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The calibration of the metallicity versus C/M relation

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Abstract. This paper presents a critical reassessment of the C/M ratio in the Local Group galaxies that have been surveyed by us in the last few years. We update distances, reddenings and metallicities with particular care to obtain coherent values for each galaxy. A new equation for the bolometric correction of M stars in terms of their $(R - I)$ colours is obtained from Bessell et al. (1998) data. We present a critical discussion on the colour – spectral type relation for M stars which reveals a dramatic lack of reliable data for late M stars. Finally, we show that – when homogeneous data are used – the log(C/M0+) is well correlated to the [Fe/H] of the parent galaxy.

Key words. stars: AGB and post-AGB – stars: carbon – stars: late-type – galaxies: abundances – Local Group

1. Introduction

Early objective prism surveys of the Milky Way revealed that C stars and late M stars were not spatially distributed in the same way. Blanco (1965) showed that M stars are found preferentially inside the Sun's orbit while C stars favor the anticenter region. Westerlund (1965) also noticed that late M stars are much more numerous toward the Galactic center. More than ten years later, when deep late-type star surveys of the Magellanic Clouds were initiated, a pronounced difference between galaxies was discovered. Blanco et al. (1978) were the first to point out the tremendous differences between the ratio of the number of C stars and of *late M stars* in the Galactic bulge, in the Large Magellanic Cloud (LMC) and in the Small Magellanic Cloud (SMC). They rightly suggested that the ratios were anti-correlated with the metal abundance.

Iben & Renzini (1983) gave two reasons to explain the trend of the C/M ratio with the abundance of the parent population. First, the effect of the carbon dredge-up on the stellar spectrum is more pronounced for stars of low metallicity: it is easier to transform an O-rich star into a C-rich star when there is little oxygen to start with. Second, the giant branch of metal-poor systems is steeper, therefore bluer than the metal-rich one, thus there are few if any M or late M stars in very metal-poor systems.

The spectral type approach to classify C and M stars was replaced in the nineteen eighties by a photometric technique based on two narrow band filters (Richer et al. 1984; Cook et al. 1986). This is the technique that we have exploited to survey a number of Local Group galaxies. The great differences found by Blanco et al. (1978) correspond to the numbers of C and M5+ stars. Our version of the C/M ratio, presented in this paper, refers to stars of spectral types M0 and later, denoted by M0+. The spectral limit is defined in term of $(R - I)$ colour as described in Sect. 3.2. When using a selection criterion based on the colour of stars there is a technical problem with the adoption of M5+ as a limit: too few late M stars have $V - I$ or $R - I$ colours to define an empirical spectral type – colour relation. Furthermore, the number of M5+ is quite small or even zero in galaxies with $[Fe/H] < -1.5$.

Note that throughout this paper we use the Kron-Cousins V, R, and I photometric system, however to lighten the text, we omit the KC subscript. Therefore, $(V - I)$ and $(R - I)$ must be considered as $(V - I)_{\rm KC}$ and $(R - I)_{\rm KC}$.

In Sect. 2 we summarize the status of our ongoing survey of C stars in Local Group galaxies and present the revised distances and reddenings for those galaxies with new recently published estimates.

In Sect. 3 we obtain, using up to date material available in the literature, some useful photometric empirical relations, namely: the $(V-I)$, spectral types and the bolometric correction (BC) for cool stars as a function of their $(R - I)$ colours.

In Sect. 4 we present the properties of the AGB populations in each galaxy, redetermined according to what was obtained in Sects. 2 and 3.

Finally, in Sect. 5, we discuss the link between metallicity and C/M and present a new empirical calibration of the [Fe/H] vs. Log(C/M0+) relation.

2. The status of our C star survey

Table 1 summarizes our ongoing effort; the galaxies surveyed by us are listed in order of right ascension. The table gives the number of C stars found, the adopted distance and reddening at the time of publication. Our goal was to produce a homogeneous set of C stars for the various galaxies. However, during the course of the survey we slightly modified some of our procedures. It has thus become evident that we need to standardize the treatment of the data. For example, earlier papers used Rieke & Lebofsky (1985) reddening relationships while later ones adopted the Schlegel et al. (1998) values. The adoption of bolometric correction in term of the colour is also critical. Furthermore, since the bolometric correction is often given in terms of $(V-I)$, the relation between our observed $(R-I)$ and $(V-I)$ is needed.

A literature search yielded several recent distance and/or reddening determinations. Table 2 presents the latest values. Galaxies with our reference have no new data since our publication. Reddening and extinction are now taken from Schlegel et al. (1998), with the exception of a few galaxies: for IC 10, we use our own estimate (Demers et al. 2004); Sgr DIG is from Momany et al. (2003); M 31 where the disc reddening is variable (Battinelli et al. 2003) and for NGC 3109 where three independent estimates suggest that the Schlegel et al. (1998) value is too high.

Changes in the reddening modify the $(R-I)_0$ limit and thus the number of M and C stars. A new value for the distance of a galaxy influences the number of its M-AGB stars (because we have a different I magnitude limit corresponding to the $M_{\rm bol}$ of the RGB tip.) All these changes imply that some of our published numbers have to be modified accordingly.

3. The new adopted photometric relationships

3.1. $(V-I)$ versus $(R-I)$

Because the bolometric corrections, needed to define M stars, are in general given in term of $(V-I)$, Battinelli et al. (2003) established a preliminary relationship between the two colour indices. An extensive literature search yielded a number of observations that allow a better link between the two colours. These include photometry of bright stars by Cousins (1980), a sample of nearby red dwarfs by Patterson et al. (1998), some Hipparchos stars by Koen et al. (2002), southern NLTT stars by Reid et al. (2002) and Mira variables observed by Celis (1986). These publications were selected because they include red and very red stars. The relation between the two colours is shown in Fig. 1. A straight line is fitted to the points with $(V-I) < 1.7$ and a curve for larger values. The equations are:

$$(R-I) = 0.006 + 0.4850(V-I) \quad (V-I) < 1.70$$

$$(R-I) = -8.6924 + 8.8221(V-I)^{0.14465} \quad (V-I) > 1.70.$$

One set of photometry of M-giants by Fluks et al. (1994) does not fit the other data; it is shown by open dots in Fig. 1. Fluks' relation has been used in the past, by for example Groenewegen (2002), to select C or M stars of a given spectral type.

Table 1. Number of C stars and originally adopted distances and reddenings.

Galaxy	$N_{\rm c}$	$(m-M)_0$	$E(B-V)$	Reference
WLM	149	24.90	0.04	Battinelli & Demers (2004a)
IC 10	684	24.35	*var*	Demers et al. (2004)
NGC 147	288	24.39	0.12	Battinelli & Demers (2004c)
NGC 185	145	24.12	0.19	Battinelli & Demers (2004b)
NGC 205	550	24.54	0.08	Demers et al. (2003a)
M 31	945	24.41	*var*	Battinelli et al. (2003)
IC 1613	195	24.36	0.03	Albert et al. (2000)
Fornax	26	20.76	0.03	Demers et al. (2002)
NGC 3109	446	25.56	0.04	Demers et al. (2003b)
Leo I	13	22.04	0.02	Demers & Battinelli (2002)
Sgr DIG	16	25.30	0.07	Demers & Battinelli (2002)
NGC 6822	904	23.49	0.24	Letarte et al. (2002)
DDO 210	3	24.89	0.03	Battinelli & Demers (2000)
Pegasus	40	24.9	0.03	Battinelli & Demers (2000)

Table 2. Newly adopted distances, reddenings and extinctions.

Galaxy	$(m-M)_0$	$E(R-I)$	$A_{\rm I}$	Reference
WLM	24.90 ± 0.07	0.03	0.07	Battinelli & Demers (2004)
IC 10	24.35 ± 0.11	*var*		Demers et al. (2004)
NGC 147	24.39 ± 0.05	0.13	0.34	Han et al. (1997)
NGC 185	24.12	0.13	0.35	Salaris & Cassisi (1998)
NGC 205	24.54 ± 0.05	0.04	0.12	van den Bergh (2000)
M 31	24.41	*var*		van den Bergh (2000)
IC 1613	24.31 ± 0.06	0.02	0.05	Dolphin et al. (2001)
Fornax	20.76 ± 0.04	0.01	0.04	Saviane et al. (2000)
NGC 3109	25.56 ± 0.04	0.05	0.13	Demers et al. (2003b)
Leo I	22.04 ± 0.14	0.03	0.07	Held et al. (2001)
Sgr DIG	25.15 ± 0.18	0.05	0.14	Momany et al. (2002)
NGC 6822	23.36 ± 0.17	0.17	0.46	Clementini et al. (2003)
DDO 210	24.89 ± 0.10	0.04	0.10	Lee et al. (1999)
Pegasus	24.9 ± 0.1	0.05	0.13	Aparicio (1994)

It appears that red dwarfs and red giants fit the same relations, however far away Galactic red giants may suffer reddening which would affect $(V-I)$ and $(R-I)$ differently. The reddening vector, corresponding to $E(B-V) = 0.2$, shown in Fig. 1, is nearly parallel to the relation thus reddening would have little effect on the position of the curve.

The influence of the metallicity on the $(V-I)$ vs. $(R-I)$ relation appears to be within the scatter of the data points. Indeed, we evaluate the importance of such an effect both theoretically and observationally: 1- $(V-I)$ and $(R-I)$ colours for isochrones of various metallicities (from Girardi et al. 2002) are contrasted; 2- V, R, I photometry of NGC 6822 (Gallart et al. 1996), a galaxy of non-solar metallicity and with non-negligible reddening, is compared with our data. In both cases we find that the metallicity effect is quite small.

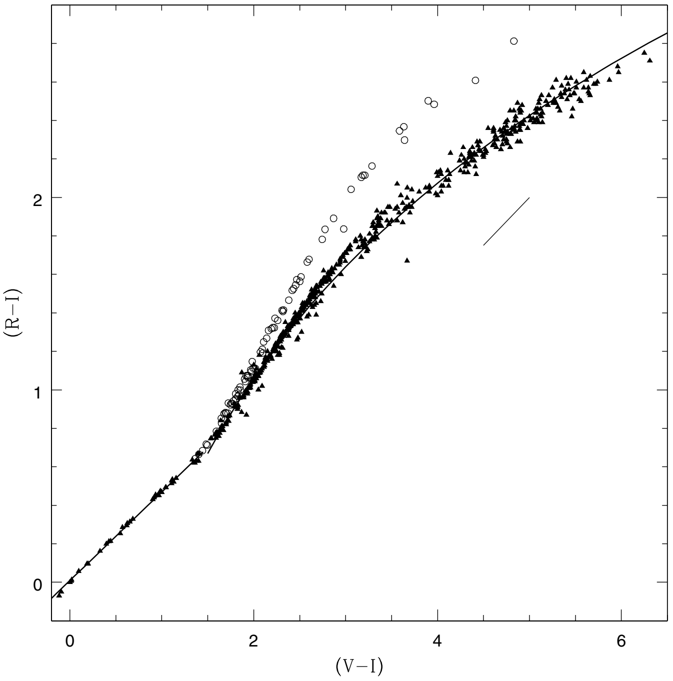

Fig. 1. The $(V - I)$ versus $(R - I)$ colours. The curve is our adopted relation. The open circles represent the Fluks et al. (1994) data points. The reddening vector corresponding to $E(B - V) = 0.2$ is drawn.

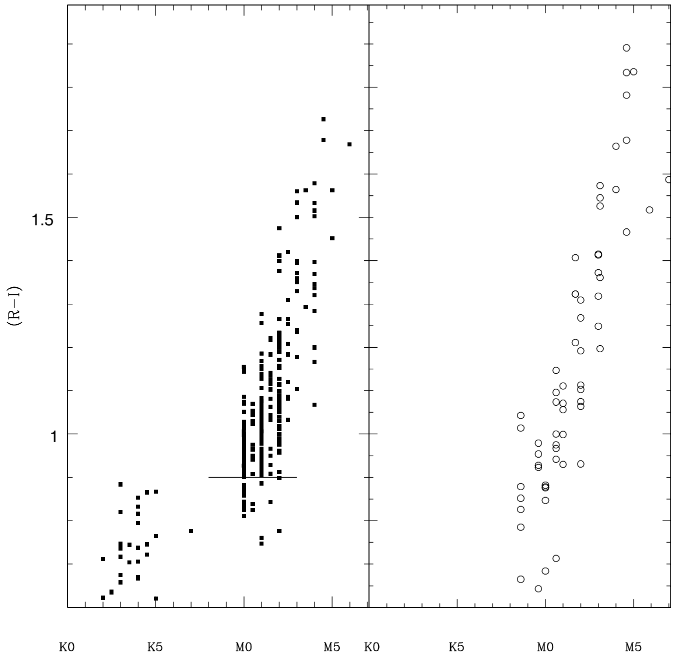

Fig. 2. The spectral types versus the $(R - I)$ colours show substantial scatter. The left panel is our compilation and the right panel displays Fluks et al. (1994) data.

3.2. (R – I) versus spectral types

The colour definition of M stars has always been rather ill-defined. Richer et al. (1985) obtained a $(V-I)$ colour threshold for M5+ (stars type M 5 or later) by observing half a dozen late M stars and two K stars in the LMC. It is however impossible, from their plot, to determine the limit between M and K stars because no early M-type were observed and one of the two K stars has a $(V - I)$ colour similar to the M5+ stars. Their adoption of $(V - I) = 2.0$ for M5+ stars still influences the discussions of C/M ratios even though in their subsequent paper, Pritchet et al. (1987), they caution about the blind use of this limit since Galactic M 5 stars have $(V - I) \approx 3.3$ in the Kron-Cousins system and "... our criterion of $(V - I) = 2.0$ in fact corresponds to a spectral type of M 2–M 3 in the Milky Way!".

In our survey we have adopted, as a limit to represent the M0 spectral type, $(R - I)_0 = 0.90$ (which corresponds to $(V-I)_0 = 1.8$) from the Thé et al. (1984) relation. Since this relation is based on a limited number of stars, we have decided to re-investigate the question. We now use a compilation of photometric data of stars of known spectroscopic types from Cousins (1980), Koen et al. (2002) and Menzies et al. (1989). The results are displayed in the left panel of Fig. 2. It is evident that it is nearly impossible to set a tight relationship between the colour of a star and its spectral type. For example, at a colour of $(R-I) = 1.1$ one may find stars from M 0 to M 4. In principle this could be explained by the inhomogeneous spectral types, but in the right panel of Fig. 2 we show the data from Fluks et al. (1994) where spectral types were homogeneously determined in the Case spectral classification. The scatter is less than in the left panel but each spectral type shows a substantial range of colour.

The reddening could of course also be a source of the scatter, however the Fluks et al. (1994) data were carefully de-reddened by the authors and we observe that the scatter is not appreciably reduced. Moreover, the stars selected in the left panel are bright, presumably not too distant stars.

It would be of interest to investigate the metallicity effect on the spectral-type colour relation but we have too few observational data points to do that. Photometry is easy to acquire but well classified spectra are rare, especially for faint stars of low metallicity.

It is often a common practice in the literature to blindly adopt a colour – spectral type relation for the compilation of the C/M ratios. For late M stars the scatter is such that the selection based on colours is of no use: for example, if based in Fig. 2a, we set $(R - I) = 1.10$ for M3+ stars, the sample would include 62% stars earlier than M 3. This figure reveals how difficult it would be to adopt a photometric criterion for M5+ stars. Too few observations are available to calibrate the relationship. In the light of these new results we believe that our earlier adoption of $(R - I)_0 = 0.90$ for M0+ stars is justified and will be retained.

3.3. The bolometric correction versus (R – I)

As explained in Battinelli et al. (2003), we adopted, for this series of papers, the Bessell & Wood (1984) BC. They provide a BC both in terms of $(R - I)$ and $(V - I)$ but due to the smaller scatter, the $(V - I)$ relation is deemed preferable to the $(R-I)$ relation forcing us to adopt a colour–colour relation (see Battinelli et al. 2003).

In the last few years several papers dealing with BC have been published. Tinney et al. (1993) and Decin et al. (2003) present only near infrared colours thus are unsuitable for our needs. Montegriffo et al. (1998) and Houdashelt et al. (2000) present the BC in terms of the $(V-I)$ but they do not extend the analysis to sufficiently red colours to cover the observed range. On the other hand, Bessell et al. (1998) present a natural upgrade to the Bessell & Wood (1984) results. Their colours reach far to the red; furthermore, the BC is presented in terms of $(R-I)$, thus does not require the conversion of the $(R-I)$ into $(V-I)$. Indeed, to obtain a BC in terms of $(R-I)$ we select stars with solar abundance or less ([Fe/H] ≤ 0.0) in Table 6 of Bessell et al. (1998). The reasons why we prefer a single fit for a range in metallicity (rather than different relations for different metallicity) are: *i)* we want to apply this relation to galaxies that contain populations of different metallicities; *ii)* we do not see significant differences for the subsamples of Bessell et al.'s Table 6. For stars with $(R-I) > 0.90$ we obtain the following polynomial fit:

$$BC_I = 1.7103 - 2.2968(R-I) + 1.66464(R-I)^2 \\ -0.43399(R-I)^3,$$

such equation will be used in the next section to determine the population of AGB M stars in each galaxy.

4. Updated properties of AGB star populations

We adopt the integrated apparent visual magnitudes of galaxies as listed by Mateo (1998); their absolute magnitudes are calculated using the extinctions and distances given in Table 2. Table 3 presents a compilation of the calculated M_V for each galaxy, the adopted abundance, the up-dated number of C stars along with their mean magnitude and colour. Comments on each of the adopted [Fe/H] determinations and on the revised selection procedure are outlined below.

Table 3. C star populations in each galaxy.

Galaxy	M_V	[Fe/H]	N_c	$\langle M_I \rangle$	$\langle (R-I)_0 \rangle$	$C/M0+$	$\langle M_{\rm bol} \rangle$
WLM	−14.6	−1.4	147	−4.69	1.103	15.0 ± 7.1	−4.91
IC 10†	−15.6	−0.8	684	–	1.112	0.23 ± 0.02	–
NGC 147	−15.6	−1.0	297	−4.42	1.117	0.30 ± 0.03	−4.66
NGC 185	−15.6	−1.3	162	−4.48	1.108	0.24 ± 0.03	−4.71
NGC 205	−16.7	−0.85	498	−4.53	1.131	0.20 ± 0.01	−4.80
M 31‡	−21.1	−0.7	(780)	−4.55	1.181	0.08 ± 0.004	−4.88
IC 1613	−14.8	−1.2	173	−4.76	1.176	1.48 ± 0.31	−5.08
NGC 3109	−15.7	−1.7	421	−4.77	1.163	1.85 ± 0.21	−5.07
Leo I	−12.1	−1.5	13	−4.68	1.061	6.50 ± 6.40	−4.85
Sgr DIG	−11.0	−2.1	16	−4.96	1.083	4.0 ± 3.0	−5.16
NGC 6822	−15.0	−1.25	927	−4.57	1.190	0.90 ± 0.08	−4.91
DDO 210	−10.3	−1.9	2	−4.91	1.007	0.09 ± 0.08	−5.01
Pegasus	−13.1	−1.1	26	−4.68	1.084	0.62 ± 0.22	−4.88

† The distance modulus for IC 10 was obtained by Demers et al. (2004) from the average I-luminosity of C stars.

‡ The number of C stars refers to the SW1 field (see Battinelli et al. 2003).

WLM: Minniti & Zijlstra (1997) adopt [Fe/H] = −1.45 ± 0.2 from the colour of the red giant branch. Their adopted reddening is identical to ours. Dolphin (2000) gives a lower metallicity for the oldest stars, [Fe/H] = −2.18 ± 0.28 but concluded that few stars formed at this low metallicity. He calculates that [Fe/H] was −1.34 ± 0.14 at the tail end of 3 Gyr. Even though younger stars were found recently to have a much higher abundance (Venn et al. 2003), it seems reasonable to adopt −1.4 for WLM.

IC 10: Data from Demers et al. (2004), $M_V = -15.64$ using de Vaucouleurs & Ables (1965) integrated magnitude. We adopt [Fe/H] = −0.8 based on Garnett's (1990) oxygen abundance of HII regions.

NGC 147: The metallicity comes from the colour of the giant branch as determined by Han et al. (1997). They adopt a $E(B-V)$ from Burstein & Heiles (1984), a value nearly identical to the one given in Table 2.

NGC 185: From the colours of the red giant branch, Lee et al. (1993) determined [Fe/H] = −1.23 ± 0.16 while Martínez-Delgado & Aparicio (1998) determined −1.43 ± 0.15. We adopt a mean value, [Fe/H] = −1.3.

NGC 205: Mould et al. (1984) quote [Fe/H] = −0.85 ± 0.20 from the colour of the red giant branch. Salaris & Cassisi (1998) also obtain −0.9 from a recalibration of the TRGB method.

IC 1613: Salaris & Cassisi (1998) obtain −1.2 from their recalibration of the TRGB method. Skillman et al. (2003) estimate from various SFH models that ~5 Gyr stars have [Fe/H] = −1.2. We adopt this value.

Fornax and Leo I: Recent spectroscopy by Tolstoy et al. (2003) provides abundance for intermediate-age stars. We adopt [Fe/H] = −1.2 for Fornax and −1.5 for Leo I. There are no published I magnitudes for the C stars of Fornax; for this reason Fornax is not listed in Table 3.

NGC 3109: We adopt [Fe/H] = −1.7. Méndez et al. (2002) obtain [Fe/H] = −1.69 ± 0.06, Lee (1993) obtains [Fe/H] = −1.6 ± 0.2 and Minniti et al. (1999) get [Fe/H] = −1.8 ± 0.2, all estimates based on the colour of the RGB.

SagDIG: We adopt the metallicity, [Fe/H] = −2.1 ± 0.2, the reddening and distance given in Table 2 and obtained by Momany et al. (2002).

NGC 6822: This galaxy has several recent abundance estimates. Davidge (2003), from the slope of the RGB in the $(K, J-K)$ CMD, obtains [Fe/H] = −1.0 ± 0.3. Clementini et al. (2003) obtain [Fe/H] = −1.92 ± 0.35 from the average period of ab-type RR Lyrae variables. They mention that this low value is in good agreement with the abundance of one of the old globular clusters of NGC 6822 and must represent the old population. Gallart et al. (1998) obtain [Fe/H] = −1.5 ± 0.3 from the colour of the RGB. From high resolution spectroscopy, Venn et al. (2001) evaluate the abundance of the young population to be [Fe/H] = −0.49. These results suggest that an evident metal enrichment took place among the successive generations in NGC 6822. Since we are dealing with the intermediate-age population, we adopt [Fe/H] = −1.25 ± 0.2.

DDO 210: We adopt the estimate from Lee et al. (1999), based on the colour of the RGB, [Fe/H] = −1.9 ± 0.1.

Pegasus: If one adopts the low reddening alternative for Pegasus, then from Aparicio (1994) we get [Fe/H] = −1.1.

4.1. The number of C stars

The revised number of C stars in each galaxy is given in Table 3. All the targets, with the exception of M 31, have been surveyed over essentially their entire volume. The identification of C stars is based on the so-called Four Band Photometric System, a method pioneered by Richer et al. (1984) and Cook et al. (1986) based on a combination of two broad-band and two narrow-band filters. In our survey we use the R, I, CN, TiO system (see Albert et al. 2000). Since C stars are selected on the basis of their $(R-I)_0$ and (CN – TiO) colour indices, a knowledge of the colour excess $E(R-I)$ is needed (note that the effect of reddening on the (CN – TiO) colours is in most cases negligible, see Battinelli & Demers 2000). Minor differences from the published number of C stars and those listed in Table 3 result from: 1- the update of C star counts using the Schlegel et al. (1998) reddening law rather than the Rieke & Lebofsky (1985) one (see Sect. 2); 2- the adoption of new estimates for the reddening that appeared after the publication of our papers. The large differences in the numbers of C stars for IC 1613 and Pegasus arise from the adoption of a photometric error threshold $\epsilon = \sqrt{e^2_{(R-I)} + e^2_{(\mathrm{CN-TiO})}} = 0.125$. Again, this is necessary to standardize the adopted error threshold for all the galaxies.

Contrary to M star counts which, as we will see in the next sub-section, require a careful correction for the foreground contamination, C star counts do not. Indeed, the foreground contamination for cool C stars (N-type) in the galactic halo is essentially nil. The nearby dwarf carbon stars, having a surface density of one star per 20 square degrees, are also negligible (Downes et al. 2004). NGC 205 is a special case being seen behind the disc of M 31 and thus significantly contaminated by M 31 C stars. For this galaxy the observed N_C has been corrected using the C-star radial density in the outer disc of M 31 as determined by Battinelli et al. (2003).

4.2. The number of AGB M stars

M stars are selected from the colour–colour plane as those stars with (CN – TiO) < 0 and $(R-I)_0 > 0.9$. Two steps are needed to evaluate the number of AGB stars belonging to the target galaxies: 1) select only AGB stars (see Battinelli et al. 2003); 2) correct the sample for galactic M dwarf contamination which for low latitude galaxies is far from negligible. The first step is accomplished by adopting a lower limit for the AGB star bolometric magnitudes of $M_\mathrm{bol} = -3.5$, i.e. the standard luminosity for the tip of the red giant branch. The number of M AGB stars thus depends on the adopted BC which, in our case, is obtained through the relation given in Sect. 3.3. The foreground contamination is generally estimated using one or more control field(s) outside the target galaxy. To determine the number of AGB M stars in NGC 205 we count these stars in the 10′ core and estimate the number of foreground M stars by averaging their numbers in two similar areas on both sides the galaxy. For a detailed description of this step for each galaxy we refer the reader to the papers listed in Table 1.

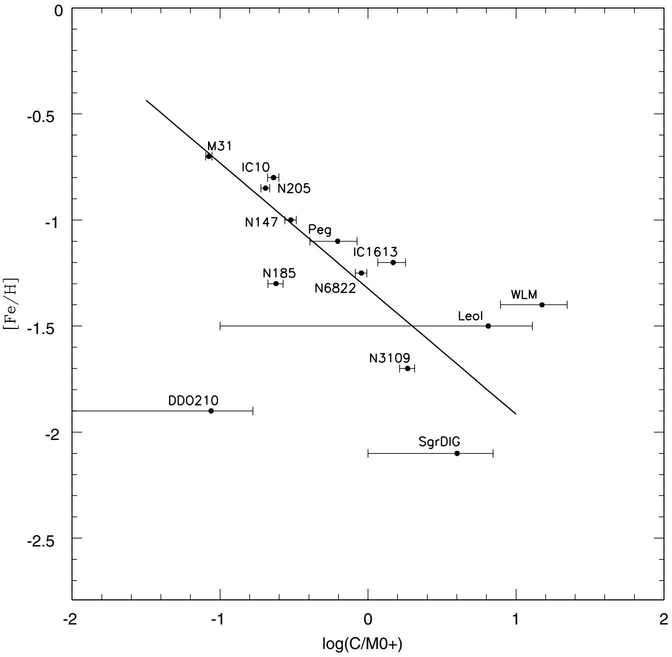

Fig. 3. The metallicity of galaxies as a function of their C/M ratio.

The C/M ratio is expected to be more sensitive to the metallicity when only late M-type stars are selected. In light of the discussion in Sect. 3.2 we know however that the selection of M3+ or M5+ samples on the basis of the $(R-I)$ or $(V-I)$ color indices is quite unsatisfactory. For this reason we keep our adopted threshold of $(R-I)_0 = 0.90$ which is a reasonable compromise to include a large fraction of M 0 stars without polluting the sample with warmer and fainter K stars. More precisely, with this limit we lose 15% of the M 0 stars plotted in Fig. 2.

5. The C/M vs. metallicity relation

The log(C/M0+) relation, where the foreground contamination from Galactic M stars has been carefully evaluated for each galaxy, is presented in Fig. 3 as a function of the adopted respective abundance listed in Table 3. Errors bars account for the statistical fluctuations of the numbers of both C and M stars and do not include the contribution due to the uncertainty in the galaxies' distance moduli.

The straight line is a weighted least square fit ($w_i = \frac{1}{e_i^2}$, being e_i the relative error of C/M0+). We neglect the uncertainties in the adopted [Fe/H]. The fit yields:

$$[\mathrm{Fe/H}] = -1.32(\pm 0.07) - 0.59(\pm 0.09) \times \log\left(\frac{C}{\mathrm{M0+}}\right),$$

with a correlation coefficient of $r = 0.90$. We note that this equation remains unchanged when the statistically poorly known C/M0+ for DDO 210 (with only two known C stars) is removed. Of course, this is also due to the weighting in the least square fit procedure. Even though we get a very good correlation coefficient, a closer look at the plot reveals that metal-poor galaxies show a much larger scatter than galaxies with [Fe/H] > −1.5. Low metallicity galaxies have in general low masses and therefore very few cool AGB stars. Small numbers of C and M stars imply large statistical uncertainties for their C/M ratios, thus making particularly difficult the calibration of the low–metallicity end of the [Fe/H] – C/M relation. In this respect, it would be extremely valuable to observe a luminous galaxy with a very low metallicity.

The correlation between [Fe/H] and the C to M ratio often has been predicted by theoretical models and explained by two effects: the paucity of M stars in metal-poor systems and the ease of reaching C/O > 1 in metal-poor stars. Models by Mouhcine & Lançon (2003) also suggest a similar behavior. The C/M ratio is highly dependent on the M spectral-type limit which, for theoretical models, depends on the stellar radius. Any slight error on the latter leads to errors in the computed C/M ratios (Izzard et al. 2004). Mouhcine & Lançon (2003) compute their theoretical C/M5+ setting a lower limit of $(V-I) = 2.0$ for the theoretical colour. As discussed in Sect. 3.2, this limit seems to correspond to M 1–M 3 stars. Since we adopt $(R-I)_0 = 0.9$, corresponding to M0 stars, for any given metallicity, as expected, our C/M ratio is found to be systematically lower than their predicted value.

6. Discussion

It is important to stress once more that the well-defined relation shown in Fig. 3 results form the internal homogeneity of the sample rather than from C/M estimates more accurate than those available in the literature. In other words, we are not claiming that the latter are necessarily wrong, rather that they differ substantially from ours. To demonstrate this statement we present in Fig. 4 a C/M compilation from the literature. The Magellanic Clouds are from DENIS data by Cioni & Habing (2003). NGC 55, NGC 300 and NGC 2403 are pioneering results obtained with small CCDs by Pritchet et al. (1987), Richer et al. (1985) and Hudon et al. (1989). As mentioned in Sect. 3.2, even though their C/M are presented as C/M5+, their $(V-I)$ colour limit corresponds to M0+. M 31 is from Brewer et al. (1995). NGC 147 and NGC 185 were surveyed by Nowotny et al. (2003). Harbeck et al. (2004) provided a further estimate for NGC 147 (identical to Nowotny et al.) and for And VII. The Fornax C/M ratio is an estimate by Groenewegen (2002). Finally, for M 33 we use the recent results by Rowe et al. (2005). More precisely we adopt their value in the radial range 10′–20′ where Galletti et al. (2004) provide a reliable estimate of the [Fe/H]. It is evident from Fig. 4 that the majority of the points do not fit our relation and seem to suggest the opposite trend (which of course contrasts with theoretical predictions). Such marked disagreement arises from several causes: 1- differences in the photometric definition of C stars (narrow band photometry, near IR, etc.); 2- differences in the C- and M-boxes in the colour–colour diagram; 3- differences in the selection of M-AGB stars (which may also involve differences in the adopted BCs); 4- M-AGB foreground corrections for pollution by Galactic dwarf and giant M stars; 5- deep enough photometry to detect all the very red M stars (particularly important when V, rather than R, is used).

It is not surprising that M 31 and M 33 fall very close to our relation. Indeed, in our survey we followed the prescriptions established by Brewer et al. (1995) with the only difference being the use of R rather than V. Furthermore, their colour threshold $(V-I)_0 = 1.8$ corresponds exactly to our $(R-I)_0 = 0.90$ (see Fig. 1). Rowe et al. (2005) also adopted Brewer's methodology.

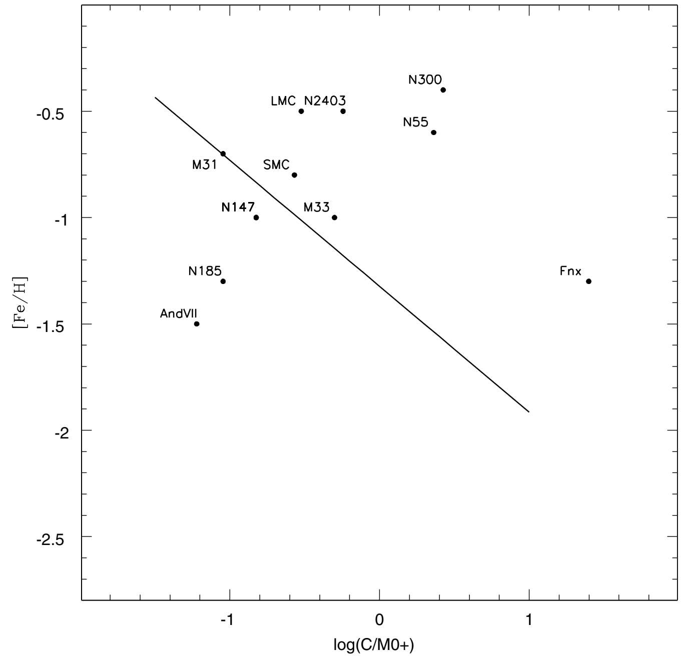

Fig. 4. The metallicity of galaxies as a function of their C/M ratio from data available in the literature other than ours. The line is the fit drawn in Fig. 3.

In the light of the above consideration we feel that one aspect of the C/M – [Fe/H] calibration is accurately known. The major uncertainties at the moment are related to the adoption of a representative metallicity for each galaxy. The "metallicity of a galaxy" is an elusive parameter because galaxies are chemically evolving and contain multiple populations. For most of the Local Group galaxies the [Fe/H] is obtained from the position or the slope of the red giant branch, thus representing the metallicity of the oldest population. Planetary Nebulae are also used to determine the metallicity of a somewhat younger population while the oxygen abundance in HII regions provides the abundance of the young population. Only very recently metallicity determinations based on high resolution spectroscopy of individual supergiants in nearby galaxies have been obtained (see e.g. Venn et al. 2001). Of course, attempts to link [Fe/H] to the C/M ratio need to address the fact that metallicity estimates well suited for the intermediate-age population are lacking.

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