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LATE-TYPE RED SUPERGIANTS: TOO COOL FOR THE MAGELLANIC CLOUDS?

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ABSTRACT

We have identified seven red supergiants (RSGs) in the Large Magellanic Cloud (LMC) and four RSGs in the Small Magellanic Cloud (SMC), all of which have spectral types that are considerably later than the average type observed in their parent galaxy. Using moderate-resolution optical spectrophotometry and the MARCS stellar atmosphere models, we determine their physical properties and place them on the H-R diagram for comparison with the predictions of current stellar evolutionary tracks. The radial velocities of these stars suggest that they are likely all members of the Clouds, rather than foreground dwarfs or halo giants. Their locations in the H-R diagram also show us that these stars are cooler than the current evolutionary tracks allow, appearing to the right of the Hayashi limit, a region in which stars are no longer in hydrostatic equilibrium. These stars exhibit considerable variability in their V magnitudes, and three of these stars also show changes in their effective temperatures (and spectral types), with respective variations of over a magnitude and 3%–4% on the timescales of months. One of these stars, [M2002] SMC 055188, was caught in an M4.5 I state, as late as that seen in HV 11423 at its recent extreme: considerably later, and cooler, than any other supergiant in the SMC. In addition, we find evidence of variable extinction due to circumstellar dust and changes in the stars' luminosities, also consistent with our recent findings for HV 11423—when these stars are hotter, they are also dustier and more luminous. We suggest that these stars have unusual properties because they are in an unstable (and short lived) evolutionary phase.

Subject headings: stars: evolution — stars: late-type — stars: mass loss — supergiants

Online material: color figure

1. INTRODUCTION

Red supergiants (RSGs) are a He-burning phase in the evolution of moderately high mass stars (10–25 $M_{\odot}$). Until recently, the location of RSGs on the Hertzsprung-Russell diagram was at odds with predictions of stellar evolutionary tracks. Levesque et al. (2005, hereafter Paper I) fitted the new generation of MARCS atmosphere models (Gustafsson et al. 1975, 2003; Plez et al. 1992; Plez 2003) to moderate-resolution optical spectrophotometry of Galactic RSGs. The physical parameters derived from this work brought the stars into much better agreement with the Geneva evolutionary tracks for solar metallicity (Meynet & Maeder 2003). Subsequently, we performed a similar analysis (Levesque et al. 2006, hereafter Paper II) for RSGs in the Magellanic Clouds, where the metallicity is significantly lower ($Z/Z_{\odot} = 0.5$ for the LMC and $Z/Z_{\odot} = 0.2$ for the SMC; see Westerlund 1997), with a similar improvement seen.

Paper II emphasized that, on average, RSGs in the Magellanic Clouds were not as cool as Galactic RSGs, in accordance with the shifting of the rightmost extension (the Hayashi limit, as described in Hayashi & Hoshi 1961) of the evolutionary tracks to warmer effective temperatures at lower metallicities. Stars in this region are fully convective, and cooler stars would not be in hydrostatic equilibrium. This fact is reflected in the shifting of the observed average spectral subtypes of RSGs in these galaxies, from M2 I in the Milky Way to M1 I in the LMC and K5–K7 I in the SMC (Massey & Olsen 2003), in accordance with the observation and explanation originally put forth by Elias et al. (1985).

However, Massey & Olsen (2003) did find a few SMC and LMC RSGs that were considerably later in type than average. Radial velocities (Massey & Olsen 2003) of these spectral outliers had suggested that these could not be foreground Galactic dwarfs, but could not rule out the possibility that they were Galactic halo giants, as their radial velocities would be similar to confirmed SMC and LMC members. Were these Magellanic Cloud members? Or did they present a challenge to evolutionary theory? We identified additional late-type RSG candidates from our own previously unpublished spectroscopy (from late 2004, described below) and/or broadband colors ($V - K$, primarily) and decided to reinvestigate their membership and physical properties.

Here we present moderate-resolution spectrophotometry of seven late-type RSGs in the LMC and four late-type RSGs in the SMC (§ 2.1). In analyzing the data (§ 3), we begin by first considering the question of whether or not these stars are members in the Clouds (§ 3.1). Next, we determine their spectral types and physical properties (§ 3.2) from our spectrophotometry. As a

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TABLE 1
PROGRAM STARS

STAR [M2002.0]	α_{2000}	δ_{2000}	PHOTOMETRY[a]				SPECTRAL TYPE				RADIAL VELOCITY[c] (km s^{-1})
			V	$B-V$	K_s	$V-K$	EFH85[b]	MO03[c]	New (2004)	New (2005)	
SMC 046662.....	00 59 35.04	−72 04 06.2	12.75	1.95	8.35	4.36	M0 Ia	M2 I	K2–K3 I	M0 I	180.2
SMC 052334.....	01 01 54.16	−71 52 18.8	12.87	1.91	8.69	4.14	M0 Iab	K7 I	...	K5–M0 I	165.5
SMC 055188.....	01 03 02.38	−72 01 52.9	14.23	2.22	8.62	5.57	...	M2 I	M4.5 I	M3–M4 I	176.8
SMC 083593.....	01 30 33.92	−73 18 41.9	12.83[d]	1.60	8.60	4.19	M2 Ia	...	...	M2 I[d]	180.1
LMC 143035.....	05 29 03.58	−69 06 46.3	14.10	1.93	7.90	6.16	...	M3–M4.5 I	M4.5–M5 I	M4 I	268.3
LMC 148035.....	05 30 35.61	−68 59 23.6	13.42	1.98	7.55	5.83	...	M4 I	...	M2.5 I	284.5
LMC 150040.....	05 31 09.35	−67 25 55.1	13.09	1.90	7.63	5.42	...	M4 I	M3–M4 I	M3–M4 I	280.0
LMC 158646.....	05 33 52.26	−69 11 13.2	13.80	2.18	7.90	5.86	...	M3–M4 I	...	M2 I	288.3
LMC 162635.....	05 35 24.61	−69 04 03.2	14.58	2.20	8.66	5.88	...	M1 I	...	M2 I	296.9
LMC 168757.....	05 37 36.96	−69 29 23.5	14.62	1.80	8.21	6.37	...	M3 I	...	M3–M4 I	272.3
LMC 170452.....	05 38 16.10	−69 10 10.9	13.99	2.24	7.87	6.08	...	M4.5–M5 I	M4.5–M5 I	M1.5 I	289.4

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] V-band photometry is derived from the spectrophotometry itself, while K_s values are from 2MASS. The $B-V$ values are from Massey (2002). The $V-K$ values have been computed by transforming K_s to the Bessell & Brett 1988 "standard" K by using the Carpenter (2001) relationship $K = K_s + 0.04$.
[b] From Elias et al. (1985).
[c] From Massey & Olsen (2003).
[d] This value was determined from the merged spectrum of our 2004 and 2005 spectra.

reality check, we also derive the physical properties from broadband $V-K$ photometry (§ 3.3). In order to better understand the nature of these objects, we also examine their photometric and spectral variability (§ 3.4). In § 4 we place these stars on the H-R diagram (HRD) and also revise our metallicity-dependent effective temperature calibration of RSGs based on the new data. In § 5 we summarize our findings and discuss our future work on the subject.

2. OBSERVATIONS AND ANALYSIS

2.1. *Observations*

We list our sample of late-type Magellanic Cloud RSGs in Table 1. Observations were made on 2005 December 20–23 using the RC Spectrograph on the 4 m Blanco telescope. The detector was a Loral CCD (3000 × 1000 pixel). We used a 316 line mm^{-1} grating (KPGL2) in first order, which gave us 2 Å pixel^{-1}. A 225 μm (1.5″) slit was used, yielding a spectral resolution of 7.5 Å (3.8 pixels). We observed with two different grating tilts, one covering 3400–6200 Å, and one covering 5300–9000 Å. For the blue observations we used a BG-39 blocking filter to eliminate any possibility of scattered red light affecting our observations, particularly in the far blue and near-UV, where the stellar flux is small; in the red, we used a WG-495 filter to block out second-order blue light. Exposure times ranged from 200 to 900 s in the blue and from 150 to 600 s in the red.

Observations were made at the parallactic angle, to ensure good flux calibration, and numerous spectrophotometric standard stars (chosen from the list of Hamuy et al. 1992) were also observed. We observed several "featureless" stars in order to remove telluric absorption, following Bessell (1990). The reduced blue and red spectra were combined in order to bring the flux levels into agreement.

For six of our stars (SMC 046662, SMC 055188, LMC 143035, LMC 150020, LMC 158646, and LMC 170452) we also had full or partial spectrophotometry obtained during 2004 November and December with the same instrument. (The details of that instrumental setup are given in Paper II.) For SMC 046662 and SMC 055188 the data are complete from 4100 to 9100 Å. For the other four stars observed in 2004, we have only partial data in the "blue" (4100–6450 Å). Although we could not use the latter for determining physical properties (as the baseline was insufficient for accurate extinction determinations), these data nevertheless proved very useful, as it provided a means for checking for spectral variability and determining the relevant timescales. For one of our stars (SMC 083593) we had incomplete data during both observing runs: the blue was observed in 2004, and the red was obtained during this paper's primary observing run in 2005. The slopes and line depths agreed well in the region of overlap, and so we combined the two halves for our analysis of the spectra.

3. ANALYSIS

We classify all of the stars in this sample (from the 2005 data and, when available, the 2004 data), based primarily on the TiO band depths. While all of the TiO bands are examined, the TiO bands at $\lambda\lambda$5847, 6158, and 6658 all become distinctively and progressively stronger at later spectral types, and as a result are the primary features considered in our classification. For most of the 2004 observations our data extend only up to 6450 Å, and so we made do with the first two bands. Our method of classification was consistent with that used in Papers I and II.

3.1. *Membership in the Clouds*

A magnitude- and color-selected sample of RSG candidates will be contaminated by foreground Galactic dwarfs and potentially by more distant halo dwarfs and giants. Of these, only the foreground dwarfs can be easily recognized on the basis of radial velocities, but these are by far the major contaminant in studying RSGs in Local Group galaxies (see, for instance, Massey 1998). Massey & Olsen (2003) obtained precision radial velocities, with the CTIO 4 m and Hydra fiber positioner feeding a bench-mounted spectrograph, of a sample of red stars seen toward the Clouds. Indeed, most of the stars in their sample had radial velocities consistent with those of the Magellanic Clouds, plus a small fraction (11% for the SMC and 5.3% for the LMC) that had much smaller radial velocities. The latter are readily identified as foreground dwarfs, while the former are tentatively identified as bona fide RSGs. However, since most of the SMC's and LMC's apparent radial velocity is simply a reflection of the Sun's motion, the sample of RSGs could be contaminated by red stars in the Milky Way's halo. In

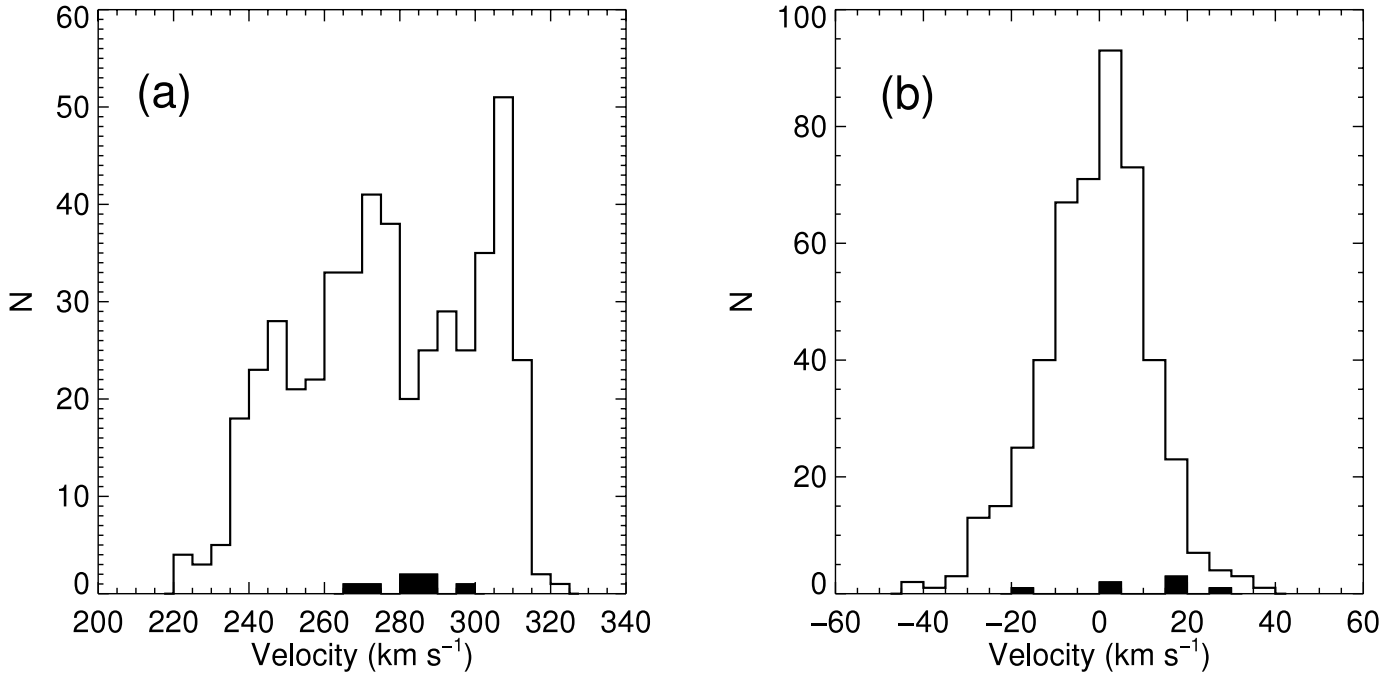


FIG. 1.—Kinematics of the LMC. (*a*) Histogram of LMC RSG velocities analyzed in Olsen & Massey (2007), in bins of 5 km s^{-1}, with our seven LMC stars overplotted as a solid histogram, showing that the velocities are consistent with those of other RSGs in the LMC. (*b*) Velocity residuals of our RSGs after subtracting a kinematic model fit to the Olsen & Massey (2007) RSG sample, with our LMC stars again plotted as a solid histogram. Standard deviation of the velocity residuals is 12 km s^{-1} for the larger sample and 14 km s^{-1} for our stars.

Paper II we estimated that this would be a few percent or less, but here we reconsider the issue.

The sample of stars in Paper II and here mostly have $12 < V < 14$, with a few fainter stars. Their $B - V$ colors are greater than 1.6 (see Table 1 of Paper II and Table 1 of the present paper). According to an updated version of the Bahcall & Soneira (1980) model, kindly provided by Heather Morrison, we expect a surface density of halo stars (all giants) of about 0.2 ± 0.15 deg^{-2} in this magnitude/color range toward either the LMC or the SMC, where the uncertainty reflects the effects of different assumptions. The area of the Massey (2002) survey was 14.5 deg^2 toward the LMC and 7.2 deg^2 toward the SMC, so we might expect 2.9 ± 2.1 halo giants (0.6% of the bright and red stars) seen toward the LMC and 1.4 ± 1.1 (0.9%) seen toward the SMC in his catalog. Thus, we expect only a fraction of a star in the entire spectroscopic sample of 84 stars (73 discussed in Paper II and 11 discussed here). Of the 11 stars in Table 1, 1% (0.1 stars) is probably a large overestimate, as the vast majority of these few halo contaminates have $B - V < 1.8$, while all but two of the stars in Table 1 have $B - V > 1.8$.

Finally, we can use a more exacting test of the kinematics than the simple radial velocity cutoff used by Massey & Olsen (2003) and ask whether the LMC stars discussed here follow the radial velocities of other RSGs as a function of spatial position in the LMC. The kinematics of the SMC are quite complex, and so we restrict the argument here to the LMC, where the kinematics are relatively well understood (Olsen & Massey 2007). Recall that differences in the radial velocities within the LMC are dominated by the transverse motion of the LMC coupled to the change in position factor due to the LMC's large angular extent, and that other effects, such as rotation, are a relatively minor perturbation (see, for example, Meatheringham et al. 1988, Schommer et al. 1992, and van der Marel et al. 2002). Figure 1 shows a histogram of LMC RSG velocities analyzed in Olsen & Massey (2007). The LMC RSGs discussed here follow the kinematics of the galaxy, something we do not expect to be true of halo giants. We conclude that the sample we discuss here is unlikely to contain foreground objects.

3.2. *Modeling the Spectrophotometry*

The observed spectral energy distributions of the sample stars were compared to MARCS stellar atmosphere models of metallicity $Z/Z_\odot = 0.2$ for the SMC and $Z/Z_\odot = 0.5$ for the LMC. The models ranged from 3000 to 4500 K in increments of 100 K and were interpolated for intermediate temperatures at 25 K increments. The log g values for the models ranged from -1 to $+1$ in increments of 0.5 dex.

When fitting the data, we reddened the models using a Cardelli et al. (1989) reddening law with $R_V = 3.1$. The reddening and $T_{\rm eff}$ for each object was determined by finding the best fit by eye to both the spectral features and continuum, initially using a model with $\log g = 0.0$. For these later type stars with distinct TiO features, our precision was about 50 K, while for the earlier K-type stars from Paper I, our precision was approximately 100 K. The extinction values A_V are determined to 0.15 mag. After fitting the reddening and $T_{\rm eff}$, we examined the appropriate log g value for the star: the bolometric corrections from the models were used with the reddening and photometry to compute the bolometric luminosity, assuming distance moduli of 18.9 for the SMC and 18.5 for the LMC (van den Bergh 2000). From the bolometric luminosity and $T_{\rm eff}$, the physical log g was determined. If the resulting value indicated that a model with $\log g = -0.5$ or +0.5 would be more appopriate than the initial estimate of $\log g = 0.0$, the star was refitted with the more appropriate surface gravity value, and the process was repeated. A changed log g value did not affect the $T_{\rm eff}$ determination, but did slightly affect the extinction value. Typically, this process converged on a satisfactory log g choice for the model after two or three iterations.

Our fits are shown in Figure 2. For the purposes of scaling, we have truncated the spectra to 4000 Å. In general the models show

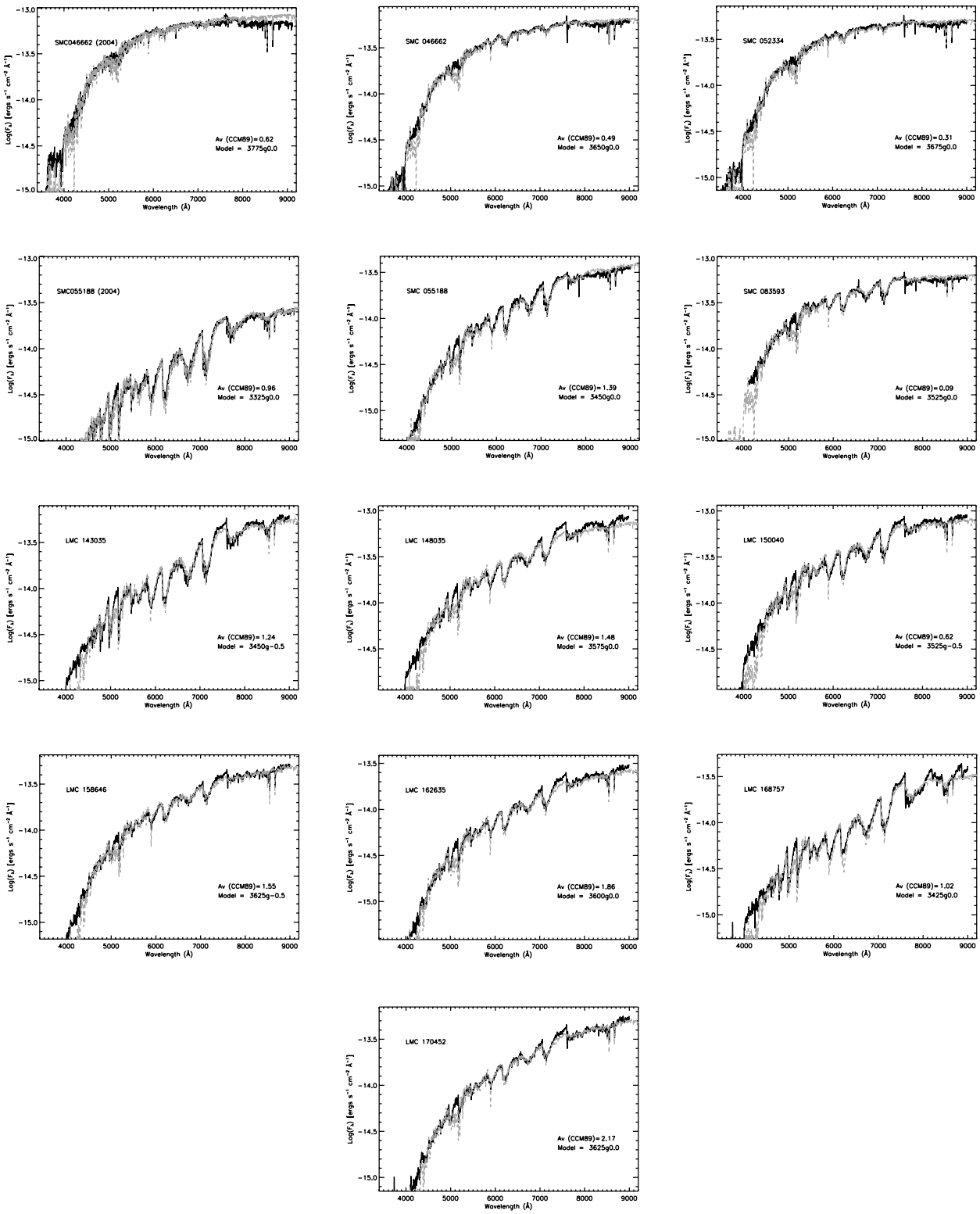


FIG. 2.—Fits of the MARCS stellar atmosphere models to our spectrophotometry. The data are shown as a solid black line, while the reddened MARCS models are shown as a dotted gray line. Note the additional fits for the 2004 spectrophotometry in the cases of SMC 046662 and SMC 055188. [*See the electronic edition of the Journal for a color version of this figure.*]

excellent agreement with our observed spectral energy distributions. The excess flux in the near-UV region of the spectra is likely due to circumstellar dust, scattering the light from the star into the line of sight; see Massey et al. (2005). The synthetic spectra has to be smoothed to match the resolution of the data. While a small mismatch can lead to discrepancies in the comparison of atomic lines (such as the superimposing of the Mg I triplet near 5200 Å, a feature only partially resolved in our spectra, onto TiO λ5167), the details of the smoothing are unimportant for comparison of the broader TiO molecular bands.

Since these stars are considerably variable in V (§ 3.4), we chose to use our spectrophotometry to provide a contemporaneous

TABLE 2
PHYSICAL PROPERTIES

						Spectral Fitting				$(V-K)_0$		
Star	HJD − 2,450,000	Type	V	M_V	A_V	$T_{\rm eff}$	$\log g$ (Model)	$R/R_\odot$	$M_{\rm bol}$	$T_{\rm eff}$	$R/R_\odot$	$M_{\rm bol}$
SMC 046662.....	3340.58	K2–K3 I	12.38	−7.14	0.62	3775	0.0	1000	−8.41	4050	730	−8.03
	3725.63	M0 I	12.75	−6.65	0.50	3650	0.0	960	−8.19	3829	760	−7.89
SMC 052334.....	3725.67	K5–M0 I	12.87	−6.34	0.31	3675	0.0	800	−7.82	3851	640	−7.55
SMC 055188.....	3341.59	M4.5 I	14.99	−4.87	0.96	3325	0.0	870	−7.57	3355	800	−7.43
	3725.68	M3–M4 I	14.23	−6.07	1.40	3450	0.0	1100	−8.23	3667	730	−7.62
SMC 083593.....	[a]	M2 I	12.83	−6.16	0.09	3525	0.0	970	−8.06	3751	680	−7.54
LMC 143035.....	3725.81	M4 I	14.10	−5.64	1.24	3450	−0.5	1020	−8.06	3482	870	−7.78
LMC 148035.....	3725.81	M2.5 I	13.42	−6.57	1.49	3575	0.0	1130	−8.44	3612	1010	−8.26
LMC 150040.....	3725.82	M3–M4 I	13.09	−6.03	0.62	3525	−0.5	990	−8.11	3523	950	−8.01
LMC 158646.....	3725.82	M2 I	13.80	−6.25	1.55	3625	−0.5	870	−7.94	3619	870	−7.92
LMC 162635.....	3725.83	M2 I	14.58	−5.78	1.86	3600	0.0	740	−7.56	3696	610	−7.25
LMC 168757.....	3727.84	M3–M4 I	14.62	−4.90	1.02	3425	0.0	780	−7.45	3411	760	−7.39
LMC 170452.....	3727.83	M1.5 I	13.99	−6.68	2.17	3625	0.0	1060	−8.37	3720	890	−8.10

[a] From merged 2004 and 2005 data.

measurement. We obtained these values from our spectrophotometry following the procedures of Bessell et al. (1998). We also computed contemporary $B-V$ values the same way. These values are listed in Table 1. This then allows the bolometric luminosity we derive to be directly related to the reddening and effective temperatures we derive, both of which may vary with time (Massey et al. 2007). To derive $M_{\rm bol}$, we first calculated M_V through the simple equation

$$M_V = V - A_V - {\rm DM},$$

assuming true distance moduli (DM) of 18.9 for the SMC and 18.5 for the LMC. The bolometric correction BC_V was calculated as a function of effective temperature based on fits made to the MARCS models; the equations are given in § 3.2 of Paper II. With these quantities, $M_{\rm bol}$ is then simply

$$M_{\rm bol} = M_V + {\rm BC}_V.$$

From the bolometric luminosity we can derive

$$L/L_\odot = 10^{(M_{\rm bol}-4.74)/(-2.5)}$$

and use the luminosity-radius-temperature relation,

$$R/R_\odot = (L/L_\odot)^{0.5}(T_{\rm eff}/5770)^{-2},$$

to obtain the stellar radii.

3.3. *Alternative Method Using K-Band Photometry*

In Papers I and II we found it was very useful to have some (nearly) independent check on our results by using the existing K-band photometry. In general, the variability at K is less than that at V (Josselin et al. 2000); we find below (§ 3.4) that this is true for these stars as well.

In order to derive (nearly) independent values of $T_{\rm eff}$ and $M_{\rm bol}$ from the K-band photometry, we dereddened the $V-K$ values from Table 1 using $(V-K)_0 = V-K-0.88A_V$, where the numerical value was derived in Paper II (and is in agreement with that of Schlegel et al. 1998), and the values for A_V are taken from Table 2. We derive the effective temperatures from $(V-K)_0$ using relations derived from the models and given in § 3.3.1 of Paper II.

To derive the bolometric luminosity using these new temperatures, we first calculated M_K by

$$M_K = K - A_K - {\rm DM},$$

where $A_K = 0.12A_V$. We then derived the bolometric corrections to the K band (BC_K) using the K-band effective temperatures and the relations given in Paper II. The bolometric luminosity is then simply

$$M_{\rm bol} = M_K + {\rm BC}_K,$$

and the stellar radius follows as shown in § 3.2. The values for BC_K came from adopting the $(V-K)_0$ temperatures and using a relation derived from the MARCS models in Paper II.

We include these values in Table 2, and they show good general agreement with the values obtained from spectrophotometry. Systematically, the K-band temperatures yield a median difference of −200 K in temperature for the four SMC stars and −96 K in temperature for the seven LMC stars, in the sense that the K-band values are larger. These systematic differences are similar to those found from the larger sample considered in Paper II, where we found median differences of −170 and −105 K between the K-band photometry and spectral fitting for the SMC and LMC, respectively. The median K-band luminosities are lower, 0.41 mag for the SMC and 0.18 mag for the LMC. In Paper II we attributed the differences to the inherent limitations of the one-dimensional atmosphere models.

3.4. *Variability*

3.4.1. *Photometric Variability*

Many of the objects in our sample demonstrate large variability in their V magnitudes. Photometry was obtained from the All Sky Automated Survey (ASAS) project (Pojmanski 2002). To this, we added some additional data of our own. First, we used the CCD photometry of Massey (2002) and obtained individual measurements for each of our stars, rather than the averages given in that paper. These new values are given in Table 3. Included as well are the values we derive from our spectrophotometry,

TABLE 3
TIME-RESOLVED DATA[a]

HJD − 2,450,000	V[b]	A_V	$B-V$	$T_{\rm eff}$	Spectral Type
[M2002] SMC 046662					
1186.58	12.90	...	1.88	...	...
2188.56	13.32	...	...	...	M2 I
3340.58	12.38	0.62	...	3775	K2–K3 I
3725.63	12.75	0.50	1.95	3650	M0 I
[M2002] SMC 052334					
1186.58	12.89	...	1.94	...	...
2187.56	12.72	...	...	...	K7 I
3725.67	12.87	0.31	1.91	3675	K5–M0 I
[M2002] SMC 055188					
1186.58	14.96	...	2.25	...	...
2188.56	...	...	...	...	M2 I
3341.59	14.99	0.96	...	3325	M4.5 I
3725.68	14.23	1.40	2.22	3450	M3–M4 I
[M2002] SMC 083593					
1186.59	12.64	...	1.87	...	...
3334.60	12.81	...	...	...	...
3724.60[c]	12.83	0.09	1.60	3525	M2 I
[M2002] LMC 143035					
1186.67	13.53	...	1.93	...	...
1998.51	13.51	...	1.93	...	...
2188.72	14.24	...	...	...	M3–M4.5 I
3334.60	13.99	...	...	...	M4.5–M5 I
3725.81	14.10	1.24	1.93	3450	M4 I
[M2002] LMC 148035					
1186.67	12.94	...	1.82	...	...
1996.53	13.89	...	1.71	...	...
1998.51	13.87	...	1.62	...	...
2188.72	12.94	...	...	...	M4 I
3725.81	13.42	1.49	1.98	3575	M2.5 I
[M2002] LMC 150040					
1186.71	12.86	...	1.97	...	...
1997.54	12.81	...	1.96	...	...
2188.82	12.93	...	...	...	M4 I
3334.60	12.60	...	...	...	M3–M4 I
3725.82	13.09	0.62	1.90	3525	M3–M4 I
[M2002] LMC 158646					
1186.71	12.66	...	2.19	...	...
1996.53	13.10	...	2.23	...	...
2188.79	13.54	...	...	...	M3–M4 I
3725.82	13.80	1.55	2.18	3625	M2 I
[M2002] LMC 162635					
1996.53	14.23	...	2.33	...	...
2188.79	13.52	...	...	...	M1 I
3725.83	14.58	1.86	2.20	3600	M2 I
[M2002] LMC 168757					
1996.53	14.08	...	1.77	...	...
2188.76	13.23	...	...	...	M3 I
3727.84	14.62	1.02	1.80	3425	M3–M4 I
[M2002] LMC 170452					
1996.53	13.99	...	2.39	...	...
2188.76	...	...	...	...	M4.5–M5 I
3341.70	15.31	...	...	...	M4.5–M5 I
3727.83	13.99	2.17	2.24	3625	M1.5 I

[a] Measurements from 2,451,186 to 2,451,999 were obtained using the CCD images described in Massey (2002). The uncertainties in these values are 0.01 mag or smaller. Later measurements come from our 2004 November/December and 2005 December spectrophotometry.
[b] The V magnitudes quoted for HJD 2,452,188 come from ASAS observations on the closest approximate date to the observations, from 2,452,184 to 2,452,187.
[c] From merged 2004 and 2005 data.

including that of the 2004 observing run described in Paper II. We also list the extinction A_V that we derive from our spectral fitting, in order to supplement the limited color information available. The photometry derived from the spectrophotometry was derived using the V-band curve of Bessell (1990) and the zero points given by Bessell et al. (1998).

The light curves are given in Figure 3 for 9 of our 11 objects (SMC 055188 and LMC 170452 lacked sufficient ASAS data). While normal RSGs are known to be variable in V (Josselin et al. 2000), each of the late-type stars described here show larger variations. The maximum changes we see for the stars discussed here average to a ΔV of 1.3 for the SMC sample and 1.6 for the LMC sample. For comparison, the ASAS photometry of 70 SMC and LMC RSGs studied in Paper II average to a ΔV of 0.9 mag. Many of the late-type RSG light curves also seem to suggest some level of quasi-periodicity.

While SMC 055188 and LMC 170452 are not included in Figure 3, our observations in Table 3 show that they are also quite variable in V. In addition, NOMAD (Zacharias et al. 2004) gives V magnitudes of 13.82 and 14.91 for these stars, respectively. So, it appears that these stars show V-band variability of 1.2–1.3 mag.

In contrast, we expected that the variability at K would be less; at least, this is typical of other RSGs (Josselin et al. 2000). We checked the 2MASS values against DENIS (Kimeswenger et al. 2004) and found much lower variability, with an average difference at K between the two surveys of 0.08 mag.

Finally, we note that for four of the stars, the $B-V$ photometry we derive from our (2005) spectrophotometry differs significantly (>0.1 mag) from the 1999/2000 values of Massey (2002). We list both the new and old values in Table 3. In general the agreement is good, but for four of our stars (SMC 083593, LMC 148035, LMC 162635, and LMC 170452) we see differences of several tenths in $B-V$. As discussed in our study of HV 11423 (Massey et al. 2007), $B-V$ is not very sensitive to effective temperatures for RSGs. Instead, we suggest that the variations we see in $B-V$ are indicative of changes in the amount of circumstellar dust causing differences in the reddening. (As discussed by Massey et al. 2005, dust around RSGs *should*, and apparently does, result in a significant amount of circumstellar extinction in the extreme cases in the Milky Way, amounting to several magnitudes.) We saw similar changes in $B-V$ for HV 11423 and suggest episodic dust ejection on the timescale of a few years, consistent with the study of Danchi et al. (1994).

Note that these changes in $B-V$ are not correlated in some simple way with changes in V: a redder color does not necessarily mean that the star is fainter. This demonstrates that the V-band

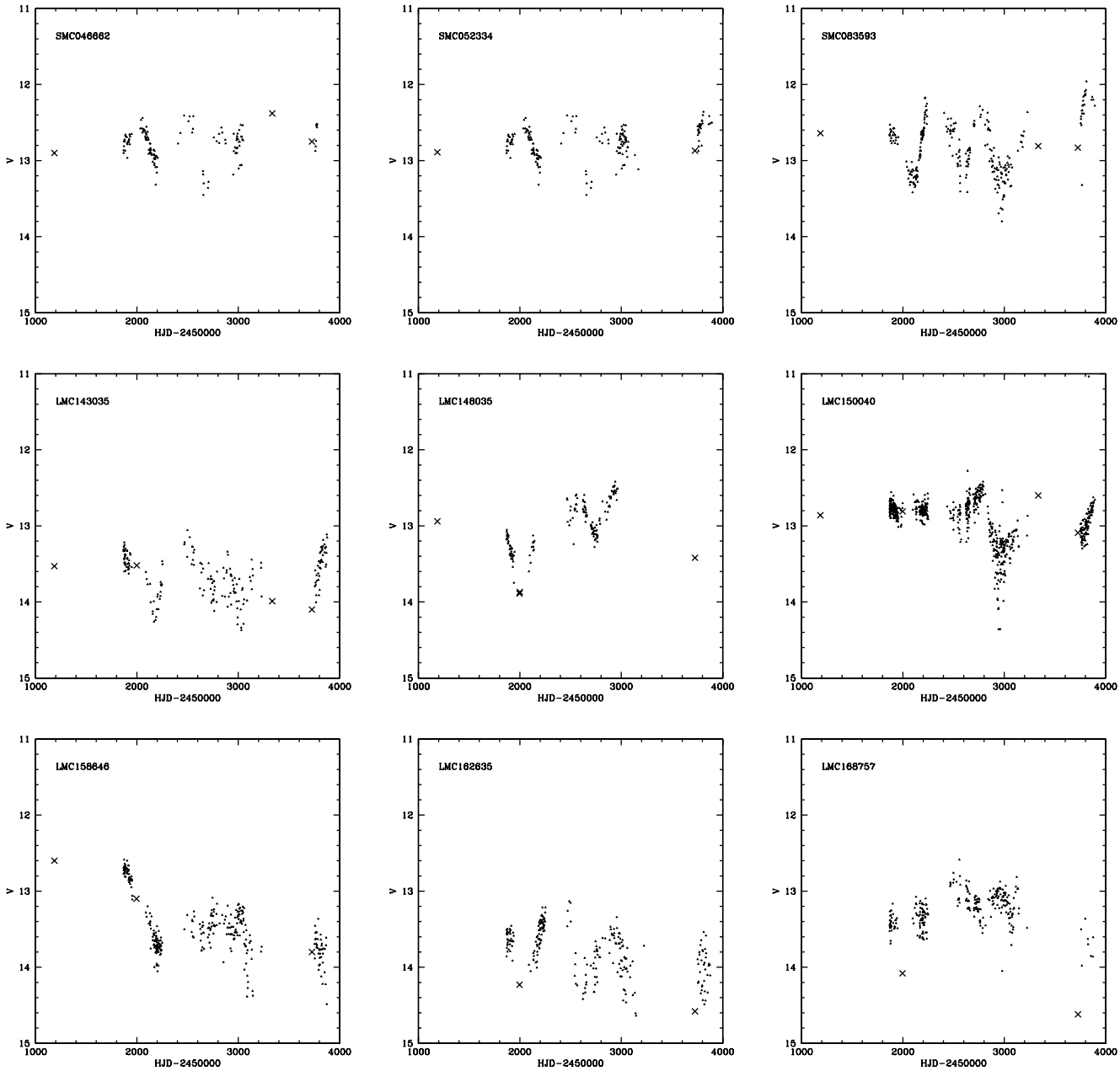


FIG. 3.—Photometric variability. We show the photometry of nine of our stars, where the small points come from the ASAS photometry and the large points come from Table 3. Very few data points were available for SMC 055188 and LMC 170452, and these stars are not included in the figure, although we argue in the text that these two stars also show large photometric variability.

variability is *not* simply caused by changes in the amount of circumstellar extinction, but that rather real changes in the star (such as effective temperature) are responsible for the change in *V*. For HV 11423 we argued that these physical changes were also triggering bursts of enhanced dust production, further complicating the light curve.

3.4.2. *Spectral Variability*

We were intrigued by the large discrepancies in spectral subtypes assigned to some of our stars by previous studies and ourselves (Table 1). Although assigning spectral types is a little subjective, we did not see many such differences in the comparison of Massey & Olsen (2003) types with ours in Paper II. Yet, spectral variability of a type or more is virtually unknown for RSGs. The notable past exception is the SMC RSG star HV 11423, recently found by Massey et al. (2007) to have varied several times between K0–K1 I and M4.5–M5 I in the past several years. At its coolest, it is the latest type supergiant in the SMC. HV 11423 shows large photometric variability at *V*, due in part to the substantial change in effective temperature (while holding relatively constant in bolometric luminosity) and in part to the increased circumstellar extinction, presumably from outbursts of dust formation resulting from mass loss.

We were therefore interested to follow up the question about whether or not the stars discussed here are truly variable or not in spectral type. We have included spectral types for these stars in Table 3 from Massey & Olsen (2003) and this study, as well as types from our 2004 data. While in most cases we do not have sufficient wavelength coverage to determine physical properties, the data we do have is sufficient to determine accurate spectral

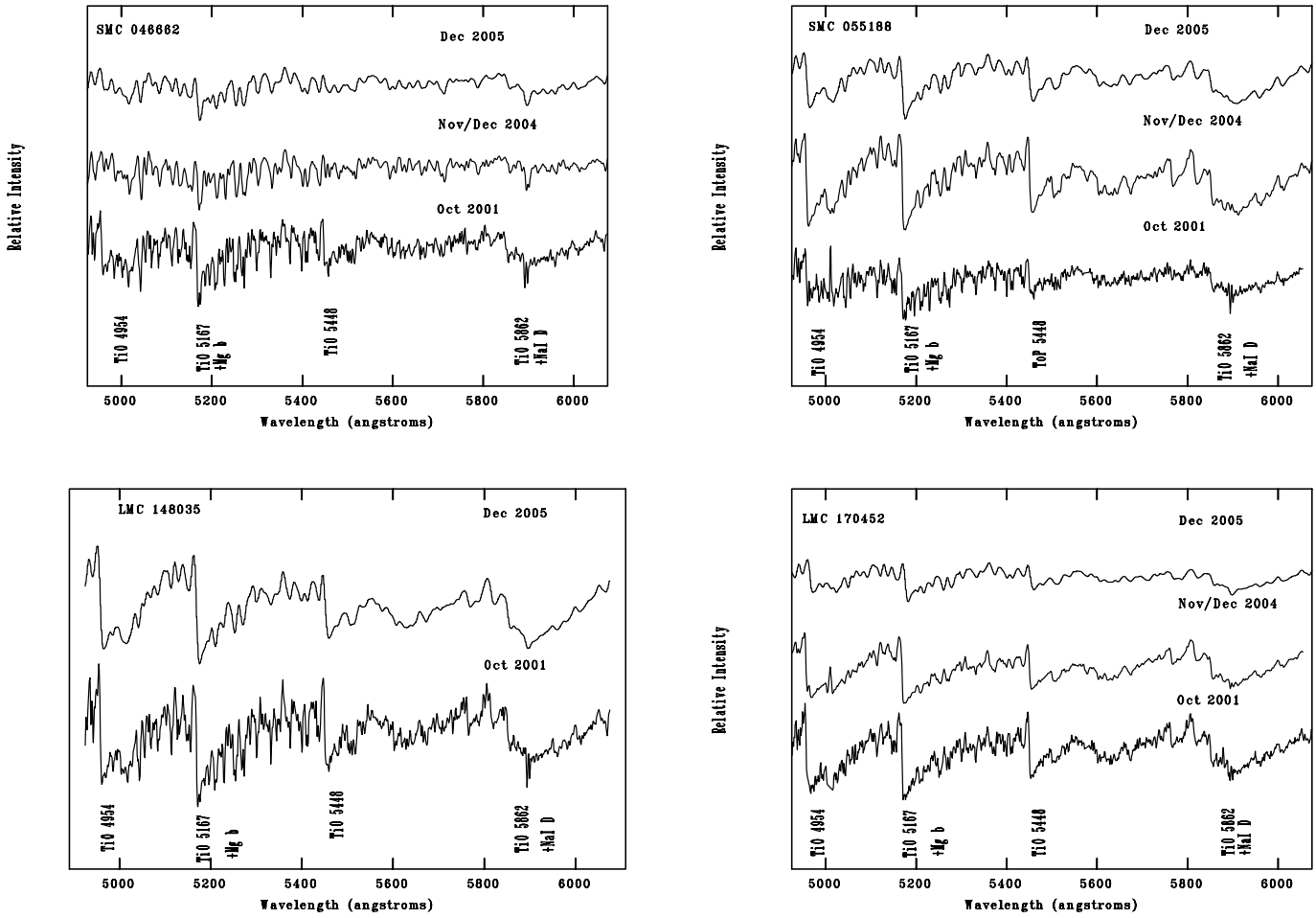


FIG. 4.—Spectral variability. We show a comparison of the 2001 October spectra (from Massey & Olsen 2003) with those obtained in 2004 December and 2005 December (from the present paper), where the spectra have been normalized and nebular emission has been removed from the 2001 October spectrum of LMC 170452 to make the comparison easier. Prominent absorption features are indicated, based on the identifications given in Turnshek et al. (1985). SMC 046662, SMC 055188, and LMC 170452 clearly show dramatic changes in the absorption line intensities, indicating a change in spectral type (and hence effective temperature); the changes in LMC 148035 are relatively unremarkable.

types, and therefore useful for evaluating the spectral variability of these stars over the past few years.

From examining the data in Table 1, we find four stars that show significant differences in their listed spectral types: SMC 046662 (M2 I to K2–K3 I), SMC 055188 (M2 I–M4.5 I), LMC 148035 (M4 I–M2.5 I), and LMC 170452 (M4.5–5 I to M1.5 I). We compare their 2001 October spectra (from Massey & Olsen 2003) with those from late 2004 and 2005 December in Figure 4. We see that indeed the spectral changes for SMC 046662, SMC 055188, and LMC 170452 are real and that the line strengths have indeed changed dramatically throughout the past few observations. In the case of LMC 148035, the differences are much less significant, and Massey & Olsen (2003) have assigned too late a spectral type.

In the case of HV 11423 (Massey et al. 2007), we were able to combine the changes in the photometric and spectrophotometric properties of the star to present a picture of the physical changes that were taking place within the star. HV 11423 varied in effective temperature from 4300 to 3500 K on a timescale of months. When the star is as cool as it gets, it has a very late spectral type, M4.5 I or so, much later than other supergiants that were known in the SMC (prior to this study) and far beyond the region where the star is hydrostatically stable. This 800 K change in effective temperature was reflected in the star's changing V and luminosity: when the star was hot, it was also brighter and slightly more luminous, with the differences amounting to -0.6 mag in both cases. Although the differences in V and $M_{\rm bol}$ are the same, this is coincidental, as the absolute *visual* magnitude M_V changed by -1.9 mag. The change in V was smaller because our analysis also showed that the amount of visual extinction also changed by 1.3 mag, due presumably to additional circumstellar dust that forms when the star is cool. Of course, with only two or three epochs of observations, it is difficult to sort out what changes sporadically rather than systematically.

Still, a very similar picture seems to emerge here. For SMC 046662, SMC 055188, and LMC 170452 we see changes in the spectral types and effective temperatures on the timescale of a year, albeit by lesser amounts. When these stars are hottest, they are also at their brightest. For SMC 046662 and SMC 055188 we can also conclude that when the stars are hottest, they are also more luminous (Table 2). The differences that we observed were smaller, with the changes in effective temperature and bolometric luminosity amounting to 125 K and -0.2 mag, respectively, for SMC 046662. At the extremes we observed, the changes for SMC 055188 amounted to 200 K and -0.5 mag. Futhermore, we can estimate the amount of extinction for these two stars and find that A_V is larger when the star is hotter. All of this behavior is remarkably similar to what we see in HV 11423.

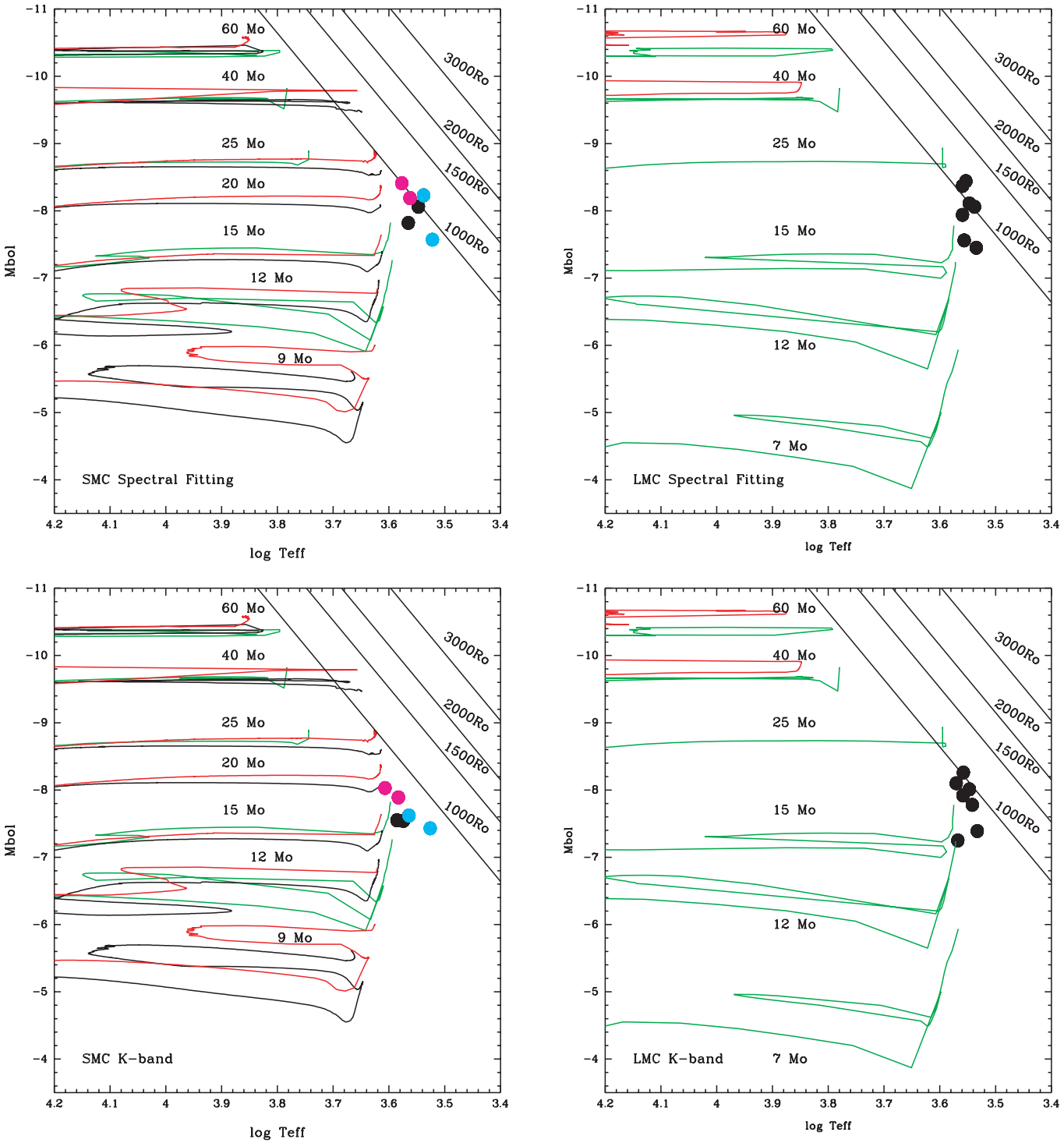


FIG. 5.—Location of the late-type MC RSGs discussed here compared to the evolutionary tracks. We show the location of the RSGs in the H-R diagram of the SMC (*left*) and LMC (*right*), where the effective temperatures and bolometric luminosities come from fitting the MARCS models to the optical spectrophotometry (*top*) and from the *K*-band photometry (*bottom*). The older, nonrotation evolutionary tracks that include the effects of overshooting are shown in green and come from Charbonnel et al. (1993) for the SMC and from Schaerer et al. (1993) for the LMC. The newer evolutionary tracks (when available) are shown in black (zero rotation) and in red (300 km s^{-1} initial rotation) and come from Maeder & Meynet (2001) for the SMC and Meynet & Maeder (2005) for the LMC. Like-colored dots are used to link the 2004 and 2005 observations of the same star (purple for SMC 046662 and light blue for SMC 055188).

4. RESULTS

4.1. *Placement on the H-R Diagram*

In Figure 5 we place our LMC and SMC sample stars on stellar evolutionary tracks of the appropriate metallicity. It is clear that stellar evolutionary theory is not in agreement with the observed parameters of these late-type stars. Specifically, the evolutionary tracks do not extend to cool enough temperatures to accommodate these stars in their current states. The location of the RSGs as derived from spectral fitting is, on average, 275 K cooler than the tracks allow for the LMC and 541 K cooler for the SMC. The agreement is better for the physical properties derived from

TABLE 4
EFFECTIVE TEMPERATURE SCALES WITH NEW DATA

	SMC			LMC			MILKY WAY[a]		
SPECTRAL TYPE	$T_{\rm eff}$ (K)	σ_μ[b]	N	$T_{\rm eff}$ (K)	σ_μ[b]	N	$T_{\rm eff}$ (K)	σ_μ[b]	N
K1–K1.5 I	4210	39	7	4300	...	1	4100	100	3
K2–K3 I	4003	56	15	4050	62	3	4015	40	7
K5–M0 I	3777	34	11	3850	18	2	3840	30	3
M0 I	3629	16	6	3738	11	4	3790	13	4
M1 I	3625	...	1	3695	8	5	3745	17	7
M1.5 I	...	...	...	3650	13	7	3710	8	6
M2 I	3500	18	2	3621	6	7	3660	7	17
M2.5 I	...	...	...	3550	12	6	3615	10	5
M3 I	...	...	...	3542	18	3	3605	4	9
M3.5 I	3450	...	1	3475	35	2	3550	11	6
M4–M4.5 I	3413	62	2	3450	18	3	3535	8	6
M5 I	...	...	...	...	...	...	3450	...	1

[a] From Paper I.
[b] Standard deviation of the mean.

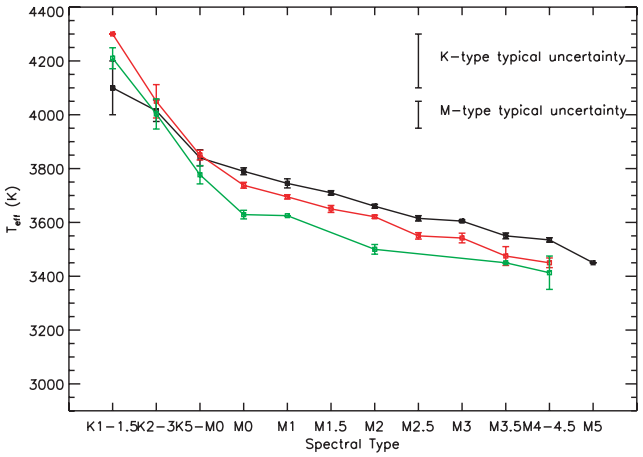


FIG. 6.—Modified full temperature scales for the Milky Way (*black*), LMC (*red*), and SMC (*green*), incorporating the 11 stars from this sample. The Magellanic Cloud scales now include more stars at the later spectral types, which allows us to examine the metallicity effects at lower temperatures. For example, a 3550 K star may appear as an M3.5 I in the Milky Way, an M2.5 I in the LMC, and an M1.5 I in the SMC.

$V - K$ photometry, although even here the tracks do not extend to cool enough temperatures—the RSG locations are 205 K too cool for the LMC and 216 K too cool for the SMC. However, this improved agreement is largely due to the fact that, as discussed in (§ 3.3), the temperatures derived from $V - K$ photometry are also generally warmer than those derived from spectral fitting. The foreshadowing of this result can be seen in Figure 8 of Paper II, where, while agreement for most SMC and LMC RSGs is good, disagreement with evolutionary theory is visible for the coolest SMC RSGs. It appears, therefore, that the location of these evolutionary tracks does not accommodate the full range of RSG properties in this low-metallicity environment.

The discrepancy appears slightly worse for the SMC than the LMC, particularly in the case of the HRD positions derived from spectral fitting. Recall that at low metallicity rotation plays an enhanced role in the luminosities of the evolutionary tracks (Maeder & Meynet 2001) due to the effects of mixing. Still, the current evolutionary models do not show much of a difference with the location in temperature due to rotation, as is evident by comparing the black (no rotation) and red (high rotation) tracks in Figure 5. For the time being, this increased discrepancy seen in the SMC remains unexplained.

4.2. *Revisions to the Effective Temperature Scale*

In Paper II we compared the effective temperatures of stars of the same spectral subtype in the SMC, LMC, and Milky Way. Because the metallicity is less in the SMC than in the LMC or Milky Way, we expect that a given band strength of TiO (the basis for the spectral classification) will require a cooler temperature in the SMC than in the LMC or Milky Way, and indeed we found such a progression: an M1 star would have an effective temperature of 3625 K in the SMC, 3695 K in the LMC, and 3745 K in the Milky Way. Put another way, stars with an effective temperature of 3550 K would have TiO band strengths corresponding (roughly) to an M1.5 I in the SMC, M2.5 I in the LMC, and M3.5 I in the Milky Way.

With the present data we can improve the comparison for the latest types. In Table 4 we update Table 4 of Paper II. Figure 6 shows updated effective temperature scales for the LMC and SMC with these new late-type members included. We have also included our results on HV 11423 (Massey et al. 2007). The error bars at the upper right show our estimate of the uncertainty when measuring the temperature of a single star −100 K for the early K type stars and 50 K for the later type RSGs, as described in § 3.2. At M0–M2 we find that a star in the LMC is about 50 K cooler than in the Milky Way, while a star in the SMC is about 130 K cooler than in the Milky Way.

5. DISCUSSION

We have determined the physical properties of a sample of seven late-type RSGs in the LMC and four late-type RSGs in the SMC; one additional star with extreme properties, HV 11423, has been studied separately (Massey et al. 2007). We argue that these stars are likely all members of the Magellanic Clouds and not foreground objects and have found that these stars possess photometric variability at V that is larger than RSGs of earlier spectral types. Although four of our stars show significant variability in $B - V$, suggesting changes in the amount of circumstellar reddening, the variable V-band magnitudes are not correlated with the color changes and therefore must be due to physical changes in the star itself. Consistent with this, three of these stars—SMC 046662, SMC 055188, and LMC 170452—have demonstrated spectral variability of several subtypes. Other than the SMC star HV 11423, this behavior is unknown for RSGs. These late-type RSGs are significantly cooler than the evolutionary tracks allow, with the discrepancy larger for the SMC than the LMC. Naively, we would argue that for the most part these stars are in the Hayashi forbidden zone of the HRD, which is also true of HV 11423 when it is in its cool state.

The extinction observed around most of these stars (Tables 2 and 3) is higher than what is typically seen for OB stars in the Clouds, for which $A_V = 0.28$ (SMC), and $A_V = 0.40$ (LMC), where the values come from Massey et al. (1995). This is similar to what was found by Massey et al. (2005) for Galactic RSGs. Both HV 11423 and SMC 055188 are among the only four known SMC RSGs that are *IRAS* sources (Massey et al. 2007), indicating that we are seeing thermal emission from circumstellar dust. In the case of HV 11423, we found evidence of a variable amount of visual extinction, which we argued was connected with the sporadic production of dust, and we now find similar evidence for sporadic dust production when comparing the 2004 and 2005 results of model fitting for SMC 055188 and SMC 046662. Like HV 11423, SMC 055188 probably produces dust quite sporadically: despite

its presence in the *IRAS* source catalog, the star was not in the *Midcourse Space Experiment* (*MSX*) 10 μm flux MSXC6 catalog (Egan et al. 2003), despite the fact that *MSX* was considerably more sensitive than *IRAS* at this wavelength. Similar sporadic dust production may be true of other stars in this sample, given that we find that four of our stars (SMC 083593, LMC 148035, LMC 162635, and LMC 170452) show a change of several tenths of a magnitude in $B - V$ colors. This could account for some of the V-band variability we observe, but clearly not all, as in some cases V has gotten larger while $B - V$ has gotten smaller (e.g., SMC 083593 and LMC 162635), or stayed the same despite changes in $B - V$ (LMC 170452). Thus, physical changes in the star are primarily responsible for the variability in V, although changes in the circumstellar extinction (as evidenced by the $B - V$ changes) probably complicated the light curves as well.

Most interestingly, HV 11423, originally thought to be a unique and extreme case, has now been joined by three fellow RSGs exhibiting similar behavior: cool stars inhabiting the Hayashi forbidden zone that show large variability in spectral type, V magnitudes, and extinction, presumed to be from circumstellar dust. These stars suffer changes in effective temperature and bolometric luminosity on timescales of months; when they are at their hottest, they are also brighter and more luminous. As described above, one would expect stars in the Hayashi forbidden region to be hydrostatically unstable, which we expect to lead to this variability and behavior. Further monitoring of these stars, both photometrically and spectroscopically, may lead to an improved understanding of this phase of massive star evolution.

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