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THE LATE-TYPE STELLAR CONTENT OF MAGELLANIC CLOUD CLUSTERS

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ABSTRACT

New broad-band infrared photometric data have been obtained for 48 late-type giants in clusters in the Magellanic Clouds (MC). Visual spectrophotometry was obtained for a subset of these stars. These observations are combined with published data for MC cluster stars and then compared with similar data for MC field giants and with predictions of various evolutionary schemes for cool, luminous, carbon and oxygen rich stars.

The MC cluster C stars are found to have a range in spectral energy distributions which is quite similar to that of MC field C stars. The luminosity function of the cluster C stars has a mean $M_{\rm bol}=-4.76$ with a dispersion of ± 0.36, also quite similar to the values for MC field C stars. However, the dispersion of the cluster C stars in M_{K_0} at a given $(J-K)_0$ is between 2 and 3 times less than it is for the field C stars. This can arise if the present sample of clusters has a significantly smaller spread in age and/or metallicity than the progenitors of the field C stars.

The LMC field contains M giants which are redder and more luminous than any so far found in LMC or SMC clusters. This is attributed to the presence in the LMC field of a significant population of stars which are younger and/or more metal rich than the stars in the cluster sample. Differences which are found to exist between the M star populations of the LMC and the SMC clusters are also attributed to age and/or metallicity effects.

In all but one of the MC clusters which have both M and C stars, the faintest C star is brighter than the brightest M star. Such a "transition" luminosity appears to be correlated with the location of the cluster in the one-dimensional classification sequence of Searle, Wilkinson, and Bagnuolo, and it can be a useful criterion in the evaluation of theories of carbon star evolution.

Finally, although the spectrophotometric data suggest that the LMC "halo-type" globular, NGC 1841 and 2257, have metallicities similar to one another and to that of M3, the locations of the NGC 1841 stars in a *C-M* diagram appear to be anomalous in the sense that its brightest stars have luminosities greater than the tips of giant branches of metal poor galactic globular clusters.

Subject headings: clusters: globular — galaxies: Magellanic Clouds — galaxies: stellar content — stars: late-type

I. INTRODUCTION

There are several lines of evidence that the red Magellanic Cloud clusters range in age from a few times 10^9 years to as old as the galactic globulars (e.g., Gascoigne 1966; Hesser, Hartwick, and Ugarte 1976; Catchpole and Feast 1973; Searle, Wilkinson, and Bagnuolo 1980). This age range will result in a cool component of the stellar population quite different from that typically found in galactic globulars and one which will generally be rare or absent from intermediate age galactic clusters because of the latter's sparseness.

As an example, the first *C-M* diagrams for clusters in the Large and Small Magellanic Clouds (LMC and SMC) showed that many of them have giant branches which terminate with stars of $B-V \gtrsim 1.9$ (e.g., Arp 1958*a*, *b*; Hodge 1960*a*, *b*; Sandage and Eggen 1960; Gascoigne 1962; Walker 1970). Van den Bergh's (1972) suggestion that these stars could be carbon stars was confirmed spectroscopically by Feast and Lloyd Evans (1973).

Application of infrared photometric techniques to studies of cool giants in three star clusters in the Large

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TABLE 1

REDDENING AND EXTINCTION CORRECTIONS

Clusters	$E_{B-V,0}$	$A_{V,0}$	$A_{K,\mathrm{MC}}$	$E_{V-K,\mathrm{M}}$	$E_{V-K,\mathrm{C}}$	$E_{J-K,\mathrm{MC}}$	$E_{H-K,\mathrm{MC}}$	$E_{\mathrm{CO,MC}}$	$E_{\mathrm{H_2O,MC}}$
Group A[a]	0.07	0.22	0.02	0.19	0.19	0.04	0.01	0.00	0.00
Group B[b]	0.10	0.32	0.03	0.28	0.27	0.06	0.02	0.00	0.005

[a]Clusters in Group A are NGC 1841, 2173, 2190, 2209, 2257, and the Small Magellanic Cloud.
[b]Clusters in Group B are NGC 1651, 1652, 1783, 1844, 1846, 1978, and 2193.

Magellanic Cloud permitted for the first time the determination of accurate absolute bolometric luminosities for carbon stars[2] (Frogel, Persson, and Cohen 1980*a*, hereafter FPC). This paper continues our study of C- and M-type giants in the Magellanic Cloud clusters. (Unless it is explicitly stated otherwise, "M stars" shall refer to cool, oxygen rich giants of spectral types K *and* M.) These stars are compared with field C amd M stars from the Magellanic Clouds and, in a rather qualitative fashion, with theoretical predictions concerning the evolution of cool giant stars. Although data are available for still a rather small number of clusters, they will be useful in interpreting *JHK* photometric observations of the integrated light of the clusters (Persson *et al.* 1982).

Some preliminary results of a spectroscopic study of stars in Large Magellanic Cloud clusters are also presented and discussed.

II. SELECTION OF STARS AND THE OBSERVATIONS

a) *Selection of Stars and Reddening Corrections*

Several criteria were employed to select the sample of Magellanic Cloud cluster stars. Carbon stars known to be cluster members were observed. The reddest stars from clusters characterized by Hesser, Hartwick, and Ugarte (1976) as having no, or at most a stubby, red horizontal branch, were also selected for observation. Additional stars with red $(B-V)$'s were observed in the clusters studied by FPC. Special attention was given to NGC 1841 and 2257, two examples of LMC clusters which are probably similar to metal poor galactic halo globulars (Gascoigne 1966; Searle, Wilkinson, and Bagnuolo 1980). A number of red stars in these clusters were identified on unpublished finding charts by Gascoigne and communicated to the authors by Mould and Aaronson. Finally, several stars were observed in the infrared because they were included in a spectroscopic program by one of us (J. G. C.) for other reasons.

A search of lists of early-type stars in the Magellanic Clouds referred to in the Appendix of Cohen *et al.* (1981, hereafter CFPE), did not turn up any OB stars, which are useful for reddening determinations, within 5 arcmin of the cluster centers. Thus, for those clusters lying on the extreme periphery of the LMC (Group A in Table 1), a value of $E(B-V)_0=0.07$ was assigned (Brunet 1975; see also discussion in CFPE), where the subscript "0" implies that this is the reddening appropriate to an A0 star. The remainder of the clusters in the LMC sample lie between the periphery of the bar and the outskirts of the Cloud itself (Group B in Table 1); hence they were assigned Brunet's (1975) value of $E(B-V)_0=0.10$ which is an average for weak absorption regions. All of the clusters in the SMC were assigned a mean value of $E(B-V)_0=0.07$. The reddening and extinction corrections appropriate to M and C type stars (the reddening law is given in Table 10 of CFPE) are given in Table 1. We have included clusters from FPC and Mould and Aaronson (1980, hereafter MA80) which were not observed in the present instance.

b) *Infrared Data*

Most of the stars listed in Table 2 were observed in the infrared with the CTIO 4 m reflector. Additional infrared observations were obtained with the 2.5 m Du Pont telescope of Las Campanas Observatory. All of these data were obtained in an identical manner, and generally on the same nights, as that employed in observing C and M stars in various fields of the Magellanic Clouds (CFPE). Subsequent to having obtained these new data, we received a preprint from Mould and Aaronson (MA80) which overlapped substantially with our data. All told, there are 11 stars in common with MA80 and 10 stars that were measured both at Cerro Tololo and Las Campanas (we include six stars from CFPE which are of similar magnitudes and colors). In both cases, the systematic differences in colors, magnitudes, and indices are ±0.01 mag or less with typical dispersions of 0.03–0.04 mag. These dispersions, which are somewhat larger than we have seen in the past, undoubtedly arise from variability of these red stars and the problems of working in crowded fields.

The cluster stars observed are listed in the first two columns of Table 2. Star G30 in N1783 was also observed by FPC. Reddening corrected magnitudes, colors, and indices are given in the columns headed "Reddening Corrected" of Table 2. Sources of *BV* photometry are indicated in the Notes column.

[2]The value of broad band infrared photometry in deriving bolometric *corrections* for cool stars was emphasized and exploited by Mendoza and Johnson (1965) and Dyck, Lockwood, and Capps (1974).

TABLE 2

STELLAR PHOTOMETRY IN MAGELLANIC CLOUD CLUSTERS

Cluster	Star[a]	Observed[b]			Reddening Corrected							Type[c]	M_{bol}[d]	Notes
		K	J-K	H-K	K_o	$(B-V)_o$	$(V-K)_o$	$(J-K)_o$	$(H-K)_o$	H_2O	CO			
N419	5-3	12.06 (9)	1.10 (8)	0.25	12.04	1.91	3.66	1.06	0.24	...	...	M1	-4.12	11, W84
	5-7	12.42 (10)	0.92 (10)	0.15	12.40	1.76	3.55	0.88	0.14	...	...	K5	-4.10	1, 11, W87
	5-8	12.63 (10)	0.83 (8)	0.15	12.61	1.65	3.33	0.79	0.14	...	...	(M)	-4.09	2, 11, W88
	5-14	12.37 (9)	0.95 (8)	0.17	12.35	1.61	3.51	0.91	0.16	...	...	(M)	-4.08	11, W90
	5-15	12.30 (9)	0.89 (8)	0.18	12.28	1.61	3.73	0.85	0.17	...	...	(M)	-4.29	12
	6-1	12.10 (9)	0.84 (8)	0.15	12.08	...	...	0.80	0.14	...	...	(M)	-4.60	12
N1651	H3304	10.50	1.16	0.31	10.47	...	...	1.10	0.29	0.115 (3)	0.29	M5	-5.15	
	H4325	11.29	1.10	0.23	11.26	...	...	1.04	0.21	0.055 (3)	0.19	M4	-4.42	
	H4328	11.53	1.31	0.40	11.50	...	...	1.25	0.38	0.085 (3)	0.135	C,3	-4.22	
	H2421	11.20	1.19	0.31	11.17	...	...	1.13	0.29	0.08 (3)	0.24	M3	-4.42	
	H4402	12.62 (3)	0.99 (3)	0.19	12.59	...	...	0.93	0.17	...	...	(M)	-3.29	
N1652	H3210	12.56	0.99	0.21	12.53	1.34	3.4	0.93	0.19	...	...	K3	-3.35	8, 22
	H2406	12.47	1.06	0.20	12.44	1.49	3.8	1.00	0.18	...	...	K3	-3.30	8, 22
N1783	G7	11.27	1.13	0.25	11.24	1.43	4.68	1.07	0.23	0.095 (3)	0.24	(M)	-4.41	13
	G12	12.83	0.97	0.20 (3)	12.80	1.47	3.30	0.91	0.18	...	...	(M)	-3.13	13
	G13	11.34	1.08	0.22	11.31	1.68	4.25	1.02	0.20	0.06	0.185	M2	-4.40	8, 13
	G14	11.59	1.07	0.22	11.56	1.58	4.20	1.01	0.20	0.08 (3)	0.15 (3)	(M)	-4.17	13
	G30	10.50	1.74	0.67	10.47	2.26	5.45	1.68	0.65	0.165	-0.01	C	-4.96	10, 13
	G32	11.10	1.09 (4)	0.24	11.07	1.71	4.75	1.03	0.22	...	...	M4	-4.62	3, 8, 13
	G40	11.74	1.03	0.20	11.71	1.9:	4.0	0.97	0.18	0.06 (3)	0.145	M1	-4.09	4, 8, 13
	G108	12.13	1.01	0.17	12.10	1.49	3.64	0.95	0.15	...	...	(M)	-3.74	13
N1841	G95	12.97	0.82	0.14	12.95	...	...	0.78	0.13	...	...	(M)	-3.27	14
	G113	12.59 (4)	0.86	0.21	12.57	...	...	0.82	0.20	...	...	(M)	-3.57	9, 14
	G117	12.23	0.84	0.16	12.21	...	...	0.80	0.15	...	...	(M)	-3.97	14
	G129	13.65 (3)	0.78 (3)	0.14 (3)	13.63	...	...	0.74	0.13	...	...	(M)	-2.66	14
	G142	12.69 (3)	0.86	0.15	12.67	...	...	0.82	0.14	...	...	Ctm	-3.38	14
	H1301	13.64 (3)	0.72 (3)	0.16	13.62	0.89	3.0	0.68	0.15	...	...	F8	-2.79	8, 22
	H2413	13.84 (3)	0.70 (3)	0.13 (3)	13.82	1.03	3.1	0.66	0.12	...	...	wkG	-2.62	8, 22
N1844	H12	12.82 (4)	0.57 (4)	0.13 (4)	12.79	0.99	1.62	0.51	0.11	...	...	G0	-3.99	5, 8, 15
	H14	12.35 (3)	0.70 (3)	0.15 (3)	12.32	0.95	1.69	0.64	0.13	...	...	F8	-4.18	5, 8, 15
N1846	H1	11.28 (5)	1.38	0.45	11.25	1.65	4.34	1.32	0.43	0.145 (3)	0.115 (3)	C	-4.41	6, 16
	H38	12.78 (3)	0.91	0.16	12.75	1.17	2.99	0.85	0.14	...	...	K3	-3.32	7, 8, 16
	H58	11.93	1.03	0.19	11.90	1.42	3.59	0.97	0.17	...	...	K5	-3.90	8, 16
N1978	H2-16	12.70	0.92	0.13	12.67	1.68	3.02	0.86	0.11	...	...	K0	-3.38	8, 17

TABLE 2—*Continued*

Cluster	Star[a]	Observed[b] K	Observed[b] J−K	Observed[b] H−K	Reddening Corrected K_0	Reddening Corrected $(B-V)_0$	Reddening Corrected $(V-K)_0$	Reddening Corrected $(J-K)_0$	Reddening Corrected $(H-K)_0$	Reddening Corrected H_2O	Reddening Corrected CO	Type[c]	M_{bol}[d]	Notes
N2173	H1401	12.48 (3)	1.06 (3)	0.21	12.46	1.47	3.5	1.02	0.20	...	...	K5	-3.25	4, 8, 22
	H4306	13.59 (3)	0.85 (3)	0.12 (3)	13.57	1.24	2.9	0.81	0.11	...	...	K3	-2.59	8, 22
	H45A	13.78 (3)	0.88 (4)	0.29 (3)	13.76	...	...	0.84	0.28	...	...	(M)	-2.33	18
	star A	11.28	1.14	0.24	11.26	...	...	1.10	0.23	...	...	(M)	-4.36	19
N2193	H2201	11.30	1.11	0.23	11.27	1.38	4.3	1.05	0.21	0.15 (3)	0.215	M4	-4.40	4, 8, 22
	H1307	14.27 (4)	0.82 (4)	0.18 (4)	14.24	1.21	3.2	0.76	0.16	...	...	M2	-2.01	8, 22
	H4303	11.04	1.14	0.25	11.01	1.50	4.8	1.08	0.23	0.08 (3)	0.27 (3)	M5	-4.62	4, 8, 22
N2209	W46	10.48	1.60	0.57	10.46	2.74	5.69	1.56	0.56	0.16	0.035	C,4	-5.03	20
	W50	10.08	1.84	0.72	10.06	2.93	6.69	1.80	0.71	0.21	-0.005	C,3	-5.32	20
N2257	H4503	12.28	0.99 (3)	0.16	12.26	1.31	4.03	0.95	0.15	...	...	K0	-3.58	8, 21, W72
	H4621	13.45 (4)	0.74 (4)	0.12 (4)	13.43	...	...	0.70	0.11	...	...	(M)	-2.94	
	H4709	12.07	1.00 (3)	0.18	12.05	1.93	4.06	0.96	0.17	...	...	K0:	-3.76	8, 21, W79
	C27	12.88	0.91 (4)	0.15	12.86	1.36	3.2	0.87	0.14	...	...	K0:	-3.16	8, 14, 22
	H62	12.86 (3)	0.82	0.13	12.84	...	...	0.78	0.12	...	...	(M)	-3.38	14

[a]With the exceptions indicated in the Notes column, the star identification numbers are from one following sources: N419, Arp 1958; N1651 and N1652, Hesser, Hartwick, and Ugarte 1976; N1783, Gascoigne 1962; N1841, four digit numbers are from Hesser, Hartwick, and Ugarte 1976; N1884, Hodge 1961; N1846, Hodge 1960*a*; N1978, Hodge 1960*b*; N2173 and N2193, Hesser, Hartwick, and Ugarte 1976; N2209, Walker 1971; N2257, four digit numbers are from Hesser, Hartwick, and Ugarte 1976.

[b]When uncertainties are greater than ± 0.02, they are given in parentheses in units of hundredths of a magnitude.

[c]Spectral types from Las Campanas (Table 3, this paper) are indicated by an 8 in the Notes column. (M) denotes that the star was judged to be a non-carbon star on the basis of its colors as described in the text. The remaining types are from Mould and Aaronson 1979, 1980.

[d]The bolometric magnitudes are derived as discussed in the text. They are based on $(m-M)_0=18.6$ (Gascoigne 1972) and 19.1 for the LMC and SMC, respectively.

NOTES

(1) Reference beam corrections of $\Delta K=-0.27$ and $\Delta(J-K)=0.13$ were applied.
(2) Reference beam correction of $\Delta K=0.22$ was applied.
(3) Infrared photometry from Las Campanas only.
(4) *JHK* measurements are averages of CTIO and Las Campanas.
(5) Observed on CTIO 1.5 m.
(6) *K* magnitude corrected by -0.09 for star in reference beam.
(7) *K* magnitude corrected by -0.05 for star in reference beam.
(8) Spectrum from Las Campanas (Table 3, this paper).
(9) *K* magnitude corrected by -0.04 for star in reference beam.
(10) Also observed by FPC.
(11) *BV* photometry from Walker 1972*b*.
(12) *BV* photometry from Arp 1958*a*; star 6-1 is from central region of cluster; no *BV* values were given, but Arp says it lies above cluster giant branch.
(13) *BV* photometry from Gascoigne 1962. G40 is variable with $\Delta V=0.8$.
(14) Identification by Gascoigne communicated to the authors by Mould and Aaronson.
(15) *BV* photometry from Hodge 1961.
(16) *BV* photometry from Hodge 1960*a*.
(17) *BV* photometry from Hodge 1960*b*.
(18) On Hesser, Hartwick, and Ugarte's 1976 finding chart, this star is located 59 mm to the S and 3 mm E of the center.
(19) This star is one of three bright stars in cluster center. The other two were too close together to measure.
(20) *BV* photometry from Walker 1971.
(21) *BV* photometry from Walker 1972*a* or from Gascoigne as quoted by Walker. Both may be small amplitude variables.
(22) *BV* photometry is from Table 3, this paper. The uncertainties are ± 0.2 and ± 0.15 mag in V and $B-V$, respectively.

TABLE 3

SPECTROPHOTOMETRIC DATA FOR LMC CLUSTER STARS

Cluster	Star	Spec.	V[a]	(B-V)[a]	(V_r)[b]
N1652	H3210	K3	16.2	1.44	neg
	H2406	K3	16.5	1.59	neg
N1783	G13	M2	...	...	...
	G32	M4	...	...	...
	G39	M0	...	...	M
	G40	M1	...	...	M
N1841	H1301	F8	16.8	0.96	neg
	H2413	wkG	17.1	1.10	neg
	H4410	wkG	17.4	0.91	neg
	H2608	F8	15.9	0.55	neg
N1844	H12	G0	...	...	315
	H14	F8	...	...	290
N1846	H38	K3	...	...	M
	H39	K5	...	...	neg
	H58	K5	...	...	M
N1978	H1-14	K0	...	...	M
	H1-25	C	...	...	...
	H2-16	K0	...	...	M
N1984	W16	K0	...	...	275
	W46	M2	...	...	255
N1994	W7	K3	...	...	260
	W31	K0	...	...	275
N2004	B5	G8	...	...	315
	B31	K0	...	...	270
	C19	K0	...	...	290
N2100	W30	M0	...	...	250
	W34	K3	...	...	280
	W57	K3	...	...	265
N2121	H1301	wkG	17.7	0.87	neg
	H1420	K0	16.7	1.19	neg
N2173	H1401	K5	16.2	1.54	M
	H1403	K3	16.9	1.07	neg
	H4304	K0	16.8	1.09	M
	H4306	K3	16.7	1.31	M
N2193	H2201	M4	15.9	1.48	neg
	H1307	...	17.8	1.31	...
	H4303	M5	16.1	1.57	M
N2210	H2306	F8	15.9	1.39	M
N2257	H4503	K0	...	...	M
	H4709	K0:	...	...	M
	C27	K0:	16.3	1.43	M

[a] V, B-V derived from spectrophotometry have uncertainties of ± 0.02 and ± 0.25, respectively, and are given only when no published values are available.

[b] Numerical values of the radial velocity are given only when the uncertainty is ± 20 km s^{-1} as determined from 2 Å resolution data. For the 4 Å data, M implies $170 \leq V_r \leq 350$ km s^{-1}, neg implies $V_r < 170$.

The column headed "Type" lists the spectroscopically determined types for the stars from Mould and Aaronson (1979), MA80, or this paper. All of the stars with no spectroscopy were judged to be oxygen rich giants by use of simple criteria to be described later.

c) *Spectrophotometry*

Spectrophotometric observations for many of the LMC cluster stars in the infrared sample were obtained with the Shectman pulse-counting intensified reticon detector at the Du Pont telescope of the Las Campanas Observatory in 1979 December. These spectra in most cases cover 3600 to 6200 Å with 4 Å resolution. For the brightest stars, scans were obtained covering 4300 to 6000 Å with 2 Å resolution. The spectra, to be discussed in detail elsewhere, were used here to obtain rough spectral classifications based on the precepts of Keenan and McNeill (1976). No account of abundance effects arising from the low mean metallicity of the LMC was made. All of the spectral types so determined are given in Table 3. The spectral types of the K stars are particularly uncertain, especially those which were observed at high dispersion where many of the commonly used absorption features with $\lambda < 4300$ Å were not included in the scans. Radial velocities were also measured and are listed in Table 3 as "M" if V_r was between 170 and 350 km s^{-1}, and "neg" if V_r was between -50 and 170 km s^{-1}. Unfortunately, these velocities are not sufficiently precise to distinguish LMC field stars from members of the LMC clusters. Radial velocities accurate to ± 20 km s^{-1} obtained from the high dispersion scans are listed in Table 3. It is interesting to note the good agreement of V_r among supposed members of the five clusters with high dispersion data. NGC 1652, 1841, and 2121 appear to have large negative radial velocities with respect to the mean of the LMC stars, not too suprising for clusters far from the LMC bar (or we have observed in these clusters exclusively galactic stars, a statistically rather remote possibility).

That there exists an old spheroidal population in the LMC analogous to the globular clusters and halo stars in the Milky Way is given added support by the observed large range in radial velocity found for the LMC cluster system.

The scans were obtained on photometric nights with good seeing through a square aperture 2 arcsec on a side when the objects were within 2 hours of the meridian and were guided with an integrating Quantex television system viewing the entrance apertures. Therefore, we have derived BV colors and magnitudes by integrating the response function from Matthews and Sandage (1963) across the low dispersion spectrophotometric scans, correcting the wavelength response of the detector using flat field calibration scans, by observing stars with known $B-V$ colors made on the same nights, and standard air-mass corrections. These values are listed in Table 3 only if no published photographic or photoelectric photometry exists as we judge the accuracy to be only ± 0.25 and ± 0.2 mag in $B-V$ and V, respectively.

III. A COMPARISON OF THE CLUSTER STARS WITH FIELD STARS: THE CARBON STARS

In this section and the next we will compare the infrared colors, magnitudes, and indices for Magellanic Cloud cluster C and M stars with those for the field stars which have been discussed in CFPE. In § V*c* we will deal specifically with the stars from NGC 2257 and 1841. The data of Table 2 are supplemented by those of MA80 and FPC.

a) *Colors and Indices*

Energy distributions of the cluster C stars as characterized by their JHK colors (*Fig. 1*) *are quite similar to those of the Magellanic Cloud field C stars* (*CFPE*). In particular, the magnitude of the separation between the galactic and Magellanic Cloud cluster C stars is essentially the same as that between the galactic and Large Magellanic Cloud field C star samples, the $(J-H)_0$, $(H-K)_0$ relationship for the cluster C stars may well be dispersionless as it appears to be for the field C stars, and the cluster C stars extend to as red a color as do the field C stars. (The mean line for Magellanic Cloud field C stars is from CFPE.)

Only C stars have $(H-K) \gtrsim 0.4$ (Fig. 1) in agreement with CFPE (their Fig. 2; there is one exception in that figure). Thus, the redder C stars can be unambiguously identified as such from infrared colors alone, as was also noted in MA80. However, for $0.2 < (H-K)_0 < 0.4$ the situation is more complex; Figure 2 of CFPE and Figure

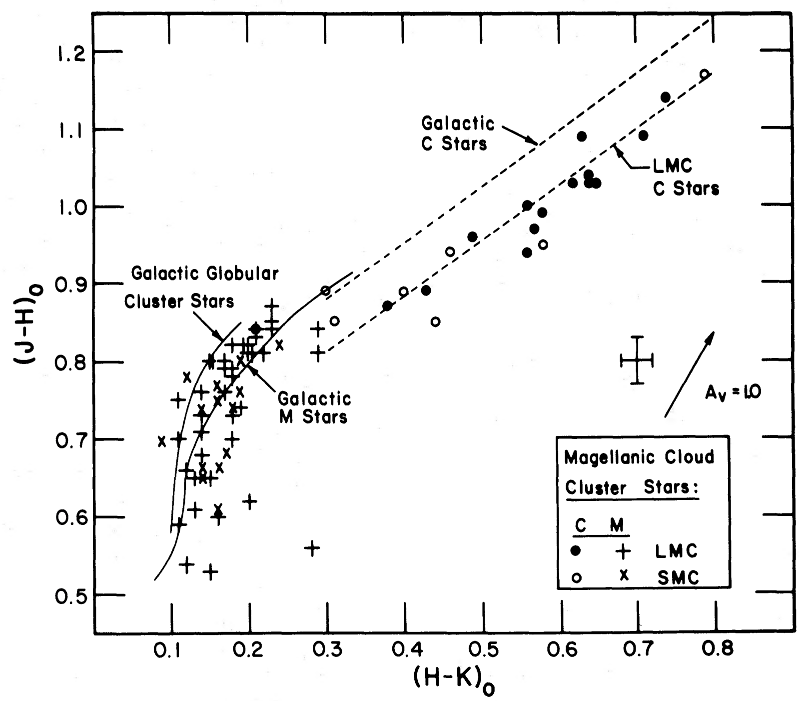

FIG. 1.—Reddening corrected JHK colors for Magellanic Cloud cluster stars from Table 2, from FPC, and from MA80. The sources for the various mean relationships are noted in the text. A reddening vector and typical error bars are shown.

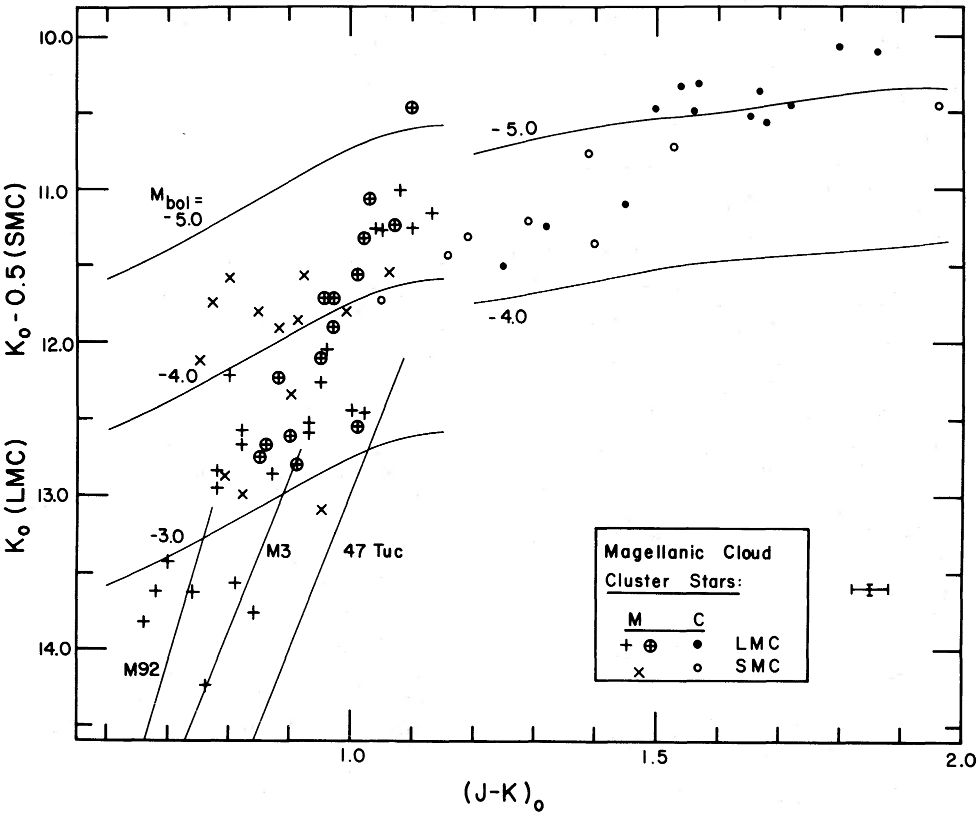

FIG. 2.—A color-magnitude diagram for Magellanic Cloud cluster stars with sources as noted for Fig. 1. Lines of constant M_{bol} (based on $J-K$ as discussed in FPC) are drawn in for C stars on the right and M stars on the left. $(m-M)_0=18.6$ and 19.1 for the LMC and SMC, respectively, were used. Fiducial giant branches for the galactic globulars are from CFP and Frogel, Persson, and Cohen 1981. The circled pluses are LMC M stars from clusters which also contain C stars.

1 here show approximately equal numbers of C and M stars in this regime. Nevertheless, of the stars in Table 2 without optical spectral classification, all but one have $(H-K)_0<0.25$. Since very few of the spectroscopically classified C stars are this blue, we feel confident in placing all of the unclassified stars of Table 2 in the M group rather than the C group.

The H_2O and CO indices as function of $(J-K)_0$ for the LMC cluster C stars from Table 1 and FPC are indistinguishable from their counterparts in the LMC field (Figs. 4 and 6 of CFPE) and will not be discussed further here.

b) *The Color-Magnitude Relation*

A color-magnitude diagram for all Magellanic Cloud cluster stars with infrared data from MA80 and Table 2 is presented in Figure 2. The SMC data have been made brighter by 0.5 mag in K_0 since we use $(m-M)_0=18.6$ and 19.1 for the LMC and SMC, respectively. Lines of constant for M_{bol} for C stars (right hand side) and M stars (left hand side), are indicated. They were calculated from the mean relations between the bolometric correction (BC_K) and $(J-K)_0$ given by FPC.[3] Fiducial giant branches for three globular clusters (Frogel, Persson, and Cohen 1981; Cohen, Frogel, and Persson 1978, hereafter CFP) are also shown. The 47 Tuc giant branch does not include the large amplitude variables V1–V4, which are probably asymptotic giant branch (AGB) stars.

The C stars in Figure 2 appear to define a color-luminosity relation with rather small dispersion at a *given color* in contrast to the rather large scatter in K_0 at constant $(J-K)_0$ for the field carbon stars drawn from

[3]We have chosen not to list effective temperatures for the stars observed. For the carbon stars, it is unlikely that they can be derived from the data available (cf. discussion in CFPE). For the M stars, $V-K$ is the best color from which to determine T_{eff}, but the necessary data are either not available or are of rather poor quality. $J-K$ can be used to determine T_{eff} via the calibration in CFP, but the reader should keep in mind that for the coolest stars, significant uncertainties may be introduced in the calibration because of small blanketing effects on the $J-K$ colors as discussed in the Appendix to Frogel, Persson, and Cohen (1981).

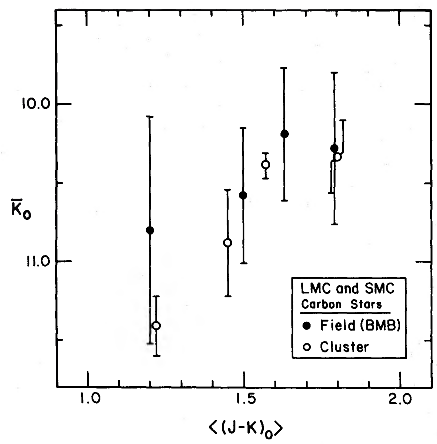

FIG. 3.—Carbon stars samples from the LMC and SMC BMB fields (CFPE) and from the clusters (sources noted in Fig. 1) were divided into quartiles in $(J-K)_0$. The mean K_0 magnitudes and dispersion for each quartile (SMC values adjusted by -0.5) are plotted at the median value of the $(J-K)_0$'s.

the Blanco, McCarthy, and Blanco (1980, hereafter BMB) samples in Figure 7 of CFPE. This result is quantified in Figure 3 where we have divided the cluster and BMB field C star samples into quartiles in $(J-K)_0$, computed the mean K_0 and dispersion for each quartile, and plotted the resulting values at the median values of $(J-K)_0$. (The mean and the median values of K_0 for both samples are essentially the same). Carbon stars from the LMC and SMC have been lumped together in both samples after the K_0 magnitudes of the SMC stars were adjusted by -0.5 mag. Although there are certain obvious biases in both samples, the data show similar distributions over $(J-K)_0$ and, in view of the large dispersion attached to the field points, no significant difference in dependence of K_0 on $(J-K)_0$.[4] The main result to be drawn from Figure 3 is that *the dispersion in magnitude in the cluster sample is* 2–3 *times less than in the field sample drawn from the BMB survey alone*. In view of the still small sample of Magellanic Cloud cluster C stars the significance of this result should be investigated further.

c) The Luminosity Function

Is the sample of Magellanic Cloud cluster C stars in this paper, in MA80, and in FPC an unbiased sample? For the brighter stars, the answer is almost certainly yes, since for all clusters surveyed we observed the brightest stars. For the fainter stars, we are somewhat less certain. Our technique, and presumably that of Mould and Aaronson as well, was for clusters with C-M diagrams available, to march down the giant branch in a fairly unselective manner, although always scrutinizing the very reddest stars, and observing those stars that were uncrowded. In each cluster of the three samples under discussion, the faintest C star at K_0 is, with one exception, brighter than the brightest M star observed in the cluster. Thus, if a significant number of faint C stars have been missed, we have the impression that they would not form a sequence continuous with the ones we have observed.

Figure 4 displays the summed luminosity function for the LMC and SMC cluster C stars as a solid line. The

[4]Since the stars selected from the BMB sample for observation in the infrared are biased toward the redder and brighter ones, correction for this effect would tend to improve the agreement between the two samples in Fig. 3, but would increase the dispersion still further.

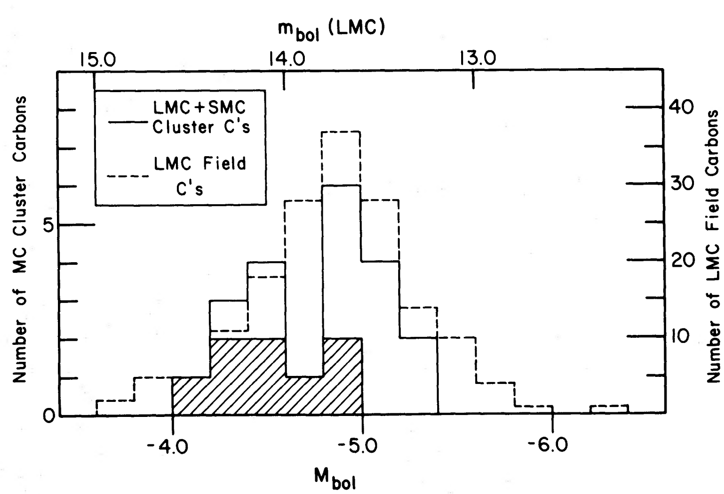

FIG. 4.—The luminosity function for SMC and LMC cluster carbon stars (*left-hand scale*) is compared with the luminosity function for LMC field carbon stars from CFPE (*right-hand scale*). The contribution of the SMC clusters alone to the former luminosity function is indicated by the shaded area. The SMC observations are from MA80.

SMC cluster contribution is represented by the hatched area. Also shown is the luminosity function of LMC carbon stars observed in the BMB fields (CFPE). This is the luminosity function of an unbiased sample of stars of type C, 2 and later and is essentially indistinguishable from the SMC field luminosity function. The mean bolometric magnitude and 1 σ dispersion of the 21 LMC plus SMC cluster C stars is -4.76 and 0.36, consistent with the first estimate by FPC. The values for the 164 LMC field C stars (Table 7 of CFPE) are -4.85 and 0.43. Thus, in spite of the apparent differences displayed in Figure 3, *the luminosity function of Magellanic Cloud cluster carbon stars has a mean magnitude and a dispersion close to the values for the LMC and SMC field carbons*. If we consider the SMC and LMC cluster C stars separately, however, the means and dispersions are -4.53 (0.27) and -4.92 (0.33), respectively. This difference is significant at the 99% level only if we consider the number of stars involved. If we consider the number of clusters from which the stars were selected, the more relevant number, the difference is not significant.

IV. THE CLUSTER M STARS

a) The Colors and Magnitudes

Unlike the carbon stars, the cluster M stars are different from their field counterparts observed by CFPE. All but two of the cluster M stars from Table 2 here, from FPC, and from MA80 have $K_0 \geq 11.0$ and $(J-K)_0 \leq 1.1$ (Fig. 2). On the other hand, 17 out of 20 of the Magellanic Cloud field M stars (Fig. 7 in CFPE) have $K_0 \lesssim 11.0$ and $(J-K)_0 \gtrsim 1.1$. We note that in Figure 1 there are only four cluster M stars with $(H-K)_0 > 0.25$ or $(J-H)_0 > 0.85$. For the Magellanic Cloud field M stars, on the other hand (Fig. 2 of CFPE), again all but three of 20 are redder than $(H-K)_0 = 0.25$. Thus with only a few exceptions, *the cluster M stars are fainter and bluer than the field M stars which have been observed*. Recall that the BMB sample of M stars from which those observed by CFPE were drawn include only those of type M6 and later. Thus, while the reddest and brightest field M stars appear to have no counterparts in the cluster observed to date, it is most likely true that field counterparts of the cluster M stars can be found.

In Figure 2 the brightest and reddest M stars tend to be from the LMC rather than from the SMC. The majority of stars in both groups, though, have luminosities greater than those of the tips of the giant branches of galactic globular clusters. These latter, empirical luminosities are consistent with theoretical predictions for the location of the helium flash marking the end of a star's first ascent of the giant branch. Thus, *most of the Magellanic Cloud cluster M stars in our sample must be on the asymptotic giant branch*. This result is independent of the fact that the galactic globulars are older than most of the Magellanic Cloud clusters since the luminosity of the He flash is predicted to *decrease* with increasing stellar mass (e.g., Sweigart and Gross 1978).

In the $(J-H)_0$, $(H-K)_0$ plane (Fig. 1), the redder cluster M stars tend to lie between the mean relationships for galactic M stars (Frogel *et al.* 1978) and that for late-type globular cluster giants (CFP; Frogel, Persson, and Cohen 1981). The latter relationship appears to be applicable to globular clusters of metallicities ranging from 47 Tuc to M92. The bluer Magellanic Cloud cluster M's show somewhat more scatter, but tend to lie to the red (in $H-K$) of the relations for the galactic field and globular cluster giants. These results differ somewhat from those of MA80, presumably because the sample of Magellanic Cloud cluster M's with *JHK* photometry is now nearly three times larger than their sample.

The upper end of the M star luminosity distribution overlaps to a considerable extent the lower half of the cluster C star luminosities. However, as was mentioned above, *in clusters where there are both C and M stars, the faintest C star is with one exception (NGC 1651), brighter than the brightest M star*.

b) The CO *and* H_2O *Indices*

Although the CO indices of the LMC cluster M stars show a considerable amount of scatter when plotted against $(J-K)_0$, the agreement between the observed CO index and the mean for a given spectral type (Frogel *et al.* 1978) is reasonably good. A plot of CO index versus K_0 (Fig. 5) suggests that the scatter in CO could just reflect a rather wide range in luminosity over a limited range in color (i.e., spectral type).

The H_2O indices of the LMC cluster M stars tend to be weaker than those of galactic M stars at the same $(J-K)_0$ but are quite similar to those of galactic globular cluster stars (e.g., CFP; Frogel, Persson, and Cohen 1981).

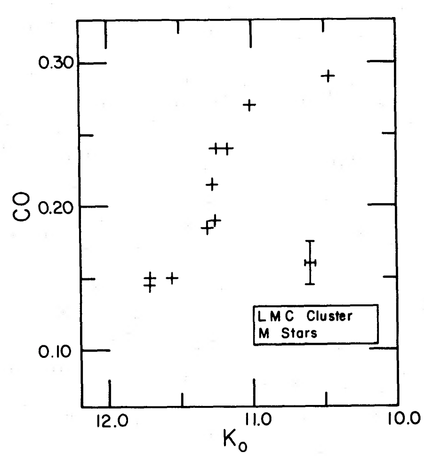

FIG. 5.—The CO index plotted against K_0 for the LMC cluster M stars with data from Table 2 and FPC.

V. DISCUSSION

a) *The Carbon Stars*

We have shown that the color distribution and the luminosity function of the carbon stars in the LMC and SMC clusters are quantitatively similar to those for carbon stars in the field of the Magellanic Clouds. Thus, the detailed discussion and comparison with galactic C stars given by CFPE will not be repeated here. We reiterate, though, one of CFPE's main conclusions, namely that the distributions over broad and narrow band infrared colors and that the small differences in the domains occupied by C star samples from the Galaxy, the LMC, or the SMC in color–color plots can largely be understood as due to the effects of blanketing by carbon bearing molecules and by the dependence of these molecular abundances on the mean metallicities of the three galaxies.

One apparently significant difference between the Magellanic Cloud cluster and field C stars is the fact that the dispersion in magnitude at a given $(J-K)_0$ for the cluster C stars is less than half of that for the field stars. We propose that this is a natural consequence of the smaller spread in age and/or metallicity among the clusters as compared with the field stars which make up the BMB sample.

Let us accept for the moment that the basic scheme for producing C stars proposed by, inter alia, Sackmann, Smith, and Despain (1974), Iben and Truran (1978), Iben (1981), and Renzini and Voli (1981) is correct. In this scheme, an oxygen rich giant with hydrogen and helium burning shells and a carbon core turns into a carbon rich giant when helium shell flashes have mixed up an adequate amount of carbon enriched material to the surface layers. For a given metallicity, the luminosity at the first thermal pulse increases significantly as the mass increases (see, for example, Renzini and Voli 1981); so we expect the luminosity at which the transition from an M to a C star occurs to increase with mass also. Furthermore, at a given mass, the transition luminosity decreases as the initial metallicity is lowered. Combining this evolutionary scheme with the discussion of CFPE on the effect of C bearing molecules on *JHK* colors, we would expect to observe the following: Given a sequence of cluster giant branches in a *C-M* diagram and given that these clusters have physical parameters (specifically the age and metallicity) which will allow them to produce carbon stars, then the C stars from each cluster should define a sequence in the *C-M* diagram which is, to first order, at redder colors and brighter magnitudes than that of the M stars and which becomes redder as luminosity increases. For clusters with a small range in age and metallicity, we expect both narrow M giant branches and little scatter in the C star sequences as well. It is easy to verify that the *C-M* diagram of Figure 2 is consistent with this hypothesis. A considerable part of the width of the M star distribution in $(J-K)_0$ at constant K_0 is due to the inclusion of clusters which contain no C stars (e.g., NGC 1841 and 2257) and to the fact that the SMC M stars tend, in the mean, to lie to the blue of the LMC C stars. The LMC M stars from clusters which also have C stars, circled in Figure 2, have relatively little scatter about some mean giant branch. It is likely that as the cluster sample is increased, the scatter will increase as well; but clearly the ultimate size of the scatter will be a measure of the mass range (i.e., age) of the carbon stars.

Thus, we suggest that the field C stars (CFPE) are drawn from a population having a considerably wider spread in age and/or metallicity than the clusters in the sample which contain both C and M stars. Without considerably improved quantitative predictions from carbon star models and model atmosphere calculations to predict carbon star colors, however, we cannot describe in detail how a particular point in the M star domain of Figure 2 gets mapped into the C star domain and how it subsequently moves within the C star realm.

In the clusters studied to date (FPC; MA80; this paper) with only one exception, the faintest C star is brighter than the brightest M star in the same cluster. This is clearly required by the evolutionary picture outlined above. As we have just noted, this scheme implies that the luminosity of the boundary between C and M stars will be a function of stellar mass (or age) and composition. Searle, Wilkinson, and Bagnuolo (1980) have argued that age and metallicity variations in Magellanic Cloud clusters are highly correlated. They have proposed a ranking sequence along which both age and metallicity vary uniformly and monotonically. Figure 6 shows that a straight average of the K magnitude of the brightest M star and faintest C star (for clusters which have only M's [C's] we use the magnitude of the brightest [faintest]) and the type assigned to the cluster by Searle, Wilkinson, and Bagnuolo's (1980) one parameter ranking scheme appear to be correlated (the magnitudes for the SMC stars have been made brighter by 0.5 mag). Since Figure 6 is based on a rather limited sample of clusters, additional data are needed to investigate the correlation further; a well defined relation between transition luminosity and an independently determined age and/or metallicity parameter would be useful in refining carbon star models.

b) *The M Stars*

The SMC cluster M stars are observed to be bluer in $(J-K)_0$ than the LMC cluster M's at the same K_0. The maximum bolometric luminosities, though, of the two samples of M stars are quite similar (see Fig. 2). The former result would obtain if the difference in the mean metallicities of the SMC and the LMC clusters reflected the difference between the clouds as a whole. Model tracks of asymptotic giant branch stars (which most of

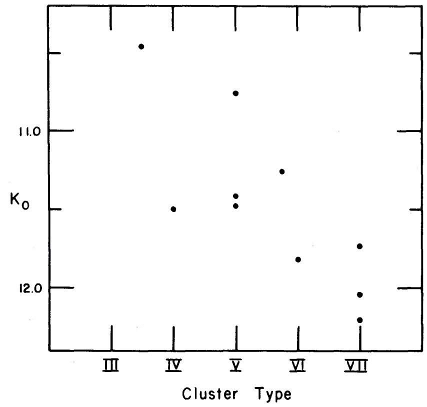

FIG. 6.—The cluster type is from the classification of Searle, Wilkinson, and Bagnuolo 1980. K_0 is a measure of the transition luminosity between C and M stars as discussed in the text.

the MC M stars in Fig. 2 must be because of their luminosity) predict that they will evolve at nearly constant temperature once they get brighter than the tip of the first giant branch (e.g., Gingold 1974). Thus, if the mean age difference between the LMC and SMC clusters in the present sample is small (less than a few $\times 10^9$ yr)[5], one would expect the SMC cluster stars to be at higher temperatures, i.e., to be bluer, than the LMC stars because of their lower metallicity, as is seen for first ascent red giants in globular clusters of differing metallicities. This effect is also expected to contribute to the almost complete absence from the SMC of stars M5 and later as found by the survey results of BMB. Hagen and van den Bergh (1974) and Harris and Dupree (1976) have also proposed that metallicity differences among the SMC, LMC, and the Milky Way can account for color differences which they find to exist among massive red stars in the three systems.

With only few exceptions, the reddest and most luminous M stars found in the clusters studied so far are significantly fainter and bluer than the red, luminous M giants found in BMB's survey (CFPE). Since the luminosity of an asymptotic giant branch stars depends primarily on its core mass (Paczynski 1971), and since a large core mass implies, to first order, a younger age, the luminous field M stars must come from a component of the field population which is younger and probably more metal rich than that represented by the cluster sample. This result is consistent with the conclusion of the previous section concerning the relative age and metallicity spreads of the cluster and field carbon star population. Whether or not such luminous M stars can be found in as yet unstudied LMC clusters would be a useful piece of information for tracing the evolution of the stellar population of the Magellanic Clouds. It would be particularly valuable to determine whether such clusters contain any carbon stars.

A survey currently underway of LMC and SMC clusters by Blanco and Frogel with a transmission grating prism at the prime focus of the CTIO 4 m telescope will presumably deal with many of the questions raised here.

c) *NGC 1841 and NGC 2257*

The LMC clusters NGC 1841 and 2257 resemble metal poor galactic globular clusters (e.g., Gascoigne 1966; Walker 1972*a*; Hesser, Hartwick, and Ugarte 1976; Searle, Wilkinson, and Bagnuolo 1980). In this section we compare infrared color-magnitude diagrams of these clusters with those for galactic globulars.

An apparent difference between the two LMC clusters and galactic globulars is apparent from Fig. 7. Data for NGC 1846 and 1783, two clusters which are quite similar to one another and most likely younger than galactic globulars (e.g., Hesser, Hartwick, and Ugarte 1976; Searle, Wilkinson, and Bagnuolo 1980) are shown for comparison. A number of stars in NGC 1841 and 2257 have luminosities brighter than the observed tips of M3 and M92. We emphasize that these observed galactic tip luminosities are in close agreement with predicted maximum luminosities that should be achieved by low mass, metal poor stars on their first ascent of the giant branch (CFP; Frogel, Persson, and Cohen 1980*b*).

What can be said about the cluster membership of the bright stars in NGC 1841 and 2257? The two brightest

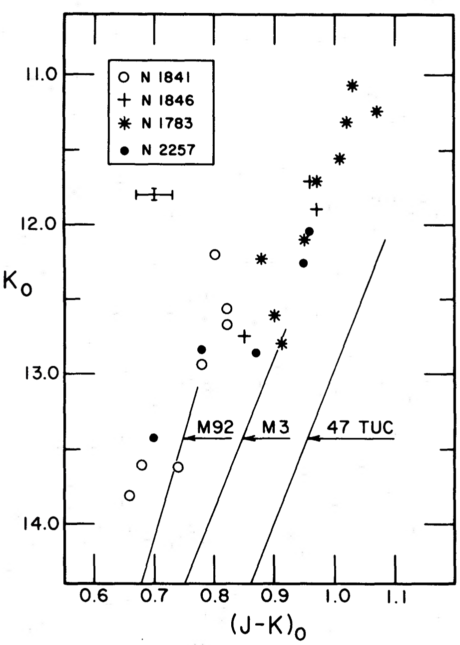

FIG. 7.—The same as Fig. 2 except only M stars from four LMC clusters from Table 2 and FPC are plotted.

[5]That this is in fact the case is suggested by the fact that the LMC and SMC clusters with the most M stars in Fig. 2 are members of the same or immediately adjacent groups in the classification scheme of Searle, Wilkinson, and Bagnuolo (1980).

stars in each of these clusters lie within 1′.5 of the cluster centers, and both clusters lie in relatively uncrowded fields approximately 15°.2 and 7°.7 from the center of the LMC, respectively. Furthermore, the two brightest stars in N2257 both appear to be variables (Gascoigne, quoted by Walker 1972*a*) typical of those found on the upper giant branches of galactic globular clusters. Thus, it seems likely that the stars under discussion are indeed members of NGC 1841 and 2257.

The application of the mean LMC distance modulus to these clusters may not be correct in view of the large angular distances of both clusters from the center of the LMC. Hesser, Nemec, and Ugarte (1980) find that the B magnitudes of the RR Lyrae variables in and around NGC 2257 imply that the cluster lies about 9 kpc (≈ 0.4 mag) closer to us than do the field variables studied by Graham (1977) around NGC 1783 and assumed to be representative of the LMC as a whole (Walker's 1972*a* horizontal branch V magnitudes, on the other hand, suggest that NGC 2257 is only 0.1 mag (2 kpc) closer than Graham's 1977 variables). Furthermore, we must apply a 0.2 mag correction to our adopted LMC distance modulus, i.e., use $(m-M)_0=18.4$, to make Graham's (1977) mean V magnitude for the RR Lyrae variables with 0.2 mag of extinction have a $M_{V_0}=+0.6$ as was used for M3 and M92.

Adopting 18.4 mag and Hesser, Nemec, and Ugarte's (1980) differential value for NGC 2257 removes the discrepancy between the luminosities of the NGC 2257 giants and those in galactic globular clusters and produces good correspondence between the NGC 2257 giant branch and that of M3.

NGC 1841 appears to be behind the main body of the LMC, as both Gascoigne (1966) and Kinman, Stryker, and Hesser (1976) find that the apparent luminosity of the horizontal branch and RR Lyraes in NGC 1841 is 0.3 mag *fainter* than Graham's (1977) RR Lyrae values. Thus, even by using $(m-M)_0=18.4$ for the LMC, the giants in NGC 1841 become 0.1 mag brighter still after both corrections are made.

In a feature by feature comparison of strong lines in the two NGC 1841 stars with infrared photometry and spectrophotometry, J. G. Cohen (in preparation) finds that the metal abundance of NGC 1841 is close to that of M3. Similarly, for three stars in NGC 2257, she finds a metal abundance slightly higher than that of NGC 1841, but still close to that of M3. For both clusters, though, the abundance is much less than that of 47 Tuc as determined from stars of the same temperature, i.e., the same infrared colors. Thus if the NGC 1841 stars in Figure 7 had colors appropriate to the M3 giant branch, which they do not, the luminosity discrepancy would be large for only one star. The color difference between the M3 and M92 giant branches in Figure 7 corresponds to a $\Delta \log T_{\rm eff}$ of 0.02 (CFP; Frogel, Persson, and Cohen 1981). Such a shift could be accounted for only with unreasonably large differences in the helium abundance ($\Delta Y \geq 0.1$) or the age ($\geq$ a factor of 2) between NGC 1841 and M3 (or NGC 2257 with its revised distance modulus as calculated above).

To summarize, if we base the absolute distances to NGC 1841 and 2257 on the same RR Lyrae scale as is used for galactic globulars, then the luminosity and colors of giants in NGC 2257 are just consistent with those for giants in M3, a cluster of similar metallicity. However, the brightest giants in NGC 1841 are brighter than the tips of the M3 and M92 giant branches. While it is possible that the most discrepant star is a nonmember, the problem of the bluer color of the NGC 1841 giant stars remains unresolved.

VI. SUMMARY

Infrared photometry is now available for cool giants in 12 clusters in the LMC and six in the SMC. Spectroscopic and photometric classification criteria have shown that six of the LMC clusters and five of the SMC clusters contain carbon stars. The conclusions we have reached in this paper may be summarized as follows:

1. The bolometric luminosity function of the carbon stars in the clusters has a mean $M_{\rm bol}=-4.76$ and a dispersion of 0.36. These values are closely similar to corresponding values for the luminosity functions of field carbon stars in both the LMC and SMC.

2. The 1.2–2.2 μm energy distributions of the cluster and field C stars are also quite similar, while both samples differ by a small but significant amount from galactic field C stars.

3. At a given $(J-K)_0$, the cluster carbon stars have a much smaller dispersion in K_0 than do the field carbon stars. If we were to take into account the biases that have gone into the selection of the field sample, this difference in dispersion would be enhanced.

4. Surveys of fields in the LMC have revealed a population of M stars which are significantly redder and more luminous than any found in the LMC clusters. The M stars in the LMC clusters, in turn, are redder, on average, than the M stars in the SMC clusters. Most of the cluster M's, though, have luminosities expected for stars in the asymptotic giant branch-double shell burning stage of evolution.

5. With only one exception, in clusters where there are both C and M stars, the faintest C star is brighter than the brightest M star.

6. NGC 1841 is usually regarded as a "true" Magellanic Cloud analog of a metal poor galactic globular cluster. Our spectroscopic data is indeed compatible with a metallicity for NGC 1841 close to that of M3. Yet no reasonable amount of fudging with the distance modulus to NGC 1841 can remove the following fact: its brightest giants are significantly brighter than the

brightest stars in M3, which suggests some fundamental difference between the two clusters.

Points 1–3 have been interpreted as arising from a smaller range in metallicity and age in the cluster sample than in the field samples. In particular, the field samples contain stars (the late M's) which come from a population younger and/or more metal rich than the clusters studied to date. These points, taken together with point 4, are qualitatively consistent with a scheme for carbon star production via mixing caused by helium shell flashes during a star's ascent of the asymptotic giant branch. However, a detailed comparison between theory and observation reveals the same serious discrepancies which we have discussed previously (CFPE).

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