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AGB STARS IN GALAXIES: C AND M IDENTIFICATION

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Abstract. The AGB branch is made essentially of two types of stars characterized by different chemical surface abundances, namely C stars (carbon rich) and M stars (oxygen rich). Distinguishing C and M stars is trivial on the basis of spectroscopic data. However, objective-prism spectroscopy is limited to the Magellanic Clouds and therefore several alternatives have been proposed over the years to reach further away in the Local Group.

The adoption of narrow-band photometric filters centered on characteristic spectral features was the first, quite successful, "next step" beyond the objective prism spectra.

All the major existing and future telescopes are optimized for near-infrared (near-IR) photometry and thus several authors have attemped to tell apart AGB C and M stars from near-IR data only.

In this paper, near-IR alone and "combined" near-IR plus narrow-band photometric selection methods are investigated, discussed and their usefulness assessed.

1. INTRODUCTION

The beginning of the Asymptotic Giant Branch's history is difficult to establish. Certainly, the discovery by Secchi of a new class of stars that did fit none of the three classes of his spectral classification, marks an important point that nowadays we would say is the distinction between M- and C-type stars.

In 1868, Secchi announced the existence of a very rare kind of red stars, he classified them into Class IV, similar in colour to Class III (orange to red stars) but with clearly different spectral features. Since the beginning, Secchi correctly realized the reason of such unusual spectral features, namely the chemical composition of the stellar atmosphere: "The two spectra [class III and IV] are not merely modification of the same type, they are evidently due to completely different substances. ... there is a marked analogy with the reverse spectrum of carbon" (Secchi, 1868). These stars are what we now refer as to "carbon" stars.

It took about a century to reach a satisfactory understanding of carbon stars. In the early 70's, Iben & Rood (1970) proposed the term "Asymptotic Giant Branch" (hereafter AGB) as a post horizontal giant branch phase characterized by a double-shell burning source and later on Iben (1974) explained the presence of carbon in the spectra of some AGB stars as a result of the "third" dredge-up process. This process, occurring during the thermally pulsating asymptotic giant branch (TPAGB) phase, carries to the stellar surface the ^{12}C synthesized in the helium-flash convection zone as well as s-process elements synthesized both during the inter-flash phase and during the flash phase.

Since the beginning, the term carbon stars was related to the presence of an over-abundance of carbon on the surface as determined by direct spectroscopic observations. However, the dredge-up process is not the only possible way to produce a star with an excess of carbon on its surface: an exhaustive description of different kinds of carbon stars can be found for instance in Wallerstein & Knapp (1998). Even though we will consider in this paper only the C N-type stars, i.e. the genuine AGB C stars, one must be aware of the existence of non-AGB C stars that can pollute the observed sample of AGB C stars, see Fig. 2 for example.

Another important aspect in the study of C stars is the shift, that occurred over the years, in the identification methods from single-star spectroscopy, to narrow-band photometry, near-IR and recently IR from the space. This dramatically extended our study of C stars but, at the same time, made it clear that the samples of C stars identified depend on the identification method adopted.

The narrow-band technique was developed in the 1980's. It requires photometric observations with four filters: two standard filters such as R and I or V and I and two narrow-band filters called CN and TiO centered at 808.6 nm and 768.9 nm. The R filter is preferable to the V filter because the red AGB's are one magnitude brighter in R than in V. Figure 1 shows an example of a colour-colour diagram, this one in for the Local Group galaxy Wolf-Lundmark-Melotte (Battinelli & Demers 2004). The vertical limit of the boxes, is set at $(R - I)_0 = 0.90$ this corresponds to the colour of stars of spectral type M0. The horizontal limits are set arbitrarily, between the two limits we expect to find stars of spectral type S. Since narrow-band filters are expensive and not available for most telescopes, people have turned to near infrared photometry. This approach is not really fully proven. Figure 2 presents a colour-magnitude diagram of the spectroscopically identified carbon stars in the Small Magellanic Cloud, from Demers et al. (2002). We see that C stars have quite a range in magnitude and colour. The cool N-type are found in the box.

In the literature there are several papers which compare the various methods: near-IR and narrow-band are compared by Battinelli & Demers (2007,2009); far-IR compared to narrow-band by Jackson et al. (2007), Matsuura et al. (2009) and Boyer et al. (2011). A discussion of this aspect is given in Battinelli & Demers (2011). Today's large telescopes – and even more tomorrow's ones – operate most efficiently in the near-IR making this approach the more suited for the study of AGB population in galaxies beyond the Local Group. Unfortunately, nowadays, different authors using near-IR very often adopt different selection criteria (e.g. different colour thresholds, CMD or two-colour diagram selections etc.). It is therefore of pivotal importance to dispose of a reliable "standard" near-IR identification technique for C and M stars.

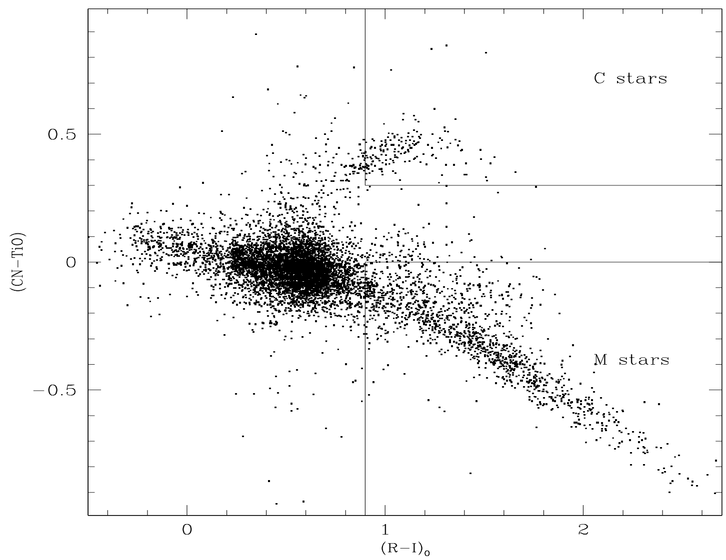

Figure 1: Example of the selection of C stars from narrow-band technique.

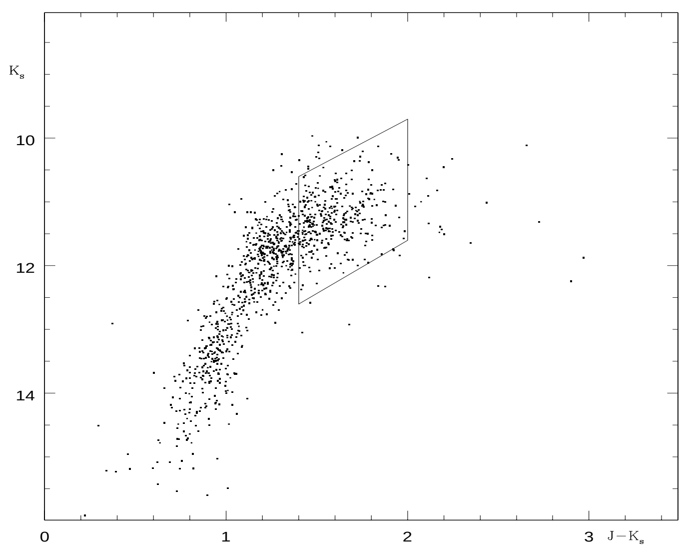

Figure 2: Spectroscopically identified C stars in the SMC. The enclosed area is the J region defined by Nikolaev & Weinberg (2000).

In this regard, the Kacharov et al. (2012) paper is of particular importance. They obtained VIMOS low-resolution spectra of some 800 bright red stars in NGC 6822 in order to spectroscopically calibrate the C and M star selection made using on near-IR photometric data. By combining the spectral classification of these stars with the near-IR photometric data recently published by (Sibbons et al. 2011) based on the UKIRT photometry, Kacharov et al. (2012) were able to compare several C and M identification techniques, both in the CMD and in the two-color planes. They proposed two slightly different methods based on the JHK CMD.

Hereafter, we will focus only on their first method since they lead to essentially similar results. As noted by Kacharov et al. (2012) both methods cannot be used to obtain the absolute number of C and M stars in a galaxy because there is an overlap in the photometric properties of the two types thus a region of the diagram must to excluded. This method can be summarized as follow: M stars are those with $16.45 < K_0 < K_{0,TRGB}$ and $0.9 < (J-K)_0 < 1.2$ while C stars are brighter than the TRGB and have $(J-K)_0 > 1.2$. A detailed description of these thresholds is given in Kacharov et al (2012).

The catalogue of spectroscopically identified AGB C and M stars in NGC 6822 published by Kacharov et al., offers us an excellent opportunity to "verify" the narrow-band selection technique and to better understand its intrinsic difference with the near-IR one. The latter aspect is not at all trivial when one intends to determine the C/M ratios and use them as proxy for the environment metallicity. As it was clearly shown by Battinelli & Demers (2011), C/M ratios determined with the two methods can significantly differ and therefore C/M vs [Fe/H] relations must be separately obtained for both narrow-band and near-IR datasets. While a reasonably good relation has been obtained by Battinelli and Demers (2005) using narrow-band data, a similar relation based on near-IR counts is still missing. Battinelli & Demers (2011, see their Figure 5) found, for a sample of 13 galaxies, a very weak – if any – dependence of C/M near-IR ratios on the metallicity. They therefore concluded that it is an obvious mistake (too often present in the literature) to estimate the metallicity using near-IR counts and C/M vs [Fe/H] relation calibrated by narrow-band counts .

NGC 6822 is an excellent galaxy to inspect these issues because of the great wealth of available data: optical broad and narrow-band (Letarte et al. 2002, Battinelli et al. 2006), near-IR (Sibbons et al. 2011) and low-resolution spectroscopy (Kacharov et al. 2012). In the next section we will therefore adopt NGC 6822 as a case study.

2. THE CASE OF NGC 6822

First we cross-identify the sample of spectroscopically classified stars by Kacharov et al. (2012) with optical R,I,CN, TiO from Letarte et al. (2002) and near-IR by Sibbons et al. (2012), respectively. Figure 3 shows clearly that the selection of C and M stars performed according to RICNTiO photometry is quite satisfactory and in agreement with the spectroscopic classification: approximately all of the spectroscopically confirmed C and M stars lie in their respective box in the RICNTiO plane. In Fig. 3 we note, however, a significant pollution, in the M-box, by foreground dwarf stars. Letarte et al. (2002) accounts for this pollution by statistically subtracting

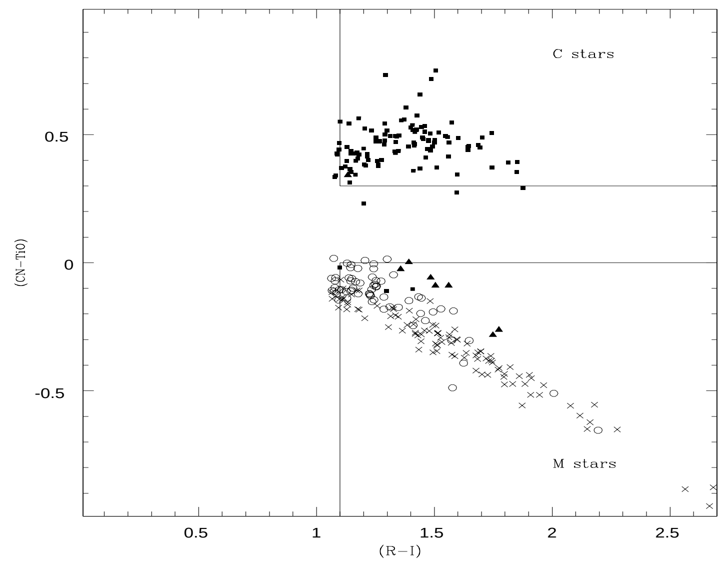

Figure 3: Comparing the narrow-band to the spectroscopic selection criterion. Solid squares: C-rich AGBs; Open circles O-rich AGBs; Crosses: foreground M dwarfs; Solid triangles: S-type AGBs. (R-I) is not corrected for the reddening here.

counts of dwarf M-stars for a foreground control field.

Figure 4 shows a combined narrow-band and near-IR two-color diagram. On one hand, it is evident how the $(J-K)$ color is much more effective in differentiating M giants and foreground dwarfs, on the other hand the $(J-K)_0 = 1.2$ threshold adopted to separate M from C stars in the CMD, cuts out a significant number of the latter. Most of these stars (but not all) are excluded by the bright K-mag cutoff at 16.45 introduced by Kacharov et al. (2012, see their Figure 11).

We should conclude, from Fig. 3 and 4, that a “combined” narrow- (CN-TiO) and broad-band (J-K)colors could - at least for NGC 6822 - be an effective way to determine the C/M ratio. Essentially, once stars brighter than the TRGB are selected, a $(J-K)_0 = 0.90$ is adopted to get rid of foreground M-dwarfs, the usual $(CN-TiO)$ boxes seem to work perfectly.

In the next section we will investigate if such combined approach may yield a reliable C/M vs [Fe/H] relation.

3. A NEW C/M VS [FE/H] RELATION?

As we mentioned in the Introduction, Battinelli & Demers (2005) were able to derive a quite reliable C/M vs [Fe/H] relation using counts from a homogeneous (i.e. obtained using only one C and M identification technique) sample of galaxies.

In this section we try to investigate if it is possible to obtain a similar relation

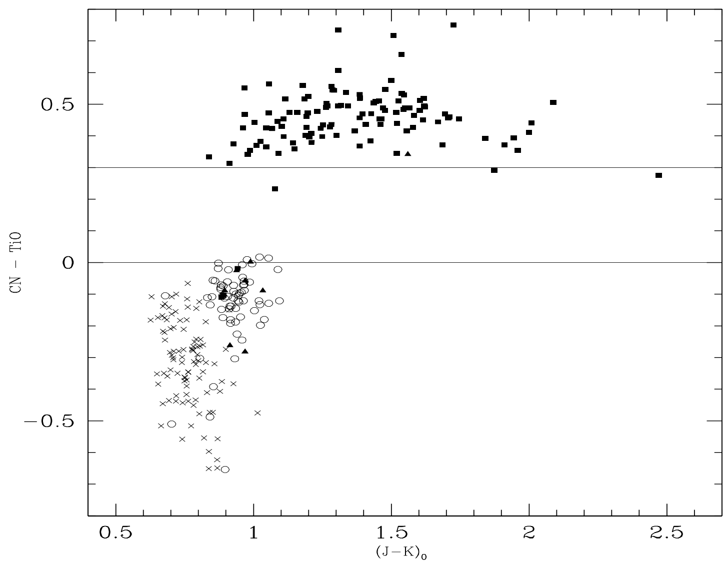

Figure 4: Spectroscopically identified red stars in NGC 6822. Solid squares: C-rich AGBs; Open circles O-rich AGBs; Crosses: foreground M dwarfs; Solid triangles: S-type AGBs.

by using the above described "combined" method. Unfortunately, we found in the literature only four galaxies for which both RICNTiO and near-IR individual photometry can be matched (for some other galaxies coordinates are given only for C stars). These four galaxies are: NGC 6022 (Letarte et al. 2002, Battinelli et al. 2006, Sibbons et al. 2011); IC 1613 (Albert et al. 2000, Battinelli & Demers 2009); IC 10 (Demers et al. 2004; Battinelli et al. 2007) and WLM (Battinelli & Demers 2004; Battinelli et al. 2007). For these galaxies we adopt metallicities from the literature as follow: NGC6822, Battinelli & Demers (2005); IC10, Kim et al. (2009); IC1613, Skillman et al. (2003); WLM, Leaman et al. (2013).

In Table 1, C/M ratios obtained using RICNTiO and "combined" counts are given, alongwith the adopted [Fe/H] for each galaxy.

Even though we are fully aware of the poor statistics of such a sample, we try to determine if a reasonable C/M vs [Fe/H] relation can be obtained. In Figure 5, the C/M vs [Fe/H] relations obtained through the RICNTiO and the "combined" methods are shown. It is evident that the latter method does not at all improve the quality of the relation. More specifically, the correlation coefficients of the two least-square fits shown are $r = 0.73$ and $r = 0.52$ for the left and right panel, respectively.

4. CONCLUSIONS

The combined use of spectroscopic data with available RICNTiO and near-IR pho-

Table 1: Adopted parent galaxy metallicities and C/M ratios obtained using RICN-TiO and the "combined" methods.

Name	[Fe/H]	RICNtiO	Combined
NGC 6822	-1.25	1.0	1.27
IC 1613	-1.00	0.64	0.48
IC 10	-1.08	0.23	0.47
WLM	-1.28	12.4	100

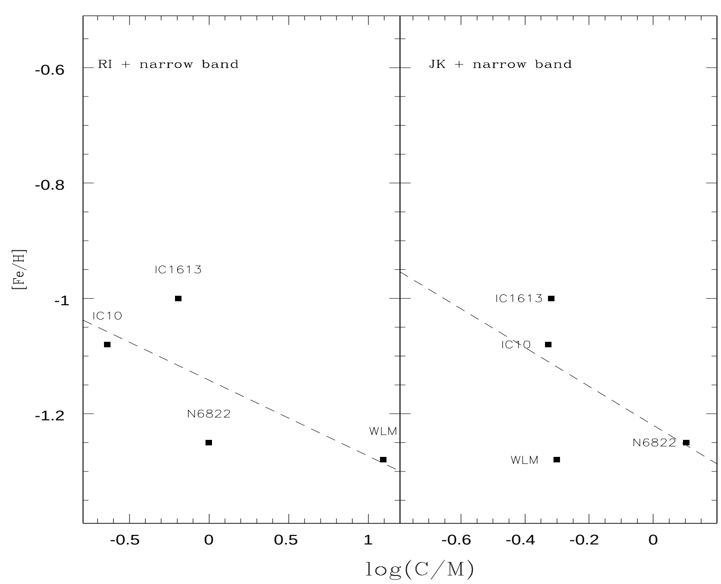

Figure 5: C/M vs [Fe/H] obtained with narrow-band (left panel) and "combined" (right panel) methods.

tometry in NGC 6822, suggests that an effective way to select AGB M and C stars is the combination of $(J-K)$ and $(CN-TiO)$ colors. This approach, in NGC6822, seems to work better that near-IR photometry alone. Indeed, this latter requires the introduction of a (J-K) color threshold (to separate M from C stars) that leads to a loss of a significant number of genuine C stars.

Four galaxies with available RICNTiO and near-IR photometric data are therefore used to investigate if the new "combined" method yields reliable C/M ratios in galaxies with different metallicity. Our result shows that this is not the case and that the C/M vs [Fe/H] relation obtained is worse that the one from RICNTiO.

We believe that this result may be due to the fact that the $(J-K)_0$ thresholds we used for NGC 6822 cannot be applied to galaxies with different metallicities, in other words, these thresholds are function of the parent galaxy metallicity.

It would be very useful if extensive single star spectroscopic data, like the one by Kacharov et al. (2012), would become soon availabe for other galaxies so to shed light on the possible dependance of the $(J-K)_0$ thresholds on the metallicity.

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