The old open cluster NGC 2112: updated estimates of fundamental parameters based on a membership analysis

G. Carraro,1,2,3,4‡ S. Villanova,2,5‡ P. Demarque,4‡ C. Moni Bidin3‡ and M. V. McSwain4,6‡

1 ESO, Casilla 19001, Santiago 19, Chile
2 Dipartimento di Astronomia, Università di Padova, vic. Osservatorio 3, Padova, Italy
3 Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
4 Astronomy Department, Yale University, PO Box 208101 New Haven, CT 06520-8101, USA
5 Departamento de Física, Facultad de Ciencias Físicas y Matemáticas Universidad de Concepción, Casilla 160-C, Concepción, Chile
6 Department of Physics, Lehigh University, 16 Memorial Drive East, Bethlehem, PA 18015, USA

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ABSTRACT
We report on a new, wide-field (20 × 20 arcmin²), multicolour (UBVI), photometric campaign in the area of the nearby old open cluster NGC 2112. At the same time, we provide medium-resolution spectroscopy of 35 (and high-resolution of additional 5) red giant and turn-off stars. This material is analysed with the aim to update the fundamental parameters of this traditionally difficult cluster, which is very sparse and suffers from heavy field star contamination. Among the 40 stars with spectra, we identified 21 bona fide radial velocity members which allow us to put more solid constraints on the cluster’s metal abundance, long suggested to be as low as the metallicity of globulars. As indicated earlier by us on a purely photometric basis, the cluster [Fe/H] abundance is slightly supersolar ([Fe/H] = 0.16 ± 0.03) and close to the Hyades value, as inferred from a detailed abundance analysis of three of the five stars with higher resolution spectra. Abundance ratios are also marginally supersolar.

Based on this result, we revise the properties of NGC 2112 using stellar models from the Padova and Yale–Yonsei groups.

For this metal abundance, we find that the cluster’s age, reddening and distance values are 1.8 Gyr, 0.60 mag and 940 pc, respectively. Both the Yale–Yonsei and Padova models predict the same values for the fundamental parameters within the errors.

Overall, NGC 2112 is a typical solar neighbourhood, thin-disc star cluster, sharing the same chemical properties of F-G stars and open clusters close to the Sun.

This investigation outlines the importance of a detailed membership analysis in the study of disc star clusters.

Key words: open clusters and associations: general – open clusters and associations: individual: NGC 2112.

1 INTRODUCTION
Gathering information on metal abundance and abundance ratios of many Galactic clusters located in different regions of the disc and with different ages is mandatory to study the chemical evolution of the Galactic disc. This, in turn, provides us with hints on the formation mechanism of the disc and its relation with the other major components of the Galaxy, the halo and bulge (Janes & Phelps 1994; Carraro, Ng & Portinari 1998).

However, a frequent, well-known problem in the study of open star clusters is the stellar contamination from the general Galactic disc field, which complicates the analysis of the colour–magnitude diagram (CMD). It also makes it difficult to derive fundamental cluster parameters, especially metallicity, when only a few stars are observed.

A notorious example in this context is the nearby old open cluster NGC 2112 (Collinder 76, C 0551-0031, OCL 509), which has a

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reputation of suffering from heavy field star contamination (Brown et al. 1996), and for this reason its basic parameters remain poorly constrained.

The first investigation on NGC 2112 was carried out by Richtler (1985, hereafter R85), who obtained photographic BV photometry for about 80 stars down to $V = 15$. Although his photometry barely reaches the cluster turn-off (TO), he nevertheless drew attention to this probably old, so far neglected cluster, and he suggested that NGC 2112 has a reddening of $\sim 0.5$ mag and lies $\sim 800$ pc from the Sun. By analysing additional Stromgren photometry, he proposed that the cluster had to be very metal-poor ([Fe/H] as low as $-1.4$).

A more accurate and deeper analysis was performed a few years later by Richtler & Kaluzny (1989). They obtained BV CCD photometry for about 500 stars in a field of 200 arcmin$^2$. Additionally, they obtained moderate-resolution spectra for a handful of bright stars. Their conclusions were that the cluster was very contaminated by field stars. Nevertheless, they were able to strengthen the metallicity of the cluster, to be very metal-poor ([Fe/H] as low as $-1.3$).

More recently, three spectroscopic campaigns have been carried out in the field of the cluster. Riefler & Janes (1993, hereafter RJ93) present moderate-resolution spectra of six stars. Out of these, five are considered members, and an average [Fe/H] of $-0.52 \pm 0.21$ has been found. This is significantly larger than all the previous determinations. Brown et al. (1996, hereafter BWGO96) used the Blanco Echelle on CTIO to obtain high-resolution spectroscopy of six stars. They accepted just one star as a definitive member, providing an even higher metal content value, [Fe/H] $\approx -0.15$, only slightly lower than the solar value. Finally, Mermilliod & Mayor (2007, hereafter MM07) enlarged the sample of spectroscopic members to 3, out of six stars observed with Coravel. They underlined the need to obtain radial velocities (RVs) for a larger sample down to $V \approx 14.5$ to better probe the shape of the red giant branch (RGB). At the same time, this would also provide much firmer metallicity estimates.

In Carraro, Barbon & Boschetti (2002) we reported a Johnson $BVI$ photometry of the cluster down to magnitude $V = 20$. Assuming the metal content found by BWGO96, we found a reddening of $E(B - V) = 0.63 \pm 0.14$, a distance of 850 $\pm$ 100 pc and an age of 2.0 $\pm$ 0.3 Gyr. We argued on a purely photometric basis that the metallicity cannot be much lower than BWGO96 value, and we stressed the need for a new, more detailed spectroscopic investigation of the cluster.

In this paper we attempt such an investigation by securing the needed information on the cluster metallicity was provided.

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In this work we present photometry and spectroscopy in the field of NGC 2112 to date. At the same time, we provide moderate- and high-resolution spectroscopy of 40 stars. With these data at hand, we present robust and updated determinations of the cluster’s basic properties.

2 OBSERVATIONS AND DATA REDUCTION

In this work we present photometry and spectroscopy in the field of NGC 2112 obtained with three different telescopes. For this reason, the details of data acquisition and reduction are presented in the next three subsections.

Figure 1. $V$ filter map of the field covered by our photometry. Stars (empty circles) are plotted according to their magnitude. North is up and east is towards the left-hand side. The field is 20 arcmin on a side and centred at $(X, Y) = (2046, 2092)$ on star #593, which has $\alpha = 05:53:43.75$ and $\delta = +06:23:56.4$. With filled circles we indicate stars observed spectroscopically.

2.1 Photometry

$U, B, V$ and $I$ images centred on NGC 2112 were obtained at the Cerro Tololo Inter-American Observatory 1.0-m telescope, which is operated by the SMARTS$^2$ consortium. The telescope is equipped with a new 4000 $\times$ 4000 CCD camera having a pixel scale of 0.289 arcsec pixel$^{-1}$, which allows one to cover a field of 20 $\times$ 20 arcmin$^2$. This allows us to cover the entire cluster, which has an estimated diameter of 18 arcmin (Dias et al. 2002).

Observations were carried out on 2005 November 30. Three Landolt (1992) areas (TPhoenix, Rubin 149 and PG 0231+006) were also observed to calibrate the instrumental magnitudes to the standard system. The night was photometric with an average seeing of 1.1 arcsec. Data were reduced using IRAF$^2$ packages CCDRED, DAOPHOT and PHOTCAL. Photometry was done employing the point spread function (PSF) method (Stetson 1987). The covered area is shown in Fig. 1, while Table 1 contains the observational log.

The calibration equations read:

\begin{align}
    u &= U + u_1 + u_2(U - B) + u_3X \quad (1) \\
    b &= B + b_1 + b_2(B - V) + b_3X \quad (2) \\
    v &= V + v_{bh} + v_{2b}(B - V) + v_3X \quad (3) \\
    v &= V + v_{1i} + v_{2i}(V - I) + v_4X \quad (4) \\
    i &= i_1 + i_2(V - I) + i_3X \quad (5)
\end{align}

where $UBVI$ are standard magnitudes, $ubvi$ are the instrumental magnitudes, $X$ is the airmass, and the derived coefficients are presented at the bottom of Table 1. To compute $V$ magnitudes when $B$ magnitudes were available, we use expression (3); otherwise we use expression (4). The standard stars in these fields provide a wide colour coverage with $-1.217 \leq (U - B) \leq 2.233$, $-0.298 \leq (B - V) \leq 1.999$ and $-0.361 \leq (V - I) \leq 2.268$. Aperture corrections

1 http://www.astro.yale.edu/smarts/

2 IRAF is distributed by NOAO, which is operated by AURA under cooperative agreement with the NSF.
Table 1. Journal of photometric observations of NGC 2112 and standard star fields together with calibration coefficients (2005 November 30).

| Field     | Filter | Exposure time (s) | Seeing | Airmass (arcsec) |
|-----------|--------|-------------------|--------|------------------|
| NGC 2112  | U      | 1200, 60, 5       | 1.1    | 1.150–1.280      |
|           | B      | 900, 30, 3        | 1.0    | 1.150–1.280      |
|           | V      | 600, 30, 1        | 1.0    | 1.150–1.280      |
|           | I      | 600, 30, 1        | 1.0    | 1.150–1.280      |
| TPhoenix  | U      | 180, 200          | 1.0    | 1.024, 1.444     |
|           | B      | 90, 120           | 1.1    | 1.023, 1.447     |
|           | V      | 20, 30            | 1.1    | 1.024, 1.450     |
|           | I      | 40, 40            | 1.1    | 1.022, 1.452     |
| PG 0231+006| U    | 200, 240          | 1.1    | 1.291, 1.801     |
|           | B      | 60, 90            | 1.1    | 1.293, 1.807     |
|           | V      | 40, 40            | 1.1    | 1.296, 1.809     |
|           | I      | 40, 30            | 1.1    | 1.294, 1.810     |
| Rubin 149 | U      | 180, 240          | 1.0    | 1.311, 1.651     |
|           | B      | 90, 120           | 1.1    | 1.316, 1.649     |
|           | V      | 30, 40            | 1.0    | 1.318, 1.647     |
|           | I      | 40, 40            | 1.0    | 1.313, 1.643     |

Calibration coefficients:

- $u_1 = + 3.285 \pm 0.004$
- $u_2 = + 0.052 \pm 0.006$
- $u_3 = + 0.46$
- $b_1 = + 2.188 \pm 0.004$
- $b_2 = - 0.160 \pm 0.006$
- $b_3 = + 0.27$
- $v_{bI} = + 2.188 \pm 0.014$
- $i_1 = + 2.789 \pm 0.044$
- $i_2 = + 0.021 \pm 0.043$
- $v_{2B} = + 0.017 \pm 0.018$
- $i_3 = + 0.06$
- $r_3 = + 0.12$
- $v_{1V} = + 2.188 \pm 0.016$
- $v_{2V} = + 0.013 \pm 0.016$

Differences in $V,B$ versus $V$ and $U,B$ versus $R85$ are illustrated in Fig. 2, and amount to

\[ \Delta V = 0.02 \pm 0.06, \]
\[ \Delta(B - V) = 0.02 \pm 0.04 \]
\[ \Delta(U - B) = -0.01 \pm 0.09. \]

Our photometry is basically consistent with R85. Only $U - B$, although in agreement, exhibits a significant scatter.

The resulting CMDs are shown in Fig. 3 for three colour combinations. The TO is located at $V \sim 14.5, (B - V) \sim 1.1$ and $(V - I) \sim 1.3$.

2.2 Spectroscopy: Hydra observations

Medium-resolution spectroscopic observations were carried out on the night of 2006 February 15 (Julian Date 245 3783.570 06) with the Hydra spectrograph onboard the Wisconsin Indiana Yale NOAO.
(WIYN) telescope at Kitt Peak National Observatory under photometric conditions and typical seeing of 1.0 arcsec. The multi-object spectrograph consists of the Hydra positioner, which in 20 min can place 89 fibres within the 1′ diameter focal plane of the telescope to 0.2 arcsec precision. This project employed the 3 arcsec diameter red-optimized fibre bundle.

The fibres feed a bench-mounted spectrograph in a thermally isolated room. With the echelle grating and the Bench Spectrograph Camera, the system produces a resolution of 15 000 at 6560 Å. The wavelength coverage of 400 Å around the central wavelength of 6560 Å provides a rich array of narrow absorption lines. We observed 35 TO–RGB stars with 2 × 45 min exposures, for a grand total of 1.5 h of actual photon collection time on each star.

The 35 stars were selected from the photometric catalogue presented in previous section. By using UCAC2 catalogue (Zacharias et al. 2004) as reference, we converted pixel coordinates into 2000.0 equinox right ascension (RA) and declination (Dec.) using 50 stars as input. The astrometry precision is 0.3 arcsec. The selected stars for Hydra are candidate RGB and TO stars according to their position in the CMD and have the right magnitudes to be observed with the WIYN 3.6-m telescope. We restricted the sample to stars brighter than $V \approx 15.0$. The stars are listed in Table 2, where column (1) reports numbering. In the following columns we report 2000.0 equinox coordinates, magnitude and colours, heliocentric RV and proper motion components from UCAC2 (Zacharias et al. 2004).

In the last column an indication of membership is provided (see next section). For some stars (#782, 655, 890 and 417), no proper motions are available from UCAC2, probably because these stars have close companions.

Images were pre-reduced using IRAF3 including bias subtraction, flat-field correction, frame combination, extraction of spectral orders, wavelength calibration, sky subtraction and spectral normalization. Some spectra turned out to have a very low signal-to-noise ratio (S/N), although all the observed stars have practically the same magnitude. This could happen for two reasons: the first is an imperfect pointing of the fibre, and the second is possibly bad fibre transmission.

2.3 Spectroscopy: MIKE observations

Echelle spectrograms of stars #535, #261, #717, #304 and #836 (see Table 2) were obtained on 2007 October 29 with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph mounted on the Nasmyth focus of Landon Clay 6.5-m telescope at the Magellan Observatory. Data were obtained with both the blue and red arms. The slit was 0.7 arcsec wide, which yielded a resolution $R = 33 000$, and the CCD was binned in steps of 2 pixels in the dispersion direction. The typical seeing was 0.6–0.8 arcsec. We used quartz lamp images without the diffuser in position for flat-field correction, and the wavelength calibration was performed with ThAr lamp images that were taken just before and after the five stellar exposures. The dark current was checked by examining several dark exposures and was found to be insignificant. The optimum algorithm (Horne 1986) was used to extract the spectra, which were also sky subtracted and normalized using IRAF routines. Additional details on the spectra are reported in Table 3.

3 MEMBERSHIP AND CLUSTER MEAN RADIAL VELOCITY

We derived RVs of the target stars using the IRAF fxcor task, which cross-correlates the object spectrum with a template. As a template, we used a synthetic spectrum calculated by SPECTRUM4 with roughly the same atmospheric parameters and metallicity of the observed stars. The final errors in the RVs, as provided by fxcor, were typically less than 1.0 km s$^{-1}$ for most of the Hydra stars and less than 0.3 km s$^{-1}$ for MIKE targets (see Table 2). In the case of Hydra spectra, these have to be considered the real errors since they have been taken from the average of the two different exposures and their combined errors. In the case of MIKE spectra, having only one exposure, we consider the reported error as a lower limit of the real error.

The distribution of RVs is shown in the histogram in Fig. 4. The bulk of stars form a peak in the heliocentric RV distribution around 30–31 km s$^{-1}$, allowing us to define a mean velocity for the cluster and the dispersion, $\sigma$. These turn out to be

$$RV_H = 30.9 \pm 0.4 \text{ km s}^{-1}.$$  \hspace{2cm} (1)

To derive this value we used 21 stars, which are listed in Table 2 as cluster members. These stars were selected using an interactive procedure in which we calculated an initial value for $RV_H$ and $\sigma$. Then stars having RVs more than 3$\sigma$ from the mean were rejected as non-members and a new value of $RV_H$ and $\sigma$ were computed. This procedure was iterated until no more stars were rejected. It is, however, possible that some of the rejected stars are binary stars.

In Table 4, we compare our measurements with literature values. RV data for NGC 2112 are poor and very inhomogeneous. We have three stars in common with BWGO96, one with F93 and two with MM07. In all cases, the RVs are compatible within the errors, as are the membership assignments.

We confirm the result of BWGO96 that star #2-4 (our star 656) is a member.

One more star, for which we do not have new RV, can be considered a member, following MM07, if it is a binary: this is star #3-18 (our 954).

Finally, we find that #3-16, 4-1 and 4-2 (our stars 1123, 711 and 759) are member stars following the analysis in MM07 and looking at Table 5.

We make use of the CMD to get additional information on the cluster membership. In Fig. 5, we indicate with filled circles (red when printed in colour) the RV members, and with filled triangles (black when printed in colour) the RV non-members. Additionally, we plot as filled squares (blue in colour) stars that are members, but RV non-members, and with filled triangles (black when printed in colour) the RV members, and with filled triangles (black when printed in colour) the RV non-members. We confirm the result of BWGO96 that star #2-4 (our star 656) is a member.

Clearly, members and non-members mix up in a way that, without RVs, it would not be possible to discriminate between them. Our member stars are partly located in the TO region and partly trace the subgiant branch and RGB of the cluster.

Among this membership sample, we find two stars with the radial velocities typical of members but located far from the most important loci in the CMD. They are stars #323 at $(V, B - V) = (14.896, 1.161)$ and #782 at $(13.510, 1.244)$. We suggest that these stars may

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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 SPECTRUM is the local thermodynamic equilibrium (LTE) spectral synthesis program freely distributed by Richard O. Gray. See http://www.phys.appstate.edu/spectrum/spectrum.html.
be binary members, as is star #3-18 (our 954, see MM07), which must be confirmed by future studies (but see Section 7 for additional details). Unfortunately, we cannot use proper motions (see Table 2) to improve our membership assignments due to the large associated errors.

4 ABUNDANCE MEASUREMENTS

4.1 Atomic parameters and equivalent widths

We performed the analysis of chemical abundances on the three members observed with MIKE using the 2007 version of the freely available program MOOG developed by Chris Sneden\(^2\) and using model atmospheres by Kurucz (1992). MOOG performs an LTE analysis. We derived equivalent widths of spectral lines by Gaussian fitting of spectral features. Repeated measurements show a typical error of about 5 mÅ for the weakest lines. The line list was taken from Carraro et al. (2008). The log(g) parameters of these lines were redetermined by a solar-inverse analysis measuring the equivalent widths from the NOAO solar spectrum (Kurucz et al. 1984), adopting standard solar parameters (\(T_{\text{eff}} = 5777\) K, \(\log (g) = 4.44\) and \(v_{\text{t}} = 0.8\) km s\(^{-1}\)). The O abundance was obtained from the infrared triplet at 7771–7775 Å, while the Na abundance was obtained from the spectral doublets at 5662–5668 and 6154–6160 Å. These features are well known to be affected by non-LTE (NLTE) effects. For this reason we applied NLTE correction to the output LTE abundances, obtained from Gratton et al. (1999).

\(^2\)http://verdi.as.utexas.edu/moog.html.
Figure 4. Distribution of radial velocities from the present study.

Table 4. Observational details of the five stars observed with MIKE.

| ID | Julian Date | Exposure time (s) | S/N |
|----|-------------|-------------------|-----|
| 535 | 245 430.823 17 | 500 | 80 |
| 261 | 245 440.816 00 | 800 | 60 |
| 717 | 245 440.835 38 | 1200 | 100 |
| 304 | 245 440.850 79 | 1600 | 90 |
| 836 | 245 440.870 42 | 1300 | 80 |

Table 5. Radial velocity: comparison with literature data.

| R85 ID | V | (B – V) | RV_H | BWGO96 | FJ93 | MM07 |
|--------|---|---------|------|--------|-----|------|
| 1-16   | 382 | -6.18 ± 0.22 | -3.6 | -4.04 |
| 2-4    | 656 | 11.724 | 1.767 | 29.53 ± 0.27 | 30.04 |
| 2-16   | 422 | 13.357 | 1.643 | -29.32 ± 0.26 | -23.3 | -22 | -29.02 |
| 3-16   | 1123 | 12.441 | 2.030 | 21 | 31.75 |
| 3-17   | 1026 | 11.805 | 2.073 | 40 | 44.76 |
| 3-18   | 954 | 13.312 | 1.550 | 25.3 |
| 4-1    | 711 | 12.380 | 1.639 | 28.56 |
| 4-2    | 759 | 11.429 | 1.423 | 21.6–30.1 | 35 | 32.53 |
| 4-16   | 883 | 12.856 | 1.546 | 44.5 | 60 |

4.2 Atmospheric parameters

Initial estimates of the atmospheric parameter $T_{\text{eff}}$ were obtained from photometric observations using the relations from Alonso, Arribas & Martínez-Roger (1999). We adopted $E(B – V)$ values from Carraro et al. (2002) to correct colours for interstellar extinction. We then adjusted the effective temperature by minimizing the slope of the abundances obtained from FeI lines with respect to the excitation potential in the curve of growth analysis. Initial guesses for the gravity log $(g)$ were derived from the canonical formula:

$$\log \left( \frac{g}{\text{g}_\odot} \right) = \log \left( \frac{M}{M_\odot} \right) + 4 \log \left( \frac{T_{\text{eff}}}{\text{K}} \right) - \log \left( \frac{L}{L_\odot} \right).$$  \hspace{1cm} (2)

In this equation, the mass $M/M_\odot$ was derived from the comparison between the position of the star in the Hertzsprung–Russell diagram and the Padova isochrones (Girardi et al. 2000). The luminosity $L/L_\odot$ was derived from the absolute magnitude $M_V$, assuming a distance moduli of $(m – M)_V = 11.6$. The bolometric correction (BC) was derived from the BC-Teff relation from Alonso et al. (1999). The input log$(g)$ values were then adjusted in order to satisfy the ionization equilibrium of FeI and FeII during the abundance analysis. Finally, the microturbulence velocity is given by the relation (Houdashelt, Bell & Sweigart 2000)

$$v_t = 2.22 – 0.322 \log(g).$$  \hspace{1cm} (3)

We then adjusted the microturbulence velocity by minimizing the slope of the abundances obtained from FeI lines with respect to the equivalent width in the curve of growth analysis. The adopted values for all these parameters, together with [Fe/H], are reported in Table 6. The results of the abundance analysis are listed in Table 7, where the abundances of the main elements are reported with their uncertainties. Two stars turn out to be giants (#304 and 836), while star #535 is clearly a dwarf. This explains the different number of lines used in the determination of the different elemental abundances.

As a final remark, we also performed an abundance analysis for the two RV non-members, and found that the two stars #261 and #717 have [Fe/H] = +0.28 ± 0.02 and +0.30 ± 0.03, confirming their nature as non-member stars.

Examples of our extracted spectra are illustrated in Fig. 6, in which the spectrum of three MIKE member stars are shown and some interesting lines indicated.
Table 7. Abundance analysis from MIKE cluster members. After each value, in parenthesis, the number of lines used is indicated. Values derived from just one line do not have any error associated.

| Element | #535 N | #304 N | #836 N |
|---------|--------|--------|--------|
| [Fe/H]  | 0.15 ± 0.02 (19) | 0.19 ± 0.02 (71) | 0.13 ± 0.01 (107) |
| [O/H]_LTE | 0.45 ± 0.07 (3) | 0.36 ± 0.01 (3) | 0.27 ± 0.03 (3) |
| [O/H]_NLTE | 0.03 ± 0.07 (3) | 0.17 ± 0.01 (3) | 0.23 ± 0.03 (3) |
| [Na/H]_LTE | 0.35 ± 0.13 (2) | 0.20 ± 0.06 (4) | 0.30 ± 0.06 (3) |
| [Na/H]_NLTE | 0.24 ± 0.13 (2) | 0.15 ± 0.06 (4) | 0.23 ± 0.06 (3) |
| [Mg/H] | 0.13 (1) | 0.18 (1) | 0.27 ± 0.03 (2) |
| [Al/H] | 0.10 ± 0.09 (2) | 0.05 ± 0.03 (3) |
| [Si/H] | 0.33 ± 0.02 (3) | 0.11 ± 0.06 (5) | 0.11 ± 0.05 (8) |
| [Ca/H] | 0.18 ± 0.07 (7) | 0.23 ± 0.04 (13) | 0.07 ± 0.05 (13) |
| [Ti/H] | 0.20 ± 0.04 (2) | 0.43 ± 0.09 (7) | 0.23 ± 0.04 (23) |
| [V/H] | −0.01 (1) | 0.31 ± 0.06 (10) |
| [Cr/H] | 0.51 ± 0.05 (2) | 0.41 ± 0.08 (6) | 0.14 ± 0.03 (11) |
| [Mn/H] | −0.18 (1) | 0.03 ± 0.03 (3) | 0.10 ± 0.02 (3) |
| [Co/H] | 0.27 ± 0.07 (2) | 0.24 ± 0.06 (4) |
| [Ni/H] | 0.17 (1) | 0.24 ± 0.05 (15) | 0.21 ± 0.03 (29) |
| [Cu/H] | 0.38 (1) | 0.12 (1) |
| [Y/H] | 0.45 (1) | 0.51 ± 0.24 (2) |
| [Ba/H] | 0.59 (1) | 0.84 ± 0.06 (2) | 0.40 ± 0.01 (2) |

Figure 6. Extracted spectra for the three MIKE member stars. A few important lines are indicated.

The mean metallicity we derive ([Fe/H] = +0.16 ± 0.03) is significantly different from any previous spectroscopic estimate. The closest determination is the one by BWGO96, who found [Fe/H] = −0.15 ± 0.15. Our result rules out any possibility that NGC 2112 is very metal-poor, as suggested in early studies. It would have been very unusual to have such a metal-poor cluster in the solar neighbourhood. Our result, in fact, suggests that NGC 2112 has a typical solar vicinity metal abundance, being as metal-rich as the Hyades (Boesgaard & Friel 1990).

Karatas & Schuster (2006) provided a new calibration of the relation between the metallicity of a dwarf star and δ_0.6, namely the (U − B) excess/deficiency with respect to the Hayles sequence at (B − V)_0 = 0.6. We compared the distribution of dwarf stars in NGC 2112 at (B − V)_0 ∼ 0.6 with respect to a zero-age main-sequence (ZAMS) from Girardi et al. (2000) having the same metallicity of the Hyades ([Fe/H] = 0.17). We found that the useful stars (13 in number) have δ_0.6 = −0.02 ± 0.11. Despite the scatter, this δ_0.6 implies a metallicity close to our spectroscopic determination (see Table 3).

5 Abundance Ratios

We derived abundance ratios for the three MIKE member stars listed in Table 7. Previously, only BWGO96 provided an estimate of a few abundance ratios in NGC 2112, but based on just one star. At any rate, we compare our findings with BWGO96 (their table 6), and find basic agreement with [O/Fe] and [Na/Fe]. However, their [Al/Fe] is much larger than our value.

Being close to the Sun and having roughly the same metallicity, it is useful to make a detailed comparison of the chemical properties of NGC 2112 with the solar neighbourhood stars and star clusters.

5.1 Comparison with field stars

Bensby et al. (2005) present a detailed abundance analysis for a sample of 102 F and G dwarf stars in the solar vicinity. "α-elements: As shown by Bensby et al. (2005), O, Mg, Si, Ca and Ti exhibit similar trends in the Galactic thin disc. At the Fe abundance of NGC 2112 (+0.16), these ratios are in the range of −0.15:0.00, 0.00:+0.15, 0.00:+0.15, 0.00:+0.15 and −0.05:0.05 dex, respectively.

According to our findings, abundance ratios for these five elements in NGC 2112 are in agreement with the thin-disc values within the errors. This confirms that NGC 2112 is a typical thin-disc star cluster. The overall [α/Fe] ratio turns out to be 0.04 ± 0.03."

Iron peak elements: We can compare only Ni and Cr with Bensby et al. (2005). Ni is basically in agreement with the thin-disc trends, whereas the [Cr/Fe] ratio is marginally overabundant.

Al and Na: While the Na abundance relative to Fe is consistent with thin-disc values, we find that Al is significantly underabundant.

r- and s-process elements: We measured Y and Ba abundance ratios. While the Ba abundance in NGC 2112 is consistent with the thin-disc trend, we find that the Y abundance is significantly larger than typical thin-disc values.

5.2 Comparison with open clusters

In general, there is not much information on abundance ratios in open clusters, and only in the last few years efforts have been made to improve this situation.

Here, we compare our NGC 2112 abundance ratios with the results presented in Friel et al. (2003). They provide a detailed abundance analysis of the old star cluster Collinder 261 and compare its abundance ratios with a sample of 10 open clusters (see their table 7). From this table, we extract estimates for NGC 2360 and 6819, two nearby clusters having roughly the same ages and metal abundances as NGC 2112. We find that within the errors, NGC 2360 and 6819 possess the same [α/Fe] as NGC 2112, +0.03 and 0.00, respectively.

The Na abundance of NGC 2112 is similar to NGC 2360 but significantly lower than in NGC 6819. As for Al, we can make a comparison only with NGC 6819, for which [Al/Fe] is similar to the value we determine for NGC 2112.
Figure 7. Two-colour diagram for NGC 2112 stars. The solid line is the Schmidt-Kaler (1982) empirical ZAMS and the dashed line is the same ZAMS shifted by $E(B-V) = 0.60$ along the reddening vector (the arrow) for a normal reddening law.

Figure 8. Isochrone fits for the derived metallicity and varying ages. Bottom panels show the fits in the $V$ versus $(B-V)$ plane, upper panels show the fits in the $V$ versus $(V-I)$ plane. Left-hand panels refer to Padova isochrones and right-hand panels refer to Yale–Yonsei isochrones.

Unfortunately, information about neither the iron-peak elements nor s- and r-process elements are reported in Friel et al. (2003).

Overall, with a few exceptions, we find that NGC 2112 is a genuine thin-disc population cluster.

6 CLUSTER FUNDAMENTAL PARAMETERS

Having an estimate of the metal content ([Fe/H] = +0.16), and of the $\alpha$-element abundances ([$\alpha$/Fe] = +0.04), we are now in the position to derive more reliable estimates of the cluster parameters.

The reddening value in the direction of NGC 2112 predicted by Schlegel, Finkbeiner & Davis (1998) maps is $E(B - V) = 1.01$. This has to be considered as an upper limit to the reddening since it takes into accounts the absorption all the way to infinity.

To get an independent estimate of the reddening in the direction of NGC 2112, we make use of the two-colour diagram in Fig. 7 since we provide deep $U$-band photometry for the first time. Here, the solid line is the zero reddening empirical ZAMS from Schmidt-Kaler (1982). The same ZAMS, shifted by $E(B-V) = 0.60$ is shown as a dashed line. The shift has been performed adopting the standard reddening law (see the expression in the bottom of Fig. 7), and the reddening vector is indicated with a solid arrow.

We compare the distribution of stars in the various colour combination CMDs and sets of theoretical Padova (Girardi et al. © 2008 The Authors. Journal compilation © 2008 RAS, MNRAS 386, 1625–1634.
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Figure 9. The best-fitting isochrone is superimposed on the NGC 2112 CMD where radial velocity members are indicated with solid circles. Left-hand panel refers to Yale–Yonsei isochrones and the right-hand panel refer to Padova isochrones. The isochrones have been adjusted using the values listed in Table 8.

Table 8. Abundance ratios from MIKE cluster members.

| Element   | #535 | #304 | #836 |
|-----------|------|------|------|
| [O/Fe]_{NLTE} | -0.12 | -0.02 | 0.10 |
| [Na/Fe]_{NLTE} | 0.09 | -0.04 | 0.10 |
| [Mg/Fe] | -0.02 | -0.01 | 0.14 |
| [Al/Fe] | -0.09 | -0.08 | -0.08 |
| [Si/Fe] | 0.18 | -0.08 | -0.02 |
| [Ca/Fe] | 0.03 | 0.04 | -0.06 |
| [Ti/Fe] | 0.05 | 0.24 | 0.10 |
| [V/Fe] | -0.20 | 0.18 |
| [Cr/Fe] | 0.36 | 0.22 | 0.01 |
| [Mn/Fe] | -0.33 | -0.16 | -0.03 |
| [Co/Fe] | 0.08 | 0.11 |
| [Ni/Fe] | 0.02 | 0.05 | 0.08 |
| [Cu/Fe] | 0.19 | -0.01 |
| [Y/Fe] | 0.26 | 0.38 |
| [Ba/Fe] | 0.44 | 0.65 | 0.27 |

Table 9. Summary of NGC 2112 fundamental parameters derived from the comparison of different isochrone sets.

| Models       | Age    | $E(B-V)$ | $(m-M)_V$ |
|--------------|--------|----------|-----------|
| Yale–Yonsei  | 1.8 ± 0.3 | 0.63 ± 0.05 | 11.80 ± 0.10 |
| Padova       | 1.8 ± 0.3 | 0.57 ± 0.05 | 11.75 ± 0.10 |

7 A ZOOM OF THE TO REGION: GETTING ADDITIONAL CLUES TO THE BINARY POPULATION

Now that we have determined the cluster’s fundamental parameters, we can use the best-fitting isochrone as a tool to investigate possible binaries among cluster members from a purely photometric point of view. In Fig 10 we provide a zoom of the TO region, and indicated with filled circles (colour coded in red) RV members. The solid line is the best-fitting Padova isochrone (see Fig. 9). The dashed curve is the same isochrone, but shifted up by 0.75 mag, to illustrate the locus of unresolved equal-mass binaries. This exercise is suggesting us
that several stars that lie off the best-fitting isochrone may in reality be unresolved binaries. In fact some of them lie very close to the binary locus, and we indicate them as filled squares (colour coded in green) in the CMD of Fig. 10. They are stars #707, 824, 782 and 601. At the same time, we indicated as filled triangles (blue when printed in colour) stars which lie neither in the single star nor in the binary star sequence. These are stars #714, 707 and 323. One may speculate that these are unequal-mass binaries or may be systems with more than two components. If we refer only to the TO region, we are left with 14 single member stars and seven possibly multiple systems, which implies a rough binary estimate of 33 per cent.

8 DISCUSSION AND CONCLUSIONS

In this paper we presented new photometric and spectroscopic data in the field of the old open cluster NGC 2112. This new data set allowed us to revise the cluster’s fundamental parameters and clarify a long-lasting debate on its properties, which for many years, have been poorly constrained due to the high level of field star contamination. By means of multifibre spectroscopy, we measured RV for 40 stars and found 21 RV members. This, in turn, allowed us to clean the CMD, providing a better comparison with stellar models.

The most important result of our study is that the cluster has a metallicity much higher than previous determinations, and somewhat higher than the Sun. Also the α-elements are marginally enhanced with respect to the Sun, but still compatible with the trends of thin-disc stars in the solar vicinity, as are all the other elements we measured.

Therefore NGC 2112 is typical of old, thin-disc star clusters, as metal-rich as the Hyades (Boesgaard & Friel 1990), and located at less than 1 kpc from the Sun in the anticentre direction.

In addition, we confirmed the age of the cluster (≈ 1.8 Gyr), previously derived on a purely photometric basis (Carraro et al. 2002). As for the distance and reddening, our values are in agreement within the errors of previous determinations.

This study stresses the importance of performing detailed membership analysis in Galactic open clusters in order to derive more robust estimates of their fundamental parameters.

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