The assessment of the near infrared identification of Carbon stars. I. The Local Group galaxies WLM, IC 10 and NGC 6822 *

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ABSTRACT

Context. The selection of AGB C and M stars from NIR colours has been done in recent years using adjustable criteria that are in need of standardization if one wants to compare, in a coherent manner, properties of various populations.

Aims. We intend to assess the NIR colour technique to identify C and M stars.

Methods. We compare the NIR colours of several C stars previously identified from spectroscopy or narrow band techniques in WLM, IC 10 and NGC 6822.

Results. We demonstrate that very few M stars have $(J-K)_0 > 1.4$ but a non negligible number of C stars are bluer than this limit. Thus, counts of M and C stars based on such limit do not produce pure samples.

Conclusions. C/M ratios determined from NIR colours must be regarded as underestimates mainly because the M numbers include many warm C stars and also K stars if no blue limit is considered.

Key words. galaxies, individual: IC 10, WLM, NGC 6822, Carbon stars

1. Introduction

Carbon stars were initially identified in large numbers by objective prism surveys, first in the Milky Way (Blanco 1965, Westerlund 1965) then a decade later similar surveys toward the Magellanic Clouds (Blanco et al. 1978) yielded hundreds of C stars. To reach fainter magnitudes thus larger distances, a photometric technique based on two narrow band filters was introduced in the nineteen eighties (Richer et al. 1984; Cook et al. 1986). This approach, based on the $[(CN-TiO)]$ index along with a colour, such as $(V-I)$ or $(R-I)$ has been successfully exploited to survey most of the Local Group galaxies (see for example: Battinelli & Demers 2005a; Brewer et al. 1995; Nowotny et al. 2003; Rowe et al. 2005). The narrow band technique presents, however, some serious drawbacks, the required filters are expensive to acquire and more importantly they are not available on major telescopes.

With the evolution of the near infrared (NIR) instrumentation Asymptotic Giant Branch (AGB) stars became the subjects of a number of observations in the Galaxy and beyond. Mould & Aaronson (1980) demonstrated that AGB stars in the SMC have slightly bluer NIR colours that their cousins in the LMC. Spectroscopically confirmed C stars were found to fall on an extend red tail in the $(J-K)$ vs $K$ plane, thus easily distinguishable from the O-rich M stars. Survey of the literature reveals, however, that the C and M star border is ill-defined. Hughes & Wood (1990) found from their NIR survey of LMC Miras, with known spectral types, that 98% of O-rich stars have $J-K < 1.6$ while 15 out of 87 C-rich stars have $J-K < 1.6$. They therefore adopted a O- to C-rich transition at $J-K = 1.6$.

Davidge (2003) in his study of NGC 205 adopts, for C stars, $(J-K) > 1.5$ and $(H-K) > 0.4$ quoting Hughes & Wood (1990). Analyzing the 2MASS data for the LMC, Nikolaev & Weinberg (2000) set their blue limit of the C star region at $(J-K) \approx 1.4$. More recently, Cioni & Habing (2003) adopted $(J-K) > 1.4$ and $(J-K) > 1.3$ for the LMC and SMC, respectively. However, Cioni & Habing (2005) used another limit for the C stars in NGC 6822, namely $(J-K)_0 > 1.24$, while Kang et al. (2006) adopted for this galaxy $(J-K)_0 > 1.4$ and $(H-K)_0 > 0.45$. For NGC 147 Sohn et al. (2006) took $(J-K)_0 > 1.25$ and $(H-K)_0 > 0.41$ for the C stars identification. The same team used for NGC 185 the color limits $(J-K)_0 > 1.6$ and

* Based on observations obtained at the Italian Telescopio Nazionale Galileo.
(H − K)$_0$ > 0.48 (Kang et al. 2005). Davidge (2005) chose (J − K)$_0$ > 1.4 and (H − K)$_0$ > 0.45 for both NGC 185 and NGC 147. Finally, Valcheva et al. (2007) assumed (J − K)$_0$ > 1.20 for the C stars in WLM. Several of the cited authors set the color limit inspecting the (J − K)$_0$ color histogram.

It is well known that the NIR colours of the RGB are function of the metallicity of the stellar population (Ferraro et al. 2000). The mean colours of O-rich or C-rich AGB stars brighter than the tip could similarly be metallicity dependent. There is at the present time no observational evidence for this effect. The NIR colour comparison of the AGB in the Magellanic Clouds and a Galactic field (Schultheis et al. 2004) does not reveal such trend. From this brief literature survey it appears evident that, we are still far from any consensus about the use of NIR photometry to select C and M AGB stars. The different colour limits adopted are often introduced to account to some extent for metallicity differences of the parent galaxies. This could certainly explain why the published C/M ratios for a given galaxy sometime wildly differ.

In order to address this question we have started a program of JHK observations of several Local Group galaxies which already have a known C star population obtained from the (CN − TiO) index. The separation between O-rich and C-rich AGB stars based on the (CN − TiO) index has been proved (Brewer et al. 1996, Albert et al., 2000) to be very reliable as long as the optical colors of the stars are redder than a certain limit (e.g. (R − I)$_0$ > 0.90). For each galaxy, it is therefore reasonable to consider the sample of C stars identified with the narrow-band approach as a template to test other photometric criteria. In this first paper we discuss the case of three galaxies of different metallicities: WLM and IC 10 with newly acquired data, and NGC 6822 already available in the literature.

1.1. The target galaxies

Wolf-Lundmark-Melotte (WLM) dwarf galaxy is located on the periphery of the Local Group and it is seen at a high Galactic latitude (ℓ = 76°, b = −74°), thus being essentially extinction free. From the investigation of Dolphin (2000), we adopt (m − M)$_0$ = 24.90 for its distance and a metallicity for its intermediate-age population of [Fe/H] = −1.4. WLM has been the target of a recent NIR study by Valcheva et al. (2007) who identified numerous C and M AGB stars. They determined a C/M ratio for WLM that is quite different from the one calculated by Battinelli & Demers (2004) from the (CN − TiO) criterion. As we shall see the difference comes mostly from the different sets of M and C stars.

IC 10 is a dwarf irregular galaxy, most probably associated with M31 and located at a rather low Galactic latitude (ℓ = 119°, b = −3°). It is often described as the only starburst galaxy of the Local Group. Its study is hindered by the high reddening E(B − V) ≈ 0.8 along the line of sight. IC 10 is not extremely metal poor, from the oxygen abundance of its HII regions Garnett (1990) determined [Fe/H] = −0.8, this value would correspond to its youngest population but intermediate-age stars should have slightly lower metallicities. The central star forming region of IC 10 has been observed in JHK by Borissova et al. (2000) who, however, did not comment on the presence of C stars. Since the starburst makes the central region difficult to investigate, our NICS observations target an outer region. IC 10 is particularly suited for NIR observations, it is relatively near at (m − M)$_0$ = 24.35, (Demers et al. 2004) and contains nearly 700 C stars distributed over an area much larger than its starburst core. From Demers et al. (2004) we have the R,I magnitudes of these C stars along with their narrow-band colors.

For NGC 6822 we will use the NIR photometry published by Kang et al. (2006) and the optical photometry by Letarte et. al. (2002).

2. Colours of C stars

When looking at spectra it is quite easy to distinguish a late M star from a C star. From the photometric point of view, the differences between the two types are not so clear cut. We believe that the best non-spectroscopic way to divide M and C stars is with the use of narrow band filters such as the (CN − TiO) index. A colour-colour diagram, based on this index and taken from Battinelli & Demers (2004) is shown in Figure 1. The upper branch, corresponding to C stars is well isolated from the lower M star sequence. Investigation of the spatial distribution of the scattered points just above the M branch reveals that they corresponds to objects uniformly distributed over the CFH12K field. We believe that they are non-stellar objects with sharpness just below the rejection limit. A very informative figure showing the CN and TiO wavelength ranges over C and M spectra can be found in Nowotny et al. (2002). This technique has limitations however, it fails for bluer AGB stars, where the two branches converge into a big clump. In this particular example there are few blueish C stars but this is not always the case. For this reason we have adopted (R − I)$_0$ = 0.90 for the blue limit of the C and M star counts. Furthermore, there is no easy way to distinguish Galactic M dwarfs from giants without using time-consuming multicolor systems (e.g. Majewski et al., 2000).

Figure 2, taken from Demers et al. (2002), displays a near infrared colour-magnitude diagram of the spectroscopically identified C stars in the Large Magellanic Cloud. Fig. 2 demonstrates that C stars, being distributed along the AGB, show an appreciable (J − K) colour range and also a large magnitude range. They are certainly not exclusively red. We also see that the use of C stars as standard candles requires a severe restriction on the selected colour range. Indeed, Weinberg & Nikolaev (2001), successfully used C stars selected in a narrow colour range as reliable standard candles to produce a 3D map of the LMC.

The study of NIR colours of spectroscopically identified C stars is unfortunately limited almost exclusively to the Magellanic Clouds. Indeed, many Galactic C stars have NIR colours but because the reddening in the plane is often far from negligible their observed colours are not so useful. Furthermore, to select C stars, one needs an unbiased colour selection not always achieved. This is certainly the case for the Fornax dwarf spheroidal galaxy where a few dozen C stars are...
Fig. 1. A typical colour-colour diagram (WLM, Battinelli & Demers, 2004) showing the C and M branches.

Fig. 2. The CMD of spectroscopically identified C stars in the LMC confirms their wide colour and magnitude ranges.

3. Observations and reduction

The $J, H, K_p$ observations were secured with NICS (Near Infrared Camera Spectrometer; Baffa et al. 2001) installed at the Nasmyth focus of the TNG (Telescopio Nazionale Galileo) on the island of La Palma. NICS is based on a HgCdTe Hawaii 1024×1024 array. The field of view for imaging is 4.2′×4.2′. One field in WLM 2.5′ from its center and one 3′ from the center of IC10 were acquired with a 4×4 dithering pattern. The central core of each galaxy is therefore excluded. Table 1 summarizes the observations obtained during two nights (IC 10: 2006-08-30; WLM: 2006-08-31) under photometric conditions with pretty stable seeing 0.7″ ± 0.8″. Data pre-reduction was performed with Speedy Near-infrared-Automatic Pipeline (SNAP, Mannucci, in preparation), described in [http://www.tng.iac.es/news/2002/09/10/snap](http://www.tng.iac.es/news/2002/09/10/snap The basic steps of SNAP are briefly described here. After flat-fielding, a first-pass sky subtraction is performed and the resulting images are combined together. Objects detected in this image are masked out to perform a second-pass sky subtraction, improving the estimate of the sky level and the photometric accuracy. The final images are combined to a sub-pixel precision by cross-correlating the object masks.

The photometric reduction of the combined images is done by fitting model point-spread functions (PSFs) using DAOPHOT-II/ALLSTAR series of programs (Stetson 1987, 1994). Since the resulting images are medians, stars as bright as $K_s = 13.5$ are not saturated. Furthermore, we see no deviation from linearity when comparing the 2MASS magnitudes to the instrumental magnitudes of the IC10 field.

4. Results

4.1. WLM

The line of sight toward WLM points far above the Galactic plane, thus our small field of view contains few Galactic stars but at faint magnitudes one would expect to detect more unresolved galaxies than stars. Cross identification with the 2MASS point source catalog yields only three matches brighter than $K_s < 14.6$, nevertheless a reliable calibration of our instrumental magnitudes is possible. We obtain the following zero point shifts:

\[ K_s = -0.442(\pm 0.036) + K_{\text{inst}}, \]
\[ J = 1.010(\pm 0.060) + J_{\text{inst}}, \]
\[ H = 0.311(\pm 0.068) + H_{\text{inst}}. \]

DAOPHOT-II provides an image quality diagnostics SHARP. Stetson (1987) devises a sharpness criterion by comparing the height of the best-fitting Gaussian function to the height of a two-dimensional delta function, defined by taking the observed intensity difference between the central pixel of the presumed star image and the mean of the remaining pixels used in the fit. For isolated stars, SHARP should have a value close to zero, whereas for semi resolved galaxies and unrecognized blended doubles SHARP will be significantly greater than zero. On the other end, bad pixels and cosmic rays produce SHARP less than zero. SHARP must be interpreted as a function of the apparent magnitude of all objects because the SHARP parameter distribution degenerates near the magnitude limit; see Stetson & Harris (1998) for a discussion of this parameter. From Figure 3 we define the stellar zone where known. Spectra of only the very red giants were obtained to confirm their C star nature (Mould & Aaronson 1980).

### Table 1. Journal of observations (J2000 coordinates)

| Galaxy | RA     | Dec     | $J$     | $H$     | $K_s$  |
|--------|--------|---------|---------|---------|--------|
| WLM 00:02:02 -15:30:00 | 3840 s | 1280 s  | 1280 s  |
| IC10 00:19:55 +59:19:26 | 5760 s | 1800 s  | 900 s   |

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SHARPs are within ±0.15 from zero. The color-magnitude diagram (CMD) of the field in WLM is displayed in Figure 4. Only stars with small SHARP parameters are plotted.

Table 2 lists the near infrared magnitude and colors of the 62 C stars previously identified. Magnitude errors are standard errors as defined by DAOPHOT thus not including the additional error from sky background variations. We note however that the calibrations of our instrumental magnitudes with 2MASS stars (particularly for IC 10 with 78 stars, next subsection) yield calibration equations with slope 1 and dispersions along the trend of just a few hundreds of magnitudes thus suggesting a very efficient sky subtraction performed by SNAP. Colour errors are quadratic sums of the magnitude errors. Optical photometry and identification number are from Demers & Battinelli (2004).

4.2. IC 10

Thanks to its low Galactic latitude, the IC 10 NICS field contains 78 2MASS stars suitable for magnitude calibrations. We obtain the following zero points:

\[
K_s = -0.264(\pm 0.032) + K_{\text{inst}},
\]
\[
J = 1.020(\pm 0.011) + J_{\text{inst}},
\]
\[
H = 0.299(\pm 0.022) + H_{\text{inst}}.
\]

The CMD of the region observed in IC 10 is displayed in Figure 5. We find in the NICS field 52 C stars, listed in Table 3, previously identified by Demers et al. (2004). According to our reddening map, the mean reddening in the NICS field is \(E(B-V) = 0.86\) which corresponds following the relations of Schlegel et al. (1998) to \(E(J-K_s) = 0.45, E(H-K_s) = 0.23\) and \(A_K = 0.32\). The optical magnitudes and colours of IC 10 are individually deredden using our reddening map.

5. Discussion

To compare the NIR properties of C and M stars identified by the narrow-band technique, we show in the left panel of Figure 6 an aspect of the cross-identification between our CFHT photometry of WLM (all stars) and our new NIR observations. We see two well separated groups of points: the C stars with \((CN-TiO) > 0.3\) and the K and M giants with negative \((CN-TiO)\). The solid vertical line at \((J-K_s)_0 = 1.4\) is the often adopted limit for the C star selection (see Sect. 1). Stars with \((CN-TiO)\) smaller than ≈ −0.3 have \((J-K_s)_0\) and \((H-K_s)_0\) colors typical of late dwarfs (see Bessell & Brett, 1988) that are seen here along the line of sight and mimic AGB stars. The dashed line is the Valcheva et al. (2007) limit to select C stars from the AGB stars found in their WLM study. They called AGB stars all the objects brighter than \((J-K_s)_0 = 1.2\) as M stars. We see from
Table 2. Known C stars in the WLM NICS field

| id  | I   | (R − I) | (CN − TiO) | Ks | $\sigma_K$ | (J − Ks) | $\sigma_{JK}$ | (H − Ks) | $\sigma_{HK}$ |
|-----|-----|---------|-------------|----|-----------|----------|------------|----------|------------|
| 23  | 20.404 | 1.233   | 0.833       | 17.428 | 0.061    | 1.904    | 0.064     | 0.731    | 0.068      |
| 24  | 20.142 | 1.532   | 0.387       | 16.795 | 0.043    | 1.730    | 0.048     | 0.609    | 0.052      |
| 26  | 20.260 | 1.026   | 0.477       | 17.729 | 0.076    | 1.293    | 0.077     | 0.362    | 0.080      |
| 29  | 20.230 | 1.083   | 0.486       | 17.428 | 0.063    | 1.364    | 0.065     | 0.347    | 0.066      |
| 31  | 20.145 | 0.965   | 0.405       | 17.885 | 0.104    | 1.114    | 0.108     | 0.154    | 0.112      |
| 38  | 20.238 | 0.971   | 0.363       | 17.665 | 0.086    | 1.147    | 0.088     | 0.239    | 0.090      |
| 41  | 19.956 | 1.218   | 0.458       | 17.446 | 0.073    | 1.526    | 0.077     | 0.476    | 0.083      |
| 43  | 19.995 | 0.931   | 0.451       | 17.531 | 0.063    | 1.281    | 0.065     | 0.285    | 0.068      |
| 44  | 20.373 | 1.000   | 0.454       | 17.937 | 0.087    | 1.178    | 0.090     | 0.268    | 0.092      |
| 45  | 21.104 | 1.128   | 0.446       | 17.255 | 0.051    | 1.703    | 0.053     | 0.549    | 0.055      |

*Table 2 is presented in its entirety in the electronic edition of Astronomy & Astrophysics. A portion is shown here for guidance regarding its form and content.*

Table 3. Known C stars in the IC 10 NICS field

| id  | I0    | (R − I0) | (CN − TiO) | Ks | $\sigma_K$ | (J − Ks) | $\sigma_{JK}$ | (H − Ks) | $\sigma_{HK}$ |
|-----|-------|---------|-------------|----|-----------|----------|------------|----------|------------|
| 51  | 20.085 | 0.911   | 0.531       | 17.036 | 0.051    | 2.220    | 0.055     | 0.831    | 0.072      |
| 58  | 19.306 | 1.193   | 0.373       | 16.494 | 0.032    | 2.089    | 0.037     | 0.713    | 0.038      |
| 60  | 19.571 | 1.194   | 0.512       | 16.720 | 0.038    | 2.067    | 0.043     | 0.752    | 0.045      |
| 62  | 20.092 | 0.985   | 0.518       | 17.247 | 0.051    | 1.989    | 0.055     | 0.694    | 0.062      |
| 63  | 20.186 | 1.037   | 0.530       | 17.147 | 0.047    | 2.247    | 0.053     | 0.762    | 0.058      |
| 68  | 19.651 | 0.900   | 0.410       | 17.237 | 0.056    | 1.732    | 0.061     | 0.552    | 0.067      |
| 70  | 20.183 | 1.203   | 0.638       | 16.879 | 0.041    | 2.533    | 0.046     | 1.052    | 0.051      |
| 71  | 19.253 | 0.992   | 0.687       | 16.606 | 0.032    | 2.039    | 0.036     | 0.717    | 0.039      |
| 73  | 20.213 | 1.088   | 0.480       | 16.900 | 0.039    | 2.234    | 0.043     | 0.853    | 0.049      |
| 75  | 19.662 | 0.963   | 0.671       | 17.362 | 0.062    | 1.770    | 0.065     | 0.524    | 0.068      |

*Table 3 is presented in its entirety in the electronic edition of Astronomy & Astrophysics. A portion is shown here for guidance regarding its form and content.*

Fig. 6. Left panel: color-color plot of the WLM AGB stars seen in our NICS field. The two vertical lines correspond to the 1.2 and 1.4 (J − Ks)0 limits. Right panel: C (filled squares) and M stars as defined from the RICN TiO photometry. In both panels only stars with K magnitudes brighter than the TRGB are plotted.

Fig. 6 that their M star sample is certainly polluted by a number of C stars and certainly by stars earlier than spectral type M0. The right panel of Fig 6, includes only C and M stars as defined from the RICN TiO photometry (Battinelli & Demers, 2004), i.e.: C stars with (CN − TiO) > 0.3 and (R − I0) > 0.9 and M stars with (CN − TiO) < 0 and (R − I0) > 0.9. From the comparison of the two panels two facts emerge: 1) while the (J − Ks)0 color threshold is appropriate as red limit for M stars it is not suitable for the blue limit of C stars. This limit implies that some C stars are misidentified as M-type; 2) the adoption
of the \((R - I)_0 = 0.9\) threshold does not show a similar draw-
back, we see that nearly all the stars in the upper group are con-
sidered as C stars. On the other hand this limit cuts drastically
the number of stars in the lower group. This is not surprising
since stars with \((J - K)_0 < 1.0\) have spectral types earlier than
M0 (Bessell & Brett 1988).

A similar plot, shown in Figure 7, has been obtained for
NGC 6822 by matching the published lists of C and M stars
identified from NIR photometry by of Kang et al. (2006) with
Letarte et al. (2002) database. We see that for the stars in the upper
group this galaxy behaves similarly to WLM. On the other
hand, the adoption of the \((R - I)_0 = 0.9\) threshold does not cut
seriously the number of stars in the bottom group, contrary to
the case of WLM. This difference might very well be due to the
higher metallicity of NGC 6822 that makes the RGB and AGB
redder. This figure suggests \((J - K)_0 = 1.2\) as an appropriate
limit for the C-M separation contrary to the \((J - K)_0 = 1.4\)
adopted by Kang et al. (2006) on the basis of the color histo-
gram. We notice the presence in the left panel of a num-
ber of red stars with \((CN - TiO) \approx 0\) that disappear in the
right panel. These objects were therefore matched to stars with
\((R - I)_0 < 0.9\). The easiest explanation for them is possible mis-
matches (within 1 arcsec). However a similar population is also
visible in Fig. 1. From the spatial distribution of these odd ob-
jects we conclude they are background galaxies with sharpness
small enough to mimic real stars.

Contrary to the two previous galaxies, nearly all C stars
identified by the narrow band technique in IC 10 (see Figure
8) have \((J - K)_0 > 1.4\). We see in this galaxy the presence of
several objects with very negative \((CN - TiO)\). Such extreme
negative \((CN - TiO)\) were already found in M 31 by Battinelli
et al. (2003).

There is no doubt that numerous foreground red stars con-
tribute to the large number of M stars seen in Fig. 8. As Demers
et al. (2004) have shown, an accurate estimate of this fore-
ground would be needed to properly determine the C/M ratio.
We, however, do not need to know here this contribution since
our aim is not to use our NIR to determine the C/M ratios but
to assess the NIR approach.

We find in the literature three other Local Group galaxies
which C star populations have been identified using NIR colors,
namely NGC 147 (Sohn et al., 2006), NGC 185 (Kang et al.
2005) and NGC 205 (David 2003). Unfortunately, the full
lists of AGB stars in these galaxies are not available since the
authors published no list or only the list of the identified C stars.
There are no \((CN - TiO)\) observations of the Magellanic Cloud
AGB stars.

We conclude, from what has been discussed above, that a
color \((J - K)_0 = 1.4\) can be regarded as a conservative limit for
the selection of C stars among the AGB stars. Indeed, stars se-
lected according to this criterion consist exclusively of C stars
even though a non negligible number of genuine C stars, bluer
than this adopted limit, may not be counted (depending on the
metallicity). Another drawback of NIR colors compared to the
narrow-band approach is the selection of AGB M stars. Beside
the fact that a number of C stars are misidentified as M-type,
very often all the stars above the TRGB and bluer than the
above limit are considered as AGB M stars while obviously
a blue \((J - K)_0\) color limit should be introduced to omit late
K stars. The determination of such blue threshold is far from
straightforward lacking a tight relation between \((J - K)_0\) colors
and spectral types. The neglect of a blue limit to select AGB M
stars led Valcheva et al. (2007) to largely overestimate the num-er of M stars. For instance, Valcheva et al. (2007) counted as
M stars objects as blue as \((J - K)_0 = 0.5\) while such colour,
according to Bessell & Brett (1988), corresponds to G2 giants.
This obviously explains why their C/M ratio is much smaller
than the value obtained by Battinelli & Demers (2004) using
narrow band photometry. For all these reasons, C/M ratios de-
duced from the use of NIR colors significantly underestimate
their real values.

Similar conclusions can be reached by comparing the \((H -
K)_0\) colors of C and M stars. We found a \((H - K)_0 \approx 0.4\) limit
is the counterpart of the \((J - K)_0 > 1.4\) even though not as
clearly defined as the latter.

5.1. Mean NIR properties of C stars

In Table 4 we list the average NIR properties of the C stars
identified in each galaxy by adopting the \((J - K)_0 > 1.4\) cri-
terion for stars brighter than the TRGB. Distance moduli and
[Fe/H] are from Battinelli & Demers (2005a). For WLM and
IC 10, we determine the magnitude of the tip using the adopted
[Fe/H] and the calibration published by Ivanov & Borissova
(2002). Data for the LMC, SMC and Fornax are from Demers
et al. (2002) while those for the other galaxies of from ref-
cences cited above. The NGC 185 colours stand out as being
quite red. A NIR survey of its AGB was done by Davidgide
(2005) who quotes a colour difference with Kang et al. (2005)
of \(A(J - K) = 0.21\). We cannot cross identify Davidgide’s C stars
with ours because their coordinates are not available.

In the last column we give the mean effective tempera-
ture calculated from Loidl et al. (2001) from the \((R - J)\) of
C stars. It is not too surprising that the C stars in each galaxy
are very similar temperature wise. Only the redder stars, with
\((J - K)_0 > 1.4\) are selected via the NIR approach. We note that
the J magnitudes of C stars in NGC 185 as published by Kang
et al. (2005) are too large making the \((R - J)\) so small that no
temperature can be calculated.

6. Conclusions

We have shown that the samples of C and M stars selected from
NIR colors differ significantly from those obtained using the
RICTiO photometry. The main differences are:

i) The NIR sample of M stars is polluted by a significant
number of C stars misidentified as M. This is not the case for
RICNTiO identified C stars where the \((CN - TiO)\) color is an
effective discriminant.

ii) Both NIR and RICTiO selection criteria for M stars
require the adoption of a blue threshold to weed out K stars
from the sample. In the RICTiO approach, a limit of \((R -
I)_0 = 0.9\) is generally adopted. Not all the authors using NIR
color consider a similar blue limit, thus ending up with a large
overestimate of the M star number.
Fig. 7. Left panel: color-color plot of the M and C stars (filled squares) as defined by Kang et al. (2006) for NGC 6822. The vertical line correspond to the \((J - K_s)_0 = 1.4\) limit. Right panel: C (filled squares) and M stars as defined from the RICNTiO photometry.

Fig. 8. Same as Fig. 6 for IC 10.

Table 4. Mean NIR properties of C stars with \(<(J - K_s)>_0> 1.4\)

| Galaxy | [Fe/H] | Nc | \(\langle K_{c,0}\rangle\) | \(\langle J - K_s\rangle_0\) | \(\langle H - K_s\rangle_0\) | \(\langle M_{K_s}\rangle\) | \(\langle R - J\rangle\) | \(T_{eff}\) |
|--------|-------|----|----------------------|----------------------|----------------------|----------------------|----------------------|-------|
| LMC    | -0.5  | 4617 | 10.59                | 1.65                 | 0.56                 | -8.01                |                        |       |
| IC10   | -0.8  | 212  | 16.77                | 1.74                 | 0.57                 | -7.68                | 2.42                 | 3400  |
| NGC147 | -1.0  | 77   | 16.80                | 1.90                 | 0.79                 | -7.60                | 2.67                 | 3200  |
| Fornax | -1.0  | 26   | 13.07                | 1.61                 | 0.57                 | -7.67                |                        |       |
| SMC    | -1.1  | 317  | 11.18                | 1.62                 | 0.58                 | -7.92                |                        |       |
| NGC6822| -1.25 | 141  | 15.85                | 1.77                 | 0.75                 | -7.51                | 2.61                 | 3250  |
| NGC185 | -1.3  | 73   | 16.19                | 2.25                 | 0.86                 | -7.93                | 0.17                 | ?     |
| WLM    | -1.4  | 38   | 17.19                | 1.89                 | 0.69                 | -7.71                | 2.39                 | 3400  |

Similarly, Groenewegen (2004), from a study spectroscopically classified long period variables in the Magellanic Clouds, concludes that \((J - K) = 1.4\) cannot be use to properly separate M and C variables. From the above considerations it is evident that the C/M ratios obtained from NIR and narrow band photometry can be very different. It is therefore not justified to adopt C/M vs [Fe/H] calibrations obtained from RICNTiO to convert NIR C/M into metallicities. A correct approach would be to calibrate the NIR C/M in terms of [Fe/H] similarly to what Battinelli & Demers (2005a) did for narrow band C/M.

On the basis of the data used in this paper the mean properties of C stars identified with NIR colors do not seem to be significantly sensitive to the metallicity of the parent galaxy. In particular, contrary to the \(\langle M_I\rangle\) of C stars that has been proved to be fairly constant (Battinelli & Demers, 2005b), the \(\langle M_{K_s}\rangle\) shows a wide range of variation.

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