1 AGB stars in the Local Group, and beyond

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1.1 Introduction

Carbon stars are tracers of the intermediate age population in galaxies. Either they are currently undergoing third dredge-up on the (Thermal-Pulsing) Asymptotic Giant Branch (TP-AGB) – the cool and luminous N-type carbon stars (or the "infrared carbon stars", when they are significantly reddened by circumstellar dust through mass-loss) –, or have been enriched with carbon-rich material in a binary system when the present-day white dwarf was on the AGB (the carbon dwarfs and CH-stars. The R-stars may be the result of a coalescing binary [McClure 1997]).

Similarly, there are "intrinsic" and "extrinsic" S-stars which represent, respectively, the stars currently on the AGB, and the stars polluted by a present-day white dwarf (e.g. Jorissen 2003).

Next to the classical oxygen-rich giants (of spectral type M and MS), there are the OH/IR stars (which are obscured by circumstellar dust) and the Barium-dwarfs and Barium-giants which are polluted by a present-day WD (e.g. Jorissen 2003).

Since their spectral signature is very different from oxygen-rich and S-type stars, it is relatively easy to identify carbon stars even at large distances. In Sect. 1.2 the main technique to identify carbon stars is briefly discussed, and various recent surveys for carbon stars in external galaxies are summarised. That section is an update of reviews I gave at IAU Symposium 191 (Groenewegen 1999; hereafter G99), and a Ringberg conference (Groenewegen 2002; hereafter G02), and here I will only refer to new results published since then. Please refer to G99, G02 and the similar review by Azzopardi (1999) for the full story. Sections 1.3 and 1.4 discuss aspects related to NIR work and variability properties of AGB stars in LG galaxies.

1.2 Optical narrow-band imaging

This has been discussed in some detail in G99. Briefly, the most effective method for large scale surveys of late-type M- and C-stars uses typically two broad-band filters from the set V, R, I, and two narrow-band filters near 7800 and 8100 Å, which are centred on a CN-band in carbon stars, and a TiO band in oxygen-rich stars, respectively. In an [78-81] versus $[V - I]$ (or $[R - I]$) colour-colour plot, carbon stars and late-type oxygen-rich stars clearly separate redwards of $(V - I) \approx 1.6$. For an illustration of this, see Cook & Aaronson (1989) or Nowotny & Kerschbaum (2002).

A caveat is that, unfortunately, not all groups adopt the same "boxes" in these diagrams to select M- and C-stars (e.g. compare Nowotny et al. 2003 and Battinelli & Demers et al. 2004b). Furthermore, in many cases, only the photometry is published for the stars the respective authors consider to be the M- and C-stars, so it is not possible to apply ones own selection criteria a-posteriori. Furthermore, one usually applies the same lower-limit on the broad band colour ($(V-I)$, or $(R-I)$) to select M-stars (usually chosen to correspond to M0 and later for solar metallicity) to C-stars, while it is known (e.g. Nowotny & Kerschbaum 2002)) that the hottest C-stars (spectral type C0) are bluer than this limit. So, applying the same lower-limit on the broad-band colour will bias against the hottest C-stars.

1.2.1 Surveys

In this section the (recent, post-2002) surveys for carbon stars in external galaxies are described.

<u>M31</u>

Battinelli et al. (2003) present results on a 2240 arcmin^2 area in the SW disk of M31, identifying 945 carbon stars and estimating a C/M ratio of 0.084. Previous work has been mentioned in G99 and G02.

<u>NGC 205</u>

Demers et al. (2003a) detect 289 carbon stars inside an 10 arcmin ellipse around NGC 205, and estimate that the actual total number is between 500 and 550, the difference being due to a lack of detections near the centre (their figure 6) due to crowding and increased photometric error. A C/M ratio of 0.09 is estimated.

Davidge (2003) present JHK results on a 3.6 arcmin^2 centred on NGC 205, and he kindly provided the K-band fits image and object list. I derived the WCS information by identifying objects on a 2MASS K-image resulting in astrometry with an rms of 0.21 and 0.30 arcsec in RA and DEC using 18 objects over the entire field. Figure 1.1 shows the K-image with plotted on top the known C-stars from Demers et al., and candidate AGB stars ($(J-K) > 1.5$ and $K < 17.2$) from Davidge.

Even in the outer annulus, where Demers et al. suggest that their survey is not hampered by crowding, there are many candidate AGB stars based on JK colours and magnitudes. Second, as both papers quote a seeing of 0.7 arcsec, it illustrates the power of infrared observations.

Of the 25 known C-stars, 23 have a counterpart in the Davidge dataset (although not all have $(J-K) > 1.5$ and $K < 17.2$). The remaining two are all visible on the K-image; one is on the edge of the frame, and the second was missed in the source detection/extraction.

One interesting exercise is to compare the bolometric magnitudes derived from JK, with those derived from RI photometry. This comparison is shown in Figure 1.2 both on a star-by-star basis and in the form of luminosity functions. Although these stars are expected to be LPVs (hence variable) the data suggests possible systematic effects, which warrants further investigation.

Table 1.1. The carbon star census

Name	D (kpc)	M_V (mag)	[Fe/H]	N_C [(b)]	Area[(c)] (kpc^2)	N_M [(d)]
M31	770	–21.2	0.0	243	12.3	789 (5+)
Galaxy[(a)]		–20.9	0.0	81	1.00	C/M ≈ 0.2
M33	840	–19.0	–0.6	15	0.20	5 (5+), 60 (0+)
LMC	50	–18.5	–0.6	1045	4.8	1300 (5+)
				7750	220.	
SMC	63	–17.1	–1.2	789	5.4	180 (5+)
				1707	12.2	
NGC 205	830	–16.4	–0.8	525	12.3	5830 (0+)
NGC 6822	490	–16.0	–1.2	904	4.5	941 (0+)
NGC 3109	1360	–15.7	–1.7	446	33	250 (0+)
NGC 185	620	–15.6	–0.8	145	4.5	850 (0+)
IC 1613	715	–15.3	–1.4	195	7.8	35 (5+), 300 (0+)
NGC 147	755	–15.1	–1.1	288	25.	1200 (0+)
SagDSph	28	–15.0	–0.5	26	7.2	
WLM	930	–14.4	–1.5	149	17.0	12 (0+)
Fornax	138	–13.1	–1.2	104	1.35	4 (5+), 25 (2+)
Pegasus	760	–12.9	–2.0	40	1.04	77 (0+)
SagDIG	1060	–12.0	–2.3	16	0.58	
Leo I	250	–11.9	–1.4	23	0.45	1 (5+), 15 (0+)
And I	790	–11.8	–1.4	0	0.33	
And II	680	–11.8	–1.5	8	0.35	1 (0+)
And III	760	–10.2	–1.7	0	0.66	
And V	810	–9.1	–1.9	0	0.66	
And VI	775	–11.3	–1.7	1	0.41	
And VII	760	–12.0	–1.5	3	0.24	
DDO210	950	–10.9	–1.9	3	0.18	1 (0+)
Leo II	205	–10.1	–1.6	8	0.47	
Cetus	775	–10.1	–1.7	1	1.1	
Sculptor	88	–9.8	–1.5	8	0.65	40 (2+), 0 (5+)
Phoenix	405	–9.8	–1.9	2	0.40	
Tucana	870	–9.6	–1.7	0	0.22	
Sextans	86	–9.5	–1.9	(0)		
Draco	79	–9.4	–2.0	6	0.50	
Carina	94	–9.4	–1.8	11	0.31	
Ursa Minor	69	–8.9	–1.9	7	0.58	
NGC 2403	3390	–20.4	0.0	4	2.0	7 (0+)
NGC 300	2170	–18.7	–0.4	16	3.2	23 (0+), 6 (5+)
NGC 55	1480	–18.0	–0.6	14	2.8	6 (5+)

[a]. In the solar neighbourhood per kpc^2 (Groenewegen et al. 1992)
[b]. Number of known carbon stars.
[c]. Survey area at the assumed distance of the galaxy.
[d]. Number of M-stars. 0+ indicates M0 and later, etc.

It might be recalled in this respect that one advantage of using VI instead of RI as broad-band colours is the fact the bolometric correction to I based on

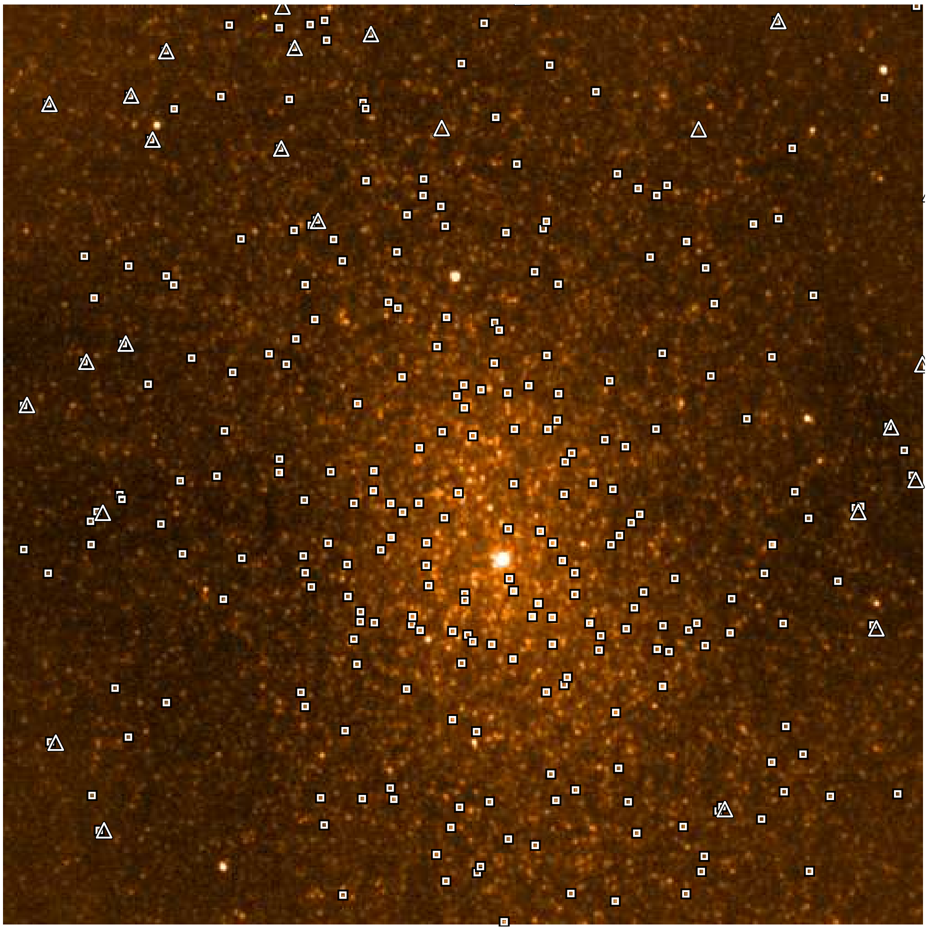

Fig. 1.1. NGC 205 in the K-band (Davidge 2003, FOV of 3.6 arcmin^2): known carbon stars from Demers et al. (triangles) and objects with $(J-K) > 1.5$ and $K < 17.2$ from Davidge (squares).

$(V-I)$ has much less scatter than the one based on $(R-I)$ (Bessell & Wood 1984).

NGC 3109

Demers et al. (2003b) present the first survey of this galaxy using the narrow-band filter technique and detect 446 C-stars, and derive a C/M ratio of about 1.8

NGC 147 & NGC 185

Nowotny et al. (2003) and Battinelli & Demers (2004b,c) independently present data on these two companions to M31, while Harbeck et al. (2004) observed NGC 147. Nowotny et al. find 146 C-stars and a C/M ratio of 0.15 in NGC 147, and 154 and 0.089 in NGC 185, respectively, over an un vignetted FOV of approximately 33 arcmin^2. Battinelli & Demers (2004c) find 288 C-stars and a C/M ratio of 0.24 for NGC 147 and Battinieli & Demers (2004b) find 145 C-

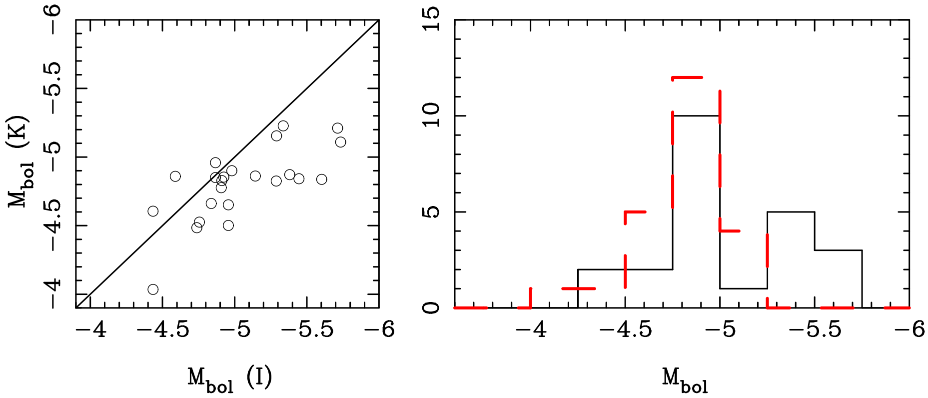

Fig. 1.2. Bolometric magnitudes for the 23 C-stars in common between Demers et al. (solid histogram) and Davidge (dashed histogram) for NGC 205, based on *JK* and *RI* photometry and standard bolometric correction formulae.

stars and a C/M ratio of 0.17 for NGC 185, both over an area of 1180 arcmin^2. Figure 3 in Battinieli & Demers (2004b) shows that most of their C-stars are located in the main body of NGC 185, which is still well covered by the smaller FOV of the Nowotny et al. observations. This is consistent with the very similar numbers of C-stars discovered in both surveys. On the contrary, the difference in number of C-stars detected between the two datasets in the case of NGC 147 is–at least in part–due to the difference in areal coverage of this galaxy and the more extended distribution of the C-stars. Harbeck et al. (2004) find 155 C-stars in their 92 arcmin^2 FOV.

And III, V, VI, VII

Harbeck et al. (2004) also observed And III, V, VI, VII to derive, respectively, 1, 0, 2, 5 C-stars, of which, respectively 0, 0, 1, 3 are believed to be genuine AGB C-stars, while the others are suggested to be low-luminosity CH-stars.

WLM

Battinelli & Demers (2004a) observe a 42 x 28 arcmin field centred on WLM to find 149 C-stars, and to derive a C/M ratio of 12.4 ±3.7.

Cetus

Harbeck et al. (2004) also observed the Cetus dwarf spheroidal to find 1 genuine AGB C-star, and 2 CH-stars.

Table 1.1 summarises the number of known carbon stars in external galaxies. Local Group members not explicitly mentioned have no published information on their C-star population. The last three entries are galaxies outside the Local Group. Listed are the adopted distance, absolute visual magnitude, metallicity (these three parameters come from Grebel et al. (2003), Mateo (1998) and van den Bergh (2000)), number of known carbon stars, the surface area on the sky of the respective survey, and the number of late-type M-stars, when known

In the near future one may expect new results from the optical narrow-band imaging technique for Carina, Sculptor, Phoenix (Groenewegen et al.), IC 10

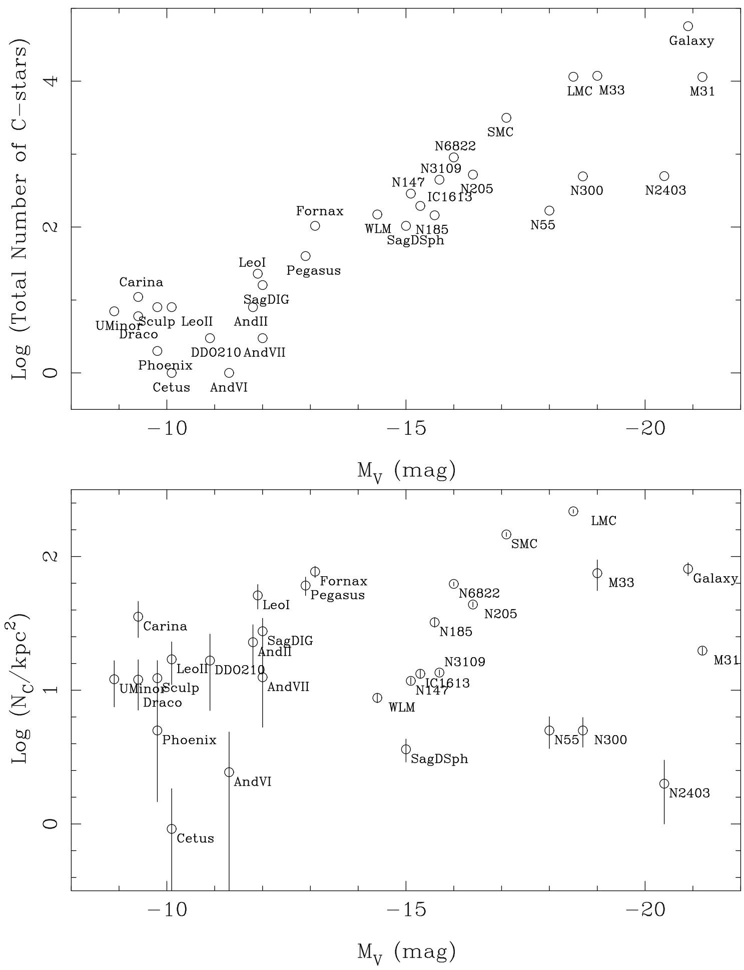

Fig. 1.3. Total number of carbon stars and surface density of carbon stars versus M_V. No correction for inclination effects has been made.

(Demers, Battinelli), and And II, M32, Leo I, Leo II, Draco, Ursa Minor (Kerschbaum, Nowotny, Olofsson, Schwarz). This last group also acquired funds to put these filters on the 4.1m SOAR (Southern Astrophysical Research) telescope.

1.3 Near-infrared results

The comparison between the optical narrow-band imaging and near-infrared observation of NGC 205 in the previous section already demonstrated the power of the latter. A disadvantage of broad-band NIR observations is that no distinction between M- and C-stars can be made, although one often sees in the literature the assumption that stars redder than $(J-K)_0 \sim 1.4 - 1.6$ are carbon stars. This is an oversimplification, as dust-obscured (mass-losing) M-stars can have

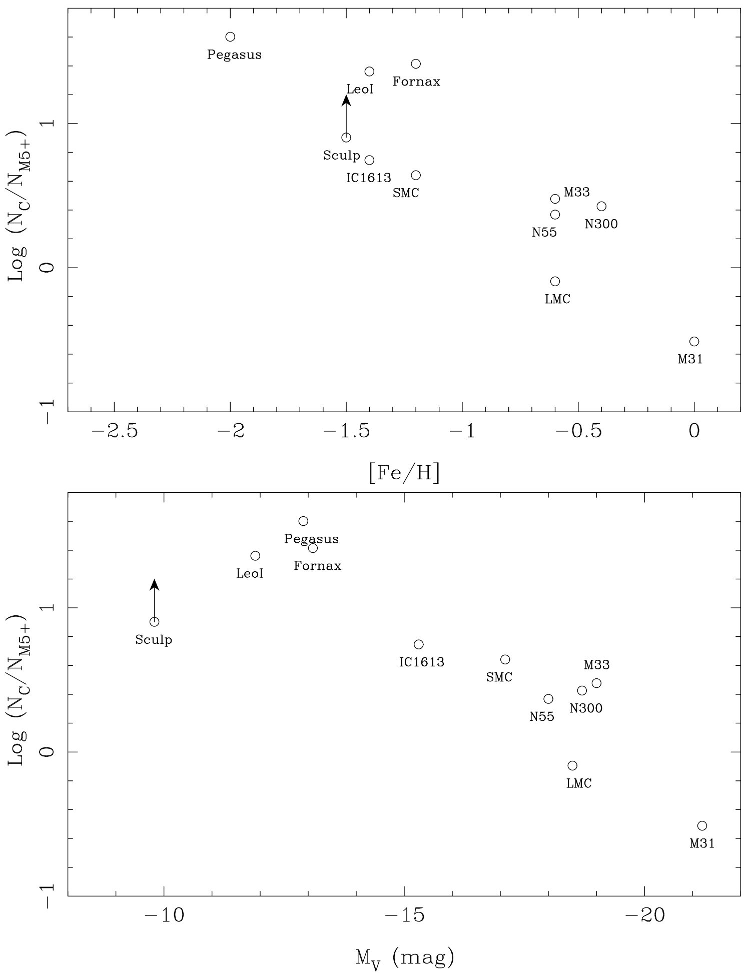

Fig. 1.4. Log (number carbon stars / number late M-stars) versus metallicity and $M_{\rm V}$.

red colours, and more importantly, hotter C-stars have NIR colours that overlap with the photospheric colours of M-giants (e.g. figure 2 in G02).

The release of the 2MASS database (as well as DENIS data) has had a large impact on the study of AGB stars in the Magellanic Clouds (MCs), e.g. Cioni & Habing (2003), but results have also been presented for Fornax (Demers et al. 2002, G02), and the counterparts of optically known C-stars at the time of the 2MASS *second data release*. More recently, an undergraduate has investigated the 2MASS data of the *all-sky release* for all LG galaxies within 1 Mpc (excluding MCs, M31, M32), and retaining objects with $(J-K)_0 > 1.22$, appropriate $M_{\rm K}$-range for AGB stars, and excluding known objects using the SIMBAD database (Marescaux 2003). Table 1.2 compares the number of resulting candidate AGB stars (C-stars and dust-obscured M-stars) to the number of known C-stars. For galaxies beyond ∼300 kpc the number of candidates becomes very

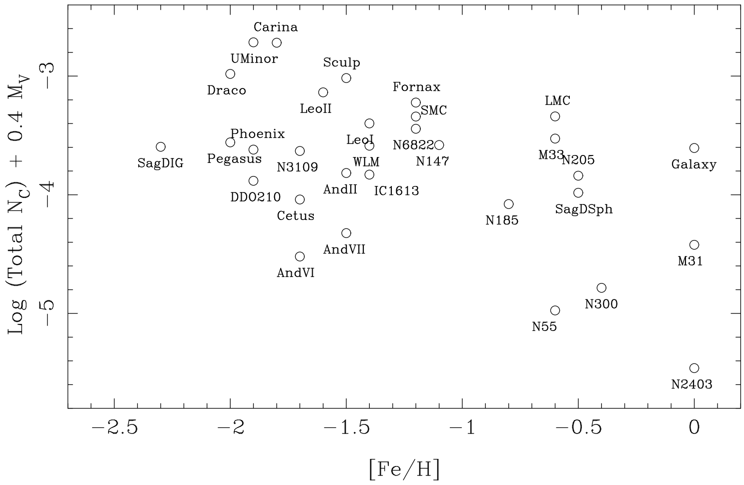

Fig. 1.5. Log (number of carbon stars / total visual luminosity) versus metallicity.

small and is limited by the survey limit of 2MASS, restricting the candidates to the intrinsically most luminous ones. For the more nearby galaxies the limiting magnitude of 2MASS is not a limiting factor and one observes that the number of candidates is a non-negligible fraction of the number of known C-stars, again indicating the power of IR observations to provide a complementary picture to the optical narrow-band imaging.

In the near future deeper ground-based IR observations will become available. Several groups are observing or even monitoring LG galaxies, e.g. Fornax, Leo I, Leo II, Carina, Sculptor, Phoenix, Sextans by E. Held using SOFI; Leo I, Fornax, (all smaller LG) using the SIRIUS camera on the IRSF (e.g. Menzies et al. 2002), NGC 6822 using the new CPAPIR camera on the CTIO 1.5m (Demers, Battinelli), Leo A, Leo I, Leo II, Sex B, NGC 6822, Draco, NGC 147, NGC 185 using INGRID on the WHT (Cioni & Habing, e.g. this conference).

Another exciting possibility is to use narrow-band filters in the NIR. A first example was recently presented by Östlin & Mouhcine (2004) who observed a 14 x 14 arcsec field in the metal-poor ([Fe/H]= -1.7) galaxy IZw 18 (at a distance modulus of 30.5 !) using the NICMOS F171M and F180M filters. In a carbon star the F171M filter is located in the continuum while the F180M is centred on a deep CN band at 1.77 μm. Combining this with a broad-band F160W there were able to identify 5 C-stars, 1 M-type AGB and 20 supergiants.

1.4 Variability

One of the characteristics of AGB stars is that they are variable on different timescales and amplitudes, as has been clearly revealed by the mircolensing surveys of the Magellanic Clouds and Galactic Bulge (e.g. Wood et al. 1999, Wood 2000). It has been found that variable AGB stars occupy different sequences

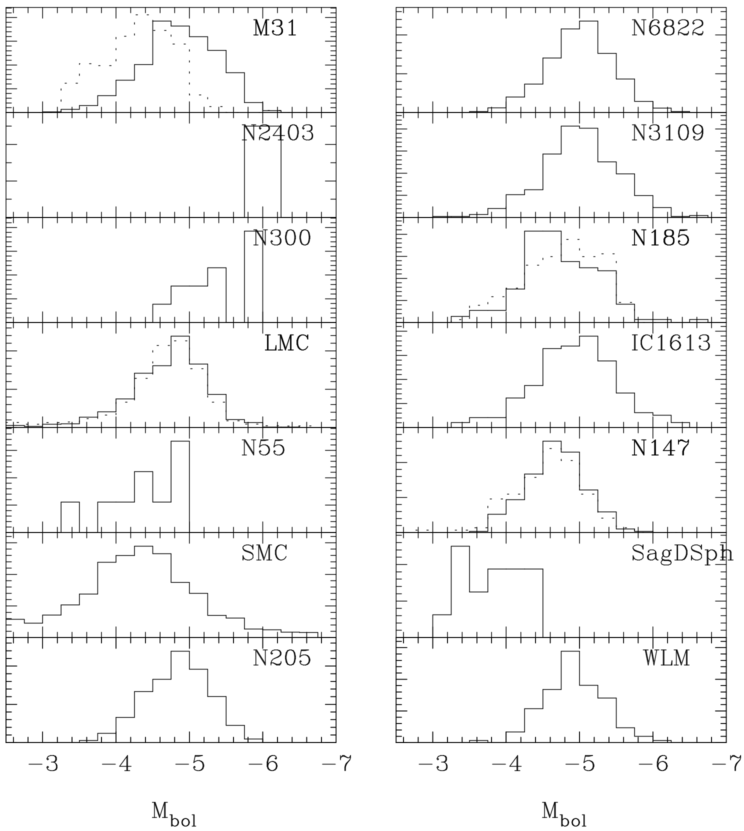

Fig. 1.6. Normalised carbon star luminosity functions, ordered by decreasing M_{V} of the galaxies, ordered top to bottom, left to right. Number of C-stars used to calculate the LFs varies from galaxy to galaxy (see Table 1.1. In the case of SMC and LMC, the lowest luminosity bin is cumulative. For M31 data from Battinelli et al. (2003, solid) and Brewer et al. (1995, dashed), for the LMC from Costa & Frogel (1996, solid) and Kontizas et al. (2001, dashed), for NGC 185 from Battinieli & Demers (2004b, solid) and Nowotny et al. (2003, dashed), for NGC 147 from Battinelli & Demers (2004c, solid) and Nowotny et al. (2003, dashed), are plotted. For the LMC, NGC 147 and NGC 185 these independent LFs are in good agreement. The difference for M31 appears to be real and related to the fact that these LFs have been derived for (a) field(s) that have different locations along the major axis of M31.

(usually labelled ABCD) in period-luminosity diagrams, with the large amplitude Mira variables on sequence C.

In G02, some earlier work on (candidate) variable AGB stars in the SagDSph, Fornax and IC 1613 was reported. Since then, Snigula et al. (2004) mention 16 candidate LPVs (Long Period Variables) in Leo A, and 5 in GR 8, Gallart et al. (2004) propose 6 LPV candidates in Phoenix, and Rejkuba (2004) present a K-band PL-relation for 240 well defined Miras in NGC 5128.

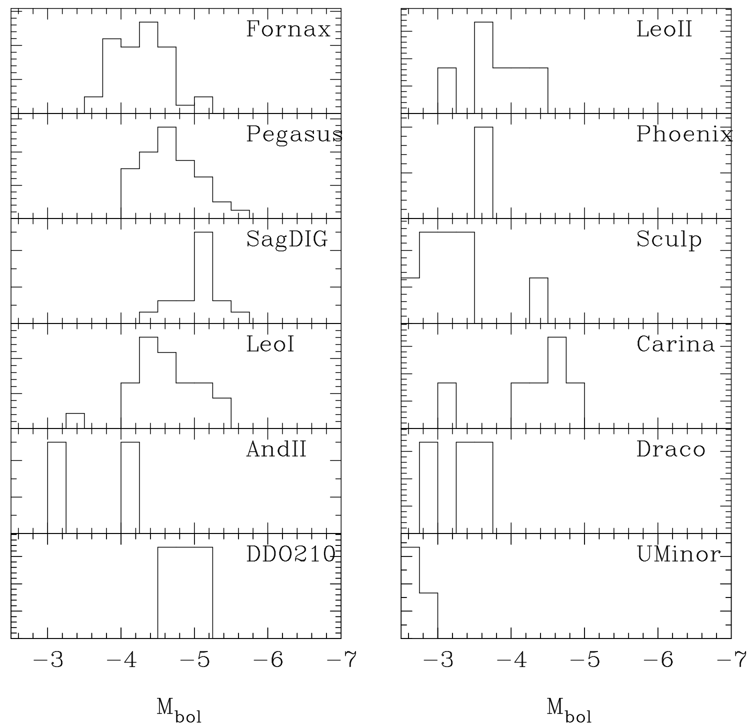

Fig. 1.7. Continued.

Table 1.2. Candidate IR AGB stars based on 2MASS compared to the number of known C-stars

Name	D (kpc)	$N_{2\mathrm{mass}}$	N_{C}	Name	D (kpc)	$N_{2\mathrm{mass}}$	N_{C}
Ursa Minor	69	8	7	NGC 6822	490	6	904
Sculptor	79	8	8	LGS 3	620	1	?
Draco	82	6	6	IC 10	660	9	?
Sextans	86	10	(0)	IC 1613	720	3	195
Carina	100	6	11	NGC 147	755	1	288
Fornax	138	34	104	And I	790	1	0
Leo II	205	1	8	Leo A	800	2	?
Leo I	250	2	23	Tucana	870	1	0

1.5 Discussion

Figures 1.3, 1.4, 1.5, 1.6, 1.7 are updates of those in G02, and for lack of space I refer to the last section in G02 for additional details.

Figure 1.3 shows the number of carbon stars in a galaxy versus M_{V} represented in two ways. First, the total number of C-stars in a galaxy was estimated by simply multiplying the known number by the ratio of total surface area of a galaxy to the survey area. As for some galaxies the survey area is less than a few percent, this correction factor can be quite large (and uncertain). To circumvent this, the bottom panel shows the surface density of carbon stars in the particular survey. The drawback of this approach is that it does not take into account the spatial variation of the density of carbon stars within a galaxy. In neither approach did I correct for the fact that we do not see these galaxies face-on. Some interesting things can be noticed. There is a clear relation between the (estimated) total number of C-stars and $M_{\rm V}$, and there seems to be a maximum surface density of about 200 kpc^{-2} averaged over a galaxy. In both plots NGC 55, 300 and 2403 are clear outliers. These are the most distant galaxies surveyed, and one might suppose that the surveys have been incomplete. For NGC 55 the explanation probably lies as well in the fact that we see this galaxy almost disk-on, and so both the total number as well as the surface density have been underestimated. Reddening within the galactic disk of the galaxy can also play a role. For NGC 2403 the small number of carbon stars lies in the fact that the survey has been incomplete. All 4 known C-stars have luminosities that are much higher than the average in galaxies for which we know the LF in more detail. The same is true for NGC 300.

Figure 1.4 shows the ratio of C- to late M-stars. The interpretation of the well known trend is that a star with a lower metallicity needs fewer thermal pulses to turn from an oxygen-rich star into a carbon star.

Figure 1.4 shows the ratio of the total estimated number of carbon stars over the visual luminosity of the galaxy. Most of the galaxies scatter between a value of –3 and –4, with a few outliers which are the same as noticed in Fig. 1.3.

Figures 1.6 and 1.7 shows the C-stars bolometric LF for the galaxies for which it could be constructed. The data show that in well populated LFs, the mean $M_{\rm bol}$ is between –4 and –5. It also shows that the mean in NGC 300 and NGC 2403 is much higher. Unless one would invoke a large uncertainty in the distance or a burst of recent star formation, the most natural explanation lies in the incompleteness of the surveys in these distant galaxies. Finally, the data shows that in the fainter galaxies the mean magnitude increases and that a fair number of C-stars are of the low-luminosity type.

In a recent paper Mouhcine & Lançon (2003) present evolutionary population synthesis models, including chemical evolution, with special focus on intermediate age populations. Their models are the first that are able to account for the observed trend in Fig. 1.4 adopting ‘typical’ SFH for Sa, Sb, Sc and Irr Hubble type galaxies. The AGB phase is included through a semi-analytical treatment of the third dredge-up, with efficiency parameters set to values that have been determined in other studies to fit the LMC carbon star LF and C/M ratio.

1.6 Conclusion

In principle, the overall carbon star LF and C/M ratio contains information about the star-formation rate history from, say, 10 Gyr ago (the low-luminosity C-stars in binaries) to a few-hundred Myr ago (the high luminosity tail of the LF). Its a challenge to theoretical models to use these constraints together with other data to derive the chemical evolution and star formation history of these galaxies. The models of Mouhcine & Lançon represent a first successful step in this direction.

Acknowledgments

I would like to thank Tim Davidge for providing the K-band fits image and his list of detections for NGC 205, and Pierre Royer (KUL) for helping in deriving the WCS parameters.

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