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ELEMENTAL ABUNDANCES IN RGB STARS OF THE LARGE MAGELLANIC CLOUD

M. Van der Swaelmen[1], V. Hill[1] and F. Primas[2]

Abstract. The present work is based on a high-resolution spectroscopic survey of two LMC fields located in the bar and the inner disc, observed at ESO/VLT with FLAMES/GIRAFFE. Three setups were used to cover about 1000 Å and enable the measurement of numerous elemental abundances. We confront the results in the inner disc and bar fields and discuss their similarities/differences in the light of the origin of the LMC bar. Both fields show that the LMC has a SFH slower than the MW, resulting in a chemical evolution dominated by SNIa and metal-poor AGB winds. Chemical anomalies for Eu, Ba and La are detected in the most metal-rich field stars, as it has been before in LMC GC stars, and cannot be explained by canonical nucleosynthesis processes.

Keywords: Abundances, Magellanic Clouds, Galaxy: evolution

1 Introduction

Despite decades of intensive observational and theoretical works, we are still far from a complete and clear understanding of our close universe, the Milky Way (MW) and its neighbours. Among the satellites of the MW, the Small and the Large Magellanic Clouds (SMC, LMC) are of particular interest since it is the closest example of galaxies in gravitational (systems: SMC+LMC, SMC+LMC+MW) and chemical interactions (Magellanic Bridge between the clouds, made of stars and gas). Therefore it is a unique laboratory to study the effect of gravitational tides and matter exchange on the chemical evolution and the star formation history of a galaxy. The LMC is an almost face-on, gas-rich galaxy with regions of active stellar formation (distance: 50 kpc (Alves 2004), mass: $10^{10}M_\odot$ (van der Marel et al. 2002)). The young population exhibits an irregular morphology, likely the stigmata of the very recent interaction with the SMC. The old and intermediate-age population are located within a regular disc and a prominent and luminous off-centre bar. The morphology of the LMC is not well understood and, in particular, we still do not know the origin and the true nature of the bar-like structure: is it a dynamical bar driven by disc instabilities like the one found at the centre of the MW or is it a stellar overdensity? was the formation of the bar driven by a close encounter with the SMC (Subramaniam & Subramanian 2009; Zaritsky 2004; Bekki 2009)? Smecker-Hane et al. (2002) have derived from deep colour-magnitude diagram (CMD) the star formation histories for field stars located in the LMC bar and the inner part of the LMC disc. They found that the LMC field stars do no exhibit an age gap, unlike the stars of the LMC globular clusters (GC), hence their usefulness to probe the epoch 3 to 13 Gyr (see also Cole et al. 2005). Moreover they show that the star formation history (SFH) of the bar and the inner disc were similar at old epochs (between 7 and 14 Gyr); but while the SFH of the inner disc has remained rather constant, the bar has experienced a dramatic increase of its SFH, 4 to 6 Gyr ago. Interestingly, it corresponds to the epoch of the formation of the bar. This work aims at investigating the chemical history of and the relation between the bar and the disc via a detailed chemical analysis of Red Giant Branch (RGB) stars located in the bar and in the inner disc.

[1] Laboratoire Lagrange, UMR 7293, Université de Nice Sophia-Antipolis, Observatoire de la Côte d'Azur, BP4229, 06304, Nice Cedex 4, France
[2] European Southern Observatory, Karl Schwarzschild Str. 2, 85748 Garching b. München, Germany

2 Data and methods

Cole et al. (2005) observed 373 RGB stars in the field of the LMC bar and derived radial velocities and metallicities for their stars. We used their metallicity distribution to select 113 RGB stars belonging to the LMC bar, taking care to sample each metallicity bin from $[Fe/H]_{CaT} = -1.69$ dex to $[Fe/H]_{CaT} = 0.14$ dex. We obtained high resolution spectra ($R \sim 20,000$) of our 113 stars at VLT/ESO with the FLAMES/GIRAFFE multifibre spectrograph (Pasquini et al. 2002). In order to measure numerous elemental abundances, we used three setups HR11, HR13 and HR14, covering a total of ≈ 1000 Å. The spectra thus cover lines belonging to the α- (Ca, O, Mg, Ti, Si), iron-peak (Sc, V, Cr, Co, Ni, Cu), s-process and r-process elements (Ba, La, Zr, Y, Eu). This complements a similar dataset in the LMC disc, located at ~ 2 kpc from the centre (Pompéia et al. 2008). We carried out the data reduction with the help of the ESO GIRAFFE pipeline (built upon the Geneva Giraffe pipeline described in Blecha et al. 2000), part of the *esorex* framework. The reduction steps include the dark current correction, wavelength calibration (using a Th-Ar lamp), spectrum extraction and flat fielding. As the pipeline does not support sky subtraction nor radial velocity correction, we carried out those operations separately. Once all exposures of the same star were sky-subtracted and in the same frame, we averaged them with k-σ clipping rejection (over the fluxes at a given wavelength) to clean for cosmic rays and increase the signal-to-noise ratio (SNR). We ended with a typical final SNR of around 25 for HR11, 40 for HR13 and 48 for HR14.

3 Stellar parameters and abundances

To derive the stellar parameters of our LMC stars (the temperature T_{phot}, the gravity $\log g$, the overall metallicity [M/H] and the microturbulent velocity ξ_{micro}), we used a combination of photometric and spectroscopic methods. For our stars, visible (V and I magnitude, from the OGLE catalogue Udalski et al. 1997, 2000; Szymanski 2005) and infrared (J, H and K magnitude, from the 2MASS catalogue Skrutskie et al. 2006) photometry is available. We used the Ramírez & Meléndez (2005a,b) photometric calibrations for giants to compute four scales of photometric temperatures, using four de-reddened colour indices. The surface gravities $\log g$ were derived using the Bayesian estimation algorithm of stellar parameters of da Silva et al. (2006), based on evolutionary tracks. The overall metallicity and the microturbulent velocity were derived simultaneously by requiring that different FeI lines of different equivalent widths (EW) give the same iron abundance [FeI/H].

We used the two traditional methods to measure the chemical abundances: EW and fitting of absorption profiles. For the first method, we used the automated tool DAOSPEC (Stetson & Pancino 2008) to measure the EW and we converted them into abundances with *turbospectrum* (*turbospectrum* is described in Alvarez & Plez 1998 and improved along the years by B. Plez) together with the grid of OSMARCS spherical model atmospheres (Gustafsson et al. 2008). The spectrum syntheses, computed by *turbospectrum*, are in spherical geometry, with LTE spherical radiative transfer. The second method, the fitting of absorption profile, consists in computing a grid of theoretical spectra by varying the abundance of an element and comparing them to an observed absorption line of this specific element. We used a χ^2 minimisation to find the best fitting, which gives the value of the elemental abundance. We re-analysed (stellar parameters+abundances) the sample of LMC disc stars of (Pompéia et al. 2008), in exactly the same fashion to insure a homogeneous comparison of bar and disc fields and we used Arcturus as a reference star to determine the zero-point of our chemical abundances scale. The abundances we derived for Arcturus are in good agreement with the literature (Ramírez & Allende Prieto 2011; Worley et al. 2009). The tests we performed on noisy Arcturus spectra (at the same SNR level of GIRAFFE spectra) allowed us to derive typical error bars for our LMC stars.

4 Results

In this section, we present the results for some key elements: O, Mg, Si (α elements), Ba, La and Eu (s- and r-elements). Figure 1 (left panel) shows the [α/Fe] trend (mean of O, Mg and Si ratios) for the LMC bar and disc stars, as well as that of the MW. α elements are thought to be produced in massive stars interiors dying as type II supernovae (SNII) while iron is mainly produced in type Ia supernovae (SNIa). Therefore, the ratio [α/Fe] can track the epoch when SNIa start to dominate the chemical enrichment of a galactic environment. Metal-poor ($[Fe/H] \leq -1.1$ dex) LMC stars possess alpha abundances similar to those of MW halo stars, but we note that stars with higher metallicity have α ratios smaller than that of the MW. Unlike for the MW, we do not see a clearly defined plateau in the LMC trends in the low metallicity regime; but despite the paucity of data, we can suspect that the transition between the SNe II-dominated regime and SNe Ia-dominated regime seems to occur at a lower metallicity in the LMC bar than in the MW. This tells us that the LMC bar has experienced a chemical enrichment different from that of the Milky Way, with a slower SFH. The LMC bar and disc do not exhibit strong differences, though a larger scatter of [α/Fe] is observed for the bar for -1 dex $\leq$ [Fe/H] ≤ -0.5 dex. Remarkably, we found an excellent agreement between globular clusters (Mucciarelli et al. 2008, 2010) and field stars at both low and high metallicities (we do not have stars at the metallicity of the metal-poor GC but the level of their [α/Fe] is compatible with that of the most metal-poor field stars).

Figure 1 (right panel) shows the [Eu/Fe] trend for the LMC bar and disc stars, and the MW stellar populations. According to chemical composition of the Sun, europium is thought to be an element mainly produced by the r-process occurring during SNII explosive nucleosynthesis. Therefore, we expect it to follow a pattern similar to that of the [α/Fe]. At low metallicity, we have enhanced [Eu/Fe] for the LMC as expected, but we have also enhanced ratios at high metallicities. For the low metallicity regime, the abundance ratios of the LMC and the MW overlap, while for [Fe/H] ≥ -1 dex the LMC trend is above the MW's. This chemical anomaly cannot be understood in the canonical nucleosynthesis picture recalled before. To explain it, we may invoke another source of Eu. Asymptotic Giant Branch (AGB) stars may be candidates: they are the place of s-process nucleosynthesis, and so, can produce Eu. Nevertheless, it is not clear whether the production of Eu would be efficient enough to reach such high [Eu/Fe]. Here again, we found an excellent agreement between LMC field and LMC GC stars. It is worth mentioning that this enhancement at high metallicity is not an artifact of our abundance analysis since we found the expected value for Arcturus.

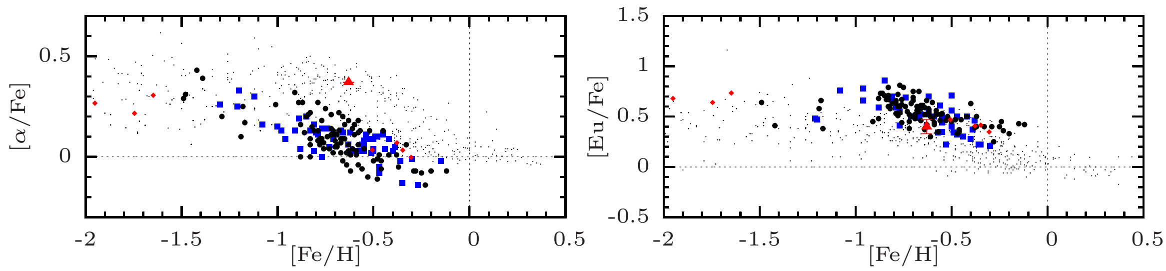

Fig. 1. Left: [α/Fe] vs [Fe/H]. **Right:** [Eu/Fe] vs [Fe/H]. Legend for both: black dots: LMC bar (this study), blue squares: LMC disc (re-analysis of Pompéia et al. 2008), red diamonds: LMC GC (Mucciarelli et al. 2008, 2010), red triangle: Arcturus (reference star of this study), black tiny points: MW thin and thick disc (Bensby et al. 2005; Reddy et al. 2003, 2006), MW halo (Fulbright 2000; Stephens & Boesgaard 2002).

Figure 2 (left panel) shows the [Ba, La/Eu] trend. Ba and La are s- and r-elements, produced by AGB and SNII; the [Ba, La/Eu] allows to track the relative importance of SNII and AGB in the chemical enrichment. For a pure r-process, Arlandini et al. (1999) predict [Ba/Eu] $= -0.67$ dex. This value is reached for the metal-poor stars of LMC GC. The s-process starts to dominate from a metallicity of about -1 dex in the LMC bar and disc. Moreover, the [Ba/Eu] and [La/Eu] increase is steeper in the LMC than in the MW: it proves that AGB played a stronger role in the chemical enrichment of the LMC, compared to the MW. Figure 2 (right panel) shows the [Ba/Fe] trend (similar pattern is observed for [La/Fe]). A very steep increase of LMC [Ba/Fe] is observed from [Fe/H] ≈ -1.1 dex, while the LMC and MW ratios overlap for lower metallicities. This dramatic increase is not expected in the canonical nucleosynthesis picture and clearly contrasts with what is observed for the MW. This is another chemical anomaly, shared by the dwarf galaxies like Fornax or Sagittarius, two galaxies also dominated by intermediate-age stellar populations. We may explain this with very efficient AGB winds.

5 Discussion and conclusion

We performed a detailed chemical analysis of LMC field stars located in the bar and the disc and compared it to LMC GC stars and MW field stars. We found that the LMC had a chemical history different from that of the MW: the SFH of the LMC was slower and the chemical enrichment was dominated by SNIa (α trend) and AGB winds ([Ba, La/Eu] vs [Fe/H]). We found chemical anomalies for Ba, La and Eu compared to the Galactic trends. Those trends are the results of a chemical enrichment occurring in a metal-poor environment and cannot be completely apprehended in the current chemical evolution scheme: they recall the importance of studying external galaxies that followed different enrichment path in order to perfect our understanding of the

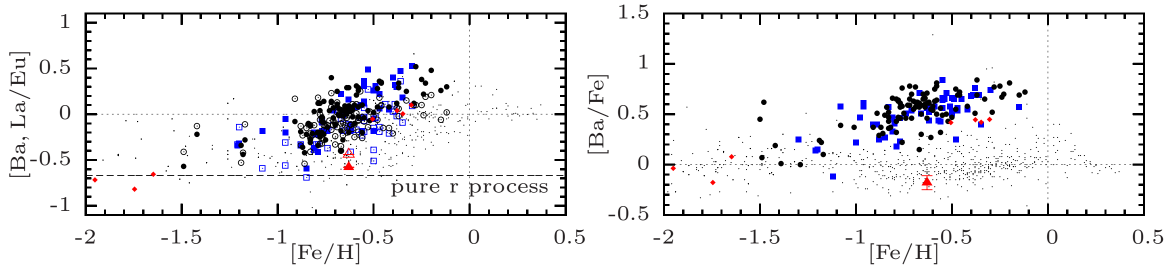

Fig. 2. Left: [Ba/Eu] vs [Fe/H] (filled symbols), [La/Eu] vs [Fe/H] (empty symbols). **Right:** [Ba, La/Fe] vs [Fe/H]. Same legend as Figure 1.

details of galactic chemical evolution. The two LMC fields do not exhibit strong differences in their abundance patterns, except for the α. For the α elements, a larger scatter is observed for the bar stars in the metallicity range $[-1, -0.5]$ and maybe related to the formation of the bar: the start of a new episode of star formation will increase the number of massive stars, in which the α elements originate, and therefore will enrich the interstellar medium with freshly formed α. If this scatter is true, then it is a proof that the bar is a stellar overdensity and not a dynamical structure. We found similar abundance ratios for the LMC field and GC populations, which is rather intriguing since we should expect a different chemical history (no GC formation between $\sim$ 10 and 3 Gyr ago, while the field star formation has never stopped).

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