A&A 403, 93–103 (2003)
DOI: 10.1051/0004-6361:20030282

Astronomy & Astrophysics

A census of AGB stars in Local Group galaxies⋆,⋆⋆

II. NGC 185 and NGC 147

W. Nowotny[1], F. Kerschbaum[1], H. Olofsson[2], and H. E. Schwarz[3]

[1] Institut für Astronomie der Universität Wien, Türkenschanzstraße 17, 1180 Wien, Austria
[2] SCFAB, Stockholm Observatory / Department of Astronomy, 106 91 Stockholm, Sweden
[3] Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile

Received 13 December 2002 / Accepted 25 February 2003

Abstract. We present results of our ongoing photometric survey of Local Group galaxies, using a four filter technique based on the method of Wing (1971) to identify and characterise the late-type stellar content. Two narrow band filters centred on spectral features of TiO and CN allow us to distinguish between AGB stars of different chemistries [M-type (O-rich) and C-type (C-rich)]. The major parts of two dwarf galaxies of the M 31 subgroup – NGC 185 and NGC 147 – were observed. From photometry in V and i we estimate the tip of the RGB, and derive distance moduli respectively. With additional photometric data in the narrow band filters TiO and CN we identify 154 new AGB carbon stars in NGC 185 and 146 in NGC 147. C/M ratios are derived, as well as mean absolute magnitudes $\langle M_i \rangle$, bolometric magnitudes $M_{\rm bol}$, luminosity functions, and the spatial/radial distributions of the C stars in both galaxies.

Key words. stars: AGB and post-AGB – stars: carbon – galaxies: Local Group – galaxies: individual: NGC 185, NGC 147 – surveys

1. Introduction

Our first paper on this topic, Nowotny et al. (2001, in the following called Paper I), presented a search for Asymptotic Giant Branch (AGB) stars in M 31, and gave a motivation as to why it is important to study such stars in galaxies of the Local Group. Here we briefly summarise the most important points.

AGB stars are evolved stars with low to intermediate masses ($\approx$ 0.8–8 $M_\odot$), which have already experienced core helium-burning and appear as late-type giants in colour-magnitude diagrams (CMDs) of stellar populations. They are characterised by long-period pulsations, strong stellar winds (leading to high mass loss rates), and a change of their chemical atmospheric compositions from O-rich to C-rich (spectral type M→C) under certain circumstances (thermal pulses, convection) during their evolution. Because of their intrinsically high luminosities of up to a few 10^4 $L_\odot$, and their enormous sizes, AGB stars are among the brightest and coolest (reddest) stars in old stellar populations. They contribute significantly to the integrated light of distant galaxies, especially in the NIR (Mouhcine & Lançon 2002). Within the galaxies of the Local Group that can be resolved into single stars due to their proximity, they form an important subsample and can easily be detected individually. On the one hand these AGB stars can give us clues about the populations (extensions, distance estimates, and kinematics of extragalactic systems, etc.), and on the other hand, by observing whole samples of stars in extragalactic systems rather than single galactic stars, one has the advantage of large numbers and the known properties of the system (type, distance, metallicity) to get information about global AGB properties and evolution. Large samples of extragalactic AGB stars are needed for this in general.

Of special interest are AGB stars of spectral type C (that is stars with an abundance of C higher than that of O, C/O $\geq$ 1), which are located close to the tip of the AGB and have very characteristic spectra (dominated by carbon species, such as CN), that differ strongly from M-type spectra (stars with an abundance of C lower than that of O, C/O $\leq$ 1, and hence their spectra are dominated by oxides, such as TiO). These very bright and red stars are typical representatives of the intermediate-age population, and can serve as standard candles because of their narrow luminosity function or can be used as probes of galaxy dynamics (Dejonghe & van Caelenberg 1999), as has been done e.g. for the Magellanic Clouds (van der Marel et al. 2002; Hatzidimitriou et al. 1997 or

Send offprint requests to: W. Nowotny,
e-mail: nowotny@astro.univie.ac.at

⋆ Based on observations made with the Nordic Optical Telescope operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

⋆⋆ Table A.1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strabg.fr/cgi-bin/qcat?J/A+A/403/93

Kunkel et al. 1997). Also, they can be used as a tracer for the extent of a galaxy, as no contamination by foreground stars is possible as for extragalactic M giants by galactic M dwarfs; an important advantage. The evolution of carbon star properties and their role in whole populations has recently been investigated by Mouhcine & Lancon (2003). As these C stars have approximately the same magnitude and colour as the much more numerous M stars, one needs some additional (at least low-resolution) spectral information to separate the two groups.

Various methods have been used to search for AGB stars in extragalactic systems. Out of these, narrow band photometry proved to be most powerful for an efficient identification and characterisation of AGB stars even in distant crowded fields (Paper I). Our method uses conventional *Vi* filters as an indicator of temperature or spectral type, whereas two narrow band Wing-type filters TiO and CN, centred on characteristic molecular features (around 800 nm) of O-rich and C-rich objects, respectively, provide low-resolution spectroscopic information to distinguish M from C stars. For further details about this method and a synthetic colour-colour diagram, the reader is referred to Paper I (Sect. 2) or Nowotny & Kerschbaum (2002).

Earlier work by e.g. Cook et al. (1986) showed that the method works well, but the number of identified AGB stars was limited by the then available small detectors. For global information on galaxies or AGB properties one needs statistically meaningful star numbers. Apart from a few well studied galaxies, information is incomplete or lacking for many of the systems of the Local Group[1], see Groenewegen (1999, 2002) or Mateo (1998). With the advent of new technologies (large CCD detectors, mosaics, wide field focal reducer instruments) and therefore larger fields of view (FOV), the Wing-filter method was applied very successfully and comprehensively e.g. by Brewer et al. (1995) and Letarte et al. (2002).

2. The galaxies

We started our photometric survey of Local Group galaxies (using the 2.56 m Nordic Optical Telescope at La Palma) with a trial field in M 31, the results of which are in Paper I.

We have continued our investigations with two M 31 companions, NGC 185 and NGC 147, using the same instrument. These two dwarf spheroidals were discovered by W. Herschel on November 30, 1787, and by J. Herschel in the 1820s. Baade (1944) recognised them for the first time as members of the Local Group, when he could resolve their stars. Being separated by only $\approx 1°$ (Fig. 12.2., van den Bergh 2000), they probably form a gravitationally bound pair on the front side of the M 31 subgroup of the Local Group (van den Bergh 1998).

The following values were measured for general parameters of NGC 185 and NGC 147: tidal radii of $16'$ and $20'$, core radii of $60''$ and $67''$, ellipticities of 0.22 and 0.44, respectively. References can be found in van den Bergh (2000) and Mateo (1998). Total magnitudes for the galaxies can be derived from their observed surface brightness profiles, which was done by Price (1985), Kent (1987), Caldwell et al. (1992), and Kim (1998). Using the values for V, $(m-M)$, and E_{B-V} from Mateo (1998), one can derive absolute visual magnitudes M_V of −15.46 and −15.51 for NGC 185 and NGC 147, respectively.

Detailed population studies of NGC 185 have been carried out by Lee et al. (1993b), Martínez-Delgado & Aparicio (1998), and Martínez-Delgado et al. (1999). A number of stars above the RGB indicate a significant intermediate-age stellar population, the AGB-stars extend up to $M_{\rm bol} \approx -5.0^{\rm mag}$ and an AGB luminosity function (LF) based on about 1300 stars is given. The colours are distinctly bluer in the central part. The stellar content of NGC 147 was investigated by Davidge (1994) and Han et al. (1997). The existence of RR Lyrae stars shows the presence of an old stellar population of about 10 Gyr, while the found AGB-stars (the tip occurs at $M_{\rm bol} \approx -5.0^{\rm mag}$) suggest a stellar population of $\approx$5 Gyr age. The younger population seems to be more concentrated toward the centre than the old population.

A few methods (tip of the RGB, HB stars brightness, and RR Lyrae stars) have been used to derive distances to the two extragalactic systems. An overview and references can be found in Tables 12.3 and 12.5 of van den Bergh (2000). Following the review by Mateo (1998), we used distance moduli of $23.96 \pm 0.21^{\rm mag}$ and $24.39 \pm 0.05^{\rm mag}$ for NGC 185 and NGC 147, respectively, which were derived from the data of Lee et al. (1993b) and Han et al. (1997) by using the magnitude of HB stars, and the I_0 magnitude of the tip of the RGB (Lee et al. 1993a). We could confirm the latter with our own photometric data (Sect. 4.1).

The median colour of RGB stars was used to derive metallicities for NGC 185. Lee et al. (1993b) found a mean value of $[\mathrm{Fe/H}] = -1.23 \pm 0.16$ dex. Taking into account their smaller FOV, this means that their metallicity estimate is consistent with the values found by Martínez-Delgado & Aparicio (1998) in the corresponding area. In addition, the latter derived decreasing metallicities for regions further away from the galaxy centre – down to −1.76 for the outermost parts – resulting in an average of -1.43 ± 0.15 dex. Based on the results of Martínez-Delgado & Aparicio (1998), we expect values around −1.2 for the area covered by our frames. The same method was used for NGC 147, by Han et al. (1997), resulting in a mean $[\mathrm{Fe/H}] = -0.91 \pm 0.03$ dex for the centre field and $[\mathrm{Fe/H}] = -1 \pm 0.03$ dex for the off-centre field (values of −0.85 for the outermost parts of their field). We adopted a mean metallicity of −1, which is also reported by Davidge (1994). Despite the not very well determined metallicities and their dispersions, NGC 185 can be regarded as the metal-poorer system of the two.

An interesting aspect of the two galaxies is that, while we can observe young stars, a significant amount of interstellar gas, and prominent dust patches in NGC 185, NGC 147 appears to be free of gas and dust. Also, NGC 185 is more concentrated in the central region, as can be seen in Figs. 1 and 6.

Table 1 summarises the properties of the two extragalactic systems. For further details one is referred to the review by Mateo (1998), and to van den Bergh (2000). The two galaxies

[1] Outside the Local Group a few carbon stars were individually identified photometrically by Richer et al. (1985) and Hudon et al. (1989), spectroscopic evidence for C stars was found in spectra of the integrated light from NGC 7252 by Mouhcine et al. (2002).

Table 1. Basic properties of the two galaxies surveyed, taken from: NASA Extragalactic Database (NED) – 1, van den Bergh (2000) – 2, Lee et al. (1993b) – 3, Han et al. (1997) – 4, and Mateo (1998) – 5.

		NGC 185	NGC 147	Ref.
α_{2000}		$0^h38^m57^s$	$0^h33^m12^s$	1
δ_{2000}		$48°20'11''$	$48°30'29''$	1
type		Sph	Sph	2
D	[kpc]	620	755	3, 4
$(m-M)_0$	[mag]	23.96	24.39	3, 4
M_V	[mag]	−15.46	−15.51	5
[Fe/H]	[dex]	−1.23	−1	see text
E_{V-I}	[mag]	0.25	0.24	1

NGC 185 and NGC 147 are quite similar, almost like twins in terms of their stellar content (see the CMDs in Fig. 2). They have almost the same Star Formation History (SFH), Fig. 8 in Mateo (1998). A more detailed comparison between them is worthwhile because they have approximately the same absolute magnitude of $-15.5^{\rm mag}$, but different metallicities. Therefore an independent test of the influence of [Fe/H] on, for example, the properties of C stars could be interesting.

The observed CMDs of NGC 185 and NGC 147 (Martínez-Delgado & Aparicio 1998; Han et al. 1997) look promising for a further investigation of their AGB populations using the Wing-filter method. In both of them a number of AGB stars are found to be as red as $(V-i)_0 \approx 4^{\rm mag}$. Until now, no C stars have been identified (Groenewegen 1999; Table 8 of Mateo 1998).

3. Data

3.1. Observations

The observations were obtained with the 2.56 m Nordic Optical Telescope (NOT, see `http://www.not.iac.es`) at La Palma (Spain) during the nights from August 30 to September 1, 2000. Using the ALFOSC focal reducer instrument with a 2k × 2k Loral-Lesser thinned CCD, we observed fields centred on NGC 185 and NGC 147 in the four filters described in Table 2. Also listed are the chosen exposure times. All three nights were photometric, the seeing varied between 0.″7 and 1.″1 on the combined frames. The two fields were observed at air masses of between 1.1 and 1.8. For the photometric calibration in V and i we additionally observed the Selected Area Fields #92, #110, and #114 from Landolt (1992). Sky flats for each filter were obtained, as were bias images. Figure 1 shows the i-filter images. With a pixel scale of 0.″189/pixel the CCD field is ≈6.′5 × 6.′5, i.e., the major fractions of the galaxies could be observed on one frame. Although this will include the majority of the stars, our survey is not totally complete in terms of area. Approximate sizes of the galaxies are given in Sect. 2 (or compare with the surface brightness profiles of Kent 1987). In addition, there are some restrictions due to vignetting and pairing, as described in more detail in Sect. 3.3. The C stars found can be used to give a rough estimate of the extent of the galaxies (Sect. 4.4).

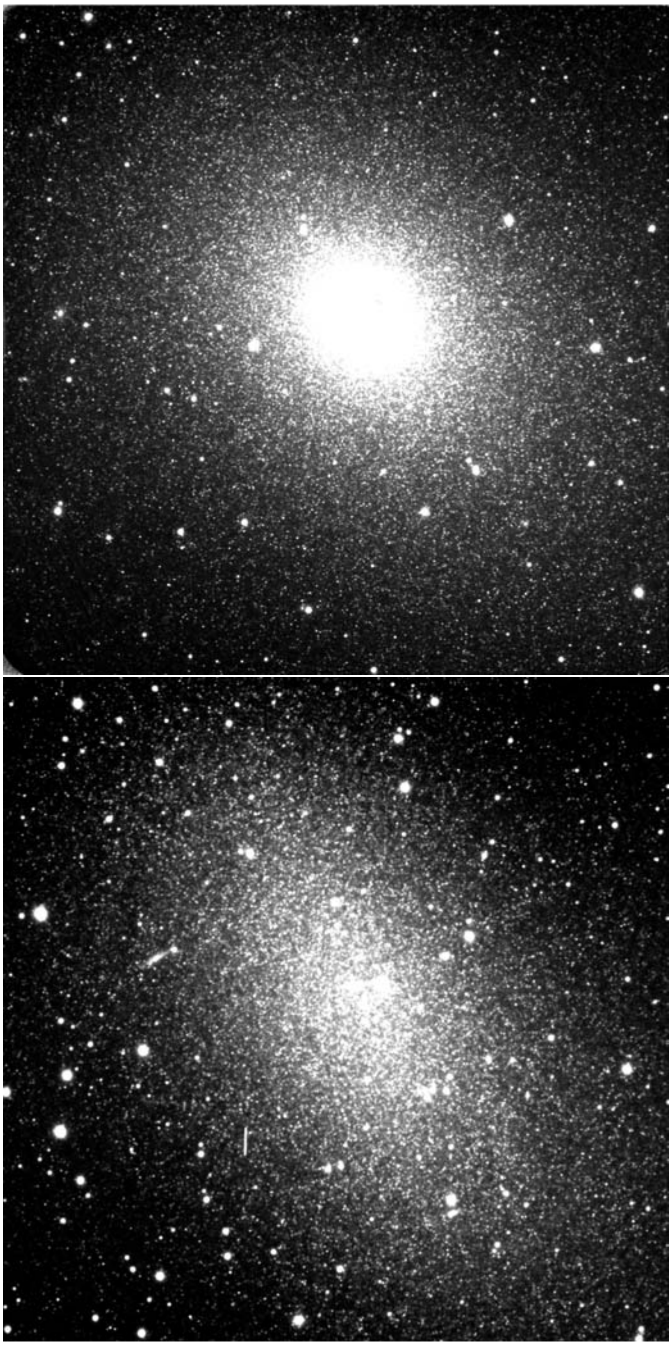

Fig. 1. i-band CCD images of the two M 31 companions NGC 185 (upper) and NGC 147 (lower), obtained at the 2.56 m Nordic Optical Telescope. The field covers ≈6.′5 × 6.′5, i.e. most of the galaxies. North is up and east is to the left. The seeing is ≈0.7″ and 1″, respectively. In the lower left foreground of NGC 147, the minor planet 2000 PT_{27} can be seen, which was discovered only 3 weeks before our observations (Nowotny & Karlsson 2000).

3.2. Reduction and calibration

For the basic reduction of the frames we used MIDAS (bias subtraction, cosmic ray removal, flat-fielding with sky flats, matching of frames, adding). The narrow band filters were used in the converging beam of the telescope to avoid differential wavelength shifts within the field due to the large angles of incidence in parallel beam instruments such as ALFOSC, which

Table 2. Observing log, the exposure times were the same for both galaxies.

Filter	NOT#	λ_c (Å)	$\Delta\lambda$ (Å)	System	exp. time (s)
V	75	5300	800	Bessell	3×1200
i	12	7970	1570	Gunn	1×1200
TiO	–	7780	110	Wing	6×1200
CN	–	8113	85	Wing	6×1200

resulted in some vignetting in the outermost parts of the TiO and CN frames (Fig. 6). Photometry was done for all stars, the ones lying in the affected areas, were sorted out afterwards. For the photometry of all four added frames we used the PSF-fitting software written by Ch. Alard for the data reduction of the DENIS-project. This program calculates a number of quality flags (correlation coefficient of the fit *"C1"*, *"error"*, etc.), which can be used to sort out data of low quality. The photometry of the stars had to meet the following criteria to be considered good enough: $C1 > 0.7$, $error < 0.5$. Stars meeting weaker criteria only blur the CMDs, and none of the bright AGB stars will be lost by excluding these stars.

To measure the atmospheric extinction at La Palma, we observed Landolt's field SA 114 in a sequence of different airmasses in all four filters. The resulting extinction coefficients ($k_V = 0.174$, $k_i = 0.067$, $k_{\rm TiO} = 0.056$ and $k_{\rm CN} = 0.069$) were taken into account.

The correction for interstellar reddening in V and i was done according to the values from the NASA Extragalactic Database (NGC 185: $A_V = 0.604^{\rm mag}$, $A_i = 0.354^{\rm mag}$; NGC 147: $A_V = 0.574^{\rm mag}$, $A_i = 0.336^{\rm mag}$). The effect of reddening on (TiO−CN) is very small, due to the negligible difference in central wavelength of these two filters (Battinelli & Demers 2000 found $E_{\rm TiO-CN} \approx 0.04 \times E_{B-V}$). Therefore, no correction was applied to the data.

Using several unsaturated but bright single stars with their neighbours subtracted from the frame, we established aperture corrections, between the PSF fitting magnitudes and the aperture photometry magnitudes for V and i. These corrections were applied to all stars.

Photometric zero-points for the filters V and i were obtained from stars of the standard fields SA 92, 110, and 114 of Landolt (1992). We used these, as we did in Paper I, because of the similarity of Landolt's Cousins i-filter ($\lambda_c = 7900$ Å and $\Delta\lambda = 1500$ Å) and our i-filter (see Table 2).

For the two narrow band filters no absolute photometric calibration was done. To be compatible with Paper I, we used the fact, that "early" spectral types lack TiO/CN-features, and therefore have $({\rm TiO-CN})_0 \approx 0^{\rm mag}$. Stars having $(V-i)_0 < 0.7$, $C1 > 0.8$, $error < 0.1$, and only one counterpart in all frames during the pairing process, were considered to be good enough for determining the special offset for $({\rm TiO-CN})_0$. 31 stars in NGC 185 and 58 in NGC 147 led to offsets of $-0.079 \pm 0.05^{\rm mag}$ and $-0.076 \pm 0.05^{\rm mag}$, respectively. These offsets were applied to all stars.

3.3. Pairing and astrometry

All single frames were shifted and added, the frames of different filters were shifted to match each other (i as reference), which resulted in small losses of covered area. The pairing of stars, detected in different filters, was done with the DENIS-software "Cross_Colour". All stars within a radius of 3 pixels ($\approx 0\farcs6$) were considered to correspond to each other. Only stars with one and only one definitive counterpart in all four filters were used in the further analysis. No multiple matches of other nearby pairing candidates were accepted. Using stars from the Guide Star Catalogue (GSC I), that appear on our frames, and the MIDAS/ASTROMET-package we produced an absolute astrometric calibration. This was then used to derive absolute coordinates for identified stars or to calculate positions for the galaxy centres in pixel coordinates. By comparing different methods to determine the centres on the i frames, such as values from the literature, surface brightness plots, average coordinates of all stars or C stars etc., we found them to differ by only about $10''$, which we considered as consistent. In the following we used the centre coordinates from Cotton et al. (1999). Stars lying in areas on the TiO and CN frames that were affected by vignetting had to be identified and removed. For this, we measured the centres and radii of the vignetted areas on original frames of both filters and transformed it to the i reference coordinates.

This resulted in a total of 26 496 stars for NGC 185 and 18 300 stars for NGC 147, having good photometry in V and i (*sample 1*). The maximum distance of a star in this sample to the centre of the galaxy is $4\farcm6$ for both galaxies.

Having detections in the narrow band filters results in an even stronger criterium. Despite the longer exposure times, also here mainly the bright red giants were detected. But as we are interested in the AGB population, which is made up of the brightest stars on the RGB/AGB sequence, this is no major drawback. 8546 stars for NGC 185 and 6332 stars for NGC 147 have photometry of good quality in all four filters (*sample 2*). The maximum central distance for this sample is $3\farcm7$ for NGC 185 and $3\farcm8$ for NGC 147.

Coordinates and photometric properties for all stars (*sample 1*) are available in electronic form at the CDS, a short extract of the results for NGC 185 is shown in Table A.1.

4. Results and discussion

4.1. Stellar content (colour-magnitude diagrams)

Figure 2 shows the CMDs for all stars of *sample 1* (mean 1σ error bars are given for different i_0 magnitude ranges). They reveal the brightest 3–$4^{\rm mag}$ of the RGB/AGB-sequence and compare well to the observations of Martínez-Delgado & Aparicio (1998) and Han et al. (1997). Both galaxies are dominated by an old, red population. Besides, a distinct group of bluer, bright stars can be seen at $(V-i) \approx 0.8^{\rm mag}$ in both CMDs. A comparison with the Galactic star count models of Ratnatunga & Bahcall (1985) shows, that most of them are probably foreground objects of our Galaxy. We find more of these stars than the model predicts, and this suggests, that some possible young red supergiants, belonging to the galaxies, could

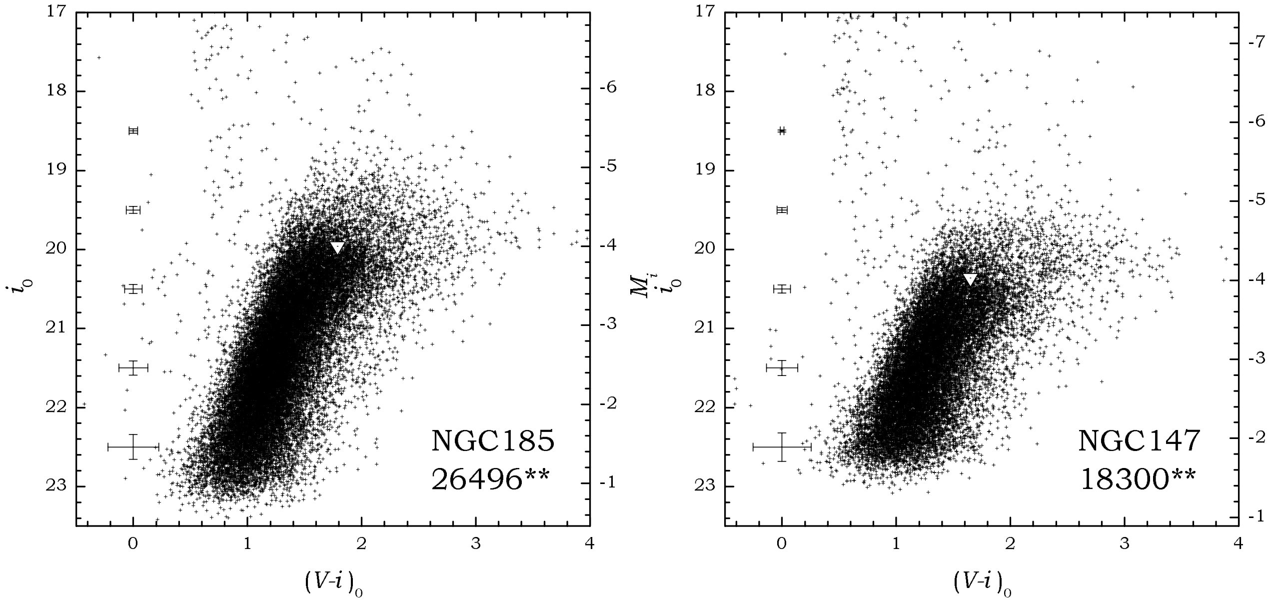

Fig. 2. Colour-magnitude diagrams for all stars having good photometry in V and i (*sample 1*; mean 1σ error bars are given for different i_0 magnitude ranges). Triangles mark the RGB-tips, as we determined it in Sect. 4.1. The absolute magnitudes are calculated using the distance moduli from Table 1.

be among them (as was also stated by Martínez-Delgado & Aparicio 1998). For the brightest red stars, the scatter due to observational effects could mimic a possible intermediate-age population (Martínez-Delgado & Aparicio 1997).

A direct estimate of the foreground contamination from our frames seems difficult as the galaxy sizes are a bit larger than our FOV (Sect. 4.4) and no extra field off the galaxies could be observed. As far as the C stars are concerned, the contamination doesn't matter at all, but it may be quite important for the M giants. Galactic M dwarfs in the directions of the two galaxies can affect the sample significantly, see e.g. Albert et al. (2000). But from the low numbers in the outermost bins of Fig. 7, we assume no huge contamination in our case, for further discussions see Sect. 4.4.

As a check of the reliability of our photometry, we measured the tip of the RGB from the photometric data. Figure 3 shows the i_0 luminosity function for all stars of *sample 1* for the two galaxies. As edge-detection algorithm we used (like Lee et al. 1993a) a zero-sum Sobel kernel [−2, −1, 0, 1, 2], the resulting histogram is also plotted in Fig. 3. To avoid "binning noise", we calculated i_0 for the tip-RGB as weighted mean of a few bins (with significantly large star counts) around the maximum bin. We obtained $19.96^{\rm mag}$ for NGC 185 and $20.36^{\rm mag}$ for NGC 147, which is in good agreement with the values of $19.92 \pm 0.1^{\rm mag}$ by Lee et al. (1993b) and $20.3 \pm 0.04^{\rm mag}$ by Han et al. (1997). This gives us confidence in the correctness of our photometry. In Fig. 2, triangles mark the corresponding RGB-tips.

Following the (tip-RGB) method as described in Lee et al. (1993a), we calculated mean colour indices $(V-i)_0$ for the RGB and derived bolometric corrections BC_I and metallicities [Fe/H] from it. Despite the good agreement in i_0 for the tip-RGB, we find considerable differences in the determination of [Fe/H]. Our $(V-i)_{-3.5}$[2] result in metallicities of −0.89 for NGC 185 and −1.11 for NGC 147, which differ from the values in the literature as given in Sect. 2. Finally, we calculated distance moduli of $24.04^{\rm mag}$ for NGC 185 and $24.44^{\rm mag}$ for NGC 147. As the discrepant metallicities have only a weak influence on the determination of the distance moduli $(m-M)_0$ we derive from our photometry, the latter still are in good agreement with the ones from the literature.

4.2. Identification of M and C stars (colour-colour diagrams)

Figure 4 (left) shows colour-colour diagrams for all stars of *sample 2*. Two well separated branches can be seen toward redder colours. M and C stars differ in $(\mathrm{TiO-CN})_0$ by up to $1.5^{\rm mag}$. The identification of the different chemistries is based on the location of the stars in this colour-colour diagram, the selection areas (also plotted in Fig. 4) were defined as follows:

- M: $(V-i)_0 > 1.6^{\rm mag}$, $(\mathrm{TiO-CN})_0 > 0.15^{\rm mag}$,
- C: $(V-i)_0 > 1.16^{\rm mag}$, $(\mathrm{TiO-CN})_0 < -0.3^{\rm mag}$

For M stars, the selection criteria in both colours were kept unchanged from those in Paper I (Sect. 4.2. and Fig. 2 in Paper I), where they were defined by the synthetic photometry of an M0 star. We also kept the same border in $(\mathrm{TiO-CN})_0$ for the C stars.

For two reasons, we changed the border in $(V-i)_0$ for C stars. The bluest C star in Fig. 2 of Paper I was approximately of spectral type C5. Doing the same synthetic photometry for another spectral library, that of Silva & Cornell (1992), we found their C0 star to have $(V-i)_0 = 1.16^{\rm mag}$. Figure 4 suggests that there are good candidates for being a C star, i.e., with a clear distinction in $(\mathrm{TiO-CN})_0$, bluer than

[2] Mean $(V-i)_0$ of all stars between $0.4-0.5^{\rm mag}$ below the tip-RGB, which is located at $M_i = -4^{\rm mag}$.

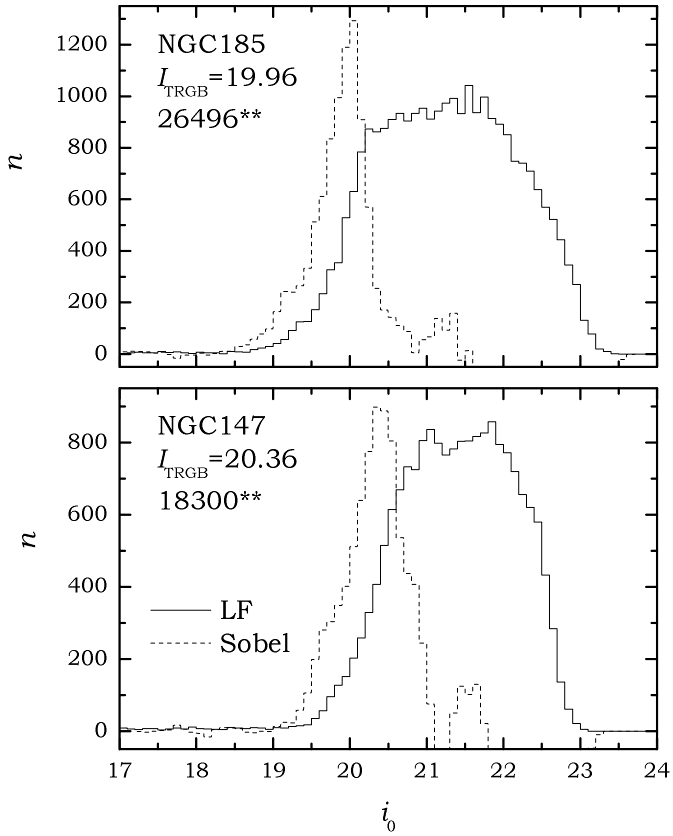

Fig. 3. i_0-LF for all stars of *sample 1* for both galaxies. Overplotted is the resulting histogram of the edge-detection algorithm (zero-sum Sobel kernel), from which we calculated the magnitude of the RGB-tip.

$(V-i)_0 = 1.6^{\mathrm{mag}}$[3]. Taking into account these facts, we adopted the border in $(V-i)_0$ for C stars to -1.16.

There may be some S type star candidates among the reddest stars, as was found by Letarte et al. (2002) and spectroscopically confirmed by Brewer et al. (1996). While S stars still show TiO bands and will therefore lie in the same area as the M stars, SC stars (C/O = 1) with no prominent feature within the filters TiO and CN are expected to have $(\mathrm{TiO}-\mathrm{CN})_0 \approx 0^{\mathrm{mag}}$ and should lie between the two selection areas (Nowotny & Kerschbaum 2002).

Using our criteria, we found 154 new C star candidates in NGC 185 and 146 in NGC 147. They can be found above, as well as below, the tip of the RGB and are – with a few exceptions – among the brightest red giants of the whole population, as can be seen in Fig. 4 (right). 1732 M stars lie in the corresponding area for NGC 185 and 950 for NGC 147. This leads to C/M ratios for the observed fields of 0.089 and 0.154, respectively[4]. In general, one would expect NGC 185 to have more C stars (larger C/M ratios), as it is the more metal-poor system, has an almost identical SFH to NGC 147, and the limiting magnitudes for both galaxies are roughly the same. This is not the case and the ratios are contrary to the expectation. Note, that one would not face this discrepancy with the metallicities we derived in Sect. 4.1. For a comparison with Groenewegen (2002) we also calculated the ratio C/M5+, where we counted all stars later than spectral type M5, using our synthetic photometry to set the $(V-i)_0$ limit (Paper I; we used the same spectral library of Fluks et al. 1994). Again we find a larger ratio for NGC 147, Table 3. Both ratios agree within the uncertainties of the method with Fig. 5 of Groenewegen (2002).

Table 3. Star counts for *sample 2* of both galaxies and the mean properties of the C star candidates identified in Fig. 4.

		NGC 185	NGC 147
# C		154	146
# M		1732	950
C/M		0.089	0.154
# M5+		195	126
C/M5+		0.79	1.16
$\langle (V-i)_0 \rangle_C$	[mag]	2.11 ± 0.40	2.06 ± 0.44
$\langle (\mathrm{TiO}-\mathrm{CN})_0 \rangle_C$	[mag]	-0.56 ± 0.16	-0.59 ± 0.16
$\langle i_0 \rangle_C$	[mag]	19.72 ± 0.46	20.15 ± 0.42
$\langle M_i \rangle_C$	[mag]	-4.24 ± 0.46	-4.24 ± 0.42
$\langle M_{\mathrm{bol}} \rangle_C$	[mag]	-4.34 ± 0.52	-4.33 ± 0.47
$\langle L \rangle_C$	$[L_\odot]$	4650 ± 2020	4530 ± 1890

Absolute star numbers, C/M ratios, and global statements should be considered with caution, as they depend on the selection criteria (especially dramatic for the M star candidates), foreground contamination for M stars, photometric variability of AGB stars, and the limiting magnitude of the observations (Brewer et al. 1995). For a quantitative comparison of star counts for different galaxies, the selection should be done consistently.

Based on the observations of other Local Group galaxies, see Fig. 2 of Groenewegen (1999) and Fig. 6 of Battinelli & Demers (2000), one would expect more C stars to be found in NGC 185 and NGC 147. The limited field is not the main reason why we detect relatively few of them. As there are only very few stars in the outermost bins of Fig. 7, we do not expect to miss many C stars. The selection in quality of the photometry can not have a large influence, as C stars are bright and easily detectable.

In Paper I, we found 515 red stars, that were not detected in V because of the short exposure time (Sect. 4.5 in Paper I). For these we plotted a special colour-magnitude diagram (Fig. 8 in Paper I), which allowed us to sort out some more C star candidates. For the observations of NGC 185 and NGC 147 we reached a fainter limiting magnitude in V and did not miss this kind of stars. As a check, we plotted the same special CMD for the stars of NGC 185 and NGC 147. The C star candidates found in this way are almost identical to the ones found using the colour-colour diagram of Fig. 4. This confirms our conclusions in Sect. 4.5 of Paper I.

Worth noticing is the fact that the photometric properties of the C star candidates are in – surprising – agreement for

[3] Demers & Battinelli (2002) also missed already spectroscopically identified C stars in Leo I by applying "too red" borders. Letarte et al. (2002) showed, that these "bluer" C stars are in general weaker and have a larger spread in their i-band luminosity function.

[4] Re-analysing the M 31 field of Paper I (with the photometry as described here) and applying the changed selection border lead to 80 C stars and a decreased C/M ratio of 0.078.

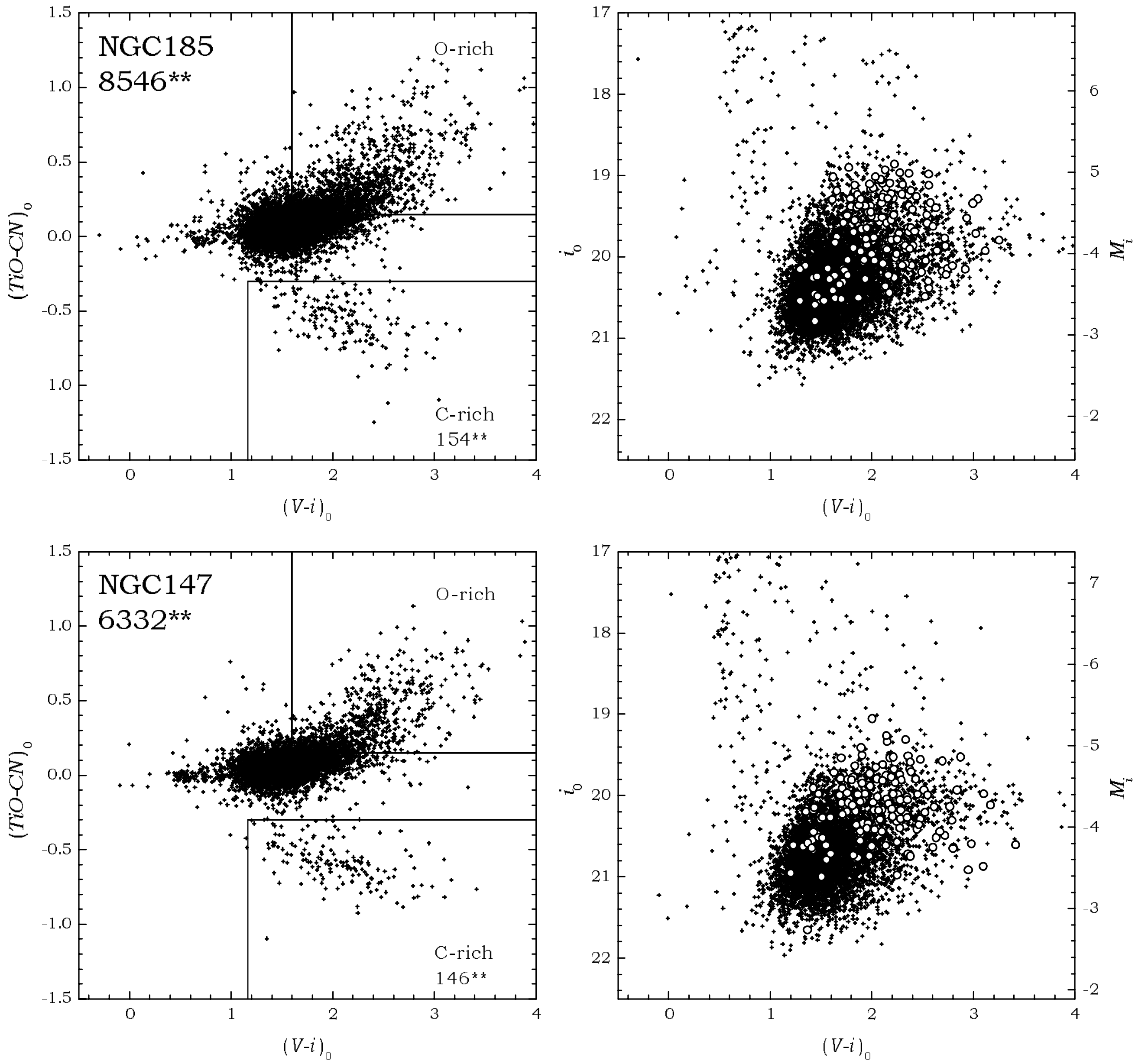

Fig. 4. *Left*: colour-colour diagrams for all stars of *sample 2.* Also plotted are the selection areas for M and C stars, as described in the text. *Right*: corresponding colour-magnitude diagrams for all stars of *sample 2*. The identified C stars from the selection areas, marked with open circles, lie on the uppermost parts of the RGB/AGB-sequences.

both galaxies (as Table 3 shows), there is no influence of the metallicity, in either direction.

4.3. Luminosity functions (LF)

Local Group galaxies have the advantage that all stars within one galaxy have, as a good approximation, the same distance, and we can estimate this distance by using various methods. Therefore we can calculate LFs for the observed stars. The scatter in magnitude for optically detectable C stars (in V or i) was found to be relatively small. This can be explained by the short time scale on which the AGB stars are in this evolutionary stage. Keeping this in mind, we can use the narrow i-LF as a standard candle to estimate distances of galaxies. To confirm this proposition, data from several galaxies are needed (one of the motivations for our survey). An absolute calibration is a worthwhile task for the future.

The influence of the chosen criteria for C stars on the shape of the LF was already mentioned in Sect. 4.2, Fig. 6 of Letarte (2002). This can introduce an additional error to the derived distances. By selecting only the "redder" more luminous C stars, the LF becomes better defined.

The two diagrams on the left in Fig. 5 show the i_0-LFs for all C stars in the selection areas of Fig. 4. Their mean photometric properties can be found in Table 3. The upper axes show our apparent magnitudes, the dotted line marks the RGB-tip as it was found in Sect. 4.1. The lower axes shows the corresponding absolute magnitudes calculated with the distance moduli

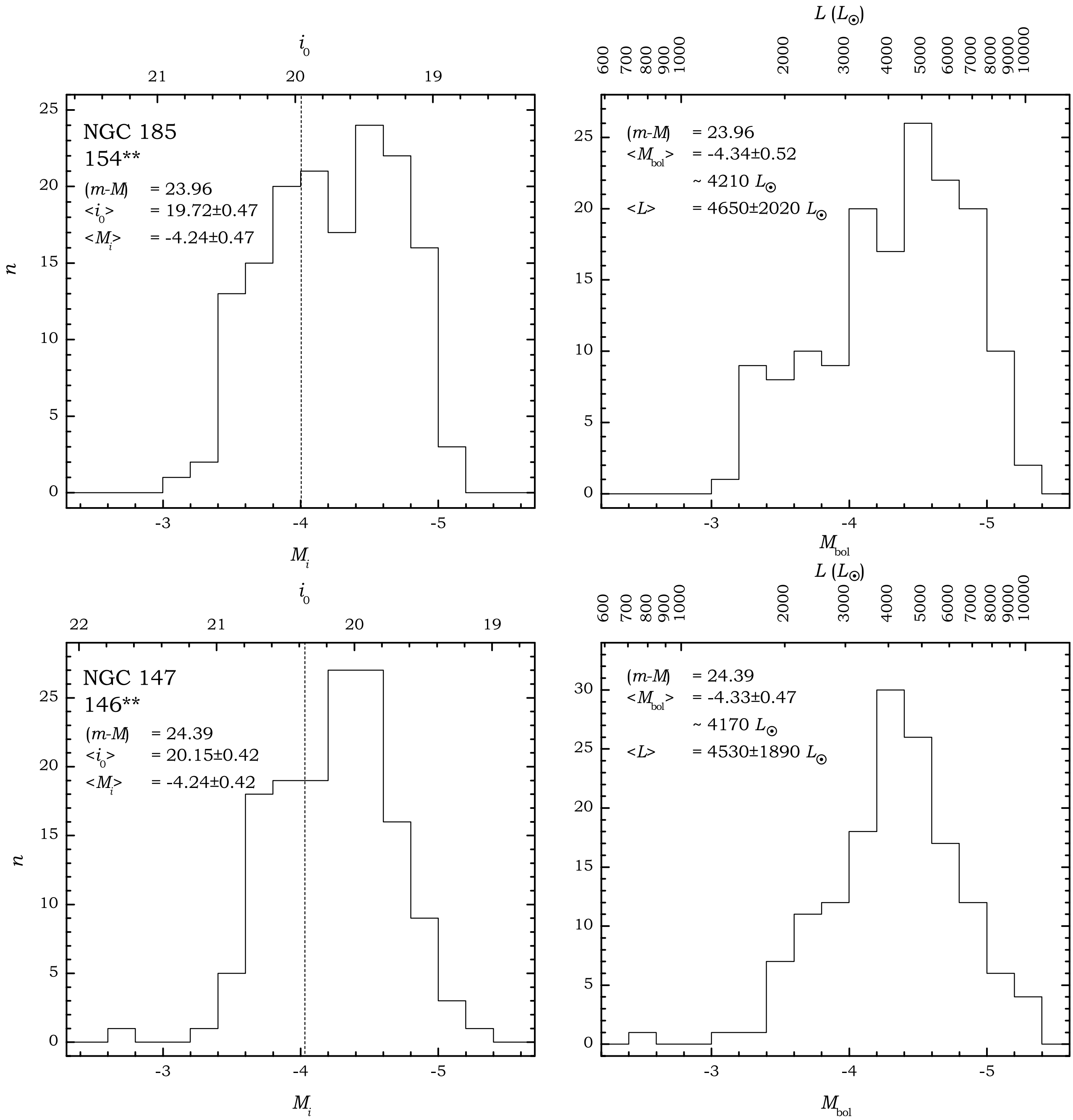

Fig. 5. *Left*: luminosity function (apparent and absolute i magnitude) for all C stars, identified in Fig. 4, of NGC 185 and NGC 147. Using the distance moduli from Table 1, one can calculate a $\langle M_i \rangle$ (upper right corner). The dotted line marks the RGB-tip from Sect. 4.1. *Right*: bolometric LFs for all C stars found in NGC 185 and NGC 147. $M_{\rm bol}$ was calculated as described in the text. Note the difference between the mean luminosity $\langle$L$\rangle$ and the luminosity calculated from the mean $\langle M_{\rm bol} \rangle$.

from Table 1. In good agreement is the absolute magnitude of the RGB-tip for both galaxies. Mean values $\langle M_i \rangle$ of all C stars were found to be -4.24 ± 0.46 for NGC 185 and -4.24 ± 0.42 for NGC 147. These values are low compared to the ones found for other nearby galaxies, see Fig. 5 of Demers & Battinelli (2002). $\langle M_i \rangle$ was found to be $-4.75 \pm 0.47^{\rm mag}$ for the LMC by Richer (1981), $-4.69 \pm 0.28^{\rm mag}$ for IC 1613 by Albert et al. (2000) and $-4.7^{\rm mag}$ for NGC 6822 by Letarte et al. (2002). On the other hand, the check with the RGB-tip in Sect. 4.1 assures us that we do not have a large error in our i_0-magnitudes.

Also plotted in Fig. 5 are the bolometric LFs for the C stars of both galaxies. For the calculation of $M_{\rm bol}$, we used a different bolometric correction (BC) than the one from Bessell & Wood (1984) that we used in Paper I. Note, that there can be relatively large differences in the BCs of different authors, especially for stars with $(V-i)_0 > 1.5^{\rm mag}$, which can be seen in Fig. 11 of Montegriffo et al. (1998). The BC of Montegriffo et al. (1998) is based on a larger set of photometric data than that of Bessell & Wood (1984). The BC which they designate “metal-rich”, fits the expected metallicities for our observations

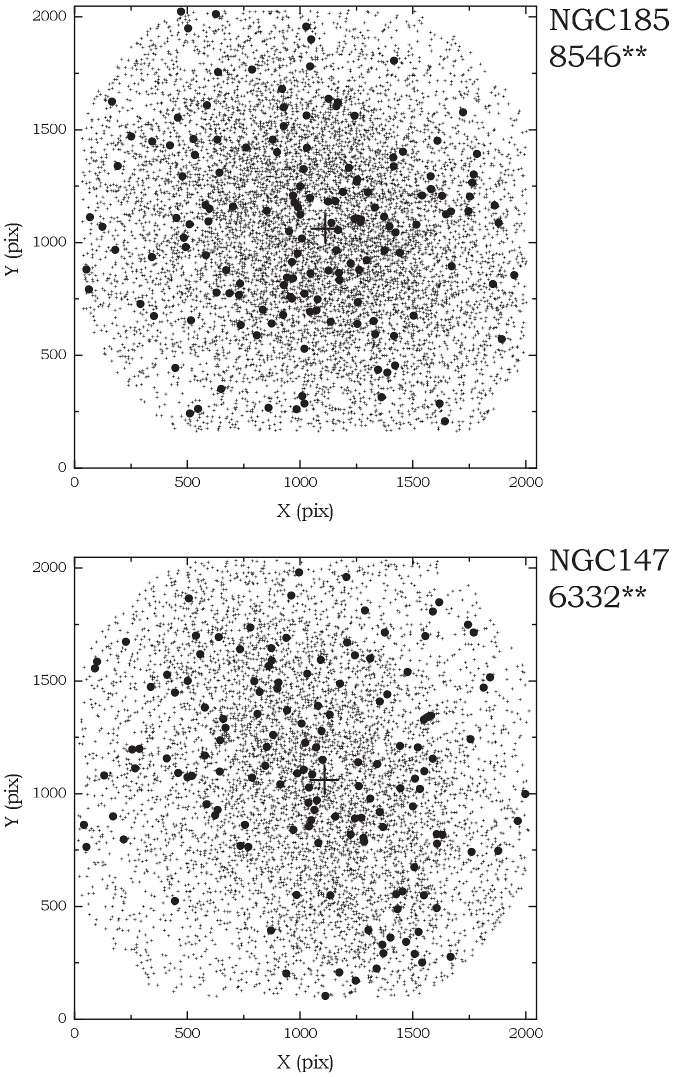

Fig. 6. Distribution of all stars of *sample 2* of NGC 185 (upper) and NGC 147 (lower) on the *i*-band frames, overplotted are the identified C stars and the galaxy centres (Sect. 3.3). One can see the effect of vignetting in the corners, the strips without stars at the lower ends are due to a shift of the telescope between observations of frames of different filters.

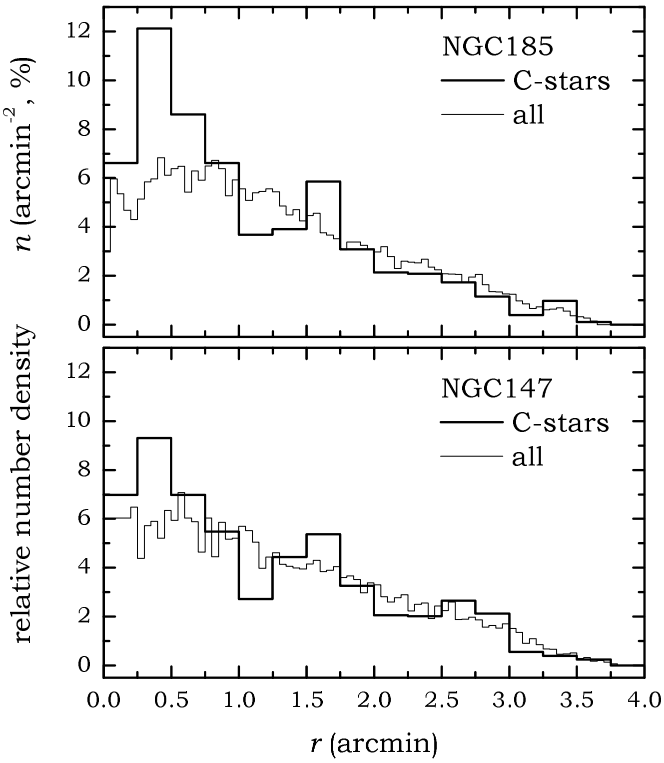

Fig. 7. Radial distributions of all stars of *sample 2* and for the found C stars.

better and reaches values of $(V-i)_0 \approx 4.5^{\rm mag}$. As it is derived from photometry of globular clusters, it can be used for our M type giants[5]. The clear deviations of the very few C stars in Fig. 1 of Bessell & Wood (1984) suggest a different BC for C giants.

Bolometric corrections for C type giants have been published by Frogel et al. (1980), Costa & Frogel (1996), Groenewegen (1997), and Bergeat et al. (2002), but not for the colour index $(V-i)_0$. From the collection of data on galactic C stars of Bergeat et al. (2002) a BC based on $(V-i)_0$ was derived. Bergeat (priv. comm.) kindly provided us with data containing stars of their groups HC5 and CV1–CV7, which are variable carbon giants, and typical members of the thin disk.

[5] A BC from M type models and synthetic spectra can be found in Houdashelt et al. (2000a) and Houdashelt et al. (2000b).

Although there remain uncertainties, we calculated the BC_V by a polynomial fit. With the distance moduli from Table 1, the bolometric magnitude can be calculated in the following way:

$$M_{\rm bol} = V_0 + BC_V - (m-M)_0$$
$$BC_V = 0.701 - 1.377 \cdot (V-i)_0 - 0.001 \cdot (V-i)_0^2.$$

As expected, this results in luminosities considerably different from those derived by adopting the M star BC.

Although our *i*-magnitudes appear to be somewhat fainter than expected, the bolometric LFs for our C stars are in good agreement with the one for the SMC (comparable [Fe/H] and statistically meaningful star numbers) as given by Groenewegen (1999) in his Fig. 5. The same goes for the mean $\langle M_{\rm bol}\rangle$, which also fit well into his Fig. 6. A possible influence of the metallicity on $\langle M_{\rm bol}\rangle$ cannot be deduced, considering the large uncertainties in the BC. From the differences of LFs for different galaxies (Groenewegen 2002) it seems that the LF and the corresponding $\langle M_{\rm bol}\rangle$ depend on metallicity and the SFH. Due to a large scatter and uncertainties for the low-luminosity end of the LF, it appears to be more suited for a rough estimation of the distance than as a standard candle.

4.4. Spatial distributions

Figure 6 shows the distributions of detected *sample 2* stars on the *i*-frames, marked are the identified C star candidates and the galaxy centres (derived as described in Sect. 3.3). The influence of vignetting of the TiO- and CN-frames can be seen for both groups, as can the concentration of stars toward the centre (the slightly inhomogeneous distribution of C stars in NGC 147 can probably be explained by small number statistics). The galaxy centres from Cotton et al. (1999) fit well. NGC 185 is more highly concentrated toward the centre.

Figure 7 shows the radial distributions of star counts for all stars and for the selected C stars in our FOV, where the number density is scaled by the area and total number. For the sake of simplicity, the star counts where made in circular annuli around the centre.

As it was stated by Albert et al. (2000), see their Figs. 6 and 8, while the distribution of M stars can be severely contaminated by foreground M dwarfs, the "clean" C star distribution is a good measure of the extent of extragalactic systems. As there are C stars all over the frames in Fig. 6, our FOV cannot cover the whole area of the galaxies on the sky, which can also be concluded from a simple visual inspection of the frames. A quanitative foreground star count from the outer regions of the frames is not possible.

From the very small numbers (on the order of 10 stars per square arcmin) in the outermost bins we conclude that we detected the majority of the (AGB) stars of these galaxies. Only few such stars lie outside our FOV, because the stellar density decreases strongly (compare the luminosity profiles of Kent 1987). This number densities can also be regarded as a crude estimate for the foreground contamination and align well with the values given by Ratnatunga & Bahcall (1985), which find ≈11 stars per square arcmin for NGC 147 and for V down to 25^{mag} (our detection limit).

The distributions for all stars and for only C stars are almost the same for all galactocentric distances[6]. The distribution for M stars is probably also similar. Therefore, the C/M ratio will be approximately constant as a function of distance from the centre for both galaxies.

5. Conclusions

The results from our four-colour CCD photometric observations of NGC 185 and NGC 147 are:

- We get photometry of good quality in the four filters used for 8546 and 6332 stars, respectively.
- From our CMDs we determine i_0 for the tip of the RGB as 19.96^{mag} for NGC 185 and 20.36^{mag} for NGC 147. We derive distance moduli of 24.04^{mag} for NGC 185 and 24.44^{mag} for NGC 147. From mean colour indices $(V-i)_0$ of the RGB we estimate metallicities [Fe/H] of −0.89 for NGC 185 and −1.11 for NGC 147.
- Our method, based on the early work by Wing (1971) is effective and efficient of telescope time for the detection and separation of the AGB content of Local Group galaxies just by photometric means.
- We separate carbon-rich (C)- and oxygen-rich (M-) stars easily with magnitude differences of up to 1.5 in the colour-colour diagrams.
- We have identified a total of 300 new carbon stars in these two dwarf galaxies, with very similar photometric properties.
- We derive C/M ratios of 0.089 (NGC 185) and 0.154 (NGC 147) and show that these are flat within the observed part of the galaxies.
- For the found C stars we derive mean absolute magnitudes $\langle M_i \rangle$ of -4.24^{mag} (for both galaxies). Also we give bolometric magnitudes and luminosity functions (in i and bolometric).

[6] With some deviation in the centre, which could be caused by losses of faint stars due to crowding, especially for NGC 185. This is not the case for the bright C stars.

Acknowledgements. The authors wish to thank J. Bergeat very much for extracting the bolometric correction for C stars from his database and also for fruitful discussions on the topic. This work was supported by the "Fonds zur Förderung der Wissenschaftlichen Forschung" under project numbers S7308–AST and P14365–PHY and the Austrian Federal Ministry of Transport, Innovation and Technology in the course of the Project FIRST–PACS. We used the Simbad database operated at CDS, Strasbourg, France.

Appendix A: Photometric results

Table A.1. Example for the NGC 185 results, extracted from the full table, which is available via CDS. Column 1 gives an ID number for every star, while Cols. 2 and 3 list the coordinates (J2000.0) in the form `hhmmss.sss` and `ddmmss.ss`, respectively. A special flag `F` is given in Col. 4, which denotes in which region of Fig. 4 the star falls (`c` for carbon stars, `o` for oxygen-rich stars, `r` for the rest), if it is member of *sample 2*. If the flag `F` is `u` (for unclassified), the star is from *sample 1* and not included in the smaller *sample 2*, which means it has only Vi-photometry. Columns 5–7 list the photometric results, `i`, `V-i`, `TiO-CN`. The astrometric data may be afflicted with a systematic error of 0.5-1.2″ introduced by the accuracy limits of the GSC reference stars (Taff et al. 1990), the mean uncertainty of the MIDAS astrometric solution is 0.05″ rms (with a maximum of 0.11″).

ID	RA	DE	F	i	V-i	TiO-CN
19990997	003254.964	483013.76	c	20.65	1.41	-0.45
19660878	003255.575	482951.47	c	20.52	1.52	-0.58
18790745	003257.190	482926.57	c	20.19	1.84	-0.59
18421515	003258.017	483150.20	c	19.91	1.42	-0.66
.	.	.	.	.	.	.
.	.	.	.	.	.	.

References

Albert, L., Demers, S., & Kunkel, W. E. 2000, AJ, 119, 2780
Baade, W. 1944, ApJ, 100, 147
Battinelli, P., & Demers, S. 2000, AJ, 120, 1801
Bergeat, J., Knapik, A., & Rutily, B. 2002, A&A, 390, 967
Bessell, M. S., & Wood, P. R. 1984, PASP, 96, 247
Brewer, J. P., Richer, H. B., & Crabtree, D. R. 1995, AJ, 109, 2480
Brewer, J. P., Richer, H. B., & Crabtree, D. R. 1996, AJ, 112, 491
Caldwell, N., Armandroff, T. E., Seitzer, P., & Da Costa, G. S. 1992, AJ, 103, 840
Cook, K. H., Aaronson, M., & Norris, J. 1986, ApJ, 305, 634
Costa, E., & Frogel, J. A. 1996, AJ, 112, 2607
Cotton, W. D., Condon, J. J., & Arbizzani, E. 1999, ApJS, 125, 409

Davidge, T. J. 1994, AJ, 108, 2123
Dejonghe, H., & van Caelenberg, K. 1999, in Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lebre, & C. Waelkens, IAU Symp., 191, 501
Demers, S., & Battinelli, P. 2002, AJ, 123, 238
Fluks, M. A., Plez, B., Thé, P. S., et al. 1994, A&AS, 105, 311
Frogel, J. A., Persson, S. E., & Cohen, J. G. 1980, ApJ, 239, 495
Groenewegen, M. A. T. 1997, in The Impact of Large-Scale NIR-Sky-Surveys, Ap&SS, 210, 165
Groenewegen, M. A. T. 1999, in Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lebre, & C. Waelkens, IAU Symp., 191, 535
Groenewegen, M. A. T. 2002 [astro-ph/0208449]
Han, M., Hoessel, J. G., Gallagher III, J. S., et al. 1997, AJ, 113, 1001
Hatzidimitriou, D., Croke, B. F., Morgan, D. H., & Cannon, R. D. 1997, A&AS, 122, 507
Houdashelt, M. L., Bell, R. A., Sweigart, A. V., & Wing, R. F. 2000a, AJ, 119, 1424
Houdashelt, M. L., Bell, R. A., & Sweigart, A. V. 2000b, AJ, 119, 1448
Hudon, J. D., Richer, H. B., Pritchet, C. J., et al. 1989, AJ, 98, 1265
Kent, S. M. 1987, AJ, 94, 306
Kim, S. C., & Lee, M. G. 1998, J. Korean Astron. Soc. 31, 51
Kunkel, W. E., Irwin, M. J., & Demers, S. 1997, A&AS, 122, 463
Landolt, A. U. 1992, AJ, 104, 340
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993a, ApJ, 417, 553
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993b, AJ, 106, 964
Letarte, B., Demers, S., Battinelli, P., & Kunkel, W. E. 2002, AJ, 123, 832
Martínez-Delgado, D., & Aparicio, A. 1997, ApJ, 480, L107
Martínez-Delgado, D., & Aparicio, A. 1998, AJ, 115, 1462
Martínez-Delgado, D., Aparicio, A., & Gallart, C. 1999, AJ, 118, 2229
Mateo, M. 1998, ARA&A, 36, 435
Montegriffo, P., Ferraro, F. R., Origlia, L., & Fusi Pecci, F. 1998, MNRAS, 297, 872
Mouhcine, M., Lançon, A., Leitherer, C., Silva, D., & Groenewegen, M. A. T. 2002, A&A, 393, 101
Mouhcine, M., & Lançon, A. 2002, A&A, 393, 149
Mouhcine, M., & Lançon, A. 2003, MNRAS, 338, 572
Nowotny, W., & Karlsson, O. 2000, M.P.C. Oct. 2000, p. 41337
Nowotny, W., Kerschbaum, F., Schwarz, H. E., & Olofsson, H. 2001, A&A, 367, 557 (Paper I)
Nowotny, W., & Kerschbaum, F. 2002, Hvar Obs. Bull., 26, 63
Price, J. S. 1985, ApJ, 297, 652
Ratnatunga, K. U., & Bahcall, J. N. 1985, ApJS, 59, 63
Richer, H. B. 1981, ApJ, 243, 744
Richer, H. B., Pritchet, C. J., & Crabtree, D. R. 1985, ApJ, 298, 240
Saha, A., Hoessel, J. G., & Mossma, A. E. 1990, AJ, 100, 108
Salaris, M., & Cassisi, S. 1998, MNRAS, 298, 166
Silva, D. R., & Cornell, M. E. 1992, ApJS, 81, 865
Taff, L. G., Lattanzi, M. G., Bucciarelli, B., et al. 1990, ApJ, 353, L45
van den Bergh, S. 1998, AJ, 116, 1688
van den Bergh, S. 2000, The Galaxies of the Local Group (Cambridge: Cambridge University Press)
van der Marel, R. P., Alves, D. R., Hardy, E., & Suntzeff, N. B. 2002, AJ, 124, 2639
Wing, R. F. 1971, Proc. of the Conference on Late-Type Stars, ed. G. W. Lockwood, & H. M. Dyck, KPNO Contribution, 554, 145