Using Star Clusters as Tracers of Star Formation and Chemical Evolution: The Chemical Enrichment History of the Large Magellanic Cloud*

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Abstract

The star formation (SFH) and chemical enrichment (CEH) histories of Local Group galaxies are traditionally studied by analyzing their resolved stellar populations in a form of color–magnitude diagrams obtained with the Hubble Space Telescope. Star clusters can be studied in integrated light using ground-based telescopes to much larger distances. They represent snapshots of the chemical evolution of their host galaxy at different ages. Here we present a simple theoretical framework for the chemical evolution based on the instantaneous recycling approximation (IRA) model. We infer a CEH from an SFH and vice versa using observational data. We also present a more advanced model for the evolution of individual chemical elements that takes into account the contribution of supernovae type Ia. We demonstrate that ages, iron, and α-element abundances of 15 star clusters derived from the fitting of their integrated optical spectra reliably trace the CEH of the Large Magellanic Cloud obtained from resolved stellar populations in the age range 40 Myr < t < 3.5 Gyr. The CEH predicted by our model from the global SFH of the LMC agrees remarkably well with the observed cluster age–metallicity relation. Moreover, the present-day total gas mass of the LMC estimated by the IRA model (6.2 × 10^8 M_☉) matches within uncertainties the observed H I mass corrected for the presence of molecular gas (5.8 ± 0.5 × 10^8 M_☉). We briefly discuss how our approach can be used to study SFHs of galaxies as distant as 10 Mpc at the level of detail that is currently available only in a handful of nearby Milky Way satellites.

Key words: galaxies: evolution – galaxies: star clusters: general – galaxies: stellar content – Magellanic Clouds

1. Introduction and Motivation

Strong starburst events or periods of quiescent evolution that take place during the lifetime of a galaxy form consequent generations of stars enriching the interstellar medium (ISM) at the end of their lives with metals produced inside them. Gas-rich mergers and gas infall from companions or cosmic filaments supply additional fuel for star formation, while the feedback from supernovae and stellar winds slow it down and can eventually quench it completely (Dekel & Silk 1986; Matteucci 1994; Chiosi & Carraro 2002; Bekki & Chiba 2005). Therefore, stellar populations of a galaxy contain a fossil record of its evolutionary path. The star formation and chemical enrichment histories of a galaxy are most directly revealed through analysis of its individual stars and resolved star clusters (see e.g., Dirsch et al. 2000; Carrera et al. 2008; Maschberger & Kroupa 2011; Livano et al. 2013; Piatti et al. 2017, and references therein). However, this approach only applies to galaxies at distances up to ~1 Mpc that are close enough to be resolved. The reconstruction of star formation and chemical enrichment histories of a galaxy from the integrated light, usually referred to as “unresolved stellar populations analysis,” is an ill-conditioned inverse problem that is subject to degeneracies between parameters and often yields nonunique solutions.

Here we propose to use massive star clusters as direct tracers of galaxy star formation and chemical enrichment histories. Massive star clusters (M > 10^4 M_☉) are luminous enough that their integrated light spectra can be collected out to much larger distances (~10 Mpc) than the limit of resolved stellar population studies (Asa’d 2014; Asa’d & Shahpurwala 2016; Asa’d et al. 2016). By using multi-object spectroscopy, one can collect up to a few hundreds of star cluster spectra in a nearby galaxy at once. On the other hand, stars in such clusters are formed almost instantaneously from the available material, so that the effects of self-enrichment of the ISM with metals can be neglected. Hence, a star cluster can be considered as a snapshot of the chemical enrichment history of a galaxy region where it was formed at the time of its formation. This also means, that star cluster spectra should be well described by simple stellar population (SSP) models (i.e., models that are constructed of stars of the same age and metallicity).

In this work, we demonstrate that we can reproduce the chemical enrichment history of the Large Magellanic Cloud (LMC) using integrated spectra of star clusters. We chose LMC for several reasons. It is superior to our Galaxy for such studies because it is relatively small and the dynamical processes in its disk (that mix stellar populations, such as radial migration) are much less important than in giant disks (see, e.g., Schroyen et al. 2013). LMC is a low-mass galaxy located in a group dominated by two giants (Milky Way and Andromeda); therefore, it must have experienced very few (if any) minor mergers with gas-rich satellites that brought metal-poor gas into it and affected the chemical enrichment history. LMC has a very shallow if any radial metallicity gradient (Feast et al. 2010), hence, the exact location of a particular star cluster in its disk is not important for the analysis of the global properties. Moreover, the SFH in the LMC is tightly connected to the galaxy evolution in the Local Group and the mass assembly history of the Milky Way. Hence, analyzing the LMC
is an important step to better understanding the evolution of the Local Group. Finally, the LMC is at the right distance (51 kpc) to allow both resolved and unresolved stellar population analyses of its star clusters (Asa’d & Hanson 2012; Asa’d et al. 2013), and the foreground dust extinction toward LMC clusters is much better constrained than in regions close to the Galactic plane. This allows us to compare our data analysis for integrated spectra against resolved stellar populations at young and intermediate ages of stellar populations.

The paper is organized as follows: In Section 2, we present some theoretical aspects of the chemical evolution and explain how they can be applied to observational data. Section 3 describes our spectroscopic observations and data reduction. In Section 4, we provide the results of stellar population analysis for 15 LMC star clusters. Then, in Section 5, we connect observations with the theory and discuss further prospective of using star clusters to study the chemical evolution of galaxies.

2. Connecting Star Formation History to Chemical Enrichment

In order to link the star formation rate (SFR) \( \psi(t) \) with the metal content of the ISM \( Z(t) \), one needs to develop a model of the galactic chemical evolution. The simplest model called the “instantaneous recycling approximation” (IRA, see, e.g., Schmidt 1963; Pagel 1997; Matteucci 2016) assumes that all stars less massive than \( 1 M_\odot \) live forever and stars above this mass die instantaneously, enriching the ISM with heavy elements formed in their interiors.

The main drawback of this approach is that it does not account for delayed chemical enrichment by asymptotic giant branch (AGB) stars and type Ia supernovae, which enter into action hundreds of millions to billions of years after the beginning of a star formation episode (see, e.g., Nomoto et al. 2013, and references therein). Therefore, in order to describe the chemical evolution of species produced by different astrophysical phenomena, we need to expand the IRA model and include the contributions by Type Ia SNe and AGB stars. In this work, we analyze absorption line spectra of IRA model and include the contributions by Type Ia SNe and carbon. Because AGB stars contribute neither to iron nor to carbon. Because AGB stars contribute neither to iron nor to carbon.

2.1. Instantaneous Recycling Approximation

The IRA model of chemical evolution (see Spitoni et al. 2017 for a detailed description) is defined by the following three parameters: \( R \)—the returned mass fraction of gas that goes back to ISM after stars evolve and can be recycled for star formation, \( y_Z \)—the metal yield per stellar generation that is a mass fraction of heavy elements formed in stars and returned into the ISM, and \( \lambda \)—the outflow (or galactic wind) coefficient (Matteucci & Chiosi 1983; Matteucci 2012) in a simple model of galactic winds directly proportional to the SFR: \( W(t) = \lambda \psi(t) \). The two former parameters \( R \) and \( y_Z \) depend on the metallicity and the initial mass function (IMF); however, the metallicity effects turn out to be minor compared to those of the IMF (Vincenzo et al. 2016). Spitoni et al. (2017) computed those coefficients and obtained the following values: \( R = 0.287 \), \( y_Z = 0.0301 \) for the Salpeter (1955) and Kroupa (2001) IMFs and \( R = 0.441 \), \( y_Z = 0.0631 \) for the Chabrier (2003) IMF. We do not consider gas infall because (i) the infall is usually considered to be a process exponentially declining in time (Chiosi 1980), but our study is concentrated on the last 3–4 Gyr of the LMC history; (ii) in the case of LMC located in the vicinity of the much more massive Milky Way, the infalling gas would likely be accreted by the Milky Way.

In this framework, the chemical evolution is described by the following system of differential equations (see Equation (7) in Spitoni et al. 2017 without the infall parts) for the gas mass \( M_{\text{gas}}(t) \) and the total mass of metals in the ISM \( M_Z(t) \):

\[
\begin{align*}
M_{\text{gas}}(t) &= -(1 - R) \psi(t) - \lambda \psi(t) \\
M_Z(t) &= (-Z(t) + y_Z)(1 - R) \psi(t) - \lambda Z(t) \psi(t) \\
M_t(t) &= M_{\text{gas}}(t) Z(t).
\end{align*}
\]

We solve it for two cases: (i) when the star formation history \( \psi(t) \) is an observable quantity and we would like to predict the chemical evolution caused by self-enrichment \( Z(t) \); and (ii) when we observe the chemical evolution \( Z(t) \) and try to recover the star formation history \( \psi(t) \).

The equation for \( M_{\text{gas}} \) can be integrated as

\[
M_{\text{gas}}(t) = M_{\text{gas}}(0) - (1 - R + \lambda) \int_0^t \psi(T) dT.
\]

Then the equation for the chemical enrichment becomes

\[
Z(t) = y_Z (1 - R) \frac{\psi(t)}{M_{\text{gas}}(0) - (1 - R + \lambda) \int_0^t \psi(T) dT},
\]

and we can then derive the chemical enrichment history as

\[
Z(t) = Z(0) + y_Z (1 - R) \int_0^t \frac{\psi(T)}{M_{\text{gas}}(0) - (1 - R + \lambda) \int_0^t \psi(T) dT} dT
\]

\[
= Z(0) + y_Z (1 - R) \int_0^t \frac{\psi(T)}{1 - R + \lambda} \frac{1}{M_{\text{gas}}(0) - (1 - R + \lambda) \int_0^t \psi(T) dT} dT
\]

If we derive \( \psi(t) \) from observations (e.g., color–magnitude diagrams or CMDs), we can then predict the metal content of the ISM by integrating Equation (4) numerically. Given that \( \psi(t) \) is non-negative, the integral in the denominator will monotonically grow, and thus is the metallicity. This solution has three free parameters, the initial ISM metallicity \( Z(0) \) and gas mass \( M_{\text{gas}}(0) \), and the outflow coefficient \( \lambda \). It is important to point out that \( Z(0) \) and \( M_{\text{gas}}(0) \) correspond to the start of the time period covered by observations that does not have to be the same as the actual galaxy formation epoch. Modern CMD analysis usually provides quite accurate metallicity estimates for old stellar populations that can be used as \( Z(0) \). At the same time, \( M_{\text{gas}}(0) \) and \( \lambda \) are degenerated. However, if we consider several regions in a galaxy where we expect similar global conditions, we would expect \( \lambda \) to stay the same across all of them.

If we observe the chemical enrichment, e.g., traced by star clusters or associations and we aim at recovering the SFH, we will have to solve the integral Equation (4) for \( \psi(t) \) by isolating...
the integral on one side and taking a derivative on \( t \):

\[
\psi(t) = \frac{\dot{Z}(t) M_{\text{gas}}(0)}{y_Z(1 - R)} \exp\left(-\frac{1 - R + \lambda}{y_Z(1 - R)} (Z(t) - Z(0))\right). \tag{5}
\]

Because this expression includes \( \dot{Z}(t) \) that is subject to noise in the data, metallicity measurements should properly sample the range of ages where the SFH needs to be recovered. We also stress that \( \dot{Z}(t) \) should stay positive, which reflects the assumption that our model does not include the infall of metal-poor gas and, therefore, the ISM metallicity can only increase with time.

### 2.2. Chemical Evolution Model Including the Contribution of Type Ia SNe

The importance of type Ia supernova for the iron enrichment was for the first time addressed by Tinsley (1980) and then studied observationally and theoretically by Greggio & Renzini (1983), Nomoto et al. (1984), and Matteucci & Greggio (1986). Massive stars exploding as core collapse supernova (SN Ibc/ SN II) enrich the ISM predominantly with \( \alpha \)-elements (Woosley & Weaver 1995; Nomoto et al. 2013). Because massive stars (\( M > 8 M_\odot \)) are short-lived (10^4–10^5 year), the IRA model is fully applicable to the abundance prediction of oxygen and \( \alpha \)-elements.

On the other hand, Type Ia SNe produce substantial amounts of iron peak elements (Nomoto et al. 1984; Iwamoto et al. 1999; Nomoto et al. 2013) but the timing of the enrichment is very different. Type Ia SNe originate from either white dwarfs exceeding the Chandrasekhar mass limit because of the gas accretion from a companion star (Whelan & Iben 1973; Kenyon et al. 1993), a so-called single degenerate or (SD); or from two white dwarfs merging because their orbit shrinks as the orbital energy is consumed by the emission of gravitational waves (Iben & Tutukov 1984, 1985), a so-called double degenerate (DD) scenario. In both scenarios, it takes significant time before the first Type Ia SNe go off, therefore iron enrichment lags that of oxygen and \( \alpha \)-elements (Matteucci 1994).

The approach we follow here treats the chemical evolution using a two-component model: the IRA plus the contribution of Type Ia SNe. The idea is described in detail in Vincenzo et al. (2017), but here we introduce some modifications: instead of using the local Schmidt–Kennicutt star formation law and dealing with the ISM surface density in a galactic disk, in the case of LMC, we can instead use the global galaxy-wide SFH because the gas is relatively well mixed and no significant metallicity gradient is observed in the LMC disk.

Given the stellar IMF, the fraction of close binary stars and the distribution of their orbital separation, one can compute the delay time distribution (DTD) of SN Ia explosions for different progenitor models (see Matteucci et al. 2009, and references therein for a detailed description). Then, the SN Ia rate \( R_{\text{Ia}}(t) \) as a function of time can be computed as a convolution of the DTD with the SFH \( \psi(t) \):

\[
R_{\text{Ia}}(t) = C_{\text{Ia}} \int_0^t \text{DTD}(t) \psi(t - T) dT. \tag{6}
\]

Here \( C_{\text{Ia}} \) is a normalization coefficient selected to match the observed SN Ia rate, 2 per 1000 \( M_\odot \) formed in stars (Vincenzo et al. 2017). Then we can rewrite Equation (1) for abundances of individual elements \( X(t) \) with the corresponding total masses \( M_X(t) \) and include the SN Ia contribution into it:

\[
\left\{
\begin{array}{l}
M_{\text{Ia}}(t) = -(1 - R + \lambda) \psi(t) + \langle m_{\alpha} \rangle R_{\text{Ia}}(t) \\
M_X(t) = -X(t)(1 - R + \lambda) \psi(t) + y_X(1 - R) \psi(t) \\
M_X(t) = M_{\text{Ia}}(t) X(t)
\end{array}
\right. \tag{7}
\]

Here the notations for the IRA part are similar to those in Equation (1), \( R_{\text{Ia}}(t) \) is the SN Ia rate, \( \langle m_X \rangle \) is the yield of the element \( X \) from SN Ia explosions, and \( \langle m_{\alpha} \rangle \) is the combined yield of all chemical species from Type Ia SNe, which is very close to 1.343 \( M_\odot \) for all SD and DD models presented in Iwamoto et al. (1999).

The equation for \( M_{\text{gas}}(t) \) can be integrated in a similar way to the IRA model as

\[
M_{\text{gas}}(t) = M_{\text{gas}}(0) - (1 - R + \lambda) \int_0^t \psi(T) dT + \langle m_{\alpha} \rangle \int_0^t R_{\text{Ia}}(T) dT. \tag{8}
\]

Here we notice an important difference compared to the IRA solution: Type Ia SNe create a positive contribution to the total gas mass; therefore, it does not have to monotonically decrease over time as it does in the IRA framework and the exact behavior of \( M_{\text{gas}}(t) \) depends on the SFH.

Then the equation for the chemical enrichment becomes

\[
\dot{X}(t) = \frac{R_{\text{Ia}}(t)(m_X - \langle m_{\alpha} \rangle X(t))}{M_{\text{gas}}(t)} + \frac{y_X(1 - R) \psi(t)}{M_{\text{gas}}(t)}. \tag{9}
\]

It can no longer be integrated analytically and requires numerical methods to be used. The free parameters defining the initial conditions are similar to the IRA, the starting gas mass \( M_{\text{gas}}(0) \) and the initial individual abundances of every element \( X(0) \) instead of the initial average metallicity \( Z(0) \). The integral equation to recover \( \psi(t) \) from observed \( X(t) \) also becomes very complex and requires inversion techniques with regularization to be used.

We solve Equation (8) for the IRA return fractions and net yields per generation of silicon and iron computed by Vincenzo et al. (2017) for the Kroupa IMF: \( R = 0.285; \gamma_{\text{Si}} = 8.5 \times 10^{-4}; \gamma_{\text{Fe}} = 5.6 \times 10^{-4} \). For the Type Ia SNe treatment, we use the DTD for SD progenitors by Matteucci & Recchi (2001) and yields for the W7 model from Iwamoto et al. (1999). Our code also has an option to use the mixed DD/SD DTD by Mannucci et al. (2006) and the yields for WDD and CCD models. We chose silicon and not magnesium because the \( \gamma_{\text{Si}} \) were already computed in Vincenzo et al. (2017) and the models of stellar populations, which we use for the analysis of star cluster spectra have the same abundance scaling for all \( \alpha \)-elements.

### 3. Spectroscopic Observations and Data Reduction

Our spectroscopic sample consists of two data sets (see Figure 1 showing the distribution of our observed clusters spanning a large region of the LMC). The first one comprises
For MagE data, we developed a dedicated data reduction pipeline, which is too complex to describe it here in detail. The pipeline merges Echelle orders and produces a sky subtracted flux calibrated two-dimensional spectrum corrected for telluric absorption and a corresponding flux uncertainty frame. We then collapse the spectrum along the slit and obtain a one-dimensional flux calibrated data product.

4. Star Cluster Ages and Metal Abundances from Integrated Light Spectra

4.1. Data Analysis Technique: Ages and [Z/H]

We used the NBURSTS full spectrum fitting technique (Chilingarian et al. 2007a, 2007b) to obtain ages and average metallicities [Z/H] of star clusters in our spectroscopic sample. We fitted each spectrum against a grid of SSP models and obtained the best-fitting SSP age and metallicity as well as a radial velocity of each cluster using a nonlinear minimization. We did not fit the internal velocity dispersion of star clusters because it stayed much below the limits imposed by the spectral resolution of our data. The fitting algorithm includes a multiplicative polynomial continuum, which makes it insensitive to the dust extinction toward the cluster and to possible flux calibration imperfections in the data. We used version 11 of a low resolution (R = 2300) SSP model grid (Vazdekis et al. 2010) with Solar-scaled abundance ratios covering the wavelength range from 3600 to 7400 Å based on the MILES stellar library (Sánchez-Blázquez et al. 2006) computed using BaSTI isochrones (Bertelli et al. 1994; Pietrinferni et al. 2004) for the Kroupa IMF.

In order to analyze SOAR spectra, which have lower spectral resolution than SSP models, we convolved the SSP grid with the wavelength-dependent SOAR spectral line spread function (LSF) derived from the fitting of a twilight spectrum against a high-resolution Solar spectrum. We quadratically subtracted the intrinsic LSF of MILES models from the SOAR LSF, which we derived. Because the MagE spectral resolution is higher than that of MILES spectra, we convolved the observed spectra to match the spectral LSF of MILES similarly to the analysis of high-resolution VLT spectra presented in Chilingarian et al. (2011). We present the best-fitting SSP ages and metallicities for the 15 LMC star clusters in Table 1. The uncertainties of age determinations were increased to 5% of the corresponding age values because the statistical errors of 1%–2% do not represent the real quality of measurements. The metallicity uncertainties are provided as they were reported by the spectrum fitting procedure. These metallicities correspond to the average metal enrichment of star clusters (Sansom et al. 2013):

\[
[Z/H] = [\text{Fe/H}] + 0.75[\alpha/\text{H}].
\]

The sensitivity of the NBURSTS technique to the wavelength coverage as well as systematics and degeneracies of age and metallicity determinations at intermediate and old ages (t > 1 Gyr) were addressed in detail in Chilingarian et al. (2008, 2017) and Chilingarian (2009). However, such analysis has never been performed for younger ages in the range of 30–1000 Myr; therefore, we needed to do some extra tests using the CMD data for young star clusters.

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Figure 1. Location of star clusters from our sample (green and red for Magellan and SOAR data respectively) in the Large Magellanic Cloud. NGC 2249 is located slightly outside the top edge of the image. The underlying image was obtained by IC and R. Muñoz in February/2016 using an amateur digital camera.

11 clusters observed with the Goodman Spectrograph (Clemens et al. 2004) on the 4 m SOAR telescope in the long-slit low resolution mode (1.03 arcsec wide slit; 600 gpm VPH grating; R = 1500; 3600 < λ < 6250 Å) in 2011 December (Asa’d et al. 2013). The second data set includes four clusters observed with the 6.5 m Magellan Baade telescope in 2016 November using the intermediate resolution Magellan Echelle (MagE, Marshall et al. 2008) spectrograph (0.5 arcsec wide slit; R = 7000; 3300 < λ < 9500 Å). Our sample was selected from clusters that had literature data on their ages derived from the analysis of CMDs obtained mostly with the Hubble Space Telescope. We selected the objects that sampled the age range from 10 Myr to 3 Gyr.

In order to collect an integrated spectrum, we scanned a cluster across the slit using the nonsidereal tracking. All star clusters from our sample have sizes between 0.8 and 3 arcmin, which provided enough area along the Goodman spectrograph slit to perform sky subtraction. MagE slit is only 10 arcsec long; therefore, we had to (i) develop a script using the telescope control software, which scans a desired square region of the sky, e.g., 30 × 30 arcsec through the slit in several back-and-forth passes during an exposure time set as a parameter (e.g., 900 s); (ii) take offset sky exposures typically 2–3 arcmin away from the cluster. Not only did our approach allow us to obtain integrated spectra of extended objects, but it also allowed us to sample background close enough to each cluster in order to remove the contribution from the LMC disk.

We reduced our SOAR long-slit data using our generic long-slit/IFU data reduction package implemented in IDL. The data reduction procedure was almost identical to that for Gemini GMOS long-slit spectra described in detail in Francis et al. (2012): we started with bias subtraction and flat fielding, then built a two-dimensional wavelength solution along the slit and used it to construct an oversampled sky model using the algorithm proposed by Kelson et al. (2001), then subtracted the sky background and performed relative flux calibration using a spectrum of a spectrophotometric standard star. At the end, we integrated the spectrum along the slit and created the final one-dimensional data product. The error frames were created using the photon statistics and processed through the same steps in order to obtain flux uncertainties.
4.2. Star Cluster Ages: Spectrum Fitting versus CMDs

It is important to demonstrate that the full spectrum fitting yields correct age estimates for young and intermediate age star clusters, because stellar population measurements at young ages are subject to the age–metallicity degeneracy similar to old stellar populations (Worthey 1994) but with a different slope in the age–metallicity space. Therefore, if age estimates are biased, metallicities will also become incorrect.

Figure 2 shows that the ages determined by the NBURSTS full spectrum fitting technique agree remarkably well with those obtained from CMDs. In this plot, we also included our age estimates for five Small Magellanic Cloud (SMC) clusters obtained from the analysis of their MagE spectra, which will be discussed in a future paper. CMD and spectral ages for 14 out of 20 clusters agree within 10%–15%, which exceeds our expectations because of known systematic problems of both CMD analysis and full spectrum fitting.

Five of six outliers: NGC 241 in the SMC (Elson & Fall 1985), [SL63]268 (Vallenari et al. 1998), [SL63]353 (Dieball et al. 2000), NGC 2065 (Hodge 1983), and NGC 2100 have CMD ages obtained from ground-based seeing limited photometric data, where the source confusion might have biased the results. On the other hand, the NGC 1831 age was estimated by two teams from the HST WFPC2 CMD (Kerber et al. 2007; Niederhofer et al. 2015), which shows the main-sequence turnover at $M_V \sim 0.0$ mag that corresponds to $t > 700$ Myr, while our MagE spectrum suggests it to be younger than $\sim 400$ Myr. It turns out, that both teams assumed zero extinction toward the cluster. However, the visual inspection of Spitzer and AKARI space telescope images reveal that NGC 1831 sits right at the tip of a filament emitting at 8 $\mu$m and in the mid-/far-IR, which suggests that the dust extinction (and maybe even the differential extinction) must play an important role for the CMD analysis of NGC 1831. The color excess $e(B-V) \sim 0.15$ mag will shift the CMD up by $\Delta V \approx 0.5$ mag and explain the discrepancy between the photometric and spectroscopic age estimates.

4.3. Determining $\alpha$-element Abundances

Recent progress in stellar population modeling led to the development of intermediate resolution SSP models with non-solar values of $\alpha$-element abundances. Here we use an extension of MILES v.11 models (Sansom et al. 2013) computed with differential corrections of MILES stellar spectra using synthetic stellar atmospheres by Coelho et al. (2005) with BaSTI isochrones and the Kroupa IMF. The models employed the same scaling for all $\alpha$-elements and were computed for $[\alpha/Fe] = 0.0$ dex and $[\alpha/Fe] = +0.4$ dex.

Because NBURSTS does not include a native feature to fit an extra parameter of stellar populations in a nonlinear minimization loop, in order to derive iron and $\alpha$-element abundances of LMC star clusters, we employed an adhoc approach. We ran NBURSTS five times for every spectrum using grids with $[\alpha/Fe]$ between 0.0 and $+0.4$ dex with a step of $+0.1$ dex computed by the linear interpolation of between the two MILES based grids and obtained age and $[Z/H]$ estimates for every grid. Then we used the $\chi^2$ values for five of the best-fitting solutions and fitted a second-order polynomial into them in order to estimate the position of the minimum. We avoided the extrapolation and, hence, obtained the best-fitting $[\alpha/Fe]$ values between $+0.0$ and $+0.4$ dex for each cluster that corresponded to the minimum of $\chi^2$. The $[\alpha/Fe]$ uncertainties were computed from the $\chi^2$ statistics. We then interpolated the age and $[Z/H]$ estimates to the best-fitting $[\alpha/Fe]$ values.

Finally, $[Fe/H]$ and $[\alpha/H]$ are estimated using Equation (10) as

$$[Fe/H] = [Z/H] - 0.75[\alpha/H]$$

$$[\alpha/H] = [Z/H] + 0.25[\alpha/H].$$

In Table 2, we present ages, $[Z/H]$ average metallicities, and $[\alpha/Fe]$ abundance ratios for 15 LMC star clusters obtained using the full spectrum fitting as described above.

### Table 1

| Object       | $t$, Myr   | $[Fe/H]$, dex | Data Set |
|--------------|------------|---------------|----------|
| NGC1651      | 1353 ± 70  | −0.25 ± 0.03  | SOAR     |
| NGC1831      | 393 ± 20   | −0.14 ± 0.02  | Magellan |
| NGC1850      | 42 ± 2     | −0.12 ± 0.01  | SOAR     |
| NGC1856      | 320 ± 16   | −0.13 ± 0.01  | Magellan |
| NGC1863      | 47 ± 3     | −0.18 ± 0.01  | SOAR     |
| NGC2031      | 140 ± 7    | −0.14 ± 0.02  | SOAR     |
| NGC2065      | 124 ± 6    | −0.16 ± 0.02  | SOAR     |
| NGC2155      | 3757 ± 190 | −0.64 ± 0.03  | SOAR     |
| NGC2159      | 121 ± 6    | −0.13 ± 0.03  | SOAR     |
| NGC2162      | 1298 ± 60  | −0.32 ± 0.04  | SOAR     |
| NGC2173      | 1423 ± 70  | −0.37 ± 0.02  | SOAR     |
| NGC2213      | 1267 ± 60  | −0.51 ± 0.02  | SOAR     |
| NGC2249      | 703 ± 35   | −0.39 ± 0.02  | SOAR     |
| [SL63]268    | 1125 ± 60  | −0.32 ± 0.01  | Magellan |
| [SL63]353    | 969 ± 50   | −0.31 ± 0.02  | Magellan |

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**Figure 2.** Comparison of ages derived from CMDs (literature data) with those determined by the NBURSTS technique. This plot includes measurements for 15 LMC clusters discussed in the paper and for five additional SMC clusters with the available Magellanic MagE spectra. If multiple CMD measurements were available, they are shown as connected data points. CMD measurements did not have available uncertainties; therefore, we assigned a 10% error to them. The six strongest outliers are marked. The CMD data sources for the outliers are provided in the text. The CMD measurements for other clusters were taken from Dirsch et al. (2000), Kerber et al. (2007), Glatt et al. (2008), Niederhofer et al. (2016), Piatti & Bastian (2016), and Martoccia et al. (2017).
This is the first occasion when NBURSTS is used to determine α-element abundances of stellar populations in a quasi self-consistent way. The detailed study of the stability of this approach, its sensitivity, and potential biases lays beyond the scope of this study and will be presented in a future paper. Here we provide a brief consistency check with the data obtained using the solar-scaled model grid. The results in this section and their discussion presented below should be considered as a proof-of-concept rather than a final conclusion, which requires a larger number of star clusters to be analyzed.

The age estimates in the case of α/Fe fit increase on average by 15% or 0.06 dex with a dispersion of 0.07 dex. Metallicities, on the other hand, become lower by 0.13 dex with a dispersion of 0.10 dex. This is likely caused by the age-metallicity degeneracy that affects the results of the full spectrum fitting (see, e.g., Chilingarian et al. 2008; Chilingarian 2009). We should also note that, because of the way α-enhanced MILES based models were constructed using synthetic stellar atmospheres with the highest effective temperature of 7500 K, the reliability of the determination of α-element abundances at stellar populations younger than ∼300 Myr is much lower than that in older star cluster.

5. Discussion

5.1. Age–Metallicity Relation (AMR) of the LMC: Star Clusters versus Average Stellar Population

Our measurements of star cluster stellar population parameters allowed us to build the AMR for LMC clusters. Now we can compare it to available data published in the literature. In this subsection, we refer to the stellar population parameters obtained from the fitting of LMC star cluster spectra against the Solar-scaled grid of MILES based SSP models presented in Table 1.

Rubele et al. (2012) presented a new generation of the resolved stellar populations analysis for the LMC based on near-infrared \( YHK_s \) CMDs obtained with the ESO VISTA telescope. This color combination is metallicity sensitive, which allowed the color recovery not only the SFH but also the metal enrichment history in four tiles in the LMC covering the area of ∼1.4 deg\(^2\) each. If we exclude their tile 6_6, which includes the Tarantula nebula and a giant star-forming complex, making it difficult to measure faint stars, all three remaining tiles demonstrate qualitatively similar AMRs (see Figures 14–16 in Rubele et al. 2012).

Two of the three tiles show that the metallicity decreases by ∼0.15–0.25 dex at young ages (<300 Myr), which we find very hard to explain from an astrophysical point of view in the framework of the LMC chemical evolution, unless there was a massive supply of metal-poor gas from outside, which we do not see any trace of in terms of an SFR increase at that time. On the other hand, their tile 8_3 (coordinates (/2000: \( \alpha = 05:04:53.9, \delta = -66:15:29 \)) has a nearly flat metallicity distribution for young stars in agreement with what is expected from Equation (4), provided there is a very moderate SFR in the last 500–1000 Myr.

In Figure 3, we overplot our LMC star cluster AMR on top of the data for the tile 8_3 from Rubele et al. (2012) shown as the shaded red boxes with sizes corresponding to their resolution in age and metallicity uncertainties. The two data sets remain in a very good agreement at all ages between 40 Myr (NGC 1865) and 3.5 Gyr (NGC 2155). Our metallicity estimates for five intermediate age (0.7 < \( t < 2 \) Gyr) star clusters are somewhat (∼0.1 dex) higher than the values in the tile 8_3 and this discrepancy requires more star cluster data to be collected.

5.2. Reproducing the Chemical Enrichment History from the Observed Global SFH

Now we can compare the AMR of LMC star clusters with the prediction of the chemical enrichment models presented in Section 2. We use the global star formation history of the LMC derived from an optical ground-based LMC photometric survey by Harris & Zaritsky (2009).

We accessed the spatially resolved SFH data from Harris & Zaritsky (2009) using the CDS Vizier service and summed up the SFR estimates in all four metallicity bins across the entire galaxy similar to the procedure used by the original authors to produce their Figure 11. We also obtained the upper and lower global SFR limits by using upper and lower SFR limits. Then we computed the chemical evolution models by integrating Equation (4) for the initial metallicity \([Z/H](0) = -1.42 \) dex, which correspond to that of the oldest LMC star clusters.
excluding several very metal-poor ($[\text{Fe}/\text{H}] < -2$ dex) globular clusters that might have been acquired by the LMC from other Local Group members, and also close to the values reported by Rubele et al. (2012) in the oldest age bin. We computed IRA models for a grid of the initial gas mass $M_{\text{gas}}$ from $2 \times 10^7$ to $1.2 \times 10^{10} M_{\odot}$ with a step of $10^8 M_{\odot}$, and a grid of the galactic wind coefficient $\lambda$ from 0 to 9 with a step of 0.1. In parallel, we estimated the evolution of $M_{\text{gas}}$ in time by integrating Equation (2) in the IRA framework. We repeated the calculation for $R$ and $\chi^2$ values for the Salpeter and Kroupa/Chabrier IMFs. Then we compared the predicted chemical enrichment history to the AMR for LMC star clusters, which we presented earlier by interpolating it at the moments of time corresponding to the ages of our star clusters in our sample and then calculating the $\chi^2$ using the statistical uncertainties of star cluster metallicities from the full spectrum fitting procedure. We used the stellar population parameters derived from the fitting of their spectra against solar-scaled SSP models.

For the Salpeter IMF, the minimum of $\chi^2$ with the star cluster AMR is reached at the following values of the parameters of our model: $M_{\text{gas}}(0) = 4.8 \times 10^9 M_{\odot}$, $\lambda = 3.1$. This $\chi^2$ value is typical for star-forming galaxies (0.0–5.8; Spitoni et al. 2017). It is worth mentioning, that the model by Spitoni et al. (2017) included the gas infall as a fundamental assumption under which the $\chi^2$ values were calculated. Our IRA model does not include the effect of infall for the reasons stated above, which should lower the expected $\chi^2$ value because no external gas supply is happening. Nevertheless, this solution yields the present-day LMC gas mass $M_{\text{gas}}(\text{now}) = 3.7 \times 10^8 M_{\odot}$ that is some 25% lower than the total LMC HI mass $4.8 \pm 0.2 \times 10^8 M_{\odot}$ (Staveley-Smith et al. 2003) or 30%–40% lower than the total mass ($5.8 \pm 0.5$) estimated assuming the molecular to atomic gas mass ratio of $0.2 \pm 0.1$ in late-type galaxies (Young & Knezek 1989). Despite this discrepancy, keeping in mind the simplicity of our chemical evolution model, the agreement is good.

The chemical evolution with the Chabrier IMF goes in a slightly different direction because of the higher return fraction $R$ and metal yield per generation $\chi^2$, therefore in order to fit the observed AMR of star clusters, we need a model with higher values of $M_{\text{gas}}(0) = 7.9 \times 10^9 M_{\odot}$ and $\lambda = 5.7$. This $\chi^2$ value is also typical for star-forming galaxies estimated for the Chabrier IMF (0.6–10.2). The present-day gas mass $M_{\text{gas}}(\text{now}) = 6.2 \times 10^8 M_{\odot}$ agrees with the observed total gas mass in the LMC within uncertainties. In Figure 4, we plot the best-fitting IRA chemical enrichment history model for the Chabrier IMF and the AMR for LMC star clusters.

Finally, we ran the IRS+SN Ia models for $\alpha$-elements and iron using the same input SFH data from Harris & Zaritsky (2009) on similar grids of $\lambda$ and $M_{\text{gas}}(0)$ and assuming the initial abundances corresponding to $[Z/\text{H}]_0 = -1.42$ dex and $[\alpha/\text{Fe}]_0 = +0.28$ dex. In a similar fashion to the approach described above for the IRA models, we computed $\chi^2$ statistics but this time considering $[\alpha/\text{H}]$ and $[\text{Fe}/\text{H}]$ as independent measurements for every LMC cluster. We excluded the two objects from the sample, NGC 1850 and NGC 2159, where the derived $[\alpha/\text{Fe}]$ values hit the upper limit covered by the models ($+0.4$ dex). Only one cluster, [SL63]353 has the solar value of $\alpha$-enhancement and we kept it in the sample.

In Figure 5, we see a satisfactory agreement between the model predictions and observed values of chemical abundances. Because of the recent active star formation in the LMC, we observe $\alpha$-enhanced young and intermediate age (40–400 Myr) star clusters. The best-fitting values for the free parameters, $M_{\text{gas}}(0) = 1.01 \times 10^{10} M_{\odot}$ and $\lambda = 6.0$ yields the underestimated total present-day gas mass of about $8 \times 10^8 M_{\odot}$. This might be caused by the biases of $[Z/\text{H}]$ and/or $[\alpha/\text{Fe}]$ estimates in the young and intermediate age regime, which is expected to improve when new generations of $\alpha$-enhanced stellar population models become available.

Using star clusters as tracers of chemical evolution of individual elements has an interesting advantage over studies of chemical abundances of individual elements in Milky Way stars in the solar neighborhood by means of high-resolution spectroscopy. Star clusters allow easy and reliable age estimates, while individual stars outside clusters are much harder to date. Therefore, when dealing with star clusters, one can use direct model predictions of $[\text{X}/\text{H}](t)$, while for individual stars, in order to remove the age determination uncertainty, it is generally required to operate in the $[\text{X}/\text{Fe}]$
versus [Fe/H] parameter space (see, e.g., Matteucci & Recchi 2001; Matteucci et al. 2009; Vincenzo et al. 2017). As one can see in Figure 5, [α/H] and [Fe/H] curves cross twice in the case of LMC: the evolution starts from [α/Fe] = +0.28 dex, then the enhancement decreases to [α/Fe] = −0.05 dex around 6 Gyr ago, then it again starts to grow and reaches [α/Fe] = +0.25 dex for young and intermediate age star clusters. Therefore, in the case of galaxies with more complex evolutionary histories (e.g., a low-metallicity starburst induced by an accretion of a gas-rich dwarf satellite), the diagnostics in the [X/Fe] versus [Fe/H] parameter space might introduce uncertainties and degeneracies. It may be possible to have several generations of stars of roughly the same [Fe/H] but formed at different epochs and, thus, having different α-element abundances. The information on stellar age that is easily accessible in the case of star clusters will break this degeneracy. In cases of “simple” galaxies, like LMC or SMC, a rich data set that will include several dozens of star clusters covering the entire age range will provide a unique opportunity to study the chemical evolution in great detail and, perhaps, will allow us to distinguish between different progenitors of Type Ia SNe because they will affect the metal enrichment in slightly different ways. It is worth mentioning that the LMC contains only one star cluster in the “age gap” between 2.5 and 10 Gyr.

5.3. Applications of Our Approach to Galaxies beyond the Local Group

Using a very limited data set containing only 15 star clusters in the LMC, we have demonstrated that our simple approach to study the chemical evolution of galaxies works remarkably well. Not only did we reproduced the observed AMR from an observed SFH, but we also obtained the present-day total gas content of the LMC that completely agrees with HI observations. With our current 15 clusters, we cannot recover the SFH from the AMR directly using Equation (5) because it is not sampled well enough in age in order to reliably estimate the derivative of the AMR Z(t). In the near future, we plan to increase our sample of young and intermediate age star clusters in the LMC and then we will be able to directly compare the global SFH derived from star clusters with CMD-based measurements.

The analysis of the stellar population of star clusters using integrated light spectra can probe star formation histories beyond the immediate vicinity of the Milky Way. A 50,000 M☉ 10 Gyr old star cluster with the Mv ≈ −5.8 mag (assuming Kroupa IMF) will have a visual magnitude mv = 22.0 mag at a distance of 3.5 Mpc, which makes it an easy target for a 6–8 m class telescope in 1–2 hr of integration. Younger or more massive clusters will be even brighter: a 1 Gyr old star cluster will have a similar brightness being 10 times less massive. Using multi-object spectroscopy, 100–300 such clusters can be observed in a single exposure, providing an opportunity to study the star formation history of galaxies like Messier 81 or Messier 83 in unprecedented detail. The recent SFH (t < 2 Gyr) can be characterized using more massive (50,000–100,000 M☉) clusters out to 10 Mpc with similar investments in the telescope time. No other techniques can be used to recover the SFH with comparable quality at such distances.

This approach has some caveats. (i) Massive spiral galaxies have star formation and metal enrichment histories that can substantially vary across the galactic disk/bar, e.g., causing radial metallicity gradients. Moreover, the radial migration causes the mixing of stellar population, which would translate into spread of the cluster AMR at a given age/radius. Sampling a galaxy cluster population at different radii, however, will allow us to estimate variations of the star formation and chemical enrichment histories along the radius. (ii) Mergers with gas-rich dwarf satellites provide supplies of metal-poor gas, which would affect the cluster AMR by abruptly decreasing the metallicity of newly formed star clusters—the detection of this feature in the AMR can provide a strong argument for past merger events, but the chemical evolution equations have to be modified accordingly in order to estimate the star formation history.

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