THE ASTROPHYSICAL JOURNAL, 288:551–557, 1985 January 15

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

MARC AARONSON[1]
Steward Observatory, University of Arizona

AND

JEREMY MOULD[1]
Palomar Observatory[2]
Received 1984 March 23; accepted 1984 July 31

ABSTRACT

A complete survey is now available for asymptotic giant branch stars in the rich star clusters of the Magellanic Clouds. Although data on the main-sequence turnoffs of these clusters are still incomplete, some systematic properties of these stars emerge, when grouped by cluster age. Clusters younger than approximately 8 billion years have carbon stars at the tip of the giant branch, produced by the third dredge-up mechanism. Clusters younger than approximately 0.8 billion years have giant branches populated by M stars. It is suggested that in stars of this mass range thermal pulses have not commenced before mass loss completely erodes the stellar envelope. Cluster stars of 5 $M_\odot$ turnoff (approximately 80 million years) suffer of order 80% mass loss in the course of their evolution, compared with approximately 30% for the oldest stars.

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

I. INTRODUCTION

The existence of a complete age sequence of rich star clusters in the Magellanic Clouds means that we can investigate in a systematic way the short-lived late stages of stellar evolution over a large range of stellar mass. Our understanding of evolution and nucleosynthesis on the asymptotic giant branch (AGB) has been both challenged and prompted by observations of red giant stars in these clusters (see Iben and Renzini 1983, Bessell 1983, and Wood 1981 for reviews).

The primary contribution of the present series of papers (Mould and Aaronson 1982, 1983, hereafter Papers I and III; Aaronson and Mould 1982, hereafter Paper II) has been the identification and photometry of AGB stars in Magellanic Cloud clusters. This task is completed in the present paper to the limits $M_v < -7$, $B-V > 0.3$ on the integrated cluster magnitudes (§§ II and III). We proceed to make use of the new wealth of reliable main-sequence turnoffs for these clusters to examine the relation between extension of the giant branch and cluster age (§ IV). We then look into one side of Iben's (1981) double-barrelled "carbon star mystery," and suggest why very luminous carbon stars do not exist (§ V). Last, the implications of the present data for the black box of stellar evolution, the initial-final mass relation, are discussed (§ VI).

II. AGB SURVEY IN THE SMC

With the examination of a further six clusters in the SMC, our survey for AGB stars in clusters with $M_v < -7$ and $B-V > 0.3$ is essentially complete. Of van den Bergh's (1981) compilation only L40 remains unsurveyed, and this cluster is so blue in $U-B$ that it must surely be younger than 10^8 years.

Although the bulk of the AGB survey has been carried out photographically, for our final observing run in 1982 November we converted to prime focus CCD imaging for the sake of speed and efficiency. The bandpasses remained V and I, but were filter defined in this case. Exposures of 30 s in bright moonlight surpassed the previous 20 minute photographic images in limiting magnitude. By examining clusters previously surveyed photographically, we were able to adjust the image display to reproduce the previous selection criteria for bright red stars.

Infrared photometry of these stars was carried out in 1982 and 1983 December and 1984 February as described in Paper II. Additional AGB candidates from Papers I–III lacking IR photometry were also selected for observation here and in the LMC (see below). Identification charts are provided in Figure 1 (Plates 15 to 18) and photometric results in Table 1. Lindsay 26, 45, and 62 were also imaged, but no red stars were seen. As indicated in column (7) of Table 1 three new "photometric carbon stars" (see Paper II) are identifiable from their red $H-K$ colors, and L53−1 belongs to the questionable transition case, many of which have been found to be S stars by Lloyd-Evans (1983).

Bolometric magnitudes and effective temperatures were determined for all the SMC program stars, using the precepts laid down in Paper II. The stars are plotted in the H-R diagram of Figure 2 and mostly lie on the extended giant branch populated by other intermediate age clusters in the SMC. Lindsay 114 is exceptional in this regard.

From the theoretical relation between AGB tip luminosity and age presented in Paper III, we conclude that L44 and L47 are intermediate age clusters with ages less than 5 and 3 Gyr respectively. The new luminous carbon star in NGC 419 is a little brighter than the brightest star known previously, but does not change the age limit on this cluster from Paper III.

III. THE LARGE CLOUD

In the LMC the AGB survey is now fully complete to the $M_v < -7$, $B-V > 0.3$ cutoff (Fig. 1). As in the past, we have

[1] Visiting Astronomers at Cerro Tololo Inter-American Observatory, operated by AURA Inc., under contract to NSF.

[2] Palomar Observatory is operated by the California Institute of Technology.

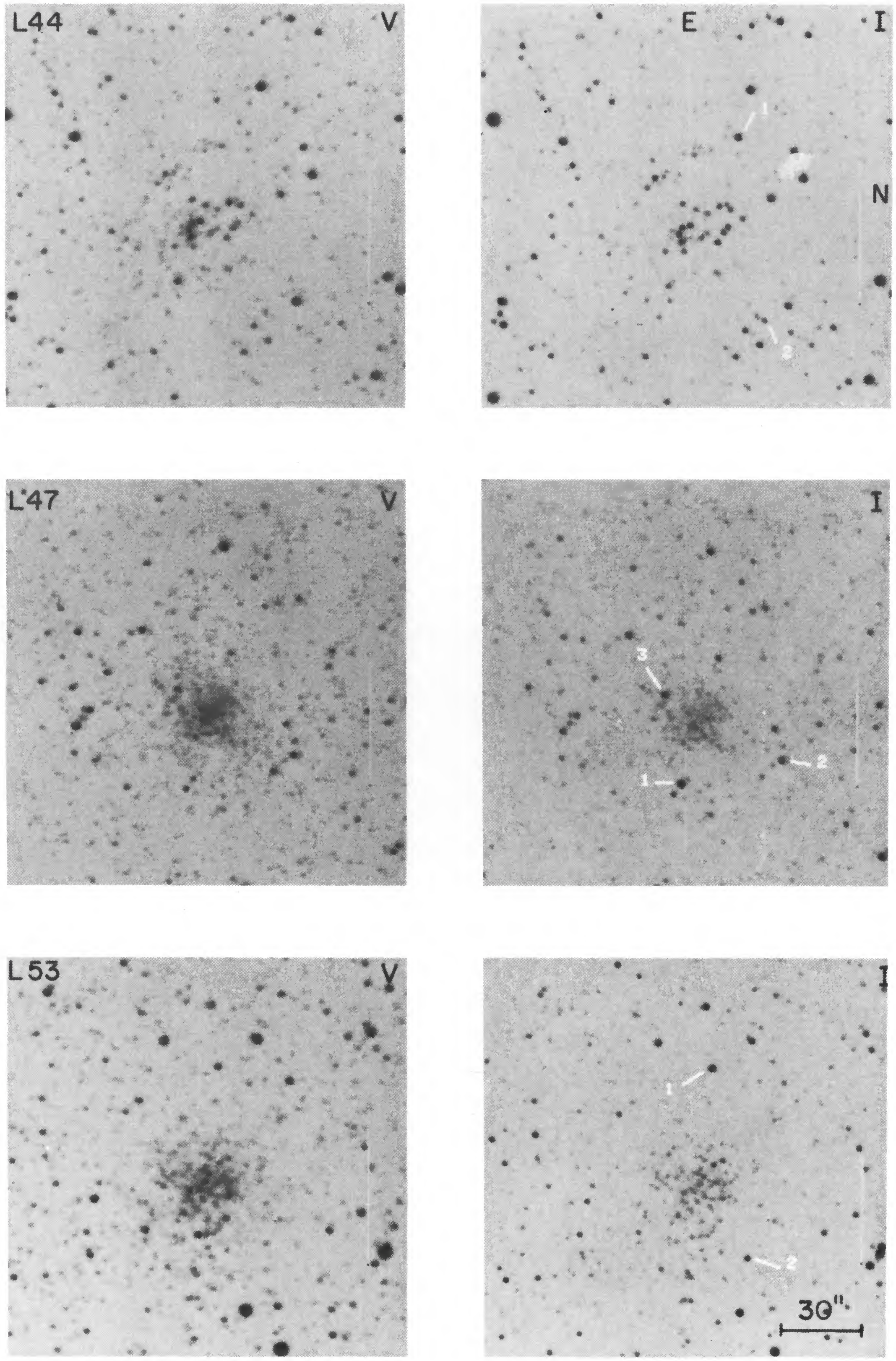

FIG. 1.—Identification charts for red stars located in the survey. Infrared frames are shown on the right and visual frames on the left. All charts have the same scale and orientation. Stars in parenthesis were selected for IR photometry rather than redness. For clusters in common with Lloyd-Evans (1983), we have adopted and/or extended his numbering scheme.

AARONSON AND MOULD (*see* page 551)

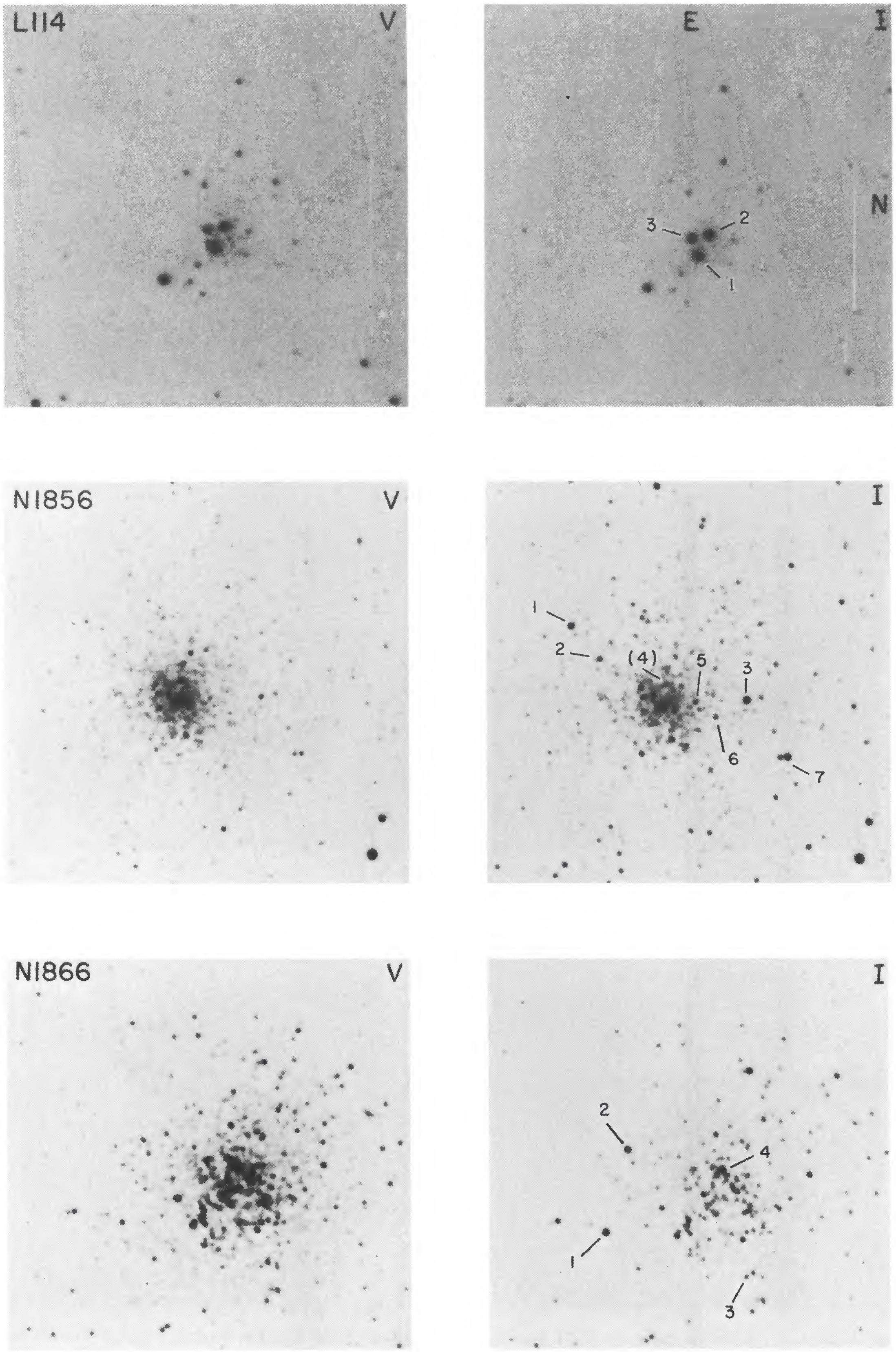

FIG. 1.—*Continued*

AARONSON AND MOULD (*see* page 551)

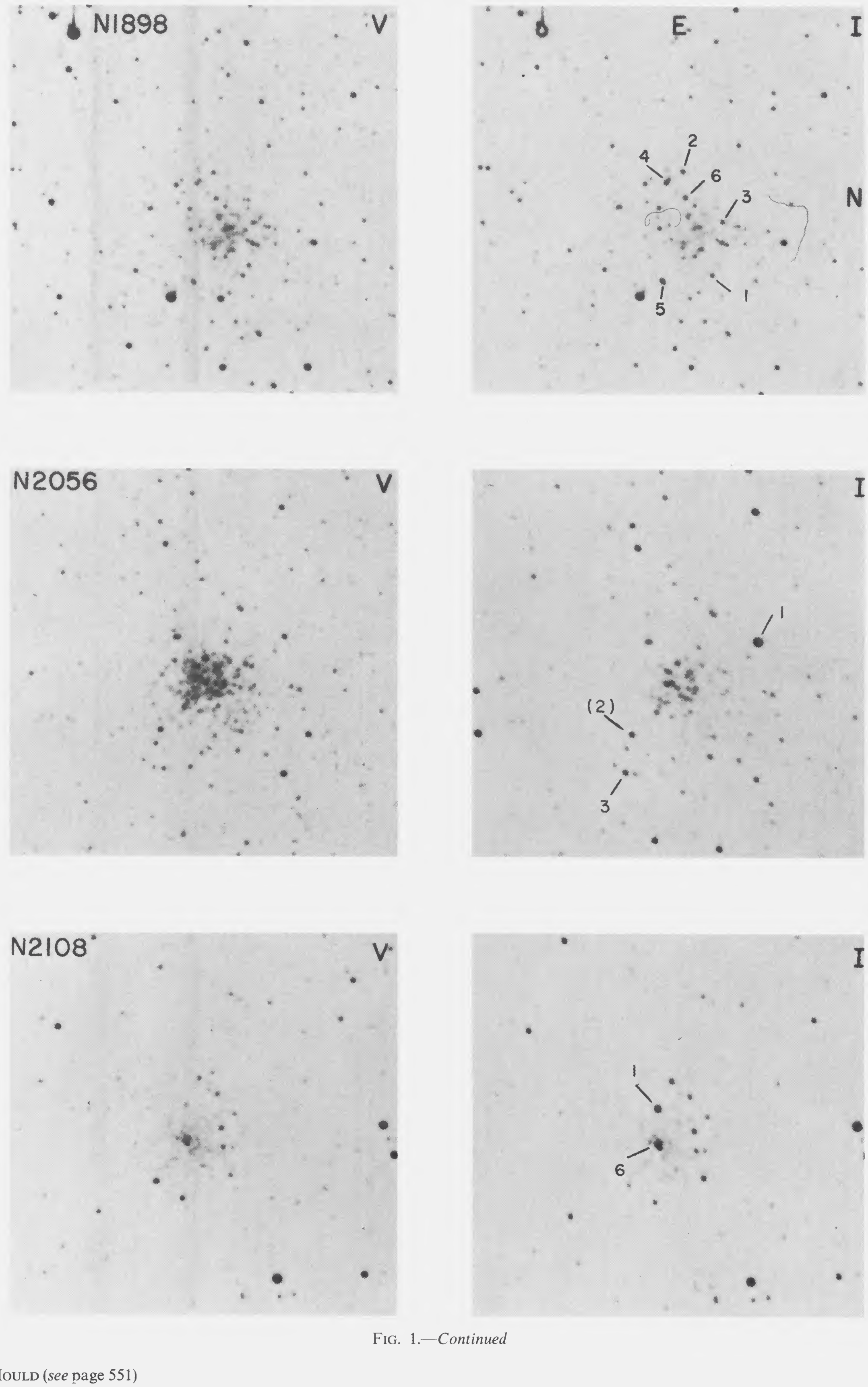

FIG. 1.—*Continued*

AARONSON AND MOULD (*see* page 551)

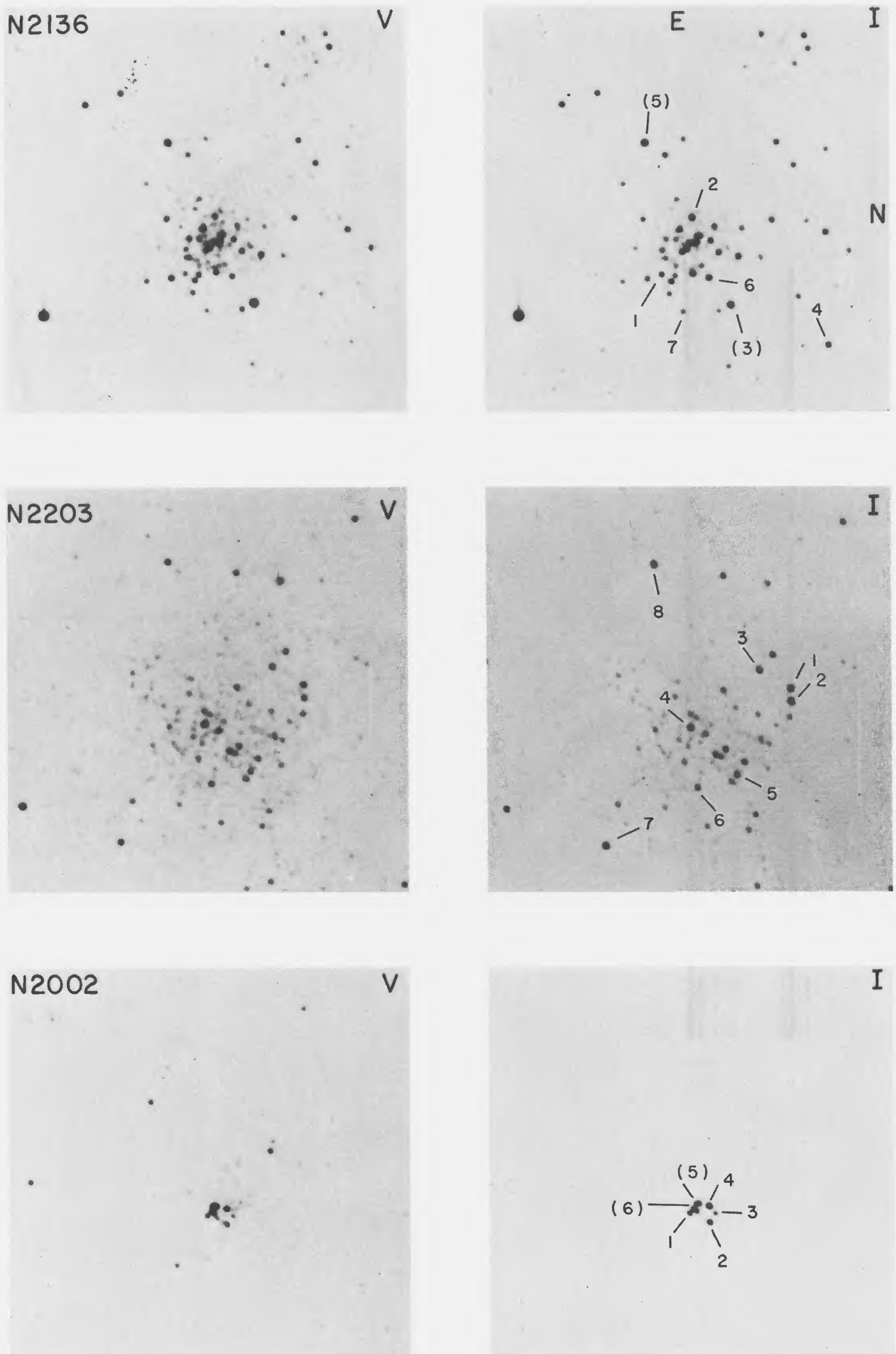

FIG. 1.—*Continued*

AARONSON AND MOULD (*see* page 551)

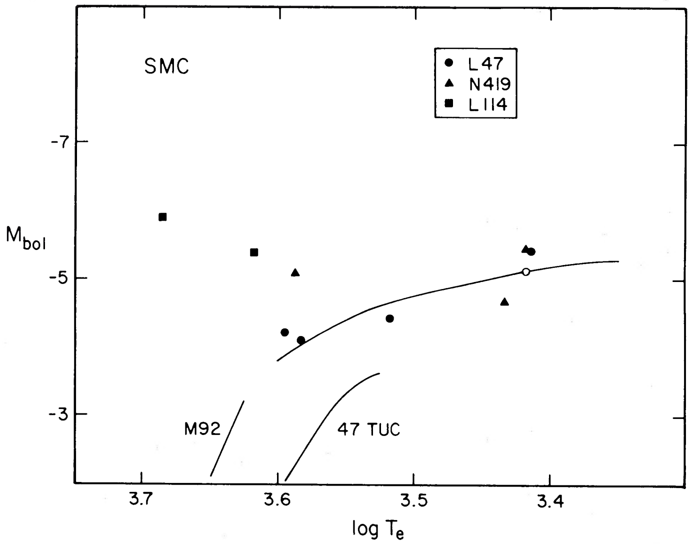

FIG. 2.—The H-R diagram for SMC stars with photometry in Table 1. Stars from Lindsay 47, 114, and NGC 419 are coded individually. Stars from other clusters are shown as open circles. The tip of the giant branch for two galactic globular clusters and the mean line for the SMC extended giant branch are from Paper III.

also examined a number of bluer clusters for the sake of comparison, specifically including NGC 1866 and 2136. Red AGB star candidates were located in NGC 1756, 1856, 1866, 1898, 2056, 2108, 2136, 2203, and 2210. These are identified in Figure 1, except for NGC 1756 and 2210, where we have simply confirmed detections by Lloyd-Evans (1980) and found no further candidates. No such stars were seen in NGC 1466, 1885, and 1895 which were also surveyed. Infrared photometry of most of the selected stars is presented in Table 1; two new photometric C stars have been found, along with three "transition case" objects. To enlarge the blue cluster sample we also obtained photometry of the reddest stars in NGC 2157 and 2164 (Robertson 1974*b*; Flower and Hodge 1975).

The H-R diagram of the program stars (Fig. 3*a*) shows an interesting phenomenon. Clusters with integrated $B-V > 0.34$ tend to populate an extended giant branch which runs to very cool temperatures ($T_e < 3000$ K) with carbon stars at the tip. Bluer clusters define a bluer giant branch (characteristic of higher mass stars), reach higher luminosities, but do not tend to very cool temperatures. This tendency is confirmed in Figure 3*b*, where we have accumulated infrared photometry in the LMC from this paper and Papers II and III. Only three stars are exceptions to the rule that clusters with $B-V < 0.34$ maintain giant branches with log $T_e > 3.5$. These are N2136

TABLE 1

PHOTOMETRY, LUMINOSITIES, AND TEMPERATURES OF CLUSTER GIANTS

Cluster (1)	Star (2)	Alternate Name (3)	K (4)	$J-K$ (5)	$H-K$ (6)	Spectral Type (7)	Source[a] (8)	m_{bol} (9)	M_{bol} (10)	log T_{eff} (11)	Notes[b] (12)
					Small Magellanic Cloud						
L44	1	...	11.06	1.62	0.58	(C)	i	14.19	−5.1	3.417	
L47	1	...	10.70	1.64	0.58	(C)	i	13.84	−5.45	3.414	1
	2	...	12.49 12.53	0.98 0.89	0.14 0.14	...	...	15.19	−4.1	3.584	1, 2, 3
	3	...	12.50	0.89(4)	0.15	...	...	15.09	−4.2	3.595	
L53	1	...	11.85	1.15	0.31	?	i	14.86	−4.45	3.518	
N419	LE26	6-3	11.54	0.92	0.18	M1	ii	14.20	−5.1	3.587	4, 5
	LE28	BR4, 5-20	11.51	1.53	0.52	C	...	14.59	−4.7	3.432	6
	LE36	...	10.70:	1.62	0.58	(C)	...	13.83	−5.45	3.417	7, 8
L114	1	...	11.89	0.37	0.05	...	i	13.38:	−5.9	...	
	2	...	11.45	0.58	0.11	...	...	13.39	−5.9	3.685	
	3	...	11.51	0.80	0.12	...	...	13.92	−5.4	3.618	
Reddening Correction		...	−0.01	−0.01	0.0	...	...	...	...	...	
					Large Magellanic Cloud						
N1756	LE1	...	11.74	0.85	0.22	dM1-2	iii	...	...	...	9
N1806	LE6	...	11.48	1.09	0.22	...	ii	14.40	−4.3	3.545	
	LE7	...	12.09	1.03	0.16	...	...	14.94	−3.75	3.559	
	LE8	...	11.82	1.03	0.20	...	...	14.67	−4.05	3.559	
N1846	LE9	...	11.59	1.09	0.22	...	ii	14.51	−4.2	3.545	4, 10
	LE14	...	11.57	1.05	0.21	...	...	14.44	−4.25	3.556	4
N1856	1	...	10.21	1.33	0.33	??	i	13.33	−5.35	3.451:	
	2	BMB87?	11.68	1.21	0.35	C	...	14.72	−4.00	3.505	11
	3	...	10.62	1.12	0.23	...	...	13.58	−5.1	3.534	
	4	...	12.78:	0.43:	0.13:	...	...	14.34:	−4.35:	3.75:	1, 12
N1866	1	...	9.67	1.14	0.25	M5	i	12.65	−6.05	3.528	13, 14
	2	...	10.24	1.13	0.24	M5	...	13.21	−5.5	3.531	14
	4	...	9.69	1.14	0.26	...	...	12.67	−6.03	3.528	
N1868	LE1	...	10.92	1.10	0.24	S4/4	ii	13.85	−4.85	3.541	5
N1898	LE1	...	12.58	0.98	0.15	...	ii	15.32	−3.4	3.575	
	LE2	...	12.49	0.98	0.17	...	...	15.23	−3.45	3.575	
	4	...	11.71:	1.08	0.25	...	i	14.62	−4.1	3.548	15
	5	...	11.78	1.02	0.19	...	...	14.60	−4.1	3.561	15
	6	...	12.38	0.94	0.17	...	...	15.03	−3.65	3.587	16
N1978	LE5	...	11.44:	1.05	0.22	...	ii	14.31	−4.4	3.556	10
	LE8	...	12.06	1.03	0.19	M2	...	14.91	−3.8	3.559	17
	LE10	...	12.12:	0.88	0.24	...	...	14.64	−4.05	3.603	9, 10, 18

TABLE 1—*Continued*

Cluster (1)	Star (2)	Alternate Name (3)	K (4)	$J-K$ (5)	$H-K$ (6)	Spectral Type (7)	Source[a] (8)	m_{bol} (9)	M_{bol} (10)	log T_{eff} (11)	Notes[b] (12)
N2056.........	1	...	9.64	1.18	0.29	?	i	12.68	−6.0	3.509	3
			9.63	1.22	0.29						
	2	...	12.98	0.87	0.15	...	...	15.51	−3.2	3.604	3
			12.99	0.88	0.15						
	3	...	11.48	1.39	0.42	(C?)	...	14.44	−4.26	3.459	
N2108.........	LE1	...	10.13	2.06	0.81	C	ii	13.41	−5.3	3.377	
	6	...	11.94:	0.96	0.22	...	i	14.63	−4.05	3.581	18
N2136.........	1	...	12.37	0.94	0.19	...	i	14.97	−3.75	3.599	3
			12.34	0.85	0.15						
N2136.........	2	...	11.34	0.94	0.19	...	i	13.94	−4.75	3.593	3, 19
			11.28	0.90	0.16						
	4	...	10.66	1.53	0.49	(C)	...	13.71	−5.00	3.435	
	5	...	11.55:	0.57	0.08	...	...	13.41:	−5.3:	3.697	20
	6	...	11.55	0.89	0.15	...	...	14.09	−4.6	3.600	
N2157.........	B4	...	11.28	0.96	0.16	...	iv	13.97	−4.75	3.581	21
N2164.........	C6	FH5	12.03	0.82	0.12	...	iv	14.42	−4.3	3.618	22
	C13	FH1	11.90	0.87	0.14	...	v	14.39	−4.3	3.605	23
N2193.........	LE6	3204	14.26(5)	0.72(6)	0.09(5)	...	ii	16.44	−2.25	3.645	
N2203.........	1	...	11.62	1.05	0.19	M4	i	14.49	−4.2	3.556	14
	2	...	11.21	1.12	0.23	M3	...	14.17	−4.55	3.534	14
	3	...	12.13	1.01	0.19	M1	...	14.93	−3.75	3.565	14
	7	...	11.51	1.08	0.21	M4	...	14.42	−4.3	3.548	14
N2209.........	W50	...	10.10	1.88	0.74	C	vi	13.33	−5.35	3.388	24
N2210.........	LE1	...	12.94:	0.67	0.08	...	ii	15.02:	−3.70:	3.658	18
	LE2	...	12.51:	0.85	0.14	...	...	14.96:	−3.75:	3.610	25, 26
N2231.........	LE1	...	10.60	1.48	0.49	(C)	ii	13.62	−5.10	3.444	
	LE2	...	13.61	0.85(4)	0.15(4)	...	...	16.06	−2.65	3.610	
Reddening Correction		...	−0.02	−0.03	−0.01	...	...	...	...	...	

[a] SOURCES.—(i) This paper (Fig. 1). (ii) Lloyd-Evans 1980. (iii) Lloyd-Evans 1983. (iv) Robertson 1974*a*, *b*. (v) Flower and Hodge 1975. (vi) Paper III.

[b] NOTES.—(1) Photometric conditions poor. (2) M_{bol} and log T estimated from mean of photometry. (3) Repeat measurements in 1982 and 1983; mean results used for BC and log T. (4) Crowded field; flux may be contaminated. (5) Spectral type from Lloyd-Evans 1983. (6) Also observed by Bessell, Wood, and Lloyd-Evans. (7) Very crowded field; unsteady signal in small beam (3″.5) used. K magnitude probably uncertain to ~ 0.1. (8) Lloyd-Evans 1983 classifies star 36 as M0, but notes poor signal-to-noise ratio. (9) JHK colors consistent with dwarf classification. (10) Asymetric signal; K magnitude uncertain to ~ 0.1. (11) A carbon star from Blanco, McCarthy, and Blanco 1980. (12) Unsteady signal; flux probably contaminated by other stars in beam. (13) K mag = 13.0 measured for N1866−3 (see Fig. 1), but very unsteady signal indicates severe crowding problems. (14) Unpublished Tololo CCD spectrum. (15) K uncertain because of contaminating star; flux correction of 0.2 mag applied. (16) Flux corrected by 0.08 mag for crowding. (17) Also measured in Paper III. (18) Flux corrected by 0.10 mag for crowding. (19) H = 12.81 mag also measured for N2136−3 (see Fig. 1). (20) Asymetric signal because of star in reference beam; flux corrected by 0.12 mag. (21) Center scanned for brighter stars but none found. (22) K = 13.26 mag also measured for FH 49; and K = 12.43 mag measured for FH 7 = C7. (23) Central region scanned for stars comparable to C6 and C13 in brightness, but none found. (24) Also measured in Papers I and II and by Frogel and Cohen 1982. (25) Flux corrected by 0.15 for crowding. (26) A 5″ aperture measurement of the cluster center yielded K = 11.26, $J-K$ = 0.66, $H-K$ = 0.14. Scans around the center did not reveal any carbon star candidates; however, at least one star probably brighter than LE1 or LE2 is present in the central region.

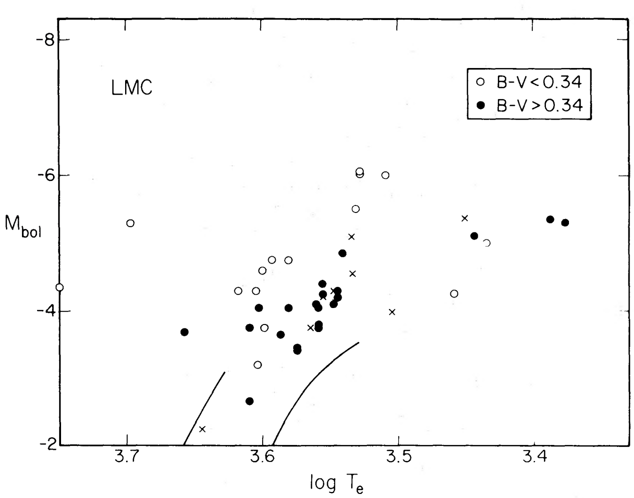

FIG. 3*a*

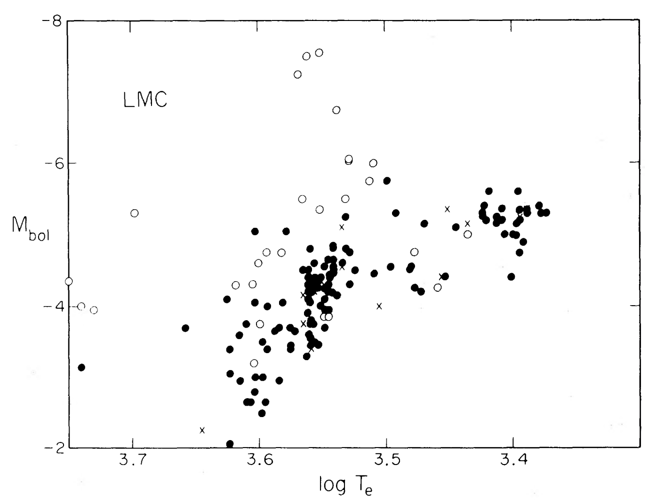

FIG. 3*b*

FIG. 3.—(*a*) The H-R diagram for LMC stars. Clusters with blue integrated $B-V$ are separated from those with red $B-V$. The fiducial lines are from Fig. 2. Crosses represent clusters with unknown colors or colors which lie on the dividing line. (*b*) The H-R diagram for the complete sample of cluster stars drawn from Papers I–IV. The symbol key is that of Fig. 3*a*.

(star 4), N2056 (star 3) and N1953 (star 3). Accurate velocities would be able to distinguish whether these stars are cluster members.

The most straightforward explanation of this phenomenon is based on a "smooth" mass loss law, which allows the more massive stars in the bluer clusters to reach higher luminosities on the AGB, and upon some process which inhibits carbon star formation in these more massive stars. We address the nature of this process in § V.

IV. THE TIP OF THE AGB VERSUS CLUSTER AGE

Earlier in this series (Papers I–III) we employed the measured AGB tip luminosities and a standard mass loss theory to put upper limits on the ages of many of the red globular clusters in the Clouds. This helped to reveal the strength of the intermediate age population of clusters in the Clouds. Now that reliable main-sequence turnoffs are being determined for increasing numbers of these clusters, it is more useful to turn the problem around, to test and modify the theory of mass loss on the AGB as a function of stellar mass (or cluster age).

In Table 2 we give $M_{\mathrm{bol},m}$ the maximum luminosity observed on the giant branch for the sample of clusters in Table 1. We have added all the clusters we know with reliably determined main-sequence ages and photometry from Paper III. Additional columns give $M_{\mathrm{bol},f}$, the statistically predicted tip of the AGB in the limit of a fully populated AGB, where there are sufficient stars to do this (see Paper III), and the cluster age from the most recent determination.

Figure 4 shows the relation between AGB tip and cluster age. The location of Galactic globulars is shown schematically for the Mira variables in metal-rich globulars (Frogel 1983) and limits on the AGB tip in metal poor clusters (see Frogel, Cohen, and Persson 1983). The extension of the AGB with decreasing cluster age is clearly traced in Figure 4, although the relation flattens considerably to take in NGC 1856 and 1866. Between 1 and 10 Gyr the theoretical relation from Paper III, based upon a Reimers (1975) mass loss law and a Renzini and Voli (1981) planetary ejection law is a reasonably close upper envelope to the data, but a proper fit would pass through the four 0.8–2 Gyr clusters with determined error bars. This suggests higher mass loss rates than predicted by theory for $M_{\mathrm{bol}} < -5$. The discrepancy becomes more severe with decreasing age, as the solid line in Figure 4 continues through 0.1 Gyr to run parallel to the dashed line according to Iben and Renzini (1983, Fig. 7). The observational data is still sparse, however, between 0.1 and 0.8 Gyr. We have not plotted the young clusters NGC 2136, 2157 and 2164, because for initial masses larger than 7 $M_{\odot}$ the first giant branch coexists with the AGB in the H-R diagram, making $M_{\mathrm{bol},f}$ indeterminate. But we cannot rule out from the present data the possibility that mass loss is so severe in these stars that the true relation turns over (i.e., a minimum value of $M_{\mathrm{bol},f}$ exists) for massive stars. Note, however, that Wood, Bessell, and Fox (1981) have shown evidence that AGB tip stars exist at $M_{\mathrm{bol}} \approx -7$.

In constructing Figure 4 we have adhered to our previously adopted distance moduli for the Magellanic Clouds (18.7, 19.3). Shorter distances as discussed by Rich, Da Costa, and Mould (1984) and Schommer, Olszewski, and Aaronson (1984) move the points diagonally across the plot as shown by the arrow.

TABLE 2

AGB Tip and Cluster Age

Cluster	$M_{\mathrm{bol},m}$	$M_{\mathrm{bol},f}$	Age (Gyr)	Source[a]
NGC 121	−4.35	...	11.5	1
NGC 152	−5.2	−5.45 ± 0.35	0.8	2
NGC 419	−5.4	−5.5 ± 0.15	1.2 ± 0.5	3
Kron 3	−4.55	...	5	4
L1	−4.4	...	8	5
L44	−5.1	...	...	
L47	−5.45	...	...	
L53	−4.45	...	...	
L114	−5.9	...	...	
L113	−5.0	...	4	6
NGC 1806	−5.25	−5.4 ± 0.35	...	
NGC 1856	−5.35	...	0.08	7
NGC 1866	−6.05	...	0.086	8
NGC 1868	−4.85	...	0.7	9
NGC 1898	−4.1	...	...	
NGC 1978	−5.6	−5.55 ± 0.35	2	10
NGC 2056	−6.0	...	...	
NGC 2108	−5.3	...	...	
NGC 2134	−5.75	...	0.12	11
NGC 2136	−5.3	...	0.02	12
NGC 2157	−4.75	...	0.02	12
NGC 2162	−4.3	...	0.6	13
NGC 2164	−4.3	...	0.03	12
NGC 2190	−5.35	...	0.6	13
NGC 2193	−4.7	...	...	
NGC 2203	−4.55	...	...	
NGC 2209	−5.4	...	0.8	14
NGC 2210	−3.75	...	...	
NGC 2213	−5.4	−5.35 ± 0.3	1.5	15
NGC 2231	−5.1	...	...	
NGC 2257	−3.4	...	14	16

[a] Sources.—(1) Stryker, Da Costa, and Mould 1984. (2) Hodge 1981*a*. (3) Hardy 1984. (4) Rich, Da Costa, and Mould 1984. (5) Gascoigne *et al.* 1981. (6) Mould, Da Costa, and Crawford 1984. (7) Hodge and Lee 1984. (8) Becker and Matthews 1983. (9) Flower *et al.* 1980. (10) Olszewski 1984. (11) Hodge and Schommer 1984. (12) Robertson 1974*a*, *b*. (13) Schommer, Olszewski, and Aaronson 1984. (14) Gascoigne *et al.* 1976. (15) Da Costa, Mould, and Crawford 1984. (16) Stryker 1983.

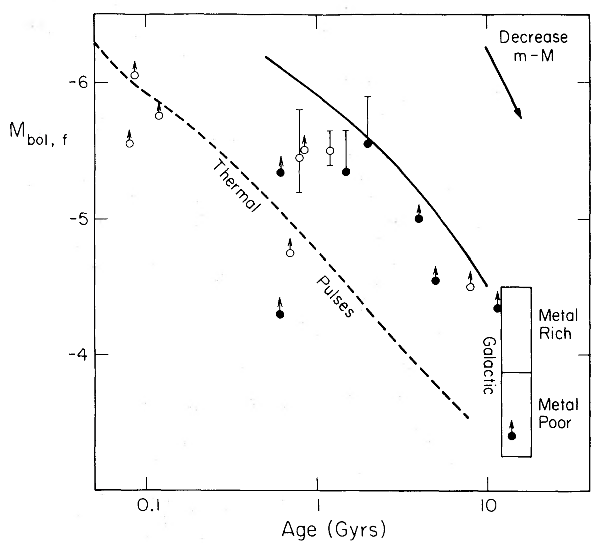

Fig. 4.—AGB tip luminosity and cluster age. The four clusters with $M_{\mathrm{bol},f}$ are shown with error bars; other values are lower limits on the true cluster tip luminosity. Solid symbols denote clusters with recent higher quality *C-M* diagrams, analyzed by point spread function fitting techniques. The box encloses the parameters for Galactic globular clusters within the uncertainties. The solid line is the theoretical relation of Paper III (see text). The dashed line is the locus of thermal pulse ignition on the AGB.

V. WHAT INHIBITS CARBON STAR FORMATION IN MASSIVE STARS?

In § III we noted a tendency for younger clusters to have luminous M stars rather than carbon stars at the giant branch tip. We consider three different hypotheses for this effect. First, it is possible that the initial oxygen (and general metal) abundance is too high in the younger clusters to be neutralized by the dredged-up carbon before $M_{\rm bol} = -6$. Evidence in favor of this hypothesis is seen in the tendency for the transition point (where S stars are observed) between M stars and C stars to rise in luminosity with decreasing cluster age and increasing metallicity (Lloyd-Evans 1983; Frogel and Blanco 1983). Evidence against the hypothesis is the existence of carbon stars in the Galactic open clusters NGC 2477, 2660 and 7789 (Hartwick and Hesser 1973, 1974; Mavridis 1960). The mean age of these clusters is 1.0 Gyr (Cannon 1970; Hartwick and Hesser 1973); their mean metallicity is [Fe/H] = −0.14. This compares with a mean metallicity [Fe/H] = −0.5 at the same age in the LMC (Cohen 1982). Since these galactic clusters are older, but *more* metal rich than the M star clusters in the Clouds, we can rule out metallicity and concentrate on age as the inhibitor.

Second, one could invoke "envelope burning" (Renzini and Voli 1981, and references therein) to process the carbon into nitrogen, before it is mixed to the surface. This hypothesis seems more attractive. Evidence that envelope burning of ^{12}C does occur on the AGB exists in the J stars (high ^{13}C/^{12}C) observed by Bessell, Wood, and Lloyd-Evans (1981). We could speculate that the existence of individual cool stars below the AGB tip in NGC 2056, and 2136 might be best understood if such a mechanism were acting in more massive stars to convert would-be carbon stars to M stars. But to properly evaluate the significance of envelope burning in these clusters and in NGC 1953, we suggest a careful comparison of CNO band strengths of stars in the region (−5, −6) in $M_{\rm bol}$ and log $T_e = 3.5$.

The third hypothesis arises from the suggestion by Frogel and Richer (1983) and Weidemann (1984) that very severe mass loss on the upper parts of the AGB may prevent some stars from ever beginning thermal pulsation. To examine this interesting suggestion we need to know the theoretical locus of thermal pulse start up as a function of age. This was obtained from Iben and Renzini's (1983) expression for the mass interior to the hydrogen burning shell immediately prior to its ignition: $M_{\rm H} = 0.59 + 0.0526\, M_i$, where M_i, the initial mass, is in the range 3–8 $M_\odot$. The core-mass/luminosity relation and main sequence ages of Becker, Iben, and Tuggle (1977) establish the upper part of the required locus. This was smoothly joined to the corresponding point for a 1 $M_\odot$ star, which has $M_{\rm H} \approx 0.53$, to produce the dashed line in Figure 4. This locus of thermal pulse ignition is similar to that shown in Figure 7 of Iben and Renzini (1983).

In the latter figure, however, the thermal pulse locus runs parallel to the theoretical tip of the AGB, for various values of the Reimers (1975) mass loss parameter. But in the previous section we noted that an empirical mass loss law appears to flatten out the run of AGB tip with decreasing age. In fact it seems likely that these lines cross in Figure 4 somewhere between 0.1 and 0.3 Gyr. This appears to be the natural explanation of the observation that clusters with $B-V < 0.34$ have M stars rather than carbon stars at the AGB tip. In these clusters thermal pulses have either not yet begun or not yet had time to dredge up sufficient carbon, before mass loss exhausts the stellar envelope. Note that Figure 4 is unfortunately sparse in the interesting crossover region.

VI. THE INITIAL-FINAL MASS RELATION

Figure 4 also serves as a direct constraint on the relation between initial and final masses (M_i and M_f) for low- and intermediate-mass stars. This relation in turn determines the mass distribution of white dwarfs, the minimum mass for supernovae, and the economics of light element synthesis in the interstellar medium. We use the core-mass/luminosity relation of Iben and Renzini (1983) to replot Figure 4 in this form (Fig. 5).

Weidemann and Koester (1983) have argued for an initial-final mass relation of the form A or B in Figure 5, based upon the appearance of white dwarfs in galactic clusters as young as the Pleiades and NGC 2516. Weidemann (1984) has also inferred from the brightest red giant in a color-magnitude diagram by Flower (1981) that NGC 1866 with $M_i = 5\ M_\odot$ is located at $M_f = 0.7\ M_\odot$ in broad agreement with relations A and B. Flower (1981) has suggested that the AGB in this cluster terminates at $M_{\rm bol} = -4.75$, ($M_f = 0.64\ M_\odot$) based upon a post–AGB hypothesis for superluminous giants (see Hodge 1981*b* for a review) found in his color-magnitude diagram. The evolutionary status of these stars is far from clear, however (Mould 1983), and their photometric reality has been questioned (Da Costa, Mould, and Crawford 1984; E. Olszewski and N. Suntzeff 1984, private communication). We conclude from the present survey that the AGB tip in NGC 1866 is brighter than $M_{\rm bol} = -6.05$, which is not well fitted by relations A or B of Weidemann.[3] Indeed, since most of the clusters plotted in Figure 5 provide *lower* limits on M_f for a given M_i, relations A and B appear to be systematically in disagreement with the present data. We need to consider why this might be.

We begin with a cautionary remark about the use of white dwarfs in open clusters to define the (M_f, M_i) relation. It has been known for a long time that there is a disagreement between the turnoff age and the main-sequence contraction age in open clusters like the Pleiades. The probable explanation of

[3] Weidemann adopted $M_i = 5.2\ M_\odot$ for NGC 1866. A value of 4.4 $M_\odot$ was used here, obtained by interpolation in model sequences by Becker (1981). This accounts for part of the discrepancy with relation A, and we thank V. Weidemann for this clarification.

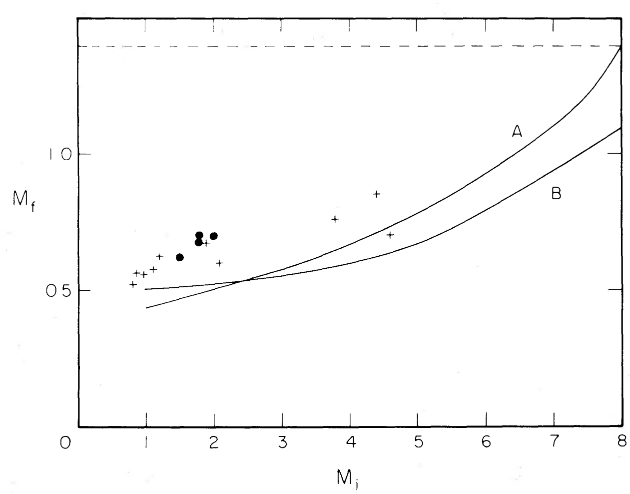

FIG. 5.—The final mass of stars evolving on the AGB vs. their initial mass on the main sequence (solar masses). Crosses are lower limits on M_f. Filled symbols are statistical estimates of M_f. The dashed horizontal line is the Chandrasekhar limit on the white dwarf progeny of these stars at 1.4 $M_\odot$. Relations A and B (*lines*) are from Weidemann and Koester (1983).

this phenomenon is a large age spread in these clusters. Low-mass stars form first over a period, followed by high-mass stars, which drive away the gas clouds and stop further star formation (Herbig 1962; Norman and Silk 1980). In this interpretation the age of the high-mass stars ($M > 6\ M_\odot$) may be 10^7 years, while the age of the low-mass stars is more than 10^8 years (Stauffer 1984; Stauffer *et al.* 1984). Hence it is possible that the turnoff masses in open clusters are wide upper limits to the true white dwarf progenitor masses, M_i.

The notation of parameter spread, however, is a two-edged sword in this discussion. Suppose mass loss in red giants were to occur at a rate which varied widely from star to star. It could be argued that the tip of the AGB monitors the low-mass loss tail of this distribution, and that the mean net mass loss in stars is considerably higher. Although we cannot reject a small spread in net mass loss (e.g., less than $\Delta M_F = 0.1\ M_\odot$ as contemplated by Weidemann 1984), we can rule out a large spread. If the spread were very large, the AGB in Magellanic Cloud globular clusters would be significantly depleted below the population predicted for no spread. Take the case of NGC 419, a billion year old cluster in the SMC. The initial mass in this case is 1.8 $M_\odot$. Suppose half the stars lost 1.1 $M_\odot$ producing the observed AGB tip, but the other half lost 1.3 $M_\odot$ as predicted by relations A and B. The AGB between -4.5 and -5.5 in $M_{\rm bol}$ would be depleted by a factor of 2 below the 1.1 $M_\odot$ prediction. The standard model which incorporates 1.1 $M_\odot$ mass loss (see Reid and Mould 1984 for details of these calculations) predicts that 78% of the 2.2 μm light is due to AGB stars brighter than -4.5. The observed fraction is 74%. Although this agreement is fortuitously good, AGB lifetimes are probably known to a factor of 2 accuracy, ruling out the bimodal 1.1, 1.3 $M_\odot$ mass loss hypothesis.

We suggest therefore that, while some spread in mass loss may well occur on the giant branch, and, indeed, relations A and B may represent the *high* mass loss tail of the distribution, the mean mass loss situation is more closely represented by our data on cluster AGB tips in the range 1–5 $M_\odot$. Between 1 and 2 $M_\odot$ this is confirmed by a relation resulting from the analysis of planetary nebula nuclei by Schönberner, illustrated in Figure 1 of Weidemann (1984). Difficulties identifying AGB stars at higher masses make it difficult to pursue our methods above 5 $M_\odot$, and, for all we can say, relations A and B may be correct above 5 $M_\odot$. But, given our earlier remarks about cluster age spread, we suggest caution.

VII. CONCLUSIONS

The primary product of these papers is a set of finding charts, which is now complete, for AGB stars brighter than $M_{\rm bol} = -4$ in the Magellanic Clouds. Our secondary industry has been photometry and spectroscopy of these stars, from which we draw the following provisional conclusions.

1. The maximum extent of the AGB in Magellanic Cloud clusters increases steadily with increasing mass from $M_{\rm bol} = -4$ in the oldest to $M_{\rm bol} = -6$ in the youngest clusters of the present sample ($B-V > 0.3$).

2. This trend is qualitatively in accord with a theory of mass loss on the AGB elaborated by Renzini and Voli (1981).

3. Quantitative agreement would require more rapid mass loss with increasing luminosity on the AGB for $M_i > 1.5\ M_\odot$, in order to reconcile theory with the flattening out of maximum luminosity with increasing initial mass.

4. For $M_i \leq 2\ M_\odot$ the third dredge-up mechanism (Iben and Renzini 1983) produces successively S stars and then carbon stars as the star ascends the AGB. This transition has been investigated in more detail by Lloyd-Evans (1983), but the transition luminosity averages about $M_{\rm bol} = -4.5$.

5. For $M_i \geq 3\ M_\odot$ thermal pulsing begins too late (if at all) on the AGB to make carbon stars. The AGB is truncated by severe mass loss before carbon stars are produced.

6. Constraints posed by the properties of star clusters on the relation between initial and final masses of evolving stars are weakened by parameter spread. The spread in mass loss on the AGB, however, appears to be confined to a range less than $\Delta M = 0.2\ M_\odot$ for clusters in the billion year old LMC population peak.

Further work is required to consolidate and test this picture. In particular, high-resolution spectroscopy is needed to examine appropriate samples of AGB stars, especially those whose characteristics have been inferred photometrically. We need to find out what initial mass range populates the interval $-6 > M_{\rm bol} > -7$ and what mass range experiences envelope burning.

Among the red cloud globulars (i.e., $B-V > 0.35$), if AGB carbon stars are present they are generally the most luminous cluster stars (NGC 1651 being apparently the only notable exception). However, in younger clusters (i.e., $0.25 < B-V \leq 0.35$), the presence of AGB C stars which are not the most luminous stars appears to be more common. Possible examples include NGC 1856, 1872, 2056, 2134, and 2136; but membership and spectral type questions remain in these cases. The suggestion (A. Renzini 1984, private communication) that nondegenerate carbon burning, rather than mass loss, may be responsible for the observed truncation of the AGB, must also be explored.

We acknowledge our debt to the staff of CTIO for supporting this project over the last 6 years. We should not single out individuals for thanks, because we have benefited from the assistance of so many, both on and off the mountain. We thank Professor Dr. Volker Weidemann for a stimulating preprint and Icko Iben and Alvio Renzini for helpful discussions. Work reported here was partially supported by NSF grants, AST 83-06139, 81-17365, and 83-16629.

REFERENCES

Aaronson, M., and Mould, J. R. 1982, *Ap. J. Suppl.*, **48**, 161 (Paper II).
Becker, S. 1981, *Ap. J. Suppl.*, **45**, 475.
Becker, S., Iben, I., and Tuggle, R. S. 1977, *Ap. J.*, **218**, 633.
Becker, S., and Matthews, G. J. 1983, *Ap. J.*, **270**, 155.
Bessell, M. S. 1983, *Mem. Astr. Soc. Italiana*, **54**, 47.
Bessell, M. S., Wood, P. R., and Lloyd-Evans, T. L. 1981, *Proc. Astr. Soc. Australia*, **4**(2), 201.
Blanco, V. M., McCarthy, M. F., and Blanco, B. M. 1980, *Ap. J.*, **242**, 938.
Cannon, R. D. 1970, *M.N.R.A.S.*, **150**, 111.
Cohen, J. G. 1982, *Ap. J.*, **258**, 143.
Da Costa, G., Mould, J. R., and Crawford, M. D. 1984, in preparation.
Flower, P. 1981, *Ap. J.* (*Letters*), **249**, L11.
Flower, P., and Hodge, P. 1975, *Ap. J.*, **196**, 369.
Flower, P. J., Geisler, G., Hodge, P., and Olszewski, E. 1980, *Ap. J.*, **235**, 769.
Frogel, J. 1983, *Ap. J.*, **272**, 167.
Frogel, J., and Blanco, V. M. 1983, in *IAU Symposium 105, Observational Tests of the Stellar Evolutionary Theory*, ed. A. Maeder and A. Renzini (Dordrecht: Reidel), in press.
Frogel, J., and Cohen, J. G. 1982, *Ap. J.*, **253**, 580.
Frogel, J., and Richer, H. B. 1983, *Ap. J.*, **275**, 84.
Frogel, J., Cohen, J. G., and Persson, S. E. 1983, *Ap. J.*, **275**, 773.
Gascoigne, S. C. B., Norris, J., Bessell, M. S., Hyland, A. R., and Visvanathan, N. 1976, *Ap. J.* (*Letters*), **209**, L25.

Gascoigne, S. C. B., Bessell, M. S., and Norris, J. E. 1981, in *Astrophysical Parameters for Globular Clusters*, ed. A. G. Davis Philip and D. Hayes (Schenectady: L. Davis Press), p. 223.
Hardy, E. 1984, preprint.
Hartwick, F. D., and Hesser, J. E. 1973, *Ap. J.*, **183**, 883.
———. 1974, *Ap. J.*, **192**, 391.
Herbig, G. H. 1962, *Ap. J.*, **135**, 736.
Hodge, P. 1981*a*, *Ap. J.*, **247**, 894.
———. 1981*b*, *J. Ap. Astr.*, **2**, 161.
Hodge, P., and Lee, S. O. 1984, *Ap. J.*, **276**, 509.
Hodge, P., and Schommer, R. A. 1984, *Pub. A.S.P.*, **96**, 28.
Iben, I. 1981, *Ap. J.*, **246**, 278.
Iben, I., and Renzini, A. 1983, *Ann. Rev. Astr. Ap.*, **21**, 271.
Lloyd-Evans, T. L. 1980, *M.N.R.A.S.*, **193**, 87.
———. 1983, *M.N.R.A.S.*, **204**, 985.
Mavridis, L. N. 1960, *Pub. A.S.P.*, **72**, 48.
Mould, J. R. 1983, in *IAU Symposium 108, Structure and Evolution of the Magellanic Clouds*, ed. S. van den Bergh and K. de Boer (Dordrecht: Reidel), p. 195.
Mould, J. R., and Aaronson, M. 1982, *Ap. J.*, **240**, 464 (Paper I).
———. 1983, *Ap. J.*, **263**, 629 (Paper III).
Mould, J. R., Da Costa, G. S., and Crawford, M. D. 1984, *Ap. J.*, **280**, 595.
Olszewski, E. 1984, *Ap. J.*, **284**, 108.
Reid, N., and Mould, J. R. 1984, *Ap. J.*, **284**, 98.
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., and Voli, M. 1981, *Astr. Ap.*, **94**, 175.
Rich, M., Da Costa, G., and Mould, J. R. 1984, *Ap. J.*, **286**, 517.
Robertson, J. G. 1974*a*, *Ap. J.*, **191**, 67.
———. 1974*b*, *Astr. Ap. Suppl.*, **15**, 261.
Schommer, R. A., Olszewski, E., and Aaronson, M. 1984, *Bull. AAS.*, **15**, 964.
Silk, J., and Norman, C. 1983, *Ap. J. (Letters)*, **272**, L49.
Stauffer, J. R. 1984, *Ap. J.*, **280**, 189.
Stauffer, J. R., Hartmann, L., Soderblom, D. R., and Burnham, N. 1984, *Ap. J.*, **280**, 202.
Stryker, L. L. 1983, *Ap. J.*, **266**, 82.
Stryker, L. L., Da Costa, G., and Mould, J. R. 1984, in preparation.
van den Bergh, S. S. 1981, *Astr. Ap. Suppl.*, **46**, 79.
Weidemann, V. 1984, preprint.
Weidemann, V., and Koester, D. 1983, *Astr. Ap.*, **121**, 77.
Wood, P. R. 1981, *Proc. Astr. Soc. Australia*, **4**(2), 145.
Wood, P. R., Bessell, M. S., and Fox, M. 1981, *Proc. Astr. Soc. Australia* **4**(2), 203.

MARC AARONSON: Steward Observatory, University of Arizona, Tucson, AZ 85721

JEREMY MOULD: Caltech, 105-24, Pasadena, CA 91125