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# THE EXTENDED GIANT BRANCHES OF INTERMEDIATE AGE GLOBULAR CLUSTERS IN THE MAGELLANIC CLOUDS[1]

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## ABSTRACT

Vidicon spectra and infrared *JHK* photometry are presented for stars near the tip of the giant branch in a sample of red globular clusters in the Magellanic Clouds. The coverage extends considerably that of our earlier spectroscopic survey. We again find numerous carbon stars, and some M stars, whose luminosities place them on the upper asymptotic giant branch (i.e., above the luminosity of the helium flash).

From the IR photometry, the mean bolometric magnitude of carbon stars in the LMC and SMC clusters is found to be $-5.02 \pm 0.10$ mag and $-4.69 \pm 0.10$ mag, respectively. These values are significantly fainter than we found previously using optical bolometric corrections. Our results may conflict with two recent studies of luminosities based on *I* magnitudes, which suggest that *field* carbon stars in the SMC are *brighter* than those in the LMC. Blanketing of the *I* bandpass may be a source of this difference. The *JHK* colors of the SMC cluster carbon stars appear in the mean bluer than those of the LMC cluster stars, a fact which may reflect a metallicity difference between the Clouds.

Effective temperatures based on $J - K$ colors are given for all stars. The noncarbon stars scatter well above the mean relation for galactic field giants in a ($J - K$, $V - K$) two-color diagram, and we argue that temperatures derived for these stars from $V - K$ colors are not to be trusted. Using a recent recalibration based on stellar angular diameters, we derive temperatures which in the mean are some 240 K cooler than those found from model atmosphere calculations. With this temperature scale the location of the cluster giant branches in the H-R diagram is compatible with theoretical isochrones.

A simplified theory of asymptotic giant branch evolution is applied to calculate ages for the full sample of clusters studied to date. Clusters with stars on the upper asymptotic giant branch are estimated to be of intermediate age, mostly in the range 2–6 billion years old. Our age ranking is consistent with a recent photometric classification scheme. The first hints are apparent of an age-metallicity correlation, which is to be expected if chemical enrichment has occurred over the cluster formation period.

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

## I. INTRODUCTION

In the Magellanic Clouds the formation of globular clusters appears to be a continuing process. Young blue globulars such as NGC 1831 and 1866 exist side by side with old clusters resembling the classical globulars of the Milky Way. It seems natural to expect, therefore, that globular clusters of intermediate age (say, 1–6 billion years) should be present in large numbers in the Clouds, since this time scale represents much of these galaxies' evolutionary history.

These clusters have proved hard to recogize, however. One or two are known for sure from the careful study of their color-magnitude diagrams down to the main-sequence turnoff (e.g., NGC 2209, Gascoigne *et al.* 1976; Lindsay 1, Gascoigne 1978). In other cases intermediate age is suspected from the absence of a horizontal branch (e.g., NGC 2190, Hesser, Hartwick, and Uguarte 1976; Kron 3, Gascoigne 1966). A further indicator of intermediate age first discussed by Mould and Aaronson (1979, hereafter Paper I) originates in a property of Magellanic Cloud clusters long dwelt on by van den Bergh (1968, 1975). That is the extension of the giant branch in the color-magnitude diagram to

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$B - V \lesssim 2.0$ and the presence of carbon stars at the giant branch tip.

The key argument in Paper I was that luminosities much beyond $M_{\rm bol} \lesssim -4$ are not attained by stars in halo globular clusters (Cohen, Frogel, and Persson 1978, hereafter CFP) and that the presence of cluster stars with mean luminosities estimated between $-6.5$ and $-5.1$ in the Clouds required more massive progenitors at the base of the giant branch. Since mass loss controls the ultimate luminosity on the asymptotic giant branch, the theory developed by Renzini (1977) was used to estimate an age of 3 billion years for clusters with a maximum $M_{\rm bol}$ of $-5.5$.

Because the luminosity of the brightest stars is the key to the cluster ages, and since the visual bolometric corrections for such cool stars are large and uncertain, a program of infrared photometry was recommended. Results for three clusters in the Large Cloud have been obtained by Frogel, Persson, and Cohen (1980, hereafter FPC). They find a mean bolometric magnitude for the carbon stars in NGC 1783, 1846, and 1978 of $-4.9$, fainter than obtained in Paper I, but still consistent with the age estimate of 3 billion years.

In the present paper we continue our spectroscopic survey of the tip of the giant branch in the red globulars of the Clouds (§ II). We have extended the coverage in four of the clusters previously studied and examined two more clusters in the SMC and six more in the LMC. Infrared photometry has been obtained (§ III) for many of these stars, together with the bulk of those remaining from Paper I. In § IV a relation is derived between the age of a cluster and the luminosity at the top of the asymptotic giant branch (AGB). This permits ages to be estimated for the full sample of clusters studied to date. These ages are consistent with the Cloud cluster classification scheme recently offered by Searle, Wilkinson, and Bagnuolo (1980) and support a correlation between age and metallicity (§ V).

## II. VIDICON SPECTROPHOTOMETRY

To permit more detailed spectroscopic classification of the program stars than was achieved in Paper I, we chose to nearly double the wavelength coverage to 4200–7000 Å. Since molecular bands are the primary features, the consequent reduction of resolution to 16 Å (FWHM) seemed an acceptable price to pay. The best configuration of the modified RC spectrograph for this format proved to be grating 32 (blaze 6750 Å) operated in the first order with a 700 $\mu$m slit (3".2) and a GG385 order separating filter.

The spectra were obtained at the CTIO 4 m telescope on the nights of 1979 October 28–30. The first night was mostly cloudy and the four spectra secured contain no magnitude information. The transparency on the remaining nights was fairly good. These nights were moonlit, with good seeing ($<2''$) and quite acceptable spectrophotometric conditions. Inspection of flat field exposures made with a quartz comparison lamp within the spectrograph and also on the twilight sky implied that the sensitivity of the SIT was constant within a few percent perpendicular to the dispersion. Sky and bias removal were therefore carried out by simple subtraction of strips of spectrum from clear regions on either side of the program object that were free from neighboring stars. The success of this procedure could be monitored by the removal of the very strong 5577 Å night-sky line (see Fig. 1). Standardization was effected by means of the regular tenth magnitude standards used with this instrument (Osmer 1977, Stone 1977). The residuals obtained are indicated below. The processing described here was carried out at the CTIO La Serena Computer Center.

A simple program was then written at KPNO to three-point smooth the data (15 Å box), display it in the form of Figure 1, and evaluate the following quantities:

1. [4930] − [6540] is the flux ratio $F_\nu(4930)/F_\nu(6540)$ in mag.
2. *Band strength* is the flux ratio $F_\nu(5615)/F_\nu(5690)$ for C stars [measuring the (0, 1) band of the Swan system] and $F_\nu(6250)/F_\nu(6150)$ for K and M stars [measuring the (0, 0) band of the $\gamma'$ system of TiO). This definition is essentially unchanged from Paper I both in wavelength and bandpass.
3. *Magnitude* is an integration of $F_\nu$ over the $V$ response function given by Johnson (1965). Conversion to magnitudes was effected using $3.50 \times 10^{-20}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ for zeroth magnitude (Hayes and Latham 1975).

The rms color and magnitude dispersion for the standards were 0.07 and 0.09 mag, respectively, with mean residuals of $0.07 \pm 0.02$ and $0.07 \pm 0.04$. These corrections were applied to the data. Further comparison was made of the synthesized magnitudes with published $V$ magnitudes for 9 of the program stars. A mean difference was found (mag $-$ $V$) of $0.18 \pm 0.06$ $(\sigma/\sqrt{n})$ with a small, but not significant, color term. We have *not* corrected the data for this effect, which is not understood, but it should be regarded as a possible systematic error in the magnitudes.

The quantities described above are recorded in Table 1 for all the program stars together with a spectral classification. In drawing up the classification scheme, the spectral scans of Fay, Stein, and Warren (1974) and Fay *et al.* (1974) proved very useful. For C stars (recognized by the band heads of the Swan system of $C_2$ at $\lambda\lambda$4737, 5165, 5635, 6191), a "carbon" subtype is given following Yamashita (1972, 1975) based on the band strength. The temperature subtype (the NaD line strength) is unmeasurable at our resolution. For M stars (recognized by the band heads of the $\gamma'$ system of TiO at $\lambda\lambda$5850, 6162) a subtype is given corresponding to the band strength. Stars are classified K type if the MgH + Mgb feature is visible at 5200 Å, but the TiO band strength is less than 0.12 mag. Absence of TiO corresponds to K4. One star in which no features were positively identifiable was classified Ctm for "Continuum" following Paper I. In Figure 1 enough of the spectroscopic material is displayed to

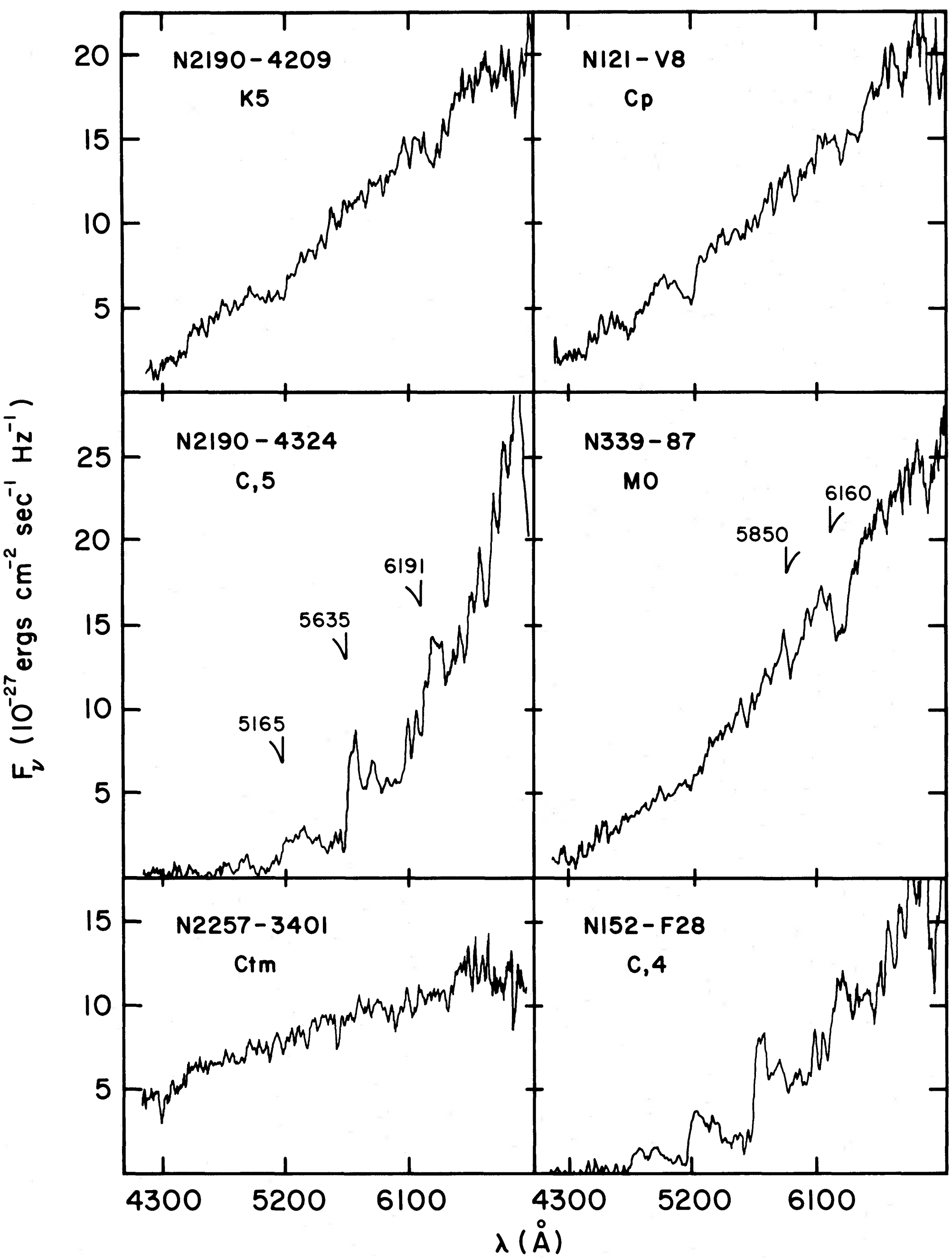


FIG. 1.—Spectra of selected stars in Magellanic Cloud globular clusters. Swan bands of $C_2$ are noted in some of the carbon stars, and band heads of TiO are noted in some of the M stars.

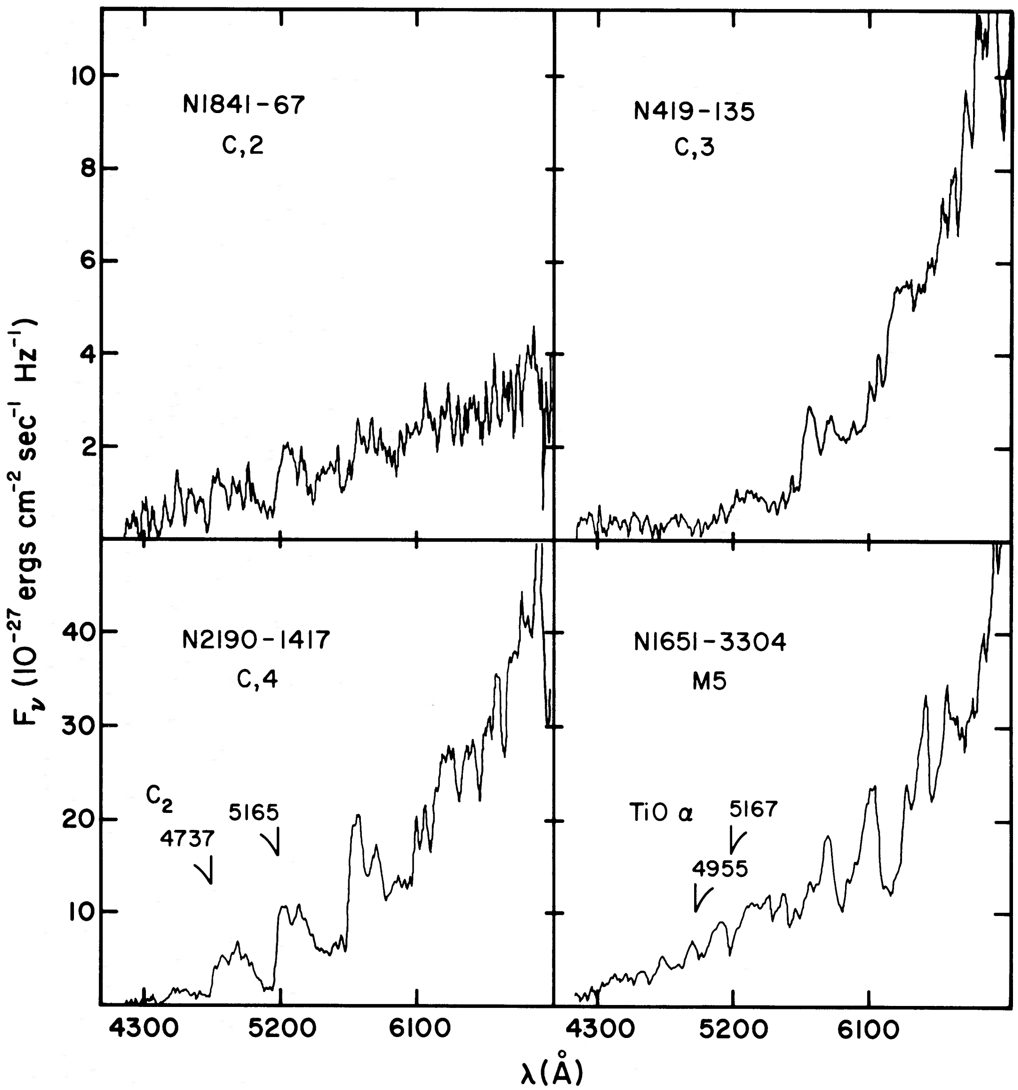


FIG. 1.—*Continued*

outline the classification scheme. We also show some of the more interesting or unusual spectra which receive comment below.

*NGC 121-V1, V8.*—Spectra of these two red variables have also been obtained by Feast and Lloyd-Evans (1973). In V1 we confirm the presence of the Balmer series in emission, which suggests that the star is a Mira variable. The spectrum of V8 is peculiar in that the (1, 0) $\lambda$4737 and (0, 0) $\lambda$5165 band heads of $C_2$ are clearly present, but the (0, 1) $\lambda$5635 band head, which is generally the strongest in C stars, is absent or very weak. Our spectrum fits the description given by Feast and Lloyd-Evans for their first spectrum of V8. On three subsequent occasions they saw no evidence of $C_2$ at all. Notably, this star is also the bluest of the carbon stars in Table 1; in fact, it fits well a correlation between band strength and color which exists for the carbon stars in Table 1 in the interval (1.0, 2.2) in [4930] – [6540]. An indication of the evolutionary state of NGC 121-V8 must await infrared photometry, which is not available at present.

*NGC 419 – 135.*—This is one of the reddest of the carbon stars whose spectra are presented here. Walker (1972) records it as a variable star, and our magnitude is ~1 mag fainter than his value. It has also been identified as a carbon star[4] by Blanco and Richer (1979).

*NGC 1841 – 67.*—Although the presence of $C_2$ bands in this spectrum clearly identifies this as a carbon star, the visual magnitude and the infrared photometry presented in § III locate this star 2 mag

[4] Note that Blanco and Richer have identified three additional carbon stars (BR 4, 5, 6) as likely members of NGC 419. In addition, BR 7 is NGC 419-IV-133 (Arp 1958*b*) observed in Paper I.

TABLE 1

SPECTROPHOTOMETRY OF RED STARS IN MAGELLANIC CLOUD GLOBULARS

| Cluster | Star | Reference | [4930] − [6540] | Band Strength | Mag | Type | Notes |
|---|---|---|---|---|---|---|---|
| | | | SMC | | | | |
| NGC 121 ............ | 1-23 | 1 | 1.25 | 0.06 | 16.8 | K5 | |
| | V8 | 2 | 1.06 | 0.08 | 16.3 | Cp | 1, 4, 10 |
| | V1 | 2 | 1.17 | 0.02 | 15.6 | K4e | 2, 4 |
| NGC 152 ............ | B11 | 3 | 1.15 | 0.00 | ... | K5 | |
| | C19 | 3 | 1.13 | 0.19 | ... | M0 | |
| | E-18 | 3 | 1.06 | 0.07 | ... | K5 | |
| | H23 | 4 | 1.46 | 0.84 | 16.5 | C, 2 | 3 |
| | F28 | 4 | 2.18 | 1.53 | 17.4 | C, 4 | 3, 10 |
| NGC 339 ............ | 87 | 5 | 1.53 | 0.12 | 16.4 | M0 | 10 |
| | 151 | 5 | 1.38 | 1.00 | ... | C, 3 | |
| NGC 361 ............ | I-77 | 6 | 1.55 | 0.05 | 16.8 | K4 | 5 |
| NGC 419 ............ | 135 | 7 | 3.58 | 1.01 | 18.4 | C, 3 | 10, 11 |
| | 5-3 | 8 | 1.53 | 0.26 | 16.3 | M1 | 12, 14, 16 |
| | 5-7 | 8 | 1.23 | 0.06 | 16.4 | K5 | 13, 16 |
| | 5-39 | 6 | 1.36 | 0.57 | 15.8 | C, 1 | 5 |
| | | | LMC | | | | |
| NGC 1651 ............ | 3304 | 9 | 1.34 | 0.53 | 16.2 | M5 | 10 |
| | 2421 | 9 | 1.56 | 0.43 | 16.9 | M3 | |
| | 4325 | 9 | 1.63 | 0.56 | 16.3 | M4 | |
| | 4328 | 9 | 1.84 | 1.16 | 17.1 | C, 3 | |
| NGC 1841 ............ | 67 | 5 | 1.55 | 0.82 | 18.3 | C, 2 | 6, 10 |
| NGC 1978 ............ | I-14 | 12 | 1.43 | 0.24 | 16.5 | M1 | 15, 16 |
| NGC 2173 ............ | 1401 | 9 | 1.37 | 0.18 | 16.4 | M0 | |
| | 4306 | 9 | 1.54 | 0.10 | 17.0 | K5 | |
| NGC 2190 ............ | 4209 | 10 | 1.11 | 0.10 | 16.4 | K5 | 10 |
| | 1417 | 9 | 1.86 | 1.20 | 16.3 | C, 4 | 10 |
| | 4324 | 10 | 3.76 | 1.78 | 17.4 | C, 5 | 10 |
| NGC 2193 ............ | 1307 | 9 | 1.79 | 0.43 | 18.0 | M2 | 6, 9 |
| | 2201 | 9 | 1.42 | 0.65 | 16.1 | M4 | |
| NGC 2209 ............ | 46 | 11 | 2.10 | 1.39 | 16.5 | C, 4 | 8 |
| | 50 | 11 | 4.48 | 1.06 | 17.2 | C, 3 | 8 |
| NGC 2257 ............ | H23 | 5 | 1.44 | 0.32 | 16.2 | M1 | |
| | 3401 | 9 | 0.53 | ... | 16.4 | Ctm | 10 |

REFERENCES.—(1) Tifft 1963; (2) Thackeray 1958; (3) Hodge 1980; (4) see note (3); (5) Gascoigne 1966, 1978; (6) see note (5); (7) Walker 1972; (8) Arp 1958*a*; (9) Hesser, Hartwick, and Uguarte 1976; (10) see note (7); (11) Walker 1971; (12) Hodge 1960.

NOTES.—(1) Peculiar carbon star: only $\lambda\lambda$5165, 4737 visible; (2) H$\alpha$, $\beta$, $\gamma$ emission: Mira; (3) we have added these identifications to Hodge's 1980 finding charts; (4) see also Feast and Lloyd-Evans 1973; (5) we have added this identification to Arp's 1958*a*, *b* finding chart; (6) low signal-to-noise ratio; (7) we have added this identification to the chart in source (9); (8) see also Richer, Olander, and Westerlund 1979; (9) strong D line, CaH?: possible foreground dwarf; (10) see Fig. 1; (11) Blanco and Richer 1979 No. 1; (12) Blanco and Richer 1979 No. 3; (13) also Walker 1972 star 87; (14) also Walker 1972 star 84; (15) also Hesser, Hartwick, and Uguarte 1976 star 4601; (16) spectrum also given in Paper I.

below the tip of the giant branch. Carbon stars in this part of the H-R diagram require a different mechanism from that discussed for upper AGB stars by Iben (1975) and in Paper I.

Finally, we note that three stars (NGC 419 5-3 and 5-7, NGC 1978 I-14) observed in Paper I and assigned uncertain or "Ctm" type were reobserved. This enabled precise spectral classifications to be made (Table 1).

## III. INFRARED OBSERVATIONS AND THE H-R DIAGRAM

### *a*) *The Data*

In order to derive reliable bolometric luminosities and temperatures, we have measured infrared *JHK* magnitudes for many of the stars discussed in § II and in Paper I. The data are presented in Table 2, and were mostly obtained during the period 1979 November 3–5 with an InSb detector and f/30 chopping secondary using the CTIO 4 m telescope. An aperture size of 5″–7″ was used, depending on seeing, which was typically 1″–2″ and never worse than 3″. The objects being observed were guided directly using an on-axis Quantex TV and dichroic filter.

A few additional stars (identified in Table 2) were measured using a second InSb detector on the 2.5 m du Pont telescope at Las Campanas during 1979 December 3–5. Because of the larger thermal background of this telescope, *K* magnitudes were not

TABLE 2

PHOTOMETRY, LUMINOSITIES, AND TEMPERATURES OF MAGELLANIC CLOUD STARS

| Cluster | Star[a] | $K$[b] | $J-H$[b] | $H-K$[b] | $m_{bol}$ | $M_{bol}$[c] | log $T$ | Notes |
|---|---|---|---|---|---|---|---|---|
| | | | | SMC | | | | |
| NGC 121 | 1-23 | 13.38 (04) | 0.73 (05) | 0.10 (05) | 15.80 | −3.50 | 3.610 | |
| | V1 | 12.25 | 0.64 (04) | 0.17 | 14.65 | −4.65 | 3.615 | |
| NGC 152 | B11 | 13.08 | 0.80 | 0.17 (04) | 15.85 | −3.45 | 3.572 | |
| | C19 | 12.31 | 0.83 | 0.20 | 15.20 | −4.10 | 3.556 | |
| | E18 | 13.60 | 0.79 (04) | 0.20 | 16.45 | −2.85 | 3.565 | |
| | H23 | 11.73 | 0.92 | 0.41 | 14.65 | −4.65 | 3.468 | |
| | F28 | 11.24 | 0.98 | 0.59 | 14.35 | −4.95 | 3.425 | |
| NGC 339 | 87 | 12.08 | 0.77 (04) | 0.19 | 14.85 | −4.45 | 3.575 | |
| | 151 | 11.29 | 0.88 | 0.45 | 14.25 | −5.05 | 3.467 | |
| NGC 419 | 135 | 10.97 | 1.20 | 0.80 | 14.25 | −5.05 | 3.378 | 1 |
| | 4-133 | 11.83 | 0.92 (04) | 0.31 | 14.70 | −4.60 | 3.485 | |
| | 5-3 | 12.01 | 0.86 (04) | 0.23 | 14.95 | −4.35 | 3.538 | |
| | 5-7 | 12.66 | 0.75 (05) | 0.21 (04) | 15.40 | −3.90 | 3.575 | |
| L1 | 64 | 12.85 | 0.81 (04) | 0.13 (04) | 15.55 | −3.75 | 3.581 | |
| | 143 | 12.25 | 0.87 (04) | 0.22 | 14.95 | −4.35 | 3.514 | |
| K3 | 24 | 11.87 | 0.97 (04) | 0.47 | 14.90 | −4.40 | 3.448 | |
| | 50 | 13.50 | 0.69 (05) | 0.17 (04) | 16.05 | −3.25 | 3.603 | |
| | 54 | 11.95 | 0.88 (04) | 0.32 | 14.80 | −4.50 | 3.491 | |
| Reddening correction | | −0.01 | −0.01 | 0 | | | | |
| | | | | LMC | | | | |
| NGC 1651 | 2421 | 11.22 | 0.88 | 0.32 | 14.25 | −4.45 | 3.509 | |
| | 3304 | 10.47 | 0.83 | 0.30 | 13.45 | −5.25 | 3.531 | 2 |
| | 4325 | 11.35 | 0.87 | 0.22 | 14.30 | −4.40 | 3.544 | |
| | 4328 | 11.54 | 0.90 | 0.40 | 14.45 | −4.25 | 3.477 | |
| NGC 1841 | 67 | ... | 0.29 (14) | ... | 17.1: | −1.6: | ... | 3, 7 |
| | 142 | ... | 0.74 (05) | ... | 15.20 | −3.50 | 3.597: | 4, 7 |
| NGC 1978 | I-18 | ... | 0.72 (06) | ... | 15.90 | −2.80 | 3.607: | 5, 7 |
| | I-25 | 10.50 | 1.07 | 0.61 | 13.70 | −5.00 | 3.405 | 6, 7 |
| NGC 2173 | 1401 | 12.53 | 0.83 (04) | 0.19 | 15.40 | −3.30 | 3.562 | |
| | 4306 | 13.60 | 0.76 (04) | 0.14 (04) | 16.20 | −2.50 | 3.598 | |
| NGC 2190 | 1417 | 10.49 | 0.97 (04) | 0.57 | 13.55 | −5.15 | 3.435 | |
| | 4324 | 10.12 | 1.15 (04) | 0.75 | 13.35 | −5.35 | 3.388 | |
| NGC 2209 | 46 | 10.50 | 1.07 (04) | 0.60 | 13.65 | −5.05 | 3.412 | |
| | 50 | 10.12 | 1.15 | 0.74 | 13.35 | −5.35 | 3.387 | |
| NGC 2257 | H23 | 12.05 | 0.84 (04) | 0.21 | 14.95 | −3.75 | 3.557 | |
| Reddening correction | | −0.02 | −0.02 | −0.01 | | | | |

NOTES.—(1) CO index = −0.10, $H_2O$ index = 0.20; (2) CO index = 0.28, $H_2O$ index = 0.095; (3) $H$ = 15.00 (10) mag; (4) $H$ = 12.77 mag; (5) $H$ = 13.57 (04) mag; (6) star also measured by Frogel, Persson, and Cohen 1980. $M_{bol}$ and log $T$ derived from mean of measurements, which agree well; (7) measured on duPont 2.5 m at Las Campanas.

[a] Sources for star designations are given in Table 1 here or Table 1 of Paper I.

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

[c] $(m-M)_0 = 19.3$ assumed for the SMC; $(m-M)_0 = 18.7$ assumed for the LMC.

obtained for all of these stars. An aperture size of 11″ was used, always in good seeing. Guiding was again accomplished using a Quantex TV, which was flipped between the object and an offset guide field. On both the 2.5 m and 4 m, special care was taken to avoid contaminating stars in the "reference" beam, whose position was adjusted where necessary.

The data in Table 2 are referred to the system of standard stars given in Frogel *et al.* (1978, hereafter FPAM). The relation between this system and that of Johnson (1966) is discussed in the Appendix of FPAM. Narrow-band CO and $H_2O$ indices were measured for two of the stars in Table 2 (see Notes) on the system of FPAM and Aaronson, Frogel, and Persson (1978). In this paper we adopt $E(B-V) = 0.06$ mag for the LMC, and $E(B-V) = 0.03$ mag for the SMC (Sandage and Tammann 1974; van den Bergh 1976). The required (small) corrections to the *JHK* photometry are given at the bottom of the SMC and LMC panels in Table 2.

### *b*) *Color-Color Relations*

The ($J - H$, $H - K$) two-color diagram is shown in Figure 2 for the stars in Table 2. In this and subsequent figures, we have also included additional LMC stars from Table 1 of Paper I and Table 1 of FPC. Also drawn is the mean relation for galactic field giants taken from FPAM, shown as a solid line up to spectral type M6, and as a dashed line for types M7–8, where the mean relation is poorly determined.

Several relevant points concerning Figure 2 can be made. First, the Cloud carbon stars overlap with and form a well-defined extension of the mean field relation. Second, the cluster carbon stars are distinctly segregated from the cluster noncarbon stars, and it seems clear that *JHK* colors alone can provide an efficient photometric method of distinguishing the two types of stars. Third, the SMC cluster stars appear to have bluer *JHK* colors than do the LMC carbon stars. We find that

$$\langle J - H\rangle_{\rm LMC} - \langle J - H\rangle_{\rm SMC} = 0.10 \pm 0.04 \text{ mag}$$

and

$$\langle H - K\rangle_{\rm LMC} - \langle H - K\rangle_{\rm SMC} = 0.16 \pm 0.07 \text{ mag},$$

differences which become even more significant if the anomalously red SMC star NGC 419 − 135 is excluded. A similar result is obtained by Blanco and McCarthy (1980), who find SMC *field* carbon stars to be in the mean 0.2–0.3 mag bluer in $R - I$ than LMC field carbon stars. Richer (1980*a*) also finds the SMC field carbon stars to be bluer from *VRI* colors, although with a larger sample Richer (1980*b*) no longer concludes the result is significant. In any event, it is tempting to speculate that explanation of the cluster (and possible field) star color effects rests with metallicity differences between the Clouds. Additional *JHK* photometry of cluster carbon stars should be obtained to verify that our results are not biased by small number statistics.

The final point to be made from Figure 2 is the generally good agreement between the position of the noncarbon cluster stars and the mean galactic giant relation. There is only a marginal tendency for the noncarbon stars to lie above the mean relation, a result that is perhaps surprising in view of the significant displacement above the mean relation found for giants in M92, M3, and M13 by CFP and in M71 by Frogel, Persson, and Cohen (1979). A simple abundance change does not seem to account for this difference between galactic and Cloud cluster stars, as the range in [Fe/H] from M71 to M13 is probably applicable to most of the cluster stars studied here (see below). A satisfactory interpretation of the difference is likely to lie with proper determination of the opacity sources in the H-band, which are governed by a number of complex and competing factors (see CFP).

In Figure 3 we have plotted the band strengths from Table 1 against $B - V$, $V - K$, and $J - K$ colors. In examining this diagram it should be remembered that different band strengths are being measured for carbon and noncarbon stars (see § II). For a number of stars without published $V$ photometry, we have used the

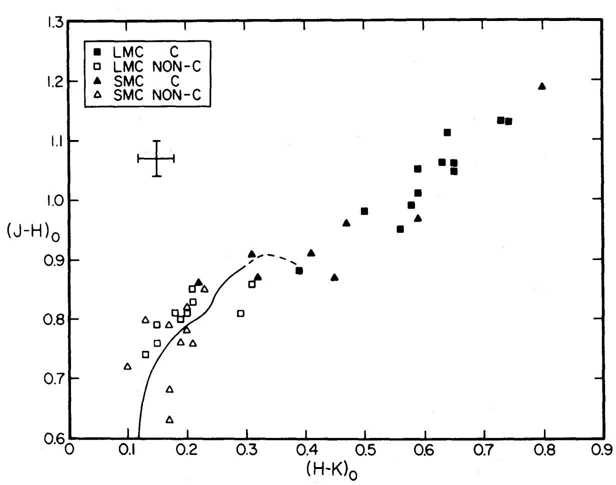


FIG. 2.—A ($J - H$, $H - K$) two-color diagram for Magellanic Cloud cluster stars. Filled symbols distinguish carbon from noncarbon stars. The line shown is the mean relation for galactic field giants, the dashed part being determined with less certainty than the solid part. The Cloud data plotted in this and subsequent figures are from this paper, Mould and Aaronson (1979), and Frogel, Persson, and Cohen (1980).

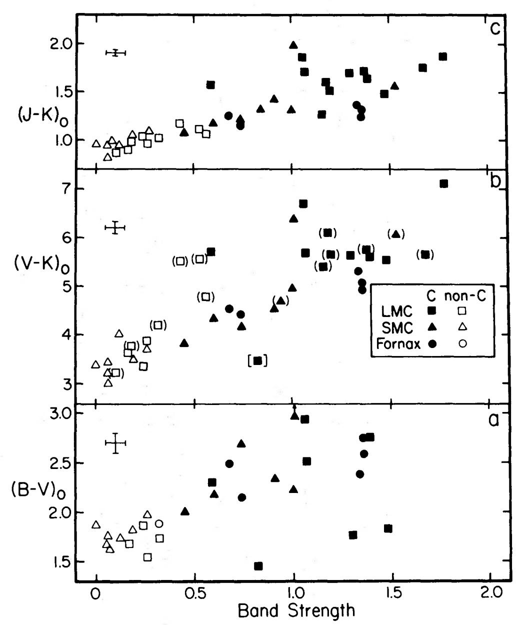


FIG. 3.—Band strength plotted against $B - V$, $V - K$, and $J - K$ color. Note that different bands are measured for carbon and noncarbon stars. In Fig. 3*b*, points surrounded by parentheses were those for which we used the spectrophotometric magnitudes given in Table 1; the error in $V - K$ for these stars is ~2 times the nominal error shown. The point in square brackets in Fig. 3*b* is the low-luminosity carbon star in NGC 1841. The point with the arrow attached in Fig. 3*a* is NGC 419 − 135, which lies off the plot with a $B - V$ of 4.16.

spectrophotometric magnitudes given in Table 1; these points are shown in parentheses in Figure 3*b*. For normal K and M giants, TiO absorption is known to be closely correlated with temperature, as are $V - K$ and $J - K$, whereas little temperature sensitivity is contained within $B - V$. The qualitative relation between TiO band strength and color in Figure 3 can thus be readily understood. Further interpretation is complicated by the abundance sensitivity expected for TiO in the metal-poor stars discussed here (e.g., Mould and McElroy 1978). This will, in particular, introduce scatter into any ($V - K$, TiO) or ($V - K$, $T_{\rm eff}$) relation due to TiO absorption in the $V$ filter itself. In this regard the small scatter in $J - K$ color in Figure 3*c* is noteworthy since we shall argue below that $J - K$ is preferable to $V - K$ as a temperature indicator for the noncarbon stars discussed here.

The $C_2$ band strength, which nominally measures carbon abundance in C stars, is also known to be correlated with temperature (Yamashita 1972), accounting for the crude correlations in Figure 3. Note that both the TiO and $C_2$ band strengths tend to be larger for LMC than SMC stars, a fact consistent with the difference in temperature and possibly metallicity indicated by Figure 2.

Also shown in Figure 3 are the carbon stars recently studied in the Fornax galaxy by Aaronson and Mould (1980). The $C_2$ band strengths of these stars are in some cases considerably larger than might be predicted from their *JHK* colors, which are similar to the bluer colors seen for the SMC.

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

Apparent bolometric magnitudes are given in Table 2 and were derived from Figure 1 of FPC, which gives the bolometric correction to the $K$ magnitude as a function of the $J - K$ color. From the discussion in that paper, the uncertainty in these magnitudes is estimated to be of order 0.1 mag.

To convert from apparent to absolute magnitudes, we need only adopt distance moduli. Unfortunately, there remains considerable disagreement concerning the Magellanic Cloud distances. From Cepheids alone, Sandage and Tammann (1974) give[5] $(m - M)_0 = 18.85$ mag for the LMC, and 19.53 mag for the SMC; while using a number of methods de Vaucouleurs (1978) obtains 18.31 mag for the LMC, and 18.62 for the SMC—differences of 0.54 mag and 0.91 mag, respectively. An independent determination by Gascoigne (1972) leads to 18.7 mag and 19.3 mag, while van den Bergh (1976) finds 18.5 mag and 18.9 mag. Part of the reason for de Vaucouleurs's low values comes from his adoption of a reddening model having significant polar-cap absorption, which now appears convincingly ruled out by the analysis of Burstein and Heiles (1978). To derive the absolute bolometric magnitudes in Table 2 we have adopted the distance moduli of Gascoigne (1972); we do not believe the conclusions of this paper are significantly affected by uncertainties in these moduli.

[5] In this discussion we have adjusted all Cepheid distances by an amount corresponding to a Hyades modulus of 3.29 mag.

Derivation of an accurate temperature scale for the stars in Table 2 also presents problems. For carbon stars, we determined temperatures from an empirical relation between $J - K$ color and $T_{\rm eff}$ constructed from data given in Mendoza and Johnson (1965). Scalo (1976) has emphasized the uncertainties in this type of procedure, which determines at best a color temperature whose true relation to $T_{\rm eff}$ is unclear. For noncarbon stars we have used the recently determined temperature scale of Ridgway *et al.* (1980). Because this scale is based on angular diameter measurements now available for a large number of K and M giants it seems preferable, for instance, to the model atmosphere scale used by CFP.

To derive noncarbon star temperatures, we first converted the ($V - K$, $T_{\rm eff}$) relation of Ridgway *et al.* (1980) to a ($J - K$, $T_{\rm eff}$) relation using the mean ($V - K$, $J - K$) relation given in the Appendix of FPAM. The values of log $T$ given in Table 2 were then found solely from the measured $J - K$ colors. We have followed this procedure in order to minimize metallicity effects on the Ridgway (1980) calibration. As discussed earlier, $V - K$ colors become sensitive to abundance changes because of the presence of TiO and other low-temperature sources of blanketing in the $V$ band. On the other hand, the $J$ band is virtually devoid of molecular absorption from such molecules as CN, CO, and $H_2O$ (Wing and Spinrad 1970; Johnson and Mendez 1970), which are found elsewhere in the infrared in K and M stars.

A dramatic illustration of the problem with using a $V - K$ color calibration based on metal-rich galactic giants as a temperature indicator for cool, metal-poor giants is provided by Figure 4, which shows a ($J - K$, $V - K$) two-color diagram for all the Cloud data. In contrast to the ($J - H$, $H - K$) two-color diagram in Figure 2, where the cluster stars scattered roughly about the mean galactic giant relation, we now see that in Figure 4 the cluster stars scatter significantly above the mean giant relation. Also shown in Figure 4 are the locations of the cluster giants in M3, M13, and M92 from CFP and M71 from Frogel, Persson, and Cohen (1979), having colors redder than $V - K = 3.0$. The effect is also visible in the galactic globulars, as was noted by CFP.

We suggest that, at least for the Cloud cluster stars and the cooler stars in M71, the shift from the mean field line is due primarily to a decrease in $V - K$ color with decreasing abundance, rather than to an increase in $J - K$ color, which might result from weaker CO absorption in the $K$ bandpass. An upper limit on the latter effect can be set by considering the difference between the observed CO index and that predicted for a mean field giant with the same $J - K$ color. For the Galactic cluster stars and the two Cloud stars with measured CO indices, we find the effect to be $0.2 \times \Delta CO \lesssim 0.02$ mag in $J - K$, where the factor of 0.2

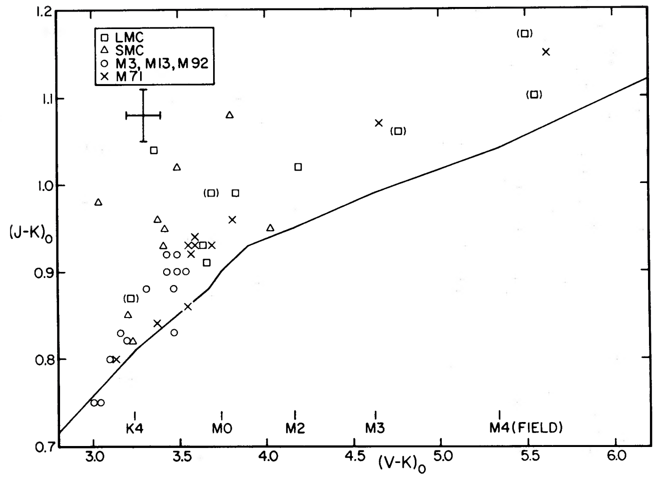


FIG. 4.—A ($J-K$, $V-K$) two-color diagram for galactic and Magellanic Cloud cluster stars. The line is the mean relation for galactic field giants. See text for further details. The galactic cluster data is taken from Cohen, Frogel, and Persson (1978) and Frogel, Persson, and Cohen (1979).

represents the fraction of the $K$ bandpass covered by CO. If we allow for an uncertainty of $\sim 0.02$ mag in the mean field relation, the discrepancy with the warmer galactic cluster stars might be removed, but it will still persist for the remaining stars. The real point to be made from Figure 4 is that temperatures derived from $V-K$ colors will be significantly warmer than those derived from $J-K$ colors for the noncarbon Cloud cluster stars, a fact that we shall see has important bearing on the interpretation of the position of these stars in the H-R diagram.

In Figure 5 we have plotted $M_{\mathrm{bol}}$ against log $T$ for stars in the SMC. A similar plot is shown for LMC stars in Figure 6. For the carbon stars from FPC, their values of $M_{\mathrm{bol}}$ and log $T$ were adopted unchanged. Values of log $T$ for their noncarbon stars were recomputed in the manner discussed above. Temperatures for four of these five stars were significantly cooler than those given in FPC, which were based on the model atmosphere calculations of CFP, the mean difference being $240 \pm 25$ K. Also shown in Figures 5 and 6 are the mean giant branches of M92 and M13 from CFP, and the upper giant branch of 47 Tuc from FPC. Temperatures for M92 and M13 were recomputed using the ($J-K$, $T_{\mathrm{eff}}$) relation from Ridgway *et al.* (1980); the 47 Tuc giant branch has already been adjusted to the Ridgway *et al.* (1980) scale.

*The most significant result in Figures 5 and 6 is the substantial extension of the Magellanic Cloud giant branches above the giant branch tips of galactic clusters* (see also Paper I and FPC). Note that this extension is smooth and continuous, and, in fact, a number of M stars in addition to carbon stars rise above the galactic giant branches. The M5 star NGC 1651 − 3304 even

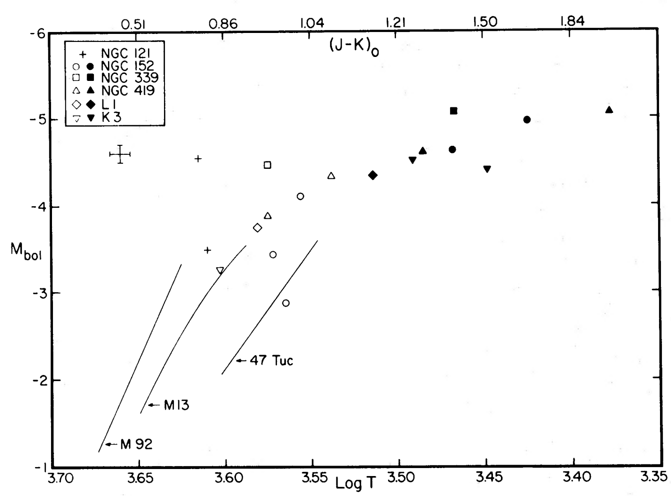


FIG. 5.—The H-R diagram for SMC cluster stars. Also shown are the upper giant branches for three galactic clusters, adopted from Cohen, Frogel, and Persson (1978) and Frogel, Persson, and Cohen (1980). The temperature scale is based solely on $J-K$ color, as discussed in the text.

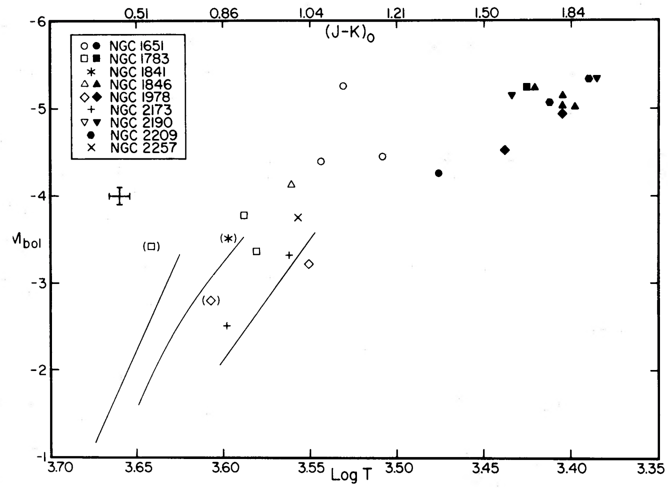


FIG. 6.—Same as Fig. 5, for LMC cluster stars. Symbols surrounded by parentheses have twice the nominal error shown.

attains a bolometric magnitude comparable with the most luminous carbon stars. The transition between M and C star characteristics appears to occur at a bolometric luminosity of $\sim -4.4$ mag and a temperature of $\sim 3100$ K in both Clouds.

The luminosities of the Cloud carbon stars range from $\sim 0.7$ mag to $\sim 1.8$ mag above the tip of 47 Tuc. (It should be noted that the reddest 47 Tuc variables rise in the mean $\sim 0.4$ mag above the 47 Tuc tip.) The carbon star luminosities also rise considerably above the theoretical giant branch tips of Rood (1972) and Sweigart and Gross (1978), which agree well with the empirical giant branches shown in Figures 5 and 6. Over a spread in $Y$ of 0.2–0.3 and in $Z$ of 0.0001–0.01, the onset of the helium flash in the models occurs at bolometric magnitudes ranging from $-3.3$ to $-3.8$.

The mean bolometric magnitudes of the carbon stars is found to be $-5.02 \pm 0.10$ mag ($n = 12$) in the LMC and $-4.69 \pm 0.10$ mag ($n = 8$) in the SMC. These values are respectively 1.5 and 0.4 mag fainter than was estimated in Paper I from the optical continuum slope. They agree with an alternative estimate made in Paper I from a (BC, $B - V$) relation. The large error in the former estimate for the LMC stars appears to result from differences in the relation between optical and $V - K$ colors between galactic carbon stars and the redder stars in the LMC. As suggested by FPC, this may be due to blanketing effects. The magnitude difference of $0.33 \pm 0.14$ mag *between the two Clouds* is significant at a formal level of 2 $\sigma$. This result may be surprising in view of Blanco and McCarthy's (1980) finding that the SMC field carbon stars are slightly more luminous in $I$ than the LMC field carbon stars by about 0.1 mag (adjusting their result to our adopted relative distance moduli). Richer (1980*a*, *b*) also finds the SMC field stars to be more luminous by an even larger amount, 0.4 mag in $I$, although this result might by influenced by incompleteness in Richer's sample. In addition, $I$ magnitudes may not be a suitable measure of bolometric luminosity. Richer (1980*a*) notes that a comparison of LMC data in Richer, Olander, and Westerlund (1979) with FPC yields $\langle M_I - M_{bol} \rangle = -0.2$.

In the SMC we find two stars in common with Richer (1980*a*), both in NGC 419: 135 and 4-133. For these two stars, $\langle M_I - M_{bol} \rangle = -0.65 \pm 0.08$ mag, a significantly larger difference than Richer finds for the LMC. If this result is applicable to the entire SMC, then Richer's data indicates $\langle M_{bol}{}^{LMC} \rangle - \langle M_{bol}{}^{SMC} \rangle \sim -0.05$ mag, in somewhat better agreement with our own results. The apparently larger difference between $M_I$ and $M_{bol}$ in the SMC than in the LMC indicates SMC carbon stars have bluer $I - K$ colors, which is consistent with the color effects discussed in § III*b*. Again, this difference may reflect a lower metallicity in the SMC—the $I$ band region is severely affected by CN absorption in carbon stars (Wing and Spinrad 1970), and may thus be particularly sensitive to abundance effects. We might expect the *JHK* colors of field SMC carbon stars to be bluer than in the LMC, just as the SMC cluster stars appear to be (e.g., Fig. 2). Clearly, more infrared data are needed to further clarify the situation.

A metallicity difference does not, however, appear to account for the 0.3 mag difference in luminosity we measure in this paper. In the next section we show that at a fixed age, a decrease in metallicity causes an increase in the tip luminosity on the upper asymptotic giant branch. A more likely explanation may therefore rest with age, in the sense that the LMC clusters are in the mean a little younger than the SMC clusters studied here.

Turning to the noncarbon stars, we first note that FPC found it difficult to account for the location of five of these stars in the H-R diagram (see their Fig. 3). By any plausible variation in age or helium abundance, they could not explain what they felt was a necessary shift by 0.06 dex in $T_{eff}$ from the blue side of the M13 giant branch to the 47 Tuc giant branch. FPC suggested that these stars presented problems for the giant branch models of Sweigart and Gross (1978), and proposed variation in the mixing length ratio as a possible solution.

For several reasons, we believe the difficulty encountered by FPC may not be a real problem. First, as discussed previously, use of the Ridgway *et al.* (1980) temperature scale and $J-K$ colors leads to temperatures about 240 K cooler, or a change of $\sim 0.025$ dex in log $T$. Second, the available evidence suggests that in fact [Fe/H] values for these clusters are not as metal-rich as 47 Tuc (i.e., § V). In particular, Danziger's (1973) line strengths imply metallicities for NGC 1783 and 1846 intermediate between 47 Tuc and M13. This range is consistent with the presence of M0 stars in these clusters at this temperature and the CO index quoted by FPC. Splitting the 0.04 dex difference in log $T$ between the M13 and 47 Tuc giant branches, we are thus only required to explain a shift of $\sim 0.015$ dex (i.e., 0.06–0.025–0.02). In the next section we shall derive cluster ages that are some $10^{10}$ years younger than the fiducial M13 age of $16 \times 10^9$ years. A shift of 0.015 dex is entirely compatible with this age difference in the models of Sweigart and Gross (1978) and Mengel *et al.* (1979). For instance, for $Y = 0.2$ and $Z = 0.01$, the shift in $\Delta \log T_{\text{eff}}$ at $\log L = 3$ corresponding to an age change of $10^{10}$ years is about 0.015 dex. The shift depends only weakly on $Y$, but decreases with decreasing $Z$. At $Z = 0.0001$, $10^{10}$ years corresponds to a shift of only about $\sim 0.01$ dex.

Only three stars are significantly warmer than the M13 giant branch in Figures 5 and 6. Two of these are in NGC 121 in the SMC, and the spectral type of these stars are consistent with the low metal abundance in this cluster implied by their location in the H-R diagram. The third star is NGC 1783-G6, whose location in Figure 6 is extremely discrepant. No $J$ magnitude is available for this star, so its estimated log $T$ must be regarded as more uncertain. We look for complete photometry and an optical spectrum to resolve the difficulty with this star. To summarize, we find no problems at this stage, except in one instance, in accounting for the giant branch locations in the H-R diagram. However, much more photometry is required to define accurate giant branches in these clusters.

## IV. AGE ESTIMATES FOR THE CLUSTER

### a) AGB Evolution

In theory the age of a cluster can be obtained from the maximum luminosity of the AGB, provided that the cluster is homogeneous in age and chemical composition and that the mass-loss rate is a function of physical stellar parameters and does not vary haphazardly from star to star. In practice such an age estimate is an upper limit for a cluster with a finite number of stars, because of the very short stellar lifetimes at the tip of the giant branch.

To obtain such age estimates we follow the theory outlined in Paper I. This is presented in more detail here to enable its general use and permit modification as required. Three relations are employed to connect age ($t_9$, in units of $10^9$ years) and maximum or final luminosity on the AGB ($M_{\text{bol},f}$).

1. A main-sequence turnoff relation,

$$M_i = M_i(t_9, Y, Z)\,, \tag{1}$$

where $M_i$ is the initial mass on the main sequence and $(Y, Z)$ denote the chemical composition. For the present purposes we have adopted equation (2.5) given by Renzini (1977).

2. A relation between the initial mass and the final core mass ($M_f$), taking into account mass loss and giant branch evolution,

$$M_f = M_f(M_i, \eta_{\text{R}}, Z)\,, \tag{2}$$

where $\eta_{\text{R}}$ is the mass loss scaling parameter in Reimers's (1975) expression. For this relation we employ equations (6.17) and (6.20) of Renzini (1977).

3. A relation between core mass and luminosity on the AGB,

$$M_{\text{bol},f} = M_{\text{bol},f}(M_f)\,. \tag{3}$$

We use Paczyński's (1970) expression.

In Figure 7 the resulting relations between final luminosity and age are presented for various values of $\eta_{\text{R}}$ and $Z$ applicable to galactic globular clusters. A helium abundance of $Y = 0.22$ was adopted. We determine the mass loss rate, $\eta_{\text{R}}$, by requiring a fit to the clusters M13 and 47 Tuc. The error boxes for final luminosity and age in these clusters are indicated in Figure 7. For M13 the AGB can be traced to $M_{\text{bol}} = -3$ but must stop before the giant branch tip at $M_{\text{bol}} = -3.5$ (Sandage 1970; CFP). For 47 Tuc we suppose that the mean luminosity of the star V3 (FPC) defines the end of the AGB. Age estimates were taken from Sandage (1970), Demarque and McClure (1977), and Carney (1980). We conclude from Figure 7 that $0.4 < \eta_{\text{R}} < 0.5$ is required to fit representative galactic globulars, and adopt a curve intermediate between these values and appropriate to $Z = 0.002$ ($[M/\text{H}] = -1$).

For stars of solar composition a relation between final luminosity and age is now available from explicitly computed stellar models by Iben and Truran (1978). The three points plotted in Figure 7 are for $M_i = 1.0$, 1.5, and 2.0 $M_\odot$. Also shown are the corresponding solar composition predictions of equations (1)–(3). A discrepancy of $\sim 0.1$ mag in the sense observed is expected for the 1.5 and 2.0 $M_\odot$ case, since Iben and Truran assumed a flat loss of 0.2 $M_\odot$ on the first giant branch independent of mass (cf. Fusi-Pecci and Renzini 1975). On the AGB Iben and Truran adopted $\eta_{\text{R}} = 1/3$. The agreement between the explicit computation and the theory presented here is good, considering the somewhat different assumptions. Note, however, that the Iben and Truran models in this mass range do not become carbon stars. Since the

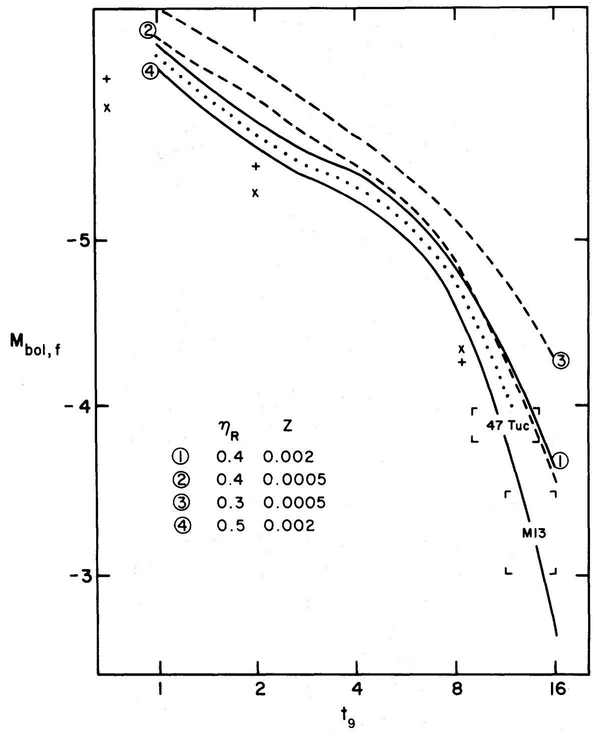


FIG. 7.—The relation between final luminosity on the AGB and turnoff age in billions of years. Curves are given for the pairs of parameters noted in the key. The mass-loss efficiency parameter is $\eta_R$ and $Z$ is the metal content. The location of two representative galactic globular clusters is denoted by the labeled boxes. The dotted curve is the adopted relation for dating clusters in the Magellanic Clouds. Results from Iben and Truran (1978) for solar composition are plotted as crosses. Results using the present theory for solar composition are shown as plus signs.

observed threshold for carbon star formation in the Clouds is $\sim -4.4$, a different dredge-up law would seem to be required in the models (Iben and Truran 1978). Models with $[M/\mathrm{H}] = -1$ would also be useful for comparison with the present data.

Our estimate of the final luminosity in the Magellanic Cloud clusters for which we have photometry is given in Table 3. Also given is the reddening-corrected integrated color of the cluster. This provides a further age estimate through the calibration of Searle, Sargent, and Bagnuolo (1973). In this case the age estimate is a lower limit, since the Cloud clusters may all be assumed to be of lower metallicity than the Galactic open clusters which form the basis of the calibration. We now discuss for all the clusters for which we have data the age estimate and its reliability, the degree of completeness of the photometry, and the individual properties of the cluster.

### *b) SMC Clusters*

*NGC 121.* The brightest star is V1, which appears to be a Mira observed close to maximum light (cf. Table 1 and Tifft 1963). Since Mira variables appear to lie on the red giant branch at their median magnitudes and colors (Eggen 1975), we have corrected the magnitude of V1 by 0.3 mag by analogy with the Miras in 47 Tuc (FPC). Although we do not have infrared photometry of V8, the other red variable, its very weak band strength and blue color suggest that it will prove fainter than Lindsay 1-143 at $-4.3$ mag. NGC 121-1-23 is the reddest star within the first five zones of Tifft (1963) and clearly lies below the first giant branch tip. The final luminosity given in Table 3 for NGC 121 is probably therefore a reasonable estimate. The upper limit on its age of 10 billion years is also probably consistent with the presence of some RR Lyrae stars in the cluster (Thackeray 1958) and with the red horizontal branch (Tifft 1963).

*NGC 152.* The two luminous carbon stars in NGC 152 are within 30″ of the cluster center and so are virtually certain members. Optical photometry by Hodge (1980) seems complete to where the star density equals that of the field, without extending the giant branch beyond B11 and C19. Our estimate of $M_{\mathrm{bol},f}$ is therefore probably a good one. We deduce an age between 2 and 6 billion years.

*NGC 339.* This cluster is in a crowded field and the two reddest stars from Gascoigne (1966) are almost 2′ from the center. The membership of these stars is questionable and the age estimate in Table 3 should be given low weight.

*NGC 419.* Additional carbon stars in NGC 419 found by Blanco and Richer (§ II) indicate that our photometry in this cluster is very incomplete. The *VRI* colors of BR5 and 6, however, suggest that their bolometric magnitudes lie between those of NGC 419-135 and 5-3. BR 4 appears to be fainter. The age estimate between 2 and 6 billion years therefore seems reliable, and is consistent with absence (Arp 1958*b*) or weakness (Walker 1972) of the horizontal branch.

*Lindsay 1 and Kron 3.* We are not confident about the completeness of the photometry in either of these clusters. The age limits, which are rather weak, may therefore also be conservative. Both clusters are in uncrowded fields. Neither cluster has a horizontal branch (Gascoigne 1966).

### *c) LMC Clusters*

*NGC 1651.* Star 3304 is the brightest in the cluster, and is unusual in that it is a late M star. All the other stars we have encountered at these luminosities in the clusters of both Clouds are carbon stars. The three other luminous giants we have observed, however, leave no doubt as to the reality of the extended giant branch in this cluster. Three other red stars ($O - D > 0$) remain to be examined in the photometry of Hesser, Hartwick, and Uguarte (1976, hereafter HHU), which is complete except for the central region of the cluster. The lack of an obvious horizontal branch, remarked on by HHU, is consistent with our age estimate of 2–5 billion years.

*NGC 1783.* The only evidence for an extended giant branch is one luminous carbon star (FPC). We prefer

TABLE 3

AGES OF MAGELLANIC CLOUD GLOBULARS

| | $M_{bol,f}$ | $t_9 <$ | $(B-V)_0$ | Source | $t_9 >$ |
|---|---|---|---|---|---|
| | | SMC | | | |
| NGC 121 .......... | −4.3[a] | 10 | 0.75 | 1, 2 | 5 |
| NGC 152 .......... | −5.0 | 6 | 0.67 | 1 | 3 |
| NGC 339 .......... | −5.1 | 6 | 0.66 | 1, 2 | 3 |
| NGC 419 .......... | −5.1 | 6 | 0.65 | 1, 2 | 3 |
| Lindsay 1 .......... | −4.3 | 10 | 0.66 | 2 | 3 |
| Kron 3 ............ | −4.5 | 9 | 0.65: | 1, 2 | 3 |
| | | LMC | | | |
| NGC 1651 ......... | −5.2 | 5 | 0.63 | 3 | 2 |
| NGC 1783 ......... | −5.1[b] | 6: | 0.57 | 1, 2 | 2 |
| NGC 1841 ......... | −3.5 | Old | 0.66 | 2 | 3 |
| NGC 1846 ......... | −5.2[b] | 5 | 0.68 | 1 | 3 |
| NGC 1978 ......... | −5.0 | 6 | 0.72 | 1 | 4 |
| NGC 2173 ......... | −3.3 | Old | 0.77 | 3 | 5 |
| NGC 2190 ......... | −5.3 | 4 | ... | ... | ... |
| NGC 2209 ......... | −5.3 | 4 | 0.45 | 2, 3 | 0.9 |
| NGC 2257 ......... | −3.8 | Old | 0.61 | 2 | 2 |

SOURCES.—(1) van den Bergh and Hagen 1968; (2) Gascoigne 1966; (3) Bernard 1975.

[a] See text.

[b] Adopted from Frogel, Cohen, and Persson 1980.

to suspend judgment on this cluster until more of the red stars seen by Sandage and Eggen (1960) have been observed in the infrared.

*NGC 1841 and 2257.* The reddest stars observed by Gascoigne (1966) lie below the tip of the first giant branch. This includes a carbon star in NGC 1841 (§ II). Consequently, we designate these clusters as "old" in Table 3. This conforms with their horizontal branch morphology. Further photometry of the reddest stars detected by HHU would be useful to verify the absence of an extended giant branch.

*NGC 1846 and 1978.* Numerous carbon stars were found in these clusters in Paper I. Infrared photometry is available for many of these stars, generally from FPC, but is still not complete. These clusters have well-populated extended giant branches and are clearly intermediate age from the present technique, with fairly tight age limits. Although Thackeray and Wesselink (1953) found 2–4 RR Lyrae stars in the vicinity of NGC 1978, study of their charts by van den Bergh (1980) indicates that the RR Lyrae star density does not exceed that of the field.

*NGC 2173.* The two reddest stars of HHU do not extend the giant branch beyond $M_{bol} = -3.3$. This appears to be an old cluster.

*NGC 2190 and 2209.* The two carbon stars in each of these clusters indicate that they both have extended giant branches. We infer that they are younger than 4 billion years. A tighter age limit might be placed by more complete photometry. NGC 2209 has an age determined from the main-sequence turnoff of 0.8 billion years (Gascoigne *et al.* 1976).

We postpone discussion of the ages for two additional clusters we have studied spectroscopically (NGC 361 and 2193) until the necessary infrared photometry is obtained.

## V. CHEMICAL ENRICHMENT IN THE CLOUDS

Photometric determination of the extension of the giant branch has enabled us to derive explicit age limits for a number of the red globular clusters in the Clouds. The results, presented in Table 3, amplify and extend the conclusions of Paper I that a considerable number of these clusters have ages between 2 and 6 billion years. The main limitation on the present technique is the difficulty of accurately locating the tip of the asymptotic giant branch in sparse clusters where stochastic effects can be significant. With photometry whose completeness is better determined we can expect to make statistical corrections for these effects.

Determination of the metallicity of these clusters can provide a record of the history of chemical enrichment in the Clouds. Metallicity estimates based on photometry and spectroscopy of individual stars are now becoming available for the LMC (Gascoigne 1979; Hartwick and Cowley 1979). The location of giant branches in the H-R diagram (corrected for age differences as indicated above) can also yield cluster metallicities. A tentative $[M/H]$ ranking based on Figures 5 and 6 does in fact give results consistent with the spectroscopic estimates summarized by Hartwick and Cowley. Our $[M/H]$ ranking can be considerably improved by further photometry.

Finally, we note the consistency of the age determinations in the previous section with the recent classification of clusters in the Magellanic Clouds by Searle, Wilkinson, and Bagnuolo (1980). In this scheme class VII clusters from Table 3 are NGC 121, 339, 1841, and 2257. With exception of NGC 339 (see § IV) these are "old" clusters, or (in the case of NGC 121) have a 10 billion year upper limit. Classes V and VI contain clusters with ages between 2 and 6 billion years (the exception is NGC 2173, which we have as "old"). Class III and IV clusters are NGC 152 ($3 < t_9 < 6$) and NGC 2209 ($0.9 < t_9 < 4$).

We further note that the continuous correlation between age and metallicity suggested by Searle, Wilkinson, and Bagnuolo (1980) is also supported by our age estimates: For the "old" LMC clusters NGC 1841 and 2257, Hartwick and Cowley (1979) give [$M$/H] values of $-2.2$ and $-1.6$, respectively; for the intermediate age cluster NGC 1978 they give $-1.4$; and for the young cluster NGC 2209 Gascoigne *et al.* (1976) found $-1.2$ (revised to $-0.5$ by Gustafsson, Bell and Hejlesen 1977). In the SMC, we note that the suggested oldest cluster in Table 3, NGC 121, also appears to be the most metal-poor in Figure 5. Further work along the lines developed here will enable this correlation to be fully explored by *independent* determinations of age and metallicity.

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