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

III. The dwarf spheroidal And II

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Abstract. Our photometric survey of Local Group galaxies, using a four filter technique based on the method of Wing (1971) allows the identification and subsequent characterization of their late-type stellar content. Two narrow band filters centred on molecular bands of TiO and CN allow us to distinguish between AGB stars of different chemistries [M-type (O-rich) and C-type (C-rich)]. The faint dwarf spheroidal galaxy And II, a member of the M 31 subgroup, was surveyed. From photometry in V and i as well as in the narrow band filters TiO and CN we were able to identify 7 new AGB carbon stars, to derive their mean absolute $\langle M_i \rangle$ and bolometric magnitude $M_{\rm bol}$, their luminosity function, and their spatial distribution. We are unable to establish the true C/M ratio because the few M stars of And II are overwhelmed by foreground Galactic M stars.

Key words. stars: AGB and post-AGB – stars: carbon – galaxies: local Group – galaxies: individual: And II – techniques: photometric – surveys

1. Introduction

Asymptotic Giant Branch (AGB) stars can play an important role in studies of intermediate age stellar populations in both galactic and extragalactic environments because of their high intrinsic luminosity and their well defined evolutionary stage. AGB stars are also interesting objects by themselves because they experience astrophysically relevant phenomena like pulsational variability, heavy mass loss, chemical enrichment by nucleosynthesis, and – when compared to other phases of stellar life – rapid evolution. Their study as members of external galaxies provides important clues on stellar evolution. Extragalactic systems with their often well-defined distances, metallicities, and star formation histories provide important tests for theoretical AGB models by limiting the parameter space.

Our first paper on this topic, Nowotny et al. (2001, in the following called Paper I), presented a search for AGB stars in M 31, and gave a more detailed motivation as to why it is important to study such stars in galaxies of the Local Group. Moreover, our applied photometric method to identify them in crowded fields is presented therein. The Wing-filter technique (Wing 1971) was applied successfully in earlier papers by e.g. Cook et al. (1986), Richer et al. (1985), Hudon et al. (1989), Brewer et al. (1995), in a number of papers by Demers and colleagues (2003, and references therein), and most recently by Harbeck et al. (2004), including observations on a number of Andromeda-subgroup systems.

In Nowotny et al. (2003, in the following Paper II) we presented results on two dwarf galaxies of the M 31 subgroup – NGC 185 and NGC 147. From photometry in V and i we estimated the tip of the RGB, and derived distance moduli of $24.04^{\rm mag}$ and $24.44^{\rm mag}$ for NGC 185 and NGC 147, respectively. Together with the photometric data taken in the narrow band filters TiO and CN we were able to 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.

2. And II

The next target in our photometric survey of Local Group galaxies was And II. This faint object is a dSph galaxy with a disk scale length of 94″, major axis PA ≈ 160°, a suggested ellipticity of 0.3, and an absolute visual magnitude of about

⋆ 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 at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/427/613

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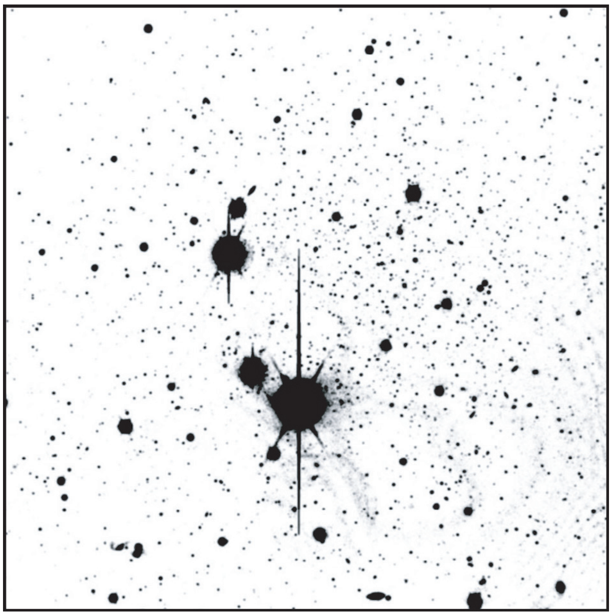

Fig. 1. *i*-band CCD image of And II obtained at the 2.56 m Nordic Optical Telescope. The field covers ≈6′.5×6′.5, i.e. most of the galaxy with its center somewhat displaced to the upper right. North is up and east to the left.

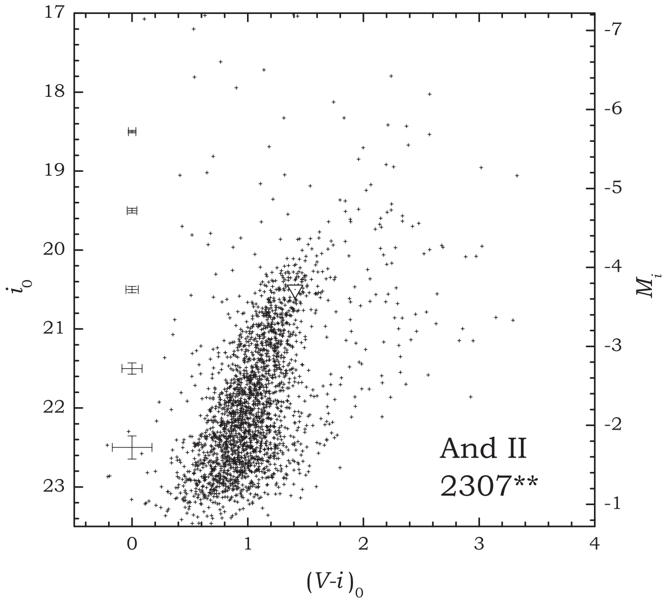

Fig. 2. Colour–magnitude diagrams for the 2307 stars with good photometry in *V* and *i* (*sample 1*; mean 1σ error bars are given for different i_0 magnitude ranges). A triangle marks the RGB-tip, as we described in Sect. 4.1. The absolute magnitudes are calculated using the distance modulus from Table 1.

–11.8. Surface brightness profiles were presented by Caldwell et al. (1992). Côté et al. (1999a) used the Keck telescope to obtain a mean radial velocity of -188 ± 3 km s^{-1} and a velocity dispersion of 9.3 ± 2.6 km s^{-1} (for seven red giants that are marked in their Fig. 2). The latter suggests a mass-to-light ratio, M/L_V, of 21^{+14}_{-10} in solar units [$L_V = 3.0^{+0.7}_{-0.5} \times 10^6\ L_{V,\odot}$ from the surface brightness profile in Fischer et al. (1992), and hence $M = 6 \times 10^7\ M_\odot$], i.e., it possesses a massive dark matter halo. The galaxy is possibly rotating. No globular clusters have been found. The extinction and reddening are measured to be, $A_V = 0.25^{\rm mag}$ and $E_{B-V} = 0.08^{\rm mag}$, respectively (Schlegel et al. 1998).

A colour–magnitude diagram in the Thuan-Gunn g, r-system obtained by König et al. (1993) at Mount Palomar, suggests a distance modulus of $23.8 \pm 0.4^{\rm mag}$, and a metallicity in the range of $-2.03 <$ [Fe/H] < -1.47 with a mean of –1.59, by comparing with Galactic globular clusters. HST-observations by Armandroff & da Costa (1999) yield a distance of ≈680 kpc [$(m-M)_0 = 24.22$], i.e., it lies in front of M 31 (their distance being between 160 and 230 kpc), and an average metallicity of ≈−1.3. Côté et al. (1999b) found a mean metallicity of -1.47 ± 0.19 and a dispersion of 0.35 ± 0.10, using Keck spectra of 42 red giants. Da Costa et al. (2000), based on HST WFPC2 data, derived a mean metallicity of –1.49, with a surprisingly large internal dispersion ≈0.36 (e.g., much larger than that of And I). Da Costa et al. also confirm the distance of about 680 kpc.

Aaronson et al. (1985) concluded that And II has an asymptotic giant branch extending to $M_{\rm bol} \approx -4.5$, and spectroscopically identify one, possibly two, carbon stars. An additional seven unpublished C-stars identified through photometry by Cook et al. are reported by Armandroff (1994). Côté et al. (1999b) identify one C-star, with a luminosity below the red giant tip, suggesting that it is a CH-star. Da Costa et al. (2000) also found that the majority of the stars in And II have ages in the range of 6–9 Gyr (from the faintness of the two Aaronson et al. AGB C-stars), although RR Lyrae stars and blue horizontal-branch stars suggest the existence of a stellar population with an age of about 10 Gyr. Guarnieri et al. (1997) discuss the use of AGB-stars as age-indicators. There are three problems associated with the use of AGB-star luminosities as age indicators; i) crowding (see also Martínez-Delgado & Aparicio 1997); ii) blue stragglers (the merged product of a close binary); and iii) a brighter core-luminosity relation for high metallicity objects.

In the most recent study, based on multi-epoch HST WFPC2 data, Pritzl et al. (2004) found 72 RR Lyrae stars and one anomalous Cepheid. From the RR Lyrae periods a mean metallicity of the red giant branch of –1.49 was derived as well as a distance of 665 ± 20 kpc from their mean magnitude.

Table 1 summarises the properties of And II. For further details one is referred to the review by Mateo (1998), and to van den Bergh (2000).

3. Data

3.1. Observations

Our 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 of September 1 and 2, 2000. Using the ALFOSC focal reducer instrument with a 2k×2k Loral-Lesser thinned CCD, we observed the field 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″.8 and 1″.2 on the combined frames which were observed at air masses

Table 1. Basic properties of And II taken from: 1 – Schlegel et al. (1998); 2 – van den Bergh (2000); 3 – Amandroff & da Costa (1999); 4 – Mateo (1998); 5 – Côté et al. (1999b).

		And II	Ref.
$\alpha_{2000}{}^{*}$		$1^{h}16^{m}27^{s}$	4
$\delta_{2000}{}^{*}$		$+33°25'42''$	4
type		dSph	2
D	[kpc]	700	3
$(m-M)_0$	[mag]	24.22	3
M_V	[mag]	−11.22	4
[Fe/H]	[dex]	−1.47	5
E_{V-I}	[mag]	0.09	1

* The observation were done following coordinates given by NASA Extragalactic Database NED, resulting in an off-centered field.

Table 2. Observing log.

Filter	NOT#	λ_c (Å)	$\Delta\lambda$ (Å)	System	Exp. time (s)
V	75	5300	800	Bessell	3 × 1200
i	12	7970	1570	Gunn	2 × 600
TiO	–	7780	110	Wing	6 × 1200
CN	–	8113	85	Wing	6 × 1200

of between 1.2 and 1.7. For the photometric calibration in V and i we additionally observed the Selected Area Fields #110, and PG 2213 from Landolt (1992). Sky flats for each filter were obtained, as were bias images.

With a pixel scale of $0\rlap{.}''189$/pixel the CCD field is $\approx 6\rlap{.}'5 \times 6\rlap{.}'5$, i.e., the major fraction of the galaxy 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 galaxy are given in Sect. 2. In addition, there are some restrictions due to vignetting and pairing, as described in more detail in Sect. 3.2. The C-stars found can be used to give a rough estimate of the extent of the galaxies (Sect. 4.4). Figure 1, an i-filter image, illustrates the low-surface brightness of the galaxy and the bright galactic foreground objects.

3.2. Reduction, calibration and astrometry

For details on reduction, calibration and subsequent astrometry we refer to the corresponding sections in Papers I and II.

In short, after basic MIDAS reduction, photometry was done for all stars using 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. We set the limits to $C1 > 0.7$ and $error < 0.5$.

The atmospheric extinction at La Palma was probed by a sequence of observations of Landolt's field SA 114 at 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. Photometric zero-points for the filters V and i were obtained from stars of the standard fields SA 110, and PG 2213 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 Papers I and II 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 $({\rm TiO-CN})_0$.

The correction for interstellar reddening in V and i was done according to the values from the NASA Extragalactic Database, namely $A_V = 0.207^{\rm mag}$, $A_i = 0.121^{\rm mag}$ (Schlegel et al. 1998).

The pairing of stars, detected in different filters, was done with the DENIS-software "Cross_Colour". All stars within a radius of 3 pixels ($\approx 0\rlap{.}''6$) were considered to correspond to each other. 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. In the following we used the centre coordinates from Mateo et al. (1998).

Altogether, this resulted in a total of 2307 stars having good photometry in V and i (*sample 1*). The maximum distance of a star to the centre of the galaxy is $5\rlap{.}'4$ in this sample. This large value for a $6\rlap{.}'5$ CCD is because of our off-centered observation.

Only 286 stars have photometry of good quality in all four filters (*sample 2*). The maximum central distance for this sample is $4\rlap{.}'6$, again because of the off-centered observation.

Coordinates and photometric properties for all stars (*sample 1*) are available in electronic form at the CDS. A short extract of the results, containing the newly detected C-stars (see below), is shown in Table A.1.

4. Results and discussion

4.1. Stellar content (colour–magnitude diagrams)

Figure 2 shows the CMD 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. The galaxy is dominated by an old, red population.

A direct estimate of the foreground contamination from our frames seems difficult as the galaxy size is a bit larger than our FOV (Sect. 4.4), and no extra field off the galaxy could be observed. As far as the C-stars are concerned the contamination is unimportant, but it may be quite important for the M giants (see below). Galactic M dwarfs in the direction of the galaxy can affect the sample significantly, see e.g. Albert et al. (2000). For further discussions see Sect. 4.4.

As described in Paper II we measured the tip of the RGB from the i_0 luminosity function in order check the reliability of our photometry. We arrived at a value of $20.5 \pm 0.2^{\rm mag}$ leading to an appoximate distance modulus of $24.5^{\rm mag}$ (790 kpc), approximate because of the poor luminosity function histogram. Nevertheless, our value seems consistent with the value of $24.22^{\rm mag}$ adopted for the rest of the paper (Amandroff & da Costa 1999).

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

# C		7
(# M)		(42)
(C/M)		(0.17)
(# M5+)		(5)
(C/M5+)		(1.4)
$\langle(V-i)_0\rangle_C$	[mag]	2.21 ± 0.34
$\langle(\mathrm{TiO-CN})_0\rangle_C$	[mag]	−0.55 ± 0.04
$\langle i_0\rangle_C$	[mag]	19.92 ± 0.50
$\langle M_i\rangle_C$	[mag]	−4.33 ± 0.50
$\langle M_{\rm bol}\rangle_C$	[mag]	−4.47 ± 0.51
$\langle L\rangle_C$	$[L_\odot]$	5170 ±2290

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

The left panel of Fig. 3 shows a colour-colour diagram for all stars of *sample 2*. Two well separated groups can be seen toward redder colours. M and C-stars differ in $(\mathrm{TiO-CN})_0$ by up to $1^{\rm mag}$. 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. 3) were defined as follows (kept unchanged from those in Paper II):

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

Using these criteria, we found 7 new C-star candidates in And II. They lie close to or above the tip of the RGB and are among the brightest red giants of the whole population, as can be seen in Fig. 3 (right). 42 M-stars lie in the corresponding area. This leads to a formal C/M ratio for the observed field of 0.17, higher than the values found for NGC 185 and NGC 147 in Paper II. This would be in agreement with the expectation that And II as the more metal-poor system should have larger C/M ratios. To be able to compare with Groenewegen (2002) we also calculated the ratio C/M5+, where we counted all stars later than spectral type M5, using our synthetic photometry (Nowotny & Kerschbaum 2002) to set the $(V-i)_0$ limit. Again we find a larger ratio for And II with a value of 1.4. The ratios agree, within the uncertainties of the method, with the results in Fig. 5 of Groenewegen (2002). Table 3 summarizes the counts for And II.

The M-star values are given in brackets since – following Sect. 4.4 below – it is questionable if there are any AGB M-giants in this And II field at all. All or most M-stars selected by our criteria may be forground M-dwarfs. Consequently, any use of the derived ratios can lead to misinterpretations. One has to check how this problem systematically effects also other C/M ratios in the literature, especially in cases of faint systems like And II.

In Harbeck et al. (2004), And II was already listed as having 2 C-stars – now we identify in total 7 C-star candidates. In the well defined relation between the number of C-stars and the luminosity of the host system presented in their Fig. 10 And II is moved up significantly from a border position to the main bulk of the discussed LG galaxies. The same applies to their metallicity relation.

4.3. Luminosity functions (LF)

Luminosity functions of C-stars in different stellar systems have turned out to be quite similar. This can be explained by the short time AGB stars spend in this evolutionary stage. Thus, one may use the narrow *i*-LF as a standard candle to estimate distances to extragalactic systems.

The influence of the chosen criteria for C-stars on the shape of the LF was already mentioned in Sect. 4.2 of Letarte et al. (2002; see their Fig. 6). This can lead to errors in the derived distances. The LF of the redder, more luminous C stars is somewhat better defined. Unfortunately for a system like And II with only seven C-stars detected the derived LF and calculated mean values are quite uncertain.

The diagram on the left in Fig. 4 shows the i_0-LFs for the seven C-stars in the selection area of Fig. 3. Their mean photometric properties can be found in Table 3. The upper axis shows our apparent magnitudes, the dotted line marks the RGB-tip as found in Sect. 4.1. The lower axis shows the corresponding absolute magnitudes calculated with the distance modulus from Table 1. A mean value of -4.33 ± 0.50 is found for $\langle M_i\rangle$ of the C-stars. This value is somewhat higher than that in NGC 147 or NGC 185. A possible reason could be our adopted distance modulus of 24.22. As mentioned already in Sect. 2, recently Pritzl et al. (2004) argued for a somewhat smaller distance modulus of 24.11. This would bring us back to a value of −4.22 for And II, in agreement with the value of −4.24 for both NGC 147 and NGC 185. Keeping in mind the small number of C-stars contributing to this number, the And II result is, at least, consistent with the possible use of C-star LFs as standard candles.

Also plotted in Fig. 4 are the bolometric LFs for the C-stars. For the calculation of $M_{\rm bol}$, we used a bolometric correction (BC) as described in Paper II. The bolometric LF for the And II C-stars are in good agreement with those previously found, keeping in mind the possible shift towards lower luminosities, when using the closer distance from Pritzl et al. (2004).

4.4. Spatial distributions and galactic foreground

Figure 5 shows the distribution of detected *sample 1* stars on the *i*-frame,the identified C-star candidates and the galaxy centre (derived as described in Sect. 3.2) are marked. The offset in the image of the faint, weakly concentrated galaxy is obvious. Also visible are small patches of "empty" space originating from very bright forground stars visible in Fig. 1 where no photometry was possible.

The M-stars are shown by full circles. It is evident that there is no concentration towards the center but a more or less random distribution in the field indicating a severe foreground fraction. A simple estimate is possible by counting the M-stars in the lower left corner (below the line), leading to 7 and an extrapolation to the whole field by $7 \times 8 = 48$. Having only 42 M-stars in the field and a simple foreground estimate of 48 leaves no room for a detection of a significant population of And II members as argued already in Sect. 4.2. Consequently, without additional information (e.g. radial velocities) our

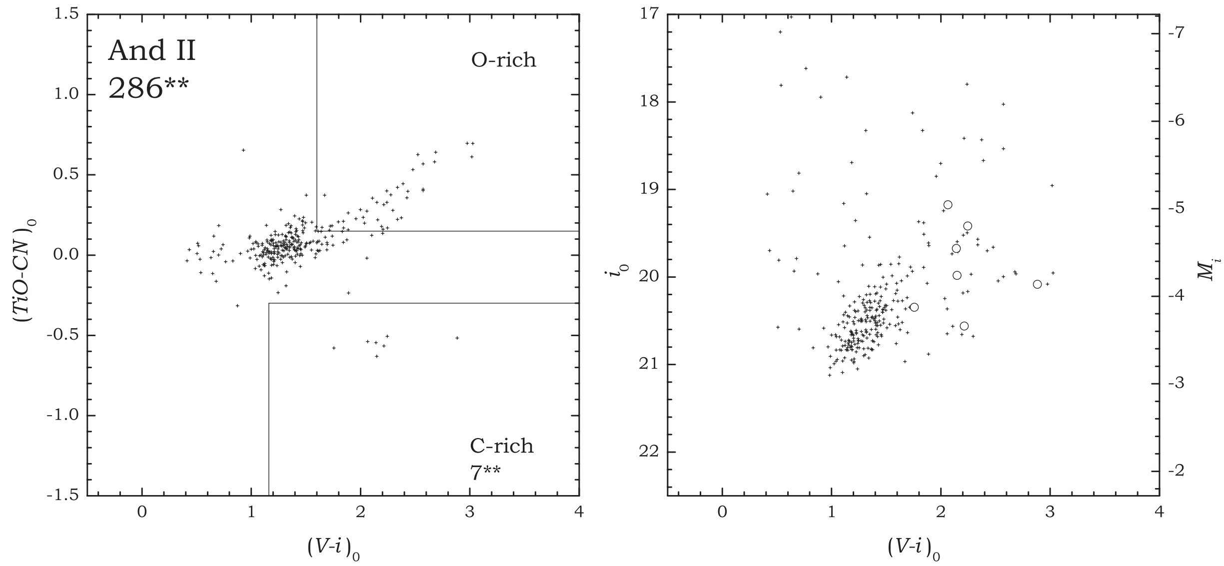

Fig. 3. *Left*: colour–colour diagram for all stars of *sample 2.* Also plotted are the selection areas for M and C-stars, as described in the text. *Right*: corresponding colour–magnitude diagram for all stars of *sample 2.* The identified C-stars from the selection areas, marked with open circles, lie on the uppermost parts of the RGB/AGB-sequences.

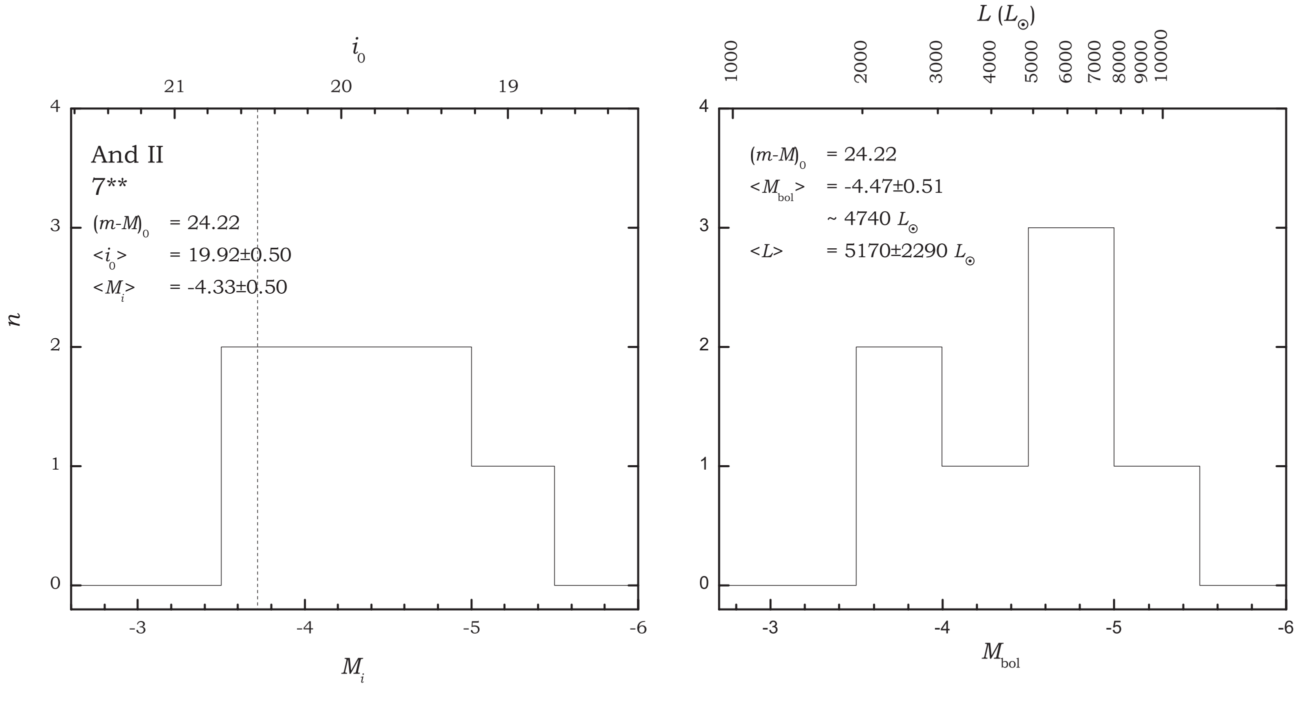

Fig. 4. *Left*: luminosity function (apparent and absolute *i* magnitude) for the seven C-stars, identified in Fig. 3. Using the distance modulus from Table 1, one can calculate a $\langle M_i \rangle$. The dotted line marks the RGB-tip from Sect. 4.1. *Right*: bolometric LFs for all C-stars found. $M_{\rm bol}$ was calculated as described in the text. Note the difference between the mean luminosity $\langle L \rangle$ and the luminosity calculated from the mean $\langle M_{\rm bol} \rangle$.

detected M-stars have to be interpreted as galactic foreground M-dwarfs.

It is clear from both a visual inspection of our frames, and from the fact that we find C-stars throughout Fig. 5, that we do not cover the entire galaxy. There is a good chance that some additional C-stars could be found in the area towards the upper right outside our field.

Figure 6 shows the radial distribution 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. The star counts were made in circular annuli around the centre. The vertical line indicates the radius beyond which part of the galaxy falls outside the CCD frame.

Within the uncertainties the distribution for all stars (*sample 1*) and that for C-stars alone are the same for all galactocentric distances.

For completeness we correlated our C-star candidates with 2MASS point sources in the field of And II. As expected from

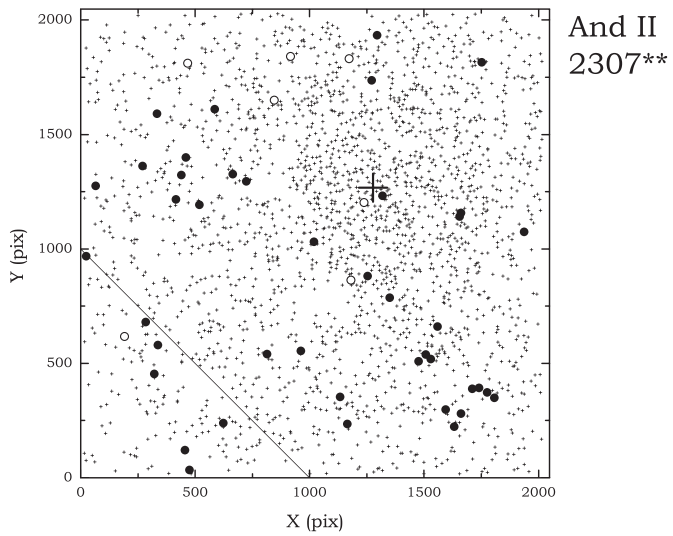

Fig. 5. Distribution of all stars of *sample 1* on the *i*-band frame, overplotted are the identified new C-stars (open circles), M-stars (full circles) and the galaxy centre (cross) (see also Sect. 3.2). The line indicates the border of the "foreground" field in the lower left corner discussed in the text.

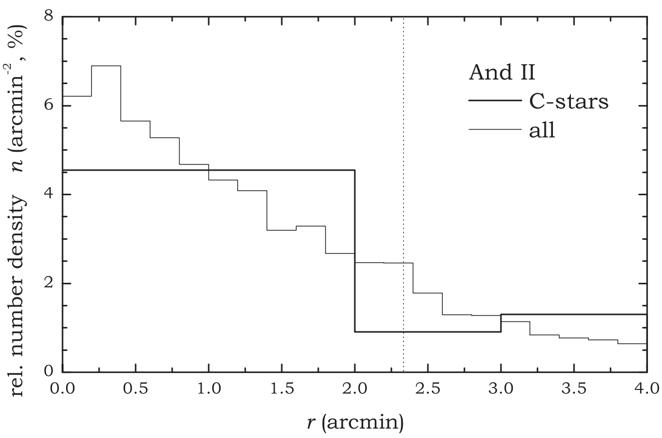

Fig. 6. Radial distributions of all stars of *sample 1* and for the found C-stars.

the limiting magnitudes of 2MASS ($J < 15.8^{\rm mag}$, $H < 15.1^{\rm mag}$ and $Ks < 14.3^{\rm mag}$) no NIR-counterparts were found.

5. Conclusions

The results of our four-colour CCD photometric observations of And II are:

- We get photometry of good quality in the V and i filters for 2307 stars, and for 286 stars in all four filters.
- With our method, based on the early work by Wing (1971), we were able to separate C- and M-stars easily with differences of up to a magnitude in the colour-colour diagrams leading to the identification of a total of seven carbon stars.
- The number of identified C-stars corresponds well with the luminosity of And II when compared to the values for other LG galaxies as presented in Fig. 10 of Harbeck et al. (2004). From their spatial distribution and number density the identified M-stars seem to be foreground galactic M-dwarfs and not AGB-stars in And II.
- For the identified C-stars we were able to derive a mean absolute magnitude $\langle M_i \rangle$ of $-4.33^{\rm mag}$. Also we give a bolometric magnitude and a luminosity function (in i and bolometric). The higher values, when compared to our results on NGC 147 and NGC 185 in Paper II, could support the somewhat lower distance determination presented by Pritzl et al. (2004).

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Appendix A: Photometric results

Table A.1. Typical example (all C-stars) for the And II results, extracted from the full table (with 2307 entries), which is available via CDS. Column 1 gives an ID code, Col. 2 the aprox. 4-digit *xy*-coordinates on CCD) for every star, while Cols. 3 and 4 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. 3 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	Pixel	RA	DE	F	i	V-i	TiO-CN
C1	12381204	011627.57	332530.15	c	20.56	2.21	-0.57
C2	11790863	011628.39	332426.30	c	20.35	1.76	-0.58
C3	11731832	011628.69	332727.74	c	19.98	2.15	-0.63
C3	09161842	011632.53	332729.53	c	19.67	2.14	-0.55
C4	08451648	011633.55	332653.10	c	19.17	2.07	-0.54
C5	04671813	011639.23	332723.67	c	19.42	2.24	-0.51
C6	01920617	011643.19	332337.96	c	20.08	2.88	-0.52
.	.	.	.	.	.	.	.
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Brewer, J. P., Richer, H. B., & Crabtree, D. R. 1995, AJ, 109, 2480
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
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