHO}$ bandpasses have been converted to Kron-Cousins (KC) V and R bandpasses using transformations determined from the internal calibrations of the MACHO database (Alcock et al. 1999). Three stars in the sample, 16.6541.22, 20.5036.12, and 21.7407.7 lie outside the top-22 fields which have been photometrically calibrated. The V and R magnitudes for these fields were obtained by bootstrapping from the top-22-field calibration and should be viewed with caution. Also, 18.3325.148, 20.5036.12, and 21.7407.7 are the three brightest stars in the sample and suffer from possible saturation problems. In particular, the MACHO $V-R$ colors for 21.7407.7 are ~ -0.2 but are actually ~ 0.2 (Goldsmith et al. 1990). The $(V-R)_{\rm KC}$ colors for each star are also plotted in Figures 1 and 2. The stars are listed in Table 1. Two designations are given for each MACHO star, the MACHO name which includes the position of the star, and the standard "field.tile.sequence" number which refers to a particular star in the database. Finding charts for the stars are shown in Figures 3, 4, and 5.

2.2. *JHK Photometry*

The Cerro Tololo Infrared Imager (CIRIM) uses a 256×256 HgCdTe NICMOS 3 array. There were two runs in 1996 and 1999 on the CTIO 1.5 m telescope. The data are listed in Table 2. The typical 1 σ errors are 0.02–0.03 mag in the J band and 0.04–0.05 mag in the H and K bands. None of the data from the 1999 run are included because of their large uncertainties. In addition, 2MASS photometry is now available for most of the sample. These data are also listed in Table 2. The typical 1 σ 2MASS errors are 0.03 mag in all three bands. The Julian Dates of the observations are also listed in Table 2.

2.3. *Spectroscopic Data*

Spectroscopic observations were obtained from 1995 to 1998. In 1995–1996, the spectra were obtained with the Reticon photon-counting system on the image-tube spectrograph on the SAAO 1.9 m telescope at Sutherland, South Africa. The grating used gives a reciprocal dispersion of 100 Å mm^{-1} and a resolution of approximately 4 Å, giving a useful range of about 3600–5200 Å at the angle setting used. The spectrograph is a two-aperture instrument recording the star and sky simultaneously. Normal operating procedure is to measure the star through one aperture and then the other, so the sequence goes arc, star in A, arc, star in B, arc. Each star is then wavelength calibrated by the two arcs on either side and the results of star in A and B are added together after flat-field correction and sky subtraction. Flux calibration is done by observing one standard star each night. The fluxes are given in ergs cm^{-2} s^{-1} Å^{-1}. In 1997–1998, the spectrograph was adapted to take a SITe CCD chip. The observations were taken using a grating with a reciprocal dispersion of 210 Å mm^{-1} and a resolution of approximately 5 Å, giving a useful range of about 3500–7600 Å at the angle setting used.

Spectra have been obtained for all the stars in Table 1 except 6.6575.13 and 16.5641.22. A spectrum of the latter star is shown in Bessell & Wood (1983). No spectrum exists for 6.6575.13 since it has been continuously in decline since 1993. A spectrum of the hot RCB star, 11.8632.2507, is shown in Alcock et al. (1996). Further spectra are shown in

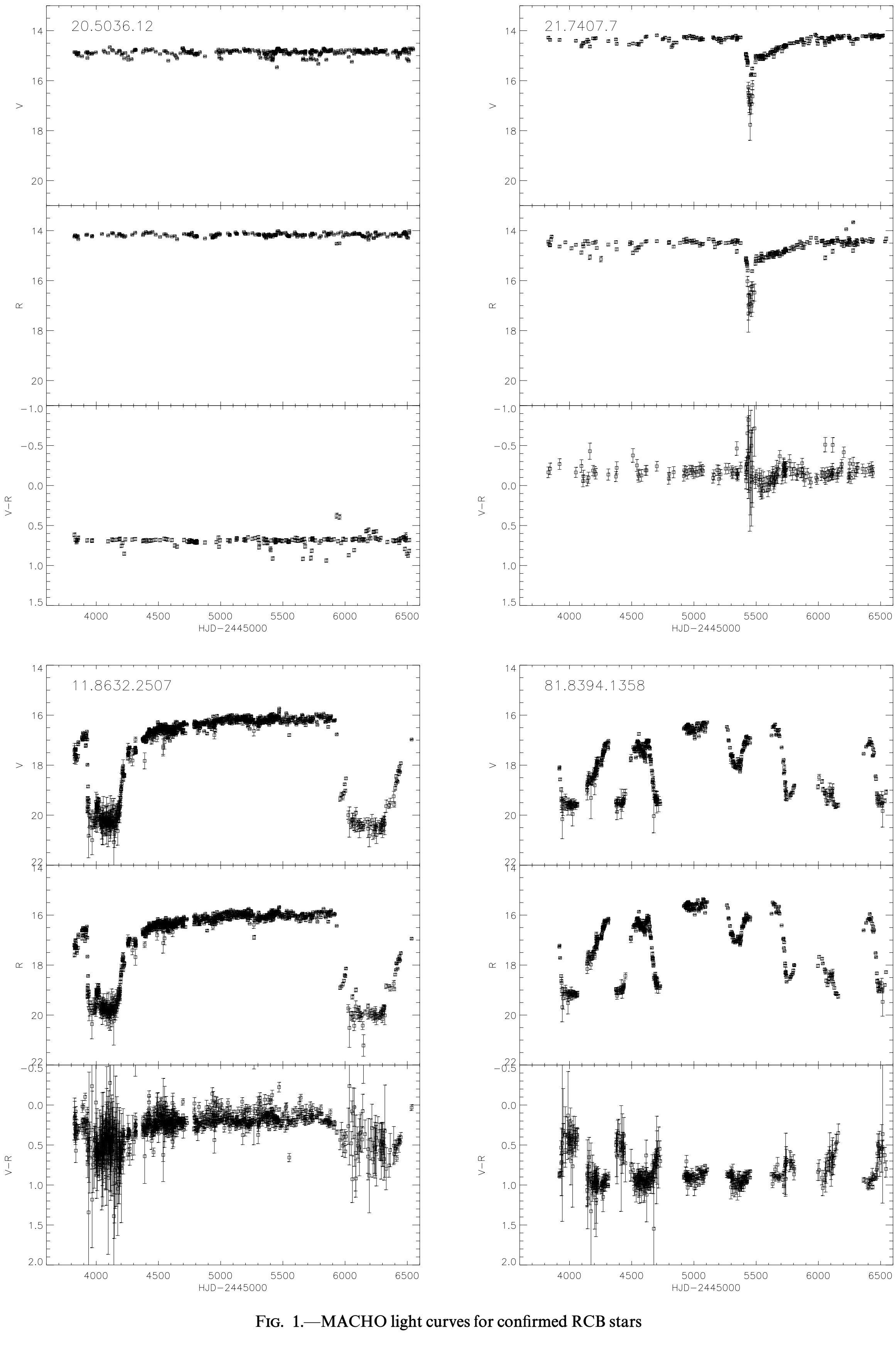

FIG. 1.—MACHO light curves for confirmed RCB stars

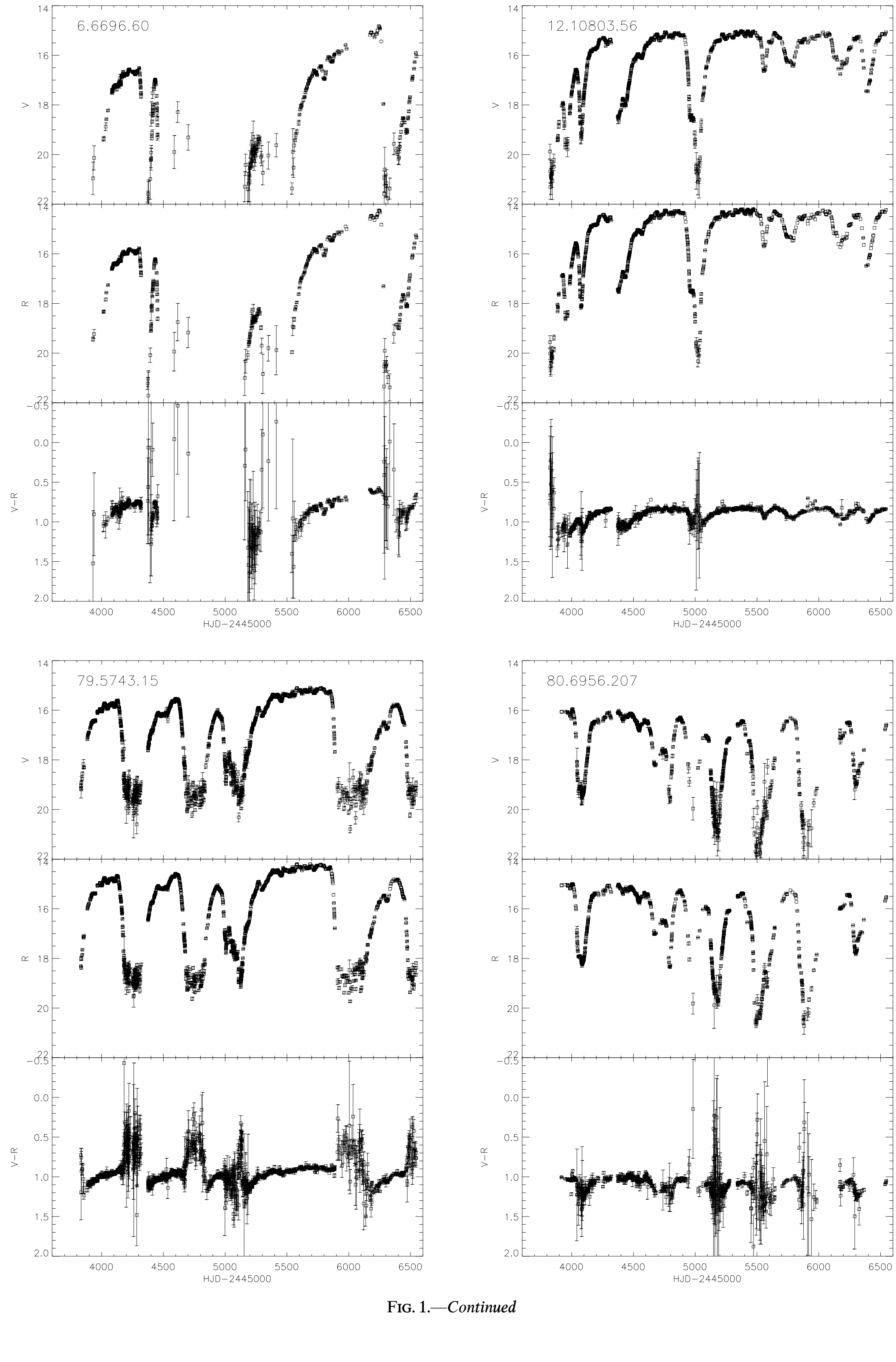

FIG. 1.—*Continued*

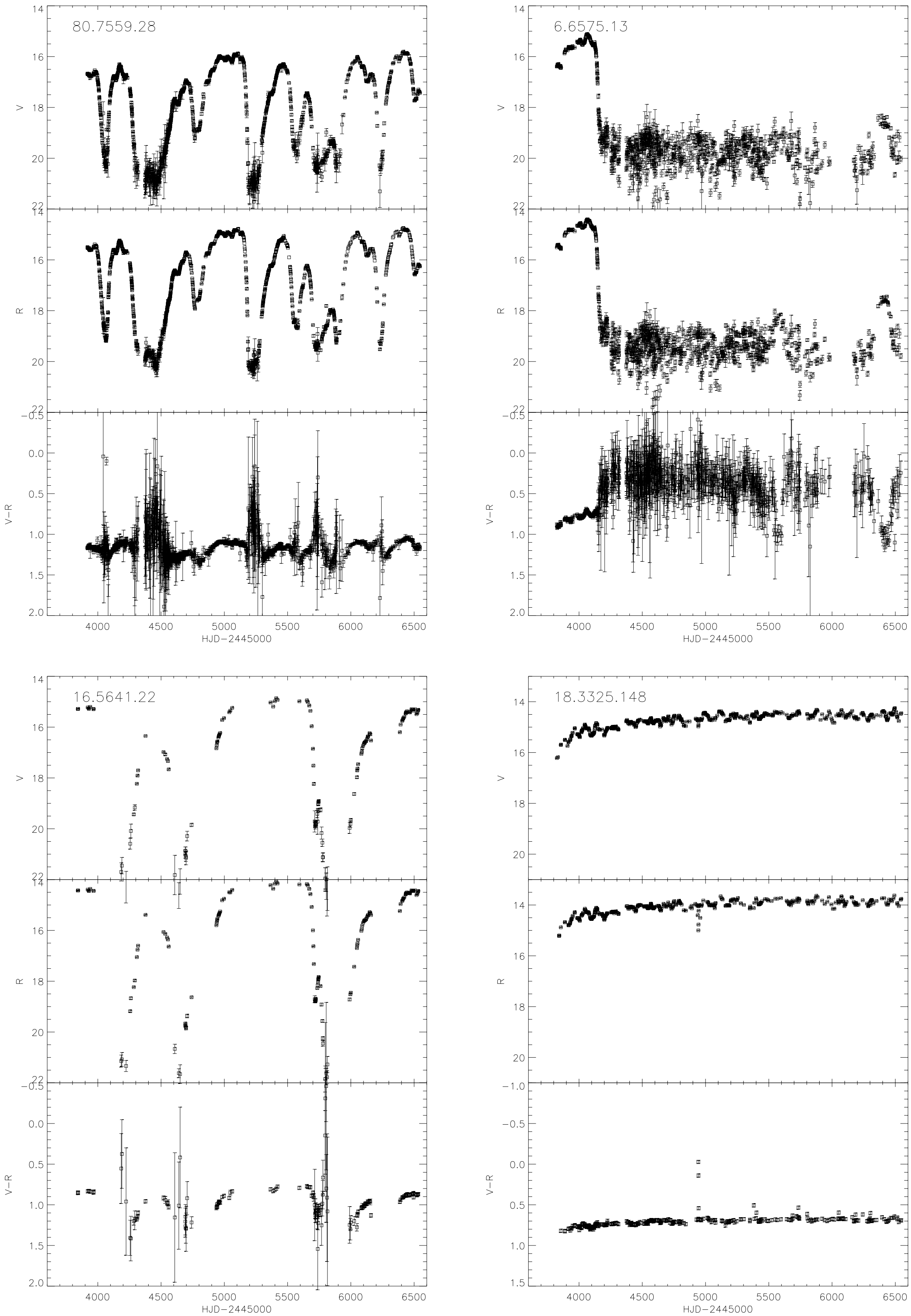

FIG. 1.—*Continued*

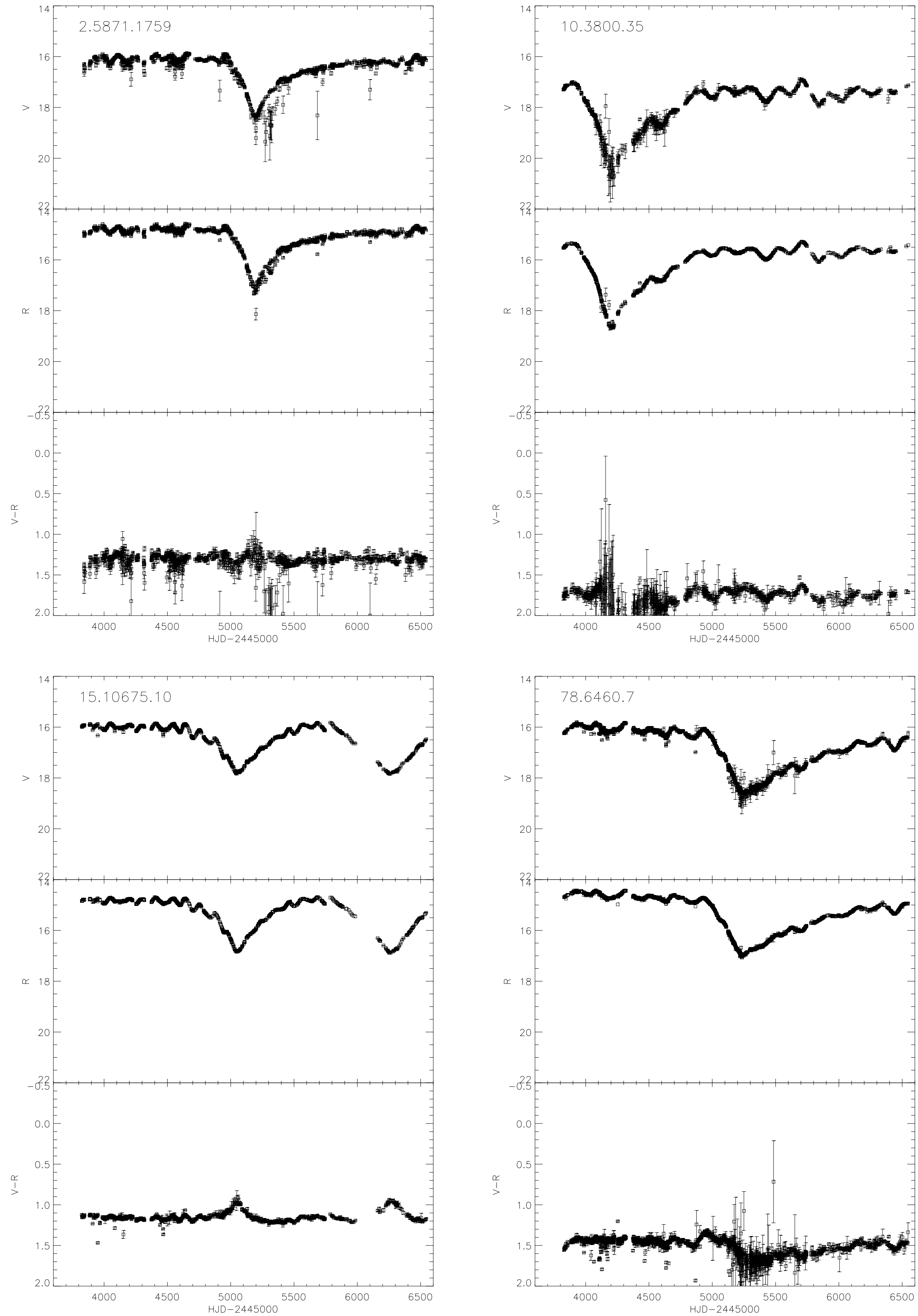

FIG. 2.—MACHO light curves for DY Per type stars

TABLE 1

LMC RCB STARS

Name	MACHO Name	α(2000)	δ(2000)	Other ID
Previously Known RCB Stars				
HV 12842	Outside MACHO Field	05 45 02.92	−64 24 23.2	F05447−6425[a]
HV 5637 (20.5036.12)	MACHO*05:11:31.4–67:55:52	05 11 31.402	−67 55 52.34	SP 37−16[b]
W Men (21.7407.7)	MACHO*05:26:24.7–71:11:13	05 26 24.761	−71 11 13.32	HV 966, R102
11.8632.2507	MACHO*05:33:49.1–70:13:22[c]	05 33 49.126	−70 13 22.49	Hot RCB star, HV 2671
81.8394.1358	MACHO*05:32:13.3–69:55:59[c]	05 32 13.263	−69 55 59.23	
Confirmed New RCB Stars				
6.6575.13	MACHO*05:20:48.2–70:12:12	05 20 48.244	−70 12 12.51	
6.6696.60	MACHO*05:21:47.9–70:09:57	05 21 47.997	−70 09 57.41	HV 942
12.10803.56	MACHO*05:46:46.2–70:38:12	05 46 46.211	−70 38 12.79	
16.5641.22	MACHO*05:14:46.2–67:55:48	05 14 46.177	−67 55 48.07	HV 2379
18.3325.148	MACHO*05:01:00.2–69:03:43	05 01 00.299	−69 03 43.53	HV 12524, SP 31−38[b]
79.5743.15	MACHO*05:15:51.8–69:10:08	05 15 51.834	−69 10 08.99	PMN J0515−6910[d]
80.6956.207	MACHO*05:22:56.9–68:58:16	05 22 56.944	−68 58 16.87	SHV 0523154−690100[e]
80.7559.28	MACHO*05:26:33.8–69:07:33	05 26 33.853	−69 07 33.21	SHV 0526537−690959[e]
DY Per Type Stars				
2.5871.1759	MACHO*05:16:51.8–68:45:17	05 16 51.890	−68 45 17.81	
10.3800.35	MACHO*05:03:44.7–69:38:12	05 03 44.790	−69 38 12.73	
15.10675.10	MACHO*05:46:13.0–71:07:40	05 46 13.045	−71 07 40.62	SHV 0546548−710843[e], SP 55−23[b]
78.6460.7	MACHO*05:19:56.0–69:48:06	05 19 56.050	−69 48 06.44	

[a] *IRAS* Faint Source Catalog (Moshir et al. 1989).
[b] Carbon star (Sanduleak & Philip 1977).
[c] Discovered previously by Alcock et al. 1996. Finding chart is given there.
[d] Parkes-MIT-NRAO Survey. Flux at 4850 MHz is 62 ± 7 mJy centered 5.3″ from the star (Wright et al. 1994).
[e] Previously discovered as an LPV in the LMC (Hughes 1989).

Clayton et al. (2001, in preparation). The spectra of the remaining stars are shown in Figures 6, 7, and 8. All of the spectra were obtained when the stars were at or near maximum light. These spectra are sums of all individual scans.

3. NEW RCB STARS IN THE LMC

From the night in 1795 when Edward Pigott first noticed that R CrB had apparently disappeared from the sky, RCB stars have been characterized primarily on the basis of their light curves. They are the only intrinsic variables that undergo sudden and severe drops in brightness from their light maximum at irregular intervals. However, this definition has resulted in many irregular variables with poor light curve coverage being identified as RCB stars (Payne-Gaposchkin & Gaposchkin 1938). Spectroscopic confirma-

TABLE 2

NEW LMC RCB PHOTOMETRY

Name	JD	*V*	*R*	*J*	*H*	*K*	Reference
HV 12842	2451158	...	...	12.87	12.53	11.79	2
HV 5637 (20.5036.12)	2451113	14.8	14.1	12.84	12.57	12.18	2
W Men (21.7407.7)	2450906	14.2	14.4	13.15	12.92	12.22	2
10.3800.35	2451112	17.4	15.6	12.18	10.91	10.17	2
11.8632.2507	2450448	16.0	15.9	15.29	14.61	12.93	1
	2450892	16.0	15.8	15.07	14.13	12.83	2
12.10803.56	2450448	15.2	14.4	12.74	12.24	11.76	1
	2450894	15.3	14.5	12.74	12.19	11.67	2
15.10675.10	2450894	16.2	15.1	12.22	11.08	10.50	2
16.5641.22	2451113	16.6	15.6	13.44	12.75	11.90	2
18.3325.148	2451112	14.6	13.9	12.71	12.37	12.08	2
79.5743.15	2450448	15.6	14.6	12.79	12.01	11.15	1
	2451113	19.1	18.2	15.43	13.96	12.42	2
80.6956.207	2450448	17.5	16.4	14.32	13.27	12.33	1
	2450906	~21	20.2	17.70	14.64	12.64	2
80.7559.28	2450448	16.4	15.2	13.03	12.17	11.35	1
	2450906	20.2	18.9	15.75	14.17	12.43	2
81.8394.1358	2450448	17.1	16.2	13.71	13.04	12.28	1
	2450906	18.8	18.0	15.02	13.92	12.62	2

REFERENCES.—(1) This paper, CTIO; (2) 2MASS.

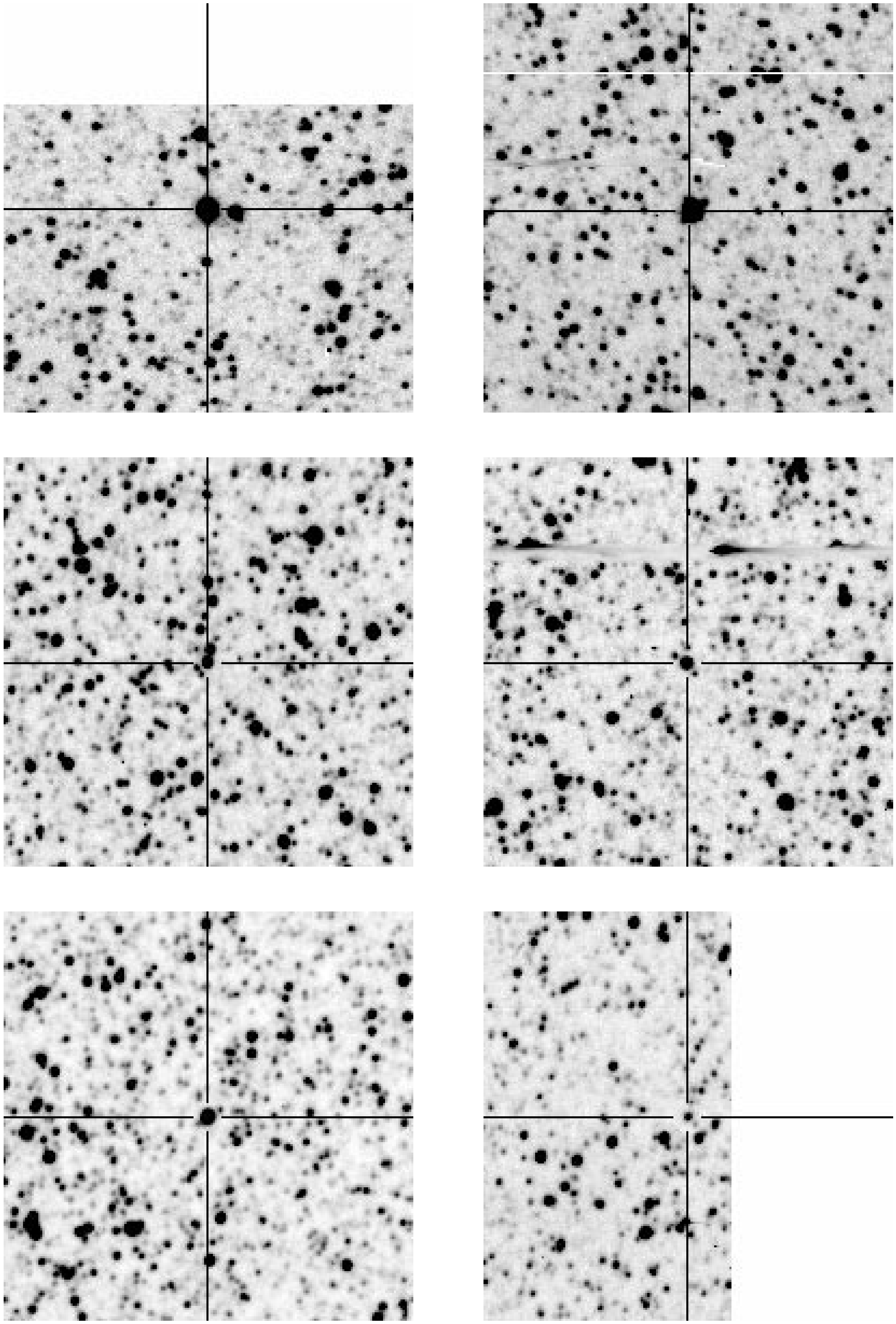

FIG. 3.—Fields of confirmed RCB stars. Each field is 2′ square. North is up and east to left. The fields are HV 5637 (*upper left*), W Men (*upper right*), 6.6696.60 (*second row left*), 12.10803.56 (*second row right*), 79.5743.15 (*third row left*), 80.6956.207 (*third row right*).

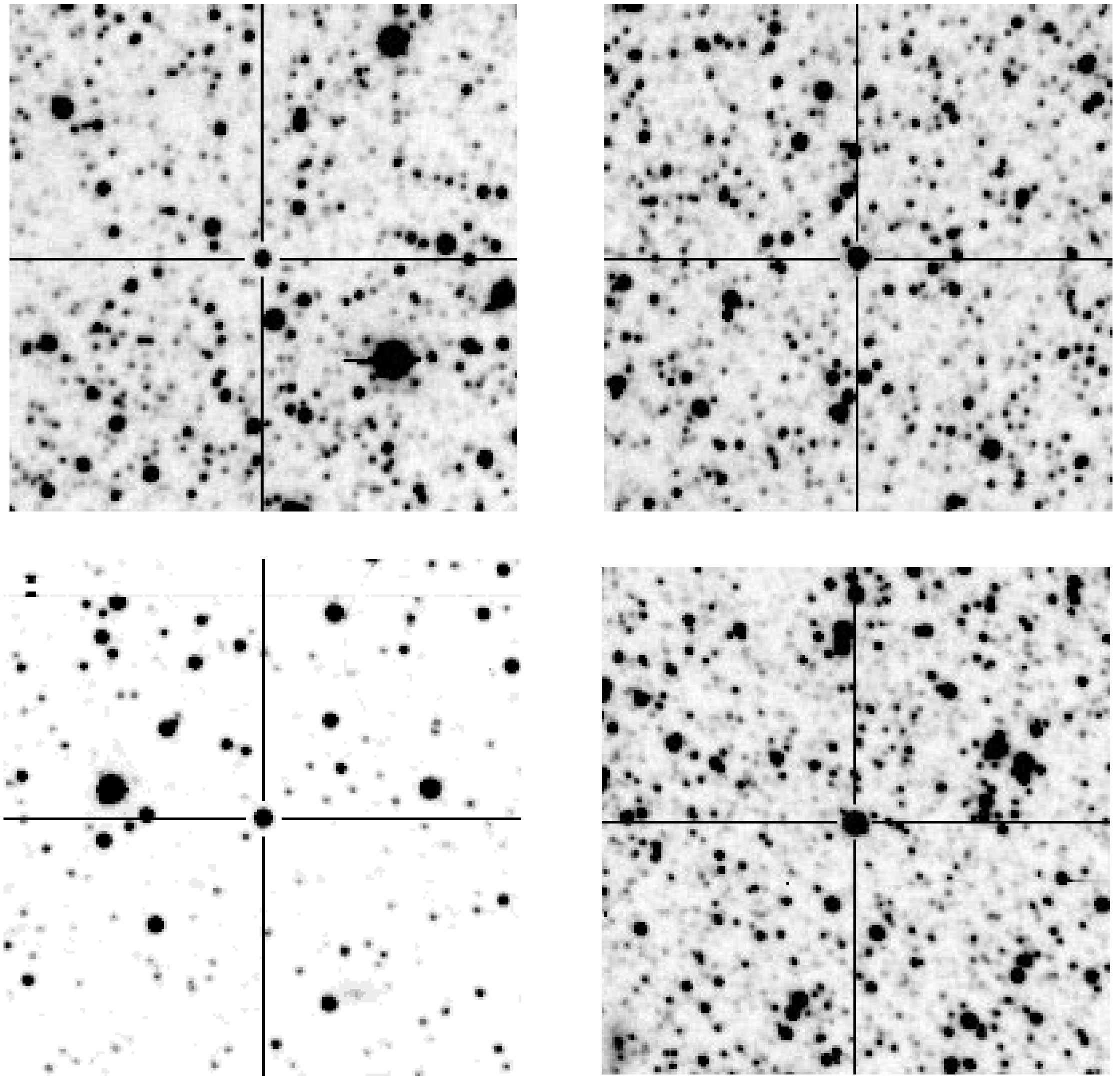

FIG. 4.—Fields of confirmed RCB stars. Each field is 2′ square. The fields are 80.7559.28 (*upper left*), 6.6575.13 (*upper right*), 16.5641.22 (*bottom left*), 18.3325.148 (*bottom right*).

tion has been used to weed out non-RCB stars from the class. Many turn out to be symbiotic, cataclysmic or semiregular variables (Lawson & Cottrell 1990a). Much of this sorely needed spectroscopic work has been performed by Kilkenny and collaborators (Clayton 1996 and references therein). However, if a well-sampled light curve is available then an identification with the RCB class may be made with fairly high confidence because of the distinctive nature of the RCB declines. Following the definition of Payne-Gaposchkin & Gaposchkin (1938), a typical RCB light curve has the following features:

1. Uniform brightness at maximum which may last for months or years.
2. A sudden drop in brightness of more than 3 mag taking a few days or weeks.
3. Recovery to maximum light, which is typically slower, taking months or years.

When spectra are obtained, we see in addition that the typical RCB star has the following features:

1. Weak or absent hydrogen lines and molecular bands (CH).[20]
2. Strong carbon lines and molecular bands (CN, C_2).
3. Little or no ^{13}C.

Other observables of the typical RCB star are as follows:

1. Regular or semiregular pulsations with ΔV of a few tenths of a magnitude and periods of 40–100 days.
2. An infrared excess.
3. Effective temperature between 5000 and 7000 K. A small subclass is much hotter with effective temperatures of about 20,000 K.

The first RCB star to be discovered in the LMC was HV 966 (W Men, 21.7407.7) (Luyten 1927). He identified it as a RCB star on the basis of its irregular and sudden dips in brightness. Much later, spectra confirming its resemblance

[20] V854 Cen, one of the most active RCB stars, shows fairly strong Balmer lines and CH band (Kilkenny & Marang 1989; Lawson & Cottrell 1989).

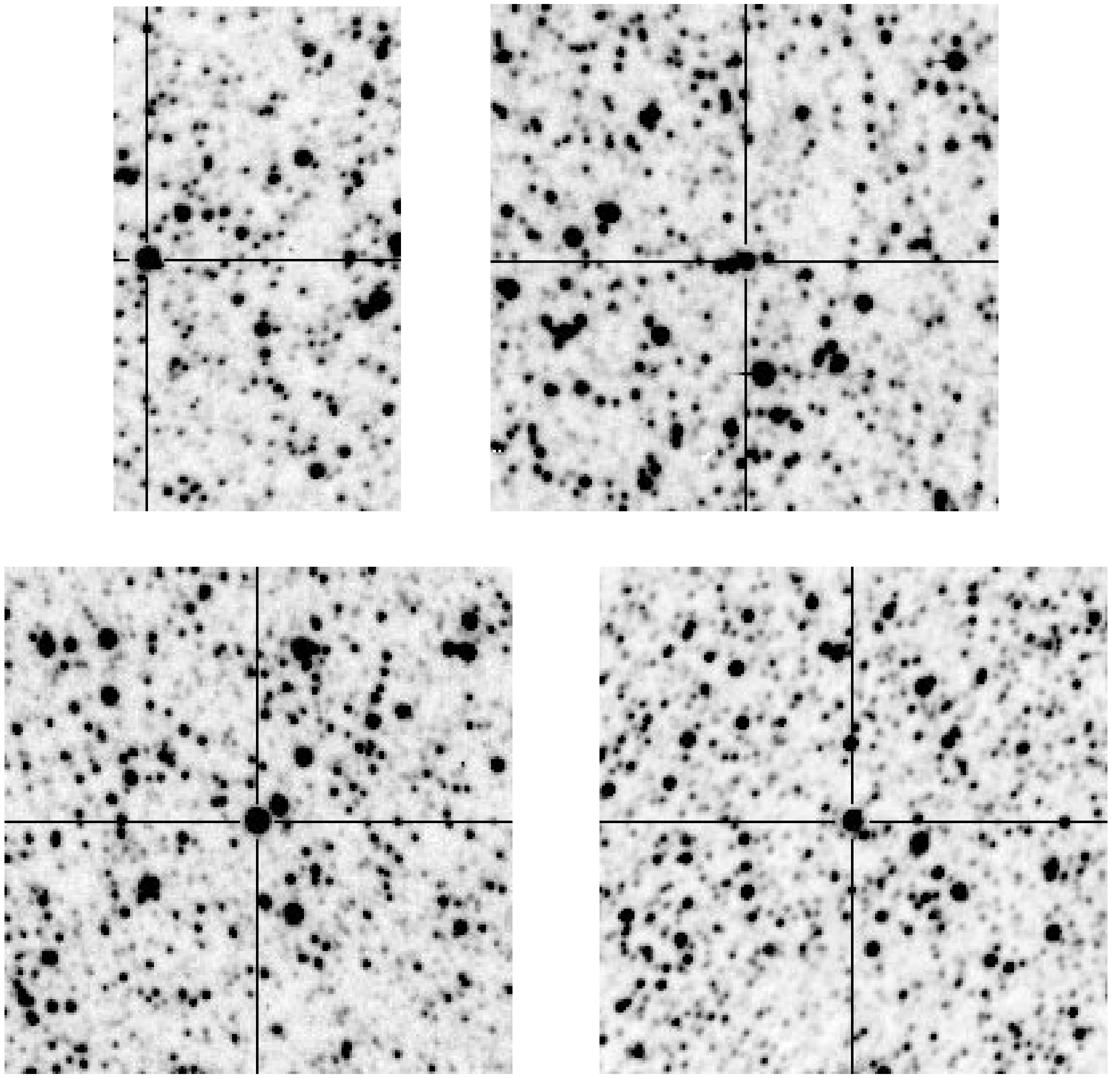

FIG. 5.—Fields of DY Per type stars. Each field is 2′ square. The fields are 2.5871.1759 (*upper left*), 10.3800.35 (*upper right*), 15.10675.10 (*bottom left*), and 78.6460.7 (*bottom right*).

to R CrB and its membership in the LMC were obtained (Feast 1956; Rodgers 1970; Feast 1972). Subsequently, two other stars, HV 5637 (Hodge & Wright 1969) and HV 12842 (Payne-Gaposchkin 1971), were identified as members of the RCB class on the basis of their light curves. Confirming spectra were soon obtained of these stars (Feast 1972). A fourth star, HV 12671, was listed by Payne-Gaposchkin (1971) as a RCB star. It is now thought to be a carbon-symbiotic star (Allen 1980; Lawson et al. 1990). Two new RCB stars were previously discovered using the MACHO database, HV 2671 (11.8632.2507) and 81.8394.1358 (Alcock et al. 1996).

The final database of MACHO variables for the top-22 fields was searched for stars which underwent large sudden brightness variations. Candidates were selected from the thousands of variable star light curves by selecting out those with large amplitude variations that were not periodic. These light curves were then viewed by eye and candidates were selected as having distinctive RCB light curve behavior.

In addition, the MACHO light curves for stars listed as irregular variables of large range by Payne-Gaposchkin (1971) were examined. HV 942 (6.6696.60) and HV 12524 (18.3325.148) were found to be RCB stars. Stars listed by Hughes (1989) as having RCB-type light curves were also checked. None of those lying in MACHO fields turned out to be RCB stars. However, three other variables in the Hughes list are members of the MACHO RCB star sample. Of the stars in our sample, three appear in the list of carbon stars in the LMC compiled by Sanduleak & Phillip (1977). However, none appear in the carbon star catalogs of Westerlund et al. (1978) or Blanco & McCarthy (1990).

In addition to the five RCB stars already known in the LMC, eight stars (6.6575.13, 6.6696.60, 12.10803.56, 16.5641.22, 18.3325.148, 79.5743.15, 80.6956.207, and 80.7559.28) which show light curves with deep, sharp declines are clearly RCB stars. See Figure 1. Two stars, 6.6575.13 and 6.6696.60 were independently discovered to be RCB stars by Wood & Cohen (2001). As summarized in Table 3, these stars share most or all of the photometric and spectroscopic criteria listed above for the typical RCB star. In particular, with the exception of 18.3325.148, as shown in

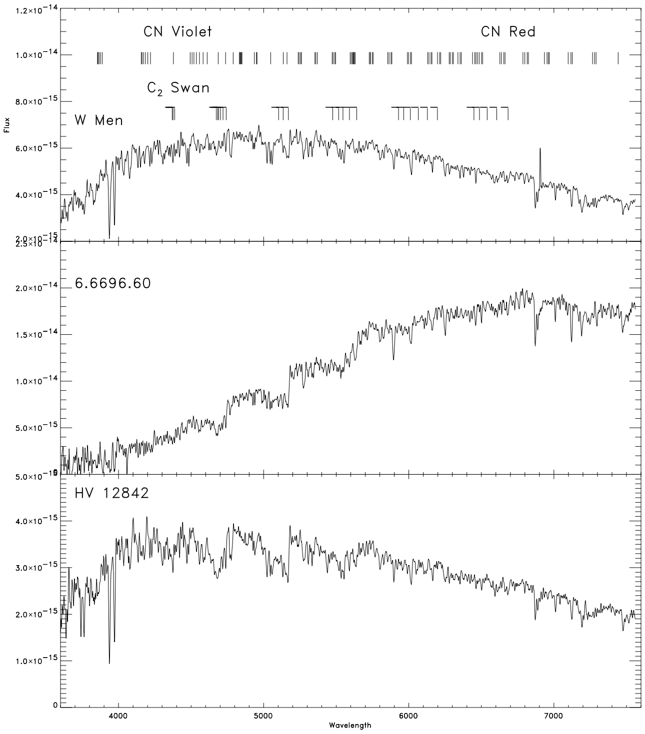

FIG. 6.—Spectra of confirmed warm RCB stars

Figure 1, all of these stars show the unique sharp, deep, irregular declines characteristic of RCB stars. This has been quantified in Table 3 as *dm/dt*, the number of magnitudes per day that the star fades. The light curve for 18.3325.148 shows only the long recovery from a decline often seen in Galactic RCB stars. Subsequently, spectra were obtained for all except 6.6575.13 showing that they are indeed RCB stars. The star, 6.6575.13, entered a very deep decline early in the MACHO era and has never recovered enough for a spectrum to be obtained. It is likely to be a RCB star based on its light curve data.

The star, 6.6696.60, joins HV 12842 and W Men as members of the warm (6000–7000 K) RCB stars showing only weak molecular bands. The others are similar to HV 5637 which is typical of the cooler (5000 K) RCB stars which have much stronger molecular bands. See Figures 6, 7, and 8. A low-dispersion spectrum of 16.5641.22 (HV 2379) was previously obtained and is also very similar to HV 5637 (Bessell & Wood 1983). The spectra were examined for evidence of hydrogen by looking at the Balmer lines and the *G* band of CH at 4300 Å. The presence of ^{13}C was searched for in the isotopic bands of C_2 and CN. In particular, the Swan bands, $^{12}C^{13}C$ and $^{13}C^{13}C$ near 4700 Å, other C_2 bands in the 6000–6200 Å region, and the ^{13}CN band near 6250 Å were examined. The results are summarized in Table 3.

Several other stars show irregular, fairly deep (2–3 mag) declines but fade much more slowly than typical RCB stars. In their light curve behavior, these stars resemble the unusual Galactic RCB star, DY Per (Alksnis 1994). This star has very deep (>4 mag) declines at irregular intervals like a RCB star, but the declines are very slow. The DY Per declines appear much more symmetrical than the prototypical RCB decline which features a much faster drop than rise. Further spectroscopic analysis has shown that DY Per is very cool, $T_{eff} \sim 3500$ K (Keenan & Barnbaum 1997). This is significantly cooler than the coolest known Galactic RCB stars, S Aps, WX CrA, and U Aqr which have estimated $T_{eff} \sim 5000$ K (Lawson et al. 1990). Keenan & Barnbaum

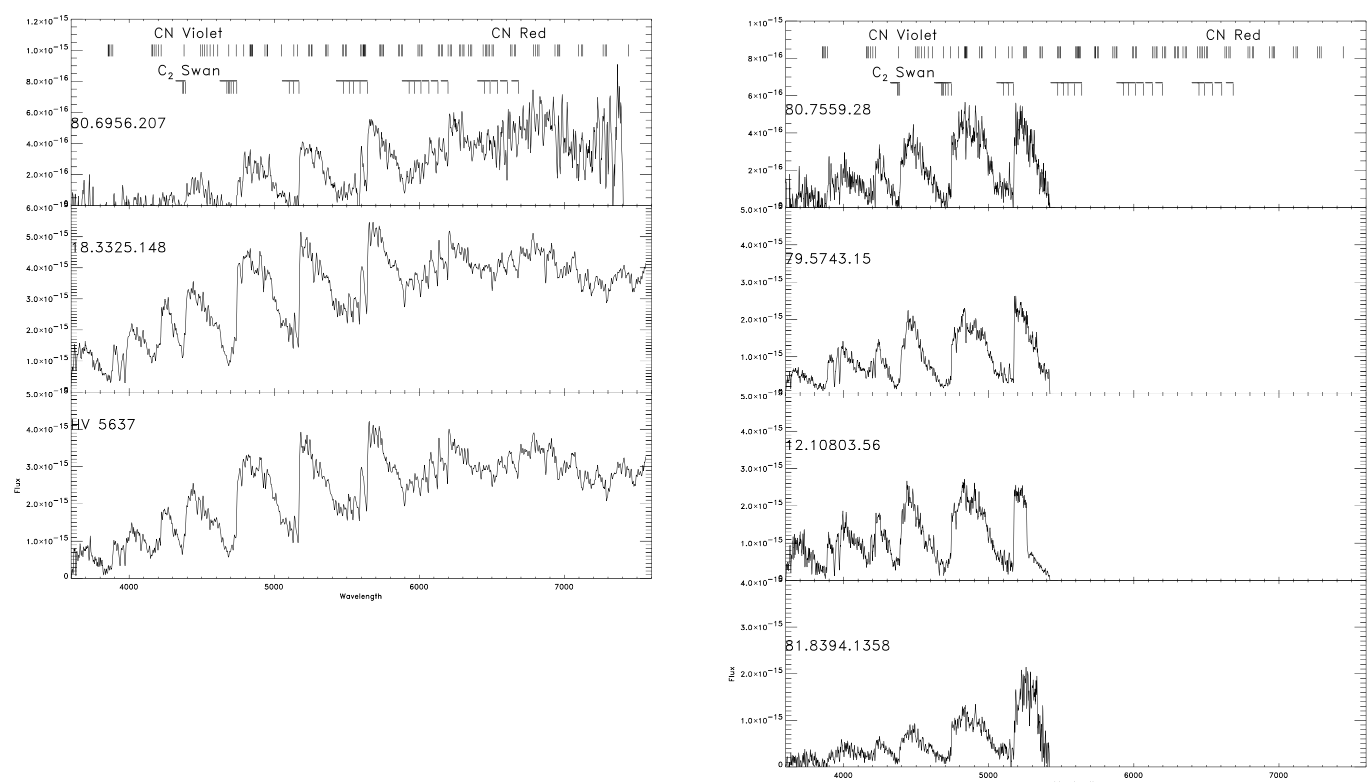

FIG. 7.—Spectra of confirmed cool RCB stars

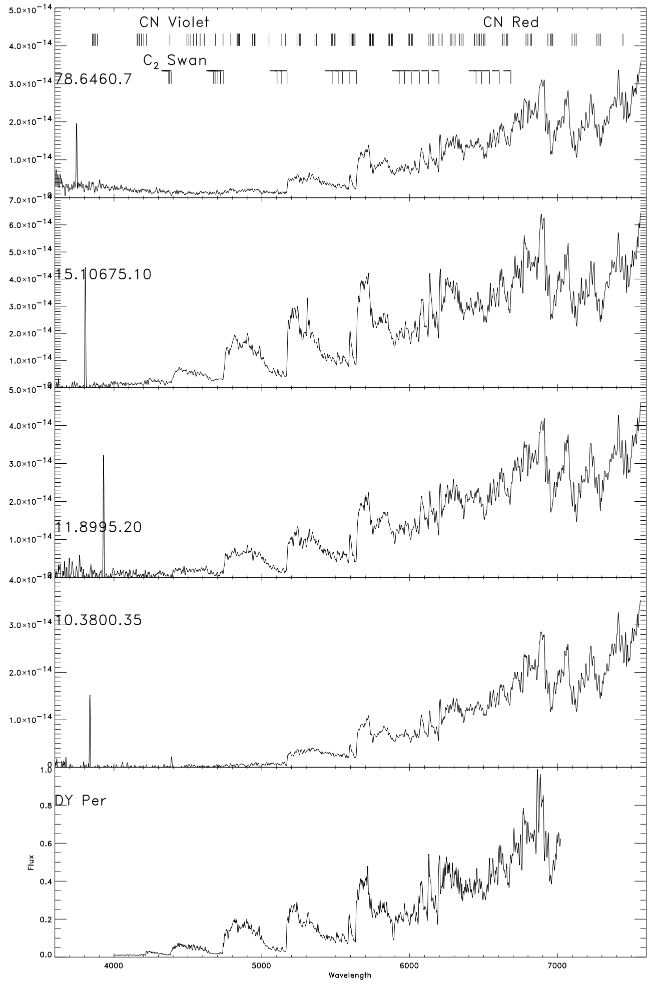

FIG. 8.—Spectra of DY Per type stars

(1997) suggest that DY Per may be hydrogen deficient. The *G* band is fairly weak. The evidence for the abundance of isotopic carbon is mixed. The isotopic Swan bands, $^{12}C^{13}C$ and $^{13}C^{13}C$ near 4700 Å, are clearly seen, but the ^{13}CN band near 6250 Å is not. The LMC DY Per stars share these characteristics. Four stars, 2.5871.1759, 10.3800.35, 15.10675.10, and 78.6460.7, show significant but slow declines of at least 2 mag. See Figure 2. They also closely resemble DY Per spectroscopically. See Figure 8. The DY Per spectrum is from Barnbaum, Stone, & Keenan (1996). Table 3 itemizes the major differences between the RCB and DY Per stars. The RCB declines are deeper and they fade faster as shown in the *dm*/*dt* column of the table. The DY Per stars show evidence for significant amounts of ^{13}C and they are cooler than the RCB stars. The molecular bands in the cool RCB stars and the DY Per stars are of comparable strength but the DY Per spectra are intrinsically much redder. The spectra of the DY Per stars resemble R-type carbon stars (Barnbaum et al. 1996). Many carbon stars also show irregular small (≤ 1 mag) declines. In addition, other stars produce dust such as carbon Miras and the V Hya stars. But these stars also show large regular variations not seen in either the RCB or DY Per stars (e.g., Feast et al. 1984; Lloyd Evans 1997). Until more extensive observations and analysis are done, it is not clear whether the DY Per stars are related to either the RCB stars or the carbon stars.

4. INDIVIDUAL STARS

Using SIMBAD, each star was checked for previous identifications. These are included in Table 1. Previous observations from the literature for the sample stars are listed below.

4.1. *HV 12842*

This is the only star in the sample that lies in an area of

TABLE 3

FINAL IDENTIFICATION

Name	V_{max}	R_{max}	$(V-R)$	Δm	Δt	dm/dt	^{13}C	H/CH	Pulsations	Comment
					RCB Stars					
HV 12842	13.70	13.50	0.20	>4.0	53	0.07	None	Weak CH	Yes	
HV 5637 (20.5036.12)	14.75	14.10	0.65	>2.4	...	...	None	Weak CH	?	Only one decline known
W Men (21.7407.7)	13.90	13.67	0.23	2.70	30	0.09	None	None?	Yes (240: d)	Possible Hβ
6.6575.13	15.25	14.50	0.75	4.00	50	0.08	...	...	Yes	No spectra at all
6.6696.60	15.00	14.40	0.60	5.40	45	0.12	None	None	Yes	
11.8632.2507	16.10	16.00	0.10	3.00	25	0.12	...	...	Yes (60.0 days)	Only Hot RCB in the LMC
12.10803.56	15.10	14.25	0.85	5.80	75	0.08	None	None	Yes (50.5 days)	No red spectra
79.5743.15	15.20	14.30	0.90	4.60	50	0.09	None	Weak CH	Yes (53.3 days)	No red spectra
16.5641.22	14.90	14.10	0.80	6.50	125	0.06	None?	None?	?	Spectrum (Bessell & Wood 1983)
18.3325.148	14.50	13.80	0.70	>1.7	...	...	None	Weak CH	Yes (83.8 days)	No declines known
80.6956.207	16.00	15.00	1.00	5.40	60	0.09	Yes	None	Yes	Similar to DY Per
80.7559.28	15.80	14.75	1.05	5.75	35	0.16	None	None	Yes	No red spectra
81.8394.1358	16.30	15.50	0.80	3.50	50	0.06	None	None	?	No red spectra
					DY Per Stars					
2.5871.1759	16.10	14.85	1.25	2.10	200	0.01	Yes	None	Yes (138 days)	
10.3800.35	17.40	15.70	1.70	3.20	275	0.01	None	None	Yes (206 days)	No flux at CH or 4700Å
15.10675.10	16.00	14.80	1.20	2.10	400	0.005	Yes	Weak Hβ?	Yes (116 days)	No flux at CH
78.6460.7	16.00	14.45	1.55	2.10	300	0.007	None	None	Yes (208 days)	No flux at CH or 4700 Å

the LMC not covered by MACHO. It was first listed as a RCB star ($m_{pg} = 14.15$–17.92 mag) by Payne-Gaposchkin (1971). Several declines have been noted (Morgan, Nandy, & Rao 1986; Lawson et al. 1990; Lawson, Cottrell, & Pollard 1991). Coordinates are from the *HST* Guide Star Catalog. HV 12842 is possibly an *IRAS* source. In the Faint Source Catalog (Moshir et al. 1989), F05447−6425, lies within 7″ of HV 12842. At 12 μm, it is 0.09 ± 0.01 Jy. This is within a factor of 2 of the expected *IRAS* brightness of a Galactic RCB star seen at the distance of the LMC. This star had a median $m_{pg} = 15.2$ mag and $\Delta m = 2.5$ mag in the early 1900's (Hodge & Wright 1967 and references therein).

4.2. *20.5036.12* (*HV 5637*)

This star was first listed as a RCB star by Hodge & Wright (1969). They found that HV 5637 ($V_{max} = 14.99$ mag, $B_{max} = 16.19$ mag) had one decline of $\Delta B \geq 2.36$ mag around JD 2425000. This star had a median $m_{pg} = 16.5$ mag and $\Delta m = 2.0$ mag in the early 1900's (Hodge & Wright 1967 and references therein). It is listed as a RCB star ($m_{pg} = 16.38$–18.20 mag) by Payne-Gaposchkin (1971). Butler (1978) noted small variations ($\Delta V = 0.2$ mag). No further declines were noted during the 7 years of MACHO coverage. See Figure 1.

4.3. *21.7407.7* (*W Men*)

This star was first identified as a RCB star by Luyten (1927). Several declines have been noted (Milone 1975; Glass 1988; Lawson et al. 1990). This star is HV 966 which had a median $m_{pg} = 14.4$ mag and $\Delta m = 1.2$ mag in the early 1900's (Hodge & Wright 1967 and references therein). It is listed as a RCB star ($m_{pg} = 13.37$–17.57 mag) by Payne-Gaposchkin (1971).

4.4. *11.8632.2507* (*HV 2671*)

This star had a median $m_{pg} = 16.4$ mag and $\Delta m = 1.8$ mag in the early 1900's (Hodge & Wright 1967 and references therein). Kurochkin (1992) reports a maximum brightness of $B = 15.5$ mag and one deep decline with $B < 19$ mag (JD 2439849.9 and 2439852.75).

4.5. *6.6696.60* (*HV 942*)

This star had a median $m_{pg} = 15.8$ mag and $\Delta m = 2.0$ mag in the early 1900's (Hodge & Wright 1967 and references therein). It is listed as an irregular variable of large range ($m_{pg} = 14.44$–17.74 mag) by Payne-Gaposchkin (1971). This star is also possibly detected by *IRAS* (Schwering 1989). As with HV 12842, the *IRAS* brightness is consistent with a RCB at the distance of the LMC.

4.6. *16.5641.22* (*HV 2379*)

This star had a median $m_{pg} = 16.5$ mag and $\Delta m = 1.8$ mag in the early 1900's (Hodge & Wright 1967 and references therein). Wright & Hodge (1971) report that in 1958, HV 2379 was seen at $B = 17.6$ and then was below the plate limit for 95 days. They also summarize several hundred Harvard plates taken between 1896 and 1949 where the star varied between 16.2 and fainter than 18.6 at B. It is listed as a long-period variable ($m_{pg} = 15.89$–18.45 mag) by Payne-Gaposchkin (1971). Feast et al. (1984) suggest that HV 2379 is related to the carbon Mira, R For, but the MACHO light curve, shows a typical irregular RCB star behavior with no sign of a Mira-type pulsation. This star is also possibly detected by *IRAS* (Trams et al. 1999). As with HV 12842, the *IRAS* brightness is consistent with a RCB at the distance of the LMC. HV 2379 was also observed with ISO (van Loon 1999).

4.7. *18.3325.148* (*HV 12524*)

This star had a median $m_{pg} = 15.9$ mag and $\Delta m = 0.6$ mag in the early 1900's (Hodge & Wright 1967 and references therein). It is listed as an irregular variable of large range ($m_{pg} = 15.27$–17.12 mag) by Payne-Gaposchkin (1971).

4.8. *80.6956.207*

This star is also SHV 0523154−690100 ($\langle m_I \rangle = 15.36$ mag, $\Delta m_I = 1.16$ mag) (Hughes 1989).

4.9. *80.7559.28*

This star is also SHV 0526537−690959 ($\langle m_I \rangle = 14.74$ mag, $\Delta m_I = 1.24$ mag) (Hughes 1989).

4.10. *15.10675.10*

This star is also SHV 0546548−710843 ($\langle m_I \rangle = 13.90$ mag, $\Delta m_I = 1.14$ mag) (Hughes 1989).

5. NEAR-IR COLORS

Most of the sample has been observed one or more times in the near-IR. We have plotted the $J-H$ versus $H-K$ colors in Figure 9. The typical RCB star colors evolve as dust forms and then disperses. Feast (1997) shows the behavior of a large sample of Galactic RCB stars. The colors evolve from those typical of the RCB star photosphere toward those of a dust shell of ~900 K. The colors for a combination of a 5500 K star and a 900 K shell are plotted in Figure 9. The LMC RCB star colors are consistent with the behavior of the Galactic RCB stars. With the exception of W Men, HV 2379, and HV 12842 (Bessell & Wood 1983; Glass, Lawson, & Laney 1994), each of the

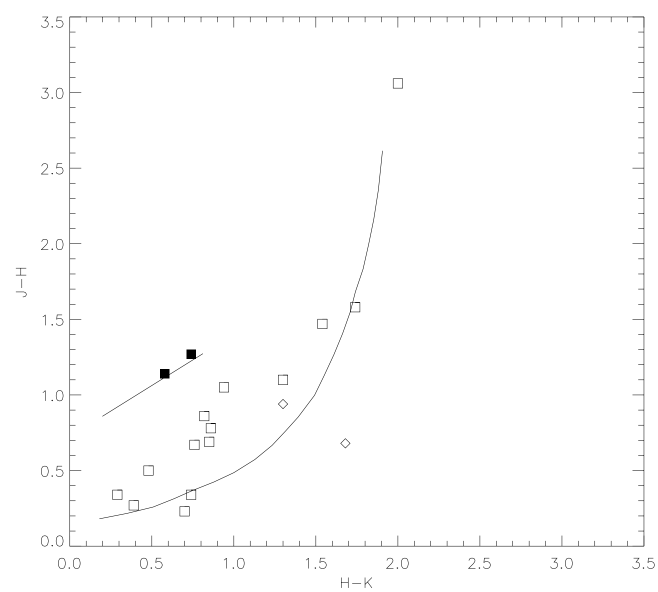

FIG. 9.—Infrared colors for the sample are plotted for the LMC RCB (*open squares*) and DY Per stars (*filled squares*). The observations of the one hot RCB star, 11.8632.2507, are shown as open diamonds. Stars with multiple IR observations are plotted more than once. The upper solid line represents the colors of LMC carbon stars (Westerlund et al. 1991). The lower line is combination of a 5500 K star and a 900 K dust shell blackbody ranging from all star to all shell. The curve is taken from Feast (1997).

LMC stars has been observed only once or twice at a random point in its light curve. So, when plotted together, the ensemble of stars includes observations at maximum light and in declines. Together these observations map out a RCB star color evolution similar to that seen for the Galactic stars (Feast 1997). Since there are a range of photospheric and shell temperatures, Figure 9 shows more scatter than the plot of individual stars as shown by Feast (1997). Another interesting feature of Figure 9 is that the DY Per stars are well separated from the RCB stars and show colors typical of carbon stars (Westerlund et al. 1991). The two DY Per stars plotted were observed at maximum light.

6. STELLAR PULSATIONS

Most or possibly all of the RCB stars are pulsators (Lawson et al. 1990). As listed in Table 3 and seen in Figure 1, most of the LMC RCB stars pulsate as well. We inspected the light curves for "dormant" sections—places where the light curve was within a magnitude or two of maximum brightness and where, if it was changing, it was increasing slowly with no obvious dust dropouts. The long-term trend in the dormant sections was subtracted, leaving just the shorter timescale oscillations. The baseline-subtracted, dormant sections of the V-band light curves was run through the Discrete Fourier Transform Fortran code of Roberts, Lehar, & Dreher (1987). The default frequency spacing was used, with a maximum period of one per day. In cases where there was an obvious signal, the period corresponding to the frequency with the highest power is reported. In most instances, the frequency spacing was about 5×10^{-4} per day. Among the RCB stars, we were able to extract periods for 18.3325.148 (83.8 days), 11.8632.2507 (60.0 days), 12.10803.56 (50.5 days), 21.7407.7 (240 days, questionable significance), and 79.5743.15 (53.3 days). For the DY Per stars, we extracted periods for 78.6460.7 (208 days), 2.5871.1759 (138 days), 10.3800.35 (206 days), and 15.10675.10 (116 days). These two classes differ also in their typical pulsation period. The RCB stars in the LMC like their Galactic counterparts have periods between 50 and 84 days, while the periods of the DY Per stars lie between 100 and 210 days. These differences are at least qualitatively in agreement with the results of theoretical models of pulsations in RCB stars (Weiss 1987). Theoretical periods for "Case 1" of Weiss for $M = 0.825\ M_\odot$ show $\sim$40 days for $T_{\rm eff} \sim 7000$ K, $\sim$100 days for $T_{\rm eff} \sim 5000$ K, and $\sim$300 days for $T_{\rm eff} \sim 4000$ K. Figure 32 of Lawson et al. (1990) shows the Galactic RCB stars plotted with Weiss "Case 1" for comparison.

In a color-magnitude diagram (CMD), most of the of the RCB stars lie within the instability strip defined by the MACHO-discovered BL Her, W Vir, and RV Tauri stars extrapolated to higher luminosities (Alcock et al. 2000). These LMC variables are believed to be low-mass Population II stars. In the CMD, the one hot RCB (11.8632.2507) lies blueward of the blue edge of the instability strip as defined by the bluest BL Her and W Vir stars. The DY Per stars lie in the same region of the CMD as carbon-rich red variables and are brighter/redder than the other observed sequences of red variables. With the exception of 11.8632.2507, the RCB and DY Per stars form an extension of the W Vir and BL Her star W-log P relation, where $W = V - 2.0*(V-R)$, to higher luminosities and longer periods, although there may be a "roll over" at long periods.

7. ABSOLUTE LUMINOSITY OF RCB STARS

The Galactic foreground reddening varies significantly across the face of the LMC ranging from $E(B-V)_{\rm Gal} = 0.00$ to 0.17 mag (e.g., Schwering & Israel 1991; Oestreicher, Gochermann, & Schmidt-Kaler 1995). Schwering & Israel (1991) estimate that most of the LMC bar, where the MACHO fields are centered, has a Galactic foreground reddening of $E(B-V)_{\rm Gal} = 0.06$–0.08. The dust inside the LMC is patchy also but a good estimate of the reddening due to dust inside the LMC foreground to the RCB stars is $E(B-V)_{\rm LMC} \sim 0.1$ (Oestreicher & Schmidt-Kaler 1996). There will also be a small amount ($E(B-V) \sim 0.1$ mag) of circumstellar reddening around each RCB star even at maximum light. We will ignore that component. The total reddening due to Galactic foreground and LMC intrinsic dust is $E(B-V) \sim 0.17$ mag or $A_V \sim 0.5$ mag.

The RCB and DY Per stars are plotted in Figure 10 in a V versus $V-R$ CMD. The values of V and $V-R$ plotted are those measured for each star at maximum light. A reddening vector is also plotted. In addition, a line is plotted representing the change in V and $V-R$ with temperature assuming $L_V \propto T^4$ with stellar radius held fixed. Temperatures and colors are assumed to be those for normal supergiants (Cox 2000). On the basis of the three pre-MACHO RCB stars, Feast (1979) noted that the cool RCB star, HV 5637 is significantly fainter than HV 12842 and W Men. He suggested that there might be a relationship between absolute magnitude and effective temperature for the RCB stars. The new observations reported here reinforce this suggestion. The intrinsically brightest RCB stars at V are the warm ($\sim$7000 K) stars, and the faintest are the cool ($\sim$5000 K) stars. There is a much wider range of absolute luminosity in the RCB stars than given by the canonical, $M_V = -4$ to -5 mag. The foreground reddening of individual stars is somewhat uncertain, but the brightest RCB stars have $M_V \sim -5$ mag, and the faintest are about

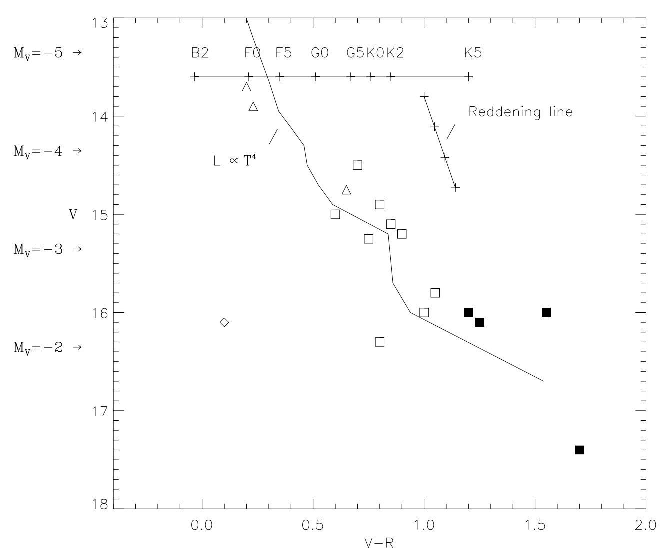

FIG. 10.—Color-magnitude diagram for the new LMC RCB (*open squares*) and DY Per stars (*filled squares*). The three pre-MACHO RCB stars are shown as open triangles. The one hot RCB star, 11.8632.2507 is shown as a open diamond. The plotted reddening vector shows the effect of average Galactic reddening of $E(B-V) = 0.1$, 0.2, 0.3 mag. The $L \propto T^4$ line is explained in the text.

$M_V \sim -2.5$ mag. The DY Per stars are cooler and fainter still, with a maximum absolute brightness of $M_V \sim -2.5$ mag.

It seems likely that 6.6696.60 is fairly heavily reddened. From Figure 6, it can be seen that the spectrum of 6.6696.60 closely resembles W Men and HV 12842. Therefore, it is likely that the effective temperatures and colors are similar for these three stars. For 6.6696.60, $V_{\rm max} = 15.0$ and $(V-R)_{\rm max} = 0.6$ compared to $V_{\rm max} = 13.8$ and $(V-R)_{\rm max} = 0.2$ for the other two stars. The simplest explanation is that some combination of circumstellar and interstellar dust in front of 6.6696.60 is responsible. The high value of reddening implied, $E(B-V) \sim 0.8$, is unlikely to be primarily interstellar reddening. More likely, a large portion of this reddening is circumstellar. From the light curve of 6.6696.60, seen in Figure 1, it is quite possible that the star was never at maximum light during the 7 years of the MACHO data. This is supported by earlier photometry of this star, previously discovered as HV 942, which found the maximum brightness to be $m_{\rm pg} = 14.4$ (Payne-Gaposchkin 1971). This corresponds to $B \sim 14.3$ mag. So assuming the same $B-V$ color as W Men, then 6.6696.60 would have $V \sim 13.85$ mag, which is the same as W Men and HV 12842 at maximum light. Similarly, 10.3800.35 may be more reddened than the other DY per stars.

8. THE POPULATION OF RCB STARS

The MACHO LMC sample of RCB stars allows us to attempt something not possible in the Milky Way, which is to estimate the total population of RCB stars in a galaxy. Figure 11 shows an image of the LMC with the locations of the RCB and DY Per stars plotted. As mentioned in the introduction there are two suggested evolutionary paths leading to the RCB stars, the Double Degenerate and the Final Helium Shell Flash (Iben et al. 1996a). Both these suggestions imply that the RCB stars are an old population. The distribution of these stars on the sky and their radial velocities give clues to their origin. The space distribution and radial velocities of the Milky Way RCB stars are similar to those of distant planetary nebulae implying that these stars may be a bulge population (Drilling 1986). However, the scale height is 400 pc for the RCB stars assuming $M_{\rm Bol} = -5$ (Iben & Tutukov 1985). So the RCB stars may be more like old disk/Population I stars. Either of the evolutionary scenarios predicts significantly more than the ~ 30 RCB stars which are known in the Milky Way. For instance, Webbink (1984) estimates a population of ~ 1000 RCB stars making reasonable assumptions for the Double Degenerate scenario. However, it should be pointed out that Schönberner (1986) suggests that the estimated lifetimes for both scenarios are too short to account for the number of RCB stars. Iben, Tutukov, & Yungleson (1996b) estimate that final flashes could produce 30–2000 RCB stars at any given time depending on the core mass. They estimate that the Double Degenerate or binary merger scenario could produce ~ 300 RCB stars.

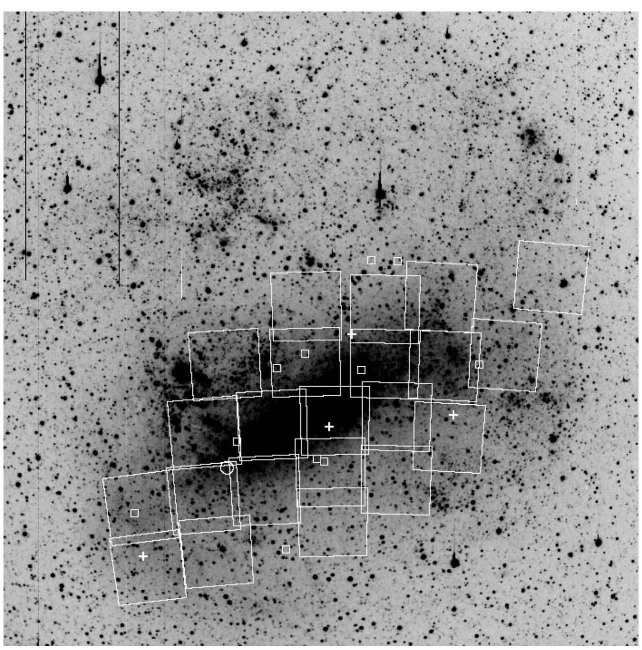

FIG. 11.—Locations of the RCB (*squares*) and DY Per stars (*crosses*) plotted on an image of the LMC (Bothun & Thompson 1988). The one hot RCB star, HV 2671 is marked with a circle. HV 12842 lies off the top of this image. [*See the electronic edition of the Journal for a color version of this figure.*]

Most of the Galactic RCB stars were discovered early in the century on the Harvard Observatory plate survey. The detection limit was about $B = 11.8$ mag on these blue sensitive plates. Stars near or below this limit, reddened stars and intrinsically red stars would have been missed (Lawson & Cottrell 1990b; Lawson et al. 1990). The results for the LMC RCB stars imply that many Galactic RCB stars are significantly fainter than previously believed, making them even less likely to have been detected.

Using evolutionary models of the pulsation periods of RCB stars, one can estimate the crossing time as a function of temperature (Lawson et al. 1990 and references therein). The model results imply relative populations of RCB stars with $T_{\rm eff} = 5000$, 6000, and 7000 K of 30:5:1. Most of the known RCB stars in the Galaxy fall in the warmest subgroup. The observed population ratio is 1:1:4. Lawson et al. (1990) suggest that the apparent lack of cool RCB stars is a selection effect. Lawson & Cottrell (1990b) estimate that if all RCB stars have $M_V \sim -5$, then the real number would be 200–300 or even larger if the number of cool stars equaled the number of warm stars. The results of this study for the LMC imply that the ratio is 7:2:1 which is consistent with the theoretical ratio given above. If this is the intrinsic ratio in the Galaxy also, then there are $\sim 10^3$ RCB stars in the entire Milky Way, most yet to be discovered.

We can estimate the number of RCB stars in the LMC from the results of the MACHO sample. The MACHO light curves for most stars have extremely good coverage for ~ 2500 days spanning the years 1993 through 1999. This is long enough to catch most but not all RCB stars in decline. RCB stars are true irregular variables. The historical light curve of R CrB itself, which now stretches back over 200 years, shows that it has gone up to 10 years with no decline and at other times has had several declines in 1 year (Mattei, Waagen, & Foster 1991). The characteristic time between declines is 1000–2000 days (Clayton, Whitney, & Mattei 1993). So any search over a short time period will detect only a fraction of the RCB stars. HV 5637 is an LMC RCB star but it is relatively inactive (Hodge & Wright 1969). It shows no evidence for a decline during the 7 years of MACHO coverage. One of the Galactic RCB stars, XX Cam, shows similar behavior. It has had only one recorded decline this century (Bidelman 1948; Yuin 1948). The AAVSO monitors 31 RCB stars including R CrB, V854 Cen, and XX Cam. Over the same timespan covered by the MACHO observations, 23 of these stars or about three quarters of the observed sample had deep declines of 3 mag or more. Another consideration is how long can a RCB star stay in a deep decline. V854 Cen is a good example (Clayton 1996). It is 7th magnitude at maximum light yet it is not in the HD, CPD, or SAO catalogs. Early in the 1900's, this star never rose above about magnitude 13. This is a much rarer phenomenon. While several of the 31 RCB stars in the AAVSO sample were very active in the 1993–1999 time period, none spent the entire time in a deep decline. Therefore, using the Galactic RCB stars as a guide, we can expect to have detected about 75% of the LMC RCB stars lying in the MACHO fields.

Nine of the new RCB stars discovered with MACHO lie within the so-called top-22 fields which have the best temporal coverage (Alcock et al. 2000). The three pre-MACHO LMC RCB stars and HV 2379 (16.5641.22) lie outside these fields. The four DY Per stars all lie in the top-22 fields. These 22 fields cover 10 $\deg^2$ centered on the LMC bar. Kim et al. (1998) estimate the mass of the LMC within a radius of 4 kpc is 1.0×10^9 $M_\odot$. The inner 4 kpc of the LMC corresponds to 71.5 $\deg^2$ at a distance modulus of 18.4. Then, extrapolating from the top-22 MACHO fields, we assume a homogeneous distribution of mass, and a 75% detection efficiency. This implies $\sim$85 RCB stars in the inner 4 kpc of the LMC. We can then make an estimate of the expected number of RCB stars in the Galaxy assuming $M_{\rm Galaxy} \sim 3.8 \times 10^{10}$ $M_\odot$. If RCB stars occur at the same frequency in the Galaxy as in the LMC and if the bar is not somehow special, then we would expect there to be $\sim$3200 RCB stars in the Milky Way. This number may be somewhat overestimated since the density of planetary nebulae and carbon stars is enhanced in the area of the LMC bar (e.g., Richer 1981; Morgan 1994). Similarly, we can estimate the expected number in the SMC. The top-6 MACHO fields in the SMC were searched in a similar manner to that described above for the LMC. These six fields in the SMC contain 2.2×10^6 stars as compared to 8.5×10^6 stars in the top-22 LMC fields (Alcock et al. 1997b). So extrapolating from the number found in the LMC, we would expect to find $\sim$2 RCB stars in the SMC. None were found.

9. SUMMARY

The final results of our study of the LMC RCB stars in the top-22 MACHO fields are the following:

1. Ten new RCB stars (eight reported in this paper) were discovered using MACHO photometry bringing the total in the LMC to 13.
2. There is a much wider range of absolute luminosity in the RCB stars than previously thought. There is a range of $M_V \sim -2.5$ to -5 mag. The warm ($\sim$7000 K) stars are brighter at V than the cool ($\sim$5000 K) stars.
3. The relative populations of LMC RCB stars with $T_{\rm eff}$ = 5000, 6000, and 7000 K is 7:2:1 close to the theoretical ratio but very different from the Galactic ratio of 1:1:4. The Galactic ratio may be severely biased due to selection effects.
4. One hot ($\sim$20,000 K) RCB star was found. Three such stars are known in the Galaxy.
5. If the population of RCB stars in the LMC is similar to that of the Galaxy then there may be $\sim$3200 RCB stars in the Galaxy.
6. Four stars were found which resemble the unusual Galactic RCB star, DY Per. These stars fade much more slowly than typical RCB stars. These stars are also cooler and fainter, with a maximum absolute brightness of $M_V \sim -2.5$ mag. It is not clear if these stars are related to the RCB stars.

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APPENDIX

In this Appendix we provide the MACHO photometric data for each of the stars in the sample. The data are given in Tables A1 to A16 and include the HJD, R magnitude, V magnitude, and the observation ID, which is the running exposure number. The magnitudes are calculated as described in § 2.1. In the paper edition, only a portion of Table A1 is given as an example. The remaining tables appear only in the electronic edition.

TABLE A1

MACHO PROJECT PHOTOMETRY FOR 20.5036.12

HJD −2,400,000	R (mag)	V (mag)	Obs. ID
48825.3106…….	14.243 ± 0.016	14.859 ± 0.017	336
48833.2274…….	14.189 ± 0.015	14.866 ± 0.015	508
48842.2419…….	14.230 ± 0.015	14.939 ± 0.015	765
48843.2827…….	14.249 ± 0.015	14.941 ± 0.015	802
48844.2223…….	14.237 ± 0.015	14.919 ± 0.015	837
48852.2494…….	14.226 ± 0.015	14.904 ± 0.015	916
48856.3140…….	14.342 ± 0.017	14.997 ± 0.016	1051
48928.1216…….	14.159 ± 0.015	14.845 ± 0.015	1633
48966.1570…….	14.236 ± 0.015	14.922 ± 0.015	2237
48967.1506…….	14.214 ± 0.015	14.906 ± 0.015	2283
49096.0556…….	14.195 ± 0.015	14.893 ± 0.015	5421
49126.9777…….	14.094 ± 0.015	14.769 ± 0.015	7271
49135.9786…….	14.117 ± 0.015	14.799 ± 0.015	7783
49165.2826…….	14.222 ± 0.015	14.899 ± 0.015	9111
49184.3319…….	14.127 ± 0.015	14.801 ± 0.015	9835
49190.2491…….	14.150 ± 0.015	14.814 ± 0.015	10257
49204.2702…….	14.211 ± 0.015	14.965 ± 0.015	10743
49212.2431…….	14.192 ± 0.015	14.910 ± 0.015	11203
49225.2646…….	14.257 ± 0.015	15.109 ± 0.015	11977
49234.2266…….	14.220 ± 0.015	14.893 ± 0.015	12109
49290.2091…….	14.167 ± 0.015	14.843 ± 0.015	13296
49313.1389…….	14.087 ± 0.015	14.756 ± 0.015	13650
49376.1739…….	14.180 ± 0.015	14.875 ± 0.015	14016
49381.1787…….	14.115 ± 0.015	14.800 ± 0.015	14235
49399.1561…….	14.055 ± 0.015	14.737 ± 0.015	14550
49406.2353…….	14.102 ± 0.015	14.801 ± 0.015	14715
49425.0567…….	14.090 ± 0.015	14.775 ± 0.015	15182
49437.1389…….	14.089 ± 0.015	14.780 ± 0.015	15661
49452.1000…….	14.050 ± 0.015	14.735 ± 0.015	16284
49478.0438…….	14.163 ± 0.015	14.841 ± 0.015	17406
49513.3355…….	14.252 ± 0.015	14.936 ± 0.015	19015
49547.2278…….	14.146 ± 0.015	14.810 ± 0.015	20717
49559.3172…….	14.154 ± 0.015	14.824 ± 0.015	21553
49573.2564…….	14.222 ± 0.015	14.898 ± 0.015	22350
49608.1654…….	14.234 ± 0.015	14.916 ± 0.015	24240
49631.1699…….	14.217 ± 0.015	14.966 ± 0.015	25388
49650.1537…….	14.349 ± 0.015	15.113 ± 0.015	26097
49705.1947…….	14.137 ± 0.015	14.818 ± 0.015	27375
49731.1965…….	14.149 ± 0.015	14.845 ± 0.015	27730
49742.9844…….	14.164 ± 0.015	14.870 ± 0.015	27905
49748.9535…….	14.145 ± 0.015	14.851 ± 0.015	28093
49752.1860…….	14.167 ± 0.015	14.851 ± 0.015	28230
49761.1006…….	14.202 ± 0.015	14.904 ± 0.015	28451
49766.2242…….	14.120 ± 0.015	14.812 ± 0.016	28594
49769.2219…….	14.086 ± 0.015	14.778 ± 0.015	28656

NOTE.—Tables A2–A16 are available in the electronic edition of the *Astrophysical Journal*.

TABLE A2

MACHO PROJECT PHOTOMETRY FOR 21.7407.7

This table is available only on-line as a machine-readable table

TABLE A3

MACHO PROJECT PHOTOMETRY FOR 11.8632.2507

This table is available only on-line as a machine-readable table

TABLE A4

MACHO PROJECT PHOTOMETRY FOR 81.8394.1358

This table is available only on-line as a machine-readable table

TABLE A5

MACHO PROJECT PHOTOMETRY FOR 6.6575.13

This table is available only on-line as a machine-readable table

TABLE A6

MACHO PROJECT PHOTOMETRY FOR 6.6696.60

This table is available only on-line as a machine-readable table

TABLE A7

MACHO PROJECT PHOTOMETRY FOR 12.10803.56

This table is available only on-line as a machine-readable table

TABLE A8

MACHO PROJECT PHOTOMETRY FOR 16.5641.22

This table is available only on-line as a machine-readable table

TABLE A9

MACHO PROJECT PHOTOMETRY FOR 18.3325.148

This table is available only on-line as a machine-readable table

TABLE A10

MACHO PROJECT PHOTOMETRY FOR 79.5743.15

This table is available only on-line as a machine-readable table

TABLE A11

MACHO PROJECT PHOTOMETRY FOR 80.6956.207

This table is available only on-line as a machine-readable table

TABLE A12

MACHO PROJECT PHOTOMETRY FOR 80.7559.28

This table is available only on-line as a machine-readable table

TABLE A13

MACHO PROJECT PHOTOMETRY FOR 2.5871.1759

This table is available only on-line as a machine-readable table

TABLE A14

MACHO PROJECT PHOTOMETRY FOR 10.3800.35

This table is available only on-line as a machine-readable table

TABLE A15

MACHO PROJECT PHOTOMETRY FOR 15.10675.10

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TABLE A16

MACHO PROJECT PHOTOMETRY FOR 78.6460.7

This table is available only on-line as a machine-readable table

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