A relic from a past merger event in the Large Magellanic Cloud

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According to the standard cosmological scenario, the large galaxies that we observe today have reached their current mass via mergers with smaller galaxy satellites. This hierarchical process is expected to take place on smaller scales for the satellites themselves, which should build up from the accretion of smaller building blocks. The best chance we have to test this prediction is by looking at the most massive satellite of the Milky Way: the Large Magellanic Cloud (LMC). Smaller galaxies have been revealed to orbit around the LMC, but so far the only evidence for mutual interactions is related to the orbital interplay with the nearby Small Magellanic Cloud, which is the most massive LMC satellite. In this work, we report the likely discovery of a past merger event that the LMC experienced with a galaxy with a low star formation efficiency and likely a stellar mass similar to those of dwarf spheroidal galaxies. This former LMC satellite has now completely dissolved, depositing the old globular cluster NGC 2005 as part of its debris. This globular cluster, the only surviving witness of this ancient merger event, is recognizable through its peculiar chemical composition. This discovery is observational evidence that the process of hierarchical assembly has worked also in shaping our closest satellites.

The Large Magellanic Cloud (LMC) is the largest satellite orbiting the Milky Way, with a total mass of $\sim 1 - 2.5 \times 10^{11} M_\odot$ (refs. 10) and a stellar mass of $\sim 3 \times 10^9 M_\odot$ (ref. 7). A satellite this massive is expected to host its own system of satellites. According to models of galaxy formation in the lambda cold dark matter theory, the number of these satellites is in the range of 4–40 (refs. 10), the most massive of them dominating the mass budget (with a mass ratio compared to the LMC of $\sim 0.1$). The Small Magellanic Cloud (SMC), with a total mass of $\sim 2 \times 10^9 M_\odot$ (ref. 20), matches this prediction well. The precise measurement of their proper motion allowed for the first time a reasonably sound reconstruction of the orbital history of the system. According to the most recent analyses the Magellanic Clouds may have become bound to each other ~3 Gyr ago and had their last close encounter ~150 Myr ago.

The other satellites of the LMC should be much smaller, with total masses from $\sim 10^9 M_\odot$ down to values typical of the ultra-faint dwarf galaxies (UFDs) that are the lowest-luminosity, oldest, most dark-matter-dominated galaxies known so far. Attempts to determine which of the known UFDs were accreted by the Milky Way together with the LMC hugely benefited from the advent of the second data release of the Gaia mission, as this enabled the possible determination of their three-dimensional kinematics.

Dynamical integration of the UFDs orbits led to the conclusion that four to six of them (depending on the details of the modelling) are indeed current satellites of the LMC. However, nothing is known about the past population of LMC satellites that may be already disrupted within the host galaxy halo. So far, the only traces of accretion of matter from another galaxy by the LMC are associated with the complex interaction with the SMC.

Chemical tagging is one of the few techniques that allow us to trace completely dissolved satellites, also in the absence of any kinematically or spatially coherent relic, identifying stars and clusters that were lost long ago by means of their anomalous chemical composition, in contrast with the environment in which they live nowadays. However, the power of the technique can be strongly hampered by the fact that spotting chemically anomalous stars in a given galaxy requires high-resolution spectroscopy for large samples, as well as extremely homogeneous chemical abundance analysis, as subtle differences in the assumptions on, for example, astrophysical parameters can wipe out (or spuriously introduce) the small abundance differences we are looking for. With the aim of digging into the past merging history of the largest Milky Way satellite, here we attempt to overcome these problems by using old globular clusters (GCs) as tracers and by deriving chemical abundances from high-resolution spectra with a strictly homogeneous analysis.

In this respect, GCs are a class of tracers that have been proven to be particularly effective in reconstructing the merger history of a galaxy such as the Milky Way or M31. This is because even a very low-mass, low-surface-brightness dwarf galaxy, which may be dissolved by the tidal force of the main galaxy at its first perigalactic passage, may host a dense stellar cluster able to survive in the same tidal field for many billions of years. Such a cluster will keep a record of the characteristics of the environment in which it was born. In particular, the chemical abundance pattern of its stars may be quite different from that of stars and clusters born in the main galaxy, due to the large differences in the star formation and chemical evolution between the hosting system and the progenitor system. We analysed optical, high-resolution spectra of red giant stars in 11 old LMC GCs and in a reference sample of 15 Milky Way GCs. These two data sets were analysed with the same methodology (that is, atomic data, solar reference abundances, model atmospheres and temperature scale), thus removing any possible systematic error between the abundances of the two families of clusters.

For 13 species, we derived the chemical abundance ratios as indicators of different production mechanisms and stellar progenitors. The LMC GCs draw well-defined sequences of each abundance.

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ratio as a function of [Fe/H] that are distinct, in most cases, from those defined by the Milky Way GCs, reflecting the different chemical evolution histories of the two galaxies\(^{30}\). Among the LMC GCs, the metal-poor cluster NGC 2005 ([Fe/H] = −1.75 ± 0.04 dex) is distinguished as a clear outlier. NGC 2005 is a relatively massive GC \((M \approx 2 \times 3 \times 10^9 M_\odot)\)\(^{31}\) located at ≈0.23 kpc from the centre of the LMC. It exhibits abundance ratios that are systematically lower (in most cases at a level >3σ) than those measured in the LMC GCs with similar metallicities (Fig. 1) for almost all the species, including elements (Si, Ca, Sc, Ti, V, Mn, Ni, Cu, Zn, Ba, La and Eu) forming from different nucleosynthesis channels (that is, from explosive and thermonuclear supernovae, hypernovae, and slow and rapid neutron-capture processes). The five LMC GCs with [Fe/H] comparable to that of NGC 2005 (−1.75 < [Fe/H] < −1.69 dex) have abundance ratios very similar to each other, constituting a homogeneous group of clusters sharing the same chemistry. This demonstrates that these GCs formed in environments that have experienced a similar chemical enrichment history, likely the LMC itself. However, the strong chemical differences between NGC 2005 and this group of clusters is indicative of a completely different chemical enrichment path. This reveals that NGC 2005 cannot have formed in the same environment as the rest of the LMC clusters at that metallicity, but that it was instead born in a system that converted its gas into stars at a slower pace.

To determine the characteristics of the most likely progenitor of NGC 2005, we computed chemical evolution models for different galactic environments. The analysed data allowed us to produce models and calibrate them with respect to the Milky Way-like and LMC-like environments, and for systems evolving with less efficient star formations (Methods). We purposely focused on elements that have highly accurate stellar yields and that are representative of different nucleosynthesis channels (Table 1 and Fig. 2): Si and Ca (mainly produced through α-capture processes), Cu (mainly produced through slow neutron-capture processes) and Zn (mainly produced in hypernovae high-energy explosions).

Our models for the LMC reproduce reasonably well the data for all the LMC GCs except NGC 2005, which is always under-abundant at fixed metallicity. We run several chemical evolutionary models for the putative NGC 2005 parent galaxy. The ones that best fit the peculiar chemistry of NGC 2005 unavoidably require systems evolving with very low star formation efficiency, for example, models of dwarf spheroidal galaxies\(^{32}\). Although it is very difficult to set precise limits to the mass of the progenitor based on the chemistry alone, the very low [Zn/Fe] abundance measured in NGC 2005 with respect to the other Magellanic Cloud GCs suggests that it formed from a gas that was enriched poorly by massive stars. In fact, in the framework of our models, Zn comes mainly from low-metallicity, metal-poor stellar systems leading to a lower upper mass limit for the galaxy-wide initial mass function (IMF). Indeed, if we consider star formation rates lower than ≈5 \times 10^4 M_\odot yr\(^{-1}\) and an upper mass limit of 40 M_\odot for the galaxy-wide IMF, a remarkably good fit of the observed [Zn/Fe] ratio for NGC 2005 is obtained. All the other abundance ratios are fitted well within their errors under the same premises. These models for NGC 2005 are to be compared with the model for the LMC GCs that assumes a star formation rate on the order of 1–1.5 \times 10^5 M_\odot yr\(^{-1}\) during the early LMC evolution and a galaxy-wide IMF upper mass limit of 100 M_\odot.

The radial velocity of NGC 2005 is similar to that of other clusters in its surroundings, and therefore any (possible) strong anomaly due to its association with an accreted satellite has been washed out after many orbits within the gravitational potential of the LMC. However, its peculiar chemical composition suggests that this cluster originated in a galaxy that formed its stars with a much less efficient star formation compared to the LMC. This evidence suggests a low-mass galaxy progenitor as massive as the dwarf spheroidal galaxies currently orbiting the Milky Way or even lighter and characterized by low star formation rates\(^{32}\). NGC 2005 is the surviving witness of the ancient merger event that led to the dissolution of its parent galaxy into the LMC, the only known case so far to be identified by its chemical fingerprints in the realm of dwarf galaxies. Our findings thus support the predictions on the self-similar nature of the process of galaxy formation by the standard cosmology on our
Table 1 | Chemical abundances of Fe, Si, Ca, Cu and Zn for LMC and Milky Way globular clusters

| Cluster    | [Fe/H] (dex) | [Si/Fe] (dex) | [Ca/Fe] (dex) | [Cu/Fe] (dex) | [Zn/Fe] (dex) |
|------------|--------------|---------------|---------------|---------------|---------------|
| NGC 1466   | −1.55 ± 0.02 (0.05) | +0.33 ± 0.01 (0.02) | +0.08 ± 0.03 (0.08) | −0.70 ± 0.11 (0.15) | —             |
| NGC 1754   | −1.45 ± 0.03 (0.05) | +0.16 ± 0.02 (0.04) | +0.10 ± 0.02 (0.04) | −0.64 ± 0.07 (0.15) | −0.11 ± 0.04 (0.10) |
| NGC 1786   | −1.72 ± 0.02 (0.04) | +0.29 ± 0.05 (0.09) | +0.19 ± 0.03 (0.06) | −0.59 ± 0.05 (0.09) | −0.24 ± 0.05 (0.10) |
| NGC 1835   | −1.69 ± 0.01 (0.01) | +0.32 ± 0.05 (0.10) | +0.14 ± 0.02 (0.04) | −0.79 ± 0.08 (0.15) | —             |
| NGC 1898   | −1.15 ± 0.02 (0.05) | +0.12 ± 0.01 (0.03) | +0.00 ± 0.03 (0.07) | −0.72 ± 0.05 (0.10) | −0.21 ± 0.15 (0.23) |
| NGC 1916   | −1.75 ± 0.03 (0.05) | +0.39 ± 0.01 (0.02) | +0.11 ± 0.03 (0.04) | −0.58 ± 0.05 (0.09) | −0.10 ± 0.08 (0.11) |
| NGC 2005   | −1.75 ± 0.04 (0.06) | +0.08 ± 0.01 (0.01) | +0.01 ± 0.03 (0.04) | −1.10 ± 0.14 (—) | −0.80 ± 0.20 (—) |
| NGC 2019   | −1.41 ± 0.05 (0.08) | +0.21 ± 0.01 (0.01) | +0.09 ± 0.04 (0.08) | −0.58 ± 0.03 (0.05) | −0.20 ± 0.20 (—) |
| NGC 2210   | −1.74 ± 0.02 (0.06) | +0.27 ± 0.03 (0.07) | +0.14 ± 0.01 (0.03) | −0.75 ± 0.03 (0.08) | −0.12 ± 0.07 (0.15) |
| NGC 2257   | −1.73 ± 0.02 (0.04) | +0.33 ± 0.02 (0.04) | +0.16 ± 0.03 (0.05) | −0.71 ± 0.01 (0.01) | −0.07 ± 0.13 (0.21) |
| HODGE 11   | −2.03 ± 0.04 (0.09) | +0.42 ± 0.08 (—) | +0.16 ± 0.01 (0.02) | −0.57 ± 0.02 (0.03) | +0.00 ± 0.05 (0.10) |
| NGC 104    | −0.75 ± 0.01 (0.03) | +0.28 ± 0.01 (0.03) | +0.21 ± 0.02 (0.07) | — | −0.03 ± 0.03 (0.09) |
| NGC 288    | −1.24 ± 0.01 (0.04) | +0.33 ± 0.01 (0.03) | +0.27 ± 0.01 (0.03) | −0.24 ± 0.02 (0.05) | −0.18 ± 0.04 (0.14) |
| NGC 1851   | −1.13 ± 0.01 (0.04) | +0.25 ± 0.01 (0.03) | +0.18 ± 0.01 (0.05) | — | +0.05 ± 0.03 (0.14) |
| NGC 1904   | −1.52 ± 0.01 (0.03) | +0.26 ± 0.01 (0.02) | +0.19 ± 0.01 (0.02) | −0.71 ± 0.01 (0.04) | −0.04 ± 0.02 (0.06) |
| NGC 2808   | −1.06 ± 0.02 (0.07) | +0.26 ± 0.01 (0.04) | +0.21 ± 0.01 (0.02) | −0.37 ± 0.04 (0.12) | +0.04 ± 0.05 (0.17) |
| NGC 4590   | −2.28 ± 0.01 (0.05) | +0.35 ± 0.04 (0.06) | +0.23 ± 0.01 (0.02) | −0.68 ± 0.02 (0.04) | +0.07 ± 0.03 (0.10) |
| NGC 5634   | −1.80 ± 0.02 (0.05) | +0.29 ± 0.01 (0.04) | +0.22 ± 0.01 (0.03) | −0.52 ± 0.04 (0.11) | −0.03 ± 0.05 (0.15) |
| NGC 5824   | −1.92 ± 0.02 (0.04) | +0.36 ± 0.03 (0.08) | +0.24 ± 0.01 (0.02) | −0.60 ± 0.04 (0.11) | −0.07 ± 0.03 (0.07) |
| NGC 5904   | −1.22 ± 0.01 (0.03) | +0.29 ± 0.01 (0.03) | +0.21 ± 0.01 (0.03) | −0.47 ± 0.02 (0.06) | −0.02 ± 0.02 (0.09) |
| NGC 6093   | −1.76 ± 0.01 (0.03) | +0.35 ± 0.01 (0.04) | +0.28 ± 0.01 (0.03) | −0.58 ± 0.01 (0.03) | −0.08 ± 0.02 (0.07) |
| NGC 6397   | −2.01 ± 0.01 (0.03) | +0.37 ± 0.02 (0.08) | +0.26 ± 0.01 (0.03) | −0.73 ± 0.04 (0.09) | +0.00 ± 0.02 (0.06) |
| NGC 6752   | −1.98 ± 0.01 (0.03) | +0.29 ± 0.01 (0.03) | +0.28 ± 0.01 (0.02) | −0.47 ± 0.01 (0.06) | −0.02 ± 0.03 (0.12) |
| NGC 6809   | −1.73 ± 0.01 (0.03) | +0.26 ± 0.01 (0.04) | +0.25 ± 0.01 (0.03) | −0.66 ± 0.01 (0.05) | −0.06 ± 0.01 (0.05) |
| NGC 7078   | −2.42 ± 0.02 (0.07) | +0.47 ± 0.04 (0.09) | +0.28 ± 0.01 (0.02) | −0.66 ± 0.03 (0.07) | −0.09 ± 0.03 (0.12) |
| NGC 7099   | −2.31 ± 0.01 (0.05) | +0.45 ± 0.01 (0.02) | +0.28 ± 0.01 (0.03) | −0.73 ± 0.03 (0.10) | +0.08 ± 0.02 (0.08) |

Average weighted abundance ratios for [Fe/H], [Si/Fe], [Ca/Fe], [Cu/Fe] and [Zn/Fe] for the analysed LMC and Milky Way old GCs with the corresponding standard error and, in brackets, the dispersion of the weighted mean.

Fig. 2 | Chemical abundances of the LMC and Milky Way clusters. Behaviour of the [Si/Fe], [Ca/Fe], [Cu/Fe] and [Zn/Fe] abundance ratios as a function of [Fe/H] for the LMC clusters (green triangles) and the Milky Way clusters (grey squares). The accreted LMC cluster NGC 2005 is highlighted as a red triangle. Solar neighbourhood stars (small grey circles) are shown as reference. Error bars are computed as the mean value of the uncertainties in individual stars and displayed only for the LMC clusters (Methods). Chemical evolution models are superimposed for the Milky Way Halo (grey line), LMC (green line) and two stellar systems with low star formation efficiencies, namely 0.075 Gyr−1 over 1 Gyr (red solid line) and 0.15 Gyr−1 over 0.5 Gyr (red dashed line) (resulting in a star formation rate of <0.5–10−4 M⊙yr−1).
closest satellite, and opens a new way to investigate the assembly history of galaxies beyond the Milky Way via the chemical tagging of their GC systems.

Methods

Spectroscopic data sets. The LMC hosts the largest system of old GCs among the Milky Way satellites, including 13 GCs
denoted with ages comparable to those of the Milky Way GCs. Chemical abundances of old LMC GCs based on high-resolution spectra of individual giant stars are available for about half of the entire population. These analyses are based on different methods and assumptions, comparing the emission among the LMC clusters and between Milky Way and LMC clusters to be affected by different systemsatics (that is, atomic data, solar reference abundances, model atmospheres, temperature scale and so on). To highlight similarities and differences in chemical composition among giant stars in LMC and Milky Way GCs, we homogeneously analysed two samples of high-resolution, optical spectra.

LMC GCs data set. This sample includes 11 out of 15 old LMC clusters; four of them (NGC 1466, NGC 1754, NGC 1835 and NGC 1916) have never been analysed using high-resolution spectroscopy of individual stars (Supplementary Table 1). The data set is composed of proprietary and archival data collected with the spectrographs FLAMES and UVES at the Very Large Telescope of the European Southern Observatory and with the spectrograph MIKE at the Magellan Telescope. Signal-to-noise ratios per pixel range from about 30–40 to 100. For nine GCs, observations with the fibre-fed spectrograph FLAMES in the UVES+GIRAFFE combined mode were secured. For all these clusters, spectra with the Red Arm 580 UVES set-up were obtained with a spectral resolution of 47,000 and a spectral coverage between about 4,800 Å and 6,800 Å. For clusters NGC 1466, NGC 1786, NGC 1898 and NGC 2257 only, a few additional cluster stars were observed with the MIKE spectrograph and the Red Arm 580 UVES set-up. In addition, 2M1514 (2.5 arcmin of diameter) of the LMC clusters and the physical size of the magnetic buttons sustaining the fibres prevent the allocation of more than ~10 FLAMES fibres on the cluster area in the same pointing. The adopted GIRAFFE/MEDUSA set-ups are HR11 (5,597–5,840 Å and resolution of 39,500) and HR13 (6,120–6,405 Å and resolution of 26,400).

For two clusters observed with FLAMES (namely NGC 2210 and NGC 2257), additional archival data acquired with the slit spectrograph UVES are available. These observations were secured with the Red Arm 580 UVES set-up, adopting slits between 1 arcsec and 1.2 arcsec and providing spectral resolutions between 38,000 and 45,000.

Finally, we analysed MIKE spectra for four GCs (NGC 1898, NGC 2005, NGC 2019 and Hodge 11), two of which were also observed with FLAMES. The MIKE spectra were acquired with a slit of 1 arcsec, corresponding to a spectral resolution of 19,000, and with a spectral range between 4,500 Å and 7,250 Å. Among the LMC GCs with metallicity between ~1.75 dex and ~1.69 dex (Fig. 1), NGC 2005 is the only one for which the spectra were obtained with the spectrograph MIKE, whereas the other five GCs were observed with the spectrograph UVES. Below we discuss the consistency between the abundances obtained from UVES and MIKE spectra.

Note that the previous analysis of NGC 2005 (ref. 13) provides abundances consistent with ours, but the lack of other LMC GCs with comparable metallicity in that sample did not allow us to highlight the peculiarity of the cluster.

Milky Way GCs data set. A sample of giant stars in 15 Milky Way GCs was collected from archival data (Supplementary Table 2). The clusters were selected to cover the entire range of metallicity of the Galactic halo or disk GC systems ([Fe/H] between −2.5 dex and −1.69 dex). All the spectra were obtained with the multi-object spectrograph UVES-FLAMES adopting the same set-up used for the LMC clusters. Signal-to-noise ratios per pixel range from about 70–80 to 150.

Chemical analysis tools. The chemical abundances of Fe, Si, Ca, Ti and Ni were derived by comparing the measured equivalent widths with those predicted by the code DAOSPEC
denoted with ages comparable to those of the Milky Way GCs. Chemical abundances of old LMC GCs based on high-resolution spectra of individual giant stars are available for about half of the entire population. These analyses are based on different methods and assumptions, comparing the emission among the LMC clusters and between Milky Way and LMC clusters to be affected by different systemsatics (that is, atomic data, solar reference abundances, model atmospheres, temperature scale and so on). To highlight similarities and differences in chemical composition among giant stars in LMC and Milky Way GCs, we homogeneously analysed two samples of high-resolution, optical spectra.

Model atmospheres for each star were calculated with the code ATLAS9 (2016 version) under the assumptions of plane-parallel geometry, hydrostatic and radiative equilibrium, and local thermodynamic equilibrium for all the species. For all the stars the model atmospheres were computed over an a-enhanced chemical mixture, except for the stars of NGC 2005 and NGC 1898, for which solar-scaled model atmospheres were used in accordance with the derived [α/Fe] abundance ratios. Still, we also verified that the use of a-enhanced model atmospheres in these two cases changes the measured abundance ratios only slightly. This means, in particular, that the observed differences between NGC 2005 and the other LMC GCs of similar metallicity cannot be reconciled by the adoption of different model atmospheres.

Note that we exclude from this discussion the light elements Na, O, Mg and Al because they are involved in the chemical anomalies due to the self-enrichment processes that characterized the early stage of life of the clusters. Therefore, these elements cannot be used as tracers of the formation of the parent galaxy. Indeed, we found evidence of star-to-star variations for the light elements Na, O, Mg and Al in the target clusters, as expected considering their mass and number. However, a null spread was found for all the elements discussed in this work, so any effect due to the internal evolution of the individual clusters does not affect our conclusions.

Determination of the atmospheric parameters. The effective temperature (T\text{eff}) is the most crucial atmospheric parameter in the determination of chemical abundances. Temperatures can be inferred from suitable calibrations of broadband colours or by requiring that no trend exist between the true and apparent potential. The two methods can often provide discrepant results. In particular, the two approaches agree with each other for metallicities higher than ~1.5 dex, whereas the spectroscopic T\text{eff} values are overly low and underestimated (down to about 300 K) for [Fe/H] < −1.5 dex because of the inadequacies in the modelling of one-dimensional local thermodynamic equilibrium (LTE) plus non-solar-size giants. This is particularly true for some clusters with spectroscopic T\text{eff} leads to underestimation of the abundances for metal-poor stars.

Due to the composite nature of the LMC data set, homogeneous photometric information is not available for all the targets: for the proprietary data, near-infrared JKs photometry is available, whereas for the archival data, optical ground-based or space-telescope photometry is in hand but in different photometric filters. Thanks to the high spectral resolution, the high number of lines and the good (or high) signal-to-noise ratio of the LMC spectra, T\text{eff} can be derived spectroscopically with high precision for all the targets. The discrepancy between spectroscopic and photometric T\text{eff} for clusters with [Fe/H] > −1.5 dex increases with decreasing signal-to-noise ratio, and we normalize this effect to put all the T\text{eff} on the same (unbiased) scale. The spectroscopic T\text{eff} for clusters with [Fe/H] < −1.5 dex were corrected according to the spectroscopic [Fe/H] to “put them onto a photometric scale”, whereas spectroscopic T\text{eff} for clusters with higher metallicity did not need any correction. A pure spectroscopic T\text{eff} scale leads to systematically lower abundances for metal-poor stars.

However, as one of the key results presented here is based on the comparison of chemical abundances among LMC and Milky Way clusters, it is particularly important to recall that T\text{eff} values for all the cluster stars are calculated using.

The surface gravities (expressed as log g) were estimated by assuming for each cluster the T\text{eff}–log g relation that is suitable for the red giant branch and that is derived from a theoretical isochrone with an age of 13 Gyr and metallicity and [α/Fe] from our chemical analysis. Because log g values were derived according to the T\text{eff} and metallicity of each star, the procedure to obtain this parameter is iterative. This approach avoids the uncertainties in log g arising from colour excess and distance modulus of each individual cluster. The assumption of a different age is not critical: a change of 1 Gyr (which can be considered as a reasonable uncertainty in the ages of the target clusters) implies a variation of 0.01 in log g, with a negligible impact on the derived abundances.

Microturbulent velocities are derived by requiring no trend between abundances of the iron lines and their strength. The stellar parameters for all the target stars are listed in Supplementary Table 3.

The two observed stars in NGC 2005 have atmospheric parameters comparable to those of the other stars in LMC clusters with similar metallicities, as expected because all the target stars belong to the brightest portion of the clusters' red giant branches. For stars with higher metallicity, the discrepancy between spectroscopic and photometric T\text{eff} for clusters with [Fe/H] > −1.5 dex increases with decreasing signal-to-noise ratio, and we normalize this effect to put all the T\text{eff} on the same (unbiased) scale. The spectroscopic T\text{eff} for clusters with [Fe/H] < −1.5 dex were corrected according to the spectroscopic [Fe/H] to “put them onto a photometric scale”, whereas spectroscopic T\text{eff} for clusters with higher metallicity did not need any correction. A pure spectroscopic T\text{eff} scale leads to systematically lower abundances for metal-poor stars. When the adopted procedure for the T\text{eff} of all the stars are on the same scale. However, for the Milky Way GCs homogeneous photometry is available and T\text{eff} values were derived from the (V − Ks)–T\text{eff} calibration.
Uranium and thorium abundances, as well as the derived age of the cluster, are in agreement with the expected values for a Population II object. The lack of significant differences in the abundance ratios of different elements suggests that the clusters are chemically similar.

Comparison between abundances from UVES and MIKE spectra: NGC 2005 is the only LMC GC among those shown in Fig. 1 that was observed with MIKE. First, we considered two clusters, namely Hodge 11 and NGC 1898, for which both UVES and MIKE spectra are available (although no stars were observed simultaneously with both instruments). Supplementary Fig. 3 shows the differences between the average abundances derived from UVES and MIKE spectra for these two clusters. No systematic difference exists for any of the measured elemental abundances, which demonstrates that the two instruments provide abundances that are fully compatible within the uncertainties. Similar to Fig. 1, Supplementary Fig. 3 compares the average abundance ratios measured in two clusters with similar [Fe/H] but observed with the two spectrographs, namely NGC 1754 (observed with UVES) and NGC 1909 (observed with MIKE). Also for this pair of clusters, no significant differences are found and the abundance ratios of NGC 2005 are not systematically lower than those measured in NGC 1754.

As an additional check, we repeated the analysis of the UVES spectra of Hodge 11 and NGC 1898 by applying a smoothing filter to reproduce the spectral resolution of the MIKE spectra and by sampling the spectra to the pixel size of MIKE. This set of MIKE-like spectra allows us to estimate whether some instrumental characteristics of the spectrophotograph (that is, the dispersion, efficiency, and pixel size) can induce systematic differences in the derived abundances, in particular for clusters with a low metallicity. Averaged over 200 stars, the abundance ratios from the two instruments are consistently lower by ~0.05 ± 0.02 dex (σ = 0.05 dex) due to small changes in the stellar parameters themselves. In both cases, the characteristics of the MIKE spectra induce a very small decrease in the iron abundances, whereas the differences cancel out for the [X/Fe] abundance ratios.

Finally, we refer to the recent analysis of the Galactic benchmark star HD 20 using both UVES and MIKE spectra. Thanks to the very high signal-to-noise ratios of the spectra of this bright star (>400 for UVES and >1,000 for MIKE), this comparison is adequate to highlight intrinsic differences solely due to the instruments (and not induced by the noise). The agreement between the abundances of Ti, Fe, and Nd (the species with the largest number of available lines in the analysis) derived from the same lines and measured with UVES and MIKE is found to be excellent, thus excluding again significant systematics between the two instruments.

All these checks demonstrate that the abundances derived from MIKE and UVES are fully consistent with each other within the uncertainties and that the low abundance ratios measured in NGC 2005 are not instrument artefacts.

Uncertainties in the chemical abundances: The total uncertainty associated with a given abundance (in the form of [X/H]) in individual stars is obtained by taking into account internal errors (mainly related to the measurement methodology) and errors arising from the atmospheric parameters. Differences in abundance ratios [X/Fe] = [X/H] − [Fe/H] is considered, the uncertainties arising from atmospheric parameters partially cancel out because metallic lines of different species but the same ionization stage respond in a similar way to variations in these parameters. The uncertainty in [Fe/H] is obtained by summing in quadrature the internal error and the variations in the Fe abundance due to errors in atmospheric parameters.

For each cluster, mean abundance ratios (and the corresponding standard errors) were computed by averaging the abundances of the member stars weighted by the uncertainty (as described above). As the formal standard errors on the weighted mean were in many cases exceedingly small (on the order of ~0.02–0.03 dex) due to the small number of stars per cluster (two to three), we decided to take the average error on individual measurements as a conservative estimate of the uncertainty on the mean abundance.

**Internal errors.** Internal errors in [X/H] were estimated considering the line-to-line dispersion of the abundance mean divided by the root mean square of the number of lines. The dispersion of the mean reflects a combination of uncertainties in the measurement and atomic data.

When only one line was available, we considered as internal error the abundance variation due to the uncertainty in the measurement process. For species for which equivalent width was measured, we transformed abundance into abundance error associated with the Gaussian fit used to measure the equivalent width. For species measured from the spectral synthesis, we performed Monte Carlo simulations of the fitting procedure. For each star, a sample of artificial spectra was generated by re-sampling the best-fit synthetic spectrum to the instrumental pixel size and by injecting Poissonian noise to reproduce the measured signal-to-noise ratio. This sample of artificial spectra was analysed with the same approach adopted for the real spectra. The dispersion of the derived abundance distribution was adopted as the 1σ uncertainty.

**Parameter errors.** Abundance errors due to uncertainties in the atmospheric parameters were estimated by re-computing abundances while varying the parameters by their uncertainties. The uncertainties in spectrophotometric Teff were estimated by applying a jackknife bootstrapping technique, leading to errors from ~50 K up to ~100 K depending mainly on the signal-to-noise ratio of the spectrum. For the clusters with [Fe/H] < −1.5 dex for which the correction to the photometric scale was applied, we added in quadrature also the 1σ dispersion (36 K) associated with the calibration itself. Temperatures were varied by the corresponding errors, gravities were modified by propagating the errors in the T_eff on the adopted T_eff-log g relation, and the microturbulent velocities were re-computed adopting the new T_eff and log g. This approach allowed us to take into account the covariance existing between T_eff and log g (ref. 13) due to the physical relation existing between these two parameters, and between T_eff and microturbulent velocity due to the correlation between line strength and excitation potential.

**Systematic errors.** Chemical abundances can be affected by several sources of systematics, mainly the accuracy of the adopted atomic data, the solar reference abundances used, the model atmospheres used (and their physical assumptions), the zero-point of the T_eff scale used and the method to infer stellar parameters. The chemical analysis of the two data sets discussed in this work (LMC and Milky Way GCs) was performed using the same approach in terms of these assumptions, to erase the main systematics and compare directly the abundances of the two families of clusters. Therefore, any possible source of systematic error arising from the analysis affects in the same way both the data sets, making the comparison between LMC and Milky Way clusters more accurate and robust.

**Chemical evolution models.** The trends of the abundance ratios of different chemical elements as a function of time (as traced by metallicity) in a given stellar system can be used to infer the structure formation timescale as well as the role of any gas inflow/outflow and the shape of the prevailing IMF. However, to do so, one needs to work out the proper chemical evolution model that is tailored to the specific object under scrutiny.

The chemical evolution model for the Milky Way adopted in this paper is described extensively in previous papers14,15. It assumes that the inner Galactic halo forms at early times from the accretion of unprocessed gas that triggers a very efficient star formation, on the order of ~10 M_☉ yr^-1 on a billion-year timescale. The Galactic disk forms later at a slower pace, but because our Milky Way GC data trace only the first ~1 Gyr of Galactic evolution, in the following we omit all the details regarding the formation of the disk component (the interested reader is referred to the original papers). As we will see in the following, it is very important to calibrate the main ingredients of the chemical evolution model against a valid reference template; the Milky Way provides indeed a very good anchor.
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The models for the LMC and the putative NGC 2005 parent galaxy rest on previous work for dwarf Galactic satellites\(^5\). As for the LMC, we implement in the model the global star formation history derived from observational pointers independent from chemical indicators (that is, long-period variable star counts that agree with those of previous studies\(^6\)). According to the adopted star formation history, most LMC stars (about 75% of the total stellar population) form during the first ~3 Gyr of evolution. The star formation rate peaks at ~1.5 \(M_\odot\) yr\(^{-1}\) during the first 1.5 Gyr of evolution, and steadily declines afterwards. As for the dwarf NGC 2005 progenitor, there are no independent indicators of star formation history that can be accessed, and hence we assume a star formation burst forming \(2 \times 10^6\) M\(_\odot\) of stars in either 0.5 Gyr or 1 Gyr. The star formation of the NGC 2005 progenitor galaxy is found to proceed at a much slower pace than that of the LMC, namely \(2 \times 5 \times 10^5\) M\(_\odot\) yr\(^{-1}\) (with the highest values corresponding to the shortest-duration burst).

In all models, cold gas of primordial chemical composition is accreted at an exponentially decreasing rate:

\[
\frac{dM_{\text{gas}}(t)}{dt} \propto e^{-t/\tau},
\]

where \(M_{\text{gas}}(t)\) is the mass accreted at time \(t\) and \(\tau = 1\) Gyr, 0.5 Gyr and 0.005 Gyr are the e-folding times for the Milky Way, LMC and UFD NGC 2005 progenitor, respectively. We note that this smooth infall law produces results that are in qualitative agreement with those obtained by adopting more complex accretion histories from cosmological simulations\(^7\).

The star formation rate is implemented according to the Kennicutt–Schmidt law\(^8\). In the model for the Milky Way, it is

\[
\Psi = \psi_{\text{gas}}(t) \propto M_{\text{gas}}(t),
\]

while for dwarfs, galaxies, it is

\[
\Psi = \psi_{\text{gas}}(t) \propto M_{\text{gas}}(t),
\]

where \(M_{\text{gas}}(t)\) is the gas mass at a given time and \(\kappa = 1.5\). In the models for dwarf galaxies, the star formation rate is implemented using a grid of IMF\(^9\).

Nucleosynthesis prescriptions. The most important ingredients of chemical evolution models are the stellar yields, namely the amounts of different chemical elements that stars produce and eject into the interstellar medium at their deaths. The chemical evolution models adopted in this study track the evolution of the abundances of several elements from hydrogen to europium, allowing us to study the evolution of elements that are produced by various nucleosynthetic processes in stars of different masses and initial chemical composition. The instantaneous recycling approximation is relaxed, that is, we consider in detail the stellar lifetimes. In this way, different chemical elements are correctly restored to the interstellar medium at different times, according to the lifetimes of their stellar progenitors.

We adopt grids of stellar yields calibrated against the Milky Way data; in particular, with the adopted prescriptions for single low-mass and intermediate-mass stars\(^10\), massive stars\(^11\) and type Ia supernovae\(^12\) (thermonuclear explosions of white dwarfs in binary systems\(^13\)), we are able to reproduce very well the average trends of the abundance ratios of several elements, including [Si/Fe], [Ca/Fe], [Zn/Fe] and [Cu/Fe], as a function of [Fe/H] in the Galactic halo\(^14\). Regarding the high-mass stars, we use a mixture of ‘normal’ core-collapse supernovae, which explode releasing energies on the order of \(10^{51}\) ergs, and hypernovae, which are characterized by much larger explosion energies. By considering hypernova explosions it is possible to explain the run of [Zn/Fe] over [Fe/H] for [Fe/H] \(>\) −1 dex. To best fit the Milky Way GC data, we further adopt zero-point shifts of −0.2 dex for both [Si/Fe] and [Zn/Fe] (well inside the range allowed by theoretical uncertainties and observational systematics that may affect the ratios).

The same stellar nucleosynthesis prescriptions (and zero-point shifts) are then adopted in the models for the LMC and the NGC 2005 parent galaxy. Interestingly, it is found that the best agreement between model predictions and relevant data is obtained with a galaxy-wide IMF that varies in qualitative agreement with the predictions of the integrated galactic IMF theory\(^15\).

Do observed counterparts of the progenitor of NGC 2005 exist? The chemical abundance patterns measured in NGC 2005 and in the other LMC GCs demonstrate that the former originated in an environment characterized by a less efficient star formation history than that of the LMC. This is typical of dwarf spheroidal (dSph) satellites of the Milky Way\(^16\). Thus, it is natural to search among them when looking for an existing galaxy similar to the putative progenitor of NGC 2005.

There are only two dSphs currently orbiting the Milky Way that were able to form globular clusters: Sagittarius and Fornax. However, the abundance pattern of the Sagittarius dSph is very similar to that of the LMC\(^17\), and as such it is not compatible with the chemical composition of NGC 2005. By contrast, Fornax seems to fit all the properties of the progenitor galaxy of NGC 2005. In fact, the abundance pattern of NGC 2005 is remarkably similar to that of Fornax stars of the same metallicity. As we show in Supplementary Fig. 5, two other dSph galaxies, Draco and Ursa Minor\(^18\), provide a good chemical match when compared to NGC 2005, but they have a stellar mass comparable to that of NGC 2005 itself \((\sim 3 \times 10^6\) M\(_\odot\)\), ref. \(^9\)). Instead, Fornax has a stellar mass large enough \((\sim 2 \times 10^9\) M\(_\odot\)\), ref. \(^9\)) to host a population of five old GCs, four of them being in the same mass range as NGC 2005 \((\sim 1 \times 10^5\) M\(_\odot\)\), ref. \(^9\)). In general, dwarf galaxies with mass comparable to that of Fornax typically host between zero and six globular clusters\(^9\). The mass ratio between Fornax and LMC is \(\sim 2\times10^{-2}\), for both stellar and total (dynamical) mass. Therefore, the merging of a progenitor galaxy of NGC 2005 similar to the Fornax dSph with the LMC would classify as a minor merger, with negligible consequences on the structure of the LMC and negligible probability of leaving a long-lived relic, except for a dense cluster with chemical composition not compatible with being born in the LMC.

We conclude that the properties of the hypothesized progenitor galaxy of NGC 2005, now dissolved into the LMC, are fully compatible with those of well-known existing galaxies, the Fornax dSph providing the most suitable local example.

Data availability

Most of the data used in this work are available in the public archive of the European Southern Observatory (http://archive.eso.org/eso/eso_archive_main.html and http://archive.eso.org/wdb/wdb/adp/phase3_main/form.html). All the data are available from the corresponding author upon reasonable request.

Code availability

The codes used for the chemical analysis are publicly available: GALA (http://www.cosmic-lab.eu/gala/gala.php), ATLAS9 (https://wwwuser.oats.inaf.it/castelli/sources/atlas9codes.html), SYNTHE (https://wwwuser.oats.inaf.it/castelli/sources/synt/he/), and DAOSEARCH (http://www.cadc-IIa.hia-hr.cra.gc.ca/en/community/STETSON/daospec/). We opt not to make the code used for the chemical evolution modelling publicly available because it is an important asset in the researchers’ tool kits.

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**Author contributions**

A. Mucciarelli designed the study, coordinated the work and performed the data analysis. D.M. led the scientific interpretation. A. Minelli contributed to the spectroscopic analysis. D.R. computed the chemical evolution models and contributed to the scientific interpretation. M.B. contributed to the scientific interpretation and to the writing. F.R.F., F.M. and L.O. contributed to the presentation of the paper. All the authors critically contributed to the work presented here.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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