

# Carbon and nitrogen abundances of stellar populations in the globular cluster M 2<sup>★,★★</sup>

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## ABSTRACT

We present CH and CN index analysis and C and N abundance calculations based on the low-resolution blue spectra of red giant branch (RGB) stars in the Galactic globular cluster NGC 7089 (M 2). Our main goal is to investigate the C-N anticorrelation for this intermediate metallicity cluster. The data were collected with DOLORES, the multiobject, low-resolution facility at the Telescopio Nazionale *Galileo*. We first looked for CH and CN band strength variations and bimodalities in a sample of RGB stars with  $17.5 \leq V \leq 14.5$ . Thus we derived C and N abundances under LTE assumption by comparing observed spectra with synthetic models from the spectral features at 4300 Å (G-band) and at ~3883 Å (CN). Spectroscopic data were coupled with UV photometry obtained during the spectroscopic run. We found a considerable star-to-star variation in both A(C) and A(N) at all luminosities for our sample of 35 targets. These abundances appear to be anticorrelated, with a hint of bimodality in the C content for stars with luminosities below the RGB bump ( $V \sim 15.7$ ), while the range of variations in N abundances is very large and spans almost ~2 dex. We find additional C depletion as the stars evolve off the RGB bump, in fairly good agreement with theoretical predictions for metal-poor stars in the course of normal stellar evolution. We isolated two groups with N-rich and N-poor stars and found that N abundance variations correlate with the  $(U - V)$  color in the DOLORES color-magnitude diagram (CMD). The  $V, (U - V)$  CMD for this cluster shows an additional RGB sequence, located at the red of the main RGB and amounting to a small fraction of the total giant population. We identified two CH stars detected in previous studies in our  $U, V$  images. These stars, which are both cluster members, fall on this redder sequence, suggesting that the anomalous RGB should have a peculiar chemical pattern. Unfortunately, no additional spectra were obtained for stars in this previously unknown RGB branch.

**Key words.** stars: abundances – globular clusters: individual: M 2

## 1. Introduction

In the past few years, a large collection of spectroscopic and photometric data have conclusively determined that globular clusters (GCs) can no longer be considered systems made up of a simple monometallic population. GCs are largely homogeneous with regard to iron and  $n$ -capture elements (with the outstanding exceptions of  $\omega$  Cen, M 22, M 54, Ter 5, and NGC 1851; see Johnson & Pilachowski 2010; Marino et al. 2012b; Carretta et al. 2010a; Origlia et al. 2011; Yong & Grundahl 2008), while they show a significant spread in the abundance of lighter elements involved in proton-capture processes, with strong anticorrelations between the abundances of C and N, Na and O, or Mg and Al, as well as bimodal distribution of CH and CN band strength (Kraft 1994; Cohen et al. 2002; Ramírez & Cohen 2003; Cohen et al. 2005; Carretta et al. 2009; Martell & Smith 2009; Kayser et al. 2008; Pancino et al. 2010b, among

others). These variations are not observed in field counterparts of the same metallicity<sup>1</sup> (but they show signs of dredged-up CNO processing, Gratton et al. 2000) or in open clusters (De Silva et al. 2009; Pancino et al. 2010a).

This peculiar chemical pattern appears to be ubiquitous for all GCs that have been studied properly. Originally, the first detection of unusual abundances came from the bright red giant branch (RGB) stars: spectroscopic investigations of the CH and CN absorption features often revealed a bimodality in the CN band strength that is accompanied by a broader distribution of CH (Kayser et al. 2008; Pancino et al. 2010b, and references therein). Here we want to concentrate on the carbon and nitrogen abundance variations for RGB stars. In spite of the large choice of literature on this topic, many questions still remain open in the understanding of how the observed chemical variations of C and N formed.

Following the classical prediction, during the H-burning phase via the CNO cycle, N is enriched at the cost of C and O. When a star evolves off the main sequence, the convective envelope starts to move inward, *dredging up* material that has

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\*\* Full Table 1 and photometric data are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/548/A107>

<sup>1</sup> Using moderate-resolution spectra of 561 giants with typical halo metallicities, Martell et al. (2011) find that 3% of the sample shows the CN-CH bandstrength typical of GC stars. They argue that these stars are genuine second-generation GC stars that have been lost to the halo field.

been processed through partial hydrogen burning by the CNO cycle and pp chains. Canonically, light-element abundances should be untouched by subsequent evolution along the RGB, but the observational evidence has shown that both various light-element abundances (particularly  $[C/Fe]$  and  $\log \epsilon(\text{Li})$ ) and isotopic ratios ( $^{12}\text{C}/^{13}\text{C}$ ) vary as the stars evolve along the RGB, and this cannot be accounted by a single first dredge-up alone.

Some further nonconvective *deep mixing* should take place in the advanced phases of RGB evolution: after the end of the dredge-up phase is reached, the star's convective envelope begins to move outward, leaving behind a sharp discontinuity in mean molecular weight (the  $\mu$ -barrier) at the point of deepest inward progress (Iben 1968). The corresponding change in molecular weight can potentially hinder further mixing. However, during the evolution along the RGB, the hydrogen-burning shell advances outward and eventually encounters the  $\mu$ -barrier. The influx of fresh hydrogen-rich material to the hydrogen-burning shell causes a temporary slowdown of the star's evolution, which manifests itself in a bump in the differential luminosity function (LF) of the cluster. Thereafter, since the molecular gradient is effectively canceled out, some further mixing episodes are allowed. Briefly, possible sources of extramixing could be rotation-induced mixing (Charbonnel 1995) or thermohaline mixing associated with the reaction  $3\text{He}(3\text{He}, 2\text{p})4\text{He}$  (Angelou et al. 2012). Extramixing is a universal mechanism that occurs in  $\geq 96\%$  of these RGB bump stars (Charbonnel & Do Nascimento 1998) in the field, in open and globular clusters and also in stars in external galaxies. As a consequence, normal stellar evolution contributes to the C-N anticorrelation observed among bright RGB stars.

However, mixing cannot be the only driving mechanism of these abundance variations, since large star-to-star light-element variations are also observed among RGB stars at the same evolutionary stage, and they are also observed in unevolved stars (Cannon et al. 2003; Ramírez & Cohen 2003; Cohen et al. 2005), indicating the occurrence of high-temperature hydrogen-burning processes (CNO, Ne-Na, Mg-Al cycles) that cannot occur in low-mass GC stars (Gratton et al. 2001). Therefore, the peculiar chemistry observed should also have an *external* origin. The so-called *multiple populations* scenario foresees the occurrence of at least two episodes of star formation: CN-weak stars being the first stars that formed, while CN-strong stars formed some tens/hundreds of Myr later from the enriched ashes of the first generation (D'Ercole et al. 2008). Up to now, we lack a complete understanding of the current mechanism that drives the observational facts, although theoretical nucleosynthesis models show that the observed chemical pattern can be provided either by intermediate-mass ( $M > 3\text{--}5 M_{\odot}$ ) asymptotic giant branch (AGB) stars (Ventura & D'Antona 2008) or fast-rotating massive stars (FRMS, Decressin et al. 2007). The detection of a bimodal distribution of CN band strength below the bump in the LF, in moderate-metallicity clusters ( $[\text{Fe}/\text{H}] \geq -1.6$ ), provides strong evidence for this scenario (Briley et al. 1991; Cannon et al. 1998; Kayser et al. 2008; Pancino et al. 2010b; Smolinski et al. 2011). Furthermore, mixing must be operating in each generation (Suntzeff & Smith 1991; Denissenkov et al. 1998) as stars evolve along the RGB. In addition to these two main scenarios, there are several different mechanisms that can potentially produce chemical inhomogeneities in GCs. We refer the reader to the comprehensive review by Gratton et al. (2012) for a discussion.

In recent years, thanks to the large capabilities of the *Hubble* space telescope (HST), accurate photometry conclusively demonstrated that a growing number of GCs host at least two

stellar generations of stars. Indeed, star-to-star variations in light- and alpha-element abundances, age, and metallicity can determine multimodal or broad sequences in the CMD observed within some galactic or extragalactic GCs (e.g., Pancino et al. 2000; Bedin et al. 2004; Sollima et al. 2007; Piotto et al. 2007; Marino et al. 2008; Milone et al. 2010; Lardo et al. 2011). Even if it is not yet clear how photometric complexity be mapped for the variations in age/or chemical abundance, there are several tempting potential connections between the photometric multiplicity and light-element abundance inhomogeneities (e.g., see Marino et al. 2009, for M 22; Yong & Grundahl 2008; Yong et al. 2009; Gratton et al. 2012; Lardo et al. 2012, for the case of NGC 1851).

With this paper we investigate the behavior of carbon and nitrogen along the RGB of M 2. This is an intermediate-metallicity ( $[\text{Fe}/\text{H}] = -1.65$ ; Harris 1996, 2010 edition) cluster, which is located 11.5 kpc from the galactic center, is relatively rich, and lies in a sparse field. This cluster was found by Smith & Mateo (1990) to have a bimodal CN distribution, with the majority of red giants found to be CN-strong stars. Earlier works have already revealed a large number of stars with strong  $\lambda 3883$  CN bands (McClure & Hesser 1981; Canterna et al. 1982; Smith & Mateo 1990). Furthermore, this cluster is found to contain CH stars (Smith & Mateo 1990; Zinn 1981). In a recent paper with a large sample of stars in all evolutionary phases, Smolinski et al. (2011) detected signs of enhanced N enrichment well before the point of first dredge-up, besides the usual CN variations on the RGB. On the photometric front, M 2  $g$ , ( $u - g$ ) CMD from Sloan digital sky survey (SDSS) photometry (see Fig. 1 of Lardo et al. 2011) shows evidence of a spread in light-element abundances, which comes from the significant spread along the RGB, which would not be detected in ( $g - r$ ), and which is incompatible with measurements errors alone or with differential reddening effects. The broadening in the  $U$ , ( $U - V$ ) CMD (and/or usual visual colors) may be a different way to search for multiple stellar populations. In these respects, Marino et al. (2008) find that the Na (or O) distribution is bimodal, with a rich sample of more than 100 giants in M 4, and this bimodal distribution is correlated with a bimodal distribution in CN strength, too (Na-rich stars are also CN strong), which is associated to a dichotomy in the color of RGB stars in the  $U$ , ( $U - B$ ) CMD. Prompted by these considerations, we thought that  $U$ -based photometry can be used, when coupled with C and N abundances from analyzing low-resolution spectra, for efficient tagging of multiple stellar populations in M 2.

This article is structured as follows. We describe the sample in Sect. 2. We outline our measurements of the CN and CH indices and their interpretation in Sect. 3. We derive C and N abundances from spectral synthesis in Sect. 4 and discuss the result in Sect. 5. We discuss and analyze the split of the RGB discovered in the  $V$ ,  $U - V$  CMD of M 2 in Sect. 6. Finally we present a summary of our results and draw conclusions in Sect. 7.

## 2. Observational material

We selected M 2 spectroscopic targets from the An et al. (2008) publicly available photometry. An et al. (2008) reanalyzed SDSS images of the GCs (and open clusters) included in the survey using the DAOPHOT/ALLFRAME suite of programs (Stetson 1987, 1994). In our previous work (Lardo et al. 2011), we used An et al. (2008) photometry to search for anomalous spread in near UV color ( $u - g$ ) along the RGB of nine Galactic GCs and study the radial profile of the first and second generation stars. We refer the reader these two papers for a detailed description of the photometric database employed to select spectroscopic

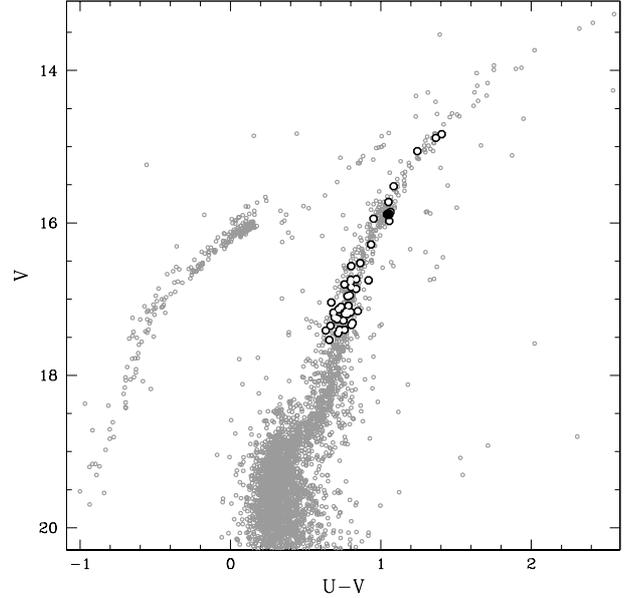
targets. The initial sample of candidate stars consisted of those located more than  $1'$  from the center of M 2 (to facilitate sky subtraction) with  $14.5 < V < 17.5$  mag. Spectroscopic targets were hence chosen as the most isolated stars (no neighbors within  $2''$ ) as close as possible to the main locus of the RGB sequence in the  $g, (u - g)$  and  $g, (g - r)$  diagrams to reduce the incidence of blended images<sup>2</sup>.

### 2.1. Photometry

In addition, we also obtained images of the cluster in the standard Johnson  $U$  and  $V$  filters for a total of 540 s shifted in three single exposures in each filter with the DOLORES camera. DOLORES (Device Optimized for the Low RESolution) is a low-resolution spectrograph and camera permanently installed at Telescopio Nazionale *Galileo* (TNG) located in La Palma, Canary Islands (Spain). The choice of pass-bands is due to the ability of separating photometric sequences at different evolutionary stages along the CMD (as discussed in Sects. 1 and 6). The DOLORES camera offers a field of view (FoV) of  $8.6' \times 8.6'$  with a  $0.252$  arcsec/pix scale. The raw frames were processed (bias-subtracted and flat-fielded) using the standard tasks in IRAF<sup>3</sup>. Point spread function (PSF) fitting photometry was thus carried out with the DAOPHOT II and ALLSTAR packages (Stetson 1987, 1994) using a constant model PSF. The photometric calibration was done using stars in common with Stetson Photometric standard field (Stetson 2000)<sup>4</sup>. Stars within  $1'$  and outside of  $4'$  from the cluster center are excluded from the CMD to reduce blending effects and the field star contamination, respectively. The rms in magnitude and the chi and sharp parameters are powerful indicators of the photometric quality<sup>5</sup>. To select a sample of well-measured stars we followed the procedure given in Lardo et al. (2012), Sect. 5.1. The catalog of the selected sample is presented in Table 1. The resulting calibrated (and corrected for differential reddening) ( $V, U - V$ ) CMD for M 2 and the spectroscopic target stars are shown in Fig. 1.

### 2.2. Spectroscopic observations and reduction

Stellar spectra were obtained with DOLORES which allows for multi-slit spectroscopy. We defined three slit masks using the stand-alone version of the Interactive Mask Design Interface, provided by the DOLORES staff at the telescope<sup>6</sup>. The positions of the program stars were determined using M 2 catalogs by An et al. (2008), as discussed in Sect. 2. The slit width on the masks



**Fig. 1.**  $V, (U - V)$  CMD for M 2 from DOLORES images. White dots mark spectroscopic targets, the black dot shows the probable field star (see Sect. 2.2).

**Table 1.** Photometry of M 2: selected sample.

ID	RA (deg)	Dec (deg)	$V$ (mag)	$\epsilon V$ (mag)	$U - V$ (mag)	$\epsilon U$ (mag)
164	323.3657998	-0.8890510	20.215	0.026	0.213	0.076
196	323.3800929	-0.8885692	19.943	0.019	0.311	0.072
234	323.3661658	-0.8882047	20.342	0.018	0.393	0.084
286	323.3795809	-0.8875061	19.015	0.012	0.220	0.028
303	323.3872881	-0.8872826	18.445	0.010	0.632	0.023
313	323.3674707	-0.8870783	19.661	0.024	0.202	0.050
330	323.3908254	-0.8869171	19.613	0.019	0.267	0.041
336	323.3657205	-0.8868386	19.325	0.012	0.305	0.037

**Notes.** A portion of the table is shown for guidance about its content, the complete table is available in electronic format through the CDS service.

was fixed to  $1.1''$ , and the slit length was chosen to be at least  $8''$  to allow for local sky subtraction. Typically, we succeeded to fit  $\approx 16$  slits onto one mask (for a total of 48 target stars). Because the goal of our spectroscopic observations was to measure the strengths of the 3880 and 4300 Å CN and CH absorption bands, we used the LRB grism with a dispersion of  $2.52$  Å/pix. In combination with the chosen slit width this results in the spectral resolution of  $R(@3880 \text{ Å}) = 353$  and  $R(@4305 \text{ Å}) = 391$  in the wavelength region of interest. The grism's spectral region covers the nominal wavelength range between 3000–8430 Å, while the actual spectral coverage depends on the location of the slit on the mask with respect to the dispersion direction. To reach a high S/N, each mask configuration was observed three times with exposure durations of 1800 s each, leading to a total exposure time of 1.5 h per mask and a typical S/N of  $\approx 20$ –30 in the CN region. Additionally, bias, flat field, and wavelength calibration observations were obtained in the afternoon.

For the data pre-reduction, we used the standard procedure for overscan correction and bias-subtraction with the routines available in the *nao.imred.ccdred* package in IRAF. First, we stacked the flat fields for each night and mask. Because each slit mask was observed three times and the alignment of the frames was quite good, we co-added the three frames for a given

<sup>2</sup> Unfortunately, by using these selection criteria, we accidentally excluded stars belonging to previously unknown additional RGB sequence (see Sect. 2.1) from our spectroscopic sample.

<sup>3</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

<sup>4</sup> Available at <http://www3.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/community/STETSON/standards/>

<sup>5</sup> On all stars we imposed the selection limits of  $\text{CHI} < 2.0$  and  $-1 < \text{SHARP} < 1$  on DAOPHOT II photometric parameters. The first of these parameters, CHI, is the ratio of the observed pixel-to-pixel scatter in the fitting residuals to the expected scatter, based on the values of readout noise and the photons per ADU specified in the DAOPHOT options file, while SHARP is a zeroth-order estimate of the square of the quantity  $\text{SHARP}^2 \sim \sigma^2(\text{observed}) - \sigma^2(\text{point} - \text{spreadfunction})$ ; see the DAOPHOTII manual at

<http://www.astro.wisc.edu/sirtf/daophot2.pdf>

<sup>6</sup> See for reference <http://web.oapd.inaf.it/mos/>

slit mask with cosmic-ray rejection enabled, providing resulting frames that were almost free of cosmic rays. For the following analysis we extracted the area around each slit with the optimal extraction and treated the resulting spectra as single-slit observations. The wavelength-calibration images and flat fields were treated in the same manner. TNG spectroscopic flats show a severe internal reflection problem in the blue regions of the spectra that could in principle heavily affect our further measurements. To minimize this effect, we fit the 2D large-scale structures in the normalized spectroscopic flat field by smoothing and dividing the original flat by the fit, keeping the small pixel-to-pixel variations, which are the ones we intend to correct for with flat fielding. The object spectra and arc images were flat-field-calibrated with these corrected flat fields. Standard IRAF routines were used to wavelength-calibrate, sky-subtract, and extract the stellar spectra. The wavelength solution from the HeNeHg arcs was fitted by a first-order spline. The typical rms of the wavelength calibration is on the order of 0.3 Å, which is largely expected at the given spectral resolution. The residual uncertainties in the wavelength calibration are then removed using the position of strong emission lines (in particular OI at 5577.7 Å and NaD at 5895 Å).

The shape of the final spectra is affected by the dependence of the instrumental response on the wavelength. Given the quite low instrument response in the blue part of the spectrum and the presence of many absorptions in this region, we avoided any attempt to remove this effect through flux calibration or continuum normalization (see [Pancino et al. 2010b](#), and references therein).

To derive the membership of candidate RGB stars, we first performed a cross-correlation of the object spectrum with the highest S/N star on each MOS mask as a template with the IRAF *fxcor* routine. The template  $V_r$  were computed using the laboratory positions of the most prominent spectral features (e.g.,  $H_\alpha$ ,  $H_\beta$ ,  $H_\gamma$ ,  $H_\delta$ , and Ca H+K, among others), yielding a mean radial velocity of  $-13 \pm 30$  km s<sup>-1</sup> for the entire sample. This value, given the low resolution of our spectra, agrees quite well with the value tabulated ( $-5.0$  km s<sup>-1</sup>) in the [Harris \(1996, 2010\)](#) catalog. Then, we rejected individual stars with values deviating by more than  $3\sigma$  from this average velocity, deeming them to be probable field stars. Only one star (ID: 10427, see Fig. 1) was rejected based on its radial velocity. In a final step, we examined each spectrum individually and rejected spectra with defects (like spikes or holes) in the measurement windows.

### 3. CH and CN band strengths

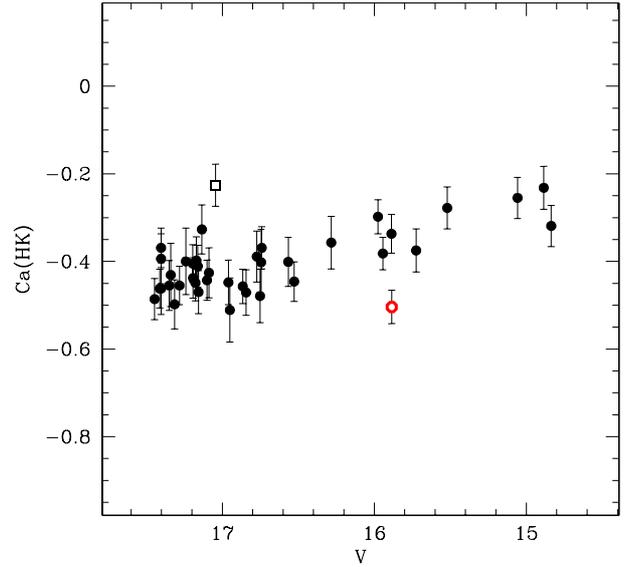
A set of indices quantifying the strengths of the UV CN band, the G band of CH and the Ca<sub>II</sub> H and K lines were measured for the spectra. To be consistent with our previous work, we adopted the indices as defined by [Harbeck et al. \(2003\)](#) and [Pancino et al. \(2010b\)](#):

$$S(3839) = -2.5 \log \frac{F_{3861-3884}}{F_{3894-3910}}$$

$$CH(4300) = -2.5 \log \frac{F_{4285-4315}}{0.5F_{4240-4280} + 0.5F_{4390-4460}}$$

$$HK = 1 - \frac{F_{3910-4020}}{F_{4020-4130}}$$

A spectral index is defined in such a way as to compare the counts in a window centered on the molecular band or atomic line we want to measure, to the counts in a comparison region – not expected to be significantly affected by absorptions from these species – which sample the continuum level. The uncertainties related to the index measure have been obtained with the



**Fig. 2.** Ca II H and K index plotted vs.  $V$  magnitude for the M 2 giants. A probable non-member star is shown as an open square. The small scatter, fully compatible with the formal measurement errors, in the Ca(HK) values as a function of  $V$  provides additional evidence that all spectroscopic targets but the notable outlier are members of M 2. The open red symbol refers to star 10427, which is not a member of M 2, according to its radial velocity.

expression derived by [Vollmann & Eversberg \(2006\)](#), assuming pure photon noise statistics in the flux measurements. To obtain additional membership information we employed the strength of the Ca<sub>II</sub> H and K lines (see Sect. 3, as in [Smith & Mateo 1990](#)) as a further discriminant between cluster and field stars, since the strength of these lines depends on the metal-abundance in this low to intermediate metallicity regime. By assuming that M 2 is chemically homogeneous with respect to the calcium abundance, we expect that stars belonging to the cluster show a tight sequence in the HK,  $V$  plane. We present the plot of HK index vs. the  $V$  magnitude in Fig. 2. A tight relation between HK index strength and the  $V$  magnitude is clearly present for all stars selected by using radial velocity criteria. From this figure, we were able to pinpoint only one outlier (ID 21729), whose spectrum has a noticeably strong-lined appearance. We also measured indices for this star to allow for a direct comparison with respect to cluster members; however, we excluded this star from the abundance analysis. Again from Fig. 2, we note that the probable field star (rejected according to its radial velocity), does occupy an anomalous position in the plot of HK index vs. the  $V$  magnitude. This evidence further confirms that this star is not a cluster member. The measured indices, together with additional information on target stars, are listed in Table 2.

#### 3.1. Index analysis

Figure 3 shows  $S(3839)$  and  $CH(4300)$  index measurements for our data set. Several low-resolution studies have demonstrated that the CN-band strength is a proxy for the nitrogen content of star atmospheres, whereas CH traces carbon (e.g., [Smith et al. 1996](#)). A visual inspection of the left hand panel of Fig. 3 reveals a clear bimodality in the CN index over the entire magnitude range, with a few mid-strength stars. The difference in  $S(3839)$  between CN-strong and CN-weak stars of comparable magnitude is  $\sim 0.2$ – $0.3$  mag. Giants considered to have relatively strong CN bands and CN-poor giants are represented in Fig. 3.

**Table 2.** Index measurements, magnitudes, colors, and radial velocities for the sample stars.

ID	ID <sub>SDSS</sub>	RA (deg)	Dec (deg)	V	U - V	V <sub>r</sub> km s <sup>-1</sup>	CN (mag)	dCN (mag)	δCN (mag)	CH (mag)	dCH (mag)	δCN (mag)
1047	205 468	323.35400060	-0.87919450	16.740	0.8360	-30 ± 23	-0.167	0.010	0.075	0.905	0.032	-0.026
1221	204 057	323.34119890	-0.87748070	16.283	0.9340	-9 ± 43	-0.196	0.015	0.003	0.861	0.022	-0.084
1249	205 374	323.35306530	-0.87727650	16.566	0.8020	11 ± 37	-0.164	0.025	0.062	0.983	0.039	0.047
1921	204 613	323.34594560	-0.87168230	15.725	1.0500	-9 ± 25	-0.088	0.017	0.060	0.976	0.024	0.012
1927	206 299	323.36152960	-0.87163050	17.403	0.7582	17 ± 62	-0.373	0.025	-0.070	0.841	0.041	-0.074
2288	205 760	323.35679530	-0.86887270	15.887	1.0400	-33 ± 21	-0.246	0.019	-0.083	0.970	0.025	0.012
3190	206 918	323.36713180	-0.86275460	17.177	0.6840	-1 ± 22	-0.216	0.012	0.066	0.871	0.022	-0.049
3285	204 469	323.34467810	-0.86211390	16.745	0.7995	11 ± 28	-0.189	0.035	0.053	1.013	0.041	0.082
3397	206 350	323.36209610	-0.86148000	17.170	0.7990	-32 ± 36	-0.110	0.009	0.171	0.903	0.031	-0.017
3760	205 848	323.35765450	-0.85923620	17.161	0.7712	-3 ± 25	-0.178	0.012	0.102	0.925	0.028	0.004
4144	206 472	323.36324840	-0.85704770	16.527	0.8623	-33 ± 30	-0.148	0.013	0.074	0.898	0.033	-0.039
5010	206 002	323.35884820	-0.85232980	15.058	1.2417	-37 ± 30	-0.140	0.015	-0.053	1.000	0.028	0.008
5149	204 376	323.34376850	-0.85158800	15.520	1.0842	11 ± 38	0.024	0.010	0.153	0.935	0.031	-0.037
5185	205 505	323.35424850	-0.85143600	17.445	0.7163	-8 ± 29	-0.148	0.023	0.159	0.888	0.031	-0.027
6609	112 780	323.36574622	-0.84405523	16.752	0.9172	-5 ± 27	-0.541	0.012	-0.298	0.935	0.023	0.004
9229	106 190	323.33041650	-0.83108230	15.976	1.0558	-30 ± 36	0.062	0.012	0.233	0.903	0.021	-0.052
10 803	105 859	323.32844101	-0.82363565	17.314	0.8108	8 ± 68	-0.314	0.009	-0.020	0.927	0.050	0.010
11 131	105 112	323.32387272	-0.82204937	16.865	0.8347	-12 ± 27	-0.244	0.024	0.009	0.848	0.031	-0.080
11 796	104 710	323.32131086	-0.81884683	17.403	0.7250	-37 ± 34	-0.125	0.014	0.178	0.921	0.024	0.006
14 343	103 672	323.31346832	-0.80667018	16.950	0.7926	5 ± 61	-0.382	0.020	-0.121	0.900	0.049	-0.026
15 217	105 961	323.32904057	-0.80229140	17.349	0.6652	10 ± 64	-0.331	0.023	-0.033	0.941	0.041	0.025
16 614	102 869	323.30469421	-0.79511601	16.843	0.8018	-32 ± 24	-0.327	0.033	-0.076	0.976	0.037	0.048
17 116	104 710	323.30401959	-0.79241062	15.856	0.7250	-14 ± 21	-0.102	0.010	0.058	0.891	0.024	-0.068
17 978	109 421	323.34565833	-0.78756009	17.282	0.7500	-28 ± 24	-0.359	0.016	-0.067	1.008	0.037	0.090
18 076	110 938	323.35382365	-0.78697660	17.157	0.8453	15 ± 60	-0.307	0.020	-0.027	0.912	0.044	-0.009
18 369	108 550	323.34180935	-0.78528604	15.944	0.9510	-7 ± 25	-0.335	0.015	-0.167	1.033	0.033	0.077
18 682	108 795	323.34281919	-0.78336333	17.101	0.7351	15 ± 36	-0.326	0.015	-0.051	0.928	0.033	0.006
19 348	105 097	323.32380781	-0.77915460	17.240	0.6913	-36 ± 29	-0.326	0.015	-0.038	0.961	0.034	0.042
19 928	110 282	323.35007852	-0.77513187	16.773	0.7985	-5 ± 25	-0.056	0.018	0.189	0.883	0.028	-0.047
20 163	112 239	323.36202881	-0.77336422	17.339	0.8046	15 ± 44	-0.136	0.022	0.161	0.916	0.045	-0.001
20 473	112 049	323.36081815	-0.77080365	17.193	0.7606	-33 ± 22	-0.198	0.011	0.085	0.927	0.028	0.007
20 654	113 091	323.36801961	-0.76926014	17.412	0.6326	-1 ± 25	-0.138	0.026	0.165	0.914	0.040	-0.001
20 871	107 606	323.33741787	-0.76723645	16.960	0.7788	19 ± 39	-0.344	0.021	-0.082	0.982	0.053	0.057
20 885	110 521	323.35133131	-0.76713157	17.195	0.7770	-28 ± 24	-0.067	0.015	0.216	0.795	0.027	-0.125
21 053	113 761	323.37197589	-0.76537623	14.885	1.3645	-7 ± 48	0.100	0.020	0.171	1.000	0.031	0.000
21 729	104 749	323.32152639	-0.75746580	17.044	0.6698	-30 ± 42	0.148	0.018	0.418	1.007	0.027	0.084
22 047	113 079	323.36788890	-0.75307288	14.836	1.4040	-33 ± 28	-0.223	0.017	-0.157	1.003	0.026	0.001
22 092	113 393	323.36985251	-0.75241609	17.134	0.7180	-9 ± 20	-0.348	0.019	-0.070	0.964	0.050	0.043
22 170	113 230	323.36891078	-0.75140570	17.088	0.7840	14 ± 54	-0.218	0.042	0.056	0.940	0.052	0.018

**Notes.** ID<sub>SDSS</sub> is the DAOPHOT ID number from An et al. (2008) photometric catalog.

The right hand panel of Fig. 3 illustrates the relation between the CN and CH band strengths for all giants: it shows a plot of the CH(4300) index vs. the V magnitude with the CN-strong and CN-weak stars. In this case the spread among the measured index is very small and, in any case, within the uncertainties. There is a tendency, as expected, for CN-strong stars to also be CH-weak, even if exceptions exist.

Out of a sample of 38 stars, 16 have weak CN bands. The number ratio of CN-weak to CN-strong that we obtained ( $\sim 0.73 \pm 0.2$ ) is very different<sup>7</sup> from what is found by Smith & Mateo (1990) (0.33; 16 RGB stars<sup>8</sup>) and Smolinski et al. (2011) (0.35; 70 MS, SGB, and RGB stars). Comparing these values directly is complicated by the fact that our study only uses RGB stars, while for example Smolinski et al. (2011) includes subgiants and dwarfs and Smith & Mateo (1990) focused on brighter stars. Dwarfs are significantly hotter than RGB stars

and less likely to show remarkable CN absorption, thus their inclusion may bias the CN-weak to CN-strong value downward.

CN and CH bands strongly depend on the temperature and gravity, when keeping the overall abundance fixed. These dependencies are usually minimized both by fitting the lower envelope of the distribution in the index-magnitude plane (or index-color plane; see for example Harbeck et al. 2003; Kayser et al. 2008) or by using median ridge lines to correct for the curvature introduced by both temperature and gravity effects (Pancino et al. 2010b; Lardo et al. 2012). To be consistent with our previous works, we used *median ridge line* (Fig. 3) to minimize the effect of effective temperature and surface gravity in the CH and CN measurements. The baselines adopted for the M 2 red giants to correct S(3839) and CH(4300) indices are

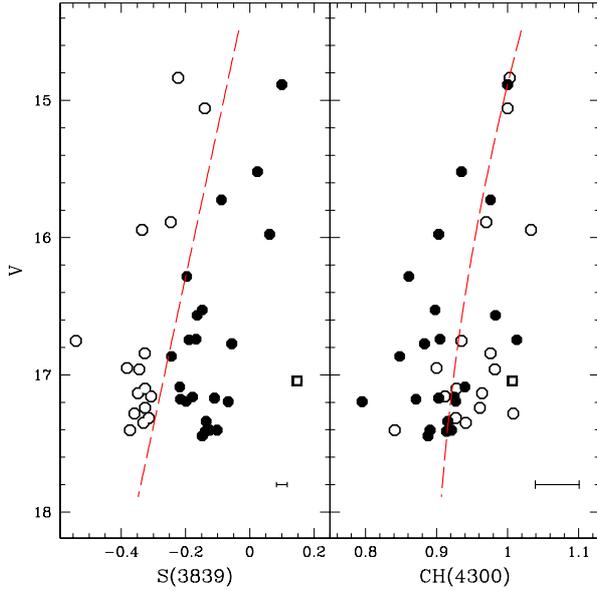
$$S_0 = -0.09 \times V + 1.3$$

$$CH_0 = 0.005 \times V^2 - 0.21 \times V + 2.88,$$

the rectified CN and CH indices are indicated as  $\delta S3839$  and  $\delta CH4300$ , respectively, and we refer to these new indices

<sup>7</sup> We emphasize that the ratio derived here is based on relatively few stars and the criteria for defining CN-strong stars are different in each work.

<sup>8</sup> If we exclude the two CH stars.



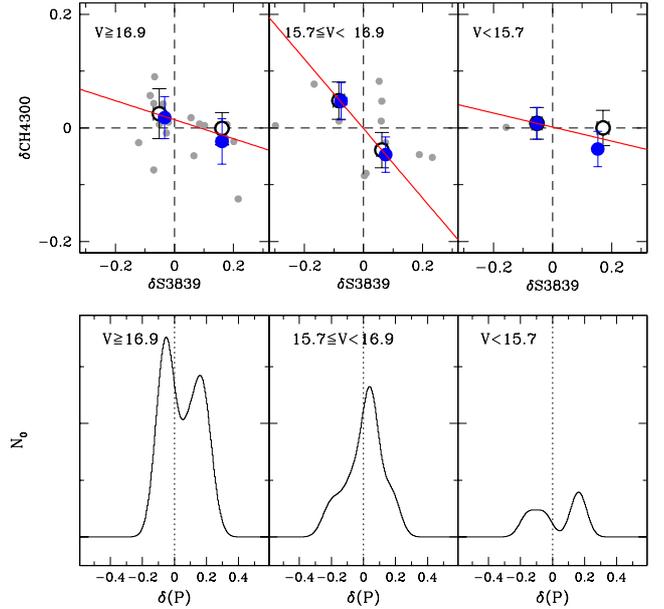
**Fig. 3.** *Left panel:* removal of gravity and temperature dependencies from CN index using median ridge line (shown as red dashed line). Stars considered to have mid-strength or strong CN bands are depicted by filled circles, while CN-weak giants are represented by open circles. A probable non-member star (see Sect. 3) is shown as an open square. The median errorbar on the S(3839) and CH(4300) measurements is also shown in the lower-right corner of each panel. *Right panel:* the same as in the left panel but for the CH index. The color code is consistent with the left panel.

in the following<sup>9</sup>. Figure 4 shows the rectified index  $\delta S3839$  as a function of  $\delta CH4300$  for all the stars studied in this paper. Abundance analysis in Sect. 5 confirmed that carbon abundance depends on the evolutionary state and decreases towards brighter luminosities. Therefore, we separately considered stars in three different magnitude bins:  $V \geq 16.9$ ,  $15.7 \leq V < 16.9$ , and  $V < 15.7$  mag, to minimize the impact of evolutionary effects on our index analysis. To better visualize the hidden substructure in the  $\delta S3839$  vs.  $\delta CH4300$  plane we adopted the method described below.

- A median is used to compute the centroids of the CH-strong ( $\delta CH4300 > 0$ ) and CH-weak ( $\delta CH4300 < 0$ ) in the CH-CN plane. The resulting centroids with their  $1\sigma$  errors are reported in Fig. 4 along with the measurements for each star. We also divided also the stars into CN-strong ( $\delta S3839 > 0$ ) and CH-weak ( $\delta S3839 < 0$ ) groups and their centroids with relative error bars are plotted in the same figure.
- A line passing through the midpoint connecting CH-strong/CN-weak and CH-weak/CN-strong centroids is traced.
- Each observed point in the CN-CH plane is projected onto this line.
- We take as origin ( $P$ ) the intersection between this line and the perpendicular line passing through the point  $(\delta S3839, \delta CH4300) = (0, 0)$ .
- A generalized histogram of the distribution of distances of projected points from the origin  $P$ . is constructed.

The histograms are shown in the bottom panels of Fig. 4, where different panels show different subsamples of RGB stars. Each

<sup>9</sup> We obtained a rough estimate of the uncertainty in the placement of these median ridge lines by using the first interquartile of the rectified indices divided by the square root of the number of points. The resulting uncertainties (typically  $\sim 0.013$  for the CN index and  $\sim 0.008$  for the CH index) are largely negligible for the applications of this work.



**Fig. 4.** *Upper panel:* anticorrelation plot for the CN and CH band strengths in three magnitude bins ( $V \geq 16.9$  mag,  $15.7 \leq V < 16.9$  mag and  $V < 15.7$  mag). Gray dots show measurements for stars. CH weak and CH strong stars are separated by the horizontal dashed line, and their centroids with  $1\sigma$  are marked as large white dots. CN strong and weak stars are separated by the vertical dashed line, and their centroids with their  $1\sigma$  are shown as large blue dots. The red continuous line connects the locus equidistant from CH-strong/CN-weak centroids and CH-weak/CN-strong ones. The generalized histograms in the bottom panels represent the distribution of distances of projected points from the origin  $P$  (see text for details).

**Table 3.** Dimension of the samples and results of KS test.

MAG BIN	$N_{\text{Stars}}$	CN-s(CH-w)	$P_{\text{KS}}$
$V \geq 16.9$ mag	21	11	$1.14e^{-0.5}$
$15.7 \leq V < 16.9$ mag	13	9	0.002
$V < 15.7$ mag	4	2	0.1

data point in this histogram has been replaced by a Gaussian of unit area and standard deviation  $\sigma = 0.04$ <sup>10</sup>. We distinguish between CN-strong (CH-weak) stars and CN-weak (CH-strong) stars by cutting at zero the histogram of distances distribution. The dimension of the subsamples, and the number of CN-strong stars in each bin is listed in the second and third columns, respectively, in Table 3. Figure 4 shows that stars fainter than  $V \approx 16.9$  display clear bimodality, with both CN-strong (CH-weak) and CN-weak (CH-strong) stars, as is common among GCs of intermediate metallicity. For brighter giants, the distribution of the projected points is still not described well by a single symmetric Gaussian curve: indeed, a two-sided Kolmogorov-Smirnov returns a probability of  $P_{\text{KS}} = 0.002$  ( $P_{\text{KS}} = 1.14 \times 10^{-5}$  for stars in the first magnitude bin, see the last column in Table 3) that the CN-strong (CH-weak) and CN-weak (CH-strong) are drawn from the same parent population. When analyzing all data sets, the underlying bimodality can be confused by evolutionary effects (mixing), but a wide spread with three notable peaks is still present. Again from Fig. 4 (top panel), for all magnitude bins we report a clear CH-CN anticorrelation for all magnitude bins.

<sup>10</sup> The 0.04 mag used as the Gaussian width in the generalized histograms of Fig. 4 is the same as the measurement error on  $\delta S3839$ .

## 4. Abundance analysis

### 4.1. Atmospheric parameters

We derived stellar parameters from photometry. The effective temperature,  $T_{\text{eff}}$ , was calculated using [Alonso et al. \(1999\)](#)  $T_{\text{eff}}$ -color calibrations for giant stars. We used the  $(U - V)$  color from DOLORES photometry (once calibrated on the Stetson standard field), using  $E(B - V) = 0.06$  and  $[\text{Fe}/\text{H}] = -1.65$  from the [Harris \(1996\)](#) catalog (2010 edition). In addition, we used – when available –  $(B - V)$ ,  $(V - J)$ ,  $(V - H)$ , and  $(V - K)$  colors from [Lee & Carney \(1999\)](#) and the 2MASS ([Skrutskie et al. 2006](#)) photometry. The final  $T_{\text{eff}}$  was the mean of the individual  $T_{\text{eff}}$  values from each color weighted by the uncertainties for each color calibration. The surface gravity was determined using  $T_{\text{eff}}$ , a distance modulus of  $(m - M)_V = 16.05$  ([Harris 1996](#)), bolometric corrections  $BC(V)$  from [Alonso et al. \(1999\)](#), and an assumed mass of  $0.8 M_{\odot}$  ([Bergbusch & Vandenberg 2001](#)). The microturbulent velocity was determined using the relation,  $v_t = -8.6 \times 10^{-4} T_{\text{eff}} + 5.6$ , adopted from the analysis by [Pilachowski et al. \(1996\)](#) of metal-poor subgiant and giant stars with comparable stellar parameters. This method leads to an average microturbulent velocity estimate of  $v_t = 1.1 \pm 0.13 \text{ km s}^{-1}$ , therefore we chose to assign a reference microturbulent velocity of  $v_t = 1.0 \text{ km s}^{-1}$  to all our program stars.

An additional check to test the reliability of our chosen atmospheric parameters was performed using theoretical isochrones downloaded from the Dartmouth Stellar Evolution Database ([Dotter et al. 2008](#))<sup>11</sup>. We chose an isochrone of 12 Gyr with standard  $\alpha$ -enhanced composition, and we projected our targets on the isochrone (following a criterion of minimum distance from the isochrone points) in the  $U$ ,  $(U - V)$  diagram to obtain their parameters. The median difference in temperature between the two methods is approximately  $20 \pm 4 \text{ K}$ , while the difference in gravity is negligible (on the order of  $0.013 \pm 0.002$ ). By projecting our targets on the isochrone in the *intrinsically* broad  $U$ ,  $(U - V)$  RGB, we could possibly erase differences in color (and thus in temperature) between spectroscopic targets; therefore, we preferred to rely on the [Alonso et al. \(1999\)](#) parameter estimates.

The residual external uncertainties, which could result only in a shift of the zero point, do not affect the amplitude of star-to-star variation in C and N, since we want to measure the internal intrinsic spread of our sample of stars. Table 4 reports the  $T_{\text{eff}}$ ,  $\log g$  values, and their uncertainties used to derive C and N abundances.

### 4.2. Abundances derivation

Abundances for a given element were derived by comparing synthetic spectra with observed spectra. The C and N abundances were estimated by spectral synthesis of the  $2\Sigma-2\Pi$  band of CH (the G band) at  $\sim 4310 \text{ \AA}$  and the  $UV$  CN band at  $3883 \text{ \AA}$  (including a number of CN features in the wavelength range of  $3876-3890 \text{ \AA}$ ), respectively. The synthetic spectra were generated using the local thermodynamic equilibrium (LTE) program MOOG ([Snedden 1973](#)). The atomic and molecular line lists were taken from the latest Kurucz compilation ([Castelli & Hubrig 2004](#)) and downloaded from the Castelli website<sup>12</sup>.

Model atmospheres were calculated with the ATLAS9 code, starting from the grid of models available on the Castelli website ([Castelli & Kurucz 2003](#)), using the values of  $T_{\text{eff}}$ ,  $\log g$ ,

**Table 4.** Atmospheric parameters and carbon and nitrogen abundances for sample stars.

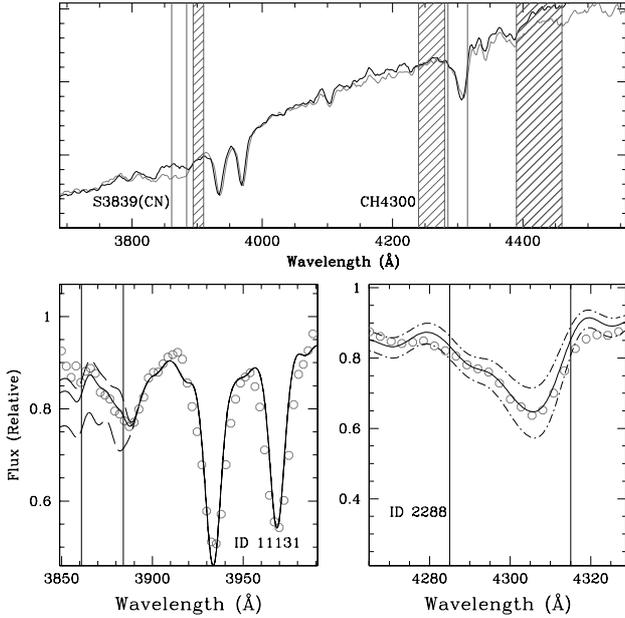
ID	$T_{\text{eff}}$ (K)	$dT_{\text{eff}}$ (K)	$\log g$ (cgs)	A(C) (dex)	A(N) (dex)
1047	5184	60	$2.7 \pm 0.03$	$5.80 \pm 0.19$	$7.50 \pm 0.23$
1221	5041	56	$2.4 \pm 0.03$	$6.11 \pm 0.19$	$6.75 \pm 0.22$
1249	5111	59	$2.6 \pm 0.03$	$6.14 \pm 0.19$	$6.30 \pm 0.23$
1921	4955	54	$2.2 \pm 0.03$	$5.92 \pm 0.16$	$7.23 \pm 0.22$
1927	5304	85	$3.0 \pm 0.03$	$6.22 \pm 0.22$	$7.25 \pm 0.25$
2288	4959	54	$2.2 \pm 0.03$	$6.07 \pm 0.18$	$7.18 \pm 0.22$
3190	5581	71	$3.0 \pm 0.03$	$6.47 \pm 0.23$	$7.48 \pm 0.27$
3397	5301	84	$2.9 \pm 0.03$	$6.28 \pm 0.20$	$7.15 \pm 0.24$
3760	5421	86	$2.9 \pm 0.03$	$6.46 \pm 0.22$	$7.44 \pm 0.25$
4144	5142	107	$2.6 \pm 0.05$	$5.87 \pm 0.21$	$7.40 \pm 0.23$
5010	4732	65	$1.8 \pm 0.03$	$5.68 \pm 0.17$	$6.96 \pm 0.22$
5149	4904	53	$2.0 \pm 0.03$	$5.59 \pm 0.20$	$7.56 \pm 0.21$
5185	5413	67	$3.0 \pm 0.03$	$6.27 \pm 0.22$	$7.06 \pm 0.25$
9229	5022	75	$2.3 \pm 0.03$	$5.87 \pm 0.21$	$7.53 \pm 0.22$
10 803	5458	88	$3.0 \pm 0.03$	$6.35 \pm 0.21$	$7.12 \pm 0.26$
11 131	5326	85	$2.8 \pm 0.03$	$6.18 \pm 0.20$	$7.17 \pm 0.25$
11 796	5282	87	$3.0 \pm 0.04$	$5.91 \pm 0.20$	$7.77 \pm 0.24$
14 343	5229	83	$2.8 \pm 0.03$	$6.12 \pm 0.20$	$7.25 \pm 0.24$
15 217	5328	88	$3.0 \pm 0.04$	$6.24 \pm 0.20$	$6.85 \pm 0.25$
16 614	5224	83	$2.7 \pm 0.02$	$6.17 \pm 0.19$	$6.75 \pm 0.24$
17 116	5006	73	$2.2 \pm 0.03$	$6.13 \pm 0.17$	$7.58 \pm 0.22$
17 978	5263	85	$2.9 \pm 0.03$	$5.98 \pm 0.19$	$7.19 \pm 0.24$
18 076	5232	82	$2.8 \pm 0.03$	$5.99 \pm 0.22$	$7.17 \pm 0.24$
18 369	4956	73	$2.2 \pm 0.03$	$6.12 \pm 0.22$	$6.11 \pm 0.22$
18 682	5397	87	$2.9 \pm 0.03$	$6.40 \pm 0.24$	$6.52 \pm 0.26$
19 348	5383	87	$2.9 \pm 0.03$	$6.41 \pm 0.22$	$6.85 \pm 0.25$
19 928	5146	81	$2.7 \pm 0.03$	$5.82 \pm 0.22$	$7.41 \pm 0.23$
20 163	5179	82	$2.9 \pm 0.04$	$5.99 \pm 0.19$	$7.10 \pm 0.24$
20 473	5200	82	$2.8 \pm 0.03$	$5.92 \pm 0.21$	$7.46 \pm 0.23$
20 654	5488	125	$3.0 \pm 0.04$	$6.46 \pm 0.22$	$6.84 \pm 0.26$
20 871	5263	83	$2.8 \pm 0.03$	$6.27 \pm 0.21$	$6.79 \pm 0.24$
20 885	5076	80	$2.8 \pm 0.04$	$5.45 \pm 0.19$	$7.47 \pm 0.23$
21 053	4661	62	$1.7 \pm 0.03$	$5.61 \pm 0.16$	$7.21 \pm 0.23$
22 047	4630	61	$1.6 \pm 0.03$	$5.57 \pm 0.28$	$6.48 \pm 0.24$
22 170	5271	83	$2.8 \pm 0.03$	$6.21 \pm 0.20$	$7.16 \pm 0.24$

and  $v_t$  determined as explained in the previous section. For all the models we adopted  $[A/H] = -1.5$ , according to the metallicity of the cluster. The ATLAS9 models we employed were computed with the new set of opacity distribution functions ([Castelli & Kurucz 2003](#)) and excluded approximate overshooting in calculating the convective flux. For the CH transitions, the  $\log g_f$  obtained from the Kurucz database were revised downward by 0.3 dex to better reproduce the solar-flux spectrum by [Neckel & Labs \(1984\)](#) with the C abundance by [Caffau et al. \(2011\)](#), as extensively discussed in [Mucciarelli et al. \(2012\)](#). Figure 5 illustrates the fit of synthetic spectra to the observed ones in CH and CN spectral regions. These stars have essentially the same stellar parameters ( $T_{\text{eff}} \sim 5000 \text{ K}$ ,  $\log g = 2.2$ ), lying at about the same place in the cluster CMD, yet their CN bands differ strongly. Because the abundances of C and N are coupled, we iterated until self-consistent abundances were obtained. Further details on the abundances derivation can be found in [Lardo et al. \(2012\)](#).

We assumed that all stars had the same oxygen abundance ( $[\text{O}/\text{Fe}] = +0.4 \text{ dex}$ ) regardless of luminosity (constant oxygen abundance as the star evolves along the RGB). The derived C abundance is dependent on the O abundance and therefore so is the N abundance. In molecular equilibrium an overestimate of oxygen produces an overestimate of carbon (and vice versa), and an overestimate of carbon from CN features is reflected in an underestimate of nitrogen. We expect that the exact O values will

<sup>11</sup> <http://stellar.dartmouth.edu/models/isolf.html>

<sup>12</sup> <http://wwwuser.oat.ts.astro.it/castelli/linelists.html>

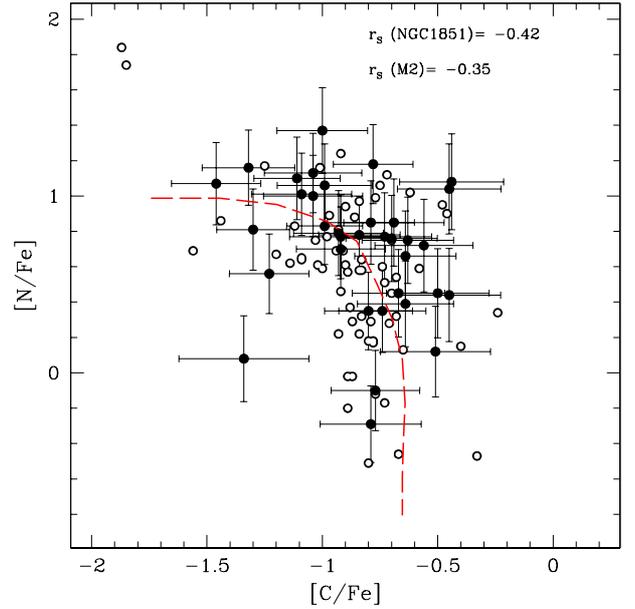


**Fig. 5.** *Top panel:* DOLores-LRB spectra of the stars 17116 (gray) and 18369 (black) in the region of the CN UV feature and CH band. The stars are essentially identical in  $V$  magnitude ( $V = 15.86, 15.94$ , respectively),  $(U - V)$  color ( $(U - V) = 1.06$  and  $0.95$ , respectively), and C abundance (see Table 4). The gray shaded regions show the continuum regions, while the solid gray lines show the window from which we measured the CN and CH indices. *Bottom panels:* observed (gray empty circles) and synthetic (line) spectra around the CN and CH band for the stars 11131 and 2288 stars, respectively. The solid line represents the best fit, while the dashed-dotted lines are the synthetic spectra computed with the derived C abundance altered by  $\pm 0.2$  dex and N abundance altered by  $\pm 0.5$  dex from the best value. Vertical lines show the location of the CN (3861 Å to 3884 Å) and CH (4285 Å to 4315 Å) absorption bandpass.

affect the derived C abundances only negligibly, since the CO coupling is marginal in cool stellar atmospheres ( $T \leq 4500$  K). To quantify the sensitivity of the C abundance on the adopted O abundance, we varied the oxygen abundances and repeated the spectrum synthesis to determine the exact dependence for a few representative stars ( $4900 \text{ K} \leq T_{\text{eff}} \leq 5400 \text{ K}$ ). In these computations, we adopted  $[\text{O}/\text{Fe}] = -0.2$  dex,  $[\text{O}/\text{Fe}] = 0.0$  dex, and  $[\text{O}/\text{Fe}] = +0.4$  dex. We found that strong variations in the oxygen abundance markedly affect the derived C abundance only for the brighter stars in our sample, for which  $[\text{C}/\text{Fe}]$  can change by as much as  $0.17$ – $0.20$  dex for a  $0.6$  dex change in assumed  $[\text{O}/\text{Fe}]$ . This is within the uncertainty assigned to our measurement. See also a discussion of the effects of considering different O abundance on carbon abundance derivation in [Martell et al. \(2008\)](#).

The total error in the derived C and N abundances was computed by taking the internal errors associated to the chemical abundances into account. Two sources of errors can contribute to this internal error: (i) the uncertainty introduced by errors in the atmospheric parameters used to compute chemical abundances, and (ii) the error in the fitting procedure and errors in the abundances that are likely caused by noise in the spectra. To estimate the sensitivity of the derived abundances to the adopted atmospheric parameters, we therefore repeated our abundance analysis and changed only one parameter at each iteration for several stars that are representative of the temperature and gravity range explored.

Typically, we found  $\delta A(\text{C})/\delta T_{\text{eff}} \simeq 0.09$ – $0.13$  dex and  $\delta A(\text{N})/\delta T_{\text{eff}} \simeq 0.14$ – $0.18$  dex for the temperature. The errors



**Fig. 6.** Derived  $[\text{N}/\text{Fe}]$  abundances for M2 stars in Table 4 as a function of the  $[\text{C}/\text{Fe}]$  abundances from our sample (filled circles). A C vs. N anticorrelation is apparent. For comparison we also plotted our previous results on a sample of MS and SGB stars in the cluster NGC 1851 (white dots). The red dashed line indicates the relationship, shown over its full range, that prevails in NGC 1851 from our earlier work.

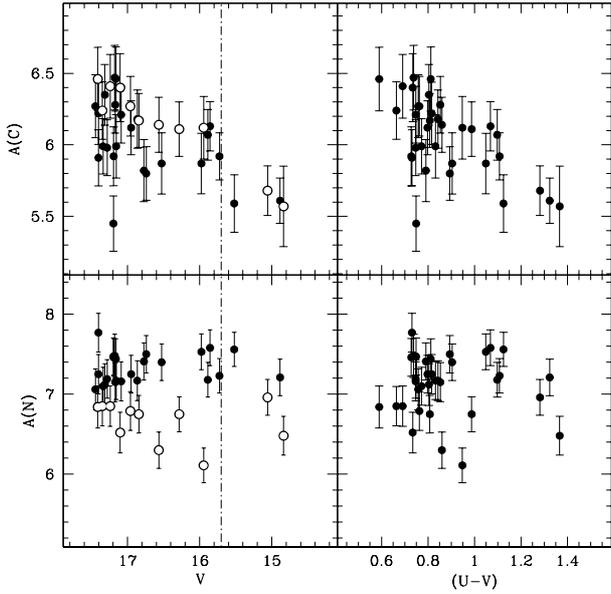
due to uncertainties on gravity and microturbulent velocity are negligible (on the order of  $0.03$  dex or less). The contribution of continuum placement errors was estimated by determining the change in the abundances as the synthetic/observed continuum normalization was varied<sup>13</sup>: generally, this uncertainty added  $0.11$  dex to the abundances. The errors derived from the fitting procedure were then added in quadrature to the errors introduced by atmospheric parameters, resulting in an overall error of approximately  $0.20$  dex for the C abundances and  $0.22$  dex for the N values.

We present the abundances derived as described above and the relative uncertainties in the abundance determination in Table 4. Additionally, this table lists the derived atmospheric parameters of all our targets.

## 5. C and N abundance results

Variations in light-element abundances were already observed in all GCs studied to date, and are also present in M2. Carbon and nitrogen exhibit the typical anticorrelation, as shown in Fig. 6, where the  $[\text{C}/\text{Fe}]$  values are plotted as a function of  $[\text{N}/\text{Fe}]$  with their uncertainties. For three stars out of 38, we were not able to derive C and N abundances because of the low S/N in the CN band spectral region. We observe modest variations in carbon abundances (from  $[\text{C}/\text{Fe}] \sim -1.4$  to  $[\text{C}/\text{Fe}] \sim -0.4$ ) mildly anticorrelated (Spearman's rank correlation coefficient  $r_s^{\text{M2}} = -0.35$ ) with strong variations in N, which span almost 2 dex, from  $[\text{N}/\text{Fe}] \sim -0.3$  up to  $[\text{N}/\text{Fe}] \sim 1.4$  dex. In the same figure we also plot C and N abundances derived for NGC 1851 in our previous work ([Lardo et al. 2012](#)) with the  $[\text{C}/\text{Fe}]$  –  $[\text{N}/\text{Fe}]$  relationship that prevails for these stars ( $r_s^{\text{NGC 1851}} = -0.42$ ). The range of the spread in both C and N is about the same

<sup>13</sup> We continuum-normalized our spectra using the same function (cubic spline) in the task IRAF *continuum* but with an order slightly higher with respect to that chosen for the first normalization.



**Fig. 7.** Derived C and N abundances plotted against the  $V$  magnitude and  $U - V$  color for M2 giants. The dot-dashed lines indicate the luminosity at which the RGB bump occurs ( $V \sim 15.7$  mag). Relatively N-rich and N-poor stars are shown in the left panels as filled and open symbols, respectively.

for M2 and NGC 1851<sup>14</sup> (and fully agrees with the C and N abundances presented by Cohen et al. 2005, for M71, 47 Tuc, M5, M13, and M15). The two anticorrelations clearly follow a similar overall pattern in the  $[C/Fe]$  vs.  $[N/Fe]$  plane.

### 5.1. Evolutionary effects

As described in the Introduction, surface abundance changes due to deep mixing are not expected to occur in stars fainter than the RGB bump. We plotted the derived abundances as a function of the  $V$  magnitude and  $U - V$  color in Fig. 7 to evaluate possible systematic effects with luminosity and temperature. While none of these effects is apparent, the top panel of Fig. 7 again illustrates the notable depletion in the carbon abundances with luminosity (Smith & Martell 2003; Gratton et al. 2000, and references therein). The surface carbon abundance depletion along the RGB of M2 can be straightforwardly interpreted within a deep-mixing framework. This implies that some form of deep mixing (i.e., meridional circulation currents, turbulent diffusion or some similar processes), which extends below the base of the conventional convective zone, must circulate material from the base of the convective envelope down into the CN(O)-burning region near the hydrogen-burning shell. The onset of the decline in the carbon abundance appears from Fig. 7 to occur at magnitude  $V \approx 15.7$ : the strong C decline for stars brighter than  $V \lesssim 15.7$  can be interpreted as the signature of the extra mixing common among metal-poor cluster giants as they cross the RGB bump. Restricting our sample to those giants fainter than the RGB bump, we found an average C abundance of  $A(C) = 6.11 \pm 0.23$ . A significant decrease in C abundance occurs at about  $V \lesssim 15.7$ , which is essentially the location of the RGB bump in this cluster ( $V_{\text{BUMP}} \sim 15.82 \pm 0.05$ , Di Cecco et al. 2010): the average value for this group of upper

<sup>14</sup> For comparison, the median value of carbon abundance is  $[C/Fe] = -0.79$  dex ( $\sigma = 0.2$ ) for M2 and  $[C/Fe] = -0.84$  dex ( $\sigma = 0.12$ ); respectively. Median nitrogen abundances are  $[N/Fe] = 0.77$  dex ( $\sigma = 0.31$ ) for M2 and  $[N/Fe] = 0.61$  dex for NGC 1851 ( $\sigma = 0.30$ ).

RGB stars is  $A(C) = 5.61 \pm 0.05$ . Naturally, the extent of the carbon (nitrogen) depletion (enhancement) depends on the value of  $[O/Fe]$  used in the analysis. For comparison, in metal-poor field giants (Gratton et al. 2000), a drop in the surface  $^{12}\text{C}$  abundance by about a factor 2.5, is seen after this second mixing episode. To connect CN index measurements with carbon and nitrogen abundances derived by spectral synthesis, we labeled CN-strong and CN-weak stars in Fig. 8 as defined in Sect. 3 in the  $A(C)$  and  $A(N)$  vs.  $V$  mag and  $A(C)$  vs.  $A(N)$  planes. From Fig. 8, we note good agreement between the underlying  $[N/Fe]$  abundance and the measured CN band strength: as expected CN-strong and CN-weak stars tend to occupy two separate regions in the  $A(C)$ - $A(N)$  diagram. Any difference of  $[C/Fe]$  at a given magnitude is difficult to interpret since it can arise from systematic differences between the analysis techniques. As discussed in Smith & Martell (2003), a reasonable estimate of the dependence of the carbon abundance on luminosity can be obtained by deriving  $d[C/Fe]/dM_V$ . To compare the behavior of  $[C/Fe]$  among field giants with M2 giants, we fit a linear least-squares regression of  $[C/Fe]$  against  $M_V$  for stars with  $-0.8 \leq M_V \leq 1.6$ . We restricted our attention to stars selected by Smith & Martell (2003)<sup>15</sup> from the Gratton et al. (2000) survey. In close analogy with Smith & Martell (2003), we limited our fit to stars with  $M_V \leq 1.6$ , because there is only a slight variation below this luminosity level (see Fig. 10 of Gratton et al. 2000). The upper limit in luminosity was chosen to compare only the overlapping region between the two data sets. As far as can be ascertained from the carbon abundances, the rate of mixing in this cluster is comparable to the one for halo field stars and many cluster giants. We found a dependence of  $d[C/Fe]/dM_V = 0.21 \pm 0.16$  that is very similar within the observational errors to that found among halo field giants ( $d[C/Fe]/dM_V = 0.20 \pm 0.03$ ) and other GCs (e.g., M3, NGC 6397, and M13; Smith & Martell 2003).

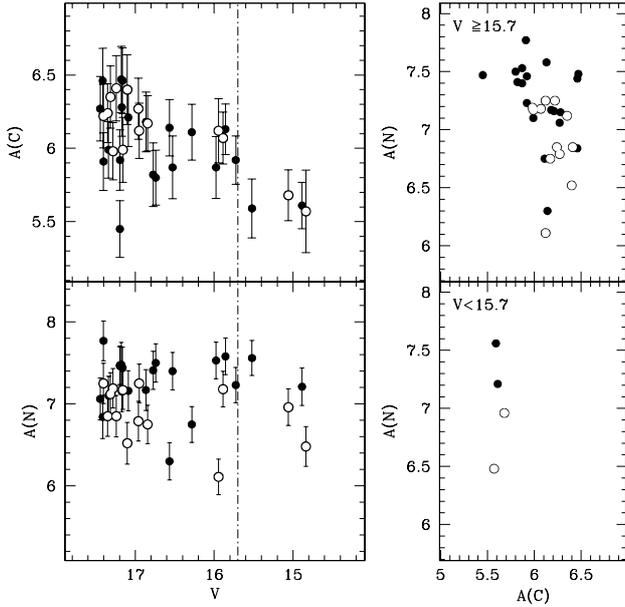
From the bottom left hand panel of Fig. 7, we see no significant trend in the N abundance with either luminosity or color: the average nitrogen abundance we found for stars fainter than the RGB bump ( $A(N) = 7.1 \pm 0.4$ ) agrees within the quite large error bar with the one obtained for the more luminous stars after the LF bump ( $A(N) = 6.9 \pm 0.6$ ). We tentatively divided the target stars between candidate first-generation and candidate second-generation (N-poor and N-rich component, respectively) stars by adopting a threshold in nitrogen abundance  $A(N) = 7.0$ . In Fig. 7, N-poor and N-rich stars are plotted, where we note that N-rich stars are systematically C-poor and vice versa, to further support the presence of C-N anticorrelation. Finally, Gratton et al. (2000) show an abrupt increase in N abundance of about  $\sim 4$  at  $\sim V_{\text{BUMP}}$  for field giants. Here we could not detect such a trend as the effect of the poor statistics (4 stars) towards higher luminosities.

### 5.2. C-N anticorrelation

We have seen in Sect. 5.1 how deep mixing affects nitrogen and (strongly) carbon abundances, because it introduces carbon-depleted material into the stellar convective envelopes. All our target stars have luminosities well above the first dredge-up onset, so we expect that their atmospheres are already depleted in carbon abundance<sup>16</sup>. A matter we plan to investigate now is how to disentangle the *intrinsic* star-to-star differences in surface carbon and nitrogen abundances from the changes resulting

<sup>15</sup> We consider the the restricted sample with the exclusion of stars HD 97 and HD 218857.

<sup>16</sup> Among the field stars, Gratton et al. (2000) data support the occurrence of a small ( $\approx 0.1$  dex) drop in the region of the first dredge-up.



**Fig. 8.** *Left panels:* derived C and N abundances are plotted against the  $V$  magnitude for M 2 RGB stars. The dot-dashed vertical lines indicate the luminosity at which the RGB bump occurs ( $V \sim 15.7$  mag). CN-strong and CN-weak stars, as defined in Sect. 3, are shown as filled and open symbols, respectively. *Right panel:* CN-strong and CN-weak stars (see Sect. 3) are plotted in the  $A(C)$  vs.  $A(N)$  plane for stars with luminosities fainter (*top*) and brighter (*bottom*) than the RGB bump. The color code is consistent with the left panel.

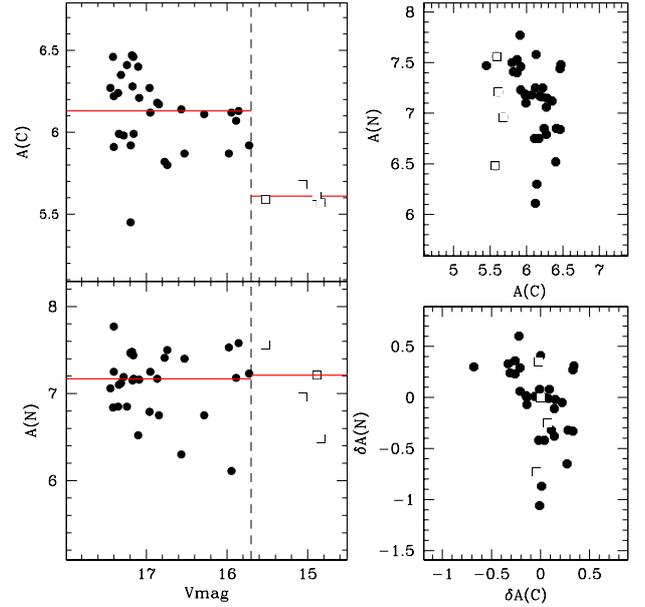
from normal stellar evolution. First, we note that we cannot arbitrarily distinguish between two groups of stars with different  $A(C)$  or  $A(N)$  for stars fainter than the LF peak, because we are unable to detect any clear bimodality. To make more quantitative statements about bimodality, a KMM test (Ashman et al. 1994) was applied to the data<sup>17</sup>. Under the assumption that the two Gaussians have the same dispersion (homoscedastic test), we can confirm that there is no bimodality in either  $A(C)$  or  $A(N)$  for stars with  $V \geq 15.7$ . At this point we proceed to analyze the C-N anticorrelation as follows:

- computed the median abundance of carbon and nitrogen for stars with  $V$  magnitude  $<15.7$  and  $\geq 15.7$  mag (traced in red in Fig. 9);
- for each measured point in the  $A(C)$ - $A(N)$  vs.  $V$  magnitude plane, and calculated the difference between  $A(C)$ ,  $A(N)$  and the *median* carbon and nitrogen abundance ( $\delta A(C)$  and  $\delta A(N)$ , respectively);
- constructed a plot of the  $\delta A(C)$  vs.  $\delta A(N)$ .

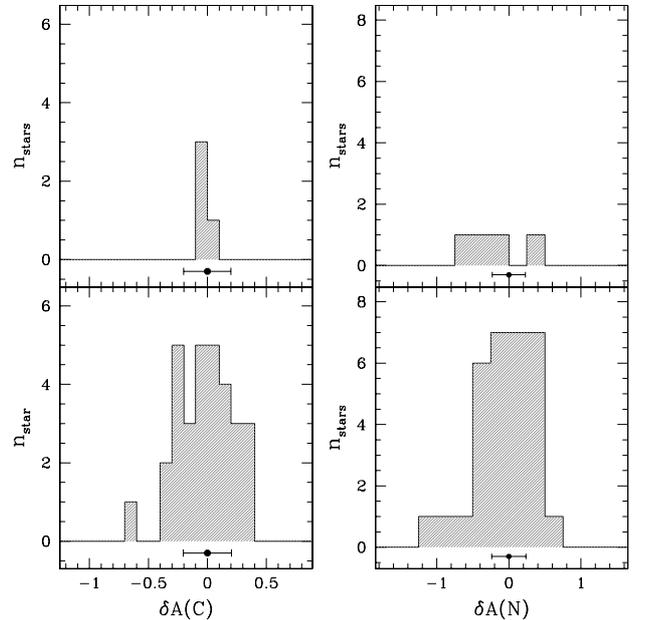
The *corrected*  $\delta A(C)$  vs.  $\delta A(N)$  anticorrelation is shown in the bottom right hand panel of Fig. 9. In this case, having corrected for the carbon decline due to normal stellar evolution, the anticorrelation appears tighter ( $r_S^{M2 \text{ corrected}} = -0.43$ ).

To better visualize the distribution of *corrected* C and N abundance in the two magnitude bins, we constructed histograms of the  $\delta A(C)$  and  $\delta A(N)$  distribution in Fig. 10. For stars below the RGB bump we note hints of bimodality in  $\delta A(C)$ . Despite the low statistics, the *corrected* C-N anticorrelation shows evidence for bimodality in the distribution of N abundances, with at least two (or three) groups of stars populating the extremes of high N or low N (see the lower right panel of Fig. 9).

<sup>17</sup> The star 22047 with an anomalously low carbon abundance ( $A(C) \approx 5.6$ ) is excluded from the fit.

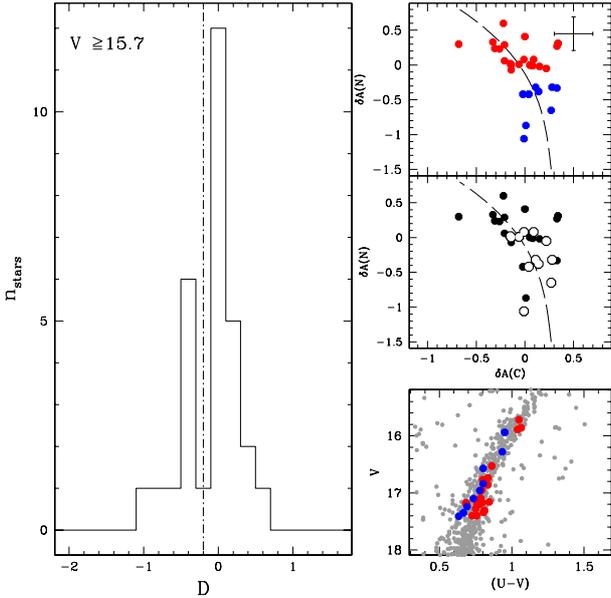


**Fig. 9.** Correction of the C-N anticorrelation for evolutionary effect. The *left panels* show the runs of  $A(C)$  and  $A(N)$  vs.  $V$  magnitude for spectroscopic targets. The vertical dashed line marks the RGB bump position. The red continuous red line indicates *median* value of the carbon and nitrogen abundance for stars in two bins of magnitude ( $V < 15.7$  and  $V \geq 15.7$  mag). The *top right panel* shows the derived C-N anticorrelation uncorrected for carbon decline (and nitrogen enhancement) due to evolution of the stars along the RGB. The *bottom right panel* shows the *corrected* C-N anticorrelation. In this case we plotted the difference of  $A(C)$  and  $A(N)$  from the *median* abundance value shown in the *left panels* (see text for further details).



**Fig. 10.** Histograms of the  $\delta A(C)$  and  $\delta A(N)$  (see text) distributions. The two vertical panels correspond to two bins of  $V$  mag ( $V \geq 15.7$  and  $V < 15.7$  mag; from bottom to up). The bin size is set to 0.1 and 0.25 for the  $\delta A(C)$  and  $\delta A(N)$ , respectively. Typical median error bars are plotted below each histogram.

To consider stars in the same evolutionary stage as much as possible, we first focused on the the *corrected* C-N anticorrelation for the faintest stars in our sample with magnitudes below the RGB bump ( $V \geq 15.7$ ). To confirm this suggestion, we analyzed



**Fig. 11.** *Left panel:* distribution of the projected distance  $D$  of stars with  $V \geq 16.9$  on the fiducial plotted in the *top right panel*. The dotted-dashed line separates stars belonging to the two different N groups. *Top right:* corrected C-N anticorrelation for stars with  $V \geq 15.7$ . We tentatively discriminated between first (blue) and second (red) populations. The error bar represents the typical errors on  $A(C)$  and  $A(N)$ . *Middle right:* CN-strong and CN-weak stars are plotted in the  $\delta A(C)$ - $\delta A(N)$  plane. *Bottom right:* first- and second-generation stars are superimposed to  $V$ ,  $(U - V)$  CMD of M2. The color code is used consistently in each panel.

the *corrected* distribution of stars along the C-N anticorrelation using a procedure similar to the one described in Marino et al. (2008). In brief, we first draw a fiducial (shown in the top right panel of Fig. 11) by putting a best-fit spline through the median abundance found in successive short intervals of  $\delta A(N)$ . Then we projected each program star in the  $\delta A(C)$ - $\delta A(N)$  anticorrelation on this fiducial and plotted the histogram of the distribution of vertical distances ( $D$ ) of the projected points from the line  $\delta A(N) = 0$ . The histogram is shown in the left panel of Fig. 11. In this case (at least) two substructures are apparent, peaked at  $\approx -0.4$  and  $0.2$ . We tentatively divided RGB stars between a candidate first generation and a candidate second generation by setting an arbitrary separation at  $D = -0.2$ . To allow a direct comparison between CN-strong (as derived in Sect. 4) and these second-generation stars, we plotted CN-strong stars in the  $\delta A(C)$ - $\delta A(N)$  plane in the same figure. We note that the smearing of CN-strong and CN-weak stars that happens in the  $A(C)$ - $A(N)$  plane (see Fig. 7) is still present in the  $\delta A(C)$  vs.  $\delta A(N)$  plot.

A visual inspection of Fig. 11 suggests that the extent of the C-N anticorrelation in the *projected* plane for second-generation (Na-N/rich) stars is greater than the errors associated with abundance measurements. This evidence possibly suggests the presence of a third group of stars<sup>18</sup>; unfortunately, because of uncertainties on abundance measurements and low statistics, we cannot provide conclusive evidence.

In general, when stars with available Na and O abundances have been identified in the  $U$  vs.  $(U-B)$  CMD (or in a different color combination that includes the blue filters), it was found that the group of Na-poor stars are systematically spread on the blue side of the RGB, while the Na-rich population define a narrow

sequence on the red RGB (Grundahl & Briley 2001; Marino et al. 2008; Han et al. 2009; Milone et al. 2010). Several authors have demonstrated that a clear correlation exists between N abundances (and so  $\lambda 3883$  CN band strength) and Na, O and Al abundances (see for example Marino et al. 2008, and references therein). N-rich (CN-strong) stars clearly show significantly enhanced Na abundance. In contrast, N-poor (CN-weak) stars have a higher O content than the N-rich ones.

In the bottom right hand panel of Fig. 11, N-rich and N-poor stars are superimposed on M2  $V$ ,  $(U - V)$  DOLORES CMD. N-poor and N-rich stars are clearly separated into two parallel sequences in the broader giant branch seen in the  $V$ ,  $(U - V)$  diagram, with the N-rich stars systematically appearing redder than N-poor ones, a behavior strictly analogous to what is observed Marino et al. (2008) in M4. It is clear that the strength of the CN and NH bands strongly influences the  $U - V$  color, the NH band around  $3360 \text{ \AA}$ , and the CN bands around  $3590$ ,  $3883$ , and  $4215 \text{ \AA}$ , located in the  $U$  being the main contributors to the effect (see also Sbordone et al. 2011).

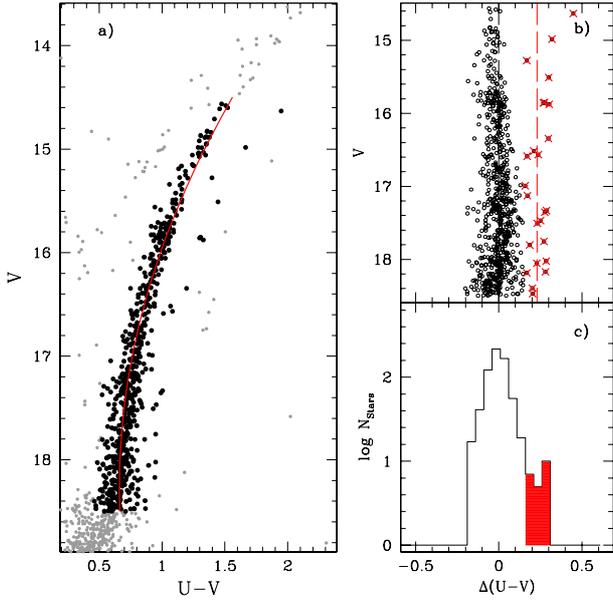
## 6. The anomalous RGB in M2

As discussed in Sect. 1, GCs are essentially monometallic, e.g., all the stars in a cluster show the same  $[\text{Fe}/\text{H}]$  abundance. Besides the remarkable exception of  $\omega$  Centauri (see Marino et al. 2012a, and references therein), variations in the heavy element content have been detected only for a few clusters: M22 (Marino et al. 2012b), Terzan 5 (Ferraro et al. 2009; Origlia et al. 2011), M54 (Carretta et al. 2010a), and NGC 1851 (Yong & Grundahl 2008; Carretta et al. 2010b). In particular, among the clusters that displayed this anomalous behavior, NGC 1851 and M22 appear rather peculiar. For these clusters, a bimodal distribution of  $s$ -process elements abundance has been identified (Yong & Grundahl 2008; Marino et al. 2012b). The chemical inhomogeneity reflects itself in a complex CMD: multiple stellar groups in M22 and NGC 1851 are also clearly manifested by a split in the SGB region (Piotto 2009; Milone et al. 2008) which appears to be related to chemical variations observed among RGB stars (Marino et al. 2012b; Lardo et al. 2012). Indeed, carefully constructed CMDs – based on colors that include a blue filter (Han et al. 2009; Lardo et al. 2012; Marino et al. 2012b) – clearly reveal that the bright SGB is connected to the blue RGB, while red RGB stars are linked to the faint SGB. The split of the RGB discovered in the  $U - I$  and  $U - V$  colors for NGC 1851 and M22, respectively, would not be detected in the usual optical colors.

M2 DOLORES photometry (see Fig. 1) displays an *anomalous* branch beyond the red edge of the main body of the RGB. The difference in color between stars belonging to this structure and *normal* RGB stars is quite large (on the order of  $0.2$ – $0.3$  mag, well above the typical measurement errors) and extends down to the SGB region. There may be a second group of stars that are  $0.3$  mag redder with respect to this sequence and can possibly be more, the anomalous RGB stars. Unfortunately, because of low statistics, we cannot provide a conclusive evidence and radial velocity and proper motion measurements should be made to see whether these stars are members of the cluster.

As a high-latitude system, M2 is not affected by high interstellar absorption ( $E(B - V) = 0.06$ ; Harris 1996, 2010 edition), and it is very unlikely that the differential reddening has caused the double RGBs. The color difference between the two RGBs in the  $U - V$  color, at the given  $V$  magnitude of the horizontal-branch (HB) level, is  $\sim 0.3$  mag, which is about three

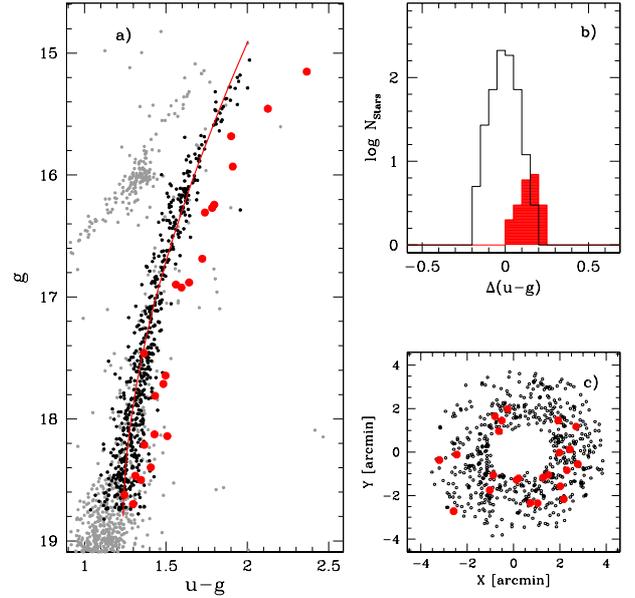
<sup>18</sup> Stars with E (Extreme) composition, by adopting the nomenclature first introduced by Carretta et al. (2009).



**Fig. 12.** **a)**  $U, V$  CMD from DOLORES images is shown in gray. Selected RGB stars are plotted as black dots, while the red continuous line is the fiducial obtained in the way described in the text. Panels **b)** and **c)** show the rectified RGB in function of the color difference and the histogram color distribution, respectively (see the text for details).

times more than the maximum color difference expected in the extreme situation where one group of stars is all reddened by  $E(B - V) = 0.06$ , while the other group has  $E(B - V) = 0.00$ . Because the additional RGB sequence only amounts to a small fraction of the total giant population, we cannot exclude field contamination as the cause of the observed additional RGB branch. We expect a very modest degree of contamination by Galactic fore/background stars, because of the combination between the relatively high (absolute) Galactic latitude of the cluster ( $b = -36^\circ$ ) and the small area of the considered annular field ( $1' < R < 4'$ ). We used the Galactic model TRILEGAL (Girardi et al. 2005)<sup>19</sup> to obtain a conservative estimate of the degree of contamination affecting the samples of candidate RGB stars with  $0.4 \leq (U - V) \leq 2$  and  $18.5 \leq V \leq 14.5$  mag in the present analysis (Fig. 12). We found that the fraction of Galactic field stars in our samples is lower than 1% in the considered annular field.

To take photometric errors into due account, we follow the method described in Anderson et al. (2009) to distinguish intrinsic color broadening from unphysical photometric error effects. We considered the two independent CMDs obtained from DOLORES and An et al. (2008) photometry. In Fig. 12 we selected the portion of the RGB sequence with magnitudes between  $14.5 \leq V \leq 18.5$  mag. In addition, we defined bona fide RGB members as the stars closer to the main RGB locus in the corrected DOLORES CMD (panel (a) of Fig. 12). We obtained the RGB fiducial as described in Milone et al. (2008). In brief, we drew a ridge line (fiducial) by putting a best-fit spline through the average color computed in successive short (0.2 mag) magnitude intervals. In panel (b) we have subtracted from the color of each star the color of the fiducial at the same magnitude and plotted the  $V$  magnitude in function of this color difference;  $\Delta(U - V)$ . The histogram color distribution on a logarithmic scale in panel (c) presents a clear substructure at the red end of the RGB, and we arbitrarily isolated RGB stars with

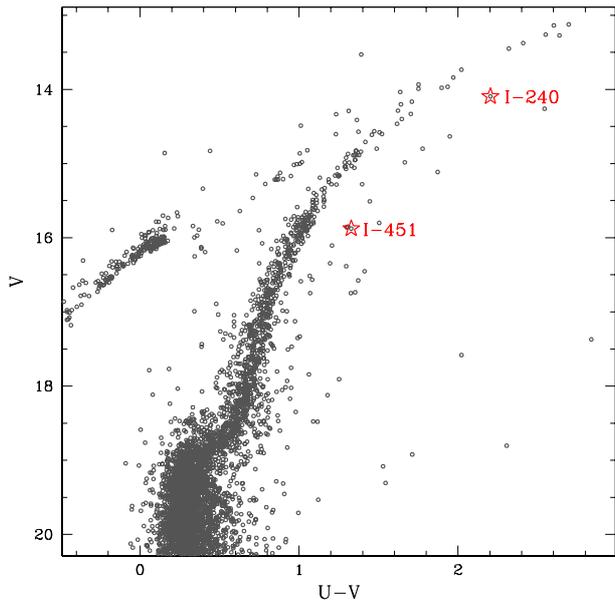


**Fig. 13.** **a)**  $u, (u - g)$  CMD from An et al. (2008) corrected photometry zoomed in around the RGB. Stars selected as red in Fig. 12 are plotted as red circles, while the red continuous line is the fiducial obtained in the way described in the text. Panels **b)** show the color distribution in the  $(u - g)$  color, while panel **c)** shows spatial distribution of the selected red stars.

$\Delta(U - V) > 0.15$ . These stars are plotted in panel (b). If the red branch we see is due to photometric errors, then a star redder than the RGB ridge line in the  $V, (U - V)$  diagram has the same probability of being bluer or redder in a different CMD obtained with different data. To this purpose, we identified the selected stars in  $u, g$  photometry (An et al. 2008) in Fig. 13. The (a) panel shows a zoom around the RGB, and again the red line is the fiducial defined as discussed above. In the following analysis, we considered only those stars in common with the DOLORES photometry and, for the sake of homogeneity, we kept only stars between  $1' < R < 4'$  from the cluster center. That the histogram distributions of the selected RGB stars systematically have red colors demonstrated that we are seeing a *real* feature: no random or systematic errors can explain that the two distribution remain confined in the CMDs obtained from independent data sets.

Similar spatial distributions of stars on the bluer and redder RGBs (panel (a) of Fig. 13) also indicate that the differential reddening, if any, is not likely the cause of the double RGBs (see panel (c) in the same figure). Having demonstrated that the split RGB shown by the  $U, (U - V)$  DOLORES photometry is *intrinsic*, we named giant stars belonging to the main body of the RGB sequence *blue*, while *red* are the stars located on the anomalous red substructure. We found that the average color difference for the *blue* stars is  $\Delta(U - V)_{\text{blue}} = -0.005 \pm 0.016$ , significantly different from the average color difference for *red* stars ( $\Delta(U - V)_{\text{red}} = -0.251 \pm 0.017$ ), which account for only  $\sim 4\%$  of the RGB population in this range of magnitude ( $14.5 \leq V \leq 18.5$  mag). For comparison,  $\sim 30\%$  of stars turn out to belong to the blue-RGB in NGC 1851 (Lardo et al. 2012). A visual inspection at the CMD of Fig. 3 from Dalessandro et al. (2009) indeed reinforces our finding and suggests that the anomalous RGB is also present in the cluster center. Moreover, Piotto et al. (2012) claim the presence of a split SGB for this cluster, with a fainter component remarkably less populous than the brighter one. We tentatively speculate that, also for M2, this newly discovered

<sup>19</sup> <http://stev.oapd.inaf.it/cgi-bin/trilegal>



**Fig. 14.** CMD for M2. The location of the carbon stars in the CMD is indicated by the open stars.

double RGB might be photometrically connected to the split SGB, in close analogy to the case of NGC 1851 and M 22.

### 6.1. CH stars along the anomalous RGB

M2 contains two CH stars, as discovered by Zinn (1981) and Smith & Mateo (1990). These stars show abnormally high CH absorption, together with deep CN bands, compared to other cluster giants. They are seen in dSph galaxies, and in the Galactic halo, but they are relatively rare within GCs. At present, a handful of stars having enhanced C and s-process elements have been reported in each of  $\omega$  Cen (e.g., Harding 1962; Bond 1975), M 22 (McClure & Norris 1977), NGC 1851 (Hesser et al. 1982), M 55 (Smith & Norris 1982), M 14 (Cote et al. 1997), and NGC 6426 (Sharina et al. 2012). Their spectra usually do not show strong Swan bands of  $C_2$ , the dominant optical spectral features of classical CH stars, suggesting that their anomalous carbon abundances probably arise through a different mechanism, such as incomplete CN processing (Vanture & Wallerstein 1992). Indeed, among this sample of CH-enhanced stars in GCs, only two are likely to be genuine CH stars. Both of these stars, RGO 55 (Harding 1962) and RGO 70 (Dickens 1972), are found in  $\omega$  Cen. The surface carbon enhancement of such stars has been attributed to a dredge-up of processed material via mixing or to the mass transfer of such material between members of a binary system (McClure 1984). Moreover, that both  $\omega$  Cen and M 22 display heavy element abundance variations suggests that in these clusters these CH stars could owe their peculiar chemical pattern to initial enrichment.

Prompted by these considerations, in Fig. 14 we identified the two CH stars discovered by Zinn (1981) (ID: I-240) and Smith & Mateo (1990) (ID: I-451) in our  $V$ ,  $U - V$  photometry. Interestingly enough, both stars belong to the additional RGB, pointing out the anomalous chemical nature of this redder branch. Regardless of the exact classification of I-240 and I-451, it is apparent that the anomalous RGB contains a population of giants that exhibit both a strong CN and strong G band. These stars may be the analogous to other CN and CH-strong RGB stars found in  $\omega$  Cen, M 22, and NGC 1851 (Hesser et al. 1982). Given the peculiarity of other clusters that

contain CH stars, it is of extreme interest to investigate the chemical pattern of stars in this red substructure. High-resolution spectroscopy of stars in the two distinct groups could be one of the next steps in deriving the chemical pattern in this cluster, with particular emphasis on the measure of heavy element abundances.

## 7. Summary and conclusions

We have presented low-resolution spectroscopy ( $R \simeq 350$ ) of RGB stars in M2, with the goal of deriving C abundances (from the G band of CH) and N abundances (from the CN band at  $\sim 3883$  Å). We were able to measure CH and CN band strengths for 38 giants and derive carbon and nitrogen abundances for 35 stars, whose spectra were obtained with DOLORES at TNG. The main results of our analysis can be summarized as follows.

- We measured the CH and CN band strengths and found large variations ( $\simeq 0.2$ – $0.3$  mag) and a bimodal distribution of CN index strengths (Fig. 3). We did report the presence of a clear CH-CN anticorrelation over the whole magnitude range (see Fig. 4).
- We used spectral synthesis to measure C and N abundances, and found variations of  $\simeq 1$  dex and  $\simeq 2$  dex, respectively, at all luminosities. C and N abundances appear to be anticorrelated, as would be expected from the presence of CN-cycle processing exposed material on the stellar surface (Fig. 6).
- Our derived C abundances show a decline with increasing luminosity. As far as can be derived from the carbon abundances, the rate of mixing in this cluster is comparable to that of halo field stars and many cluster giants. We found  $d[C/Fe]/dM_V = 0.21 \pm 0.16$ , which is very similar within the observational errors to what is found among halo field giants and other globulars (e.g., M 3, NGC 6397, and M 13; Smith & Martell 2003).
- We distinguished between first and second subpopulations and found that N-poor and N-rich stars are clearly separated into two parallel sequences in the broader giant branch seen in the  $V$ ,  $(U - V)$  diagram, the N-rich stars appearing systematically redder than N-poor ones, a result that is strictly analogous to the one of Marino et al. (2008) for M 4.
- In addition to these results, we detected an *anomalous* substructure beyond the red edge of the main body of the RGB (see Fig. 1) from DOLORES  $U$ ,  $V$  photometry. When plotting CH stars from the studies of Zinn (1981) and Smith & Mateo (1990) onto the  $V$ ,  $U - V$  DOLORES CMD (see Fig. 14), we found that both stars belong to this additional red RGB. These are giants that exhibit both enhanced CH and CN bands, and this evidence perfectly fits the suggestion that stars located on the red RGB should have a peculiar chemical nature. Moreover, this additional RGB could be connected to the less populated faint SGB detected by Piotto et al. (2012) in this cluster.

Among the GCs with photometric evidence of multiple populations, only NGC 1851 and M 22 display a bimodal SGB that is photometrically connected to the split RGB (see Lardo et al. 2012, for NGC 1851; Marino et al. 2012b, for M 22). These are rather peculiar clusters that appear to share numerous observational features. M 22 shows a spread of about 0.15 dex in metallicity (Marino et al. 2009; Alves-Brito et al. 2012), while the presence of an intrinsic iron spread among NGC 1851 stars is still controversial (Yong & Grundahl 2008; Carretta et al. 2010b; Villanova et al. 2010). The neutron-capture elements that are mainly produced by the  $s$ -process are also found to have

large star-to-star abundance variations that are correlated with both [Fe/H] and the abundances of light, proton-capture elements (Carretta et al. 2010b; Marino et al. 2012b). Finally, a spread in the abundances of individual CNO elements has been found within both the bright and faint SGB that is also correlated with the variation in heavier elements (Marino et al. 2012b; Lardo et al. 2012). Since the Na-O and C-N anticorrelations alone can be considered as signatures of multiple populations and both clusters are composed of two different groups of stars with different *s*-element content (each of them associated to the bimodal SGB and RGB) possibly with their own Na-O, C-N anticorrelations, each group should be the product of multiple star formation episodes. Both M22 and NGC 1851 host not only two subpopulations, but they have experienced a complex formation history that resembles the extreme case of  $\omega$  Centauri (see Marino et al. 2012b; Da Costa & Marino 2011; Roederer et al. 2011; D'Antona et al. 2011, for a discussion). The apparent similarity of M2 to NGC 1851 and M22 calls for a deeper and complete spectroscopic characterization of stars in this poorly studied cluster.

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