Near-IR photometry of asymptotic giant branch stars in the dwarf elliptical galaxy NGC 185^{★,★★}

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Abstract. *J*, *H* and *K'* images obtained with the Canada-France-Hawaii Telescope were used to investigate the stellar contents of the asymptotic giant branch (AGB) in the dwarf elliptical galaxy NGC 185. The bright parts of (*K*, *J* − *K*) and (*K*, *H* − *K*) color–magnitude diagrams consist of a group of bright blue stars, a dominant population of M-giants and a red C star population. There were 73 C stars with a mean magnitude of $\langle K \rangle = 16.26 \pm 0.38$, corresponding to $\langle M_K \rangle = -7.93$, and mean colors of $\langle (J - K)_0 \rangle = 2.253$ and $\langle (H - K)_0 \rangle = 0.865$. The number ratio of C stars to M-giants was estimated to be 0.11 ± 0.04 without any radial gradient from the center of NGC 185. The (*J* − *K*) and (*H* − *K*) color distributions of AGB stars showed an M-giant peak and blue and red tails, where the latter two correspond to AGB stars younger than those along M-giant peak and C stars. The bolometric luminosity functions of M-giants and C stars indicate that the M-giant AGB sequence has terminated at $M_{\text{bol}} = -6.2$, while the most luminous C star has $M_{\text{bol}} = -5.5$. The bolometric luminosity function of C stars in NGC 185 is very similar to that of recent literature values derived from *Vi* band photometry. The logarithmic slope of the luminosity function for bright M-giant stars was estimated to be 0.83 ± 0.02 in *K* band. Theoretical isochrone models, compared with the observed near-infrared photometric properties of AGB stars, indicate that star formation in NGC 185 has a wide range of ages with possibly two different epochs of star formation.

Key words. galaxies: individual: NGC 185 – galaxies: stellar content – stars: AGB and post-AGB

1. Introduction

The photometric study of resolved bright stars in Local Group galaxies provides clues for evolutionary properties of the evolved stellar populations in the systems. Among the bright giants, the asymptotic giant branch (AGB) stars allow us to study the late evolutionary stage of stars with low to intermediate masses (~ 0.8 – $8 M_{\odot}$). Moreover, photometric properties of AGB stars, which represent important constituents of the stellar population of intermediate age (1–10 Gyr), provide a direct means of probing the star formation history for the intermediate age population (Grebel 1999).

AGB stars that have already experienced core helium-burning are characterized by long-period pulsation variabilities, higher mass loss rates than typical red giant branch (RGB) stars by the orders of magnitude, and a change of atmospheric

chemical composition during the so-called thermal pulses (TP). One of the most interesting AGB problems is the formation of bright red carbon (C) stars. Starting with an oxygen-rich ($C/O < 1$) atmosphere at the start of the AGB evolution (spectral type K or M), stars can become S stars ($C/O \approx 1$) during the TP-AGB phase and finally carbon-rich ($C/O > 1$) C stars (Nowotny et al. 2001). In this sequence, C stars systematically exhibit redder color than M-giants of AGB stars. The evolutionary status of the AGB C stars is now well understood, and detailed models for the population in a galaxy with different metallicities have been recently obtained by Mouhcine & Lançon (2002, 2003). Photometric census of AGB stars and C star surveys in Local Group galaxies have also been successfully performed during the last few years (Albert et al. 2000; Battinelli & Demers 2000; Nowotny et al. 2001; Demers & Battinelli 2002; Letarte et al. 2002; Battinelli et al. 2003; Demers et al. 2003a,b; Nowotny et al. 2003; Battinelli & Demers 2004a,b,c; Harbeck et al. 2004; Kerschbaum et al. 2004), for which the narrowband, i.e. TiO and CN, photometric technique was used to differentiate C stars from the M-giants among the AGB stars.

On the other hand, near-infrared light in a galaxy is generally dominated by cool and intrinsically luminous late-type

[★] Based on observations carried out at the Canada-France-Hawaii Telescope, operated by the National Research Council of Canada, the Centre National de la Recherche Scientifique de France, and the University of Hawaii.

^{★★} Full Table 2 is only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](ftp://cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/437/61>

stars, such as supergiant stars, AGB stars and RGB stars in accordance with epochs of star formation. Because AGB stars are among the brightest and coolest stars of intermediate-age stellar population, they appear quite prominently as late-type bright giants in the near-infrared color–magnitude diagrams (CMDs) of stars in a galaxy containing intermediate-age stellar populations (e.g. Freedman 1992; Davidge 2003). AGB stars also contribute significantly to the integrated light of distant galaxies, especially in the near-infrared (Mouchine & Lançon 2002). Moreover, the reddest extreme AGB stars, i.e. C stars, can be easily distinguished from the oxygen-rich M-giant AGB stars in the broadband near-infrared CMDs. It is known that C stars occupy a particular region in near-infrared CMDs and color–color diagrams, and have near-infrared SEDs that differ from those of M-giant stars (Wood et al. 1985; Hughes & Wood 1990; Frogel et al. 1990). Recent wide field near-infrared photometry of an AGB population in the Magallanic Clouds from the 2MASS and DENIS surveys revealed the presence of a red plume of C stars in the $(K, J - K)$ CMD (Cioni et al. 1999; Nikolaev & Weinberg 2000). C stars are also known to dominate the near-infrared light in intermediate-age globular clusters (Persson et al. 1983; Frogel et al. 1990).

In the current study, deep J , H , and K' images are used to conduct the first investigation of the resolved AGB stellar contents of the nearby dwarf elliptical galaxy NGC 185 at near-infrared wavelengths. NGC 185 is a dE satellite of the Andromeda galaxy. Previous population studies of NGC 185 in optical bands (Lee et al. 1993; Martínez-Delgado & Aparicio 1997, 1998) have found a large number of RGB population stars, a small number of young blue stars, and a number of extended AGB stars up to $M_{\text{bol}} \sim -5.0$ mag, indicating that star formation in NGC 185 has occurred over an extended period of time. From four-color CCD photometry taking advantage of narrowband TiO and CN, Nowotny et al. (2003) identified 154 C stars in the central area of $6'.5 \times 6'.5$, while Battinelli & Demers (2004b) found 145 C stars scattered in the $42' \times 28'$ region centered on NGC 185. A spread of metallicity has also been detected in NGC 185. From the median color of the RGB population, Martínez-Delgado & Aparicio (1998) found a mean metallicity of $[\text{Fe}/\text{H}] = -1.43 \pm 0.15$ which decreases to -1.76 for regions further away from the galaxy center, while Lee et al. (1993) derived a mean metallicity of $[\text{Fe}/\text{H}] = -1.23 \pm 0.16$ with a range of $-1.6 < [\text{Fe}/\text{H}] < -0.9$.

The next two sections deal with J , H and K' observations of NGC 185, the data reduction procedure and photometric measurements of AGB stars in NGC 185. Photometric properties of AGB stars in CMDs and color–color diagrams are presented in Sect. 4. In Sect. 5, we discuss the photometric properties of the identified C stars, the color distributions and luminosity functions of AGB stars, and compare the brightness of AGB tips with theoretical isochrone models to discuss the star formation history in NGC 185. A summary of the results is given in Sect. 6.

2. Observations and data reduction

The images of NGC 185 were obtained during the night of UT June 3, 2004 using the CFHTIR imager mounted on

Table 1. Observational log.

RA (J2000)	Dec (J2000)	Filter	Exp. time (s)	<i>FWHM</i>
00 ^h 38 ^m 52 ^s	48°20'18''	J	8×30	0.74
		H	8×30	0.73
		K'	8×30	0.58

the f/8 Cassegrain focus of the 3.6 m Canada-France-Hawaii Telescope. The CFHTIR contains a 1024×1024 Hg:Cd:Te array with the angular scale of $0''.211/\text{pixel}$, so that each image covers a total field-of-view of $3'.6 \times 3'.6$ on the sky. Data were recorded through J , H and K' filters, and the total exposure time was 240 s per filter for the complete observing sequence of eight 30 s exposures. A four-point square dither pattern was used to assist with the identification and rejection of bad pixels and cosmic rays as well as the construction of on-sky calibration frames. The summary of the run is presented in Table 1.

Calibration frames (darks, flats and blank sky backgrounds) were also obtained from the observations. Dark frames for each integration time were recorded at the beginning and the end of the run. Dome flats were constructed by subtracting exposures of the dome white spot taken with the lamps off from those recorded with the lamps on. Thermal emission patterns for each filter were constructed by median combined flat-fielded images of blank sky regions, which were recorded at various times throughout the run.

The data were reduced using the following sequence: (1) the subtraction of a dark frame; (2) division by dome flats; (3) subtraction of the DC sky level, which was estimated by taking the mode of pixel intensity distribution in each flat-fielded frame; and (4) the subtraction of the thermal signature. The processed images were aligned to correct the dither offsets, median-combined and cropped to the region having a full 240 s exposure time. The seeings, as measured from the reduced images, are $\sim 0''.7$ *FWHM* in J , H and $\sim 0''.6$ in K' , respectively.

3. Photometric measurements

The brightness of individual objects in NGC 185 was measured with the point-spread function fitting routine DAOPHOT II/ALLSTAR (Stetson 1987; Stetson & Harris 1988). To limit the number of false detections, only those objects detected in all three filters were considered for subsequent analysis, and 7804 objects met this criterion. Photometric calibration was defined by observations of UKIRT faint standard stars (Hawarden et al. 2001).

Completeness fractions and uncertainties in the photometric measurements were estimated from artificial star experiments. The number of stars artificially added to each frame was restricted to prevent significantly increasing the amount of crowding and the frames containing artificial stars were reduced using a procedure identical to the one applied to the original frames. Figure 1 shows the results of the experiments with 1500 artificial stars, including the completeness fraction, the rms difference in magnitudes (ΔM) between the

Fig. 1. The results from artificial star experiments. *Solid, dotted and dashed lines* represent *J, H and K'* bands, respectively. The completeness is the number of recovered artificial stars divided by the total number of stars added. $\Delta M(\text{mag})$ is the mean difference between the actual input magnitudes and the measured magnitudes by DAOPHOT II/ALLSTAR, while $\sigma(\text{mag})$ is the standard deviation of the ΔM .

input and the measured brightnesses and the standard deviation of ΔM . Incompleteness becomes significant when *J*, *H* and *K'* are fainter than 18.5, 17.5 and 18.0 mag, respectively, beyond which the recovery rates of input artificial stars are less than $\sim 90\%$.

4. Photometric properties of AGB stars

4.1. Adopted reddening and distance

NGC 185 is at a relatively low Galactic latitude ($b = -14.5^\circ$) and its color excess is not negligible. Schlegel et al. (1998) obtained $E(B - V) = 0.181$ from the COBE and IRAS maps at $100 \mu\text{m}$. Lee et al. (1993) also derived $E(B - V) = 0.19$ from their direct photometry. We have corrected the interstellar reddening for stars in NGC 185 by adopting the interstellar absorption values from the NASA Extragalactic Database (i.e. $A_J = 0.165$ mag, $A_H = 0.105$ mag and $A_K = 0.067$ mag). The calculated reddening values are $E(J - H) = 0.060$, $E(J - K) = 0.098$ and $E(H - K) = 0.038$.

The distance modulus of NGC 185 was estimated from the tip of red giant branch (TRGB) by Lee et al. (1993) (23.96 ± 0.21) and Martínez-Delgado & Aparicio (1998) (23.95 ± 0.10), and RR Lyrae stars by Saha & Hoessel (1990) (23.79 ± 0.25).

Fig. 2. $(K, J - K)$ and $(K, H - K)$ CMDs of the total observed area (*upper*) and the outer region (*lower*) of NGC 185. The loci with the thin line trace the photometric evolution of the AGB tip in the range of $\log(\text{age}) = 7.8 \sim 10.2$ with $Z = 0.004, 0.008$ and 0.019 , respectively (Girardi et al. 2002). The color and magnitude range of the RGB tip at the distance of NGC 185 is also presented by the loci with thick line. Open circles indicate 27 C stars cross-identified in both near-infrared photometry (this paper) and TiO and CN band photometry (Nowotny et al. 2003).

From the re-evaluation of the TRGB method, Salaris & Cassisi (1998) estimated the distance modulus of NGC 185 to be 24.12 ± 0.32 , and this value was adopted for the subsequent analysis.

4.2. Color-magnitude diagrams and color-color diagrams

Figure 2 shows the $(K, J - K)$ and $(K, H - K)$ CMDs of stars in the total observed area and a region outside of the core radius ($r = 60''$, van den Bergh 2000) of NGC 185. The artificial star experiments in Fig. 1 indicate that the incompleteness and errors become significant when $K \geq \sim 18$, and blending effects between stars fainter than this brightness will appear due to the onset of RGB stars (cf. Davidge 2003). Therefore, the present study focuses on stars with $K \lesssim 18$, which evolve on the upper AGB.

A distinct group of the brightest blue stars can be seen at $0.6 \lesssim (J - K) \lesssim 1.2$ and $(H - K) \sim 0.1$ in the CMDs. Most of these stars are considered as foreground stars according to the Galactic star count model of Ratnatunga & Bahcall (1985), which predict approximately 30 bright blue stars with $(B - V) < 1.3$ and $V < 22$ in the field-of-view of the CFHTIR imager. Young supergiant stars are also possibly among them, according to Nowotny et al. (2003) and Martínez & Aparicio (1998). The loci with thin line in Fig. 2 trace the photometric evolution of the AGB tips in the range of $\log(\text{age}) = 7.8 \sim 10.2$ with

$Z = 0.004, 0.008$ and 0.019 , which were extracted from the compiled isochrones (Girardi et al. 2002) in the J, H and K photometric system. These indicate that some of the evolved brightest intermediate-age AGB populations could also be included in the brightest blue stars of the CMDs.

Valenti et al. (2004) calibrated the J, H and K band RGB tip brightness as a function of metallicity, from which we estimated the range of K magnitudes and the colors of the RGB tip at the distance of NGC 185 in the metallicity range of $-1.8 < [\text{Fe}/\text{H}] < -0.8$ (see Sect. 1) to be $17.65 < K < 18.25$, $1.02 < (J - K) < 1.29$ and $0.15 < (H - K) < 0.26$. The loci with thick lines in Fig. 2 present the color and magnitude of the RGB tip at the distance of NGC 185. The AGB stars above the loci of the RGB tip extend up to the upper envelopes around $K \sim 16$ mag, most of which are M-giant stars. The feature of the CMDs of the outer region is not significantly different from those of the total area, which implies that the blending effects of bright stars are negligible. The brightest redder stars in CMDs can be considered as C stars, while there may be some S type star candidates (Brewer et al. 1996; Letarte et al. 2002). Then, the CMDs of $K \lesssim 18$ consist of the brightest ~ 2 mag sequences of the AGB stars and the evolved red C stars, i.e. (1) a vertical AGB sequence of oxygen-rich M-giants, and (2) a red plume with $K < 17.25$ and $(J - K) > 1.70$ and $(H - K) > 0.54$, which is populated by C stars (Bessell & Wood 1984; Wood et al. 1985; Hughes & Wood 1990).

Detections of the M-giants, C stars and the brightest blue stars in our near-infrared observations may lead to the confirmation that NGC 185 is not solely made up of old stellar population stars, and star formation in NGC 185 has occurred over an extended period of time (e.g. Martínez-Delgado et al. 1999). Note that the discovery of more than one hundred RR Lyrae variables by Saha & Hoessel (1990) suggests that the bulk of stars in NGC 185 are old stars.

Near-infrared two-color diagrams (TCDs) are a diagnostic tool often used to identify C star candidates from observed AGB star samples (Marigo et al. 2003). Figure 3 shows the $(H - K)-(J - H)$ and $(H - K)-(J - K)$ TCDs for AGB stars brighter than $K = 17.25$. Dotted boxes contain stars with $(J - K) > 1.70$ and $(H - K) > 0.54$, which are well separated from the bulk of M-giant stars. A total of 73 stars fall into the boxes that we classified as C stars. The loci also follow the color sequence of the tip of AGB stars as in Fig. 2, and the brightest blue stars make up the tails of TCDs. The equatorial coordinates and photometric properties of the 73 C stars are listed in Table 2.

5. Discussion

5.1. C stars and C/M ratio

The mean magnitude and colors of the 73 C stars, classified in the near-infrared wavelength, are $\langle K \rangle = 16.26 \pm 0.38$, $\langle (J - K) \rangle = 2.351 \pm 0.456$ and $\langle (H - K) \rangle = 0.903 \pm 0.248$, corresponding to $\langle M_K \rangle = -7.93$, $\langle (J - K)_0 \rangle = 2.253$ and $\langle (H - K)_0 \rangle = 0.865$ with the adopted distance modulus and reddening values in Sect. 4.1. From the C star survey in the Local Group galaxies, Battinelli & Demers (2004b) found that

Fig. 3. $(H - K)-(J - H)$ and $(H - K)-(J - K)$ two-color diagrams for AGB stars brighter than $K = 17.25$. Dotted boxes contain C stars with $(J - K) > 1.70$ and $(H - K) > 0.54$. The loci are the color sequence of the tip of AGB stars same as Fig. 2. Open circles indicate 27 C stars cross-identified in both near-infrared photometry (this paper) and TiO and CN band photometry (Nowotny et al. 2003).

the mean absolute magnitudes of C stars in the I band are essentially identical in all nearby galaxies, while the $\langle M_I \rangle$ s of NGC 185 and NGC 147 are slightly fainter than those of other nearby galaxies (see also Nowotny et al. 2003). In order to confirm this trend in the near-infrared wavelength, a more homogeneous data set is needed for the Local Group galaxies. The near-infrared surveys of C stars on nearby galaxies can be obtained from moderately short exposures, and will provide an efficient means of separating C stars from M-giant stars (Marigo et al. 2003; Davidge 2003).

Recently, Nowotny et al. (2003) and Battinelli & Demers (2004b) found 154 C stars in the $6'5 \times 6'5$ area and 145 C stars more widely scattered in the $42' \times 28'$ area of NGC 185, using the VRI and the two narrowband filters CN and TiO. A cross identification of their C stars and the 73 C stars determined from near-infrared images of a total $3'6 \times 3'6$ area have 27 and 13 matches, respectively. For these cross-identified C stars, we list the $(V - i)_0$ and $(R - I)$ indices at Cols. 10 and 12 of Table 2 with ID numbers from Nowotny et al. (2003) and Battinelli & Demers (2004b). We present the TCDs of JHK and VRI bands for the C stars in Fig. 4. The vertical dotted lines show the near-infrared color ranges of C stars, i.e. $(J - K) > 1.70$ and $(H - K) > 0.54$.

Table 2. Coordinates, near-infrared photometric properties of 73 C stars and color indices in *VRI* bands of cross-identified C stars. Columns 10 and 12 list the $(V-i)_0$ and $(R-I)$ colors of cross-identified C stars. Columns 11 and 13 give the ID numbers for stars in Nowotny et al. (2003) and Battinelli & Demers (2004b). The full table is available in electronic form at the CDS.

ID	RA(J2000)	Dec(J2000)	J	σ_J	$J-K$	$\sigma_{(J-K)}$	$H-K$	$\sigma_{(H-K)}$	$(V-i)_0^a$	ID $_N^a$	$R-I^b$	ID $_B^b$
1	00 38 48.89	+48 21 32.7	17.956	0.087	2.042	0.098	0.714	0.052				
2	00 38 50.02	+48 18 55.4	18.493	0.039	1.795	0.044	0.601	0.029	2.25	23	1.338	38
3	00 38 51.36	+48 19 48.3	18.605	0.039	2.411	0.043	1.097	0.041	1.76	25		

^a Nowotny et al. (2003).

^b Battinelli & Demers (2004b).

Fig. 4. TCDs of *JHK* and *VRI* bands for 27 cross-identified C stars with $(V-i)_0$ indices from Nowotny et al. (2003) and 13 cross-identified C stars with $(R-I)$ indices from Battinelli & Demers (2004b). Vertical dotted lines are the near-infrared color ranges of C stars, i.e. $(J-K) > 1.70$ and $(H-K) > 0.54$, while horizontal dotted lines are the color ranges of C stars in *VRI* bands, i.e. $(V-i)_0 > 1.16$ and $(R-I) > 1.06$, given by Nowotny et al. (2003) and Battinelli & Demers (2004b).

We also estimated the number ratio of C stars to M-giant stars (C/M) of the AGB population in NGC 185. To decrease the effect of the foreground stars on the total counts of M-giant stars, we assigned M-giant stars as $K < 17.25$ and $1.00 < (J-K) < 1.70$ on the $(K, J-K)$ CMD. This yields $C/M = 0.11 \pm 0.04$ for the total observed area and $C/M = 0.11 \pm 0.05$ for the inner region ($r < 60''$). We could not find any radial gradient of C/M in the observed field of NGC 185. The estimated value of C/M in NGC 185 from near-infrared photometry is comparable to those of 0.089 from Nowotny et al. (2003) and 0.17 ± 0.02 from Battinelli & Demers (2004b), who also found no apparent C/M radial gradient in NGC 185. The formation of C stars in a galaxy is known to be both a function of metallicity and star formation (Groenewegen 1999; Battinelli & Demers 2004b). Therefore, the homogeneous data set of C/Ms for the Local Group galaxies estimated from the near-infrared

Fig. 5. Histogram distributions of the $(J-K)$ (lower) and $(H-K)$ (upper) colors of stars with K between 15.25 and 17.25 mag.

observational survey will be a complementary confirmation of the correlations.

5.2. Color distributions

Figure 5 shows the histogram distributions of the $(J-K)$ (lower) and $(H-K)$ (upper) colors for stars with $15.25 < K < 17.25$ in 0.05 mag bins. Eye-fitted Gaussians are traced over the histograms with σ values equal to the random photometric errors, $\sigma_{(J-K)} = 0.094$ and $\sigma_{(H-K)} = 0.103$, predicted from the artificial star experiments (Fig. 1), and normalized to match the number of stars in the central bins of the M-giant peaks. Both $(J-K)$ and $(H-K)$ histograms have an M-giant peak and blue and red tails. The shaded histograms of the red tail correspond to the C stars, which produce an excess population of objects with respect to M-giants when $(J-K) > 1.70$ and $(H-K) > 0.54$ as defined in Sect. 4.2. The blue tails are also shown in the color histograms when $(J-K) < 1.25$ and $(H-K) < 0.15$, due to AGB stars younger than those along the M-giant peaks. Davidge (2003) analyzed the $(J-K)$ histogram distributions of AGB and C stars in NGC 205, and

Fig. 6. K band cumulative luminosity function of M-giant stars in NGC 185. Arrows indicate the range of the tip of AGB, i.e. $15.65 < K < 15.99$.

used the predicted colors from Girardi et al. (2002) to find that stars forming the blue tail in the inner region of NGC 205 have $\log(t_{\text{yr}})$, which is at least a few tenths of a dex smaller than the stars in the M-giant peak. The same predicted colors for three $Z = 0.019$ isochrones ($\log(t_{\text{yr}}) = 7.8, 8.8$, and 9.4), assuming $E(J - K) = 0.098$, are also shown in Fig. 5, indicating that the ages of stars in the blue tail are $\log(t_{\text{yr}}) \lesssim 8.5$. The Gaussian distributions in Fig. 5 evidently contain the M-giant stars in a wide range of ages. Therefore, the result of the histogram distributions of stars in NGC 185 serves as evidence that the star formation in NGC 185 took place over a wide range of ages.

5.3. Luminosity functions

Identifying the peak K brightness for AGB stars in a galaxy is not easy because of the need for large observational samples and known field star contamination. The Galactic star count model (Ratnatunga & Bahcall 1985) predicts only 5 ~ 10 field stars with similar colors and magnitudes as the AGB stars in NGC 185. From this model we disregard the field star contamination in the luminosity function analysis of our observed area. Moreover, if the blending of multiple stars is an issue, it must be taken into consideration that the location of the AGB tip can be brighter than the isolated stars. However, the similarity of the bright-end envelope morphologies of CMDs through the observed area (e.g. Fig. 2) and the scattered spatial distribution of bright AGB stars suggest that the blending effects in our near-infrared images do not have a serious effect on the luminosity function analysis of AGB stars in NGC 185.

The cumulative luminosity function of the M-giants of AGB stars is shown in Fig. 6, from which we determined the AGB tip magnitude. The upper axis shows the corresponding absolute magnitudes which are calculated from the adopted distance modulus and the reddening of NGC 185. The criteria of M-giants were $1.00 < (J - K) < 1.70$ in color and $15.25 < K < 17.25$ in magnitude excluding the bright blue stars and the C stars. The $K = 17.25$ criterion is based on the approximate lower envelope of the C star plume in the CMDs of Fig. 2. A simple Sobel filter detection method has been applied to determine the AGB tip on the cumulative

Fig. 7. *Left:* the completeness-corrected luminosity functions in M_K for M-giant stars and C stars. The inner small panel in the lower panel shows the logarithmic luminosity function of M-giant stars in NGC 185. *Right:* the completeness-corrected bolometric luminosity functions for M-giant stars and C stars.

luminosity function of Fig. 6. Two edges with significant gradients were detected at $K = 15.65 \pm 0.03$ and 15.99 ± 0.02 , the absolute magnitudes of which turn out to be $M_K = -8.54$ and -8.20 . These two edges and the apparent shape of the luminosity function suggest that the magnitude range of AGB tip is $15.65 < K < 15.99$, rather than determining a definite magnitude of the AGB tip.

As a good approximation, all resolved stars in a galaxy can be assumed to have the same distance, therefore, we can calculate luminosity functions with the magnitude bin for the observed stars. To determine the luminosity functions of AGB stars in a galaxy using the near-infrared bands is indeed much more reasonable than the optical bands, as Freedman (1992) noted that some very red bright stars that are visible on near-infrared images are not always detected on optical band images. The luminosity functions in the bolometric magnitudes for stars in a Local Group galaxy are also one of the most important concepts used for comparing models of M-giant AGB star and C star evolution with observations.

Battinelli & Demers (2004b) showed the I band LF of C stars in NGC 185 is Gaussian, but the standard deviation is approximately 50% larger than those observed in other nearby galaxies. They also found that the mean absolute magnitude of the C stars of NGC 185 is essentially identical to the $\langle M_I \rangle$ of the C stars in NGC 147, both of which are fainter than the mean value determined for seven galaxies with numerous C stars (Demers et al. 2003b), and the scatter in magnitude could certainly be explained by the compactness of NGC 185.

The two diagrams on the left in Fig. 7 show the completeness-corrected luminosity functions in M_K for M-giant stars and C stars in NGC 185. We applied two-side Kolmogorov-Smirnov tests to compare the M_K luminosity

function of C stars to the Gaussian with the mean absolute magnitude and standard deviation of $\langle M_K \rangle = -7.93 \pm 0.38$, which were estimated in Sect. 5.1. However, obtaining a 14% confidence level of having same distribution for the two indicated that the M_K luminosity function of C stars in NGC 185 is unlikely to be a Gaussian distribution. The inner small panel in the lower-left panel shows the logarithmic luminosity function of M-giant stars in NGC 185, from which we estimated the logarithmic slope of the M_K luminosity function for the bright stars ($M_K < -7.5$) in NGC 185 to be 0.83 ± 0.02 . Lee et al. (1993) estimated the logarithmic slope of the V band luminosity function of NGC 185 for the bright stars to be 0.54 ± 0.06 , which is consistent with other nearby galaxies. The universality of the slope in the K band luminosity function can be checked with more near-infrared photometry of the resolved AGB stars in nearby galaxies.

Bolometric corrections in K band, BC_K , were estimated separately for each M-giant and C star in NGC 185, using the empirical relations between BC_K and $(J - K)$ for Galactic and LMC oxygen-rich M-giant AGB stars (Bessel & Wood 1984), and for C stars in LMC (Costa & Frogel 1996). Notice that there can be relatively large differences in the BC s depending on the authors, especially for C stars, as can be seen in Montegriffo et al. (1998). Indeed, the clear deviation of the very few C stars in Fig. 1 of Bessel & Wood (1984) suggests a different BC for C stars.

Using the bolometric corrections above, the completeness-corrected bolometric luminosity functions for the M-giant stars and the C stars in NGC 185 were constructed from near-infrared photometry. For the lower limit we followed the usual $M_{\text{bol}} < -3.5$ threshold corresponding to the luminosity of the tip of RGB (Ferraro et al. 2000). The bolometric luminosity function of M-giant stars in NGC 185 extends up to $M_{\text{bol}} = -6.2$ mag, as shown in the lower-right panel of Fig. 7, while that of only C stars, in the upper-right panel of Fig. 7, spans $-5.5 < M_{\text{bol}} < -3.5$ with a mean bolometric magnitude $\langle M_{\text{bol}} \rangle = -4.50 \pm 0.42$. The shape of the bolometric luminosity function and the mean bolometric magnitude of C stars in NGC 185 estimated in this paper are in good agreement with those of Nowotny et al. (2003) which are estimated from their V_i band photometry assuming the distance modulus 23.96. Note that the M-giant AGB sequence in NGC 185 terminated at $M_{\text{bol}} = -6.2$, while the most luminous C stars had $M_{\text{bol}} = -5.5$. Davidge (2003) found a similar feature for stars in NGC 205, and attributed it to either the small number statistics of brightest AGB stars or the variability of the brightest AGB stars at the peak of AGB brightness.

5.4. AGB tip and age

The brightness of the AGB tip can be used to determine the epochs of star formation in a galaxy when it is compared to theoretical isochrones of AGB stars (e.g. Girardi et al. 2002). By applying the predicted relationship between AGB tip brightness and age to NGC 205, Davidge (2003) found that the brightest AGB stars formed within the past 0.1 Gyr and that

Fig. 8. Relation between the K magnitude of the AGB tip and age, as predicted by isochrones (Girardi et al. 2002) for $Z = 0.04$ (solid line), 0.08 (dotted line) and 0.019 (dashed line). The range of the tip of the AGB determined from Fig. 6 is indicated by the pairs of arrows.

the previous episode of star formation occurred a few tenths of a Gyr earlier in the galaxy.

We also extracted isochrones of Girardi et al. (2002) with $Z = 0.004, 0.008$ and 0.019 to derive the relationship between K brightness of the AGB tip and age. The isochrones were applied not to C stars but only to M-giant AGB stars. The results are shown in Fig. 8 with the range of AGB tip brightness in K, i.e. 15.65–15.99 mag, determined from the cumulative luminosity function of the M-giant stars in Sect. 5.3. The K brightness range of the AGB tip is consistent with stars having $\log(t_{\text{yr}}) \approx 9.0\text{--}9.4$ and $7.8\text{--}8.5$. This indicates that there were possibly two different epochs of star formation for the bright M-giant AGB stars in NGC 185. The age range of the younger bright M-giant AGB stars is very similar to the ages of the stars in the blue tail in the $(J - K)$ color distribution of Fig. 5, i.e. $\log(t_{\text{yr}}) < 8.5$. As indicated in Fig. 5 of the Gaussian distribution of M-giant stars with a wide range in color, both the older and the younger bright M-giant AGB stars could contain stars spanning a wide range of ages. Note also that the peak AGB brightness for a population with $\log(t_{\text{yr}}) = 10.0$ should occur near $K \sim 16.5$ in Fig. 8 at the distance of NGC 185. Therefore, model comparisons indicate that the bright M-giant AGB stars in NGC 185 span a wide range of ages, and they were possibly formed at two different epochs of star formation.

6. Conclusion

The near-infrared J , H and K' images were used to investigate the bright stellar contents of the AGB population in the nearby dwarf elliptical galaxy NGC 185. The results are as follows:

1. The near-infrared CMDs show RGB and AGB star populations where the latter consists of a group of bright blue stars, a dominant M-giant population and a red C star population.
2. A total of 73 C stars are clearly separated from M-giant stars in the near-infrared CMDs and TCDs. The mean magnitude of the C stars is $\langle K \rangle = 16.26 \pm 0.38$, corresponding to $\langle M_K \rangle = -7.93$, and the mean colors are $\langle (J - K)_0 \rangle = 2.253$, $\langle (H - K)_0 \rangle = 0.865$.

3. The C/M ratio of AGB stars is 0.11 ± 0.04 , which has no sign of a radial gradient within the observed area.
4. The $(J - K)$ and $(H - K)$ color distributions of AGB stars contain an M-giant peak, and blue and red tails. Stars in the blue tail are younger AGB stars than those along the M-giant peak, while the red tail corresponds to the C stars.
5. The range of the AGB tip of NGC 185 has been identified at $K = 15.65 \sim 15.99$ from the cumulative luminosity function of M-giant stars.
6. The slope of the logarithmic K band luminosity function of M-giant stars brighter than $M_K = -7.5$ is estimated to be 0.83 ± 0.02 .
7. The bolometric luminosity functions of M-giants and the identified C stars are given. That of C stars in NGC 185 is very similar to the one in Nowotny et al. (2003) derived from Vi band photometry. In the bolometric luminosity functions, the M-giant AGB sequence terminated at $M_{\text{bol}} = -6.2$, while the most luminous C star had $M_{\text{bol}} = -5.5$.
8. Comparisons to the theoretical isochrone models with the determined peak AGB brightness and the color distributions indicate that the M-giant population contains stars in a wide range of ages with possibly two different epochs of star formation (i.e. $\log(t_{\text{yr}}) \approx 9.0 \sim 9.4$ and $7.8 \sim 8.5$).

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