THE ASTROPHYSICAL JOURNAL, 305:634–644, 1986 June 15

CARBON AND M STARS IN NEARBY GALAXIES: A PRELIMINARY SURVEY USING A PHOTOMETRIC TECHNIQUE

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Received 1985 August 22; accepted 1985 December 10

ABSTRACT

A new photometric method for identifying very distant carbon and late-M stars has been developed which utilizes two intermediate-band filters centered on CN and TiO absorption bands. We have successfully tested the technique on Galactic field stars and in eight regions in the disks of five nearby galaxies: M31, M33, NGC 6822, IC 1613, and WLM. The resulting carbon to M star ratios are directly related to parent galaxy absolute magnitude, presumably reflecting a decreasing abundance in the lower mass objects. The large C/M ratios observed in the Magellanic Clouds fit smoothly onto this relation, suggesting that this property of the Clouds is an internal one not much influenced by their location in the Milky Way's halo. In particular, the presence of a significant intermediate-age component may be a general characteristic of low-luminosity, late-type systems. A more complete survey of the asymptotic giant branch population in nearby galaxies should lead to considerable insight into the dependence of star formation history on galaxy type. The potential use of the carbon star luminosity function as a distance indicator is also discussed.

Subject headings: galaxies: stellar content — luminosity function — stars: carbon — stars: late-type

I. INTRODUCTION

The asymptotic giant branch (AGB) is the luminous terminal phase of stellar evolution for low- and moderate-mass stars. In the last decade a veritable renaissance in the study of the AGB has taken place (for a recent review see Iben and Renzini 1983). Interest in these objects has focused on their role both in stellar evolution theory (especially the formation of carbon stars) and in the area of stellar populations. In particular, the AGB is a major and sometimes dominant contributor to the integrated light of composite stellar systems (e.g., Persson *et al.* 1983). Furthermore, because AGB stars are of intermediate age, they can provide direct leverage on the chemical enrichment and star formation rate. It is likely that our understanding of the evolution of very distant galaxies will in fact hinge on accurate AGB modeling.

From an observational standpoint, it would clearly be desirable to have empirical knowledge of the AGB in differing types of galactic environments. Until recently, such information has been available only for the Milky Way and its dwarf companions. Some rather intriguing results have emerged, though, relating to the large numbers of carbon stars found in the Magellanic Clouds and the halo spheroidals compared with their quite uncommon occurrence in the disk of the Galaxy, and their still rarer appearance in the bulge (see Blanco and McCarthy 1983; Aaronson, Olszewski, and Hodge 1983; Azzopardi, Lequeux, and Westerlund 1985; Azzopardi, Lequeux, and Rebeirot 1985). This disparity suggests that the Milky Way's star-forming history may be quite different from that of its satellites. It also begs the question of to what extent the stellar content in the nearby dwarfs has been perturbed by their location in the outer halo and possible tidal effects that may have thereby ensued.

Conventional photographic grism or grens work cannot reach effectively beyond ~0.5 Mpc or be used in very crowded regions, so in order to probe the AGB in other nearby galaxies, we have developed a new method for identifying very distant C and M stars. The technique utilizes charge-coupled device (CCD) imaging through two intermediate-band filters that monitor CN and TiO (see below). In order to test the method we have observed a number of Galactic field stars and have also conducted a preliminary survey of five systems: M31, M33, NGC 6822, IC 1613, and the Wolf-Lundmark-Melotte galaxy (WLM). We note that a similar approach has been independently pursued by Richer and collaborators, who have studied NGC 205 (Richer, Crabtree, and Pritchet 1984, 1985), NGC 300 (Richer, Pritchet, and Crabtree 1985), NGC 55 (Pritchet, Richer, and Crabtree 1985), and M31 (Richer and Crabtree 1985); and also by Palmer and Wing (1983) for application to Galactic globular clusters.

II. DESCRIPTION OF THE METHOD

Some details of our AGB search procedure have already been given by Aaronson *et al.* (1984) and Aaronson, Mould, and Cook (1985). For further discussion we begin with Figure 1, which shows spectra of UX Dra, a carbon star of Yamashita (1975) type C7, 3, and BS 6146 from the Hoffleit (1982) catalog, an M6 giant. (These spectra were obtained in collaboration with J. Mould using the double spectrograph on the Hale 5 m telescope.) Also illustrated in Figure 1 is the location of our two intermediate-band filters centered at ~7750 Å ($\Delta\lambda \approx 300$ Å) and 8100 Å ($\Delta\lambda \approx 350$ Å), which are essentially broader versions of ones on the Wing (1971) system. For carbon stars the "81" filter measures CN absorption and the "77" filter lies in a continuum region, while for M stars the "77" filter measures TiO and the "81" filter lies (more or less) in the continuum (see also Nassau and Velghe 1964). Hence, the "77−81" color provides an effective discriminant of the two spectral types. This color will be indicative of molecular absorption only in

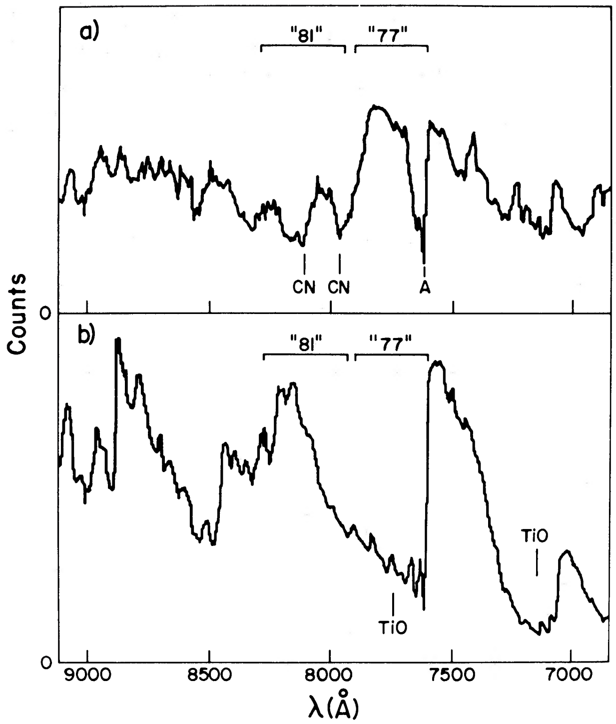

FIG. 1.—Raw spectra of (*a*) the C7, 3 star UX Dra and (*b*) M6 III BS 6146. The placement of our two intermediate-band filters is also shown.

cool stars; in hotter objects it will simply be a measure of two nearby continuum points and thus "neutral" in color.

It turns out that because of the single-sideband nature of the $77-81$ index, additional temperature information is required for the method to succeed. In particular, as progression is made toward cooler temperatures, the increasing CN absorption is counterbalanced by the redder continuum, so that in practice $77-81$ does not well separate C-type from hotter stars. The solution we have chosen for this problem is to obtain a temperature ranking from the $V-I$ color.

A number of Galactic field stars of known spectral type were observed and used to calibrate the filter response. Their location in the ($V-I$, $77-81$) two-color diagram is shown in Figure 2, where it can be seen that the giant branch splits into two forks corresponding to carbon stars (on the left) and M stars (on the right). The insets to Figure 2 also show that the $77-81$ color correlates well with the Yamashita carbon abundance class and spectral M type. Note that here and in succeeding figures the $V-I$ color is referred to the Kron-Cousins scale, while the $77-81$ index is simply given in the natural, instrumental system. Also, because of the small number of standards and the less than ideal photometric conditions (see § III), the results in Figure 2 should be considered only as a preliminary, rough calibrating guide. It is clear, however, that the separation between C and M stars in the $77-81$ index ranges from ~ 0.2 mag for early types to greater than 1 mag for the coolest stars.

In the aforementioned work of Richer and collaborators, two filters having central wavelengths close to ours are also employed, but with half-widths of only ~ 100 Å. Nevertheless, the discrimination in the two systems appears similar (compare Fig. 1 from Richer, Pritchet, and Crabtree 1985 with Fig. 2 here), presumably because the absorption features themselves are several hundred angstroms wide. Aside from the obvious throughput advantage, the broader filters are less susceptible to fringing from night sky lines (and in fact no fringes were seen during any of this work) and should also be easier to standardize, as their percentage effective wavelength shift with differing telescope f ratios is smaller.

III. OBSERVATIONS AND REDUCTIONS

The measurements reported here were all obtained with the Steward Observatory CCD system at the Cassegrain focus of the Steward 2.3 m telescope. We used a 320×512 pixel RCA chip, which at f/9 gave an 0ʺ29 pixel spacing and a 1ʹ5 × 2ʹ5 trimmed field. One region each in M33, WLM (DDO 221), M31, and IC 1613, and two in NGC 6822 were observed during the nights of 1982 September 18 and 19. An additional field in both IC 1613 and M31 were observed during the nights of 1982 October 19 and 20. During these times the Galactic field stars in Figure 2 were also measured.

Our two M31 fields lie along the major axis near the centers of Baade's Fields II (nuclear distance $R \approx 7$ kpc) and III ($R \approx 10$ kpc), these being interarm and arm regions respectively (see Baade and Swope 1963). The M33 field is along the major axis ($R \approx 2$ kpc) in an interarm region perhaps somewhat similar to Field II in M31 but relatively closer to the nucleus (a photograph of the selected area is provided in Aaronson, Cook, and Norris 1985). In terms of the familiar isophotal diameter system of de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2), the two M31 fields are at radii corresponding to $\log(A/D_1) = -0.3$ and -0.2, while the M33 field lies at $\log(A/D_1) = -0.5$.

The two NGC 6822 fields are located along the central bar on opposite sides and a few arcminutes from the geometric center. The two IC 1613 fields lie adjacent to each other near the central, low surface brightness region of this dwarf and away from the active star-forming areas. Finally, the WLM frame is positioned near this object's center. Note that the field size corresponds to a linear dimension of $\sim 220 \times 360$ pc at the distance of our nearest object, NGC 6822, and to $\sim 380 \times 630$ pc at the distance of the farthest object, WLM. (Coordinates and finding charts of candidate C and M stars are available from the authors on request.)

Our observing log is presented in Table 1. Generally, three frames of each field were obtained through each filter. The individual I exposures were either 240 or 300 s, while the V, "77," and "81" exposures were usually twice as long. Seeing, as determined by the full width at half-maximum of the stellar profiles, varied from 1ʺ1 to 1ʺ9. A nice surprise was the ease with which the disk giants in M31 and M33 resolved (see Aaronson, Cook, and Norris 1985). Resolution of the three dwarf irregulars was also no problem, even under the poorer seeing conditions.

Each frame was bias-subtracted and successfully flat-fielded to a few percent across the chip, using a frame of a uniformly illuminated area of the wind screen taken through the appropriate filter. Fields with three or more exposures in a single band were combined to form a median frame. This procedure satisfactorily removed cosmic-ray events. For the fields with only two exposures, instrumental magnitudes were determined for each and then averaged together. The "thick" chip in use at the time, though very sensitive at I, was unfortunately of poor cosmetic quality, and it was necessary to column-interpolate the data over about half-dozen regions, a procedure greatly assisted by the oversampling of the data.

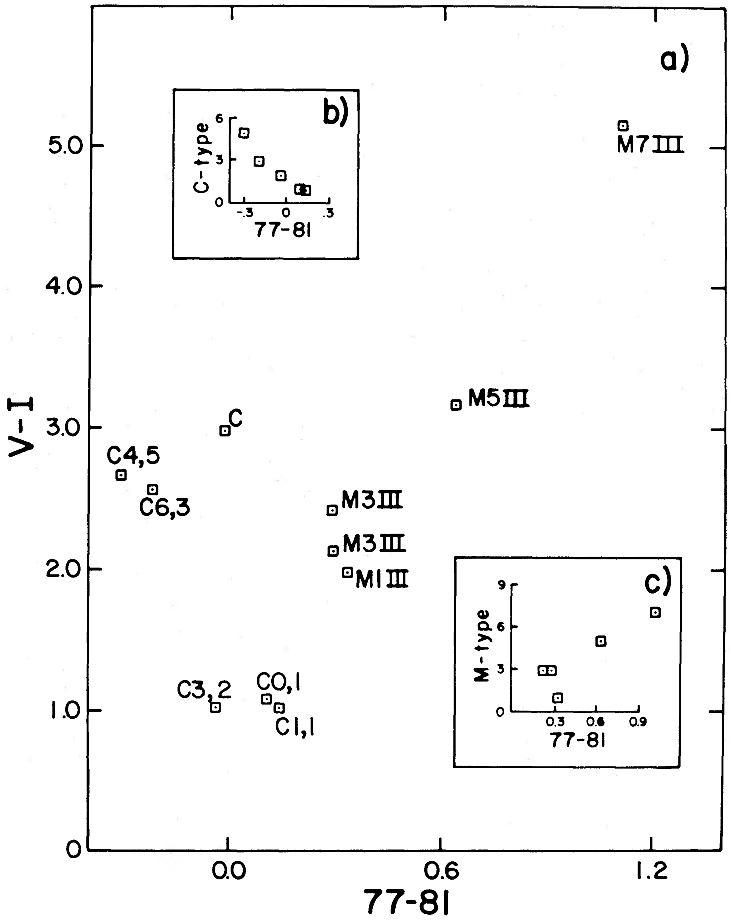

FIG. 2.—(*a*) ($V-I$, 77−81) two-color diagram for Galactic field carbon and M stars. The C stars were selected from Yamashita (1972, 1975), except for one object (labeled "C") taken from Fuenmayor (1980); the M stars were chosen from Hoffleit (1982). The inserts show the relation between the 77−81 color and (*b*) carbon abundance class and (*c*) spectral M type.

During some of the observations, the photometric quality of the sky was poor (a significant fraction being covered by thin cirrus). In view of this and of the cosmetic nature of the chip, it seemed unlikely that photometric zero-points could be determined to better than 10%. Because of these factors and the preliminary nature of this study, and for reasons of efficiency, even though each field was relatively crowded we chose to continue the reductions using an aperture photometry routine rather than a more powerful PSF fitting program such as RICHFLD. For this purpose we used H. Butcher's "Mountain Photometry Code" (described in Adams *et al.* 1980).

The instrumental magnitudes were obtained using 1″.5–2″.5 diameter apertures (depending on the seeing) for the brightest several hundred nonoverlapping images in each frame. Using the least crowded stars, the magnitude profile was then determined out to a diameter (typically 9″) such that a 1-pixel

TABLE 1

JOURNAL OF OBSERVATIONS

Parameter	M31-BII	M31-BIII	M33	NGC 6822-F1	NGC 6822-F2	IC 1613-F1	IC 1613-F2	WLM
Field center:								
Decl.	$00^h38^m11^s$	$00^h37^m34^s$	$01^h30^m58^s$	$19^h42^m07^s$	$19^h42^m10^s$	$01^h02^m13^s$	$01^h02^m13^s$	$23^h59^m25^s$
Date (1982)	+40°31′.9	+40°20′.7	+30°33′.3	−14°56′.9	−14°53′.8	+01°50′.5	+01°52′.0	−15°44′.6
Seeing	Oct 20	Sep 18	Sep 19	Sep 19	Sep 18	Sep 18	Oct 20	Sep 19
Exposure (s):	1″.3	1″.1	1″.2	1″.3	1″.7	1″.2	1″.9	1″.1
I filter								
V filter	3 × 300	3 × 240	3 × 300	3 × 240	3 × 240	2 × 240	3 × 300	3 × 300
77&81 filter	3 × 600	2 × 480	3 × 600	3 × 480	3 × 480	2 × 480	3 × 600	3 × 600
−4.4 limit[a]	3 × 600	3 × 480	3 × 600	3 × 480	4 × 480	3 × 480	3 × 600	3 × 600
7% error depth[b]	20.0	20.0	20.1	19.6	19.6	20.0	20.0	20.3
	20.7	20.9	20.7	20.1	20.3	20.8	20.7	20.9

[a] The −4.4 limit represents the apparent *I* mag for $M_I = -4.4$ in each field; the photometry is believed roughly complete to this limit.

[b] The 7% error depth represents the point at which the instrumental error for photometry in the *I* band was 0.07 mag (except for NGC 6822, where the point at which the photometry was stopped is listed). The photometry to these limits is incomplete by varying amounts.

increase in aperture radius produced a $\lesssim 0.01$ mag change. After applying this aperture correction, the magnitudes were then adjusted for extinction using a combination of mean Kitt Peak values, extinction measured by Barnes (1984) during a photometry run at Kitt Peak in 1982 September, and our own measurements during the October run. As previously mentioned, the "77" and "81" values have been left instrumental. Extinction corrections per unit air mass for the "77" and "81" bands were measured as 0.060 mag and 0.053 mag respectively, which compare well with the expected monochromatic extinction of 0.056 and 0.051 (Hayes 1982). The reasonable extinction value for the "77" filter shows that the atmospheric A-band is not interfering with the photometry at that wavelength (see Fig. 1).

Transformation to the Kron-Cousins system for V and I was effected from standards observed in three globular clusters: M92, NGC 2419, and NGC 7790 (Christian *et al.* 1985; Davis 1985). The color coefficients for the different nights had a mean slope of 1.01 ± 0.03 and an 0.02 mag standard deviation in zero point. No color term was necessary in the relation between real and instrumental V, which showed an rms scatter of 0.05 mag in each nightly transformation, somewhat better than anticipated.

Because of the variations in crowding, seeing, and exposure times, the photometry from field to field does not reach the same depth in apparent magnitude. For a fair comparison, we have chosen a fiducial magnitude limit of $M_I = -4.4$, down to which we are reasonably complete. The apparent I-magnitude corresponding to this limit (which of course depends on the adopted distance moduli and reddening values) is given in the penultimate row of Table 1; below this value the relative completeness is quite variable. The statistical error in instrumental magnitude at the -4.4 limit is for all fields 6% or less in "77" and "81," and 5% or less in v and i. The corresponding uncertainty in the instrumental $77-81$ color is thus $\lesssim 0.10$ mag. The uncertainty in the $V-I$ color is a combination of the photometric errors and the uncertainty in the transformation and is also estimated to be $\lesssim 0.1$ mag for $V-I \lesssim 1.8$ at $M_I = -4.4$. For extremely red stars at our I limit, the V-magnitude uncertainty becomes quite large: ~ 0.5 mag at $V-I \approx 3.5$ and ~ 1 mag at $V-I \approx 5.0$. All these errors may be underestimated because of crowding effects; nevertheless, the confirming spectroscopy presented below indicates their complete adequacy for this preparatory study.

The final row of Table 1 gives the limit at which the statistical error in apparent I reached 7% (the practical limit of the photometry), or in the case of NGC 6822 the point at which the photometry stopped. At this alternative limit the corresponding statistical errors in the individual "77" and "81" values are below 0.10 mag.

IV. COLOR-COLOR DIAGRAMS

Two-color ($V-I$, $77-81$) diagrams constructed from the eight observed fields are shown in Figure 3; only stars down to the completeness limit $M_I = -4.4$ mag have been plotted. Stars without significant TiO or CN form a locus in these plots which runs almost vertically, since $77-81$ is insensitive to temperature. As the giant branch climbs redder, it eventually splits into the separate C-star and M-star forks, an effect perhaps most clearly visible for M33 in Figure 3*c*.

To additionally check the technique, we have in collaboration with J. Mould obtained spectra using the Hale 5 m telescope of candidate stars in seven of the eight observed fields. The resulting spectral types are shown plotted as letter symbols in Figure 3. Note that a particularly detailed survey was made of NGC 6822-F1 (Fig. 3*e*; see also Fig. 1 of Aaronson, Mould, and Cook 1985). These results provide further confirmation of the filter band method's validity, as all stars lying within the carbon and M star areas (see below) were so verified.

There is clearly, however, a transition region at $V-I \approx 1.5$, where early C and M and late K stars are difficult to disentangle from one another. More accurate photometry should help in this regard. Giants earlier than M0 should be bluer than 1.6 mag at $V-I$ (Johnson 1966; Bessel 1979). We might also expect the C stars to separate from the giant branch at a bluer $V-I$ than the M stars (and there is some hint in Fig. 3 that this is the case), since, after all, the carbon star temperature sequence reaches values as hot as early K types. On the other hand, M stars earlier than $\sim$M3 are found at the top of the giant branch before it splits much and are not readily distinguished because of their low TiO level and the scatter in the photometry.

In view of the above considerations, and using our spectra as a guide, we have separated stars into C or M type as follows: The $77-81$ color of the giant branch at $V-I = 0$ was first determined. Then, stars 0.06 mag bluer than this fiducial in $77-81$ and redder than 1.5 mag in $V-I$ were classified as type C. Stars with $77-81$ greater than the fiducial value by 0.18 mag (0.43 mag) and redder than 1.6 mag were classified as M3 (M5). The corresponding areas in which C or M3+ stars (i.e., those of type M3 and later) are found have been explicitly blocked out in Figure 3. Note that the $V-I$ boundaries for NGC 6822 were shifted upward by 0.1 mag to account for reddening, while the M-star $V-I$ boundary for M33 was shifted downward by 0.1 mag to allow for the apparent earlier giant branch separation.

It is evident that the five galaxies in Figure 3 present strikingly different types of red stellar populations, which is the primary observational result of this paper. The three dwarf irregulars WLM, IC 1613, and NGC 6822 have many carbon stars that outnumber the M stars and few (if any) late M stars. M33 has C stars, but proportionately more M stars and later M stars. M31 has many M stars and late M stars, but only one carbon star was found in each field to the -4.4 mag limit. The underlying cause of this progression is considered in the next section.

There does not appear to be a significant difference in results for the galaxies in which two regions were observed. This is an interesting point with regard to M31, as it suggests that in the arm and interarm regions, which have similar abundances, we are primarily measuring an old-disk component little affected by the presence of extreme Population I.

We also note that some number of red stars lying above the top of the giant branch at $V-I > 2$ fall between the blocked-out areas in Figure 3. These are good candidates for S stars, and in fact the first such object in NGC 6822 has been spectroscopically identified by Aaronson, Mould, and Cook (1985).

The reddening arrows in Figure 3 show that the effect of foreground extinction on our results is small. These values were estimated using van de Hulst curve 15 (Johnson 1968), from which we derive $E(V-I)/A_V = 0.39$ and $E(77-81)/A_V = 0.043$. For NGC 6822, A_V was taken from McAlary *et al.* (1983); otherwise a simple cosecant law was used. It is also probable that the stars are somewhat internally reddened

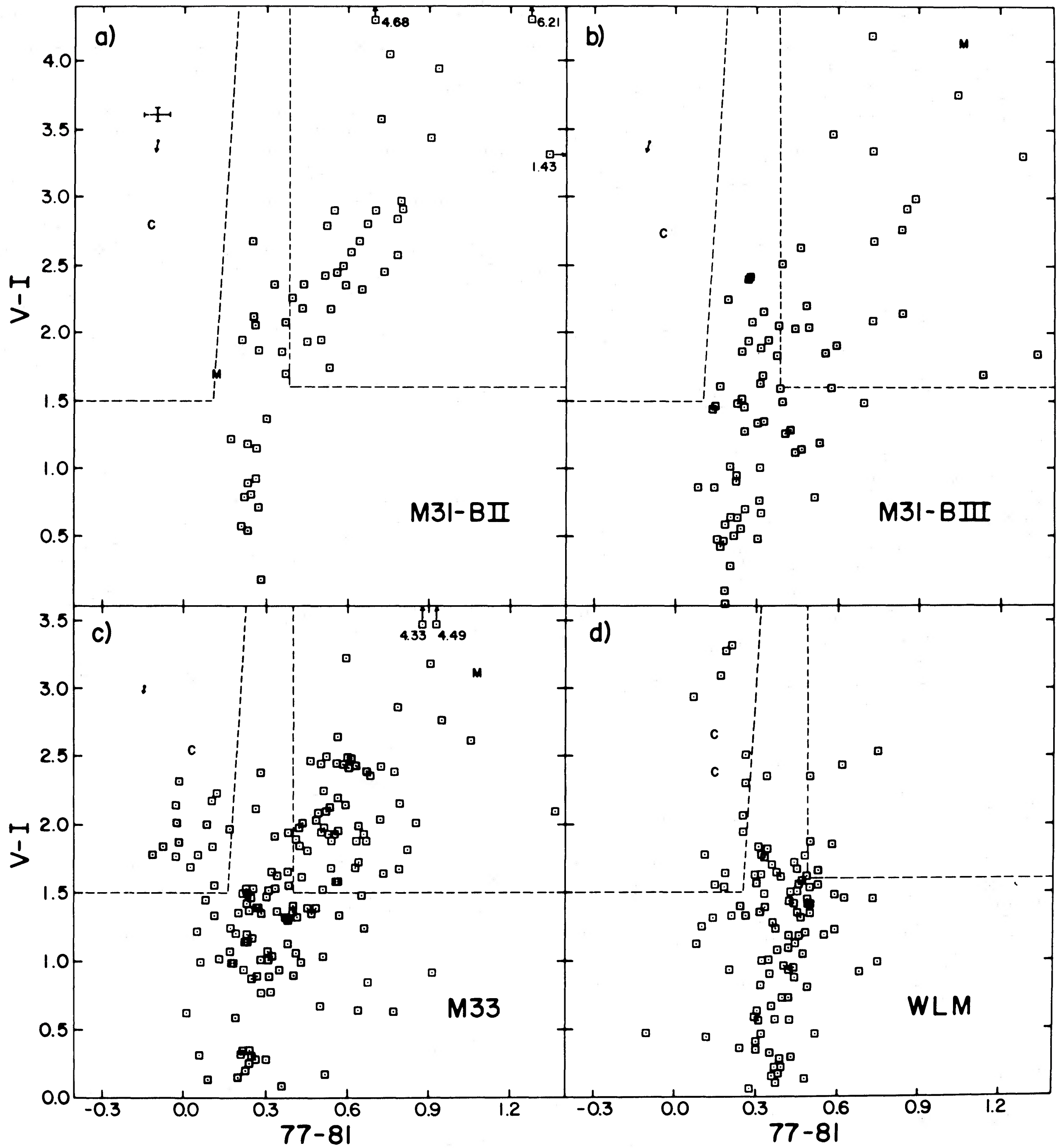

FIG. 3.—Color-color diagrams of 77−81 vs. $V-I$ for each field surveyed. Only stars with $M_I < -4.4$ mag are plotted, a depth to which all fields are believed roughly complete. Stars with spectral identifications are represented by the symbol of their type (C, K, M, or S). The adopted boundaries for the carbon star region and the M3 or later region are also shown. Each panel contains a reddening arrow showing the effect of Galactic absorption ($A_V = 0$ for WLM). The error bars in (*a*) and (*e*) illustrate the typical photometric uncertainties at $M_I = -4.4$.

(especially in M31 and M33, where dust lanes are visible running through the frames), but this is not likely to much alter the C/M ratios derived next.

V. C/M RATIOS

The carbon to M star ratios C/M3+ and C/M5+ found from Figure 3 are listed in the first part of Table 2, where the results for the objects with two observed regions have simply been averaged together. The upper limits listed for IC 1613 and WLM reflect the fact that no stars M5 or later were identified. The uncertainties in the ratios arising from small number statistics, photometric errors, and sample completeness effects are difficult to estimate precisely. For comparison, a second set of C/M ratios is also listed in Table 2 determined from the 7% depth sample (see Table 1). These quantities are derived from a larger number of stars and thus may be more statistically sig-

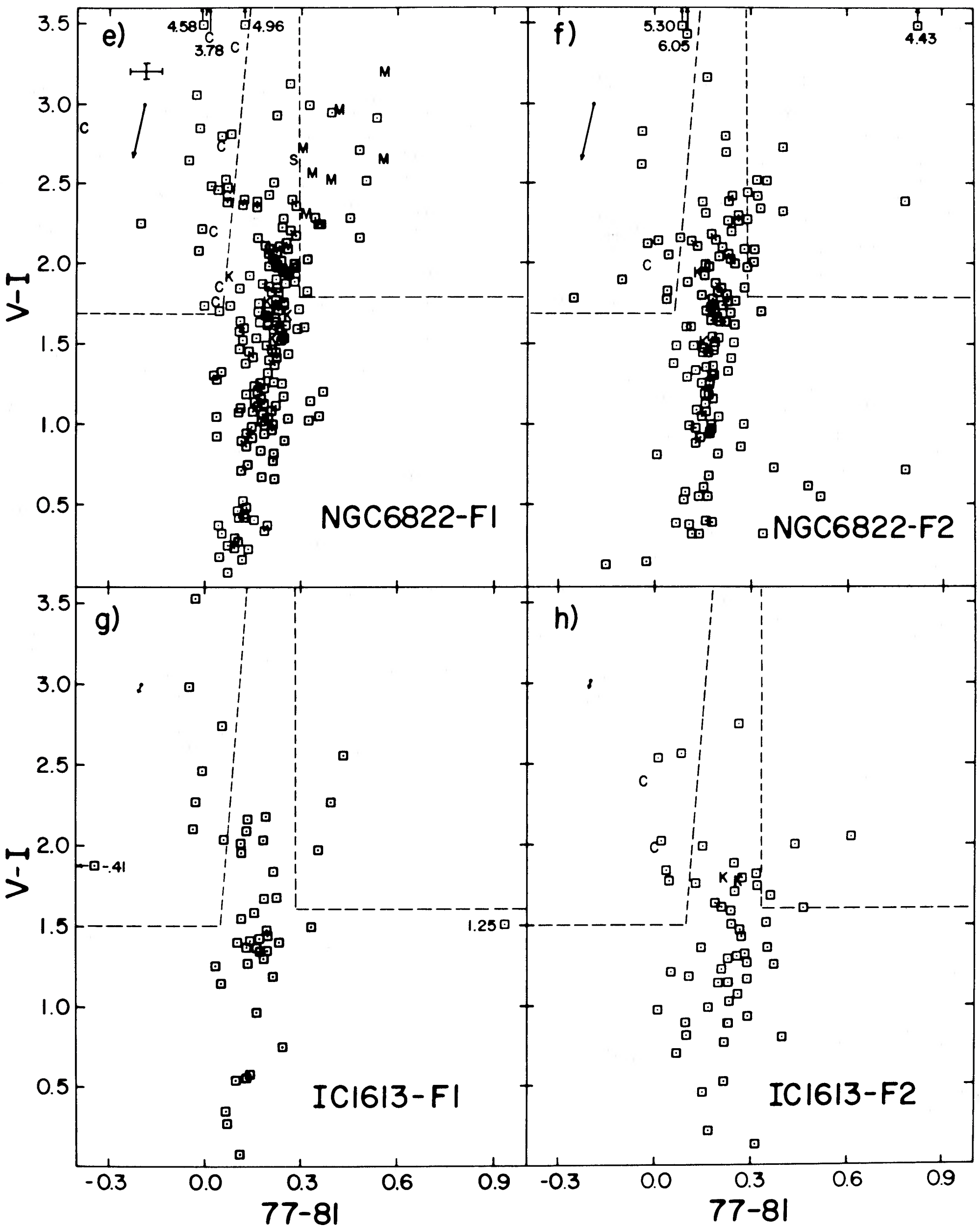

FIG. 3.—*Continued*

nificant, if there are no selection effects below $M_I = -4.4$ mag; they will not, however, be used in the diagrams presented below. In any event, within the vagaries of small number statistics, our results for M31 agree well with those of Richer and Crabtree (1985), who also report a small C/M value. Also listed at the bottom of Table 2 are C/M ratios for the Magellanic Clouds taken from Blanco and McCarthy (1983). We have directly adopted their listed C/M2+ values as our C/M3+ values. This seems reasonable, since these authors report only moderate completeness for spectral types M2–M4.

Our limiting depth of $M_I = -4.4$ mag only reaches about halfway down the C-star luminosity function, while the Blanco and McCarthy (1983) survey, being at least 1 mag deeper, is thought to completely sample the carbon-star population. In comparing our results with theirs, we should consider how our sampling incompleteness is likely to affect the C/M ratios.

In a coeval population, the C/M ratio would be sensitive to the magnitude limit simply because the carbon stars evolve from the M stars; the ratio would then be expected to decrease as the sampling is extended fainter. However, the situation in the field, where variable age, mass, and abundance effects all come into play, is likely to confound any such straightforward dependence of C/M ratio on depth, especially since the M stars (unlike the C stars) are not confined to a restricted luminosity or mass range.

We can use the LMC data from Blanco, McCarthy, and Blanco (1980) to explicitly test for a change in C/M ratio with sample depth. For the Optical Center field, we find no difference in the C/M ratio between the complete sample and a sample of stars restricted to $m_I \leq 14.1$ mag (equivalent to $M_I \leq -4.4$ mag with our adopted modulus). However, in both the Bar West and Radio Center fields, we do find that the C/M ratio increases by $\sim 30\%$ when the magnitude restriction is applied. On the other hand, no such trend is apparent in a comparison of the M33 ratios in rows (1) from Table 2 here with the deeper results from rows (2). Similar tests made with the other fields in Table 2, with the deeper fields in the SMC from Blanco, McCarthy, and Blanco (1980), or with the deeper M31 field of Richer and Crabtree (1985) are in all cases rendered ambiguous by the small statistics involved in the numbers of either carbon or M stars. While a more complete exploration of the AGB in our fields would be of obvious value, we do not believe that such a survey is likely to alter any of the basic conclusions which follow.

Provided in the latter part of Table 2 are a number of other salient galaxy properties. Morphological types taken from the RC2 are listed in row (3). Absolute blue magnitudes are given in row (4). These were obtained from the apparent blue magnitudes in either Sandage and Tammann (1981, hereafter RSA) for M31, M33, and NGC 6822, or the RC2 for IC 1613 and WLM, corrected for internal and Galactic extinction using the RSA prescriptions, and converted to absolute values using the distance moduli in row (5). The latter are generally based on the continuing work of Madore and collaborators involving infrared photometry of Cepheids. For WLM we have assumed a modulus 0.4 mag greater than M31, following de Vaucouleurs (1975). The adopted foreground extinction is given in row (6).

The final two rows in Table 2 list the hydrogen mass to blue luminosity ratio, log $(M_{\rm H}/L_B)$, and the H II region oxygen abundance determined from optical emission line studies. The former are derived from Roberts (1969) and Fisher and Tully (1975), after converting their values to the distances and luminosities used here. The latter are adopted from Talent (1980; NGC 6822 and IC 1613); Dufour (1984; the Clouds); Blair, Kirshner, and Chevalier (1982; M31); and Blair and Kirshner (1985; M33). Both M31 and M33 are believed to have radial abundance gradients, and the results in the cited references have been interpolated to the radii of our observed fields; in the case of M31 the listed quantity is the mean of [O] = 9.0 at $R = 7$ kpc (Field II) and 8.9 at $R = 10$ kpc (Field III).

The C/M ratios in Table 2 might be considered lower limits, due to the possibility of foreground contamination from M dwarfs. To estimate this effect we have used the star count model of Bahcall and Soneira (1980). For NGC 6822 a substantial foreground component is present, and a large (but rather uncertain) fraction of the M stars are probably dwarfs. The estimated corrections to the C/M ratios are given in Table 2. Contamination of the remaining fields appears negligible, except for M31, where a few interlopers may be present, but they will not materially alter the results.

The C/M ratios are plotted against parent galaxy absolute magnitude in Figure 4. A strong correlation between C/M3+ and M_B is evident, while the dependence with C/M5+ is even steeper. An alternative representation using log (C/M) is shown in Figure 5, where remarkably the galaxies are seen to fall along roughly straight-line relations. In particular, both the LMC and SMC fit naturally onto the sequences defined by the other relatively isolated systems. Hence, we conclude that the large C/M ratios observed for the Clouds are not unusual, and we further infer that the star formation history of these systems is probably influenced more by their internal properties than by any tidal effects.

It is also interesting to point out where the dwarf spheroidals would lie in these figures. In fact, while C stars have been found in all the spheroidals, no stars of type M3 or later have been conclusively identified. Fornax, the brightest of these systems at $M_B \approx -12$, probably contains at least a few early M stars along with ~ 70 C stars (see Aaronson and Mould 1980). Thus, these dwarfs would, in a manner of speaking, fit smoothly onto the C/M sequence, though with the same sort of upper limits as for IC 1613 and WLM.

VI. DISCUSSION

A hint of the cause underlying the trends in Figures 4 and 5 is indicated in Figure 6, where the C/M ratios are plotted against oxygen abundance. Clear relations are again obvious, and not surprising, since the gaseous abundance is known to correlate with absolute magnitude.

A decrease in metallicity can drive the C/M ratio higher through two mechanisms. First, the giant branch will shift bluer in the H-R diagram, and at the same time the TiO absorption will be lower at fixed temperature (e.g., Mould, and McElroy 1978; Mould, Stutman, and McElroy 1979), both

TABLE 2

C/M RATIOS AND OTHER GALAXY PROPERTIES

Parameter	M31	M33	NGC 6822	IC 1613	WLM	LMC[a]	SMC[a]
1. −4.4 limit:							
C/M3+	0.04	0.25	1.25 (2.3)[b]	2.8	2.8	0.2	0.6
C/M5+	0.08	1.0	18 (33)[b]	>14	>14	0.8	4.3
2. 7% depth:							
C/M3+	0.03	0.25	0.9	1.2	3.2	...	...
C/M5+	0.07	0.8	6.0	8.0	16	...	...
3. Type	Sb	Scd	Im	Im	Im	Sm	Sm
4. $M_B^{0,i}$	−21.2	−18.7	−14.6	−14.5	−13.6	−18.1	−16.5
5. $(m-M)_0$	24.3	24.4	23.5	24.4	24.7	18.5	19.0
6. A_V	0.18	0.09	0.92	0.02	...	...	...
7. log $(M_{\rm H}/L_B)$[c]	−0.70	−0.39	0.00	−0.24	+0.13	−0.73	−0.11
8. [O][d]	8.95	8.45	8.27	7.86	...	8.43	8.02

[a] Magellanic Cloud C/M ratios adopted from Blanco and McCarthy 1983.

[b] Value after applying an estimated correction for foreground M dwarf contamination, in parentheses.

[c] Hydrogen mass to blue luminosity ratio.

[d] Gaseous oxygen abundance log [O/H] + 12.

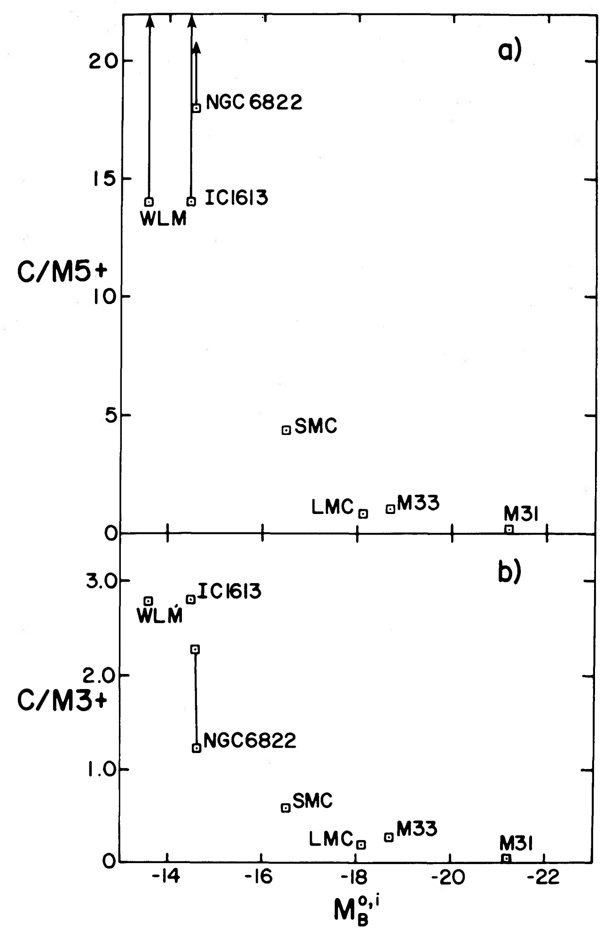

FIG. 4.—Carbon to M star ratios for (*a*) M5 or later types and (*b*) M3 or later types vs. parent galaxy absolute magnitude. Data for the Magellanic Clouds from Blanco and McCarthy (1983). The two locations for NGC 6822 in (*b*) correspond to the observed ratio (*lower value*) and the ratio corrected for foreground contamination from M dwarfs (*upper value*). The latter point in (*a*) lies off the plot. The long arrows for WLM and IC 1613 in (*a*) reflect the fact that no M5 or later stars were found in these systems.

effects combining to diminish the total number of M stars and also the proportion of late-M to early-M types. Second, making C stars should become "easier," because less carbon needs to be brought to the surface in order to force [C] > [O], and furthermore the dredge-up efficiency itself may be abundance-sensitive (Wood 1981).

There is some indication that the former of these effects is primarily responsible for the changing C/M ratio, at least for the less luminous galaxies. This comes from consideration of the total carbon-star population in the Magellanic Clouds, which Blanco and McCarthy (1983) place at 2900 for the SMC and 11,000 for the LMC. As these numbers scale almost directly with the Cloud absolute magnitudes, the change in C/M ratio must mainly result from differences in the M star population. There is actually some theoretical justification for expecting such a "bottoming out" in the sensitivity of carbon-star production to abundance effects from the work of Iben (1983), who found that only one dredge-up episode was necessary to turn an $M = 0.7\ M_\odot$, $Z = 0.01$ model into a C star. Hence, any further lowering of the metallicity may not be of much additional help. This might also explain why the fractional carbon-star number in the dwarf spheroidals is roughly independent of mean abundance (Aaronson and Mould 1985). Higher mass metal-poor models would be of considerable value for testing these ideas.

Metallicity variations, however, cannot be the whole story, since we do not find luminous AGB stars (carbon or otherwise) in Galactic globular clusters. Age must also come into play, and it is of interest in this regard to consider the lifetimes and progenitor masses M_i of the stellar objects being sampled. The C stars range in luminosity from $M_{\rm bol} \approx -4.5$ to -6 mag (§ VII). This implies an age spread from ~ 1 to 10 Gyr (Mould and Aaronson 1982) and corresponding M_i values from ~ 2 to 1 $M_\odot$ (e.g., Fig. 7 of Iben and Renzini 1983). The lower age, upper mass limit here is set by the known absence of any carbon stars brighter than $M_{\rm bol} \approx -6$ mag. Our sample M stars should have an age spread similar to that of the C stars but will also include a younger component, as M stars up to

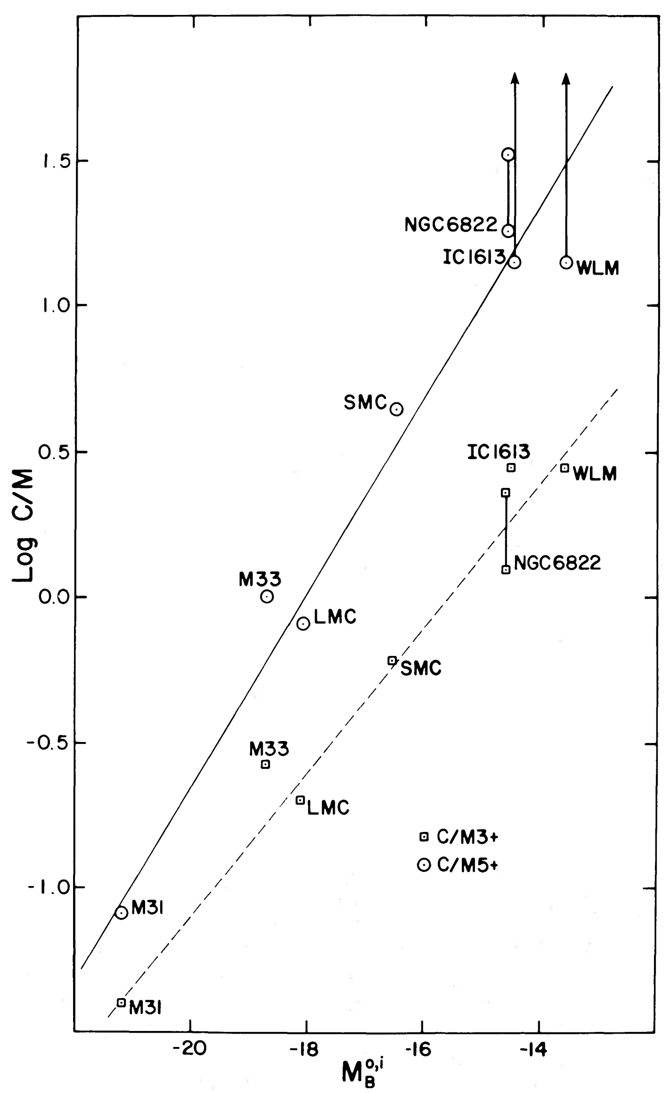

FIG. 5.—Same as Fig. 4, for log (C/M). The straight lines are eye fits meant to be suggestive only.

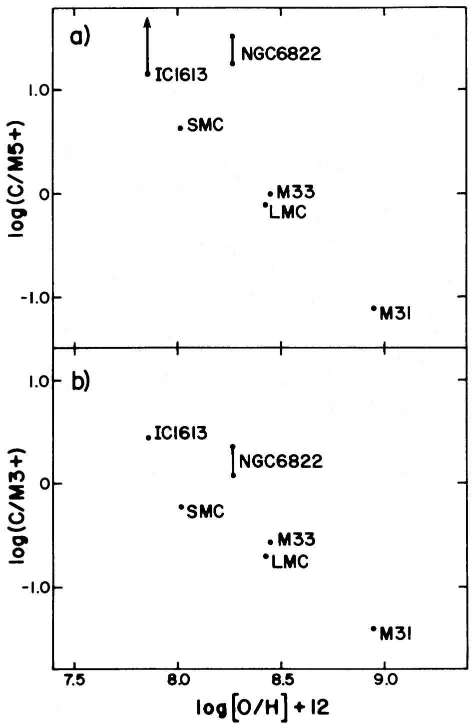

FIG. 6.—Carbon to M star ratios vs. H II region oxygen abundances determined from optical emission line spectra.

the theoretical AGB limit at $M_{bol} \approx 7$ mag do in fact exist (Wood, Bessell, and Fox 1983). Some first giant branch M supergiants having $M_i > 8\ M_\odot$ may also be present. However, following the simple evolutionary models of Reid and Mould (1984), we do not expect the RGB + AGB contribution from stars having $M_i > 5\ M_\odot$ (or age < 0.1 Gyr) to be any larger than ~10%.

The presence of large carbon-star populations in the Clouds is often cited in support of the idea that a substantial star formation burst occurred ~3 Gyr ago (e.g., Blanco and McCarthy 1983), as also suggested by the turnoff in the field main sequence (Butcher 1977). However, in our view, the Cloud carbon-star numbers do not provide especially compelling evidence favoring a burst over a more steady formation rate. In particular, a constant rate can adequately reproduce the peak in the Cloud C star luminosity function at $M_{bol} \approx -5$ mag (see Fig. 9 of Iben and Renzini 1983), though the mystery of the missing bright carbon stars remains. In this regard, Aaronson and Mould (1985) have pointed out that the total bolometric contribution of C stars to the integrated light implies that only ~40% of the Cloud component older than 1 Gyr is of intermediate age, though the argument is a crude one.

We cannot yet estimate the total carbon-star population in the dwarf galaxies observed here, but it seems likely from the results in Figures 4 and 5 that these systems also contain a significant intermediate-age component. Hence, although the less luminous galaxies have not been as efficient at converting gas to stars as their larger cousins (Table 2), we infer that they have nonetheless made stars over a significant fraction of their lifetimes, and furthermore that the presence of a substantial intermediate-age component is likely to be a general characteristic of smaller luminosity, late-type galaxies.

Future measures of the C/M ratio in other extragalactic systems should yield a plausible metallicity estimate. It should be remembered, though, that this ratio is a gauge of gaseous abundance at intermediate ages, and not at the present time. Even so, the results obtained here imply that the relative metallicities of our sample galaxies were no different ~5 Gyr ago than today, and therefore the relative enrichment rates over this time must have been similar enough to have preserved this ranking.

Because there is in fact no other direct evidence concerning the amount of metals present in our galaxies at intermediate times, it could be claimed that the trend between absolute luminosity and C/M ratio has nothing to do with abundance but is purely an age effect. However, we do not regard this as a tenable view and cite as an argument against it the reasonable agreement in the carbon-star luminosity functions presented in § VII.

Finally, before closing this section we wish to call particular attention to a comparison between M33 and the LMC. Both objects have a similar total luminosity, and the abundance at the radial location of our observed M33 region is very close to the mean value for the LMC as a whole (Table 2). Nevertheless, given the very distinct morphological types of these galaxies, the similarity in C/M ratios may come as a surprise. To us, this result implies that local conditions govern disk star formation history to a greater degree than overall morphology or (again) galactic environment. A particularly interesting test of this idea would be to see how well the C/M ratio and the total number of AGB stars in M31 and M33 track the apparent H II region disk abundance gradient.

VII. LUMINOSITY FUNCTIONS

The observed carbon-star luminosity functions are presented in Figure 7. Except perhaps for NGC 6822, their appearance is dominated by small number statistics. Bearing this caveat in mind, along with the absence of any correction for internal absorption, the relative luminosities are seen to be roughly consistent with each other and with results for the Magellanic Clouds.

An important point to be made from Figure 7 is that no very luminous, $M_I < -6$ mag carbon stars have been found in any of our galaxies. The lack of such objects has been a longstanding embarassment to the theory of the AGB (see Iben and Renzini 1983). Recently, Reid and Mould (1984) have determined a total AGB luminosity function for a region of the LMC and find that the AGB deficit extends to the oxygen-rich stars as well (beginning at $M_{bol} \approx -5$), in comparison to a theoretical distribution that assumes constant star formation and a Salpeter initial mass function (IMF). One way to fix up the problem is by varying the star formation with either an exponentially declining rate or a steeper IMF, but in view of other evidence neither solution seems plausible (see Reid and Mould 1984). The other, more likely possibility is to alter the AGB tip evolution through a mass-dependent mass loss rate or the convective overshoot process or both (Bertelli, Bressan, and Chiosi 1985).

Further observational information on this situation can be obtained by examining the total AGB luminosity function in other galaxies, but we consider the sample of stars here too statistically small to make the comparison worthwhile. However, with more complete surveys (e.g., Reid and Mould 1985), and if the AGB tip evolution can be independently sorted out, detailed constraints might be placed on the star-forming rate, allowing a choice to be made, for instance,

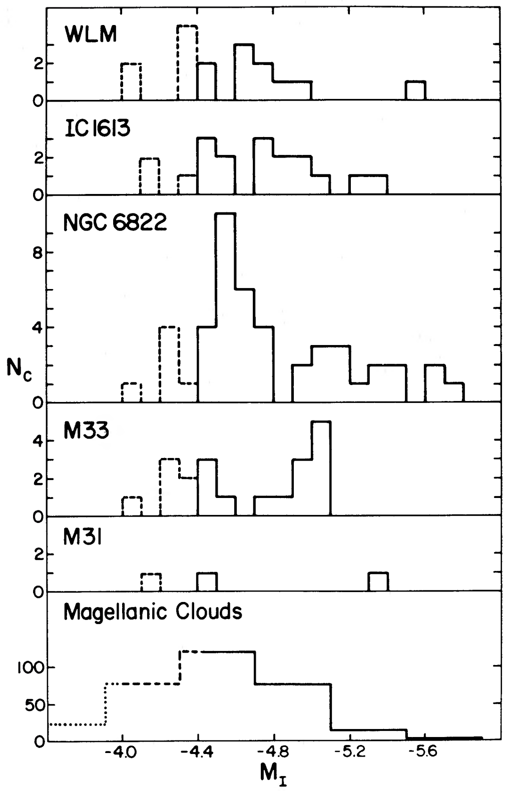

FIG. 7.—Observed carbon-star luminosity functions. Results for the Clouds are taken from Blanco, McCarthy, and Blanco (1980). Except for these and NGC 6822, the samples are not complete below $M_I = -4.4$ mag.

between burst models and those having steady stellar production. Such data will in addition provide further testing of the extent to which the stellar content of the Magellanic Clouds is abnormal or not.

The good agreement in Figure 7 can also be interpreted to mean that our adopted relative distances are sound. Indeed, the problem can be completely turned around and the carbon-star luminosity function used to derive distance moduli. The possible advantages underlying such a procedure have been summarized recently by Richer, Pritchet, and Crabtree (1985). The chief disadvantage is that the unproven assumption of a universal carbon-star luminosity function must be adopted. This, in turn, depends on a common IMF and star formation rate. Without forgetting these points, it is nonetheless interesting that our "guesstimated" WLM modulus, which has led to reasonable C-star luminosities, is in good agreement with the new Cepheid modulus of 24.9 mag reported by Sandage and Carlson (1985). On the other hand, the M33 results do not on the face of it appear to add much support to Sandage and Carlson's (1983) proposed increase in modulus to 25.35 mag, and any internal absorption correction would only worsen the problem in this regard. Again, a larger and more complete AGB sample would clearly be of interest.

VIII. SUMMARY

A rapid, photometric method for dissecting the red stellar content of resolvable stellar systems has been developed and successfully tested in five nearby galaxies. The carbon to M star ratio and the proportion of late to early M stars has been found to be a strong function of parent galaxy absolute magnitude. These results can be understood as primarily reflecting the effects of abundance change in intermediate-age stars. The Magellanic Clouds fit smoothly onto the relations defined by the sample here, so their large population of carbon stars is not especially unusual. Rather, the presence of a substantial metal-poor, intermediate-age stellar population may be a general characteristic of low-luminosity galaxies, though more complete surveys are needed to better test this hypothesis.

In the next few years we hope to fully map out the surface distributions and luminosity functions of AGB carbon and M stars in a number of systems. By observing Galactic field and cluster stars of known metallicity, we are also planning to obtain an explicit abundance calibration of the 77 − 81 index for M stars. From this effort we anticipate gaining considerable insight into the star formation histories of galaxies spanning a wide range in mass and morphology. As a by-product, useful distance information may also result.

This work was partially supported with funds from NSF grant AST 83-16629. We are indebted to Pete Stockman, whose initial development of the Steward CCD system and assistance at the telescope was crucial for obtaining the observations reported here. We also acknowledge Pat Hartigan for aid with the data reduction, Jay Gallagher for helpful discussion, Harvey Richer (the referee) for valuable comments on the manuscript draft, and KPNO for the use of their computing facilities. M. A. thanks the Center for Astrophysics, where part of this paper was prepared, for an SAO summer fellowship and for providing a working environment at $T < 315$ K.

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