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# THE ASYMPTOTIC GIANT BRANCH OF MAGELLANIC CLOUD CLUSTERS

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## ABSTRACT

Thirty-nine clusters in the Magellanic Clouds have been surveyed for carbon and M-type asymptotic giant branch (AGB) stars. We identified and obtained near-infrared photometry for about 400 such stars in and around the clusters. The cluster classification scheme of Searle, Wilkinson, and Bagnuolo (SWB), which we show to be closely correlated with cluster age, is a key element in the analysis of our data. The principal results of our investigation are as follows.

In a *C-M* diagram the cluster M stars shift steadily redward in $J-K$ as one goes from clusters of SWB type I to VI. This is due to the increasing age of the clusters along the sequence. There are two peaks in the color distribution of the M stars which could indicate two epochs of enhanced cluster formation: one about 100 Myr ago, the other about 1 Gyr ago. These correspond to similar enhancements deduced for M stars in the Bar West region of the LMC. For LMC clusters in the 1 Gyr old group we estimate the spread in [Fe/H] to be on the order of 0.2–0.3 dex. This implies that chemical enrichment was fairly uniform throughout the LMC at that epoch. The brightest stars in SWB type VII clusters have luminosities and colors that are closely comparable to the brightest stars in Galactic globular clusters; with one possible exception they have no luminous AGB stars. We deduce that the SWB VII clusters in the Clouds are as old as Galactic globular clusters and have a range in metallicity of about a factor of 10.

Luminous carbon stars are present only in SWB IV–VI clusters. They are easily distinguished from M stars by their color and luminosity. The effects of age and metallicity are apparent in luminosity functions for C stars: for those in SWB type VI clusters the luminosity function is several tenths of a magnitude fainter than that for earlier type clusters: both cluster and field SMC C stars are intrinsically fainter than their LMC counterparts. The shape of the luminosity functions for C stars from the various types of clusters are consistent with each being drawn from the same sample of field stars in the Clouds, so that the latter is clearly a composite population with a range in age and metallicity that must closely overlap that for the clusters.

For the SWB-type clusters in which C stars are present, they are almost always brighter than the M stars in the same clusters. The transition luminosity between the two types of stars gets systematically brighter as one passes from the latest to the earliest type clusters. The existence of such a transition luminosity is an important prediction of the theory of carbon star formation and evolution.

The youngest clusters in which C stars are found have an age of about 100 Myr implying a maximum initial mass for these stars of 3–5 $M_{\odot}$. In clusters younger than 100 Myr, the brightest stars are M giants; even though these are the brightest stars in the entire sample, they still cannot account for the missing luminous AGB stars. Therefore, the hypothesis that luminous C stars turn back into M stars appears to be ruled out. Convective overshooting or high mass-loss rates are promising hypotheses for the absence of luminous C stars. The former could also explain the fact that we see luminous C stars in clusters with turnoff masses as low as 1.0 $M_{\odot}$ in the SMC. In intermediate-age clusters, $\sim$40% of the bolometric luminosity is contributed by C and M type AGB stars, a somewhat smaller fraction than predicted by Renzini and Buzzoni. However, because the C star luminosity function is shifted to fainter magnitudes than predicted, the age range in which AGB stars make a significant contribution is shifted to substantially older ages. If the contribution of AGB stars is removed from a cluster's light, the resulting distribution of integrated $J-K$ colors shows a jump at types IV–V. This corresponds to the age at which the helium core switches from being degenerate to nondegenerate and is in reasonable agreement with theory.

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

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## I. INTRODUCTION

The clusters of the Magellanic Clouds span a large range in age and chemical composition. Thus they present us with a unique opportunity to test a number of key predictions of the theory of stellar evolution and, because of the richness of many of the clusters, to study short-lived late stages of evolution from an empirical standpoint (e.g., Iben and Renzini 1983; Renzini and Buzzoni 1986; Bertelli, Chiosi, and Bertola 1989). We have carried out a spectroscopic survey of Magellanic Cloud clusters for M and C type asymptotic giant branch (AGB) stars and obtained infrared photometry for a complete sample of them. With these new data we can synthesize a number of areas of AGB research that we and our colleagues have worked on for nearly a decade.

The survey and data are described and compared with previous observations of cluster giants in § II. The classification scheme established by Searle, Wilkinson, and Bagnuolo (1980, hereafter SWB) provides a preliminary age calibration for the clusters. The relevance of their scheme to the present work is discussed in § III. The colors and magnitudes of the stars are discussed in § IV and compared with other samples of luminous giants. Sections V and VI discuss the color distribution and the luminosity functions of the AGB stars in both Clouds. An examination of the contribution that these stars make to the total luminosity of the clusters and a detailed comparison with theoretical predictions is presented in § VII. Section VIII summarizes our conclusions.

## II. THE DATA

### a) *Selection of Stars*

Most of the clusters in our survey were chosen from those classified by SWB. For each of the clusters, short-exposure *R* or *I* direct plates were obtained either at the prime focus of the 4 m or at the f/7.5 Cassegrain focus of the 1.5 m on Tololo. In addition, multicolor digital images were obtained for many of the clusters with a red-sensitive SIT tube on the 1.5 m. Plates taken with a red grism at the 4 m prime focus were used to classify M and C type giants in and around each of the clusters. The technique is described in Blanco, McCarthy, and Blanco (1980). For some of the clusters crowding caused problems for identifying and classifying late-type giants from the grism plates. For these clusters, blinking of the SIT frames proved to be an efficient way to identify candidate M and C stars with colors and magnitudes comparable to those stars identified spectroscopically. In general, though, the grism surveys should be complete for all carbon stars and for all but the earliest type M giants as discussed in Blanco, McCarthy, and Blanco (1980) and in Blanco (1986, 1987).

The assignment of cluster membership was rather subjective. Generally, a circle was drawn around each cluster with a diameter guided by the overall stellar density on the direct plates. As it turns out, the circle diameters were generally close to or somewhat larger than 1′. All stars within the circle were considered to be members. If a color-magnitude diagram was available that gave some estimate of field contamination, it would be used as a further guide in setting the diameter of the circle. On the whole we felt it better to err in the direction that would underestimate cluster membership rather than including potential field stars. Finding charts for the C and M stars found in and around the clusters will be presented separately (Blanco and Frogel 1990).

The first four columns of Table 1 contain, respectively, the cluster name, our numbering sequence for the stars identified on the grism plate or from the red SIT frames, the spectral classification from the grism survey, and whether or not the star lay within the circle defining cluster membership. Underneath the cluster name is the SWB type. No spectral type is given in column (3) for stars picked out solely on the basis of redness from the SIT frames. The next two columns contain alternative identification numbers and spectral types, respectively, for the stars. The sources for both of these are given by the numbers in parenthesis in the two columns. There are a few cases where previous studies showed the presence of luminous cool giants in a cluster we surveyed, but these stars were not selected by us. In these instances entries in the first three columns of Table 1 will be missing. Such cases arose either from crowding problems or from the difficulty the grism technique has in identifying the earliest M stars.

### b) *Infrared Observations*

The new infrared data presented in this paper were obtained with the CTIO D3 InSb system on the 4 m reflector during 1981 and 1982. These data have been transformed to the photometric system defined by the CIT/CTIO standards of Elias *et al.* (1981). This is the same system as the Magellanic Cloud cluster and field data we have previously published with our collaborators. Hence, all of these data are directly comparable. Typically, aperture diameters used were between 3″ and 6″. These small sizes will minimize the contribution from the cluster background. The spacing between the signal and reference beams was varied to minimize contamination from neighboring stars.

Columns (7)–(9) of Table 1 give the newly measured *JHK* colors and magnitudes for the stars. Observational uncertainties $\geq 0.03$ mag are indicated in parentheses in hundredths of a magnitude. Reddening corrected magnitudes and colors (see below) are given in columns (10)–(12). For data taken from the literature, only reddening corrected values are given. However, uncertainties associated with these values are still put in columns (7)–(9). Apparent bolometric magnitudes calculated from the mean relations in Frogel, Persson, and Cohen (1980) are given in column (13). An M or C in this column indicates the assumed spectral type for the calculation if not given in columns (3) or (6). The code in column (14) indicates the date of the observation and where other infrared measurements of a given star may be found. Finally, column (15) contains references to notes given at the end of the table and additional identifications for the stars.

In addition to *JHK* colors, narrow-band $H_2O$ and CO indices were determined for a subset of the stars in Table 1. $K-L$ colors were determined for a subset of these. These additional data, corrected for reddening, are given in Table 2. For convenience, the colors and magnitudes from Table 1 are repeated for those stars that were deemed to be cluster members; the nonmembers are listed at the end of Table 2 with only the additional data. Table 2 also gives previously published narrow-band data for stars from Table 1 if no new data were obtained.

### c) *Reddening Corrections*

For the LMC Brunet (1975) gives four values for $E(B-V)$: 0.07 for the foreground value; 0.18 in high-absorption regions; 0.10 in low-absorption regions; 0.12 as a "global" value. The latter three values include the 0.07 foreground value. However, if an $E(B-V)$ for a cluster could be derived from photometry

TABLE 1

AGB STAR PHOTOMETRY

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kron 3 | 1 | C | Y | W54 (1) | C (2) | 11.94 | 1.22 | 0.33 | 11.93 | 1.19 | 0.32 | 14.76 | A,E | |
| (VI-VII) | 2 | C | Y? | MA1 (6) | | 12.26 | 1.13 | 0.31 | 12.25 | 1.10 | 0.30 | 14.99 | A,H | |
| | 3 | C | Y? | W24 (1) | C (2) | 11.71 | 1.25 | 0.39 | 11.70 | 1.22 | 0.38 | 14.56 | A,E,H | |
| | 4 | C | N | | | 11.63 | 1.22 | 0.35 | 11.62 | 1.19 | 0.34 | 14.45 | A | |
| | 5 | | Y | | | 13.07 | 1.01(3) | 0.16 | 13.06 | 0.98 | 0.15 | 15.88 | A | |
| | - | | Y | MA2 (6) | | ... | ... | ... | 12.73 | 0.85 | 0.11 | 15.26 | H | TLE26 |
| | - | | Y | E12 (12) | | ... | ... | ... | 13.35 | 0.78 | 0.07 | 15.75 | I | |
| N121 | 1 | M1 | Y | TLE1(2) | Ctm(1) | 11.76(4) | 0.80(4) | 0.15(3) | 11.75 | 0.77 | 0.14 | 14.12 | A,E | 36 |
| VII | 2 | C | Y | V8 (3) | Cp (6) | 12.88 | 0.87 | 0.18 | 12.87 | 0.84 | 0.17 | 15.28 | A,E | |
| | 3 | | Y | V1 (3) | K4e(6) | 12.82 | 0.94 | 0.25 | 12.81 | 0.91 | 0.24 | 15.48 | A,E | |
| | 4 | | Y | 1-23 (4) | K5 (6) | ... | ... | ... | 13.37 | 0.80 | 0.09 | 15.79 | E | |
| N152 | 1 | C | N | | | 11.85 | 1.13 | 0.29 | 11.84 | 1.10 | 0.28 | 14.58 | A | |
| IV | 2 | C | N | | | 11.62 | 1.12 | 0.30 | 11.61 | 1.09 | 0.29 | 14.34 | A | |
| | 3 | C | N | | | 12.59 | 1.15(3) | 0.30 | 12.58 | 1.12 | 0.29 | 15.34 | A | |
| | 4 | C | N | | | 10.75 | 1.49 | 0.53 | 10.74 | 1.46 | 0.52 | 13.78 | A | |
| | 5 | C | Y | MA1 | | 11.62 | 1.21 | 0.35 | 11.61 | 1.18 | 0.34 | 14.43 | A | |
| | 6 | M0 | Y | C19 (5) | M0 (5) | 12.33 | 1.00 | 0.18 | 12.32 | 0.97 | 0.17 | | | |
| | - | | Y | TLE26(2) | | ... | ... | ... | 11.52 | 0.88 | 0.12 | 14.12 | H | |
| | - | | Y | W84 (7) | S (12) | ... | ...(4) | ... | 11.99 | 1.05 | 0.21 | 14.66 | E,I | 5-3 |
| | - | | Y | TLE30(2) | K5 (6) | ... | ...(6) | ...(4) | 12.64 | 0.92 | 0.19 | 15.15 | E,I | 5-7, W87 |
| | - | | Y | TLE35(2) | (C)(6) | ... | ... | ... | 10.83 | 1.48 | 0.56 | 13.88 | | |
| | 11 | C | Y | H23 (5) | C,2 (5) | 11.68 | 1.16 | 0.32 | 11.67 | 1.13 | 0.31 | 14.44 | A,E,H | |
| N220 | 1 | C | N | | | 11.90 | 1.13(3) | 0.32 | 11.88 | 1.09 | 0.30 | 14.61 | A | |
| III | 2 | C | N | | | 11.35 | 1.53(3) | 0.53 | 11.33 | 1.49 | 0.51 | 14.39 | A | |
| | 3 | M | N | | | 11.78 | 0.86(3) | 0.22 | 11.76 | 0.82 | 0.20 | 14.22 | A | |
| | 4 | M | N | | | 10.11 | 1.06 | 0.20 | 10.09 | 1.02 | 0.18 | 12.98 | A | |
| | 5 | M | N | | | 11.36 | 1.06 | 0.23 | 11.34 | 1.02 | 0.21 | 14.23 | A | |
| | 6 | C | N | | | | | | | | | | A | 4 |
| N231 | 1 | C | N | | | 10.59 | 0.99 | 0.25 | 10.57 | 0.95 | 0.23 | 13.13 | A | |
| (II-III) | 2 | C | N | | | 11.33 | 1.40 | 0.48 | 11.31 | 1.36 | 0.46 | 14.28 | A | |
| | 3 | M | N | | | 10.77 | 0.80 | 0.23 | 10.75 | 0.76 | 0.21 | 13.10 | A | |
| | 4 | C | N | | | 11.62 | 1.60 | 0.58 | 11.60 | 1.56 | 0.56 | 14.71 | A | |
| | 5 | C | N | | | 11.46 | 1.34 | 0.43 | 11.44 | 1.30 | 0.41 | 14.36 | A | |
| N265 | 1 | M2 | Y | | | 10.95 | 1.05 | 0.20 | 10.92 | 0.99 | 0.18 | 13.76 | A | 1 |
| III | 2 | C | N | | | 11.43 | 1.64 | 0.58 | 11.40 | 1.58 | 0.56 | 14.52 | A | |
| | 3 | C | N | | | 11.56 | 1.55 | 0.56 | 11.53 | 1.49 | 0.54 | 14.58 | A | |
| N269 | 1 | C | N | | | 10.12 | 1.62 | 0.58 | 10.09 | 1.56 | 0.56 | 13.19 | A | |
| III-IV | 2 | C | N | | | 10.49 | 1.64 | 0.60 | 10.46 | 1.58 | 0.58 | 13.58 | A | |
| | 3 | C | N | | | 11.78 | 1.39(3) | 0.45 | 11.75 | 1.33 | 0.43 | 14.69 | A | |
| | 4 | C | N | | | 11.13 | 1.30 | 0.43 | 11.10 | 1.24 | 0.41 | 13.97 | A | |
| | 5 | C | N | | | 10.16 | 1.62 | 0.57 | 10.13 | 1.56 | 0.55 | 13.24 | A | |
| | 6 | M | Y | | | 10.86 | 1.04 | 0.23 | 10.83 | 0.96 | 0.21 | 13.62 | A | strong Hα |
| N299 | 1 | C | N | | | 11.54 | 1.27 | 0.38 | 11.51 | 1.21 | 0.36 | 14.35 | A | |
| I | 2 | C | N | | | 12.24 | 1.13(3) | 0.35 | 12.21 | 1.07 | 0.33 | 14.91 | A | |
| | 3 | C | N | | | 10.76 | 1.58 | 0.56 | 10.73 | 1.52 | 0.54 | 13.81 | A | |
| | 4 | C | N | | | 11.06 | 1.47 | 0.53 | 11.03 | 1.41 | 0.51 | 14.04 | A | |
| | 5 | M0? | Y | | | 9.91 | 0.91 | 0.15 | 9.88 | 0.85 | 0.13 | 12.41 | A | |
| N306 | 1 | C | N | | | 12.22 | 1.01 | 0.28 | 12.19 | 0.95 | 0.26 | 14.75 | A | |
| (III) | 2 | C | N | | | ... | ... | ... | ... | ... | ... | ... | | 2 |
| | 3 | C | N | | | 11.51 | 1.47 | 0.50 | 11.48 | 1.41 | 0.48 | 14.49 | A | |
| | 4 | M2 | Y | | | 11.80 | 0.81 | 0.13 | 11.77 | 0.75 | 0.11 | 14.10 | A | |
| | 5 | M3? | Y | | | 3.40 | 0.71 | 0.13 | 13.37 | 0.65 | 0.11 | 15.49 | A | |
| | 6 | M2 | Y | | | 13.15 | 0.18 | 0.05 | 13.12 | 0.12 | 0.03 | | A | |
| | 7 | M1 | Y | | | 11.67 | 0.84(3) | 0.13 | 11.64 | 0.78 | 0.11 | 14.02 | A | |
| | 8 | | Y | | | 11.62 | 0.85 | 0.15 | 11.59 | 0.79 | 0.13 | 13.99 | A | |
| N339 | 1 | C | N | | | 11.27 | 1.33 | 0.43 | 11.26 | 1.30 | 0.42 | 14.18 | A | |
| VII | 2 | C | N | G151 | C,3 (6) | 11.36 | 1.45 | 0.48 | 11.35 | 1.42 | 0.47 | 14.37 | A,E,H | |
| | 3 | M1 | Y | TLE2(2) | | 13.03(4) | 0.95 | 0.16 | 13.02 | 0.92 | 0.15 | 15.71 | A,H | |
| | 4 | C? | Y | TLE4 | | 13.19 | 0.87 | 0.13 | 13.18 | 0.84 | 0.12 | 15.59 | A,H | |
| | 5 | M0 | Y | TLE3 | | 12.93(3) | 0.92(3) | 0.17 | 12.92 | 0.89 | 0.16 | 15.54 | A | G22(7) |

TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 6 | C | N | | | 13.54(3) | 0.91(3) | 0.13(3) | 13.53 | 0.88 | 0.12 | 15.99 | A | |
| | 7 | ... | | | | ... | ... | ... | ... | ... | ... | | | |
| | | | N? | TLE1 | M0 (6) | ... | ... | .... | 12.07 | 0.93 | 0.18 | | E,H | G87(7) |
| N346 | | | | | | | | | | | | | | 3 |
| N361 | 1 | M2 | Y | I-45(13) | M (2,6) | 11.99 | 0.98 | 0.21 | 11.97 | 0.94 | 0.19 | 14.71 | A,E | |
| | 2 | C | N | | | 10.75 | 1.98 | 0.81 | 10.73 | 1.94 | 0.79 | 14.00 | A | |
| | | | Y? | I-9 | Ctm(6) | ... | ... | ... | 12.94 | 0.87 | 0.14 | 15.52(M) | E | |
| | | | Y | I-16 | | | | | 12.86 | 0.90 | 0.11 | 15.50(M) | E | |
| | | | Y | I-35 | | 13.57 | 0.84 | 0.06 | 13.55 | 0.80 | 0.04 | 15.97(M) | E | |
| | | | Y | I-40 | | ... | ... | ... | 13.27 | 0.82 | 0.14 | 15.73(M) | E | |
| N411 | 1 | C | N | | | 12.11 | 1.26 | 0.41 | 12.09 | 1.22 | 0.39 | 14.94 | A | |
| V-VI | 2 | C | N | | | 11.00 | 1.85 | 0.77 | 10.98 | 1.81 | 0.75 | 14.21 | A | |
| | 3 | C | N | | | 10.87 | 1.14 | 0.27 | 10.85 | 1.10 | 0.25 | 13.59 | A | |
| | 4 | C | Y | AM-2(6) | | 11.17 | 1.45 | 0.51 | 11.15 | 1.41 | 0.49 | 14.16 | A,E | |
| | 5 | C | Y | AM-1(6) | | 11.12 | 1.43 | 0.53 | 11.10 | 1.39 | 0.51 | 14.09 | A,E | |
| N416 | 1 | C | N | | | 11.05 | 1.44 | 0.48 | 11.02 | 1.38 | 0.46 | 14.01 | A | |
| VI | 2 | C? | Y | TLE1(2) | | 12.25(3) | 1.02(3) | 0.28(3) | 12.22 | 0.96 | 0.26 | 14.80 | A,E | |
| | 3 | C | N | | | 11.43 | 1.55 | 0.57 | 11.40 | 1.49 | 0.55 | 14.46 | A | |
| | 4 | C | N | | | 11.76 | 1.29 | 0.40 | 11.73 | 1.23 | 0.38 | 14.59 | A | |
| | 5 | C | N | | | 11.59 | 1.39 | 0.44 | 11.56 | 1.33 | 0.42 | 14.50 | A | |
| | 6 | | Y | TLE2(2) | | ... | ... | ... | 12.85 | 0.89 | 0.13 | 15.47(M) | E | 19 |
| | 7 | | Y? | | | 12.04(4) | 0.73(3) | 0.11 | 12.01 | 0.67 | 0.09 | 14.18 | A | 20 |
| N419 | 4 | C | N | | | 11.34 | 1.46 | 0.50 | 11.32 | 1.42 | 0.48 | 14.34 | A | |
| V | 5 | C | N | W135(7) | C,3 (6) | 10.70 | 1.82 | 0.71 | 10.68 | 1.78 | 0.69 | 13.90 | A,E,I | (=BR1) |
| | 6 | C | N | | | 10.63 | 1.63 | 0.65 | 10.61 | 1.59 | 0.63 | 13.73 | A | 6 |
| | 7 | C | N | | | 11.43 | 1.55 | 0.56 | 11.41 | 1.51 | 0.54 | 14.48 | A | |
| | 8 | C | N | | | 11.67 | 1.09 | 0.31 | 11.65 | 1.05 | 0.29 | 14.34 | A | |
| | 9 | C | N | | | 11.28 | 1.57 | 0.59 | 11.26 | 1.53 | 0.57 | 14.34 | A | |
| | 10 | C? | N? | TLE16(2) | | 10.62 | 2.51(3) | 1.14 | 10.60 | 2.47 | 1.12 | 13.92(C) | A,H | |
| | 11 | C | Y | TLE20 | C,1 (6) | ... | ... | ... | 10.96 | 1.56 | 0.57 | 14.07 | E,I | |
| | 12 | C | Y | TLE21 | C (2) | ... | ... | ... | 10.78 | 1.64 | 0.62 | 13.93 | E,I | |
| | 13 | - | Y | TLE19 | K5 (12) | ... | ... | ... | 12.35 | 0.91 | 0.15 | 14.86 | D,I | W90,5-14 |
| | 14 | C | Y | S-15 | | ... | ... | ... | 12.28 | 0.85 | 0.16 | 14.71 | D,E | |
| | 15 | C | Y | TLE18 | | 10.94(3) | 1.78 | 0.70 | 10.92 | 1.74 | 0.68 | 14.12 | A,E,H, | BR6 |
| | 16 | C | Y | TLE22 | C (2) | 10.64(4) | 1.76 | 0.65 | 10.62 | 1.72 | 0.63 | 13.81 | A,E | 8 |
| | 17 | C | Y | TLE23 | C (2) | 11.17(4) | 1.50 | 0.54 | 11.15 | 1.46 | 0.52 | 14.19 | A,E | 8 |
| | 18 | C | Y | TLE29(2) | C (2) | ... | ... | ... | 11.28 | 1.43 | 0.50 | 14.30 | E,I | BR5 |
| | 19 | C | Y | TLE28 | | 11.52 | 1.51 | 0.56 | 11.50 | 1.47 | 0.54 | 14.54 | A,H,I | S-20 |
| | 20 | C | Y | TLE36 | | 10.60(4) | 1.58 | 0.57 | 10.58 | 1.54 | 0.55 | 13.67 | A,H | 7 |
| | 21 | | Y | | | 11.04(4) | 1.18(4) | 0.30(3) | 11.02 | 1.14 | 0.28 | 13.80 | A | 7 |
| | | | | | | | | | | | | 14.04 | | |
| | 22 | | Y | TLE27 | | 10.76(4) | 1.60 | 0.62 | 10.74 | 1.56 | 0.60 | 13.85(C) | A,E, | Not 6-2 |
| | 23 | | Y | TLE24 | | 11.45(4) | 1.05(8) | 0.21 | 11.43 | 1.01 | 0.19 | 14.07 | A | 6-4 ,9 |
| | | | | | | | | | | | | 14.31 | | |
| | 24 | C | Y | TLE25 | | 11.06(4) | 1.35 | 0.49 | 11.04 | 1.31 | 0.47 | 13.97 | A,H | 6-5 ,9 |
| | 25 | C | N | | | 11.71 | 1.13 | 0.30 | 11.69 | 1.09 | 0.28 | 14.41 | A,H | 4-133 |
| | - | | Y | TLE26 | | ... | ... | ... | 11.52 | 0.88 | 0.12 | 14.12 | H | |
| | - | | Y | W84 (7) | S (12) | ... | ...(4) | ... | 11.99 | 1.05 | 0.21 | 14.66 | E,I | 5-3 |
| | - | | Y | TLE30 | K5 (6) | ... | ...(6) | ...(4) | 12.64 | 0.92 | 0.19 | 15.15 | E,I | 5-7, W87 |
| | - | | Y | TLE35 | (C)(6) | ... | ... | ... | 10.83 | 1.48 | 0.56 | 13.88 | E | |
| | - | | Y | TLE37 | ? (6) | ... | ... | ... | 11.51 | 0.98 | 0.24 | 14.33 | E | 6-6 |
| | - | | Y | W71 (7) | | ... | ... | ... | 13.33 | 0.90 | 0.14 | 15.97 | E,I | 5-5 |
| | - | | Y | W108 (7) | | ... | ... | ... | 12.99 | 0.88 | 0.13 | 15.59 | E | |
| | - | | Y | TLE31 | K5(12) | ... | ... | ... | 12.65 | 0.94 | 0.26 | 15.39 | I | 5-6 |
| | - | | Y | TLE33 | K5(12) | ... | ... | ... | 12.17 | 0.89 | 0.14 | 14.79 | I | 6-2 |
| | - | | Y | TLE34 | K5(12) | ... | ... | ... | 12.62 | 0.91 | 0.13 | 15.29 | I | |
| | - | | Y | 6-1 | K5(12) | ... | ... | ... | 12.15 | 0.85 | 0.13 | 14.68 | I | |
| N602 | 1 | M | Y? | | | ... | ... | ... | ... | ... | ... | | | 5 |
| | 2 | C | N | | | 11.04 | 1.52 | 0.55 | 11.03 | 1.49 | 0.54 | 14.09 | A | |
| | 3 | C | N | | | 11.61 | 1.29 | 0.41 | 11.60 | 1.26 | 0.40 | 14.49 | A | |
| | 4 | M | N | | | 10.91 | 1.12 | 0.21 | 10.90 | 1.09 | 0.20 | 13.87 | A | |
| | 5 | M | N | | | 11.39 | 0.80 | 0.25 | 11.38 | 0.77 | 0.24 | 13.75 | A | |

TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N1651 | 2 | M | N | | | 10.98 | 1.18 | 0.39 | 10.95 | 1.12 | 0.37 | 13.95 | A | |
| (V) | 3 | M | N | | | 12.59 | 0.87 | 0.29 | 12.56 | 0.81 | 0.27 | 15.00 | A | |
| | 4 | C | Y | H4328 | C,3 (6) | ... | ... | ... | 11.50 | 1.25 | 0.38 | 14.38 | D,E | |
| | 5 | M | Y | H4325 | M4 (6) | ... | ... | ... | 11.26 | 1.04 | 0.21 | 14.18 | D,E | |
| | 6 | M | Y | H3304 | S (12) | 10.50 | 1.16 | 0.28 | 10.47 | 1.10 | 0.26 | 13.45 | A.D.E,I | |
| | 7 | M | Y | H2421 | S (12) | ... | ... | ... | 11.17 | 1.13 | 0.29 | 14.18 | D,E | |
| | 8 | C | N | | | 11.72 | 1.35 | 0.42 | 11.69 | 1.29 | 0.40 | 14.60 | A | |
| N1652 | 1 | M0? | Y | | | 12.75 | 0.92 | 0.15 | 12.72 | 0.86 | 0.13 | 15.27 | A | |
| (VI) | 2 | M0? | Y | | | 12.41 | 0.98 | 0.16 | 12.38 | 0.92 | 0.14 | 15.07 | A | |
| | 3 | M0? | Y | H3210 | K3(8) | ... | ... | ... | 12.53 | 0.93 | 0.19 | 15.24 | D | |
| | 4 | M0? | Y | AM-1 | | ... | ... | .... | 12.28 | 0.89 | 0.14 | 14.90 | E | |
| | 5 | M0? | N | | | 12.48 | 0.99 | 0.16 | 12.45 | 0.93 | 0.14 | 15.16 | A | |
| | 6 | M | N | HHU2406 | | 11.68 | 1.07 | 0.21 | 11.65 | 1.01 | 0.19 | 14.53 | A | |
| N1751 | 1 | M1 | Y | TLE 5 | | 11.54 | 1.05 | 0.21 | 11.50 | 0.98 | 0.18 | 14.32 | B.H | |
| V | 2 | M3 | Y | TLE 4 | | 11.34 | 1.12 | 0.23 | 11.30 | 1.05 | 0.20 | 14.23 | B.H | |
| | 3 | C | Y | TLE 1 | C (2) | 9.91 | 1.62 | 0.57 | 9.87 | 1.55 | 0.54 | 12.97 | A.B.E | |
| | 4 | C? | Y | TLE 2 | | 10.45 | 1.72 | 0.64 | 10.41 | 1.65 | 0.61 | 13.57 | B.E | |
| | 5 | M? | Y | TLE 8 | | 11.10 | 1.23 | 0.33 | 11.06 | 1.16 | 0.30 | 14.10 | B | |
| | 6 | M3 | Y | TLE 3 | M (2) | 10.91 | 1.11 | 0.22 | 10.87 | 1.04 | 0.19 | 13.79 | B,E | |
| | 7 | M5 | N | | | 11.07 | 1.16 | 0.30 | 11.03 | 1.09 | 0.27 | 14.00 | A | |
| | 8 | C | N | | | 10.39 | 1.85 | 0.69 | 10.35 | 1.78 | 0.66 | 13.57 | A | |
| | 9 | C | N | | | 11.42 | 1.19 | 0.31 | 11.38 | 1.12 | 0.28 | 14.14 | A | |
| | 10 | C | N | | | 11.02 | 1.54 | 0.50 | 10.98 | 1.47 | 0.47 | 14.02 | A | |
| | 11 | C | N | | | 10.42 | 1.78 | 0.66 | 10.38 | 1.71 | 0.63 | 13.56 | A | |
| | 12 | M6.5 | N | | | 10.46 | 1.15 | 0.37 | 10.42 | 1.08 | 0.34 | 13.38 | A | |
| | 13 | C | N | | | 11.31 | 1.48 | 0.48 | 11.27 | 1.41 | 0.45 | 14.28 | A | |
| N1783 | 1 | M | Y | TLE 2 | | ... | ... | ... | 11.24 | 1.07 | 0.23 | 14.19 | D,H | G7 |
| V | 2 | M | Y | TLE 8 | | 11.49 | 1.08 | 0.20 | 11.46 | 1.02 | 0.18 | 14.35 | B,H | |
| | 3 | M | Y | TLE 7 | | ... | ... | ... | 11.56 | 1.01 | 0.20 | 14.20 | D,H | G14 |
| | 4 | M | Y | TLE 6 | M4 (8) | ... | ... | ... | 11.31 | 1.02 | 0.20 | 14.20 | D | G13 |
| | 5 | | Y | | | 12.95(3) | 0.95(3) | 0.17(3) | 12.92 | 0.89 | 0.15 | 15.54(M) | B | |
| | 6 | M | Y | TLE14 | | 12.73(3) | 0.96(3) | 0.16 | 12.70 | 0.90 | 0.14 | 15.35 | B | G4 |
| | 7 | C | Y | TLE10 | | 11.36 | 1.06 | 0.21 | 11.33 | 1.00 | 0.19 | 13.95 | B,E | |
| | 8 | C | Y | G6 (9) | | 13.17 | 0.80 | 0.13 | 13.17 | 0.74 | 0.11 | 15.44 | C,G | 21 |
| | 9 | M | Y | TLE15 | M1 (8) | 11.78 | 1.00 | 0.18 | 11.75 | 0.94 | 0.16 | 14.49 | A,D | G40,LPV?(9) |
| | 10 | C | Y | TLE 1 | C (2) | 10.26 | 1.93 | 0.77 | 10.23 | 1.87 | 0.75 | 13.47 | B,H | |
| | 11 | M | Y | TLE11 | | 11.51 | 1.00(3 | 0.18(3) | 11.48 | 0.94 | 0.16 | 14.21 | A,H | |
| | 12 | M | Y | | | 11.84 | 0.97(3 | 0.18 | 11.81 | 0.91 | 0.16 | 14.47 | A | |
| | 13 | M | Y | TLE 9 | S (2) | 10.93 | 1.11 | 0.27 | 10.90 | 1.05 | 0.25 | 13.83 | B,E, | |
| | 14 | M | Y | TLE 5 | S (2) | 11.23 | 1.09 | 0.23 | 11.20 | 1.03 | 0.21 | 14.11 | B,H | |
| | 15 | C | Y | TLE 3 | C (2) | ... | ... | ... | 10.33 | 1.54 | 0.57 | 13.41 | C,D | G30 |
| | 16 | M | Y | TLE 4 | M4 (8) | ... | ... | ... | 11.07 | 1.03 | 0.22 | 13.98 | D,H | G32 |
| | 17 | C | Y? | | C (10) | 10.09 | 1.46 | 0.49 | 10.06 | 1.38 | 0.47 | 13.05 | A | V2 |
| N1806 | 1 | C | Y | AM9(6) | | 10.32(3) | 1.81(3) | 0.68(3) | 10.28 | 1.74 | 0.65 | 13.48 | A.E | |
| V | 2 | M | Y | TLE 5 | | 11.08 | 1.04 | 0.19 | 11.04 | 0.97 | 0.16 | 13.84 | A.H | |
| | 3 | C | Y | TLE 1 | | 10.42(3) | 1.68 | 0.63 | 10.38 | 1.61 | 0.60 | 13.52 | A,E | |
| | 4 | | Y | TLE 2 | Ctm (2) | 11.28(3) | 1.04 | 0.21 | 11.24 | 0.97 | 0.18 | 14.04 | A,E | |
| | 5 | M | Y | TLE 3 | | 11.37(3) | 1.02 | 0.21 | 11.33 | 0.95 | 0.18 | 14.09 | A,E | |
| | 6 | M | Y | TLE 6 | | 11.41 | 1.07 | 0.22 | 11.37 | 1.00 | 0.19 | 14.23 | A,H | |
| | 7 | M | Y | TLE 7 | | 12.04 | 1.03 | 0.19 | 12.00 | 0.96 | 0.16 | 14.78 | A,H | |
| | 8 | M? | Y | TLE 8 | | 11.79 | 0.99 | 0.18 | 11.75 | 0.92 | 0.15 | 14.44 | A,H | |
| | 9 | M? | Y | | | 12.18 | 0.99 | 0.16 | 12.14 | 0.92 | 0.13 | 14.83 | A | |
| | 11 | M | N | | | 11.22 | 1.15 | 0.25 | 11.18 | 1.08 | 0.22 | 14.14 | A | |
| | 12 | M | N | | | 11.59 | 1.08 | 0.20 | 11.55 | 1.01 | 0.17 | 14.43 | A | |
| | 13 | C | N | | | 11.35 | 1.37 | 0.42 | 11.31 | 1.30 | 0.39 | 14.23 | A | |
| | 14 | M | N | | | 10.92 | 1.17 | 0.29 | 10.88 | 1.10 | 0.26 | 13.86 | A | |
| | 15 | C | N | | | 10.64 | 1.74 | 0.65 | 10.60 | 1.67 | 0.62 | 13.77 | A | |
| | 16 | C | Y? | | | 10.61 | 1.62 | 0.56 | 10.57 | 1.55 | 0.53 | 13.67 | A | |
| | 17 | C | Y? | | | 10.66 | 1.80 | 0.68 | 10.62 | 1.73 | 0.65 | 13.82 | A | |
| | 18 | M | N? | | | 11.35 | 1.09 | 0.20 | 11.31 | 1.02 | 0.17 | 14.20 | A | |
| | 19 | M | N? | | | 11.53 | 1.12 | 0.21 | 11.49 | 1.05 | 0.18 | 14.42 | A | |
| | 20 | M | N? | | | 11.12 | 1.10 | 0.21 | 11.08 | 1.03 | 0.18 | 13.99 | A | |
| | 21 | M | Y? | | | 12.17 | 1.02 | 0.19 | 12.13 | 0.95 | 0.16 | 14.89 | A | |
| | | | Y | TLE 4 | | 11.58(3) | 1.00 | 0.18 | 11.54 | 0.93 | 0.15 | 14.25 | A,H | |

TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N1841 | 1 | M | Y | G117 | | 12.20 | 0.84 | 0.15 | 12.88 | 0.80 | 0.14 | 15.30 | A,D | 10,11 |
| VII | 2 | M | Y | G117 | | | | | | | | | A,D | 11 |
| | 3 | M | Y | TLE 2 | | ... | ... | ... | 12.57 | 0.82 | 0.20 | 15.03 | D | G113 |
| | 4 | M | Y | TLE 1 | | 12.80 | 0.78(3) | 0.12 | 12.78 | 0.74 | 0.11 | 15.09 | A,H | |
| | 5 | M | Y | | | 13.34 | 0.71 | 0.12 | 13.32 | 0.67 | 0.12 | 15.49 | A | |
| | 6 | M | Y? | | | 13.31 | 0.80(3) | 0.15 | 13.19 | 0.76 | 0.14 | 15.54 | A | G51 |
| | 7 | M | N | | | 12.29(3) | 0.64(4) | 0.12(3) | 12.27 | 0.60 | 0.12 | 14.09 | A | |
| N1846 | 1 | C | Y | TLE 1 | C (2,6) | ... | ... | ... | 10.56 | 1.68 | 0.64 | 13.73 | C,I | H21 |
| V | 2 | C | Y | TLE 2 | C (2,6) | ... | ... | ... | 10.45 | 1.72 | 0.63 | 13.64 | C,I | HHU4403 |
| | 3 | C | Y | TLE 5 | | 10.30(3) | 1.79 | 0.69 | 10.27 | 1.73 | 0.67 | 13.54 | A,B, | |
| | 4 | C | Y | TLE 4 | | 10.28(3) | 1.69(3) | 0.61(3) | 10.25 | 1.63 | 0.59 | 13.40 | B,E | |
| | 5 | C | Y | TLE11 | | 10.82(3) | 1.58(3) | 0.51 | 10.79 | 1.52 | 0.49 | 13.87 | B,H | |
| | 6 | M | Y | TLE14 | | 11.55(4) | 1.12 | 0.22 | 11.52 | 1.06 | 0.20 | 14.46 | B,H | |
| | 7 | M | Y | H39 | M (6) | 11.74 | 1.03 | 0.18 | 11.71 | 0.97 | 0.16 | 14.51 | B,C | |
| | 8 | M | Y | TLE10 | K5 (8) | ... | ... | ... | 11.90 | 0.97 | 0.17 | 14.70 | D | H58 |
| | 9 | M | Y | TLE8 | | 11.25(3) | 1.08(3) | 0.18(3) | 11.22 | 1.02 | 0.16 | 14.11 | A,H, | |
| | 10 | M | Y | TLE 9 | | 11.62 | 1.09 | 0.20 | 11.59 | 1.03 | 0.18 | 14.50 | A,H | |
| | 11 | M | Y | | | 11.43(3) | 1.06 | 0.22 | 11.40 | 1.00 | 0.20 | 14.26 | A | |
| | 12 | M | Y | | | 12.20 | 1.01 | 0.17 | 12.17 | 0.95 | 0.15 | 14.92 | A | |
| | 13 | M | Y | TLE13 | S (12) | 11.00 | 1.12 | 0.27 | | 1.08 | 0.26 | 13.92 | B,E,G,I | |
| | 14 | M | Y | TLE16 | | 11.44 | 1.01 | 0.22 | 11.41 | 0.95 | 0.20 | 14.17 | A,I | |
| | 15 | C | Y | TLE 3 | C (2,6) | 10.30 | 1.70 | 0.61 | 10.27 | 1.64 | 0.59 | 13.42 | A,C,I | HHU4508 |
| | 16 | C | Y | | | 11.55(3) | 1.21 | 0.36 | 11.52 | 1.15 | 0.34 | 14.31 | A | |
| | 17 | M | Y | TLE17 | | 11.91 | 1.08 | 0.24 | 11.88 | 1.02 | 0.22 | 14.77 | A,H | |
| | 18 | C | Y | TLE12 | C (2,6) | ... | ... | ... | 11.25 | 1.32 | 0.43 | 14.19 | D,I | H1 |
| | 19 | C | Y | TLE 6 | C (2,6) | ... | ... | ... | 10.31 | 1.57 | 0.58 | 13.43 | C,I | H6,HHU1302 |
| | 20 | M? | Y | | | 12.55(3) | 0.94(3) | 0.15 | 12.52 | 0.88 | 0.13 | 15.12 | A | |
| | 21 | M | Y? | TLE 7 | | 11.40 | 1.08 | 0.21 | 11.37 | 1.02 | 0.19 | 14.26 | A,I | HH4251 |
| | 22 | C | N | | | 10.77 | 1.40 | 0.44 | 10.74 | 1.34 | 0.42 | 13.69 | A | |
| | 23 | C | N | | | 10.70 | 1.66 | 0.61 | 10.67 | 1.60 | 0.59 | 13.80 | A | |
| | 24 | C | N | | | 12.47 | 0.96 | 0.23 | 12.44 | 0.90 | 0.21 | 14.93 | A | 13 |
| | 25 | C | N | | | 11.26 | 1.31 | 0.42 | 11.23 | 1.25 | 0.40 | 14.11 | A | |
| | 26 | C | N | | | 10.37 | 1.62 | 0.59 | 10.34 | 1.56 | 0.57 | 13.45 | A | |
| | – | | N? | TLE15 | | 11.53 | 1.09 | 0.21 | 11.50 | 1.03 | 0.19 | 14.41 | A,H | |
| | – | | Y | TLE18 | | 12.44 | 1.05 | 0.20 | 12.41 | 0.99 | 0.18 | 15.25(M) | A,I | H1, HHU4406 |
| N1850 | 1 | M | Y | C27 | | 12.91 | 0.69 | 0.13 | 12.86 | 0.60 | 0.10 | 14.88 | G | 26 |
| (II) | 2 | M | Y | B43 | | 13.87(4) | 0.10(3) | 0.03(3) | 13.82 | 0.01 | 0.00 | | G | |
| | 3 | M | Y | B36 | | 10.84 | 0.95 | 0.21 | 10.79 | 0.86 | 0.18 | 13.59 | G | |
| | 4 | M0 | N? | C11 | | 11.27 | 1.01 | 0.21 | 11.22 | 0.92 | 0.18 | 13.91 | G | |
| | 5 | M1 | N | C20 | | 9.61 | 0.98 | 0.19 | 9.56 | 0.89 | 0.16 | 12.18 | G | |
| | 6 | ? | Y | B24 | | 11.70(3) | 0.95 | 0.20 | 11.65 | 0.86 | 0.17 | 14.25 | G | |
| | 7 | M3? | Y | B4 | | 11.13(4) | 0.72 | 0.10 | 11.08 | 0.63 | 0.07 | 13.40 | G | 23 |
| | 8 | M | Y | A39? | | 12.53(4) | 0.72(3) | 0.13 | 12.48 | 0.63 | 0.10 | 14.80 | G | 24 |
| | 9 | ? | Y | A37 | | 12.26(4) | 0.82 | 0.13 | 12.21 | 0.73 | 0.10 | 14.65 | G | 24 |
| | 10 | C | Y | B62? | | 10.76(3) | 1.62 | 0.58 | 10.71 | 1.53 | 0.55 | 13.90 | G | |
| | 11 | ? | Y | B58 | | 12.26(3) | 0.79 | 0.12 | 12.21 | 0.70 | 0.09 | 14.61 | G | |
| | 12 | M2 | N | D11 | | 11.33 | 0.98 | 0.20 | 11.28 | 0.89 | 0.17 | 13.90 | G | |
| | 13 | C | N | | | 10.63 | 1.79 | 0.66 | 10.58 | 1.70 | 0.63 | 13.76 | G | |
| | 14 | M4 | N | D49 | | 11.28 | 1.10 | 0.23 | 11.23 | 1.01 | 0.20 | 14.11 | G | |
| | – | M0 | Y? | C15 | | 11.03 | 0.96 | 0.19 | 10.98 | 0.87 | 0.16 | 13.81 | G | 25 |
| | – | M2 | Y? | C77 | | 11.45 | 0.94 | 0.17 | 11.40 | 0.85 | 0.14 | 14.09 | G | |
| | – | M0: | N | D41 | | 10.98 | 0.88 | 0.16 | 10.93 | 0.79 | 0.13 | 13.33 | G | |
| | – | | Y | A29 | | 11.22 | 0.99(3) | 0.17 | 11.17 | 0.90 | 0.14 | 14.06 | G | 25 |
| N1854 | 1 | ? | Y | AG9 | | 11.66(4) | 0.72 | 0.13 | 11.62 | 0.65 | 0.10 | 13.74 | G | 26,2 |
| II | 2 | ? | Y | A15 | | 11.14(4) | 0.86 | 0.16 | 11.10 | 0.79 | 0.13 | 13.44 | G | |
| | 4 | M0 | Y | C1 | | 10.67(3) | 0.77 | 0.14 | 10.63 | 0.70 | 0.11 | 13.03 | G | |
| | 5 | ? | Y | B3 | | 11.89(4) | 0.82 | 0.15 | 11.85 | 0.65 | 0.12 | 13.97 | G | |
| | 6 | ? | Y | B5 | | 12.55(4) | 0.74 | 0.12 | 12.51 | 0.67 | 0.09 | 14.67 | G | |
| | 7 | ? | Y | A33 | | 11.65(4) | 0.88 | 0.17 | 11.61 | 0.81 | 0.14 | 13.99 | G | |
| | 8 | M2? | Y | B93 | | 11.65(6) | 0.82 | 0.15 | 11.61 | 0.75 | 0.12 | 13.93 | G | |
| | 9 | M1 | N? | C24 | | ... | ... | ... | ... | ... | ... | ... | | |
| | 10 | C | N | | | 12.60 | 0.83 | 0.14 | 12.56 | 0.76 | 0.11 | 14.85 | G | |
| | 11 | M1 | N | D2 | | ... | ... | ... | ... | ... | ... | .... | | 27 |

TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | C | N | | | 12.36 | 0.84 | 0.15 | 12.32 | 0.77 | 0.12 | 14.63 | G | |
| | 13 | M2 | N | D9 | | ... | ... | ... | ... | ... | ... | ... | | |
| | 14 | M4 | N | | | ... | ... | ... | ... | ... | ... | ... | | |
| | 15 | M2 | N | | | ... | ... | ... | ... | ... | ... | ... | | |
| | 16 | M1 | N | D28 | | 11.18(3) | 0.95 | 0.17 | 11.14 | 0.88 | 0.14 | 13.74 | G | |
| | 17 | M2 | N | D33 | | ... | ... | ... | ... | ... | ... | ... | | |
| | - | - | Y | A63 | | 12.14(6) | 0.81(3 | 0.09 | 12.10 | 0.74 | 0.06 | 14.41 | G | |
| | - | - | N? | | | 11.41(3) | 0.96 | 0.16 | 11.37 | 0.89 | 0.13 | 13.99 | G | |
| N1866 | 1 | | Y | MA4 | | 9.70 | 1.09 | 0.24 | 9.67 | 1.03 | 0.22 | 12.58 | A,H | 12 |
| III | 2 | M | Y | BIV-55(11) | | 10.79 | 1.01 | 0.19 | 10.76 | 0.95 | 0.17 | 13.52 | A | |
| | 3 | M | Y | BI-36(11) | M5(6) | 10.24 | 1.14 | 0.25 | 10.21 | 1.08 | 0.23 | 13.18 | A,H | MA2 |
| | 4 | M | Y | BII-16(11) | M5(6) | 9.69 | 1.17 | 0.27 | 9.66 | 1.11 | 0.25 | 12.65 | A,H | MA1 |
| | 5 | M | N | | | 11.19 | 1.16 | 0.26 | 11.16 | 1.10 | 0.24 | 14.14 | A | |
| | 6 | M | N | | | 10.95 | 1.01 | 0.19 | 10.92 | 0.95 | 0.17 | 13.68 | A | |
| | 7 | C | N | | | 10.82 | 1.44 | 0.44 | 10.79 | 1.38 | 0.46 | 13.78 | A | |
| N1978 | 1 | C | Y? | | | 13.11(3) | 0.92(3) | 0.23 | 13.08 | 0.86 | 0.21 | 15.52 | B | |
| VI | 2 | C | Y? | TLE11 | C (2,6) | 11.60(3) | 1.45(3) | 0.44(3) | 11.57 | 1.39 | 0.42 | 14.56 | B,E | HHU2509 |
| | 3 | M? | Y | TLE5 | | 11.50(4) | 1.13(3) | 0.25(3) | 11.47 | 1.07 | 0.23 | 14.43 | B | |
| | 4 | M: | Y | TLE 4 | | 11.29(4) | 1.13(3) | 0.25(3) | 11.26 | 1.07 | 0.23 | 14.22 | B,E | |
| | 5 | C | Y | | | 11.16(3) | 1.18 | 0.32 | 11.13 | 1.12 | 0.30 | 13.90 | B | |
| | 6 | M? | Y | TLE10 | | 12.00(3) | 1.12(3) | 0.21(3) | 11.97 | 1.06 | 0.19 | 14.92 | B | |
| | 7 | C? | Y | TLE 3 | | ... | ... | ... | 9.87 | 1.75 | 0.71 | 13.07 | | |
| | 8 | M0? | Y | | | 12.78(4) | 0.91(3) | 0.12 | 12.75 | 0.85 | 0.10 | 15.28 | B | |
| | 9 | C | Y | TLE 6 | | 10.83(4) | 1.35(3) | 0.39(3) | 10.80 | 1.29 | 0.37 | 13.71 | B,H | |
| | 10 | M1 | Y | | | 11.14 | 1.12 | 0.21 | 11.11 | 1.06 | 0.19 | 14.05 | B | |
| | 11 | C | Y | TLE 7 | | 11.22(3) | 1.48(3) | 0.47(3) | 11.19 | 1.42 | 0.45 | 14.20 | B.E | |
| | 12 | M2 | Y | TLE 8 | | 11.99(3) | 1.13(3) | 0.21(3) | 11.96 | 1.07 | 0.19 | 14.91 | B,H | |
| | 13 | C | Y | TLE 1 | C (2,6) | ... | ... | ... | 10.50 | 1.66 | 0.62 | 13.66 | C | H1-25,HHU |
| | 14 | M2 | Y | | | 12.59(4) | 0.96(4) | 0.09 | 12.56 | 0.90 | 0.07 | 15.21 | B | |
| | 15 | M0? | Y | TLE 9 | | 12.25(6) | 1.08(3) | 0.19(3) | 12.22 | 1.02 | 0.17 | 15.11 | B,H | |
| | 16 | C | N? | TLE 2 | C (2,6) | ... | ... | ... | 11.10 | 1.45 | 0.49 | 14.13 | C | H1-12,HHU |
| | IR1- | | Y | | | 11.30 | 2.53(3) | 1.26 | 11.27 | 2.47 | 1.24 | 14.57(C) | A | |
| | IR1 | | | | | 10.91 | 2.72(3) | 1.41 | 10.88 | 2.66 | 1.39 | 14.12 | B | |
| | IR1 | | | | | 11.17 | 2.69(4) | 1.32 | 11.14 | 2.63 | 1.30 | | G | |
| | 17 | M0? | Y | | | 12.56 | 0.97 | 0.17 | 12.53 | 0.91 | 0.15 | 15.20 | G | |
| | 18 | M0? | N? | | | 13.23 | 0.98(3) | 0.17 | 13.20 | 0.92 | 0.15 | 15.89 | G | |
| | 19 | C | N | | | 11.17 | 1.01 | 0.24 | 11.14 | 0.95 | 0.22 | 13.70 | G | |
| N1987 | 1 | M | Y | | | 11.98 | 1.07(3) | 0.21 | 11.94 | 1.00 | 0.18 | 14.80 | A | 14 |
| IV | 2 | C | Y | TLE 5 | C (2) | 10.16 | 1.73 | 0.63 | 10.12 | 1.66 | 0.60 | 13.28 | A,E | |
| | 3 | | Y | | | 12.24(3) | 0.98 | 0.18 | 12.20 | 0.91 | 0.15 | 14.86 | A | |
| | 4 | M | Y | TLE 6 | | 11.53(3) | 1.10 | 0.24 | 11.49 | 1.03 | 0.21 | 14.40 | A | |
| | 5 | M | Y | TLE 1 | M (2) | ... | ... | ... | ... | | | | E | 18 |
| | 6 | M? | Y | TLE 2 | | ... | ... | ... | 10.23 | 0.96 | 0.20 | 13.02 | E | 18 |
| | 7 | M | Y? | TLE 4 | | 10.83 | 1.14 | 0.27 | 10.79 | 1.07 | 0.24 | 13.74 | A,E | |
| | 8 | C | Y? | TLE 3 | | 10.46 | 1.83 | 0.70 | 10.42 | 1.76 | 0.67 | 13.63 | A,E | |
| | 9 | C | N? | | | 11.33(3) | 1.69 | 0.64 | 11.29 | 1.62 | 0.61 | 14.43 | A | |
| | 10 | M | N | | | 12.25(3) | 1.02(3) | 0.19 | 12.21 | 0.95 | 0.16 | 14.97 | A | |
| | 11 | M | N | | | 12.11(3) | 1.07 | 0.21 | 12.07 | 1.00 | 0.18 | 14.93 | A | |
| | 12 | M | N | | | 10.95 | 1.10 | 0.24 | 10.91 | 1.03 | 0.21 | 13.82 | A | |
| | 13 | M | N | | | 11.10 | 1.18 | 0.29 | 11.06 | 1.11 | 0.26 | 14.05 | A | |
| | 14 | M | N | | | 11.14 | 1.15 | 0.26 | 11.10 | 1.08 | 0.23 | 14.06 | A | |
| | 15 | M | N | | | 11.48 | 1.15 | 0.23 | 11.44 | 1.08 | 0.20 | 14.40 | A | |
| | 16 | M | N | | | 11.52 | 1.11 | 0.25 | 11.48 | 1.04 | 0.22 | 14.40 | A | |
| | 17 | C | N | | | 10.22 | 1.73 | 0.64 | 10.18 | 1.66 | 0.61 | 13.35 | A | |
| | 18 | C | N | | | 10.71 | 1.46 | 0.54 | 10.67 | 1.39 | 0.51 | 13.66 | A | |
| | 19 | M | N | | | 12.00(3) | 1.02 | 0.19 | 11.96 | 0.95 | 0.16 | 14.72 | A | |
| | 20 | M | N | | | 12.17 | 1.09 | 0.22 | 12.13 | 1.02 | 0.19 | 15.02 | A | |
| N2058 | 1 | M5 | Y | | | 11.49 | 1.14 | 0.24 | 11.44 | 1.04 | 0.20 | 14.36 | G | 29 |
| III | 2 | M0-1 | Y | | | 12.76 | 0.82 | 0.17 | 12.71 | 0.72 | 0.13 | 14.98 | G | |
| | 3 | M0-1 | Y | | | 12.25(4) | 0.77 | 0.15 | 12.20 | 0.67 | 0.11 | 14.38 | G | 24 |
| | 4 | M3: | Y | | | ... | ... | ... | ... | ... | ... | | | 30 |
| | 5 | M2 | Y | | | 10.21 | 1.08 | 0.25 | 10.16 | 0.98 | 0.21 | 12.98 | G | |
| | 6 | M1: | Y | | | 11.83 | 0.77 | 0.13 | 11.78 | 0.67 | 0.09 | 13.95 | G | |
| | 6B | - | Y | | | 10.79 | 1.22 | 0.31 | 10.74 | 1.12 | 0.27 | 13.74 | G | |

TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 7 | M7 | Y? | | | 10.27 | 1.43 | 0.42 | 10.22 | 1.33 | 0.38 | 13.35 | G | 31 |
| | 8 | M0 | Y | | | ... | ... | ... | ... | ... | ... | | | 32 |
| | 9 | M1-2 | Y | | | 12.26 | 0.56 | 0.12 | 12.21 | 0.46 | 0.08 | 13.95 | G | 24 |
| | 10 | M1: | Y | | | ... | ... | ... | ... | ... | ... | | | 30 |
| | 11 | M0: | Y? | | | 11.99 | 0.85 | 0.15 | 11.94 | 0.75 | 0.11 | 14.27 | G | |
| | 12 | M3 | N? | | | 1'2.69 | 1.00 | 0.20 | 12.64 | 0.90 | 0.16 | 15.28 | G | |
| | 13 | M0 | N? | | | ... | ... | ... | ... | ... | ... | | | 30 |
| | 14 | M1: | N | | | 13.06(4) | 0.95(5) | 0.13(4) | 13.01 | 0.85 | 0.09 | 15.54 | G | |
| | 15 | M0: | N | | | 12.47 | 0.96 | 0.16 | 12.42 | 0.86 | 0.12 | 14.97 | G | |
| | 16 | M0: | N | | | 12.70 | 0.80 | 0.16 | 12.65 | 0.70 | 0.12 | 15.05 | G | |
| | 17 | M5 | N? | | | 12.40 | 0.94 | 0.16 | 12.35 | 0.84 | 0.12 | 14.86 | G | |
| | 18 | M4? | N? | | | ... | ... | ... | ... | ... | ... | | | 30 |
| | 19 | C | N | | | 10.66 | 1.37 | 0.41 | 10.61 | 1.27 | 0.37 | 13.50 | G | |
| | 20 | M7 | N | | | 11.98 | 1.19 | 0.26 | 11.93 | 1.09 | 0.22 | 14.90 | G | |
| | 1 | C | N | | | ... | ... | ... | .... | ... | ... | | | 32 |
| | 22 | C | N | | | 10.93 | 1.54 | 0.51 | 10.88 | 1.44 | 0.47 | 13.91 | G | |
| | 23 | M1 | N | | | 10.73 | 1.17 | 0.32 | 10.68 | 1.07 | 0.28 | 13.63 | G | |
| | 24 | M1 | N | | | ... | ... | ... | .... | ... | ... | | | |
| | 25 | C | N | | | 10.59 | 1.65 | 0.58 | 10.54 | 1.55 | 0.54 | 13.64 | G | |
| N2107 | 1 | M4 | Y | | | 9.94 | 1.21 | 0.28 | 9.88 | 1.10 | 0.24 | 12.86 | G,E | |
| IV | 2 | C | N | | | 10.07 | 1.66 | 0.59 | 10.01 | 1.55 | 0.55 | 13.11 | G | |
| | 3 | M3 | N? | | | 10.50 | 1.18 | 0.26 | 10.44 | 1.07 | 0.22 | 13.39 | G | |
| | 4 | M5 | N | | | 11.08 | 1.23 | 0.29 | 11.02 | 1.12 | 0.25 | 14.02 | G | |
| | 5 | M1 | Y? | | | 10.13 | 1.08 | 0.22 | 10.07 | 0.97 | 0.18 | 12.87 | G | |
| | 6 | M4 | N | | | 9.85 | 1.23 | 0.32 | 9.79 | 1.12 | 0.28 | 12.79 | G | |
| | 7 | M1 | N | | | 12.90(3) | 1.09 | 0.26 | 12.84 | 0.98 | 0.22 | 15.66 | G | |
| | 8 | C | N? | | | 10.62 | 1.75 | 0.64 | 10.56 | 1.64 | 0.60 | 13.71 | G | |
| | 9 | C | N | | | 10.73 | 1.31 | 0.38 | 10.67 | 1.20 | 0.34 | 13.51 | G | |
| | 10 | C | N | | | 10.04 | 1.72 | 0.62 | 9.98 | 1.61 | 0.58 | 13.12 | G | |
| | 11 | M0: | N | | | 12.47(3) | 1.17 | 0.23 | 12.41 | 1.06 | 0.19 | 15.35 | G | |
| N2108 | 1 | M1 | Y | TLE 2 | | 12.90 | 1.00 | 0.18 | 12.85 | 0.90 | 0.14 | 15.49 | G | |
| (V) | 2 | M? | Y | TLE 4 | | 13.30(3) | 0.79(3) | 0.11(3) | 13.25 | 0.69 | 0.07 | 15.46 | G | |
| | 3 | M? | Y | TLE 5 | | 13.73(3) | 0.81(3) | 0.18(3) | 13.68 | 0.71 | 0.14 | 15.93 | G | |
| | 4 | M2 | Y | TLE 3 | | 13.10(3) | 0.95 | 0.20 | 13.05 | 0.85 | 0.16 | 15.58 | G | |
| | 5 | C | Y | TLE 1 | C | 9.99 | 1.82 | 0.68 | 9.94 | 1.72 | 0.64 | 13.13 | G,H | |
| | 6 | M1? | Y | MA6 | | 11.80 | 0.93 | 0.18 | 11.75 | 0.83 | 0.14 | 14.23 | G,H | 33 |
| | 8 | C | N | | | 11.39 | 1.36 | 0.37 | 11.34 | 1.26 | 0.33 | 14.23 | G | |
| | 10 | M6 | N | | | 11.18 | 1.24 | 0.31 | 11.13 | 1.14 | 0.27 | 14.15 | G | |
| | 17 | C | N | | | 11.04 | 1.29 | 0.39 | 10.99 | 1.19 | 0.35 | 13.82 | G | |
| | 18 | C | N | | | 10.31 | 1.39 | 0.42 | 10.26 | 1.29 | 0.38 | 13.17 | G | |
| | 19 | C | N | | | 10.49 | 2.15 | 0.95 | 10.44 | 2.05 | 0.91 | 13.73 | G | |
| N2121 | 1 | M | Y | TLE 4 | | 12.29 | 1.13 | 0.23 | 12.26 | 1.07 | 0.21 | 15.21 | A,H | |
| VI | 2 | M | Y | TLE 2 | | 11.49(3) | 1.12 | 0.22 | 11.46 | 1.06 | 0.20 | 14.40 | A,H | |
| | 3 | M | Y | TLE 1 | | 11.79 | 1.08 | 0.22 | 11.76 | 1.02 | 0.20 | 14.65 | A,H | |
| | 4 | M | Y | | | 12.78 | 1.01(3) | 0.18 | 12.75 | 0.95 | 0.16 | 15.50 | A | |
| | 5 | | Y | TLE 6 | | 10.50 | 2.67 | 1.13 | 10.47 | 2.61 | 1.11 | 13.73 | G | |
| | | | | | | 10.14 | 2.29 | 0.98 | 10.11 | 2.23 | 0.96 | 13.43(c | A,H | 15 |
| | 6 | - | Y | | | 13.09 | 0.92 | 0.17 | 13.06 | 0.86 | 0.15 | 15.61 | A | |
| | 7 | M | Y | | | 13.25(3) | 0.92(3) | 0.18 | 13.22 | 0.86 | 0.16 | 15.77 | A | |
| | 8 | M | Y? | | | 12.25 | 1.08 | 0.22 | 12.22 | 1.02 | 0.20 | 15.11 | A | |
| | 9 | M | N | TLE 3 | | 12.70 | 0.80 | 0.15 | 12.67 | 0.74 | 0.13 | 14.98 | A | |
| | 10 | M | Y | | | 13.73 | 0.82(3) | 0.12 | 13.70 | 0.76 | 0.10 | 16.05 | A | |
| | 11 | M | Y | | | 13.35(3) | 0.94(4) | 0.17(3) | 13.32 | 0.88 | 0.15 | 15.92 | A | |
| | 12 | M | Y? | | | 12.69 | 1.01 | 0.18 | 12.66 | 0.95 | 0.16 | 15.41 | A | |
| | 13 | M | Y | | | 13.72 | 0.80 | 0.05 | 13.69 | 0.84 | 0.03 | 16.20 | A | |
| | 14 | M | Y | | | 12.78(3) | 0.99(3) | 0.17 | 12.75 | 0.93 | 0.15 | 15.46 | A | |
| | 15 | M | N? | | | 10.39 | 1.14 | 0.25 | 10.36 | 1.08 | 0.23 | 13.32 | A | |
| | 16 | M | N? | | | 11.67 | 1.02 | 0.19 | 11.64 | 0.96 | 0.17 | 14.42 | A | |
| | 17 | M | Y | | | 12.85(3) | 0.96 | 0.18 | 12.82 | 0.90 | 0.16 | 15.46 | A | |
| | 18 | M | Y | | | 12.85 | 0.73 | 0.12 | 12.82 | 0.67 | 0.10 | 14.98 | A | |
| | 18A- | | N? | | | 12.33 | 1.05 | 0.22 | 12.30 | 0.99 | 0.20 | 15.14 | A | |
| | 19 | M | N? | | | 12.45 | 1.05 | 0.20 | 12.42 | 0.99 | 0.18 | 15.26 | A | |
| | 20 | M | N? | | | 12.59(3) | 0.75(3) | 0.13(3) | 12.56 | 0.69 | 0.11 | 14.77 | A | |
| | 21 | M | N | | | 12.22 | 1.05 | 0.23 | 12.19 | 0.99 | 0.21 | 15.03 | A | |
| | 22 | M | N | | | 11.73 | 0.92 | 0.17 | 11.70 | 0.86 | 0.15 | 14.25 | A | |

TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 23 | M | N | | | 13.05 | 0.92 | 0.15 | 13.02 | 0.86 | 0.13 | 15.57 | A | |
| | 24 | M | N | | | 12.16 | 0.98 | 0.16 | 12.13 | 0.92 | 0.14 | 14.82 | A | |
| | 25 | M | N | | | 12.33 | 1.03 | 0.20 | 12.30 | 0.97 | 0.18 | 15.10 | A | |
| | 26 | M | N | | | 13.02(3) | 0.96(3) | 0.15 | 12.99 | 0.90 | 0.13 | 15.63 | A | |
| | 27 | C | N | | | 10.92 | 1.60 | 0.56 | 10.89 | 1.54 | 0.54 | 13.98 | A | |
| | 28 | M | N | | | 13.04 | 0.74 | 0.22(3) | 13.01 | 0.68 | 0.20 | 15.20 | A | |
| | 29 | M | N | | | 12.44 | 1.06 | 0.18 | 12.41 | 1.00 | 0.16 | 15.27 | A | |
| | 30 | M | N | | | 12.03 | 1.09 | 0.20 | 12.00 | 1.03 | 0.18 | 14.91 | A | |
| | 31 | M | N | | | 12.25 | 1.11 | 0.22 | 12.22 | 1.05 | 0.20 | 15.15 | A | |
| N2136 | 1 | M1 | N? | | | ... | ... | ... | ... | ... | ... | | | 34 |
| III | 2 | C | N? | E5,MA4 | | 10.76(3) | 1.53 | 0.49 | 10.73 | 1.47 | 0.47 | 13.77 | G,H | |
| | 3 | - | Y | MA2 | | 11.31(5) | 0.94 | 0.17 | 11.28 | 0.88 | 0.15 | 13.88 | G,H | |
| | - | - | Y | B89,MA6 | | 11.62(3) | 0.85 | 0.13 | 11.59 | 0.79 | 0.11 | 13.98 | G,H | |
| | - | - | Y | MA1 | | ... | ... | ... | 12.32 | 0.83 | 0.15 | 14.80 | H | |
| N2154 | 1 | C | Y | TLE 1 | | 10.18 | 1.88 | 0.73 | 10.15 | 1.82 | 0.71 | 13.38 | B,E | |
| V | 2 | C | Y | TLE 2 | | 10.17(3) | 1.84(3) | 0.70(3) | 10.14 | 1.78 | 0.68 | 13.36 | B,E | |
| | 3 | M | Y | TLE 3 | | 11.44 | 1.06 | 0.21 | 11.41 | 1.00 | 0.19 | 14.27 | B,E | |
| | 4 | M | Y | TLE 4 | | 11.92(3) | 1.07(3) | 0.24(3) | 11.89 | 1.01 | 0.22 | 14.77 | B | |
| | 5 | - | Y | TLE 5 | | 12.26 | 0.98 | 0.17 | 12.23 | 0.92 | 0.15 | 14.93(M) | A,B | |
| | 6 | M | N | | | 11.65 | 1.04 | 0.22 | 11.62 | 0.98 | 0.20 | 14.44 | A | |
| | 7 | Em? | N | | | 12.89 | 2.05(3) | 1.10 | 12.86 | 1.99 | 1.08 | | A,F | |
| | 7 | Em? | N | | | 12.93 | 2.07 | 1.12 | | | | | G | |
| N2173 | 1 | M | Y | TLE 1 | M (2) | 11.28 | 1.15 | 0.24 | 11.26 | 1.11 | 0.23 | 14.25 | A,B,D | ,M 16 |
| V-VI | 2 | C | Y | TLE 2 | | 11.06(4) | 1.26 | 0.32 | 11.04 | 1.22 | 0.31 | 13.89 | B | |
| | 3 | M | Y | TLE 3 | | 11.39(5) | 0.96(3) | 0.15(3) | 11.37 | 0.92 | 0.14 | 14.06 | B | |
| | 4 | - | Y | TLE 5 | | 12.25 | 1.03 | 0.18 | 12.23 | 0.99 | 0.17 | 15.07(M) | A,H | |
| | 5 | M | Y | K5 | (8) | ... | ... | ... | 12.46 | 1.02 | 0.20 | 15.35 | D,E | HHU1401 |
| | - | M2 | Y | TLE 4 | | 12.13(3) | 0.97 | 0.16 | 12.11 | 0.93 | 0.15 | 14.84 | A,B, | |
| N2209 | 1 | C | Y | W46 | | 10.38 | 1.51 | 0.50 | 10.36 | 1.47 | 0.49 | 13.40 | G,D, | |
| III-IV | 2 | C | Y | W50 | | 10.12 | 1.90 | 0.73 | 10.10 | 1.86 | 0.72 | 13.34 | G,H | HHU3201 |
| | 3 | M? | N? | TLE 3 | | 11.86 | 1.05 | 0.21 | 11.84 | 1.01 | 0.21 | 14.72 | G,H | HHU4533 |
| | 4 | M | N | | | 13.92(3) | 0.85(3) | 0.16(3) | 13.90 | 0.81 | 0.15 | 16.34 | G | |
| | 5 | C | N | | | 11.32 | 1.27 | 0.37 | 11.30 | 1.23 | 0.36 | 14.16 | G | |
| | - | | Y | HHU4502 | | ... | ... | ... | 12.36 | 0.99 | 0.19 | 15.20 | H | |
| N2213 | 1 | C | Y | TLE 1 | | 10.78 | 1.87 | 0.68 | 10.75 | 1.81 | 0.66 | 13.98 | B,E | HHU2310 |
| V-VI | 2 | C | Y | TLE 2 | | 11.07(3) | 1.81(3) | 0.67(3) | 11.04 | 1.75 | 0.65 | 14.24 | B,E | |
| | 3 | M3 | N? | TLE 3 | | 11.21 | 1.13 | 0.24 | 11.18 | 1.07 | 0.22 | 14.13(M) | B,E | HHU4402 |
| | 4 | M1 | Y | TLE 4 | | 12.50 | 0.99 | 0.16 | 12.47 | 0.93 | 0.14 | 15.19(M) | B | |
| | 5 | M0? | Y | TLE 5 | | 13.18(3) | 0.89 | 0.12 | 13.15 | 0.83 | 0.10 | 15.63(M) | B | |
| | 6 | M? | Y | AM-12 | | 11.55(3) | 1.03 | 0.22 | 11.52 | 0.97 | 0.20 | 14.33(M) | B,E | |
| | 7 | C | Y | AM-11 | | 10.23 | 1.61(3) | 0.56(3) | 10.90 | 1.55 | 0.54 | 14.00 | B,E | 17 |
| | 8 | C? | Y | | | ... | ... | ... | ... | | | | | |
| | 9 | M2 | N | | | 13.18(3) | 0.86(3) | 0.24(3) | 13.15 | 0.80 | 0.22 | 15.57 | G | |
| | 10 | M1 | N | | | 12.66 | 0.81 | 0.20 | 12.63 | 0.75 | 0.18 | 14.96 | G | |
| | 11 | M1 | N | | | ... | ... | ... | ... | ... | ... | | G | |
| | 12 | M1 | N | | | ... | ... | ... | ... | ... | ... | | G | |
| | 13 | C | N | | | 11.67 | 1.13 | 0.31 | 11.64 | 1.07 | 0.29 | 14.35 | G | |
| | 14 | M2 | N | | | ... | ... | ... | ... | ... | ... | | G | |
| | 15 | M2 | N | | | ... | ... | ... | ... | ... | ... | | G | |
| | 16 | M6 | N | | | 14.43 | 1.05 | 0.32 | 11.40 | 0.99 | 0.30 | 14.24 | G | |
| N2214 | 1 | M2 | N? | D22 | | 11.57(3) | 1.08(3) | 0.21 | 11.54 | 1.02 | 0.19 | 14.43 | G | |
| II | 2 | C | N? | D10 | | 10.71(3) | 1.48 | 0.45 | 10.68 | 1.42 | 0.43 | 13.70 | G | |
| | 3 | M1 | Y? | D1 | | 10.64(4) | 0.85 | 0.22 | 10.61 | 0.79 | 0.20 | 13.01 | G | |
| | 4 | M? | Y | B69 | | 9.93 | 1.04 | 0.24 | 9.90 | 0.98 | 0.22 | 12.72 | G | |
| | 5 | Hα | Y | B72? | | ... | ... | ... | ... | ... | ... | | | |
| | 6 | M? | Y | A100 | | 10.31 | 1.00 | 0.19 | 10.28 | 0.94 | 0.17 | 13.02 | G | |
| | - | - | Y? | D2 | | 9.66(4) | 0.83 | 0.20 | 9.63 | 0.77 | 0.18 | 12.00 | G | Dwarf? |
| | - | - | Y? | D17 | | 10.45 | 0.95 | 0.18 | 10.42 | 0.90 | 0.16 | 13.06 | G | |



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TABLE 1—*Continued*

| Cluster (1) | # (2) | Class (3) | Mem (4) | I.D. (5) | Class (6) | K (7) | J-K (8) | H-K (9) | $K_0$ (10) | $(J-K)_0$ (11) | $(H-K)_0$ (12) | $m_{bol}$ (13) | Source (14) | Notes (15) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N2231 | 1 | - | Y | TLE 2 | | 13.60(3) | 0.78(4) | 0.16 | 13.57 | 0.72 | 0.14 | 15.84 | A,H | |
| V | 3 | C | Y | TLE 1 | | 10.71 | 1.47 | 0.49 | 10.68 | 1.41 | 0.47 | 13.69 | A,H | |
| | 4 | M? | Y | | | 13.99(3) | 0.87(5) | 0.13(3) | 13.96 | 0.81 | 0.11 | 13.39 | A | |
| | 6 | M? | Y | | | 14.13(3) | 0.80(3) | 0.15 | 14.10 | 0.74 | 0.13 | 16.40 | G | |
| | 7 | M? | Y | | | 14.51(5) | ... | ... | 14.48 | ... | ... | ... | G | |
| | 8 | M2 | N | | | 10.41 | 0.77 | 0.25 | 10.38 | 0.71 | 0.23 | 12.63 | G | Dwarf |
| | 9 | C? | N | | | 10.36 | 1.68 | 0.62 | 10.33 | 1.62 | 0.60 | 13.47 | G | |
| | 10 | M2 | N | | | 12.08 | 0.80 | 0.20 | 12.05 | 0.74 | 0.18 | 14.36 | G | |
| | 11 | M? | N | | | 13.03 | 0.78 | 0.20 | 13.00 | 0.72 | 0.18 | 15.27 | G | |

REFERENCES FOR COLS. (5) AND (6).—(1) Walker 1970; (2) Lloyd Evans 1980*b*, 1983, 1984; (3) Thackeray 1958; (4) Tifft 1963; (5) Hodge 1981; (6) AMMA I–IV; (7) Walker 1972; (8) Frogel and Cohen 1982; (9) Gascoigne 1962; (10) Westerlund (n.b.: the authors have been unable to trace this reference); (11) Robertson 1974; (12) BWLE; and (13) Arp 1958.

REFERENCES FOR COL. (14).—(A) This paper, 1981 Dec; (B) This paper, 1981 Mar; (C) Frogel, Persson, and Cohen 1980; (D) Frogel and Cohen 1982; (E) AMMA I and II; (F) J. H. Elias, 1982 private communication; (G) This paper, 1982 Feb; (H) AMMA III; (I) BWLE.

NOTES.—(1) Cluster surveyed by AMMA II but no red stars found. (2) Member of close pair—could not do photometry. (3) Five C stars were found in cluster vicinity, none of which are considered as members. No IR photometry was obtained. (4) For this star $H = 14.73(3)$, $J-H = 0.53(4)$. (5) Member of close pair—could not do photometry; however, it is not particularly bright or red. (6) Measurement probably affected by faint star in aperture. (7) Stars N419-20 and 21 are very close; measurement of one is probably contaminated by radiation from the other. (8) Stars N419-16 and 17 are very close; see note (7). (9) Stars N419-23 and 24 are very close; see note (7). (10) All stars in survey of N1841 are M1 or earlier. (11) Stars N1841-1 and 2 are a very close pair of about equal magnitude with a separation of not more than 1″. The measurements of G117 in Frogel and Cohen 1982 and here were made with both stars in the aperture. (12) Bright, red star located close to cluster center. (13) N1846-24 is rather blue on grism plate. (14) TLE 7, 8, 9, 10 in N1987 were not picked out by grism survey. (15) N2121-5 is very faint on grism and direct plates taken for survey but quite bright on SIT-direct frames. It does not appear to be an M star. (16) This is "star A" of Frogel and Cohen 1982. (17) N2213-7, 8 are double stars with a separation less than 1″ and apparently equal mag in the IR. When plotting data point, use $K + 0.7$. (18) As noted by AMMA, stars TLE1 and 2 of NGC 1987 were measured together. (19) N416-6 is too crowded to classify on grism plate. (20) N416-7 is not a C star; too early on grism plate to be an M; nonmember? (21) N1783-8 appears rather blue on grism plate. Is it an $\omega$ Cen type C star? (22) N306-6. The apparent TiO bands on grism plate may be plate flares. (23) N1850-7. Two or three faint stars in aperture. (24) Severe crowding problems. (25) Crowded and poor seeing. (26) In addition to stars selected from grism survey, the reddest and brightest stars in these two cluster as listed by Robertson 1974 were also observed. All of the C? Stars show only weak CN bands; they could all be early Ms. NGC 1850 was assigned SWB type II on basis of *C-M* comparison with NGC 1854. (27) Could not observe in IR because of star to west. (28) Photometry of all stars in center of cluster suffers from crowding. (29) In references noted no other photometry of individual stars exists for cluster. (30) Faint (and too crowded) for IR photometry; spectral class very uncertain. (31) Not visible on TV. (32) Too crowded to do photometry. (33) On TV this appears to be an unresolved cluster of stars. (34) All bright stars in cluster center visible on TV were checked at *K*. Some are so close to one another that they could not be measured individually; however, none appeared to be significantly brighter at *K* than star 3 in the present list. (36) AMMA considered this star to be a foreground star. Lloyd-Evans 1980*a* notes that it is a large-amplitude variable similar to V1 and V8. Also, since it is quite close to the center of the cluster, the case for nonmembership is not clear cut. (37) *K* or *M* type from CCD spectra.

of early-type stars in its vicinity, that value was used (see Persson *et al.* 1983, hereafter PACFM). If not, or only one early-type star was found near a cluster, the following procedure was adopted: for clusters on the outskirts of the Cloud, $E(B-V) = 0.7$ was used. For clusters located near the ridge line of the bar, Brunet's high value was used; on the periphery of the bar, the global value was used. For other cases, the weak value was used. If a nearby cluster with early-type stars existed, its $E(B-V)$ value served as a guide in choosing the final $E(B-V)$ value for the cluster in question.

In the direction of the SMC $E(B-V) = 0.04$ for 47 Tuc from Galactic reddening alone. We assumed that internal reddening in the SMC is in the mean equal to the weak value for the LMC and, therefore, used $E(B-V) = 0.07$ for all of the SMC clusters.

### *d) Comparison with Published Photometry*

Photometry of 117 of the stars with new data in Table 1 has also been published by Aaronson and Mould (1982, 1985, hereafter AMMA II and IV, respectively), Mould and Aaronson (1980, 1982, hereafter AMMA I and III, respectively), and Bessell, Woods, and Lloyd Evans (1983, hereafter BWLE), as indicated in the table. In order to compare our new data with these published sources we first transformed BWLE's photometry to the CTIO/CIT system with the equations given by Elias *et al.* (1983). The mean differences in the sense (Table 1 − published) for $K$, $J-K$, and $H-K$, respectively are 0.002, 0.019, 0.000 mag for the 117 stars. There is no significant difference between carbon stars and non–carbon stars in this comparison. Nor do we find any systematic deviation from the linear transformations between the two photometric systems given by Elias *et al.* for $J-K$ and $H-K$ as red as 2.0 and 1.0, respectively. The only hint of inhomogeneity in the data is a tendency for the transformed photometry of BWLE to be $\simeq 0.03$ brighter in $K$. This trend could arise from use of a larger aperture and greater chopper throw for the AAO observations than for the CTIO ones, thus increasing contamination from the cluster background. In any case, the effect is too small to be of concern for the present purposes.

The variance of an individual pair (Table 1 − published) of measurements in $K$, $J-K$, and $H-K$ is 0.19, 0.13, and 0.13 mag, respectively, and is dominated by a few stars. This is illustrated in Figure 1. As noted above, the measuring errors in the present work are almost always less than 0.03 mag; a

TABLE 2

ADDITIONAL PHOTOMETRY FOR AGB STARS[a]

| Cluster | # | sp | $J-K$ | $H-K$ | $M_{bol}$ | $K-L$ | $H_2O$ | CO |
|---|---|---|---|---|---|---|---|---|
| N299 | 5 | M0 | 0.85 | 0.13 | 12.11 | | 0.02 | 0.19 |
| I | | | | | | | | |
| N1651 | 4 | C | 1.25 | 0.38 | 14.38 | | 0.09 | 0.14 |
| V | 5 | M | 1.04 | 0.21 | 14.18 | | 0.06 | 0.19 |
| | 6 | M | 1.10 | 0.26 | 13.45 | 0.33 | ... | ... |
| | 7 | M | 1.13 | 0.29 | 14.18 | | 0.08 | 0.24 |
| N1751 | 1 | M1 | 0.98 | 0.18 | 14.32 | 0.23 | ... | ... |
| V | | | | | | | | |
| N1783 | 1 | M | 1.07 | 0.23 | 14.19 | | 0.10 3 | 0.24 |
| V | 3 | M | 1.01 | 0.20 | 14.20 | | 0.08 | 0.15 |
| | 4 | M | 1.02 | 0.20 | 14.20 | | 0.06 | 0.19 |
| | 9 | M | 0.94 | 0.16 | 14.49 | | 0.06 | 0.15 |
| | 10 | C | 1.87 | 0.75 | 13.47 | 0.67 6 | ... | ... |
| | 15 | C | 1.54 | 0.57 | 13.41 | | 0.14 4 | -0.01 3 |
| N1846 | 1 | C | 1.68 | 0.64 | 13.73 | | 0.18 4 | -0.01 3 |
| V | 2 | C | 1.72 | 0.63 | 13.64 | | 0.18 | 0.03 |
| | 7 | M | 0.97 | 0.16 | 14.51 | | 0.06 | 0.15 |
| | 15 | C | 1.64 | 0.59 | 13.42 | | 0.21 | 0.00 |
| | 18 | C | 1.32 | 0.43 | 14.19 | | 0.15 3 | 0.12 3 |
| | 19 | C | 1.57 | 0.58 | 13.43 | | 0.15 | 0.01 |
| N1866 | 1 | M | 1.03 | 0.22 | 12.58 | | 0.22 4 | 0.24 |
| III | 2 | M | 0.95 | 0.17 | 13.52 | | 0.07 3 | 0.19 |
| | 3 | M | 1.08 | 0.23 | 13.18 | | 0.12 3 | 0.21 |
| | 4 | M | 1.11 | 0.25 | 12.65 | | 0.14 3 | 0.21 |
| N1978 | 13 | C | 1.66 | 0.62 | 13.66 | | 0.16 | 0.00 |
| VI | IR1 | C | 2.59 | 1.31 | 14.37 | 1.88 | ... | ... |
| | IR1 | | | | | 1.74 8 | ... | ... |
| | IR1 | | | | | 1.73 5 | 0.41 3 | -0.24 |
| N2058 | 5 | M2 | 0.98 | 0.21 | 12.98 | | 0.07 4 | 0.21 |
| III | 6B | M | 1.12 | 0.27 | 13.74 | | 0.11 4 | 0.31 |
| | 7 | M7 | 1.33 | 0.38 | 13.35 | 0.20 12 | 0.23 4 | 0.39 |
| N2107 | 1 | M4 | 1.10 | 0.24 | 12.86 | | 0.14 3 | 0.23 |
| IV | 5 | M1 | 0.97 | 0.18 | 12.87 | | 0.05 | 0.20 |
| N2108 | 5 | C | 1.72 | 0.64 | 13.13 | 0.64 5 | ... | ... |
| V | | | | | | | | |
| N2121 | 5 | C | 2.42 | 0.53 | 13.58 | 1.05 5 | 0.31 3 | -0.15 |
| VI | 5 | | | | | 1.09 7 | ... | ... |
| N2209 | 1 | C | 1.47 | 0.49 | 13.40 | | 0.16 | 0.04 |
| III-IV | 2 | C | 1.86 | 0.72 | 13.34 | | 0.21 | -0.01 |
| N2214 | 4 | M? | 0.98 | 0.22 | 12.72 | | 0.07 | 0.16 |
| II | D2 | M | 0.77 | 0.18 | 12.00 | | 0.10 | 0.01 |
| non-members | | | | | | | | |
| N220 | 4 | M | | | | | 0.03 3 | 0.19 |
| N231 | 1 | C | | | | | 0.08 3 | 0.12 |
| | 3 | M | | | | | 0.09 3 | -0.04 |
| N269 | 5 | C | | | | 0.48 8 | ... | ... |
| N419 | 10 | C? | | | | 1.08 8 | ... | ... |
| N602 | 4 | M | | | | | 0.06 3 | 0.03 |
| | 5 | M | | | | | 0.19 3 | -0.06 |
| N1651 | 2 | M | | | | 0.22 | ... | ... |
| N1806 | 14 | M | | | | | 0.18 4 | 0.25 3 |
| N1850 | 5 | M1 | | | | | 0.08 4 | 0.24 |
| | D41 | M0 | | | | | 0.07 | 0.18 |

TABLE 2—*Continued*

| Cluster | # | sp | K–L | | $H_2O$ | | CO |
|---|---|---|---|---|---|---|---|
| N1866 | 6 | M | | | 0.09 | 3 | 0.22 |
| N1978 | 16 | C | | | 0.12 | | -0.01 |
| N1987 | 12 | M | | | 0.17 | 4 | 0.25 |
| N2107 | 2 | C | 0.49 | 5 | ... | | ... |
| | 6 | M | | | 0.20 | | 0.23 |
| N2108 | 19 | C | 1.09 | 4 | ... | | ... |
| N2154 | 7 | Em | 1.68 | 12 | ... | | ... |
| N2231 | M2 | N | 0.22 | 3 | 0.00 | | ... |

[a] $M_{bol}$ for SMC stars has been adjusted by −0.3 mag. Some of the CO and $H_2O$ data are from Frogel, Persson, and Cohen 1980 and Frogel and Cohen 1982.

similar error distribution pertains to the other published studies. Evidently, the values for the variance reflect small-amplitude variations in the light of the red giant stars. There is a weak correlation in Figure 1 in the expected sense (Elias, Frogel, and Humphreys 1985): the stellar atmospheres become cooler (redder) when the star becomes fainter.

### III. THE SWB TYPE AS AN AGE INDICATOR

The classification scheme of SWB provides a framework that aids interpretation of our cluster data. They argued that the clusters in the Magellanic Clouds could be arranged in a one-dimensional sequence and that this sequence reflects a monotonic change in age and metallicity. SWB assigned types I–VII to the clusters they observed corresponding to increasing age and decreasing metallicity. We assigned SWB types to clusters they did not observe based on Figure 8 of Frenk and Fall (1982) and the integrated *UBV* colors of van den Bergh (1981). This was not possible for NGC 361 because of a superposed bright star. The *C-M* diagram for Kron 3 (Rich, Da Costa, and Mould 1984) differs so much from that of a type VII cluster (implied by its *UBV* colors) that we used the *C-M* diagram instead to assign a type of VI–VII. SWB types assigned by us are parenthesized in Table 1.

Although some of the individual cluster classifications may be in error, subsequent work has shown that SWB's underlying premise is correct, namely that the age and metallicity of the Magellanic Cloud clusters are closely linked (e.g., Cohen 1982; Bica, Dottori, and Pastoriza 1986). The relationship between these two quantities, however, may conceivably differ for the two Clouds if the chemical enrichment histories of the LMC and SMC were different (e.g., SWB). As Cohen and others have shown, metal enrichment in both Clouds proceeded at a much slower pace than in the Galaxy (see, for example, Twarog 1980).

Thirteen of the 35 clusters in the present sample have well determined ages tabulated by Mould and Da Costa (1988). Absolute ages require knowledge of the distance modulus of the Magellanic Clouds. In this paper we shall adopt 18.3 as $(m - M)_0$ of the LMC, following Mould's (1988) review, and $(m - M)_0 = 18.6$ for the SMC. Both values are systematically uncertain by $\pm 0.2$ mag. These adopted moduli necessitate an adjustment of $-0.029$ dex to the cluster ages collected by Mould and Da Costa. Figure 2 shows the correlation between these ages and SWB type. For this subsample age is predicted by SWB type with a variance of 0.25 in the logarithm of the age, which corresponds to 0.6 in SWB type, i.e., approximately the precision in specifying the type. The slope of this relation is not well determined, however, and so we have added a further seven, mostly younger, clusters from the review by Hodge (1983). His ages were increased by 0.115 dex to match the LMC

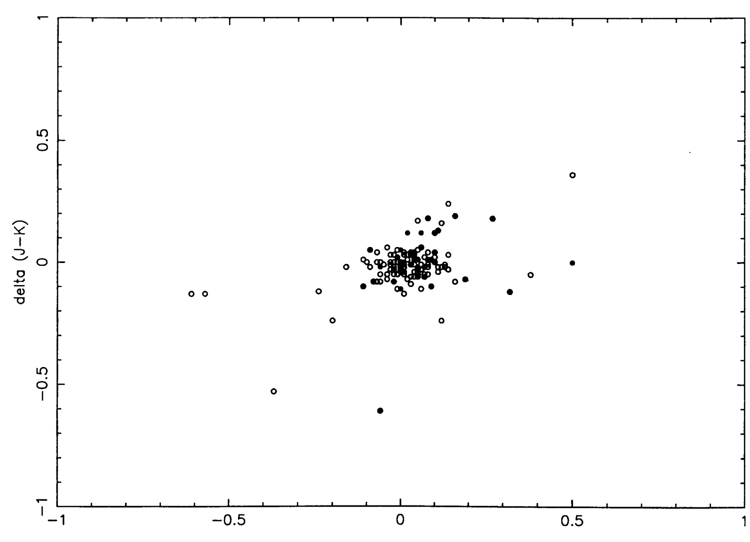


FIG. 1.—For stars in Table 1 with previously published photometry this figure illustrates the difference (in the sense Table 1 − published) in $J-K$ as a function of the difference in $K$ magnitude.

TABLE 3
PROPERTIES OF CLUSTERS BY SWB TYPE[a]

| Type | ⟨C⟩ | ⟨M⟩ | $m_{\mathrm{bol},t}$ | [M/H] | Age (Myr) | $M_{\mathrm{to}}$ |
|---|---|---|---|---|---|---|
| I ............ | — | — | — | — | 13 | 10.8 |
| II ............ | 13.9 | 12.9 | 13.4 | — | 40 | 6.9 |
| III ........... | 13.4 | 12.8 | 13.1 | −0.1 | 120 | 4.0 |
| IV ........... | 14.1 | 12.9 | 13.5 | −0.8 | 370 | 2.7 |
| V ............ | 14.5 | 13.6 | 14.1 | −0.6 | 1100 | 2.0 |
| VI ........... | 14.6 | 14.1 | 14.4 | −1.0 | 3300 | 1.4 |
| VII .......... | 15.1 | 15.1 | 15.1 | −1.4 | $10^4$ | 1.0 |

[a] Half-integral types are rounded down.

distance modulus of 18.3 adopted here. Unadjusted ages for three more young clusters were taken from Mateo (1988). Mean ages for SWB types II–VII from the fit to this larger sample are given in Table 3. Turnoff masses corresponding to these ages are also given in Table 3. These were calculated for an assumed helium content $Y = 0.25$, and mean metallicities, based on values in Mould and Da Costa (1988), for each SWB type as specified in the table (Becker, Iben, and Tuggle 1977; Iben and Renzini 1984).

## IV. PHOTOMETRIC CHARACTERISTICS OF THE CLUSTER STARS

This section presents a brief qualitative description of the colors and magnitudes of the cluster members. A number of trends with cluster type are obvious. These will be quantified in subsequent sections.

### a) $J-H, H-K$ Colors

Near-infrared two-color diagrams for stars identified as cluster members in Table 1 are plotted in Figure 3. They are grouped according to age: types I, II, and III are in the upper left panel; types III–IV and IV are in the upper right panel; type V in the lower left panel; and types V–VI, VI, and VII in the lower right panel. We subsequently shall refer to clusters in the upper left panel as "early-type" and those in the lower right panel as "late-type." The C and M stars show little overlap in Figure 3. The transition to carbon spectra is quite sharp and occurs at $(H-K)_0 \simeq 0.25$ for all groups that possess these stars. The carbon stars follow a well-defined sequence that appears to be independent of SWB type with the possible exception of those from the latest type clusters. It agrees closely with the mean relation for noncluster carbon stars in the Magellanic Clouds, the lower straight line in Figure 3 (Cohen *et al.* 1981, hereafter CFPE); both clearly differ from that for Galactic C stars, the upper straight line. The difference between the LMC and Milky Way C stars is interpreted as a metallicity-related blanketing effect by CFPE. The SMC C stars may show a greater displacement from the local carbon star line than the LMC ones. Again, this could be a metallicity effect.

Cluster M giants in Figure 3 also follow a well-defined sequence. They mostly lie between the mean sequences defined by solar neighborhood field giants and globular cluster giants. There is a tendency for the stars from the latest SWB types, i.e., the oldest and most metal-poor clusters, to lie closer to the globular cluster line, while stars from the earliest types, hence youngest and most metal-rich, lie closer to the field line. Such a variation with metallicity would be expected from the analysis of Galactic bulge stars by Frogel and Whitford (1987), although the absorber responsible for these color shifts has not been identified with any certainty. A few of the M stars in Figure 3 lie significantly below the mean sequences with $(J-H)_0 < 0.6$ and $(H-K)_0 \simeq 0.2$. These are probably M dwarfs and are so designated in Table 1.

### b) *The H-R Diagram*

Apparent bolometric magnitude is plotted versus $(J-K)_0$ in Figure 4 for the stars designated as cluster members in Table 1. Dwarf interlopers have been excluded. The groups are as in Figure 3, except that the stars from SWB VII clusters are displayed separately. To better define the trend for this latest type, we have added additional data for NGC 121, 1841, and 2257 from Frogel and Cohen (1982) and AMMA I and II. SMC stars have been brightened by 0.3 mag to correct them to the LMC distance. Two exceptionally red stars from NGC 1978 and 2121 lie off the right-hand edge of the lower right panel of Figure 4. Three obvious features of Figure 4, previously noted for smaller samples of cluster stars (Frogel,

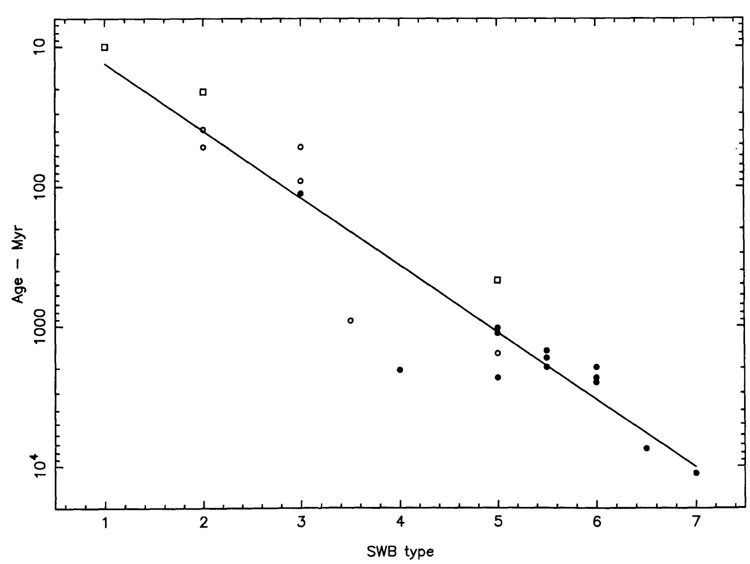


FIG. 2.—SWB type for clusters as a function of age as tabulated by Mould and Da Costa (1988) (*solid dots*), Hodge (1983) (*circles*), and Mateo (1988) (*squares*). The solid line is the least-squares fit to all of the points.

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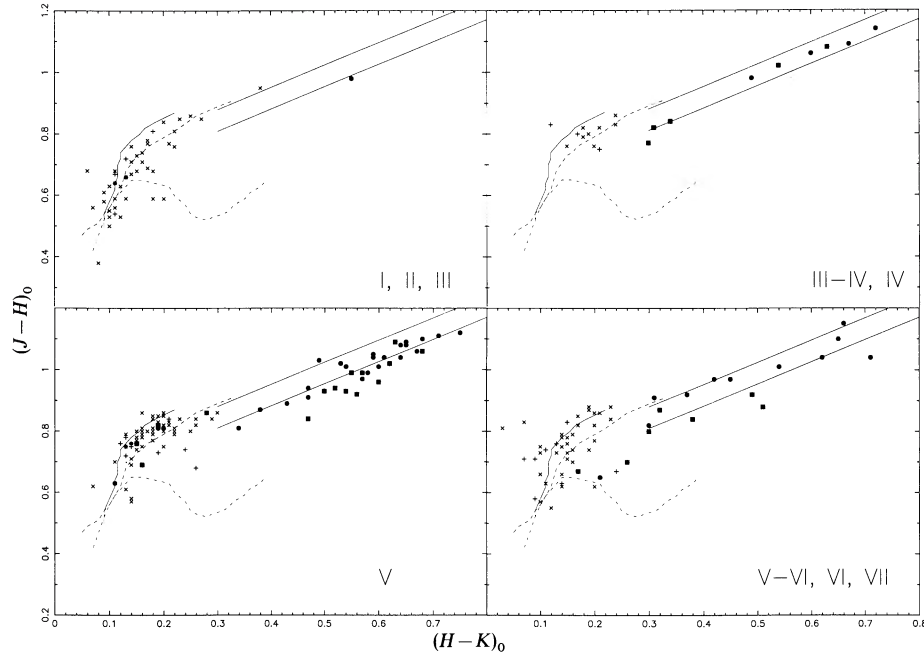


FIG. 3.—$J-H$, $H-K$ relations for cluster members from Table 1. The clusters are divided into four groups in order of increasing age and decreasing metallicity. The solid curved line is the mean relation for globular cluster giants (Frogel, Persson, and Cohen 1983). The dashed and dot-dashed curved lines are the mean relations for field giants and dwarfs, respectively (Frogel *et al.* 1978). The straight lines are the mean relations for Galactic (*upper*) and Magellanic Cloud (*lower*) field carbon stars (CPFE). The symbol code is the same as on Fig. 4.

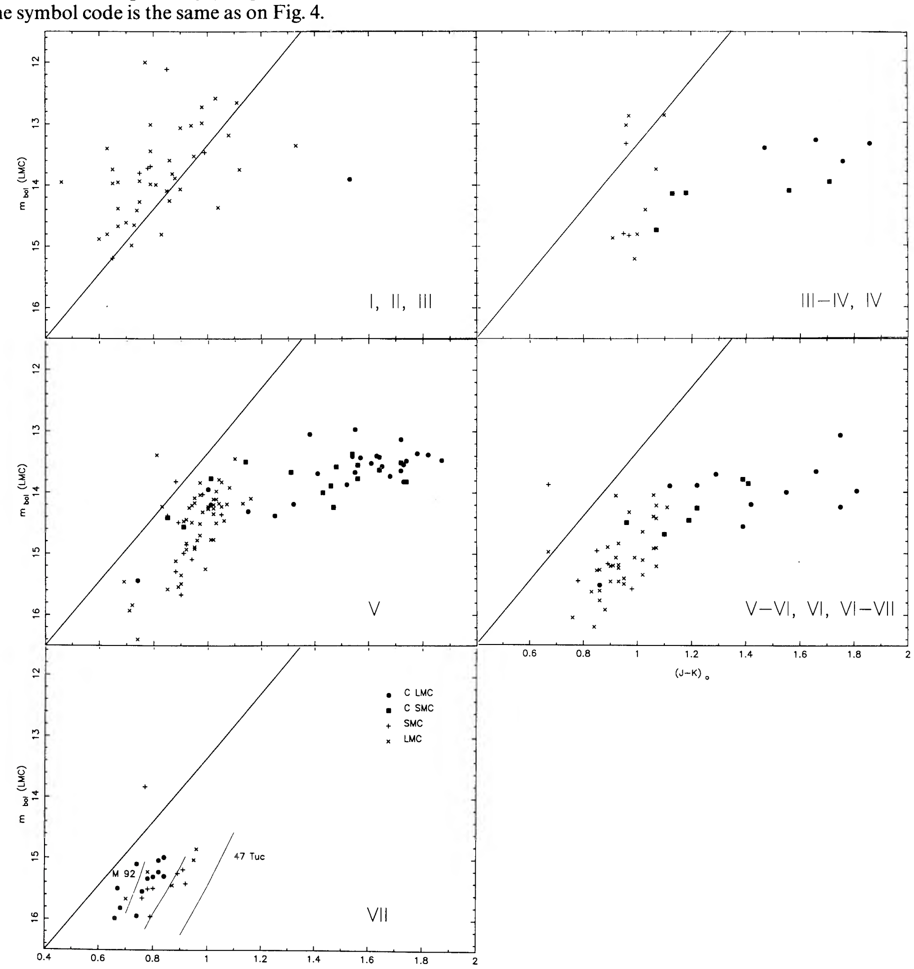


FIG. 4.—Color-magnitude diagrams for clusters from Table 1. The clusters are divided into five groups in order of increasing age and decreasing metallicity. Each panel is labeled with the SWB types present. The long solid line is the approximate division between stars from the youngest (I–III) clusters and from all other types. Fiducial lines for the brightest parts of the giant branches of the Galactic globular clusters M92, M3, and 47 Tuc are indicated in the last panel.

Persson, and Cohen 1980; AMMA IV; Frogel 1984), deserve comment.

1. As in the color-color plot (Fig. 3), carbon stars segregate themselves from M stars in the H-R diagram by their red colors. With one possible exception, luminous C stars are present only in clusters of types IV–VI. Those from the type VI clusters appear to be somewhat fainter than their counterparts in the younger clusters. The C stars in the SWB VII clusters are significantly less luminous than those in the earlier type clusters.

2. With the exception of those from the type VII clusters, the M stars populate giant branches that are ordered by SWB type: those from younger clusters lie on bluer AGBs. There is a particularly noticeable difference between the stars from the youngest (I–III) group of clusters plotted and those from the second youngest group. Also, the luminosity achieved by the M stars increases with decreasing cluster age.

3. The most luminous AGB stars in *young* clusters are not C stars, but M stars. These are also among the brightest of the cool giants observed.

4. Among the SWB VII clusters there appears to be only one star that is brighter than the tip of the giant branches of Galactic globular clusters. All others found have luminosities comparable to or less than the point of degenerate helium core ignition in the globular clusters.

### c) CO *and* $H_2O$ *Indices*

The two panels of Figure 5 show the dependence of the CO and $H_2O$ indices for all cluster members from Table 2 on $(J-K)_0$. The carbon star distributions closely parallel those for Magellanic Cloud field carbon stars (CPFE, Figs. 4 and 6). In particular, while the $H_2O$ indices overlap those of Galactic carbon stars of the same color, the CO indices are systematically weaker by 0.05–0.10 mag (since no $H_2O$ absorption is actually present in a carbon star, this index is just a measure of the continuum slope). This difference was attributed by CFPE to the lower metallicity of the Clouds that would result in weaker CO bands, the same explanation advanced to account for the differences in the *JHK* colors pointed out above. We also note that the locations of the two reddest C stars from the cluster sample in Figure 5 are similar to those of the reddest C stars in the Cloud field sample of CFPE.

Figure 6 is an expanded view of the cluster M star distributions from Figure 5. Each star is plotted with a number giving its cluster's SWB type. In the mean the distribution of CO indices for the M stars is well represented by the mean line for Galactic stars. Magellanic Cloud field M stars (CFPE, Fig. 4) lay systematically above the Galactic line, but the former are also systematically redder than the cluster M stars as they were selected to be the latest M stars in the Bar West field. Therefore, we cannot draw any conclusions from differences in the relative distributions of the CO indices of the cluster and field Magellanic M stars.

An examination of the luminosities of the cluster M stars in Figure 6 shows that in any given interval of $J-K$ the brightest stars do not have the strongest CO indices. However, there may be a tendency for the stars from the earliest SWB types to have stronger CO indices. If not due to luminosity, this could be a result of higher metallicities for the younger clusters. The $H_2O$ indices are strongly correlated with SWB type at constant color and probably correlated with luminosity as well. The present data are not adequate to separate the effects of luminosity and metallicity on the $H_2O$ indices.

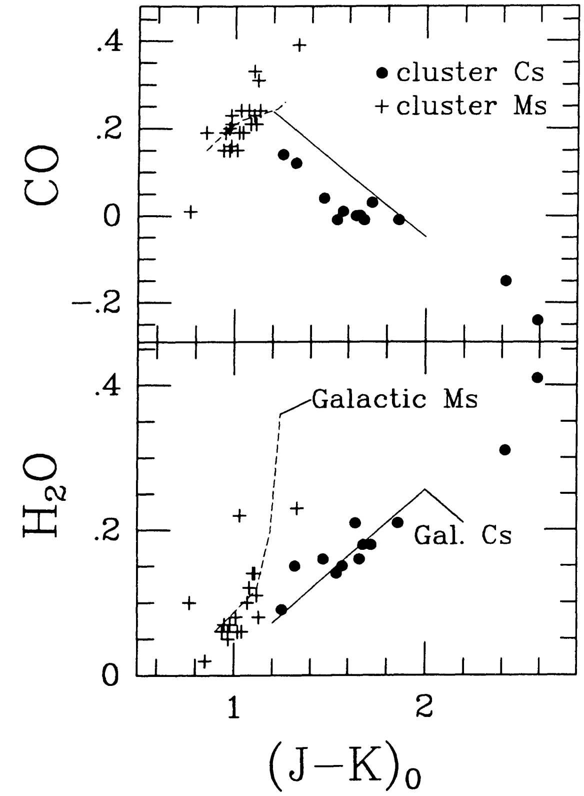


FIG. 5.—The CO and $H_2O$ indices for cluster members from Table 3. Mean lines for Galactic stars are shown.

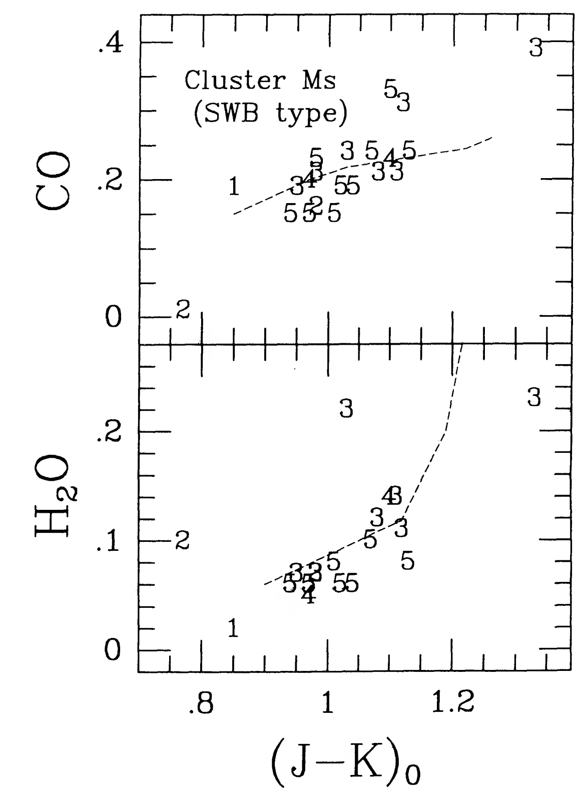


FIG. 6.—Same as Fig. 5 except that the M star distributions are shown in more detail. The SWB type of the parent cluster for each M star is indicated.

### *d) The Reddest Stars*

The reddest C stars observed in the course of our survey have colors that clearly separate them from all other stars in Table 1. NGC 419-10 is just outside of the membership circle so is classified as a nonmember in Table 1. The rarity of such red stars, though, suggests that it may be a cluster member. NGC 2108-19, on the other hand is about 5′ from the cluster center, so its classification as a nonmember is more likely to be correct. Two observations of NGC 2121-5 given in Table 1 indicate that this star is probably a long-period variable (LPV). NGC 1978-IR 1 is the reddest star in our survey and was found by accident. It was not visible on the acquisition TV at any time and is judged to be fainter than 19 at $V$. It too displays large-amplitude variations in its colors and magnitudes and is also a likely LPV. All four of these stars have red $K-L$ colors (Table 2) indicative of extensive circumstellar dust. This dust is most likely the origin of the red $JHK$ colors as well, due to a combination of reddening and thermal emission. Bolometrically, these stars do not stand out from the rest of the AGB stars observed, except that NGC 1978-IR 1 appears somewhat underluminous; it may have significant luminosity at longer wavelengths. That LPVs have colors distinct from non–LPVs has been found to be true for Galactic globular clusters (Frogel and Elias 1988) and M giants in the bulge (Frogel and Whitford 1987). In all cases, a high mass-loss rate that results from the large-amplitude pulsation must result in the large amounts of dust that in turn cause the distinct colors of the LPVs.

## V. M STARS, CLUSTER METALLICITIES, AND AGES

### *a) M Star Colors and Cluster Ages*

Figure 4 shows that for SWB types I–VI the cluster M stars shift steadily redward as one advances from the earliest to the latest type. For types IV–VI the shifts are small, whereas between these types and the I–III clusters the shift is large. Stars from the SWB VII clusters do not follow this trend.

In order to measure the relative location of the M giants in Figure 4 we have drawn a fiducial line that approximately separates stars from clusters of type I–III from the rest. We define $x$ to be the perpendicular distance of each star from this line and display the resulting distribution in Figure 7. In the lower panel of Figure 7 is the field star distribution for the Bar West region of the LMC (Frogel and Blanco 1983) calculated in the same manner as the cluster star distribution. Both distributions show a strong peak at $x \simeq 0.2$ mag and a weaker one at $x < 0$ mag. On the basis of this distribution for the LMC field M stars, Frogel and Blanco argued that two major epochs of star formation occurred in the western part of the bar of the LMC—one several Gyr in the past, the other a few hundred Myr ago. Figure 7 is consistent with two epochs of cluster formation as well. The peaks at positive $x$ are similar to one another. The peak at negative $x$ in the SWB sample, corresponding to AGB stars from the recent epoch of star formation, is enhanced because of selection effects in the cluster sample itself in favor of young objects. Wood, Bessell, and Paltoglou (1985) have found evidence for two periods of star formation in another region of the bar from a study of Cepheids and long-period variables. Chiosi *et al.* (1986) suggest, also on the basis of the cluster age distribution, that a major star-forming event happened in the LMC $\sim$4 Gyr ago, although from an analysis of the colors of the clusters, Chiosi, Bertelli, and Bressan (1988) find "no convincing evidence for strong discontinuities in the rate of formation of LMC clusters"; they add, though, that their data are not adequate to rule out such discontinuities.

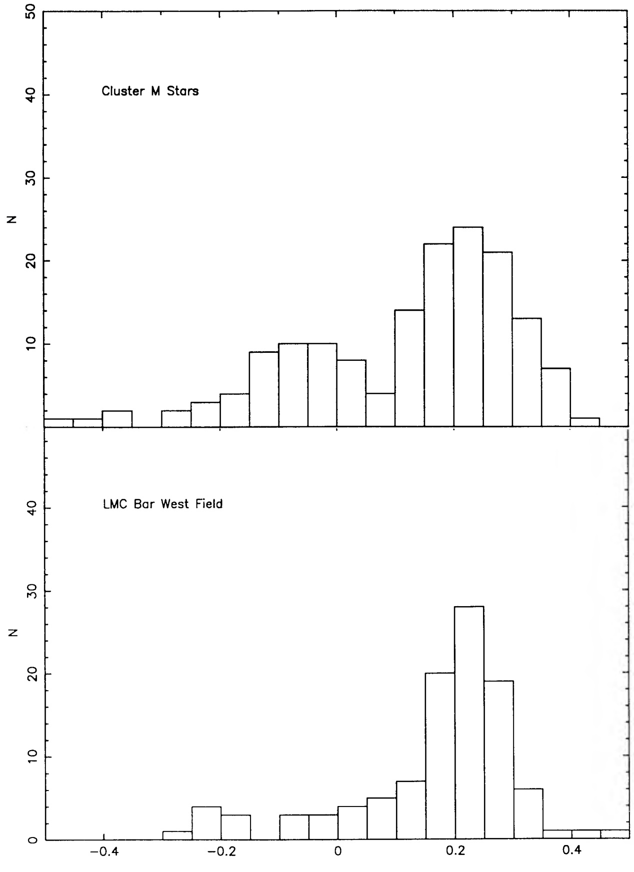


FIG. 7.—*Top*: The distribution of the perpendicular distance, $x$ (in mag) of *all* cluster M stars from the long solid line in the panels of Fig. 4. *Bottom*: a similar distribution for M stars in the Bar West field of the LMC (Frogel and Blanco 1983).

The location of the stars from type VII clusters in Figure 4 indicates that cluster formation also occurred at a much earlier epoch. This epoch could correspond with the time of formation of the many field RR Lyrae stars. Such an old stellar population accounts for about 6% of the total mass of both Clouds, about the same as the ratio of halo mass to total mass for the Milky Way within the solar circle (Frogel 1984). We also note that except for one star in NGC 121, the brightest stars from these clusters show the same effect found by Frogel, Cohen, and Persson (1983) for the brightest stars in Galactic globular clusters, namely, they correspond closely in luminosity with predicted values for core helium flash in first ascent giants. In the lower left panel of Figure 4 NGC 1841 ([M/H] = −2.3; Cohen 1982) can be directly compared with M92, and NGC 2257 ([M/H] = −1.4) with M3. The location of the LMC type VII clusters in Figure 4 is therefore consistent with their identification as Magellanic Cloud analogs of true globular clusters. They are too old and metal-poor to have AGB stars. This is contrary to the inference by AMMA III that the LMC globular cluster system could be $\simeq$3 Gyr younger than that of the Galaxy. These authors adopted a distance modulus 0.4 mag larger than we are presently using. Second, the fact that the mean location of the stars from type VII clusters spreads across the loci of the giant branches of globular clusters with a considerable range in abundance is consistent with abundances derived for the individual type VII clusters.

### b) *The Correlation of Age and Metallicity*

At a given $K$ magnitude level, the $J-K$ color of a globular cluster's giant branch is monotonically correlated with metallicity in the sense that higher metallicity clusters have redder giant branches (Frogel, Cohen, and Persson 1983). We would expect that the same trend should be present for a group of clusters of any age. However, for a large enough range in age, the metallicity effect may become masked as clusters of younger age should have hotter and bluer giant branches than older clusters of the same composition. SWB's analysis indicated a one-to-one correlation between cluster age and composition for the Magellanic Clouds. Our data show a clear trend of bluer colors for cluster M stars with earlier SWB type. In the past few years, color-magnitude diagrams for Magellanic Cloud clusters based on digital data have resulted in considerably improved age determinations for a number of clusters (Mould and Da Costa 1988). We can reexamine the correlation of age and composition with the help of the new infrared data.

For each cluster in the present survey with a sufficient number of M stars to define the giant branch, the value of $J-K$ was determined at $K = 12.8$ in the LMC (13.1 in the SMC) which corresponds to $M_K = -5.5$, the value used for calibration of Galactic globular clusters (Frogel, Cohen, and Persson 1983). These values are given in Table 4. Also given in Table 4 are the $J-K$ values at $K = 12.0$ in the LMC which includes some clusters that have sparse data at 12.8. The results of the following analysis, though, are identical for the two values. A value in parentheses means that it is based on extrapolation or is particularly uncertain because of the scarcity of stars. Extrapolation assumed that cluster giant branches are linear in the $K$, $J-K$ plane. If non–LPV M stars only are considered, there is no evidence to the contrary from the present data or from Frogel, Persson, and Cohen (1983). The best available age and metallicity determinations are also given in Table 4. These are from $C$-$M$ diagrams and isochrone fit-

TABLE 4

INTEGRATED CLUSTER PARAMETERS[a]

| Cluster | SWB | $m_{bol}$ | Cluster colors minus AGB | | AGB fraction of $m_{bol}$ | | GB color: $J-K$ at $K=$ | | age | [Fe/H] |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $J-K$ | $H-K$ | C | C and M | 12.8 | 12.0 | | |
| Kron 3 | 6.5 | 11.60 | 0.49 | 0.06 | 0.05 | 0.05 | 0.88 | ... | 8. | -1.20 |
| N121 | 7.0 | 10.77 | 0.71 | 0.13 | 0.00 | 0.05 | 0.83 | 0.96 | 12. | -1.40 |
| N152 | 4.0 | 12.05 | 0.56 | 0.10 | 0.36 | 0.36 | ... | 0.96 | 2.2 | -0.80 |
| N220 | 3.0 | 12.68 | 0.49 | 0.14 | 0.00 | 0.00 | ... | ... | ... | ... |
| N231 | 2.5 | ... | ... | ... | 0.00 | 0.00 | ... | ... | ... | ... |
| N265 | 3.0 | 11.79 | 0.23 | -0.01 | 0.00 | 0.16 | ... | ... | ... | ... |
| N269 | 3.5 | 11.60 | 0.48 | 0.06 | 0.00 | 0.16 | ... | ... | ... | ... |
| N299 | 1.0 | 10.95 | 0.81 | 0.13 | 0.00 | 0.26 | ... | ... | ... | ... |
| N306 | 3.0 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| N339 | 7.0 | 12.45 | 0.55 | 0.07 | 0.00 | 0.00 | ... | ... | ... | ... |
| N361 | 0.0 | 12.16 | ... | ... | ... | ... | 0.85 | 0.92 | ... | ... |
| N411 | 5.5 | 12.35 | 0.74 | 0.10 | 0.20 | 0.20 | ... | ... | 1.8 | -0.90 |
| N416 | 6.0 | 10.94 | 0.61 | 0.13 | 0.03 | 0.03 | ... | ... | 2.5 | ... |
| N419 | 5.0 | 9.98 | 0.66 | 0.13 | 0.37 | 0.37 | 0.85 | 0.91 | 1.2 | ... |
| N1651 | 5.0 | ... | ... | ... | ... | ... | 0.90 | 0.98 | 2.5 | -0.50 |
| N1652 | 6.0 | ... | ... | ... | 0.00 | 0.00 | 0.88 | 0.96 | ... | -1.10 |
| N1751 | 5.0 | 10.88 | 0.82 | 0.22 | 0.23 | 0.44 | ... | ... | ... | ... |
| N1783 | 5.0 | 10.51 | 0.65 | 0.10 | 0.04 | 0.15 | 0.89 | 0.95 | 1.1 | -0.45 |
| N1806 | 5.0 | 10.38 | 0.60 | 0.07 | 0.11 | 0.25 | 0.88 | 0.93 | ... | ... |
| N1841 | 7.0 | 13.38 | 0.66 | 0.15 | 0.00 | 0.00 | 0.79 | 0.91 | ... | -2.30 |
| N1846 | 5.0 | 10.40 | 0.63 | 0.06 | 0.22 | 0.40 | 0.88 | 0.96 | ... | -1.10 |
| N1850 | 2.0 | 8.81 | 0.52 | 0.11 | 0.00 | 0.03 | 0.61 | 0.73 | 0.05 | ... |
| N1854 | 2.0 | 9.95 | 0.44 | 0.14 | 0.00 | 0.17 | 0.62 | 0.69 | 0.04 | ... |
| N1866 | 3.0 | 9.44 | 0.48 | 0.09 | 0.00 | 0.06 | ... | 0.79 | 0.12 | -0.1 |
| N1978 | 6.0 | 10.06 | 0.74 | 0.18 | 0.13 | 0.17 | 0.88 | 1.01 | 2.1 | -0.70 |
| N1987 | 4.0 | 11.18 | 0.11 | -0.21 | 0.14 | 0.38 | 0.85 | 0.95 | ... | ... |
| N2058 | 3.0 | 10.86 | 0.43 | 0.01 | 0.00 | 0.24 | 0.60 | 0.73 | 0.09 | ... |
| N2107 | 4.0 | 10.88 | 0.56 | 0.16 | 0.00 | 0.16 | ... | ... | ... | ... |
| N2108 | 5.0 | 11.40 | 0.80 | 0.39 | 0.20 | 0.28 | 0.81 | ... | ... | ... |
| N2121 | 6.0 | 11.37 | 0.65 | 0.19 | 0.13 | 0.24 | 0.91 | 0.99 | 2.7 | -1.00 |
| N2136 | 3.0 | 10.20 | 0.56 | 0.11 | 0.00 | 0.06 | 0.71 | 0.80 | 0.05 | ... |
| N2154 | 5.0 | 11.25 | 0.68 | 0.16 | 0.28 | 0.28 | 0.85 | 0.95 | ... | ... |
| N2173 | 5.5 | 12.25 | 0.73 | 0.29 | 0.22 | 0.57 | 0.92 | 0.98 | 2.1 | -0.75 |
| N2209 | 3.5 | 12.74 | 0.49 | 0.08 | 0.58 | 0.58 | ... | ... | 1.0 | -1.00 |
| N2213 | 5.5 | 11.61 | 0.12 | -0.15 | 0.31 | 0.39 | 0.88 | 0.95 | 1.6 | -0.50 |
| N2214 | 2.0 | 10.42 | 0.11 | 0.04 | 0.00 | 0.21 | ... | ... | 0.05 | ... |
| N2231 | 5.0 | 12.85 | 1.20 | 0.23 | 0.46 | 0.46 | 0.86 | ... | 1.56 | ... |
| N2257 | 7.0 | 14.51 | 0.56 | 0.09 | 0.00 | 0.00 | 0.83 | 0.98 | 15.9 | -1.80 |

[a] The AGB in this table refers to all stars with $M_{bol} \leq -3.6$. The GB colors for SMC clusters have been determined after adjusting its distance modulus by $-0.3$ mag to correspond to that of the LMC. The values of $m_{bol}$ tabulated have not been so adjusted: they are the observed values.

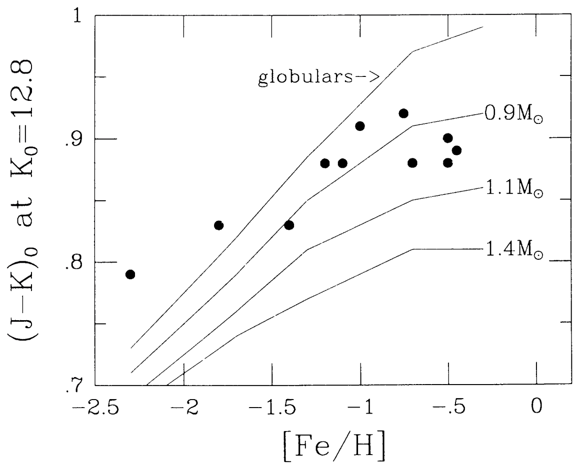


FIG. 8.—The $J-K$ color of a cluster's giant branch at $K = 12.8$ (for the LMC) is plotted against [Fe/H] from Table 4. The line labeled "globulars" is the relation between these two quantities for Galactic globular clusters (Frogel, Cohen, and Persson 1983). The other lines show the predicted shifts of the relation for stars of increasing mass from the evolutionary tracks of Sweigart and Gross (1978). For Galactic globulars, 0.7 $M_{\odot}$ is assumed.

tings and from spectral analysis of individual stars (e.g., Mould and Da Costa 1988 and Hodge 1983 with ages adjusted as discussed in § III; Cohen 1982) rather than from photometry of the integrated cluster light. Figures 8 and 9 show the dependence of the $J-K$ color of a cluster's giant branch on its age and [Fe/H], respectively, at $K = 12.8$. On Figure 8 is drawn the relationship between $J-K$ at $M_K = -5.5$ and [Fe/H] for globular clusters from Frogel, Cohen, and Persson (1983). Also indicated on this figure is the shift in this relation expected for stars of higher mass from the tracks of Sweigart and Gross (1978). To calculate these shifts the temperature calibration of Cohen, Frogel, and Persson (1978) was used; it was assumed that globular clusters giants have $M = 0.7\ M_{\odot}$. Figure 9 is a quantitative presentation of the effect seen in Figure 4: cluster giant branches get progressively redder as one goes from the youngest clusters to those of intermediate age. Then the giant branches get bluer again. The first effect is interpreted as arising from an increase in cluster age dominating any change that would arise from a decrease in metallicity. For the oldest clusters, on the other hand, the decrease in metallicity dominates the increase in age, and the giant branch becomes bluer. The changing color of the giant branch with metallicity is also closely coupled with the integrated colors of clusters (Frogel *et al.* 1978; Aaronson *et al.* 1978; Frogel, Cohen, and Persson 1973). Figure 8 shows that this behavior is expected theoretically—changes in the location of the most metal-rich giant branches, presumably the youngest, have the shallowest slope in $J-K$ as a function of decreasing metallicity, so that increasing age, i.e., decreasing mass, will dominate and cause $J-K$ to get redder.

There are seven LMC clusters with ages in the range 1.0–2.5 Gyr. For this group the dispersion in $J-K$ of the giant branch at $K = 12.8$ is $\pm 0.02$ (Fig. 9). This scatter can be entirely accounted for by the $\pm 0.02$ mean uncertainty in the determination of the $J-K$ values themselves. The range in [Fe/H] of these seven clusters is 0.5 dex (Table 3), although the scatter in the values compared with the individual uncertainties of 0.2–0.3 dex is consistent with constant [Fe/H]. If we assume, though, that this range is due entirely to the age-metallicity relation and correct the $J-K$ values for this, we derive an upper limit to the permissible range in [Fe/H] at constant age as measured by $J-K$ of $\pm 0.2$ dex. Since these seven clusters are scattered over the face of the LMC, we conclude that the process responsible for metal enrichment was efficient on a global scale.

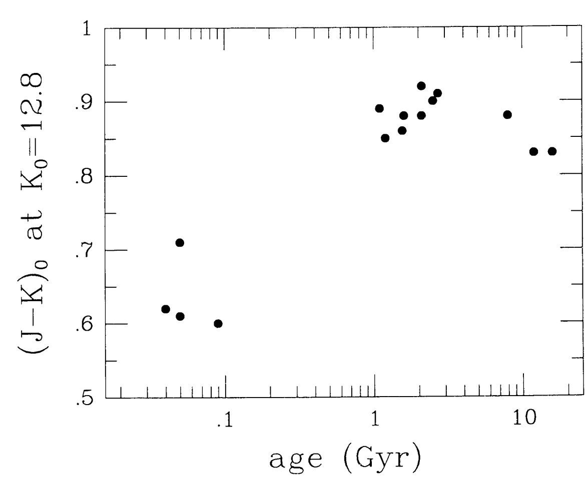


FIG. 9.—The $J-K$ color of a cluster's giant branch at $K = 12.8$ (for the LMC) is plotted against age from Table 4. This magnitude corresponds to the same absolute magnitude used to order the giant branches of Galactic globular clusters (Frogel, Cohen, and Persson 1983).

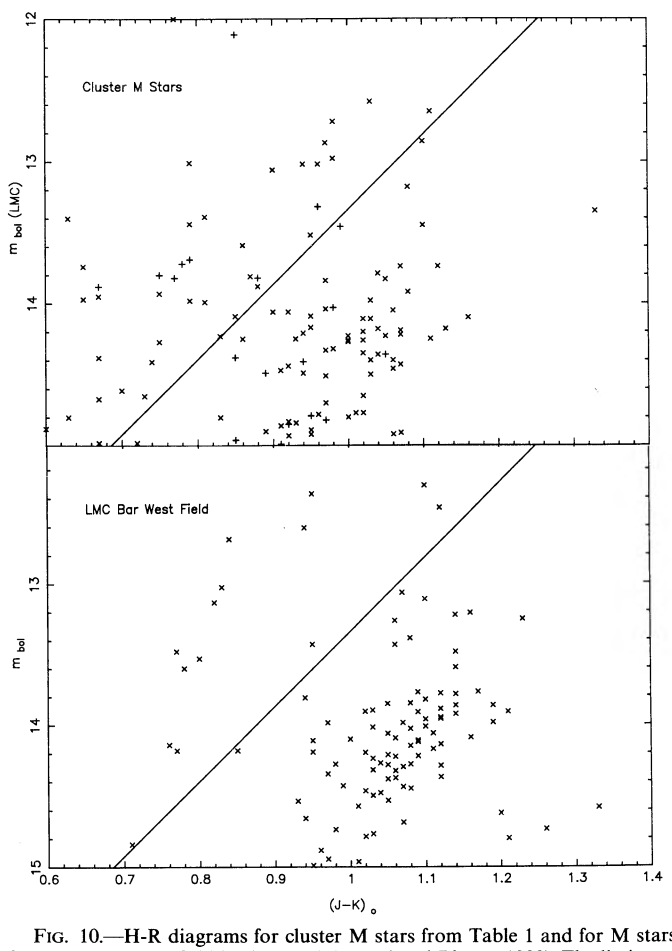


FIG. 10.—H-R diagrams for cluster M stars from Table 1 and for M stars from the Bar West field in the LMC (Frogel and Blanco 1983). The limits on the axes have been set to draw attention to the region redward of $J-K = 1.0$ and brighter than $m_{\rm bol} = 14$.

### c) *A Comparison of Cluster and Field M Stars*

With a much larger data base of clusters than was available to Frogel and Cohen (1982) we can show that there is a population of red *and* luminous M stars in the field that is absent from the cluster population. Figure 10 is a *C-M* diagram for all cluster M stars and for a complete unbiased sample of field M stars from the Bar West region of the LMC. The excess of cluster stars to the left of the fiducial line arises from type I–II clusters (Fig. 4-*upper left*). There appears to be an excess of field stars redward of $J-K = 1.05$ and brighter than $m_{\rm bol}$ of 14.0. A more quantitative representation of this may be seen in Figure 11. which compares the luminosity functions of the two samples of M stars with giants from the I–III clusters removed. The excess of red, luminous AGB stars in the field sample could arise from a somewhat larger percentage of relatively metal rich stars in it that have not yet turned into C stars because of higher [Fe/H]. Further study of these stars might clarify their orgin and evolutionary state.

## VI. CARBON STAR LUMINOSITY FUNCTIONS

For the oxygen-rich stars, we can investigate only the upper end of the luminosity function because of the manner in which the stars were selected. However, from the appearance of Figure 4 and from what we know about field carbon star luminosity functions in the Magellanic Clouds (CFPE), we can be certain that our sample of cluster carbon stars is nearly complete and should, therefore, be representative of the different types of clusters. Furthermore, with the many noncluster carbon stars in Table 1, we can compare the environment of the clusters to the clusters themselves.

Table 5 gives the mean values and dispersions of the bolometric luminosity functions for a number of different samples of carbon stars including those from Table 7 of CFPE. The apparent mean values for the SMC have been made brighter by 0.3 mag. Figure 12 illustrates the functions for the three groupings of clusters. Figure 13 shows the functions for all cluster members together and for all nonmember C stars in Table 1. A simple Student *t*-test shows that the difference in luminosity function between the SWB V–VI and VI clusters, and the type V clusters is statistically significant at greater than the 99% level of confidence for both Clouds individually and combined. This confirms the impression one gets from inspection of Figure 12. There are too few stars in the earliest cluster group to say whether or not its function differs from the others. On the other hand, a *t*-test also shows that *each* of the cluster group luminosity functions can be drawn from the CFPE field sample from the appropriate Cloud: the field luminosity functions appears to be made up of a combination of C stars from the three groups of clusters. Finally, we find that the nonmember C star luminosity functions from the vicinities of clusters of different types are indistinguishable from one another within a given Cloud. The fields around the types I–III clusters, on the other hand, do show somewhat brighter and bluer M stars than the fields around the later type clusters.

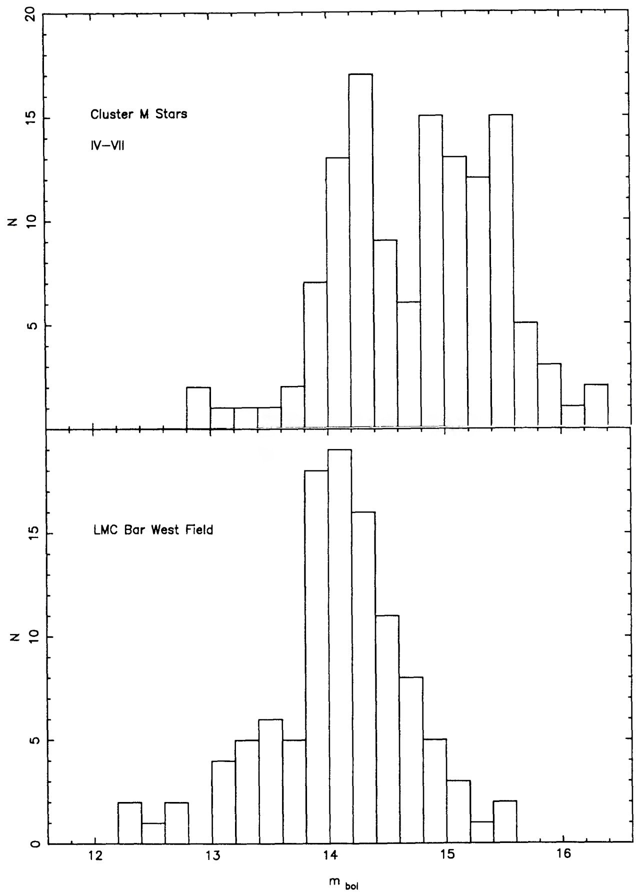


FIG. 11.—Luminosity functions for the complete samples of cluster M stars, except those of types I–III, and M stars from the Bar West Field used to construct Fig. 10.

There appear to be differences in the C star luminosity functions between the two Clouds. Both cluster and field carbon stars from the LMC tend to be brighter in the mean than those from the SMC. Bear in mind, though, that the uncertainties in the differences are dominated by the uncertainty in the relative distance modulus of the Clouds. Each of the three cluster groups from the LMC has a brighter mean than the corresponding group in the SMC. Although the individual differences are not statistically significant, when lumped together the cluster luminosity functions for the two clouds differ at the

TABLE 5

CARBON STAR LUMINOSITY FUNCTIONS

| Sample | SMC | | | LMC | | | Both | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | $\sigma$ | Number | Mean | $\sigma$ | Number | Mean | $\sigma$ | Number |
| CFPE | 13.96 | 0.49 | 111 | 13.75 | 0.43 | 164 | ... | ... | ... |
| Table 1 (nonmember) | 13.99 | 0.54 | 45 | 13.88 | 0.44 | 39 | ... | ... | ... |
| Table 1 (members) | 14.08 | 0.47 | 28 | 13.78 | 0.53 | 44 | ... | ... | ... |
| SWB 2–4.5 | 14.21 | 0.27 | 5 | 13.51 | 0.23 | 5 | 13.86 | 0.44 | 10 |
| SWB 5 | 13.82 | 0.34 | 15 | 13.69 | 0.50 | 26 | 13.74 | 0.45 | 41 |
| SWB 5.5–6.5 | 14.26 | 0.33 | 6 | 14.05 | 0.56 | 13 | 14.12 | 0.52 | 19 |

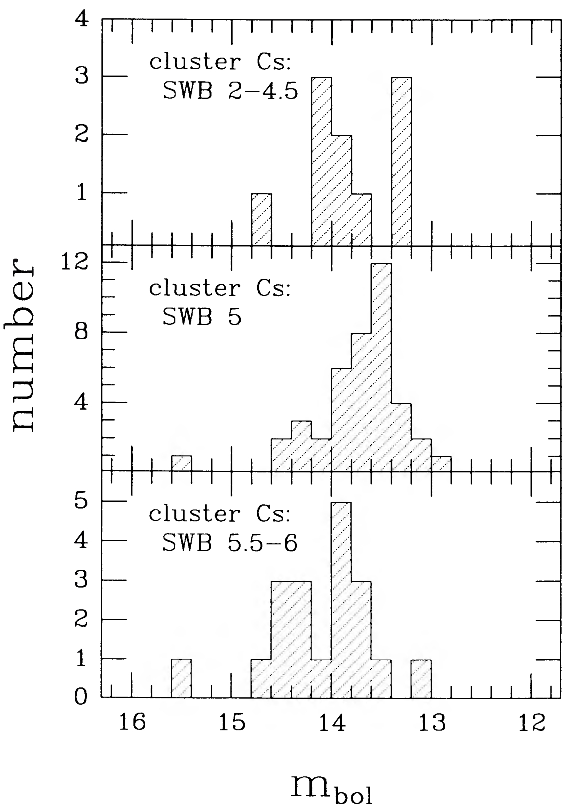


FIG. 12.—Apparent bolometric luminosity functions for cluster C stars from Table 1. SMC stars have been shifted to the LMC distance. The clusters are put into three groups according to their SWB type.

98% level of confidence. Figure 13 illustrates the two luminosity functions. Although the difference in the nonmember C star luminosity functions from Table 1 is not statistically significant, that for the much larger field samples from CFPE is significant at greater than the 99% level.

The brighter mean value for the luminosity of C stars in the type V clusters than for those in the type VI clusters may be indicative of an age-luminosity trend for the C stars in the Magellanic Clouds. Similarly, fainter C stars in the SMC than in the LMC could result if their mean age were greater in the former than the latter. A lower mean metal abundance for the SMC would also result in fainter C stars than found in the LMC at constant age. Both the age and metallicity effects are predicted by carbon star formation theories as reviewd by Iben and Renzini (1983). The relatively larger number of later SWB type clusters in the SMC sample than in the LMC sample could contribute to the extension of the SMC cluster C star luminosity function to fainter magnitudes (Fig. 13). However, as may be seen from Table 5, even for a given cluster type, SMC C stars are still fainter in $m_{bol}$ than those in the LMC.

If the field carbon stars do indeed consist of a composite population with components representative of the various SWB type clusters, particularly types IV–VI, then this composite population must have a spread in age and metallicity comparable to the range in these parameters covered by the clusters. Of course, the actual range in age and [Fe/H] of the field stars may be greater than the limits set by the carbon stars alone. The same inferences can be drawn for the IV–VI clusters from the width of the distribution in $J-K$ (or really the $x$ parameter) of M stars. For a given cluster type, this width is significantly narrower than that for the three types together or for the field sample. Again this is evidence that clusters of a given type are specific subsamples of the field star population; taken together, the range in age and metallicity of the clusters

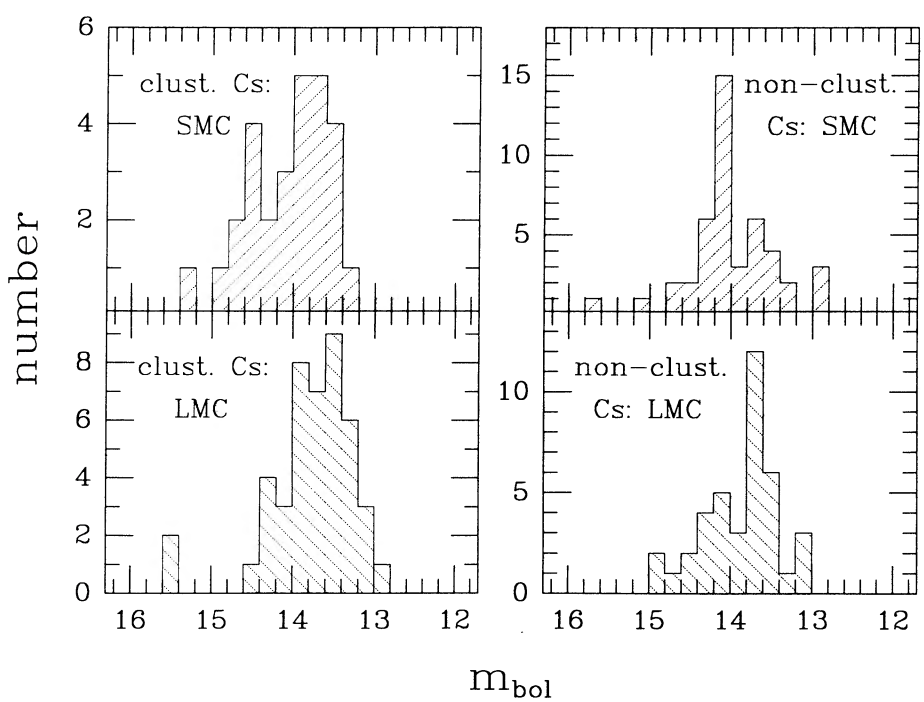


FIG. 13.—Luminosity functions for cluster member and nonmember C stars from Table 1 for the SMC and LMC

is a fair measure of that range for the field stars. *There do not appear to be types of stars—either* C *or* M*—in the clusters that are not also found in the field.* However, we have shown (§ V) that the converse is not true: there are bright red M stars in the field that do not have counterparts in the clusters.

## VII. COMPARISON OF THEORY AND OBSERVATION

### *a) The Transition Luminosity*

Figure 14 shows the distribution of bolometric magnitudes from Table 1 over SWB types. Carbon stars and noncarbon stars are distinguished, but individual clusters are not. For clarity the SWB type attached to each star has been randomly perturbed by 0.1 rms. Borderline types (e.g., V–VI) were taken as half-integers. The apparent bolometric magnitudes of SMC stars have been plotted 0.3 mag brighter in Figure 14 than the values given in Table 1 to correct for the relative distances of the LMC and SMC. A number of properties of the AGB star luminosity distribution are readily apparent from Figure 14: (1) The upper luminosity envelope rises monotonically with decreasing type. This reflects the relation between maximum AGB luminosity and age described by Aaronson and Mould (1982). (2) The lower luminosity envelope shows a similar trend, but this is almost certainly a selection effect due to the survey technique. (3) There appears to be a transition luminosity between M stars and C stars.

An important prediction of the theory of "third dredge-up" (Iben and Renzini 1983) for carbon star formation is that a transition luminosity should occur on the AGB at the point at which sufficient carbon has been mixed into the stellar envelope that the number density of carbon atoms equals that of oxygen. Unless carbon is reprocessed in the stellar envelope, no M stars should exist above this luminosity, and few carbon stars should be found below it. These few faint carbon stars would result from a subluminous phase for carbon stars that is predicted to occur after a thermal pulse. There are one or two archetypal rich clusters in which the expectations of third dredge-up theory are exactly realized, e.g., NGC 1783. For this cluster, the data of BWLE and Mould *et al.* (1989) reveal a monotonic progression in the luminosity of M stars, followed by S stars (in which C = O), followed by carbon stars. For less populous clusters, this picture suffers from the small numbers of AGB stars, and so it is best to define a transition luminosity in a very simple statistical manner.

We have quantified the apparent transition luminosity in Figure 14 in the following manner. For each SWB type the faintest carbon stars, up to four in number, were identified and their median magnitude calculated. The brightest M stars, up to four in number, were also selected and their median magnitude calculated. The average of these quantities was defined to be the transition luminosity for that SWB type and is indicated by the solid line in Figure 14; the transition values are given in Table 3. It is clear that the transition luminosity rises with decreasing SWB type as first pointed out by Frogel and Cohen (1982) and Lloyd-Evans (1984). The difference in transition luminosity between the two Clouds must have its origin in the fact that the SMC has a lower mean metallicity than the LMC—the same explanation proposed for the difference in the C star luminosity functions discussed earlier.

### *b) Presence of C Stars as a Function of SWB Type*

The three latest type clusters in the present sample which contain carbon stars are Kron 3 (VI–VII), NGC 121 (VII), and NGC 339 (VII); all of these are in the SMC. There are no known SWB VII clusters in the LMC with carbon stars. Neither are there any AGB carbon stars in Galactic globular clusters, all of which are old and of type VII (SWB). Evolved stars from such old clusters are of low mass ($\simeq 0.8\ M_\odot$) with small stellar envelopes. Except for long-period variables, these stars fail to populate the AGB beyond the luminosity of the helium core flash at the top of the first giant branch (Frogel and Elias 1988). Thus they are probably unable to begin the cycle of thermal pulses which results in the carbon dredge-up described by Iben and Renzini (1983) as necessary to produce a carbon star.

If this is the explanation for the absence of carbon stars in type VII clusters, why do we find exceptions in the SMC? Since

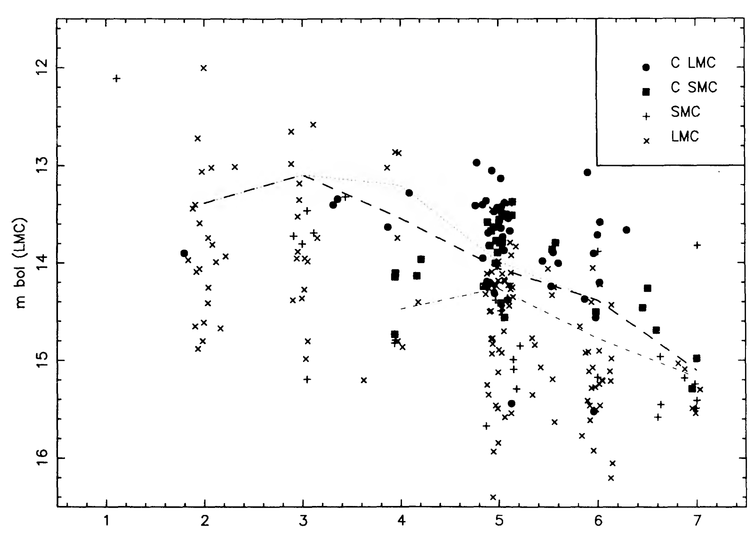


FIG. 14.—Bolometric magnitudes for all cluster members from Table 1 are plotted. SMC stars have been shifted to the LMC distance. To minimize overlap, many points have been displaced somewhat horizontally. The dashed line is the M to C transition luminosity for all stars. The upper dotted line and lower dot-dashed lines are the transition luminosities for LMC and SMC stars, respectively.

Kron 3 has been shown to be significantly younger than Galactic globular clusters (Rich, Da Costa, and Mould 1982), the presence of carbon stars in this cluster *is* consistent with the dredge-up concept. According to Mould and Da Costa (1988), the red giants in Kron 3 have masses of 1.0 $M_\odot$. The corresponding excess in envelope mass over Galactic globular cluster giants may be sufficient to carry these stars up on to the thermal pulsing AGB. (One should also recall that the SWB class of Kron 3 was inferred from its *UBV* colors; it is not in the original SWB sample with *uvgr* colors). Stryker, Da Costa, and Mould (1985) have argued that NGC 121 is also younger than Galactic globular clusters. However, the age difference in this case is only significant at the $\sim 1\ \sigma$ level.

According to the data in Table 1, the bolometric luminosities of the carbon stars in NGC 121 and 339 place them well below the point of helium core flash. Carbon stars are observed in $\omega$ Cen at approximately the same luminosity. Such carbon stars are thought to be produced by a mechanism different from direct third dredge-up in single stars (see Mould and Aaronson 1986; McClure 1989), but the details remain obscure. Mould and Aaronson (1979) and AMMA III have associated a more luminous carbon star with NGC 339. However, under the present stricter membership criteria, we do not count NGC 339–G151 as a member.

In addition to their absence in SWB VII clusters, the frequency of carbon stars is also very low in types I–III. The two earliest type clusters in the present sample that contain carbon stars are NGC 1850 (II) and NGC 2209 (III–IV). The *C-M* diagrams for these two clusters are consistent with their SWB classification according to Hodge (1983) and Gascoigne *et al.* (1976). An optical spectrum of the C star in the former cluster has confirmed this classification. For the moment we simply point out that since the carbon star in NGC 1850 is the only one found in all of the type II and III clusters in Table 1 and there is no way to confirm its membership, we must be cautious about supposing that AGB carbon stars are found at all in clusters younger than NGC 2209. We return to this matter in the next section.

### *c) The Brightest Stars*

The present sample of clusters is richer in young clusters than any sample previously studied. This allows us to consider in some detail the question of why in SWB types I–III clusters the brightest stars are all M stars, not C stars. These M stars are also among the brightest stars observed. In Figure 14 the most luminous carbon stars have $m_{\text{bol}} \simeq 13.0$. The most luminous M stars in Figure 14 reach $m_{\text{bol}}(\text{LMC}) = 12.1$ mag in NGC 299 star 5. There are several M stars between these luminosities in early SWB type clusters (see Figs 4 and 14). We particularly draw attention to NGC 1866, an intensely studied cluster that, according to Renzini and Voli (1981), should have about 10 thermally pulsing AGB stars but in which we find a complete absence of C stars. Possible reasons why luminous AGB stars in young clusters fail to become carbon stars have been a subject of intense interest in recent years (e.g., Iben 1981; Mould and Reid 1987; Hughes and Wood 1988; Renzini *et al.* 1985). Three possible explanations for the absence of luminous C stars can be summarized as follows:

1. Luminous AGB stars are prevented from becoming carbon stars by $^{12}$C burning reactions at the base of the stellar envelope (Renzini and Voli 1981).

2. Massive AGB stars do not undergo enough thermal pulses before mass loss has completely removed the stellar envelope (Frogel and Richer 1983; AMMA IV). Alternatively, for $M_{\text{core}} > 0.85$, i.e., for $M_{\text{tot}}$ in the range 5–9 $M_\odot$, the envelope may be removed by one of the first thermal pulses themselves (Wood and Faulkner 1986).

3. The minimum initial mass for nondegenerate ignition of a carbon core is as low as 5–6 $M_\odot$ due to convective overshooting (Becker and Iben 1979; Bertelli, Bressan, and Chiosi 1985; Bertelli, Chiosi, and Bertola 1989).

At first sight, the present data would appear to be consistent with the first hypothesis, although high-resolution spectra of the M stars with $m_{\text{bol}}(\text{LMC}) < 13$ would be required to test its prediction that there should be a nitrogen excess in these stars. However, we shall see in § VII*d* below that the AGB luminosity fraction in Magellanic Cloud clusters falls below theoretical expectations: there is a deficiency of AGB stars generally, not just C stars. The first hypothesis, then, fails by this criterion. Frogel and Richer (1983), Mould and Reid (1987, and Reid, Tinney, and Mould (1990) have noted a similar deficiency of luminous stars in fields of the LMC.

The present data are consistent with the third hypothesis. Evolutionary calculations reviewed by Lattanzio (1990) indicate that thermal pulses do not commence until $L_{\text{TP}} \simeq 10^4\ L_\odot$ in initial 4 $M_\odot$ stars (which corresponds to $m_{\text{bol}} = 12.95$ for $(m - M)_0 = 18.3$ for the LMC). There is a rapid rise in $L_{\text{TP}}$ between 3 and 5 $M_\odot$. Carbon stars would therefore not be expected in SWB III clusters until $m_{\text{bol}} < 13$. The calculations of Bertelli, Bressan, and Chiosi (1985) further show that the inclusion of convective overshooting in models of intermediate-mass stars results in the elimination of stars with masses greater than about 6 $M_\odot$ from the AGB luminosity function as these stars will not undergo thermal pulses. More recent calculations (Bertelli, Chiosi, and Bertola 1989) reduce the mass limit above which degenerate core C ignition does not occur even further to 4.5–5.2 $M_\odot$. Bertelli, Bressan, and Chiosi (1985) argue that the second, or mass-loss, hypothesis would be likely to have "devastating consequences" for our understanding of other evolutionary phases. However, this is only true if a parameterized mass-loss law such as Reimers's applies for all red giant evolutionary phases. The termination of the AGB phase may result from the action of a "superwind" (Iben and Renzini 1983) or envelope ejection (Wood and Faulkner 1986) whose consequences are quite limited (but possibly ad hoc). Finally, Chiosi *et al.* (1986) have shown that stellar evolution with convective overshooting and a modest excess, over the Reimers rate, of mass loss can fit the AGB luminosity function in the LMC. The overshooting hypothesis is, therefore, a real rival to the second hypothesis mentioned above as an explanation for the absence of luminous carbon stars; we discuss it further in the next section.

### *d) Contribution of the AGB to the Integrated Cluster Light*

Renzini and Buzzoni (1986) examine theoretically what they refer to as a "simple stellar population (SSP)," namely "an assembly of coeval, initially cehically homogeneous, single stars." A star cluster may be assumed to have such a population. The clusters surveyed in the Magellanic Clouds cover a sufficient range in chemical composition and age that a detailed comparison of our results with the first-order predictions of the theory outlined by Renzini and Buzzoni will be instructive. To carry out such a comparison, it is necessary to determine the relative contributions of stars in different evolution stages to a cluster's integrated luminosity and to compare the colors of clusters to those of true globular clusters. The next two subsections discuss such a comparison.

*i) The Contribution of the AGB to a Cluster's $M_{\rm bol}$*

In terms of their observable impact, the two most important components in a SSP relevant to the clusters included in our survey are the red giant branch, RGB, and the AGB. Now for giants fainter than the level of core He flash in low-mass stars, a star on the AGB cannot be separated from one on the RGB for the Magellanic Cloud clusters. However, it is observationally established that $M_{\rm bol}$ at the RGB tip is only a slowly varying function of metallicity and is in close agreement with the theoretically predicted dependence (Frogel, Cohen, and Persson 1983). We take $M_{\rm bol} = -3.6$ as the dividing point brighter than which will only be AGB stars, although some AGB stars fainter than this limit will occur as well. The present survey is nearly complete for all cluster C and M giants several tenths of a magnitude fainter than this limit. We will refer to the AGB stars brighter than this limit as luminous AGB stars.

Most of the clusters in Table 1 have integrated infrared colors and magnitudes in PACFM. We determined which of the Table 1 stars would have been included within the largest aperture measurement made by PACFM and calculated the total fluxes for these stars in the *JHK* bands. Stars that would be on the edge of the aperture were included as the centering procedure used for making the integrated measurements would, in all likelihood, have included them. We also calculated bolometric magnitudes for the integrated cluster light in the biggest aperture; these values are given in the third column of Table 4. A program was used that took into account the *UBV* fluxes as well as an estimate of the flux longward of the *K* band. In a few cases it was necessary to guess at $U-V$ based on the other colors. The summed bolometric luminosities for the luminous AGB stars were subtracted from the appropriate values for the cluster light. The colors and magnitudes of the light remaining from the clusters after this subtraction are given in Table 4. The sixth and seventh column of the table indicate the fractional contribution of all luminous AGB stars and of C stars alone to the bolometric luminosity of a cluster. In order to illustrate these results and minimize the effects of small number statistics, we also did the sums and calculated the fractional contributions for all clusters in each SWB group separately. These results are shown in Figures 15 and 16. Uncertainties were calculated based on the number of stars and clusters in each SWB group.

First consider the contribution of the luminous AGB stars to the luminosity. Figure 15 shows that they are present only marginally if at all in SWB VII clusters. As argued in § V*d* above, this is consistent with their being Magellanic Cloud analogs of Galactic globular clusters. Beginning at SWB type VI, luminous AGB stars rapidly become an important contributor to the bolometric luminosity and remain so through the type IV clusters. Earlier than type IV, the contribution from bright AGB stars falls rapidly. Whether there is a real minimum in their contribution before an increase again for the earliest types or whether the falloff is followed by a reduced but more or less constant contribution for types II–III, cannot be decided from the present data. SWB I clusters are young enough that they could contain M supergiants.

Figure 16 shows, like Figure 14, that carbon stars are found only in type IV–VI clusters. The one point at type III–IV with a C star is NGC 2209, a rather poor cluster with two luminous C stars that together account for nearly all of its bolometric

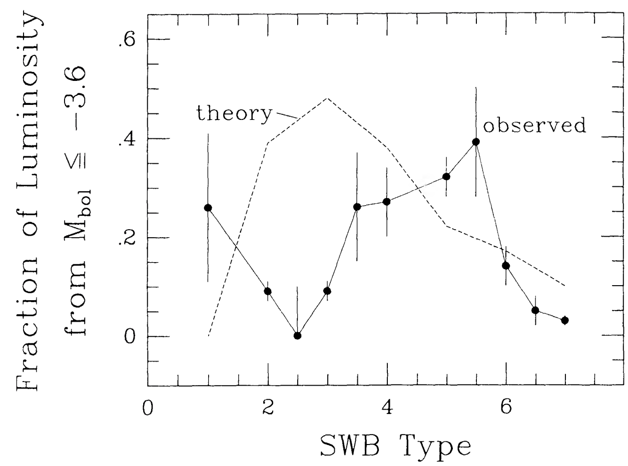


FIG. 15.—The fractional bolometric luminosity of Magellanic Cloud clusters that arises from bright AGB stars is shown as a function of SWB class. The dots with uncertainties indicated are the observed values for each class calculated as described in the text. The dashed line is the predicted AGB contribution from Renzini and Buzzoni (1986) with a 25% contribution from the RGB subtracted. The conversion between SWB class and cluster age, or turnoff mass, is given in Table 3.

luminosity. Only one of them, though, is contained within the aperture used by PACFM. When present, carbon stars account for 50%–100% of the bolometric luminosity from the AGB above the point of core He flash.

With the help of Figure 4 of Renzini and Buzzoni (1986) we can compare the observed contribution of the luminous AGB to a cluster's $M_{\rm bol}$ with theoretical predictions. For $Y = 0.28$, $Z = 0.02$, and $\eta = \frac{1}{3}$, this figure shows the relative contributions to the bolometric luminosity of a SSP from major stellar evolutionary stages as a function of age and turnoff mass. Although derived with a value of $Y = 0.25$ and a solar $Z$ value, differences between these values and values that would be more appropriate to the clusters will have only a minor effect on the comparison. The line labeled "theory" in Figure 15 is the contribution of the AGB from Renzini and Buzzoni's Figure 4 with the ages for a given SWB type taken from Figure 2 and Table 3. At each age, a 25% contribution from the RGB was subtracted from the AGB line given by Renzini and

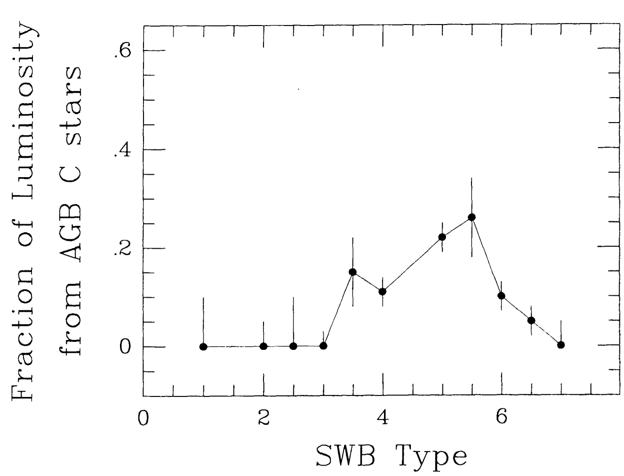


FIG. 16.—The observed fractional bolometric luminosity of Magellanic Cloud clusters that arises from bright C stars is shown as a function of SWB class.

Buzzoni to allow for the fact that we have not included AGB stars fainter than the tip of the first giant branch. The difference between the theoretical line and the observational one in Figure 15 for the latest type clusters is judged not to be significant.

A major difference between theory and observation is the age interval during which AGB stars are important contributors to the bolometric luminosity. According to Renzini and Buzzoni (1986), the AGB rises rapidly in importance at an age corresponding to a turnoff mass of $\sim 9\ M_{\odot}$; the SSP undergoes a "phase transition" in Renzini and Buzzoni's parlance. Stars more massive than this do not have degenerate carbon cores and do not become AGB stars. Less massive stars—older ones—do have carbon degenerate cores and burn helium and hydrogen in shells. Our observations show the rapid rise in the AGB contribution begins only for clusters later than SWB II–III. Since a number of these clusters contain Cepheids (e.g., NGC 1850, 1854, and 2214), we can be reasonably certain that their age is on the order of 100 Myr with a corresponding mass of 3–5 $M_{\odot}$ (Table 3). We can rule out the possibility that these clusters contain luminous stars that were not found in our grism surveys: for all type II and III clusters with published optical *C-M* diagrams, all bright stars were examined in the infrared. None were found to be significantly brighter bolometrically than those found in the survey. Hence, the most massive progenitors for AGB stars that we can identify are only in the range 3–5 $M_{\odot}$. We again draw particular attention to one of the most populous clusters, NGC 1866. Note only does it not contain C stars, but the few luminous AGB M stars in it contribute only 6% of its bolometric luminosity, whereas, on average, clusters of this SWB type are predicted to have more than 40% of their bolometric luminosity from such stars (Table 3 and Fig. 15).

The theoretically predicted decline in importance of the AGB corresponds to a second phase transition in a SSP for masses less than 1.7 $M_{\odot}$. This second transition occurs over a stellar mass range of only a few tenths of a solar mass (Sweigart, Greggio, and Renzini 1989). Now stars on the first giant branch with degenerate He cores become important. Our data in Figure 15 show that this decline does not happen until a somewhat older age than that which corresponds to SWB VI clusters. In other words, luminous AGB stars can be produced at significantly lower turnoff masses than theory predicts. Comparison of Figures 15 and 16 shows that most of this luminosity is coming from C stars. Therefore the disagreement between theory and observation subsumes the "carbon star problem": where are the very luminous carbon stars predicted by theory but not observed and why are there AGB carbon stars of significantly lower luminosity than theory predicts (Iben 1982; Iben and Renzini 1983). What can account for the differences between theory and observations evident from Figure 15? There are certain parallels here to the carbon star problem; i.e., Renzini and Buzzoni (1986) note that their predictions for SSP evolution have not taken into account convective overshoot (Bertelli, Bressan, and Chiosi 1985). If it were included (see their Fig. 2), the effect would be to shift the theoretical distribution in Figure 15 to the right, resulting in better agreement with the observations. As noted in the previous section, (1) a higher than predicted mass-loss rate on the upper AGB would effectively terminate an AGB star's evolution at a relatively low luminosity; and (2) the calculations of Chiosi *et al.* (1988) show that convective overshooting plus a *modest* increase in mass-loss rate can successfuly reproduce both the absence of luminous AGB stars and the relatively reduced luminosity function for the AGB stars known to be present, i.e., with luminosities comparable to those found in the clusters we have studied. Lattanzio (1989), though, points out that convective overshooting is *not* needed for third dredge-up, and hence C star production, in stars as low as 1.5 $M_{\odot}$ with solar abundance or 1.0 $M_{\odot}$ in stars that are metal-deficient.

Can we distinguish between the convective overshoot hypothesis and the mass-loss hypothesis for explaining the deficiency of luminous AGB stars? In principle, this is difficult because the net effect is the same, whether one chooses to eject the AGB envelope and thus terminate AGB evolution, or to change the ratio of envelope to core mass through overshooting. Possibly one might expect the overshooting mechanism to act as a sharp guillotine at 5–6 $M_{\odot}$ turnoff, whereas mass loss would manifest itself as a more stochastic process. Evidence that some luminous AGB stars are found in the LMC has been presented by Wood, Bessell, and Fox (1983), but Mould and Reid (1987) have argued that they are an order of magnitude fewer than predicted. Also, since the candidates suggested by Wood *et al.* are not in a cluster, it is difficult to definitely establish their evolutionary status. If we could point to a few irrefutable AGB stars of sufficient luminosity in type II or earlier Magellanic Cloud clusters, we would have a basis for preferring the mass-loss hypothesis, although Bertelli, Bressan, and Chiosi (1985) have argued against this hypothesis. If star 5 can be shown to be a single AGB member of NGC 299, and if the age of NGC 299 is less than 45 Myr, then we can be sure that stars initially exceeding 6 $M_{\odot}$ can develop a degenerate CO core. Further study of the early-type clusters would be critical for deciding between the two hypotheses.

ii) *Clusters after Removal of Luminous AGB Stars*

Figure 17 illustrates integrated $J-H$, $H-K$ colors for Magellanic Cloud clusters from Table 4 after removal of bright AGB stars. The remaining stellar population in most of these Cloud clusters should be comparable to the stellar content of true globular clusters except for differences in age and chemical composition. The outer contour in Figure 17 defines the area

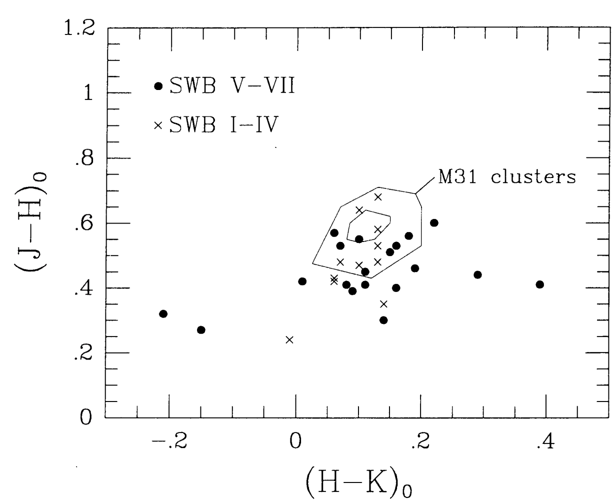


FIG. 17.—$J-H$, $H-K$ diagram for the integrated light of the Magellanic Cloud clusters after bright AGB stars have been removed as discussed in the text. The contour labeled "M31 clusters" contains all but a couple of the M31 clusters observed by Frogel, Persson, and Cohen (1980). The inner contour contains half of these clusters.

occupied by all but two of the M31 globular clusters observed by Frogel, Persson, and Cohen (1980), while the inner one is the area occupied by half of these M31 clusters. Except for some extreme cases, the Magellanic Cloud clusters of SWB type V–VII lie within the outer contour but in the blue $J-H$ half. These extreme cases tend to be intrinsically poor clusters whose light is dominated by only a few bright AGB stars. Clusters of type I–IV have $J-H$ colors bluer than those of the M31 globulars. Since the range in chemical composition for the M31 and Magellanic Cloud clusters is probably comparable, the bluer colors of the Cloud clusters must result from increasing contribution of main-sequence and horizontal branch stars in these younger clusters; see, for example, Renzini and Buzzoni's (1986) Figure 4.

The distribution of integrated $J-K$ color as a function of SWB type for Magellanic Cloud clusters after removal of luminous AGB stars is shown in Figure 18. If the outliers are ignored, we see a jump in $J-K$ at type IV–V. For V–VII clusters, the mean $J-K$ is about 0.65 independent of type. For earlier types, the mean color is about 0.5. The change in turnoff mass between type V and IV clusters is between 1.8 and 2.5 $M_{\odot}$ (Table 3). A discontinuity or rapid color change at SWB type IV–V is evident in $B-V$ as well (Fig. 13 of Renzini and Buzzoni 1986). It is not seen in the *total* integrated $J-K$ colors (PACFM) as these are dominated by the luminous AGB star contribution. Renzini and Buzzoni (1986) consider several explanations for the transition in $B-V$. Chiosi, Bertelli, and Bressan (1988) claim that the transition observed in the $B-V$ colors is *not* due to the red giant branch phase (RGB) phase transition but rather arises from a combination of rate of cluster formation and disruption and the rapid fading of the young, blue clusters. We, on the other hand, claim the RGB phase transition is the most likely cause: since we have already removed luminous AGB stars, stars on the RGB will dominate the infrared light of intermediate to old age stellar populations (e.g., Frogel 1988, and references therein). Recall that from our previous discussion of AGB stars we found no discrepancy between the predicted and observed location of the RGB phase transition. Only for the AGB phase transition was a serious discrepancy found. The calculation of Sweigart, Greggio, and Renzini (1989) show that the appearance of the RGB transition occurs abruptly at a mass of 2.0 $M_{\odot}$ for an [Fe/H] of $-0.7$, in excellent agreement with values in Table 3 for SWB type IV–V.

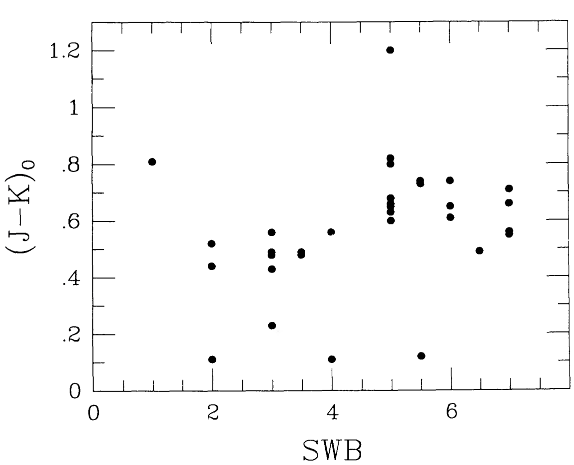


FIG. 18.—The $J-K$ colors of the Magellanic Cloud Clusters after bright AGB stars have been removed are plotted against SWB type.

A mass change of only a few tenths of a solar mass results in a change in luminosity of the tip of the red giant branch of about 2.5 mag. Figure 14 of Renzini and Buzzoni illustrates the effect of the sudden appearance of a RGB on a cluster *C-M* diagram. Obviously, the effect on the integrated $J-K$ color will be to make it significantly redder as first ascent giants are an important contributor to the infrared light of an old cluster. Counteracting somewhat the tendency for $J-K$ to get bluer due to the correlation between increasing age and decreasing metallicity for Magellanic Cloud clusters (§ V*b*).

## VIII. SUMMARY AND CONCLUSIONS

We have surveyed for carbon and M stars most of the Magellanic Cloud star clusters studied in integrated optical light by SWB and infrared light by PACFM. Within and around these clusters, our survey should be complete for stars brighter than about $M_{\rm bol}$ of $-3.6$. We have obtained infrared photometry for all of these stars. Analysis of the data yields the following results:

1. The AGBs in these clusters are arranged systematically in the H-R diagram: (i) The oldest clusters (type VII) tend not to contain carbon stars or luminous AGB stars of any kind. The colors and magnitudes of their giant branches overlap those of Galactic globular clusters and imply a metallicity range at least as great as that between M92 and M3. Particularly impressive is the coincidence of the luminosity of the RGB tip in Cloud and Galactic globulars as a function of color. (ii) Intermediate-age clusters (types V and VI) with an age range of $\sim 2.5$ Gyr, contain both AGB M stars and carbon stars. The latter are the reddest AGB stars in the sample, while the M stars are the reddest M giants in the sample. A narrow range in [Fe/H] for these clusters of not more than 0.5 dex, and possibly as low as 0.2 dex, is required to confine the M star part of the giant branches to the observed small spread in color. (iii) Young (types I–III) clusters have the bluest GBs in the sample corresponding to higher mass Hayashi tracks. They tend not to contain carbon stars. Their M stars are among the brightest of any stars in the sample and are too bright to be core He-burning stars (Becker, Iben, and Tuggle 1977); they most likely are AGB stars.

2. The tendency for the AGBs to become bluer and more luminous with decreasing age yields a bimodal distribution when cluster M stars in the H-R diagram are viewed in a suitable projection. This distribution is in qualitative agreement with that found by Frogel and Blanco (1983) for field M stars in the LMC. The two peaks could result from two discrete epochs of star formation with ages corresponding to those identified in results 1(ii) and 1(iii) above. Elson and Fall (1988), though, have found no evidence for global bursts in cluster formation in the LMC, although they do not rule out small-amplitude variations in the rate. A more detailed study is required to translate the observed color distribution functions for the cluster and field M stars into a statement about star formation rate as a function of time (see Chiosi, Bertelli, and Bressan 1988).

3. If both M and C stars are present in the same cluster, the faintest C star is almost always brighter than the brightest M stars. The luminosity of transition from M stars to carbon stars in Cloud clusters rises monotonically with decreasing SWB type. Figure 19 shows this rise as a function of turnoff mass for each SWB type from Table 3. Over the range 1–4 $M_{\odot}$ in initial mass, the agreement with recent evolutionary calculations by Lattanzio (1989*a*, *b*) is quite good. Earlier calculations by

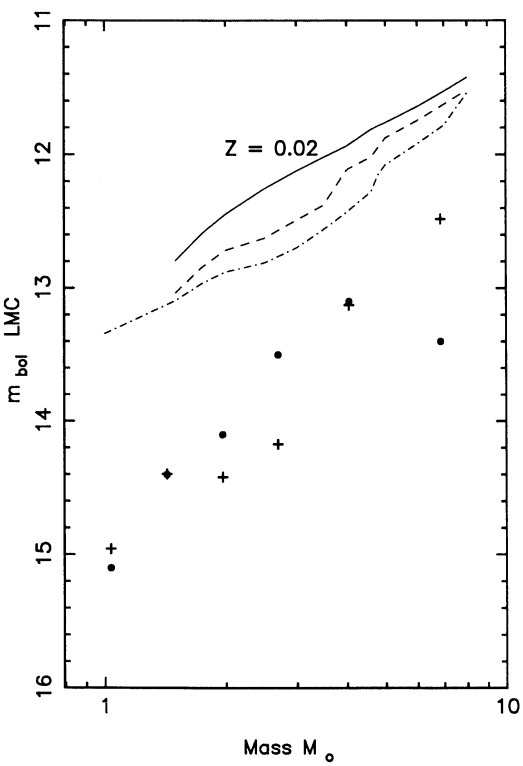


FIG. 19.—The transition luminosity is shown as a function of turnoff mass for SWB types II to VII. Empirical values from Table 3 are denoted by filled circles. Predictions from Lattanzio's (1989) interpolation formulae are shown as plus signs. The curves are taken from Renzini and Voli (1981) for $Z = 0.001$, 0.004, and 0.02, the latter of which is labeled.

Renzini and Voli (1981) considerably overestimated the transition luminosity.

4. At a given SWB type, the transition luminosity is ~0.4 mag fainter in the SMC than in the LMC. It is hard to tell whether an age difference between SMC and LMC clusters or a metallicity difference is behind this magnitude difference because there is very little overlap in age between the relevant clusters.

5. The difference in transition luminosity between the two Clouds is reflected in the difference between their carbon star luminosity functions: SMC C stars both from clusters and the field are fainter than those in the LMC. This difference seems to exceed the uncertainty in the relative distance moduli. The differences in both the transition luminosity and the luminosity functions are likely to have the same physical origin.

6. There is a deficiency of luminous AGB stars ($M_{\rm bol} < -6$) of any kind in Magellanic Cloud clusters compared with theoretical expectations. This deficiency is now firmly established for both clusters and the field from studies of individual stars (AMMA I–IV; CFPE; Frogel and Richer 1983; and Reid and Mould 1984) and from calculation of the fractional contribution of the AGB to the total cluster light (this paper).

7. Since this deficiency of luminous stars is not confined to carbon stars but applies to the M stars as well, we can rule out envelope burning of carbon to nitrogen as its source. Competing hypotheses to explain the deficiency are higher-than-expected mass loss in luminous AGB stars and convective overshooting leading to early carbon ignition for initial masses exceeding 6 $M_\odot$ (Becker and Iben 1979; Bertelli, Bressan, and Chiosi 1985; Bertelli, Chiosi, and Bertola 1989).

8. Decisive tests which would be fatal to the overshooting hypothesis are (i) observation of *any thermally pulsing AGB stars* in clusters with turnoff masses exceeding 6 $M_\odot$, (ii) observation of *any stars with* $m_{\rm bol}(LMC) < 12$ in such clusters. According to Bertelli, Bressan, and Chiosi (1985) and Bertelli, Chiosi, and Bertola (1989), carbon ignition occurs at $m_{\rm bol}({\rm LMC}) = 11.8$ for initial mass 9 $M_\odot$ without convective overshooting and 12.0 for initial mass 5–6 $M_\odot$ with overshooting for the distance modulus adopted here. Further detailed study of the brightest stars in type I–III clusters is required.

9. After correcting the integrated light of Cloud clusters for the effect of AGB stars, we see a color discontinuity which we identify with the red giant branch phase transition in SWB type IV–V clusters (Renzini and Buzzoni 1986; Sweigart, Greggio, and Renzini 1989). This corresponds to the change in circumstances of helium ignition in ~2.0–2.7 $M_\odot$ stars without overshooting or about 1.7 $M_\odot$ with overshooting.

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