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THE EXTENDED GIANT BRANCHES OF INTERMEDIATE AGE GLOBULAR CLUSTERS IN THE MAGELLANIC CLOUDS. III.

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ABSTRACT

We report on the latest findings of a photographic near-infrared survey of the red globular clusters in the Magellanic Clouds for upper asymptotic giant branch stars. New infrared (JHK) photometry for some 80 cluster stars is also presented. These results combined with earlier data are used to derive age estimates for a nearly complete sample of Cloud clusters having $M_v < -7$. The age distribution of clusters in the Large Cloud, which shows a pronounced peak at $t \sim 4$ Gyr, may be different from that in the Small Cloud. This peak could be a result of luminosity evolution of clusters, however, and a constant rate of cluster formation in the Large Cloud cannot be ruled out. A cluster age–metallicity relation clearly exists in the Large Cloud, although the degree of scatter about this relation is somewhat uncertain and may be significant.

Subject headings: clusters: globular — galaxies: Magellanic Clouds — photometry — stars: carbon — stars: evolution — stars: late-type

I. INTRODUCTION

Determination of the ages of the star clusters of the Magellanic Clouds holds the key to understanding the star formation history and the chemical enrichment history of these dwarf galaxies. As indicated in previous papers in this series (Mould and Aaronson 1980; Aaronson and Mould 1982—Papers I and II, respectively), the extension in luminosity of the upper asymptotic giant branch is a monotonic function of age for clusters in the 10^8-10^{10} year range, an age span which is of vital interest for the study of the evolution of galaxies.

The extension of the asymptotic giant branch (AGB) can therefore be used directly with a theoretical calibration from stellar evolutionary models to estimate cluster ages—assuming that evolutionary and mass-loss rates are the same function of physical parameters in the Clouds as in the Galaxy. Alternatively, as main-sequence turnoff ages for a few Cloud clusters become available, an empirical calibration can be constructed of the more readily obtainable data on the AGB tip.

The immediate aim of the present series of papers is a photometric survey of the upper AGB in a sample of Cloud clusters complete to integrated absolute magnitude $M_v < -7$. In this paper we present the latest results of the photographic survey of these clusters (§ II) and report photometry for a significant fraction of the remaining upper AGB sample (§§ III, IV). In §§ V and VI we discuss the age distribution of the clusters and the age-metallicity relation in the Magellanic Clouds.

II. THE PHOTOGRAPHIC SURVEY

Two nights of 1″–2″ seeing with the CTIO 4 m Ritchey-Chrétien camera have approximately doubled the number of clusters surveyed for upper AGB stars. At this point the survey is nearly complete, within the limits $B-V>0.35$, $M_{V_t}<-7$. There are five such clusters in the SMC and two in the LMC unphotographed from van den Bergh's (1981) compilation.[3] For clusters appreciably fainter ($M_{V_t}>-7$), whether stars are found on the upper AGB is to some extent a matter of chance rather than cluster age (see Paper II and § V).

Table 1 lists the clusters photographed on this occasion. Plate sensitizing and exposure times were the same as we used previously (Paper II). Red stars were selected

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[2]KPNO and CTIO are operated by AURA, Inc., under contract with the National Science Foundation.

[3]We include in this tally clusters photographed by Lloyd-Evans (1980). Stars in his color classes 1–5 tend to be upper AGB stars ($M_{bol}<-4$). Photometry of stars down to class 3 yields a virtually complete sample of stars with $M_{bol}<-4.5$. Note also that the absence of magnitude estimates in the cluster list of Shapley and Lindsay (1958) makes it hard to know whether the van den Bergh list is complete to the required limit in the LMC.

TABLE 1

CLUSTERS SURVEYED FOR RED STARS

Cluster	Red Stars	Area (Sq. min)	Field (in 16 sq min)	Notes
NGC 152	5	5.1	1	1,3
NGC 339	1	6.3	1	2
L1	2	7.9	0	3
L11	2	7.9	0.5	3
L27	2	2.7	5	3
K3	4	9.8	0.5	3,4
NGC 1644 ...	0	3.5	0	
NGC 1651 ...	3	6.3	0	2,6
NGC 1754 ...	0	3.5	0	2
NGC 1786 ...	0	3.5	1	
NGC 1830 ...	1	1.6	0	3
NGC 1835 ...	1	1.6	0	2
NGC 1872 ...	4	3.1	3	3
NGC 1917 ...	3	1.6	7	2,3
NGC 1953 ...	1	1.6	1	3
NGC 2005 ...	0	1.6	...	
NGC 2133 ...	0	1.6	1	3
NGC 2134 ...	2	2.4	1	3,7
NGC 2209 ...	4	6.3	1	2,3,5
SL 506	0	1.6	0	
IC 2146.......	0	3.5	0	

NOTES.—(1) Hodge 1982; (2) Lloyd-Evans 1980; (3) See Fig. 1; (4) Walker 1970; (5) Walker 1971; (6) From the 4 stars noted by Lloyd-Evans 1980, 4325 fails to meet the present criteria; (7) Stars 3 and 4 in Fig. 1 are outside the formal boundary of the cluster.

on the same criteria, complete to a fixed color and limiting *I* magnitude and within a characteristic cluster radius judged on the *V* plates. Information on the red star density in the clusters and their adjacent fields is given in Table 1. The photographs are reproduced in Figure 1 (Plates 10–13) for clusters in which red stars were found. In clusters which have been studied previously (especially Lloyd-Evans 1980), we have adopted already assigned star numbers to avoid duplication.

III. INFRARED PHOTOMETRY

Photometry in the *JHK* bandpasses was obtained for as many of the survey stars as possible (§ 2; Paper II; Lloyd-Evans 1980) over the period 1981 October 12–15. As before, we used the CTIO InSb detector system at the f/30 Cassegrain focus of the 4 m telescope. The large scale and generally good seeing combine to unique advantage for photometry in difficult cluster fields. With care and with appropriate calibration it was possible to use apertures as small as 3″6 where necessary. In good seeing (and small apertures were generally not used except in good seeing), the correction to the standard aperture size was 10%. This correction was checked whenever small apertures were required and found to be constant under appropriate seeing conditions. Further details of the observing technique were given in Paper II.

Table 2 records the *JHK* magnitudes of 78 stars in 25 clusters on the standard system of Frogel *et al.* (1978). These stars are shown in the $(J-H, H-K)$ two-color diagram in Figure 2. Stars with spectral types from the sources noted in Table 2 are identified in this diagram. Ten stars in Table 2 have previous photometry obtained at CTIO. The rms difference between the new data and previous values is 0.07 at K, 0.10 at $J-K$, and 0.04 at $H-K$, which lends support to the argument in Paper II that the Cloud AGB cluster stars do not vary greatly in the infrared. The long red tail in the *JHK* diagram is populated exclusively by carbon stars, hence "photometric carbon stars" were able to be identified as in Paper II and are given in parentheses in Table 2. This allows us to identify three new clusters with carbon stars—Lindsay 11, NGC 1953, and NGC 2121. NGC 2134 is not among these, as star 4 is outside the adopted cluster radius (Table 1). Spectroscopic confirmation of these and other photometric carbon stars is very desirable. This is especially true of stars near the transition point (indicated with queries in Table 2) where Bessell, Wood, and Lloyd-Evans (1982, BWLE) have succeeded in finding MS stars.

Among these photometric carbon stars is the reddest star observed to date in the Magellanic Clouds, NGC 419-LE 16. As indicated in Paper II, if we remove NGC 419 from the sample, the SMC carbon stars tend to be the bluer ones in the *JHK* diagram, although Cohen

TABLE 2

PHOTOMETRY, LUMINOSITIES, AND TEMPERATURES OF MAGELLANIC CLOUD STARS

Cluster	Star[a]	Alternate Name	K[b]	J - K	H - K	Spectral Type	Source[c]	m_{bol}	M_{bol}	log T_{eff}	Notes
					Small Magellanic Cloud						
NGC 152	1		11.56	1.16(4)	0.35(4)	(C??)		14.35	-4.95	3.501	
	2		12.36	1.05(4)	0.29(4)	(?)		15.27	-4.05	3.551	
	3		10.98	1.60(5)	0.60(4)	(C)		14.10	-5.20	3.420	1
	4		12.18	0.96(5)	0.21(4)			14.95	-4.35	3.575	1
NGC 339	LE 1	G 87	12.05	1.01	0.19	MO	1	14.85	-4.45	3.565	2
	LE 2		13.03	0.91(4)	0.17			15.65	-3.65	3.591	
	LE 4		13.19	0.87(4)	0.14(04)			15.75	-3.55	3.600	1
	G 151		11.34	1.37	0.47	C,3	1	14.25	-5.05	3.464	2
NGC 419	LE 16		10.68	2.57(4)	1.18	(C?)		14.0:	-5.3:	3.35:	
	LE 18	BR6	11.02(4)	1.96(5)	0.80(4)	C	2	14.20	-5.10	3.385	3,4,5
	LE 25	A6-5	11.16(6)	1.35(6)	0.46(6)	(C)		14.10	-5.20	3.464	3
	A4-133	BR 7	11.76	1.14(4)	0.29	C	2,3	14.60	-4.70	3.494	2,4
L 1	G 64		12.87	0.87	0.11	Ctm	3	15.45	-3.85	3.595	2
	1		12.76	0.89	0.14			15.35	-3.95	3.595	1
	2		13.36	0.82(4)	0.14			15.80	-3.50	3.612	1
	3		12.20	0.95	0.15			14.90	-4.40	3.578	
	4		13.13	0.86	0.22	(?)		15.65	-3.65	3.603	
	5		13.25	0.47(4)	0.12			14.95	-4.35	3.728	6
L 11	1		11.21	1.61(4)	0.61	(C)		14.35	-4.95	3.418	
	2		11.64	1.35(4)	0.47	(C)		14.60	-4.70	3.464	7
	3		12.92	0.80	0.14			15.30	-4.00	3.618	
L 27	1		12.27	1.01(4)	0.28(4)	?		15.15	-4.15	3.559	
	2		12.32	0.96(4)	0.19(4)			15.05	-4.25	3.575	
K 3	W24		11.78	1.19	0.40	C	3	14.75	-4.55	3.469	2
	1	A25	12.28	1.14	0.34	C	6	15.30	-4.00	3.522	
	2	A26	12.74	0.88	0.12	K	6	15.30	-4.00	3.597	
Reddening	Correction		-0.01	-0.01	0.						
					Large Magellanic Cloud						
NGC 1751	LE4		11.44(4)	1.14(5)	0.20(5)	?		14.40	-4.30	3.528	
	LE5		11.59	1.10(4)	0.23(4)			14.50	-4.20	3.541	
NGC 1783	LE1		10.15	1.83	0.73	C	4	13.35	-5.35	3.394	7
	LE2	G7	11.26	1.07(4)	0.23	MS	4,6	14.20	-4.50	3.541	8
	LE4	G32	11.15	1.10(4)	0.24	MS	3,5,6	14.05	-4.65	3.541	8
	LE5		11.23	1.08(4)	0.23	M	4	14.15	-4.55	3.548	1
	LE7	G14	11.66	1.02(4)	0.18			14.50	-4.20	3.558	8
	LE8		11.57(5)	1.03(5)	0.19(5)			14.40	-4.30	3.559	3
	LE11		11.55(5)	1.04(5)	0.17(5)			14.40	-4.30	3.558	3
NGC1806	LE4		11.59	1.04(4)	0.20			14.45	-4.25	3.558	1
	LE5		11.05	1.03(4)	0.19			13.90	-4.80	3.559	
NGC 1841	LE1		12.71	0.83(4)	0.18	Ctm	4	15.10	-3.60	3.615	
NGC 1846	LE8		11.23	1.08	0.24	M 2-3	6	14.15	-4.55	3.548	
	LE11		10.62(5)	1.34(5)	0.43(5)	(C?)		13.55	-5.15	3.469	1
	LE15		11.54	1.04	0.19			14.40	-4.30	3.558	
	LE17		11.85	1.08	0.26			14.75	-3.95	3.548	
NGC 1852	2		12.25	0.98(4)	0.21(4)			15.00	-3.70	3.575	9
NGC 1872	1		10.95	0.97(4)	0.19(4)			13.65	-5.05	3.578	
	2		11.09	1.29(4)	0.32(4)	??		14.15	-4.55	3.48:	
	3		11.42	1.01(4)	0.21(4)			14.20	-4.50	3.565	
	4		11.96	1.02(4)	0.19(4)			14.80	-3.90	3.561	
NGC 1917	LE1		11.35	1.09(4)	0.24	?		14.25	-4.45	3.545	
	LE2		11.56	1.06(4)	0.22			14.45	-4.25	3.553	
	LE3		11.60	1.02(4)	0.23			14.40	-4.30	3.561	1
	LE4		12.35	1.05(4)	0.22			15.20	-3.50	3.556	
NGC 1953	LE1		13.10(6)	0.48(6)	0.15(6)			14.75	-3.95	3.73:	3
	LE2		11.92(6)	1.09(6)	0.22(6)			14.85	-3.85	3.545	3
	3		11.07(6)	1.30(6)	0.43(6)	(C?)		13.95	-4.75	3.477	1,3
NGC 1978	LE6		10.59	1.23(4)	0.37(5)	(C??)		13.40	-5.30	3.491	10
	LE8		12.04	1.07(4)	0.20(4)			14.95	-3.75	3.551	
	LE9		12.36	1.06(4)	0.20(4)			15.25	-3.45	3.553	
NGC 2019	2		12.31	1.04(4)	0.17(4)			15.15	-3.55	3.559	5
NGC 2121	LE1		11.80	1.07	0.22			14.70	-4.00	3.551	
	LE2		11.53	1.08	0.23	?		14.45	-4.25	3.548	
	LE4		12.28	1.02	0.20			15.10	-3.60	3.561	
	LE5		11.66	1.04	0.20			14.50	-4.20	3.558	
	LE6		10.13	2.14	0.96	(C)		13.40	-5.30	3.373	11
NGC 2133	1		11.94	1.08(4)	0.22(4)			14.85	-3.85	3.548	

TABLE 2—*Continued*

Cluster	Star[a]	Alternate Name	K[b]	J − K	H − K	Spectral Type	Source[c]	m_{bol}	M_{bol}	log T_{eff}	Notes
NGC 2134	1		9.94	1.19	0.28	?		12.95	-5.75	3.512	12
	2		10.43	1.07(4)	0.23(4)	?		13.35	-5.35	3.551	
	3		8.57	1.20(4)	0.37(4)	?		11.60	-7.10	3.509	13
	4		10.48	1.72(4)	0.65(4)	(C)		13.65	-5.05	3.406	13
	5		13.10	0.45(4)	0.12(4)			14.70	-4.00	3.74:	
NGC 2173	LE1		11.21	1.15(4)	0.25	M	4	14.20	-4.50	3.524	
	LE4		12.12	0.92(4)	0.16			14.70	-4.00	3.593	
	LE5		12.30	0.99(4)	0.21(4)			15.05	-3.65	3.572	
NGC 2190	LE3		12.45	1.04(4)	0.22(4)			15.30	-3.40	3.558	
NGC 2209	LE3	HHU 4533	11.83	1.08(4)	0.21(4)			14.75	-3.95	3.548	
	5	HHU 4502	12.38	1.03(4)	0.20(4)			15.25	-3.45	3.559	
	W9		-	(0.47)	-			15.55	-3.15:	-3.74:	14
NGC 2257	LE4		>12.71	0.73(4)	0.15(4)			>14.90	>-3.80	3.64	15
	LE11	HHU 1617	12.25	0.79(4)	0.15(4)			14.60	-4.10	3.625	
Reddening	Correction		-0.02	-0.03	-0.01						

[a]Numbers standing alone are identifications assigned in this paper (Fig. 1) or in Paper II. References for other star names are given in Papers I and II and Lloyd-Evans (1980).

[b]Observed values, uncorrected for reddening. Errors larger than 0.03 mag are given in parentheses in hundredths of a magnitude.

[c]Sources from spectral types are: (1) Mould and Aaronson (1980); (2) Blanco and Richer (1979); (3) Mould and Aaronson (1979); (4) Lloyd-Evans (1980); (5) Frogel and Cohen (1982); and (6) Bessel, Wood, and Lloyd-Evans (1982).

NOTES:
1. Crowded field.
2. Star also measured in Paper I. Mean results used to calculate M_{bol} and log T_{eff}.
3. Seeing poor.
4. Star also observed by BWLE.
5. Star also measured in Paper II; mean results used to calculate M_{bol} and log T_{eff}.
6. Possible foreground star?
7. Star far from cluster; possible nonmember.
8. Star also measured by FC; mean results used to calculate M_{bol} and log T_{eff}.
9. Star 1 also observed in very poor seeing; it does not appear to be a carbon star.
10. Unsteady signal at H.
11. A $K - L$ color of 0.86(10) was measured.
12. Star 1 measured twice during the course of the run; separate results at K, $J - K$, and $H - K$ were 9.93, 1.18(4), 0.29 mag and 9.95, 1.20(4), 0.27(4) mag.
13. Compact cluster; probable nonmember.
14. H = 13.96, $J - K$ = 0.40(4). Results derived from mean JHK relation.
15. Beam probably contaminated by other objects.

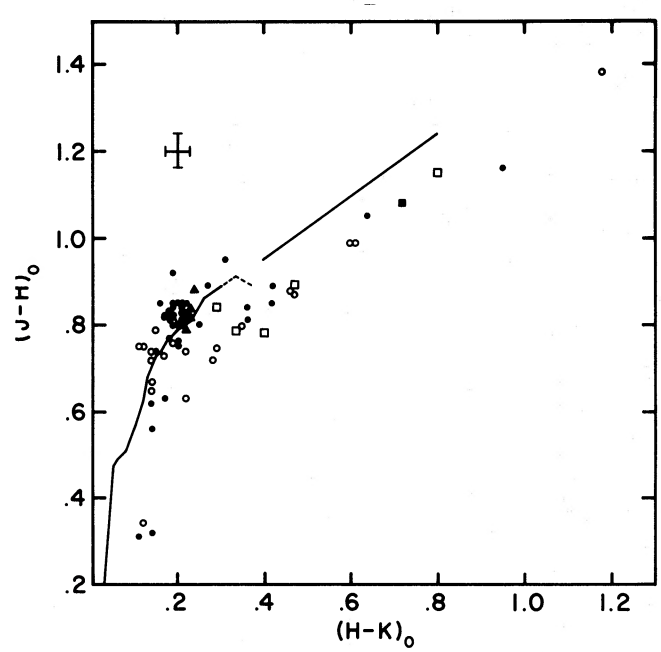

FIG. 2.—A *JHK* two-color diagram for stars from Table 2. Fitted symbols are LMC, open are SMC stars. *Squares*: *spectroscopic* carbon stars; *triangles*: *spectroscopic* M stars; *circles*: unclassified spectroscopically. Mean photometric uncertainties are shown by the error bar. The polygonal curve is the standard two-color relation for Galactic K and M stars. The straight line is the locus of Galactic carbon stars from Cohen *et al.* 1981.

et al. (1981) have commented that our sample size was too small. However, our observation does make sense when one looks at the age distribution of Cloud clusters (Paper II and below): the strong peak at age $\sim 4 \times 10^9$ years of LMC clusters with the reddest, most luminous carbon stars is missing in the Small Cloud. Figure 2 does tend to confirm the observation by Cohen *et al.* that SMC stars are slightly bluer in $J-H$ at a given $H-K$, as one might expect if CN blanketing were dominant at J and K (BWLE), and if primordial nitrogen abundances were lower in the Small Cloud (see also Mould *et al.* 1982). But, of course, our sample size is rather too small for such fine distinctions.

IV. THE H-R DIAGRAM

Bolometric magnitudes and effective temperatures of the stars observed were calculated following the procedures of Paper II and are given in the right-hand columns of Table 2. Figure 3 is the resultant H-R diagram. From their location there, the majority of the program stars are clearly upper AGB stars, i.e., they are more luminous than stars at the tip of the first giant branch of galactic globular clusters. There are four stars in Figure 3 with $Te > 5000$ K. These were not selected as red stars from the survey criteria (§ II). They are among the stars (in parentheses in Fig. 1) photometered for completeness. It is possible to account statistically for these as Galactic foreground stars in terms of the models of Bahcall and Soneira (1980) and Gilmore and Reid (private communication). Spectra would be useful to verify this.

We draw attention to a number of clusters in which upper AGB stars are recognized here for the first time, and which may consequently be added to the list of intermediate age clusters in the Clouds, based on the extended AGB criterion ($M_{\rm bol} < -4.25$; $t_9 < 8$ Gyrs). These are Lindsay 11 and 27 in the SMC and NGC 1872, 1953, 2121, and 2134 in the LMC.

It is also interesting to note in Figure 3 that the SMC giant branches appear to form an extension of the lowest metallicity Galactic globular cluster giant branches, whereas the LMC clusters are distributed more toward the metal-rich giant branch tips. Since age is a very weak influence on the position of the giant branch in the H-R diagram (see Papers I and II), this effect is probably a result of the lower mean metallicity of intermediate age clusters in the SMC.

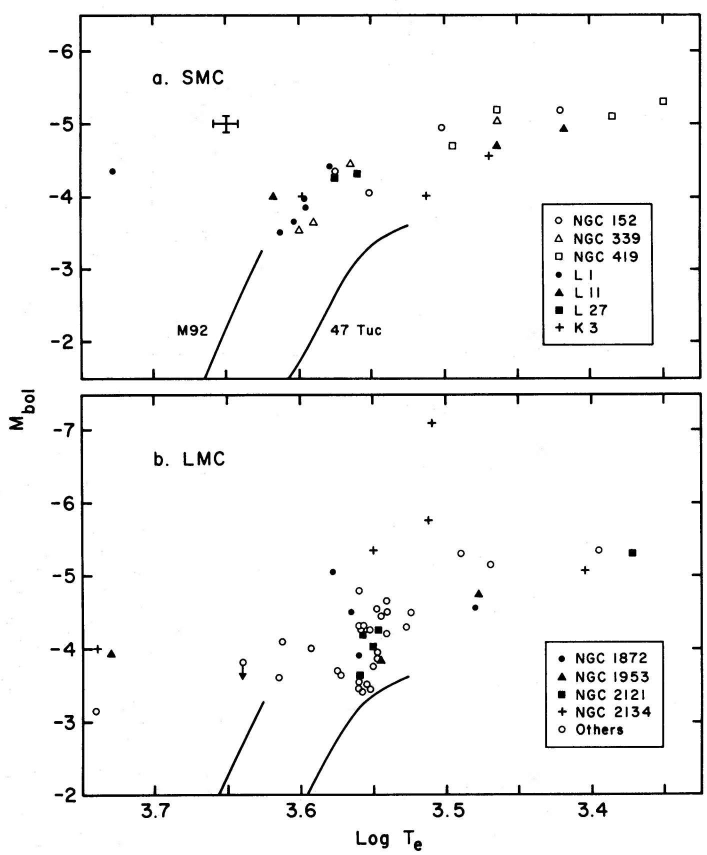

FIG. 3.—The physical H-R diagram for stars from Table 2 (*a*) from the SMC (*b*) from the LMC. The symbol key is shown in the boxes. The upper giant branches for two galactic globular clusters were derived as in Paper II.

V. CLUSTER AGES

The extent of the AGB above the tip of the first giant branch is a measure of the age of a cluster, relative to galactic globular clusters, in which this extent is essentially zero. The key assumption required to properly calibrate this effect is that an AGB star of a given *L*uminosity, *R*adius, and *M*ass has a unique mass-loss rate proportional to LR/M (Reimers 1975) whether in the Clouds or in the Galaxy. Strong limits have been derived on the composition dependence of mass-loss rates for low mass stars on the first giant branch by Renzini (1978).

In Paper II we derived such a calibration. A modified version is given in Table 3 following our detection of a numerical error in the original work. These results were calculated as described in Paper II for a composition $Z=10^{-3}$ (to which the results are rather insensitive) and a mass loss parameter, $\eta=0.45$. The latter value yields $M_{\mathrm{bol},f}=-3.5$ at $t_9=16$ Gyrs, to match galactic globular clusters. The mean difference between the calibration of Table 3 and the incorrect one in Paper II reaches 0.3 mag between 1 and 8 Gyrs. With $\eta=1/3$ the present results agree with those of Iben and Renzini (1982) within 0.1 mag. This value of η would not fit the giant branch tips of galactic globular clusters, but does allow direct comparison with Figure 7 of Iben and Renzini. Iben and Renzini also give a linear relation connecting $\log t$, $M_{\mathrm{bol},f}$, and η. The values in Table 3 are well fitted by this relation for ages between 0.5 and 8 Gyrs, but diverge at larger ages.

Table 4 summarizes all the information available on the luminosity of the AGB tip in the present cluster sample. The survey is photographically complete to the extent indicated in § II. However, eight clusters in the LMC (and one in the SMC) are missing from Table 4 for lack of infrared photometry. Four of these LMC clusters are probably without upper AGB stars: with this exception, the missing clusters are unlikely to bias the distribution very much. Cluster types from Searle, Wilkinson, and Bagnuolo (1980, SWB) are given in column (2). Column (3) gives the total V magnitude following Harris and Racine (1979) and van den Bergh (1981). The luminosity of the brightest star on the AGB ($M_{\mathrm{bol},m}$) is given in column (4), together with the corresponding upper limit on the cluster age (in Gyrs—column [5]). Two clusters are indicated as "old?", because $M_{\mathrm{bol},m}>-4.0$, but, as $M_{V_t}>-7$, there is a fair probability that the lack of upper AGB stars might arise in some cases by chance.[4] In eight cases it is possible to make statistical estimates of the true tip of the AGB following the methods of Paper II. These values and the corresponding cluster ages are given in columns (6) and (7) together with their respective uncertainties.

TABLE 3
AGE CALIBRATION

Age t_9 (Gyrs)	Luminosity $M_{\mathrm{bol},f}$ (mag)
0.5	−6.2
1	−5.9
2	−5.6
4	−5.2
8	−4.7
10	−4.5

If we can assume (an unproven hypothesis) that the SWB types of Cloud clusters are uniquely determined by their ages, the results in column (7) can be of assistance in calibrating the SWB classification scheme. The six type V clusters yield a mean age of 2.5 Gyrs. Given the *systematic* uncertainty in our age calibration of 0.2 dex (see Paper II), this result is consistent with the tentative estimate of 3–6.5 Gyr for the age range of type V clusters by Rabin (1982) from integrated spectroscopy. The above result is also consistent with an age estimate of 3 Gyr by Cohen (1982). The latter estimate is based on interpolation of very sparse data on cluster turnoffs (see Hodge's [1982] compilation), and should not be taken as strong support for our result.

Unfortunately, this is as much as we are able to offer in the way of independent calibration of the SWB scheme. We have two type IV and one type VI cluster, but their ages are not significantly different from the type V mean. If one adopts Rabin's (1982) calibration, this is not very surprising, given the quoted uncertainties.

VI. THE AGE DISTRIBUTION OF CLUSTERS

Figure 4 shows the distribution of maximum luminosity on the AGB over the sample defined in Table 4. The distribution of absolute magnitudes of the clusters is also indicated. If we adopt the age calibration of the AGB tip from Table 3, it is tempting to consider Figure 4 as a graphical description of the cluster formation rate in the Clouds. Lest inappropriate conclusions be drawn, we make the following cautionary remarks.

1) The data are binned in $M_{\mathrm{bol},m}$, which is expected to be fainter than $M_{\mathrm{bol},f}$ to which the age calibration applies. The difference is stochastic, but depends upon the absolute magnitude of the cluster. For clusters with $M_{V_t}<-7$, which is the intended completeness limit of the sample, the difference will generally be less than one bin, however. This has been verified in the numerical experiments described below.

[4] At $M_{V_t}=-7$ we estimate one or two stars will be present in a cluster of age ≈ 3 Gyrs with $M_{\mathrm{bol}}<-4.5$. For clusters of greater age the population of the upper AGB ($M_{\mathrm{bol}}<-4$) will decrease with the length of the AGB and with the turnoff rate ($\sim t^{-0.6}$). This decreased population at a given magnitude is offset by the evolutionary fading (increase in M/L) of the cluster. These factors tend to cancel, leaving the -7 limit reasonably suitable for all ages in the present sample.

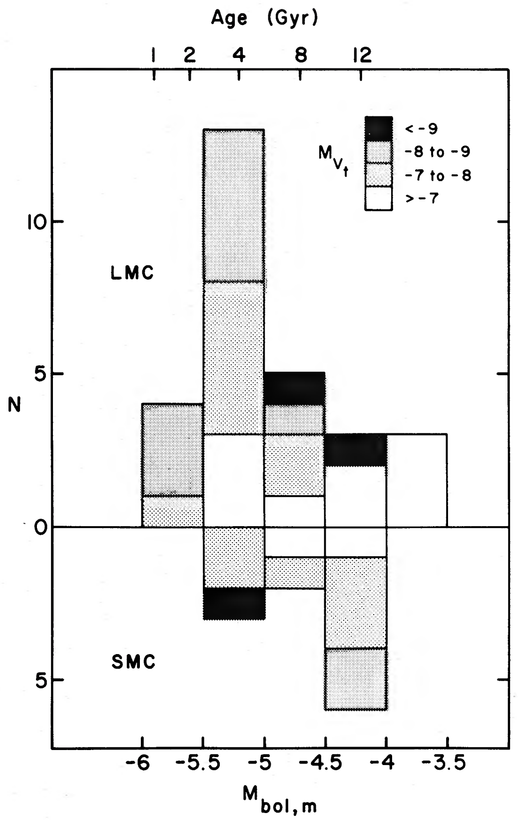

FIG. 4.—The distribution of maximum observed luminosity on the AGB for clusters from Table 4. LMC clusters are plotted upward and SMC clusters downward. The histogram is coded by the absolute magnitudes of the clusters as shown in the key (*upper right*). An age calibration of $M_{\mathrm{bol},m}$ is shown in units of 10^9 years.

2) Stellar evolution causes clusters to fade steadily over their lifetimes. The present sample is magnitude limited, and younger clusters would tend to dominate the sample, even if the cluster formation rate were uniform.

3) If Figure 4 could be "corrected" for the abovementioned effects, we would have the current age distribution of clusters, but not the cluster formation history. In our own Galaxy, disruption, presumably by tidal processes, has had a marked effect on the distribution of *open* clusters on timescales between 0.1 and 1 Gyr (van den Bergh 1982). Globular clusters are more tightly bound and hence less affected by these processes. However, the difference in tidal radii between the inner and outer clusters of the Galactic halo (Harris and Racine 1979) indicates that disruption may well have occurred of loosely bound globulars in the Galaxy. The lower masses of the Magellanic systems, of course, make tidal forces proportionally less, but it is unclear whether we can neglect their effect on this sample.

Although we refrained from drawing any such conclusion from the more limited sample of Paper II, it has been suggested that the strong peak in the $M_{\mathrm{bol},m} = -5.25$ bin of Figure 4 for the LMC might reflect the onset of the major epoch of star formation in the LMC detected in the main-sequence luminosity function by Butcher (1977) (see also Brück 1980 and Stryker 1981). Alternatively, could this peak correspond to a burst of star formation of the kind modeled for dwarf galaxies by Gerola, Seiden, and Schulman (1980)?

It should be clear from the preceding remarks that such hypotheses are not *required* by the present data. But it is interesting to ask a question from a more conservative standpoint: Are the present data consistent with a constant rate of cluster formation over the lifetime of the Clouds (and negligible destruction rate)?

To answer this question we have constructed simple models with the following additional assumptions: (1) luminosity evolution of clusters according to Tinsley (1972) with a Salpeter initial mass function for the stellar content; (2) a power law initial mass function for clusters *of the same form* as that assumed for stars by Tinsley (1972), with a similar slope parameter, x; (3) a high luminosity cutoff $M_{v,\mathrm{min}}(t)$ in this initial distribution which declines (logarithmically) with time. This seems to be required, though not physically understood, as there are no clusters as massive as NGC 121, formed in the last few Gyrs; (4) stellar evolutionary rates given by Renzini (1977) equations 2.5 and 6.18 and stochastic population of the upper AGB.

Not surprisingly, given the number of free parameters, it is possible to fit the LMC data with these assumptions and $0 \lesssim x \lesssim 2$, $M_{v,\mathrm{min}}$ (16 Gyr) ≈ -13, $M_{v,\mathrm{min}}$ (0.1 Gyr) ≈ -11. (These luminosity cutoffs are quoted for age 0.1 Gyr.) Results for a large sample (200 clusters scaled down to 20) are compared with the strictly complete ($M_v < -7$) data set in Figure 5. Evidently, the present results are not inconsistent with a constant cluster formation rate in the LMC over the past 16 Gyr. Furthermore, the model is not very sensitive to the assumed age of the LMC. A model with age 6 Gyrs will fit the data equally well (see Fig. 5). If cluster destruction is not important in shaping Figure 5, limits can be placed on the size of bursts of cluster formation within the very coarse time resolution available. For example, if the cluster formation rate had been double the mean rate in the interval 2–6 Gyrs, a significantly larger peak would be present in the LMC histogram.

More difficult to reproduce with this model, however, are the results for SMC clusters. Of course, the number of data points is small, but there is no peak due to evolution in the SMC distribution. Even with the optimum choice of parameters the steady cluster formation model will produce a distribution of 10 clusters with $n(-3.5 \text{ to } -4.5) > n(-4.5 \text{ to } -6)$ in less than 1% of trials. It seems that the cluster age distribution in the SMC may be different from that of the LMC.

A final comment in this section relates to the age of the Magellanic Cloud cluster system as a whole. The

TABLE 4

AGB TIPS AND CLUSTER AGES

Cluster (1)	SWB Type (2)	V_t (3)	$M_{bol,m}$ (4)	t_{9m}< (5)	$M_{bol,f}$ (6)	log t_f (7)	Notes (8)
NGC 121	VII	10.6	-4.35	11	-	-	1
152	IV	12.3	-5.2	4	-5.45±0.35	9.4 ±0.35	
339	VII	11.9	-4.45	10	-	-	
361	-	12.1	-4.45?	10	-	-	1
411	V-VI	11.5	-5.1	5	-	-	1
416	VI	11.0	-4.2	12	-	-	1
419	V	10.0	-5.4	3	-5.5 ±0.15	9.4 ±0.15	2
Lindsay 1	-	12.0:	-4.4	11	-	-	
11	-	13.3:	-4.95	6	-	-	
113	-	12.9	-5.0	6	-	-	1
27	-	12.9:	-4.25	12	-	-	
Kron 3	-	11.4	-4.55	9	-	-	
NGC 1651	-	11.9	-5.25	4	-	-	1
1652	-	12.4	-3.7	old?	-	-	1
1718	-	11.6	-5.4	3	-5.20±0.2	9.6 ±0.15	1
1751	V	11.4	-5.6	2	-5.75±0.45	9.15±0.4	
1783	V	10.3	-5.35	3	-5.25±0.25	9.6 ±0.15	3
1795	-	11.9	-3.95	old?	-	-	1
1806	V	10.6	-5.25	4	-5.4 ±0.35	9.5 ±0.2	
1831	V	10.5	-5.3	4			1
1841	VII	12.6	-4.05	13	-	-	3
1846	V	10.7	-5.25	4	-5.55±0.25	9.35±0.2	3
1852	-	11.5	-5.3	4	-5.60±0.4	-9.3 ±0.3	
1872	III-IV	10.3	-5.05	5	-	-	4
1916	-	9.4:	-5.05	5	-	-	1
1917	-	9.6	-4.45	10	-	-	
1953	-	11.0	-4.75	8	-	-	
1978	VI	9.9	-5.6	2	-5.55±0.35	9.35±0.3	3
1987	IV	11.5	-5.35	3	-5.65±0.45	9.25±0.35	1
2019	VII	10.6	≳ -4.75	~8	-	-	
2107	IV	10.8	-5.75	1.5	-	-	1
2121	VI	11.2	-5.3	4	-	-	
2134	IV	10.4	-5.75	1.5	-	-	4
2154	V	11.5	-5.3	4	-	-	1
2162	V	12.0	-4.3	11	-	-	1
2173	V-VI	11.6	-4.5	10	-	-	
2190	-	-	-5.35	3	-	-	5
2193	-	-	-4.7	8	-	-	3,5
2209	III-IV	12.8	-5.4	3	-	-	
2213	V-VI	11.7	-5.4	3	-5.35±0.3	9.55±0.2	1
2257	VII	13.5	-4.1	13	-	-	3
Hodge 11	VII	11.2	-3.4	old			1

NOTES:
1. No further photometry since Paper II.
2. Photometry of this cluster remains incomplete, with no results available for stars 24, 26, 36, and 39. Stars 16 and 4-133 are outside our adopted cluster radii. Photometry of stars 28 and 6-1 by BWLE indicates our cluster survey is not complete to M_{bol} = -4.5. Consequently we have used -5 as the base in the calculation of $M_{bol,f}$ rather than -4.5.
3. Photometry by Frogel and Cohen (1982) and Frogel, Persson, and Cohen (1980) included.
4. Brighter stars are outside the adopted cluster radii (see Table 1, Fig. 1).
5. We assumed V_t > 11.9.

coarse binning of the histograms we have been discussing conceals the emerging evidence that every Magellanic Cloud cluster in the $M_{V_t} < -7$ sample (with the exception of Hodge 11) has a giant branch which is extended relative to galactic globulars of similar metallicity. Of the famous "old" Magellanic Cloud clusters, NGC 121 was shown in Paper II to have an extended giant branch, NGC 1841 was similarly invested by Frogel and Cohen (1982), and NGC 2257 now appears to have a star (LE 11) with $M_{bol} = -4.1$. (Note that this star is rather distant from the cluster center.) Of this group only NGC 1466 remains. It is a disputed member of the cluster system (Cowley and Hartwick 1981). Rabin (1982) has reached a similar conclusion about NGC 1841 from Balmer line strengths, and points out that for a very metal-poor composition the horizon-

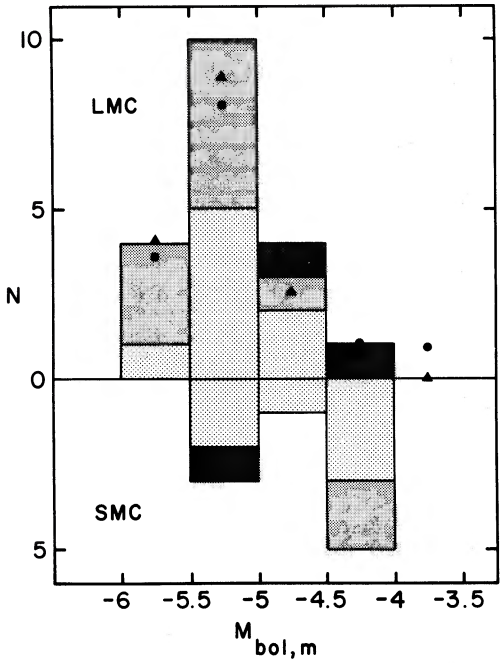

FIG. 5.—The sample plotted in Fig. 4 is restricted to clusters with $M_V < -7$. Solid symbols are the predictions of a model which assumes a constant rate of cluster formation (● for 16 Gyrs, △ for 6 Gyrs) and a zero rate of destruction; see text.

tal branch (which these clusters clearly have) may be able to absorb an age change of a few Gyrs before moving to the red.

Our present data suggest that the cluster system of the LMC (SMC) may be some 3 (5) Gyrs younger than that of the Galaxy. It is obviously of some importance to test the membership of the key stars in these clusters.

VII. CHEMICAL ENRICHMENT HISTORY

In Paper II we pointed out from preliminary results on the cluster system that the chemical enrichment history of the Clouds has been a much more gradual process than that of the Galaxy. In a sense the Magellanic Clouds have spent a lifetime reaching a chemical state which the Galaxy achieved during its first billion years (or possibly less). Indeed the Simple Model of chemical enrichment (see Pagel and Patchett 1975 for a review) seemed to provide a plausible fit to the Cloud cluster data.

Considerably more data are now available, principally quantitative metal abundances for LMC clusters from the analysis of individual red giants by Cohen (1982). In Figure 6 we show the relation between metallicity and age for the LMC clusters from Table 4 with metal abundances available from the review by Hodge (1982). We have taken the mean of spectroscopic results only in Hodge's Table 4. For NGC 1978 we have preferred Cohen's value of [M/H] = −0.5 to Hartwick and Cowley's (1982) −1.8 (see also Paper II). For those clusters where our ages are just upper limits, arrows give an indication of the probable range within which the true age lies.

Also shown in Figure 6 are the predictions of the Simple Model by Cohen (1982). This curve is an acceptable fit to the data; only NGC 1846 is more than 2 σ discrepant. However, there is a great deal of scatter, more scatter than Cohen has found using SWB types of clusters as an age indicator.

As indicated by the size of the error bars, we have not detected any intrinsic scatter about a monotonic age-metallicity relation for the LMC. Nonetheless, we insist that the present results are a useful check on the chemical enrichment history in the LMC, because the age estimates used here from the AGB tip have been shown (Paper II) not to be sensitive to metallicity at a significant level. Age and metallicity are determined independently. Cohen, however, explicitly assumes that clusters of the same SWB type have the same age, which is equivalent to assuming that a unique age-metallicity relation exists. If this assumption is *not* valid, clusters lying in those parts of the optical 2-color diagram where metallicity and age changes cause roughly parallel displacements will have their ages determined by "majority vote" rather than individually, leading to a compression of the deduced age-metallicity relation.

Comparison of the chemical enrichment histories of SMC and LMC must await abundance analyses of equal quality in the SMC.

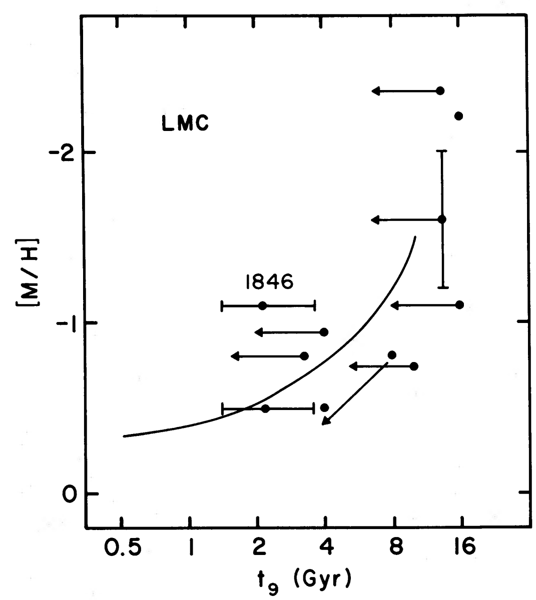

FIG. 6.—The age-metallicity relation in the LMC for clusters with [M/H] available from the compilation by Hodge (1982). The curve is a Simple Model of chemical enrichment shown by Cohen (1982). See text for the significance of the arrows.

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REFERENCES

Aaronson, M., and Mould J. 1982, *Ap. J. Suppl.*, **48**, 161 (Paper II).
Bahcall, J., and Soneira, R. 1980, *Ap. J. Suppl.*, **44**, 73.
Bessell, M., Wood, P. and Lloyd-Evans, T. 1982, M.N.R.A.S., in press (BWLE).
Blanco, V. M., and Richer, H. B. 1979, *Pub. A.S.P.*, **91**, 659.
Brück, M. T. 1980, *Astr. Ap.*, **87**, 92.
Butcher, H. R. 1977, *Ap. J.*, **216**, 372.
Cohen, J. G. 1982, *Ap. J.*, **258**, 143.
Cohen, J. G., Frogel, J. A., Persson, S. E., and Elias, J. H. 1981, *Ap. J.*, **249**, 481.
Cowley, A. P., and Hartwick, F. D. A. 1981, *A.J.*, **86**, 667.
Frogel, J. A., and Cohen, J. G. 1982, *Ap. J.*, **253**, 580.
Frogel, J. A., Persson, S. E., Aaronson, M., and Matthews, K. 1978, *Ap. J.*, **220**, 75.
Gerola, H., Seiden, P. E., and Schulman, L. S. 1980, *Ap. J.*, **242**, 517.
Harris, W. E., and Racine, R. 1979, *Ann. Rev. Astr. Ap.*, **17**, 241.
Hartwick, F. D. A. and Cowley, A. P. 1982, *Astrophysical Parameters for Globular Clusters*, eds. A. G. D. Philip and D. S. Hayes, (Schenectady: L. Davis Press), p. 245.
Hodge, P. 1982, in *Astrophysical Parameters for Globular Clusters*, ed. A. G. D. Philip and D. S. Hayes (Schenectady: L. Davis Press), p. 205
Iben, I., and Renzini, A. 1982, preprint.
Lloyd-Evans, T. 1980, *M.N.R.A.S.*, **193**, 87.
Mould, J., and Aaronson, M. 1979, *Ap. J.*, **232**, 421.
______. 1980, *Ap. J.* **240**, 464. (Paper I).
Mould, J. R., Cannon, R. D., Aaronson, M., and Frogel, J. A. 1982, *Ap. J.*, **254**, 500.
Pagel, B. E. J., and Patchett, B. E. 1975, *M.N.R.A.S.*, **172**, 13.
Rabin, D. 1982, preprint.
Reimers, D. 1975 in *Problems in Stellar Atmospheres and Envelopes*, ed. B. Baschek, W. H. Kegel, and G. Traving (Berlin: Springer-Verlag), p. 229.
Renzini, A. 1977, in Advanced States in Stellar Evolution, ed. P. Bouvier and A. Maeder (Sauverny: Geneva Observatory), p. 149.
______. 1978, in *Stars and Star Systems*, ed. B. E. Westerlund (Dordrecht: Reidel), p. 155.
Searle, L., Wilkinson, A., and Bagnuolo, W. 1980, *Ap. J.*, **239**, 803 (SWB).
Shapley, H., and Lindsay, E. M. 1958, *Irish Astr. J.*, **6**, 74.
Stryker, L. 1981, Ph.D. thesis, Yale University.
Tinsley, B. M. 1972, *Ap. J.*, **178**, 319.
van den Bergh, S. 1981, *Astr. Ap. Suppl.* **46**, 79.
______. 1982, *Pub. A.S.P.*, **93**, 712.
Walker, M. F. 1970, *Ap. J.*, **161**, 835.
______. 1971, *Ap. J.*, **167**, 1.

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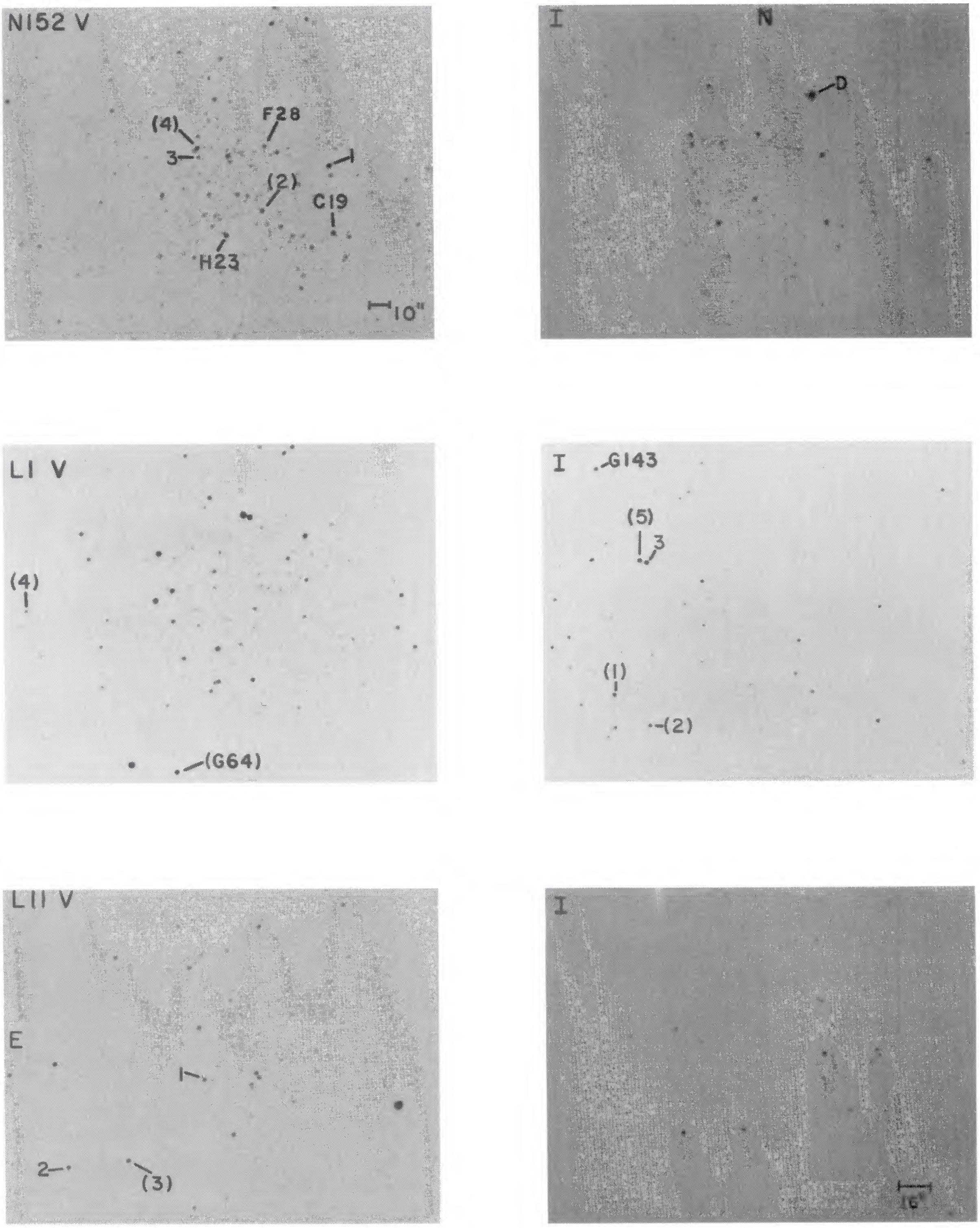

FIG. 1.—Enlargements of 4 m Ritchey-Chrétien photographs in the *V* and *I* bandpasses of Magellanic Cloud clusters. Red stars, selected as upper AGB stars, are indicated. Numbers in parentheses indicate objects for which photometry was obtained, but which were not selected as red. An object marked "D" is a plate defect. Scale and orientation are as indicated and the same for all charts.

MOULD AND AARONSON (*see* page 630)

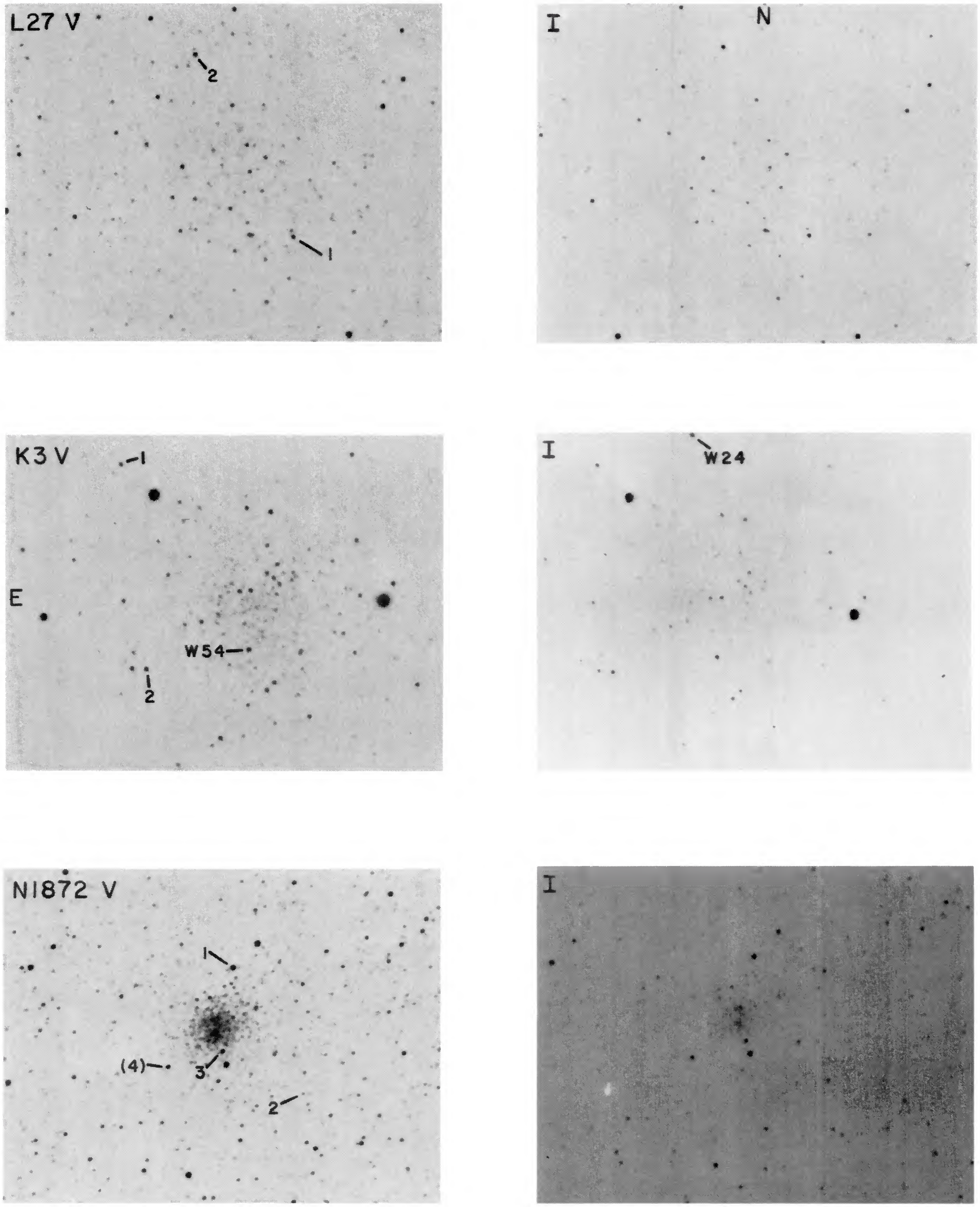

FIG. 1.—*Continued*

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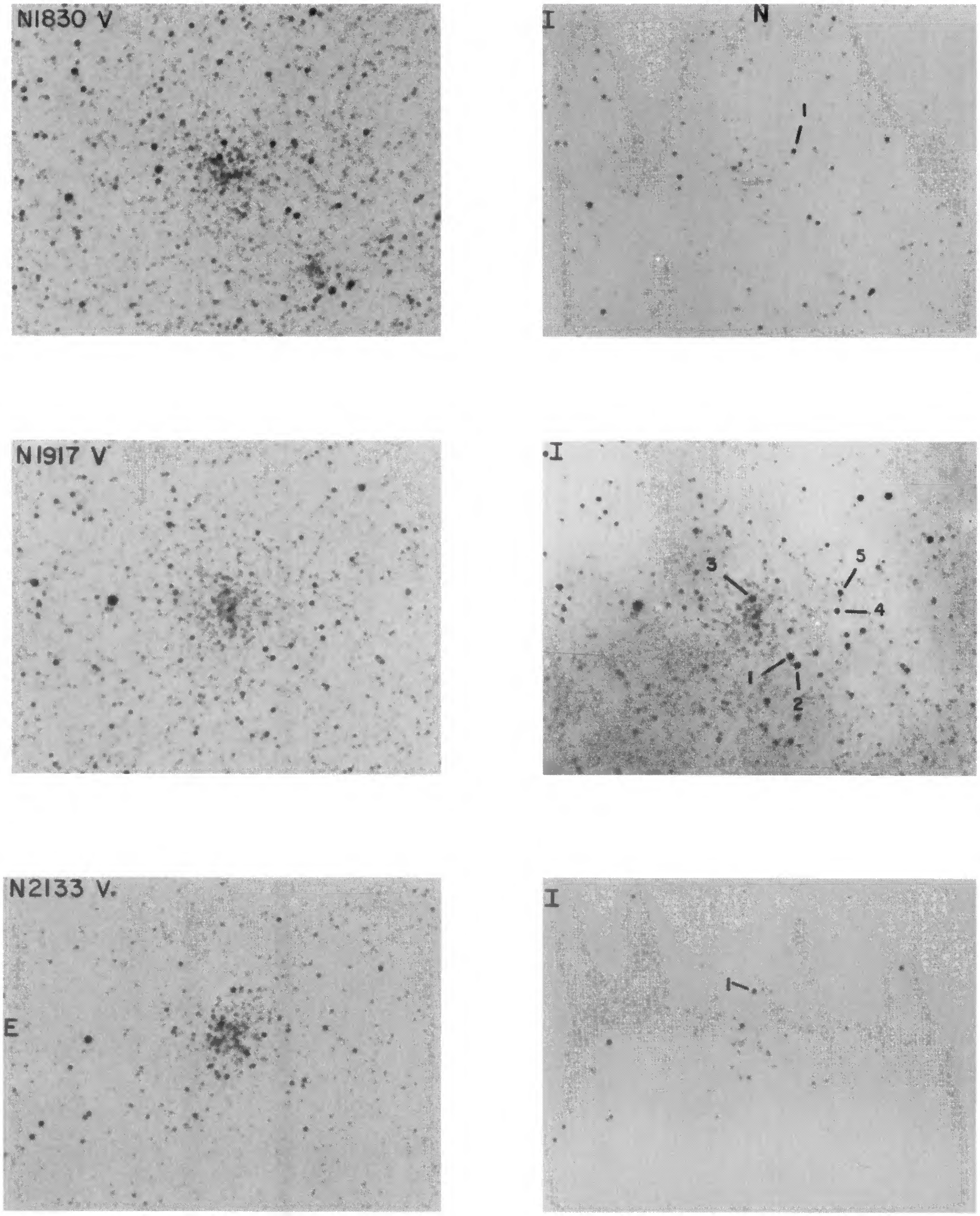

FIG. 1.—*Continued*

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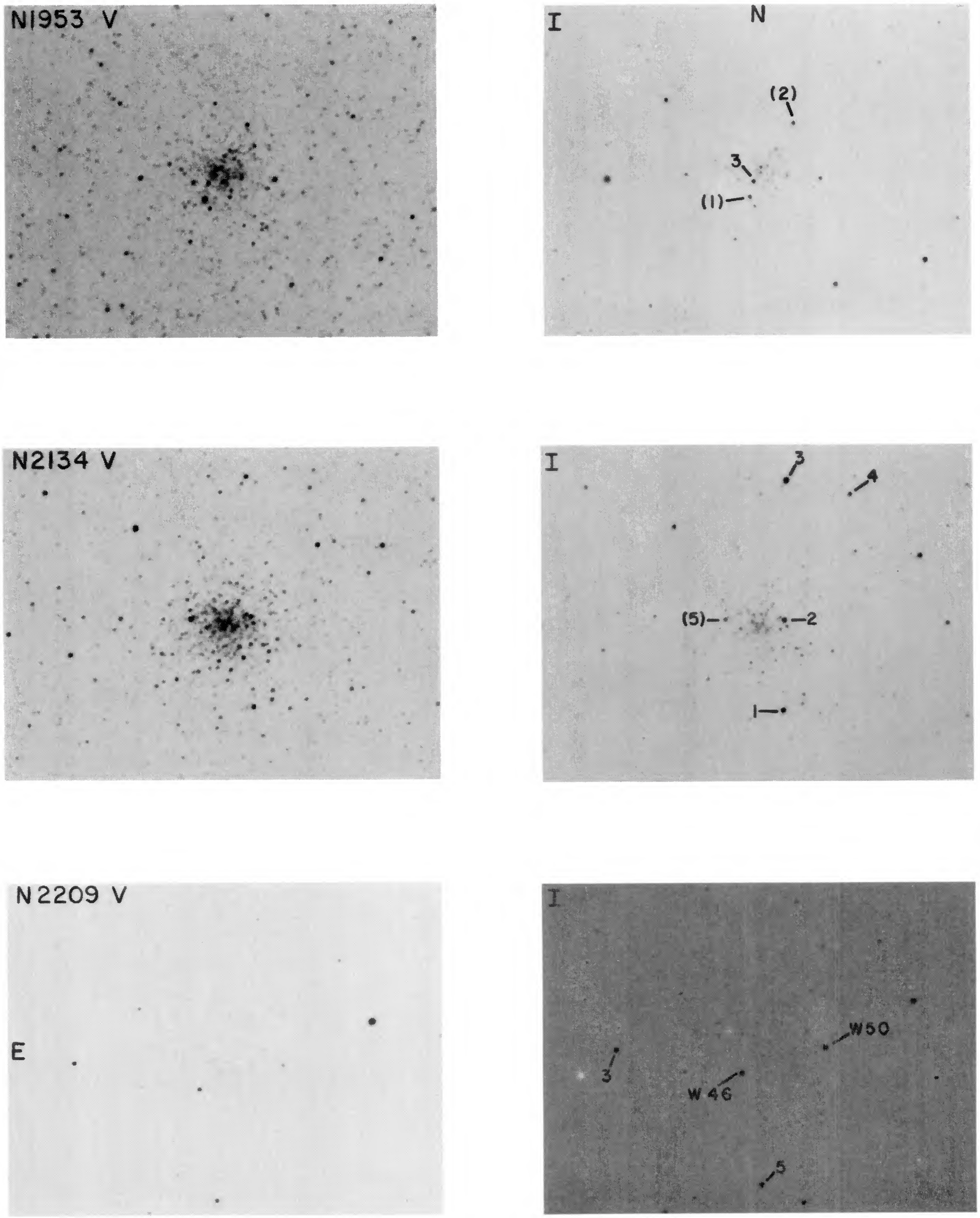

FIG. 1.—*Continued*

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