Carbon and nitrogen abundances of stellar populations in the globular cluster M 2

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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 ω Centauri, 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 metallicity1 (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.

** Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/1

** 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.
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 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 ε(Li)) and isotopic ratios (12C/13C) 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 μ-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 μ-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 (ΔL) 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 3He(3He,2p)4He (Angelou et al. 2012). Extramixing is a universal mechanism that occurs in ≥ 96% of these RGB bump stars (Charbonnel & D’Orazi 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 ≥ 3-5 M⊙) 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 ([Fe/H] ≥ −1.6), provides strong evidence for this scenario (Brisley 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, and Yong & Grundahl 2008, Yong et al. 2009, Gratton et al. 2012 and 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 ([Fe/H] = −1.65; Harris 1996, 2010 edition) cluster, which is located at 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 λ4383 CN bands (McCleire & Hesser 1981; Canetra 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...
In our previous work (Lardo et al. 2011), we used An et al. (2008) photometry to search for anomalous spread in near UV color $\langle u-g \rangle$ 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.

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 3. 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) 4. 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 5. 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.

### 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 | 323.357998    | -0.8890510 | 20.215    | 0.026               | 0.213       | 0.016               |
| 196 | 323.380029    | -0.885692  | 19.943    | 0.019               | 0.311       | 0.072               |
| 234 | 323.366158    | -0.882047  | 20.342    | 0.018               | 0.393       | 0.084               |
| 286 | 323.3795809   | -0.875061  | 19.015    | 0.012               | 0.220       | 0.028               |
| 303 | 323.3872881   | -0.872826  | 18.445    | 0.010               | 0.632       | 0.023               |
| 313 | 323.3674707   | -0.887072  | 19.661    | 0.024               | 0.202       | 0.050               |
| 330 | 323.3908254   | -0.8869171 | 19.613    | 0.019               | 0.267       | 0.041               |
| 336 | 323.3657205   | -0.886836  | 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.

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).

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 6. 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 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 $\simeq 16$ 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 $2.52\AA/pix$. In combination with the chosen slit width this results in the spectral resolution of $R(@3880\AA) = 353$ and $R(@4305\AA) = 391$ in the

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2 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.

3 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.

4 available at http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/standards/

5 On all stars we imposed the selection limits of CHI < 2.0 and $-1 <$ 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 $S_{\text{HARP}}^2 \sim \sigma^2(\text{observed}) - \sigma^2(\text{point spread function})$; see the DAOPHOT II manual at http://www.astro.wisc.edu/sirtf/dapivot2.pdf.

6 see for reference http://web.oapd.inaf.it/mos/
wavelength region of interest. The grism’s spectral region covers the nominal wavelength range between 3000 – 8430Å, 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 hr per mask and a typical S/N of ∼ 20-30 in the CN region. Additionally, bias, flat field, and wavelength calibration observations were obtained in the afternoon.

For the data prereduction, we used the standard procedure for overscan correction and bias-subtraction with the routines available in the noao.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 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 Vr were computed using the laboratory positions of the most prominent spectral features (e.g., Hα, Hβ, Hγ, Hδ, and Ca H+K, among others), yielding a mean radial velocity of -13 ± 30 km/s for the entire sample. This value, given the low resolution of our spectra, agrees quite well with the value tabulated (-5.0 km/s) in the Harris 1996 (2010 edition) catalog. Then, we rejected individual stars with values deviating by more than 3σ 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 CaH 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):

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

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

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

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 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 CaII 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 the 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.

Fig. 2. The 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.
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 the plot of HK index vs. the V magnitude. This evidence further confirms that this stars 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 ~0.2-0.3 mag. Giants considered to have relatively strong CN bands and CN-poor giants are represented in Fig. 3. 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 (~0.73±0.2) is very different from what is found by Smith & Mateo (1990) (0.33; 16 RGB stars⁷ 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 in the following⁹. 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 1σ 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 CN-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.

⁷ 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.

⁸ If we exclude the two CH stars.

⁹ 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.
The histograms are shown in the bottom panels of Fig. 4, where different panels show different subsamples of RGB stars. Each data point in this histogram has been replaced by a Gaussian of unit area and standard deviation $\sigma=0.04$. 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 $V=16.9$ 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 Kolgomorov-Smirnov returns a probability of $P_{KS} \approx 0.002$ ($P_{KS} = 1.14 \times 10^{-5}$) 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.

Table 2. Dimension of the samples and results of KS test.

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

Notes. $ID_{SDSS}$ is the DAOPHOT ID number from An et al. (2008) photometric catalog.
from DOLORES photometry (once calibrated on the Stetson ors from Lee & Carney (1999) and the 2MASS (Skrutskie et al. when available — (Harris (1996) catalog (2010 edition). In addition, we used —

each color calibration. The surface gravity was determinedus-

tion, —

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temperature,

We derived stellar parameters from photometry. The e

strengths in three magnitude bins (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 1σ are marked as large white dots. CN strong

and weak stars are separated by the vertical dashed line, and their cen-

troids with their 1σ 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 bot-

tom panels represent the distribution of distances of projected points

from the origin P (see text for details).

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 [Fe/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 av-

erage microturbulent velocity estimate of $v_t = 1.1 \pm 0.13$ km s$^{-1}$, therefore we chose to assign a reference microturbulent velocity of $v_t = 1.0$ km s$^{-1}$ to all our program stars.

An additional check to test the reliability of our chosen atmos-

pheric parameters was performed using theoretical isochrones downloaded from the Dartmouth Stellar Evolution Database (Dotter et al. 2008)$^{11}$. We chose an isochrone of 12 Gyr with standard α-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±4 K, while the difference in gravity is negligible (on the order of 0.013±0.002). By pro-
jecting 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; there-
fore, 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 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 abun-
dances.

4.2. Abundances derivation

Abundances for a given element were derived by comparing syn-

thetic spectra with observed spectra. The C and N abundances were estimated by spectral synthesis of the 2E–2I1 band of CH (the G band) at ~4310Å and the UV CN band at 3883Å (including a number of CN features in the wavelength range of 3876-3890Å), respectively. The synthetic spectra were generated using the local thermodynamic equilibrium (LTE) program MOOG (Sneden 1973). The atomic and molecular line lists were taken from the latest Kurucz compilation (Castelli & Hubrig 2004) and downloaded from the F. Castelli website$^{12}$.

Model atmospheres were calculated with the ATLAS9 code, starting from the grid of models available on the F. Castelli web-

site (Castelli & Kurucz 2003), using the values of $T_{\text{eff}}$, log g, 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 compet-
ted with the new set of opacity distribution functions (Castelli & Kurucz 2003) and excluded approximate overshooting in cal-

culation 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 illus-

trates the fit of synthetic spectra to the observed ones in CH and CN spectral regions. These stars have essentially the same stel-

lar parameters ($T_{\text{eff}} \sim 5000$ 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 ($[O/Fe]=+0.4$ 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 affect the derived C abundances only negligibly, since the CO

$^{11}$ http://stellar.dartmouth.edu/models/isolf.html

$^{12}$ http://wwwuser.oat.ts.astro.it/castelli/linelists.html
coupling is marginal in cool stellar atmospheres (T ≤ 4500K). 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 K ≤ T eff ≤ 5400 K). In these computations, we adopted [O/Fe] = -0.2 dex, [O/Fe] = 0.0 dex, and [O/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 [C/Fe] can change by as much as 0.17-0.20 dex for a 0.6 dex change in assumed [O/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 δA(C)/δT eff ≈ 0.09 - 0.13 dex and δA(N)/δT eff ≈ 0.14 - 0.18 dex for the temperature. The errors 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\(^\text{13}\); 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 M 2. Carbon and nitrogen are two elements that are known to be affected by the internal processes of stars, such as the CNO cycle and the coupling to the stellar envelope.

\(^{13}\) 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.
nitrogen exhibit the typical anticorrelation, as shown in Fig. 6, where the [C/Fe] values are plotted as a function of [N/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 [C/Fe]~ -1.4 to [C/Fe]~ -0.4) mildly anticorrelated (Spearman’s rank correlation coefficient $r^2_{\text{M}2} = -0.35$) with strong variations in N, which span almost 2 dex, from [N/Fe]~ -0.3 up to [N/Fe]~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 [C/Fe]-[N/Fe] relationship that prevails for these stars ($r^2_{\text{NGC} 1851} = -0.42$). The range of the spread in both C and N is about the same for M 2 and NGC 1851$^{14}$ (and fully agrees with the C and N abundances presented by Cohen et al. 2005, for M 71, 47 Tuc, M 5, M 13, and M 15). 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 M 2 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 ($V_{\text{BUMP}} ~15.82 \pm 0.05$, Di Cecco et al. 2010): the average value for this group of upper RGB stars is $A(C)=5.61 \pm 0.05$ dex. 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 $^{12}$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

Fig. 6. Derived [N/Fe] abundances for M 2 stars in Table 4 as a function of the [C/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.

Fig. 7. Derived C and N abundances plotted against the V magnitude and $U-V$ color for M 2 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.
the carbon abundance on luminosity can be obtained by deri-
vating $d[C/Fe]/dM_V$. To compare the behavior of [C/Fe] among
field giants with M 2 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)\textsuperscript{15} 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 $d[C/Fe]/dM_V=0.21\pm0.16$
that is very similar within the observational errors to that found
among halo field giants ($d[C/Fe]/dM_V=0.20\pm0.03$ dex) and
other GCs (e.g., M 3, NGC 6397, and M 13; Smith & Martell
2003).

From the bottom left hand panel of Fig. 7, we see no signifi-
cant trend in the N abundance with either luminosity or color:
the average nitrogen abundance we found for stars fainter than
the RGB bump ($A(N)=7.1\pm0.4$) agrees within the quite large
error bar with the one obtained for the more luminous stars after
the LF bump ($A(N)=6.9\pm0.6$). 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 sup-
port the presence of C-N anticorrelation. Finally, Gratton et al.
(2000) show an abrupt increase in N abundance of about $\sim 4$ at
$V_{BUMP}$ for field giants. Here we could not detect such a trend
as the effect of the poor statistics (4 stars) towards higher lumi-
nosities.

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 on-
set, so we expect that their atmospheres are already depleted in
carbon abundance\textsuperscript{16}. A matter we plan to investigate now is how
to disentangle the intrinsic star-to-star differences in surface car-on and nitrogen abundances from the changes resulting from
normal stellar evolution. First, we note that we cannot arbitrar-
ily distinguish between two groups of stars with different A(C)
or A(N) for stars fainter than the LF peak, because we are un-
able to detect any clear bimodality. To make more quantitative
statements about bimodality, a KMM test (Ashman et al. 1994)
was applied to the data\textsuperscript{17}. Under the assumption that the two
Gaussians have the same dispersion (heteroscedastic test), we can

\textsuperscript{15} We consider the the restricted sample with the exclusion of stars
HD97 and HD218857.

\textsuperscript{16} Among the field stars, Gratton et al. (2000) data support the occur-
rence of a small ($\simeq 0.1$ dex) drop in the region of the first dredge-up.

\textsuperscript{17} The star 22047 with an anomalously low carbon abundance ($A(C)$
$\simeq 5.6$) is excluded from the fit.
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 ($f_{S2}^{M2\text{ corrected}} = -0.43$).

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). 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 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/Na-rich) stars is greater than the errors associated with abundance measurements. This evidence possibly suggests the presence of a third group of stars$^{18}$; 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 $\delta A(N)$ in the $A(C)$-$A(N)$ plane (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 $\delta A(N)$ in the $A(C)$-$A(N)$ plane (Marino et al. 2008; Han et al. 2009; Milone et al. 2010).

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$^{18}$ Stars with E (Extreme) composition, by adopting the nomenclature first introduced by Carretta et al. (2009).
abundances (and so λ3883 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 en-
hanced 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 M 2 V (U − V) DOLORES CMD. N-
poor and N-rich stars are clearly separated into two parallel se-
quences in the broader giant branch seen in the V (U − V) dia-
agram, 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 M 4. It is clear that the strength of the CN
and NH bands strongly influences the U − V color, the NH
band around 3360Å, and the CN bands around 3590, 3883,
and 4215Å, located in the U being the main contributors to the effect
(see also Sbordone et al. 2011).

6. The anomalous RGB in M 2

As discussed in Sect. 1, GCs are essentially monometallic, e.g.,
all the stars in a cluster show the same [Fe/H] abundance.
Besides the remarkable exception of ω Centauri (see Marino
et al. 2012a, and references therein), variations in the heavy el-
lement content have been detected only for a few clusters: M 22
(Marino et al. 2012b), Terzan 5 (Ferraro et al. 2009; Origlia et al.
2011), M 54 (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
M 22 appear rather peculiar. For these clusters, a bimodal dis-
tribution of s-process elements abundance has been identified
(Yong & Grundahl 2008; Marino et al. 2012b). The chemical in-
homogeneity reflects itself in a complex CMD: multiple stellar
groups in M 22 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, care-
fully 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 M 22, respectively, would not be detected in the usual opti-
cal colors.

M 2 DOLORES photometry (see Fig. 1) displays an anoma-
lous 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
mags, 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 mags redder with respect to this sequence and can
possibly be more, the anomalous RGB stars. Unfortunately, be-
cause 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, M 2 is not affected by high inter-
stellar 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 ~0.3 mag, which is about three times more
than the maximum color difference expected in the extreme sit-
uation 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 mod-
derest degree of contamination by Galactic fore/background stars,
because of the combination between the relatively high (abso-
lute) Galactic latitude of the cluster (b = 36°) and the small
area of the considered annular field (1′ < R < 4′). We used the
Galactic model TRILEGAL (Girardi et al. 2005)12 to obtain a
conservative estimate of the degree of contamination affecting
the samples of candidate RGB stars with 0.4 ≤ (U − V) ≤2 and
18.5 ≤ V ≤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 in-
trinsic color broadening from unphysical photometric error ef-
fects. We considered the two independent CMDs obtained from
DOLORES and An et al. (2008) photometry. In Fig. 12 we se-
lected the portion of the RGB sequence with magnitudes be-
 tween 14.5 ≤ V ≤ 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 ob-
ained 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: Δ(U − V). The histogram color distribution on a log-
arithmetic scale in panel (c) presents a clear substructure at the
red end of the RGB, and we arbitrarily isolated RGB stars with
Δ(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

12 http://stev.oapd.inaf.it/cgi-bin/trilegal
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 |V − R| < 0.4′ 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 Δ(U − V)blue = −0.005 ± 0.016, significantly different from the average color difference for red stars (Δ(U − V)red = −0.251 ± 0.017), which account for only ~4% of the RGB population in this range of magnitude (14.5 ≤ V ≤ 18.5 mag). For comparison, ~30% of stars turn out to belong to the blue-RGB in NGC 1851 (Lardo et al. 2012). A visual inspection of 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 M 2, this newly discovered 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

M 2 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 ω 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 C2, the dominate 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 ω 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 ω 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 ω 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 these 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≈350) of RGB stars in M 2, with the goal of deriving C abundances (from the G band of CH) and N abundances (from the CN band at ~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 (~0.2-0.3 mag) and a bimodal distribution of C/N 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 ~1 dex and ~2 dex, respectively.
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 by 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. 2010; 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 M 22 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 M 2 to NGC 1851 and M 22 calls for a deeper and complete spectroscopic characterization of stars in this poorly studied cluster.

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