TAGGING THE CHEMICAL EVOLUTION HISTORY OF THE LARGE MAGELLANIC CLOUD DISK*

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ABSTRACT

We have used high-resolution spectra obtained with the multifiber facility FLAMES at the Very Large Telescope of the European Southern Observatory to derive kinematic properties and chemical abundances of Fe, O, Mg, and Si for 89 stars in the disk of the Large Magellanic Cloud (LMC). The derived metallicity and \([\alpha/Fe]\), obtained as the average of O, Mg, and Si abundances, allow us to draw a preliminary scheme of the star formation history of this region of the LMC. The derived metallicity distribution shows two main components: one component (comprising \(\sim 84\%\) of the sample) peaks at \([Fe/H] = -0.48\) dex and it shows an \([\alpha/Fe]\) ratio slightly under solar \((\sim -0.1\) dex). This population probably originated in the main star formation event that occurred 3–4 Gyr ago (possibly triggered by tidal capture of the Small Magellanic Cloud). The other component (comprising \(\sim 16\%\) of the sample) peaks at \([Fe/H] \sim 0\) dex and it shows an \([\alpha/Fe]\) \sim 0.2 dex. This population was probably generated during the long quiescent epoch of star formation between the first episode and the most recent bursts. Indeed, in our sample we do not find stars with chemical properties similar to the old LMC globular clusters nor to the iron-rich and \(\alpha\)-poor stars recently found in the LMC globular cluster NGC 1718 and also predicted to be in the LMC field, thus suggesting that both of these components are small (<1%) in the LMC disk population.

Key words: Magellanic Clouds – stars: abundances – techniques: spectroscopic

Online-only material: machine-readable tables

1. INTRODUCTION

Despite several years of studies, the chemical evolution history of the Large Magellanic Cloud (LMC), as well as its star formation history (SFH), is still poorly understood. The LMC has experienced a complex SFH due to the interaction that occurred both with the Small Magellanic Cloud (SMC) and the Galaxy (Bekki & Chiba 2005). Clear evidence of this quite complex evolution can be recognized in the LMC star cluster system, characterized by a wide range of ages and metallicities. The study of these cluster stellar populations reveals the existence of at least three components: the old (\(\sim 13\) Gyr; Brocato et al. 1996; Olsen et al. 1998), metal-poor component \(([Fe/H] < -0.5\) dex; Olszewski et al. 1991; Grocholski et al. 2006; Mucciarelli et al. 2010) which probably formed during the first episode of star formation (SF); the intermediate-age component \((1–3\) Gyr; Gallart et al. 2003; Ferraro et al. 2004), which is the dominant one; and a young component \((\leq 1\) Gyr; Brocato et al. 2003; Mucciarelli et al. 2011) that includes the most recently formed clusters.

The SFH of field stellar populations is less known. Smecker-Hane et al. (2002) found that the dominant stellar population in the central bar was formed between 4–6 Gyr and 1–2 Gyr ago. This result was substantially confirmed by the simulations of Bekki & Chiba (2005), who found that the formation of young stellar populations in the LMC bar is associated with efficient SF in the last few Gyr (in particular, \(\sim 2\) Gyr ago).

A comprehensive spectroscopic study of field populations was performed by Cole et al. (2005), measuring the infrared Ca triplet of 373 giant stars located around the center of the bar. They found a distribution peaked at \([Fe/H] \sim -0.4\) dex with a low metallicity tail reaching \([Fe/H] \lesssim -0.0\) dex. Carrera et al. (2008) have measured the infrared Ca triplet in four fields at different radial distances \((\sim 3^\circ, 5^\circ, 6^\circ, \text{ and } 8^\circ; \text{ that is, between } 2.6 \text{ and } 7 \text{ kpc})\) from the center of the LMC. They found an average \([Fe/H] \sim -0.5\) dex for the closest fields; a lower value of \([Fe/H] \sim -0.8\) dex was found only in the more distant field. A detailed spectroscopic analysis of 59 giant stars located in the inner disk at \(\sim 1.2\) kpc from the center was performed by Pompéia et al. (2008), who found a distribution peaked at \([Fe/H] \sim -0.75\) dex.

This paper is part of a project devoted to the investigation of the kinematic and chemical properties of the stellar populations in the LMC through the use of high-resolution spectra, able to provide accurate information about the kinematics, the metallicity, and the chemical abundance of individual elements of these stars. Previous papers in the project have discussed the properties of old (Mucciarelli et al. 2009, 2010), intermediate-age (Ferraro et al. 2006; Mucciarelli et al. 2008), and young (Mucciarelli et al. 2011, 2012) globular clusters (GCs) in the LMC. This paper is the first of the project dedicated to the kinematic and chemical characterization of the LMC field stellar populations: we present chemical patterns for a sample of 89 red giant branch (RGB) stars that are members of the LMC and located in the field around the old metal-poor GC NGC 1786.

To date this represents the largest sample of field giants in the LMC for which high-resolution spectra have been obtained.

2. OBSERVATIONS

We have observed 91 stars located in the region surrounding the old GC NGC 1786 at \(\sim 2^\circ\) NW from the center of the LMC (Kim et al. 1998). The spectra have been acquired with the multi-object spectrograph FLAMES (Pasquini et al. 2002) at the Kueyen European Southern Observatory Very Large Telescope (ESO-VLT).

The spectroscopic targets have been selected using the near-infrared \((J, H, \text{ and } K\) bands) photometric catalog, which was obtained by combining the SOFI catalog for the inner

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* Based on observations collected at the ESO-VLT at Cerro Paranal (Chile) under the Program 080.D-0368(A).
Table 1

| ID  | R.A. (J2000) | Decl. (J2000) | $J$ (mag) | $H$ (mag) | $K$ (mag) |
|-----|-------------|--------------|----------|----------|----------|
| 353 | 74.8429031 | -67.7529937 | 14.55    | 13.80    | 13.61    |
| 1415| 74.7569885 | -67.7277374 | 14.52    | 13.75    | 13.57    |
| 1593| 74.7403107 | -67.7499858 | 14.34    | 13.56    | 13.36    |
| 1954| 74.6935583 | -67.7596817 | 14.11    | 13.28    | 13.12    |
| 1980| 74.6899948 | -67.7497635 | 14.52    | 13.74    | 13.58    |
| 2353| 74.7275314 | -67.7429553 | 12.56    | 11.87    | 11.71    |
| 2363| 74.7172394 | -67.745918 | 14.67    | 13.97    | 13.82    |
| 2376| 74.7086487 | -67.7584584 | 14.62    | 13.93    | 13.81    |
| 90012| 74.2391357 | -67.7102280 | 13.91    | 13.05    | 12.93    |
| 90119| 74.5896658 | -67.9048157 | 14.27    | 13.38    | 13.23    |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

~2.5 arcmin, corresponding to the area covered by GC NGC 1786 (see Mucciarelli et al. 2010 for details) and the Two Micro All Sky Survey (2MASS) catalog for the outermost region, in order to sample the surrounding field population. The final catalog was placed onto the 2MASS photometric and absolute astrometric system by following the standard procedure used in Ferraro et al. (2004). Photometric uncertainties are about 0.01–0.02 and 0.03–0.05 for SOFI and 2MASS targets, respectively. The targets have been selected along the RGB and in the magnitude range $K_0 \approx 12.3$–14.0, in order to reach a sufficient signal-to-noise ratio ($S/N > 30$–40) and excluding stars brighter than the magnitude level ($K_0 \approx 12.3$, see Cioni et al. 2006) of the RGB Tip of the intermediate-age LMC population.

Observations consist of a series of 45 minute exposures obtained with HR11 (5600–5840 Å and $R = 24200$) and HR13 (6120–6400 Å and $R = 22500$) gratings using the GIRAFFE/MEDUSA configurations. The data reduction was performed with the GIRAFFE ESO pipeline which includes bias subtraction, flat fielding, wavelength calibration, and spectrum extraction. Individual stellar spectra have been cleaned from the sky contribution by subtracting the corresponding median sky spectrum. Finally, multiple spectra of each target have been co-added, reaching an S/N per pixel of ~40 in the faintest stars and up to ~100 in the brightest ones. Identification number, right ascension, and declination of each target are listed in Table 1.

3. KINEMATIC AND CHEMICAL ANALYSIS

Radial velocities ($v_r$) have been measured by means of the DAOSPEC code (Stetson & Pancino 2008). For each star, the spectra from the two different gratings have been analyzed independently and the derived $v_r$ averaged together by using the individual uncertainty as weight. Typical internal errors (computed as $\sigma/\sqrt{N_{\text{lines}}}$) are ~0.15–0.20 km s$^{-1}$. Finally, we applied the heliocentric correction to each $v_r$.

The chemical analysis has been performed using the suite of codes developed by R. L. Kurucz (see Sbordone et al. 2004) aimed at computing abundances from the observed equivalent widths (EWs) and synthetic spectra. The model atmospheres were computed with the ATLAS9 code, assuming plane-parallel geometry and local thermodynamical equilibrium for all species, without the inclusion of the approximate overshooting in the computation of the convective flux. The ATLAS9 model atmospheres were calculated with the new set of Opacity Distribution Functions by Castelli & Kurucz (2004).

The line list has been selected starting with the Kurucz/Castelli data3 updated with recent laboratory data from VALD and NIST databases. We included only transitions with theoretical/laboratory atomic data and checked against spectral blendings through the inspection of suitable synthetic spectra convolved at GIRAFFE resolution. In particular, we adopted for the Fe lines the atomic data from the critical compilations by Fuhr et al. (1988) and Fuhr & Wiese (2006) that represent the most updated data set of theoretical/laboratory log $gf$ for the iron lines.

For some unblended transitions for which theoretical/laboratory oscillator strengths are not available (or for those lines not well reproduced in the solar spectrum), we derived astrophysical oscillator strengths (labeled as SUN in Table 2) by using the solar flux spectra of Neckel & Labs (1984) and the model atmosphere for the Sun computed by F. Castelli4 adopting the solar abundances of Grevesse & Sauval (1998). We estimated for these oscillator strengths an accuracy $<15\%$, according to the uncertainties in the line profile fitting and in the continuum placement. We decide to include in our final line list some Fe I transitions listed by Fuhr et al. (1988) and Fuhr & Wiese (2006) with high quoted uncertainties after verification that these lines are well reproduced in the solar spectrum of Neckel & Labs (1984) and provide an iron abundance within $\pm0.1$ dex of the value of Grevesse & Sauval (1998).

Concerning the van der Waals damping constants, we adopted, whenever possible, the damping values by Barklem et al. (2000), while for the other transitions the van der Waals constants were calculated according to Castelli (2005). The complete line list used is available in Table 2, including wavelength, element code, oscillator strength (and corresponding accuracy), lower excitational potential, and reference source.

The atmospheric parameters have been derived as follows.

1. A preliminary estimate of $T_{\text{eff}}$ for each star was obtained from photometric $(J - H)_0$ and $(J - K)_0$ colors adopting an average color excess of $E(B - V) = 0.12$ (Persson et al. 1983), the extinction law by Rieke & Lebofsky (1985), and the color–temperature calibrations by Alonso et al. (1999) based on the Infra-Red Flux Method. The 2MASS magnitudes of our targets have been converted to the TCS photometric system (where the Alonso et al. 1999 relations are defined) by using the transformations provided by Carpenter (2001). We used the photometric $T_{\text{eff}}$ as first-guess values and then we refined them by imposing the lack of any trend between Fe I abundances and the excitation potential $\chi$. Basically, we find a good agreement between the photometric and spectroscopic $T_{\text{eff}}$, with an average difference of $T_{\text{eff}} - T_{\text{eff}}^{\text{spec}} = 139$ K $\sigma = 173$ K), so the spectroscopic $T_{\text{eff}}$ has been adopted for the following analysis. Typical uncertainties in the spectroscopic temperatures (calculated according to the slope in the plane $A$(Fe I) versus $\chi$) range from ~80 up to ~130 K.

2. Microturbulent velocities have been derived by requiring the lack of any trend between Fe I abundances and the reduced EW (defined as $\log(EW) / \lambda$). Typical uncertainty in the $v_t$ determination is 0.1–0.2 km s$^{-1}$.

3. Surface gravities have been estimated from the photometry, because the classical method to infer $\log(g$ from the comparison between Fe I and Fe II lines cannot be applied due to the...

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3 http://wwwuser.oat.ts.astro.it/castelli/filinest.html
4 http://wwwuser.oat.ts.astro.it/castelli/sun/ap00t5777g44377k1odfnew.dat
Table 2

| λ (Å) | El. | log gf | Accuracy | E.P. (eV) | References |
|-------|-----|--------|----------|-----------|------------|
| 5586.756 | Fe i | −0.144 | <10% | 3.37 | Fuhr & Wiese (2006) |
| 5607.664 | Fe i | −2.270 | <50% | 4.15 | Fuhr et al. (1988) |
| 5611.364 | Fe i | −2.990 | <50% | 3.64 | Fuhr et al. (1988) |
| 5616.632 | Fe i | −1.126 | <18% | 4.21 | Fuhr & Wiese (2006) |
| 5619.225 | Fe i | −3.270 | <50% | 3.69 | Fuhr et al. (1988) |
| 5619.595 | Fe i | −1.670 | >50% | 4.39 | Fuhr & Wiese (2006) |
| 5624.022 | Fe i | −1.140 | <15% | 4.39 | SUN |
| 5633.946 | Fe i | −0.320 | <50% | 4.99 | Fuhr & Wiese (2006) |
| 5636.696 | Fe i | −2.560 | >50% | 3.64 | Fuhr et al. (1988) |
| 5638.262 | Fe i | −0.840 | <50% | 4.22 | Fuhr & Wiese (2006) |
| 5640.307 | Fe i | −1.700 | <15% | 4.64 | SUN |
| 5646.684 | Fe i | −2.500 | <50% | 4.26 | Fuhr et al. (1988) |
| 5650.690 | Fe i | −0.960 | >50% | 5.09 | Fuhr & Wiese (2006) |
| 5651.469 | Fe i | −2.000 | <50% | 4.47 | Fuhr et al. (1988) |
| 5652.318 | Fe i | −1.920 | >50% | 4.26 | Fuhr & Wiese (2006) |
| 5653.867 | Fe i | −1.610 | >50% | 4.39 | Fuhr & Wiese (2006) |
| 5661.021 | Fe i | −2.430 | <50% | 4.38 | Fuhr et al. (1988) |
| 5661.345 | Fe i | −1.756 | <10% | 4.28 | Fuhr & Wiese (2006) |
| 5662.516 | Fe i | −0.573 | <10% | 4.18 | Fuhr & Wiese (2006) |
| 5677.684 | Fe i | −2.700 | <50% | 4.10 | Fuhr et al. (1988) |
| 5678.601 | Fe i | −4.670 | <50% | 2.42 | Fuhr et al. (1988) |
| 5680.240 | Fe i | −2.540 | >50% | 4.19 | Fuhr & Wiese (2006) |
| 5691.497 | Fe i | −1.490 | >50% | 4.30 | Fuhr & Wiese (2006) |
| 5693.640 | Fe i | −0.680 | <15% | 4.96 | SUN |
| 5704.733 | Fe i | −1.250 | <15% | 5.03 | SUN |
| 5705.465 | Fe i | −1.355 | <10% | 4.30 | Fuhr & Wiese (2006) |
| 5714.551 | Fe i | −1.770 | <15% | 5.09 | SUN |
| 5720.886 | Fe i | −1.950 | <50% | 4.55 | Fuhr et al. (1988) |
| 5731.762 | Fe i | −1.270 | <50% | 4.26 | Fuhr & Wiese (2006) |
| 5732.296 | Fe i | −1.560 | <25% | 4.99 | Fuhr et al. (1988) |
| 5741.848 | Fe i | −1.670 | <25% | 4.26 | Fuhr & Wiese (2006) |
| 5760.345 | Fe i | −2.440 | >50% | 3.64 | Fuhr & Wiese (2006) |
| 5767.972 | Fe i | −3.200 | <15% | 4.29 | SUN |
| 5775.081 | Fe i | −1.298 | <18% | 4.22 | Fuhr & Wiese (2006) |
| 5776.224 | Fe i | −3.400 | <15% | 3.69 | SUN |
| 5778.453 | Fe i | −3.430 | <25% | 2.59 | Fuhr & Wiese (2006) |
| 5793.915 | Fe i | −1.660 | >50% | 4.22 | Fuhr & Wiese (2006) |
| 5805.757 | Fe i | −1.590 | <25% | 5.03 | Fuhr et al. (1988) |
| 5806.725 | Fe i | −1.030 | <50% | 4.61 | Fuhr & Wiese (2006) |
| 5811.915 | Fe i | −2.430 | <50% | 4.14 | Fuhr et al. (1988) |
| 6102.249 | Fe i | −5.970 | <7% | 0.91 | Fuhr & Wiese (2006) |
| 6151.618 | Fe i | −3.299 | <10% | 2.18 | Fuhr & Wiese (2006) |
| 6156.360 | Fe i | −1.474 | <18% | 4.14 | Fuhr & Wiese (2006) |
| 6187.989 | Fe i | −1.670 | >50% | 3.94 | Fuhr & Wiese (2006) |
| 6200.313 | Fe i | −2.437 | <18% | 2.61 | Fuhr & Wiese (2006) |
| 6226.734 | Fe i | −2.220 | <50% | 3.88 | Fuhr et al. (1988) |
| 6246.319 | Fe i | −0.877 | <10% | 3.60 | Fuhr & Wiese (2006) |
| 6252.555 | Fe i | −1.687 | <10% | 2.40 | Fuhr & Wiese (2006) |
| 6322.686 | Fe i | −2.426 | <18% | 2.59 | Fuhr & Wiese (2006) |
| 6330.849 | Fe i | −1.190 | <15% | 4.73 | SUN |
| 6335.330 | Fe i | −2.177 | <18% | 2.20 | Fuhr & Wiese (2006) |
| 6336.824 | Fe i | −0.856 | <10% | 3.69 | Fuhr & Wiese (2006) |
| 6380.743 | Fe i | −1.376 | <25% | 4.19 | Fuhr & Wiese (2006) |
| 6303.304 | O i | −9.717 | <2% | 0.00 | Storey & Zeippen (2000) |
| 5711.095 | Mg i | −1.724 | <10% | 4.35 | NIST |
| 5665.555 | Si i | −2.040 | 20% | 4.92 | Garz (1973) |
| 5666.677 | Si i | −1.710 | <15% | 5.62 | SUN |
| 5690.425 | Si i | −1.870 | 20% | 4.93 | Garz (1973) |
| 5701.104 | Si i | −2.050 | 20% | 4.93 | Garz (1973) |
| 5792.073 | Si i | −2.040 | <20% | 20% | Garz (1973) |
| 6155.144 | Si i | −0.880 | <15% | 5.62 | SUN |
| 6237.319 | Si i | −1.100 | <15% | 5.61 | SUN |
Table 4

| ID  | [Fe/H] (dex) | [O/Fe] (dex) | [Mg/Fe] (dex) | [Si/Fe] (dex) |
|-----|--------------|--------------|---------------|--------------|
| 353 | −0.42 ± 0.03 | 0.01 ± 0.05  | −0.16 ± 0.08  | −0.07 ± 0.06 |
| 1415| −0.62 ± 0.03 | 0.19 ± 0.04  | −0.21 ± 0.02  | 0.16 ± 0.03  |
| 1593| −0.58 ± 0.02 | 0.04 ± 0.06  | 0.06 ± 0.09   | 0.14 ± 0.05  |
| 1954| −0.45 ± 0.03 | −0.18 ± 0.09 | −0.13 ± 0.10  | 0.17 ± 0.05  |
| 1980| −0.46 ± 0.02 | 0.06 ± 0.04  | −0.22 ± 0.10  | 0.13 ± 0.02  |
| 2353| −0.37 ± 0.02 | −0.38 ± 0.08 | −0.16 ± 0.09  | −0.09 ± 0.03 |
| 2363| −0.50 ± 0.03 | −0.03 ± 0.07 | −0.12 ± 0.10  | 0.03 ± 0.04  |
| 2376| −0.08 ± 0.03 | 0.28 ± 0.05  | −0.14 ± 0.11  | 0.18 ± 0.06  |
| 90012| 0.24 ± 0.02 | 0.38 ± 0.09  | 0.02 ± 0.07   | 0.37 ± 0.07  |
| 90119| −0.64 ± 0.02 | 0.24 ± 0.09  | −0.11 ± 0.13  | −0.04 ± 0.05 |

Note. The adopted solar values are 7.50, 8.76, 7.58, and 7.55 for Fe, O, Mg, and Si, respectively. (This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

Table 5

| Element | Parameters | \( \delta T_{\text{eff}} \) (100 K) | \( \delta \log g \) (dex) | \( \delta v_r \) (0.1 km s\(^{-1}\)) | Quadrature |
|---------|------------|-------------------------------|-------------------|------------------|------------|
| Fe      | ±0.01      | ±0.03                         | ±0.02             | ±0.04             | ±0.05      |
| O       | ±0.02      | ±0.01                         | ±0.05             | ±0.02             | ±0.05      |
| Mg      | ±0.04      | ±0.03                         | ±0.01             | ±0.02             | ±0.04      |
| Si      | ±0.06      | ±0.07                         | ±0.03             | ±0.02             | ±0.08      |

Notes. The second column is the total uncertainty estimated by following the prescriptions by Cayrel et al. (2004). The other columns show the variations in abundance due to the variation of only one parameter, while the last column is the sum in quadrature of these terms, without taking into account the covariance terms.

The uncertainty arising from the atmospheric parameters has been computed following the approach described by Cayrel et al. (2004). The usual method to derive the errors due to the stellar parameters is to vary one only parameter each time, keeping the other ones fixed and finally adding in quadrature the derived abundance variations. Obviously, this method does not take into account the correlations among the atmospheric parameters, providing only a conservative value for the uncertainty. In our case, \( T_{\text{eff}} \) and \( v_r \) have been optimized spectroscopically (and \( \log g \) has been derived according to the spectroscopic temperature), thus all the parameters are not independent of each other. For each star, the temperature has been varied by \( \pm 1 \sigma_{T_{\text{eff}}} \), because the uncertainty in \( T_{\text{eff}} \) dominates the derived abundances as pointed out by Cayrel et al. (2004). Then, we repeated the optimization procedure described above by keeping the temperature fixed and deriving new values for \( \log g \) and \( v_r \). The advantage of this method is to naturally take into account the covariance terms among the parameters (see also Shetrone et al. 2003).

The procedure has been repeated independently for each star by considering the corresponding \( T_{\text{eff}} \) uncertainty computed from the error of the slope in the A(Fe)–\( \chi \) plane. Table 5 lists the results of this procedure for a representative star of our sample: the second column shows the final uncertainty for each abundance ratio, while the other columns are the results obtained with the usual approach of independently varying of each parameter. The last column of Table 5 is the sum in quadrature of the uncertainties due to only one parameter: these values are larger than those obtained with the Cayrel et al. (2004) approach because the covariances among the parameters are neglected. Typical abundance uncertainties due to the atmospheric parameters are of the order of [Fe/H] = ±0.03 dex, [O/Fe] = ±0.04 dex, [Mg/Fe] = ±0.06 dex, and [Si/Fe] = ±0.09 dex.

Finally, the total internal error for each abundance ratio was obtained by adding in quadrature the error associated with EW measurements and atmospheric parameters. For [Fe/H] it turns out to be of the order of \( \sim 0.04–0.05 \) dex because of the large number of measured lines.

5. RESULTS

The heliocentric radial velocity distribution of the stars in our sample is shown in the left panel of Figure 1. Stars with radial velocity in the range 170 km s\(^{-1}\) ≤ \( v_r \) ≤ 380 km s\(^{-1}\) are considered LMC members, according to Zhao et al. (2003): Only two stars with \( v_r \) ∼ 100 km s\(^{-1}\) have been excluded (likely belonging to the Galaxy). The mean velocity of the sample is \( v_r = 259.3 \) km s\(^{-1}\) (\( \sigma_v = 33.9 \) km s\(^{-1}\)), in good agreement...
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Figure 1. Heliocentric radial velocity distribution (left panel) and the metallicity distribution (right panel) of our sample of LMC disk stars. The shaded histograms show the distribution of the seven member stars of NGC 1786 (Mucciarelli et al. 2009, 2010).

Figure 2. Comparison of our normalized metallicity distribution (a) with that of (b) Cole et al. (2005) and (c) Pompéia et al. (2008).

with previous measurements in other samples of the LMC disk by Cole et al. (2005), Carrera et al. (2008), and Pompéia et al. (2008).

The metallicity distribution of our sample is shown in the right panel of Figure 1. The entire sample has an average $[\text{Fe}/\text{H}] = -0.58$ dex ($\sigma_{\text{Fe}/\text{H}} = 0.25$ dex). Also, two main components can be distinguished.

1. A principal component (hereafter LMC-R), comprising $\sim 84\%$ of the observed sample with $[\text{Fe}/\text{H}] > -0.7$ dex, peaked at $[\text{Fe}/\text{H}] = -0.48$ dex with a quite small dispersion ($\sigma_{\text{Fe}/\text{H}} = 0.13$ dex).

2. A secondary component (hereafter LMC-P), comprising $\sim 16\%$ of the sample, peaked at $[\text{Fe}/\text{H}] = -0.06$ dex ($\sigma_{\text{Fe}/\text{H}} = 0.18$ dex) with an extended tail up to $[\text{Fe}/\text{H}] \sim -0.5$ dex.

The peak of the metallicity distribution of LMC-R (see Figure 2(a)) is in good agreement with those obtained by Cole et al. (2005) ($[\text{Fe}/\text{H}] = -0.45$ dex, $\sigma_{\text{Fe}/\text{H}} = 0.31$ dex; see Figure 2(b)) from the central bar and Carrera et al. (2008; $[\text{Fe}/\text{H}] = -0.47$ dex ($\sigma_{\text{Fe}/\text{H}} = 0.30$ dex), $[\text{Fe}/\text{H}] = -0.50$ dex ($\sigma_{\text{Fe}/\text{H}} = 0.44$ dex), and $[\text{Fe}/\text{H}] = -0.45$ dex ($\sigma_{\text{Fe}/\text{H}} = 0.31$ dex) for the fields located at $\sim 3^\circ$, $5^\circ$, and $6^\circ$ north of the center of the LMC, respectively). A distribution peaked at a slightly lower value ($[\text{Fe}/\text{H}] = -0.75$ dex, $\sigma_{\text{Fe}/\text{H}} = 0.23$ dex) was found by Pompéia et al. (2008; see Figure 2).

Figure 3 shows the behavior of $\text{O}$, $\text{Mg}$, and $\text{Si}$, as a function of $[\text{Fe}/\text{H}]$. We plotted for comparison the abundance ratios measured in other environments: the Galaxy (including data for the thin disk, thick disk, and halo, by Venn et al. 2004; Reddy et al. 2006), the LMC disk (Pompéia et al. 2008), the nearby dwarf spheroidals (Shetrone et al. 2001, 2003; Letarte et al. 2010; Lemisle et al. 2012; Venn et al. 2012), the Sagittarius dwarf galaxy (Sbordone et al. 2007), and the old- and intermediate-age LMC GCs (Johnson et al. 2006; Mucciarelli et al. 2008, 2009, 2010).

The $[\text{O}/\text{Fe}]$ ratio appears systematically lower than those measured in the Galaxy and is basically consistent with those by Pompéia et al. (2008), even though they provide a few measurements for this abundance ratio. The $[\text{Mg}/\text{Fe}]$ ratio turns out to be subsolar in the entire metallicity range and ever lower than the Milky Way stars; also, our targets show lower $\text{Mg}$ abundances with respect to those measured by Pompéia et al. (2008) and we attribute such a discrepancy to the different values of oscillator strengths and damping constants for the Mg line at 5711 Å employing in the two analysis. Finally, the $[\text{Si}/\text{Fe}]$ ratio seems to be barely consistent with Galactic stars, despite a larger dispersion.

Figure 4 shows the behavior of the average $[\alpha/\text{Fe}]$ ratio, obtained by averaging the abundances of $\text{O}$, $\text{Mg}$, and $\text{Si}$, as a function of $[\text{Fe}/\text{H}]$. We compared our targets with the $[\alpha/\text{Fe}]$ ratios of the other samples calculated by averaging the available $\alpha$-element abundance ratios; we excluded $\text{O}$ and $\text{Mg}$ only for the old LMC GCs, because of the intrinsic star-to-star variations of these elements due to the self-enrichment process.

5 We excluded from this comparison the LMC GCs younger than 0.5 Gyr by Mucciarelli et al. (2011, 2012) because they are associated with the last episodes of star formation, while all the targets discussed here belong to the RGB, thus they are older than $\sim 1$–2 Gyr.
Figure 3. Behavior of the \([\text{O}/\text{Fe}], \text{[Mg/Fe]}, \text{and [Si/Fe]}\) ratio as a function of \([\text{Fe/H}]\). Black dots represent our targets, the small gray diamonds are the Galaxy data (Venn et al. 2004; Reddy et al. 2006), the black pentagons are the LMC disk (Pompéia et al. 2008), the edged white squares and diamonds are the old (Johnson et al. 2006; Mucciarelli et al. 2009, 2010) and intermediate-age LMC GCs (Mucciarelli et al. 2008), respectively. The \([\text{Mg/Fe}]\) abundance ratios from Pompéia et al. (2008) were corrected by a factor of \(\simeq -0.11\) dex to take into account the effect of different oscillator strength for the line at 5711 Å used in both analysis. The average \([\text{O}/\text{Fe}]\) and \([\text{Mg/Fe}]\) ratios of the three old and metal-poor GCs from Mucciarelli et al. (2009) were obtained averaging the abundances of the stars with greater values only, in order to avoid the effects of anticorrelations. In this case, the tiny black arrows indicate them as an “upper limit.” The dark-gray arrow marks the position of NGC 1786. Dashed lines mark the solar value. The error bars in the bottom right corner indicate the cumulative (EWs + atmospheric parameters) uncertainties.

Figure 4. Behavior of the average \([\alpha/\text{Fe}]\) ratio as a function of \([\text{Fe/H}]\) (same symbols as Figure 3). At variance with the intermediate-age GCs, the \([\alpha/\text{Fe}]\) ratio of the three old and metal-poor GCs includes \([\text{Si/Fe}]\) only, in order to avoid the effect due to the intrinsic dispersion observed in the O and Mg abundances. Dashed lines mark the solar value. The error bars in the top right corner indicates the average uncertainty of iron and “\(\alpha\)-element” abundances. The upper panel shows the comparison with the Galactic stars, while the bottom panel shows the comparison with stars in the Sagittarius dwarf galaxy (asterisks) and in the nearby dwarf galaxies (gray triangles; the plotted samples include the data by Shetrone et al. 2001 and Shetrone et al. 2003 for Draco, Sextant, Ursa Minor, Sculptor, Fornax, Carina, and Leo I; Letarte et al. 2010 for Fornax; and Lemasle et al. 2012 and Venn et al. 2012 for Carina).
that occurred in the early stages of these clusters (at variance to the intermediate-age LMC GCs where the intrinsic spread in O and Mg content is not detected). The overall trend of [α/Fe] ratio with the [Fe/H] abundance shows a decrease at increasing metallicity. The most metal-poor stars with [Fe/H] < −0.7 dex show [α/Fe] ratios larger than solar value, while stars with [Fe/H] > −0.7 dex show [α/Fe] ratio from solar to sub-solar values. For a given [Fe/H], the [α/Fe] ratio measured in the LMC appears systematically lower than those measured in the Galaxy.

A substantial agreement of our abundances was generally found with the values measured in dSphs, in particular with the abundance ratios observed in the metal-poor component of the Sagittarius dwarf galaxy (Sbordone et al. 2007): such a similarity of α-elements, metallicity distribution, and fraction of metal-poor stars has already been suggested by Monaco et al. (2005).

6. DISCUSSION AND CONCLUSIONS

We determined kinematic and chemical properties for 89 giant star members of the disk of the LMC. This sample significantly increases the number of stars analyzed so far through high-resolution spectroscopy (the largest sample observed by Pompéia et al. 2008 includes 59 stars).

The derived metallicity distribution is dominated by LMC-R, a metal-rich and narrow component peaking at [Fe/H] = −0.48 dex, with a secondary component LMC-P peaking at [Fe/H] = −0.0 dex and reaching [Fe/H] = −0.5 dex (right panel of Figure 1). As shown in Figure 5, the two components show similar kinematic properties, with similar average ⟨v_r⟩ (265.9 km s^{-1} for LMC-R and 261 km s^{-1} for LMC-P) and with a small increase of the velocity dispersion decreasing the metallicity (σ_r = 25 km s^{-1} and σ_r = 29.7 km s^{-1}, respectively).

The kinematic and abundance distributions can be now compared to those observed in the stellar population of the GC NGC 1786. All the stars in our sample belong to the RGB, hence their age can range from ∼1–2 Gyr up to ∼12–13 Gyr, thus excluding very recent (last 500 Myr) burst of SF. At variance with the case of stars that belong to a stellar cluster, the determination of the age for field stars through isochrone fitting is a dangerous and uncertain technique, because the position of an RGB star in the color–magnitude diagram is weakly sensitive to the age and highly affected by uncertainties in the color excess, evolutive mass, and distance. Even if precise ages for each target star cannot be determined, we can draw the timeline of the chemical evolution in this region of the LMC by comparing our results with the recent simulations by Bekki & Chiba (2005) and the SFH inferred by Smecker-Hane et al. (2002), Harris & Zaritsky (2009), and Rubele et al. (2012) in different regions of the LMC; unfortunately, there are no determinations of SFH in the region of our targets.

1. NGC 1786 is an old LMC GC generated during the first burst of SF occurred ∼12–13 Gyr ago. Following Bekki & Chiba (2005), a loose stellar halo of old stars with a velocity dispersion of about ∼40 km s^{-1} and a broad metallicity distribution is also expected to have been formed during that event.

It is interesting to check whether some of the stars observed in our sample could belong to NGC 1786 or to the LMC halo. Note that Mucciarelli et al. (2009, 2010) found for NGC 1786 ⟨v_r⟩ = 264.3 km s^{-1} (σ_v = 5.7 km s^{-1}), [Fe/H] = −1.75 dex, and [α/Fe] = 0.37 dex. Figure 5 shows that none of the observed stars have kinematic and chemical properties compatible with the population of NGC 1786. In particular, the observed sample has a systematically higher [Fe/H] (≥−1.0 dex) and a lower [α/Fe] (≤−0.20 dex), thus demonstrating that even LMC-P did not originate in the cluster.

This evidence could be used to put some constraints on the presence of old metal-poor α-enhanced stars in the sampled LMC disk field, which turns out to be less then ∼1%. Our outcome provides a substantial confirmation of the results by Cole et al. (2005), who found ∼3% of their sample with [Fe/H] < −0.5 dex (but no measurements of [α/Fe] ratio are available) and by Pompéia et al. (2008), who found ∼2%, although the abundance patterns are incompatible with old LMC GCs. Since these samples cover different regions of the galaxy, the measured similar fraction of metal-poor stars in these three samples seems to suggest that the old, metal-poor component is distributed in a quite homogeneous way along the LMC disk.

2. After the initial burst, the LMC underwent a long period characterized by a continuous SF with low efficiency. The occurrence of this quiescent period in the LMC field is clearly visible in the SFH provided by Smecker-Hane et al. (2002), Harris & Zaritsky (2009), and Rubele et al. (2012), where a prolonged phase with very low or lacking SF is appreciable between ∼4–5 Gyr and ∼12 Gyr ago. This quiescent period is also predicted by the theoretical models proposed by Bekki & Chiba (2005) that derived a typical SF efficiency in this age range of ∼0.1 M_{⊙} yr^{-1}.

During this period, the LMC evolved in isolation, without gravitational interactions with the Galaxy and the SMC (Bekki & Chiba 2005; Besla et al. 2007). LMC-P likely formed during this period, as also suggested by the lower (by ∼0.2–0.3 dex) [α/Fe] ratio with respect to the Galactic values at similar metallicity, which indicate that during this long period mainly SNeIa contribute to the gas enrichment. If this scenario is correct, these stars were born during the period in which no GC formed (the so-called Age Gap; Rich et al. 2001; Bekki et al. 2004), hence they are unique tracers of the LMC chemical evolution history between ∼12 and 3 Gyr ago.

We also note that the LMC-P fraction (∼16%) is larger than that (≤10%) found by Cole et al. (2005). This is
probably due to the different locations of the two fields. The sample analyzed by Cole et al. (2005) is located around the central bar (at variance with our targets, which are located in the inner disk at ~1.8 kpc from the LMC center). In fact, Bekki & Chiba (2005) suggest that the central bar formed in the last 3–4 Gyr with a marginal fraction of metal-poor stars in its stellar content.

Also, it is interesting to note that the [$\alpha$/Fe] ratio of this stellar component well resembles the mean locus defined by the dSph stars (gray triangles in the lower panel of Figure 4, but see also Figure 11 in Tolstoy et al. 2009), suggesting similar chemical enrichment histories.

3. LMC-R formed during the relevant burst of SF that occurred in the last few Gyr probably due to the tidal capture of the SMC by the LMC. Numerical simulations (Bekki & Chiba 2005) predict that the first close encounter between the two clouds occurred ~3–4 Gyr ago, when the LMC and SMC become a gravitationally bound system. This strong interaction triggered the SFR up to ~0.4 $M_\odot$ yr$^{-1}$. One occurrence of this SF enhancement has been confirmed by Harris & Zaritsky (2009) by using color–magnitude diagrams of different regions of the LMC. However, the binary system status of the Magellanic Clouds and its timescales are still a matter of debate since there is no unambiguous consensus between dynamical simulation and photometric studies. For instance, Rubele et al. (2012) analyzed a new photometric data set from the Vista Magellanic Survey, finding an enhancement of SF with a peak at ~2 Gyr and in some regions a second peak at ~5 Gyr, and interpreted this as the epoch of tidal interaction between the LMC and the Galaxy. Conversely, Besla et al. (2007) suggested that the LMC–SMC system is on its first close passage about the Galaxy, having entered in the Milky Way virial radius only in the last 1–3 Gyr.

The LMC-R distribution is very narrow ($\sigma_{[\text{Fe}/\text{H}]} = 0.13$ dex), suggesting that the episode of SF associated with the first close encounter between the two clouds has been very efficient (in order to produce the majority of the LMC disk stars) and fast, because the stars have not had time to further enrich in iron. These stars show [$\alpha$/Fe] abundance ratios that are close to the solar value, in nice agreement with the values measured in the intermediate-age GCs (Mucciarelli et al. 2008) with age of 1–3 Gyr, as shown in Figure 4.

The observed [$\alpha$/Fe] ratios agree with those derived in the Sagittarius dSph giants (asterisks in lower panel of Figure 4), while the nearby dSphs studied so far do not reach such metallicity. The most metal-rich stars discussed by Letarte et al. (2010) in Fornax show [Fe/H]~ −0.6 dex, consistent with the metal-poor edge of the LMC-R population. This evidence (the similarity with Sgr and the difference with the nearby dSphs) suggests in any case a common origin of these stars from a similar burst of SF.

Thus, the scatter in [$\alpha$/Fe] abundances of the LMC-R stars reflects the larger age range in which these stars formed. However, we find a general agreement between the values observed in the field and GC stars in this metallicity range, suggesting in any case a common origin of these stars from a similar burst of SF.

It is important to recall that there is an offset between the age of the onset of the SF in the LMC field and that of the GC formation. In fact, if the SF in the field started about 4–5 Gyr ago (the precise age depends on the location in the disk and the magnitude of the tidal interactions with the SMC), the GC formation restarts about 2 Gyr ago, as suggested also by Bekki & Chiba (2005). This difference is confirmed by the measured ages in the intermediate-ages GCs (see, e.g., Rich et al. 2001; Mucciarelli et al. 2007a, 2007b) and the lack of globulars in the age range between 2 and 5 Gyr. Furthermore, the lower metallicity edge of LMC-R stars ([Fe/H] ~ −0.7 dex), if compared to that of GCs, seems to support that the SF of field stars becomes efficient slightly earlier.

Recently, Tsujimoto & Bekki (2012) discussed the unusually low [Mg/Fe] (~−0.9 dex) ratio measured by Colucci et al. (2012) in the intermediate-age, metal-rich NGC 1718, suggesting that this cluster and a fraction of LMC field stars were formed from the metal-poor gas acquired by infall from the SMC about 1–2 Gyr ago (the so-called Magellanic Squall; Bekki & Chiba 2007). In our sample we did not detect metal-rich stars characterized by such low Mg or $\alpha$-depletion, pointing out that the stars formed from metal-poor gas accreted by the SMC are (if any) a negligible (<1%) fraction of the LMC disk.

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