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The Origin of the Large Magellanic Cloud Globular Cluster NGC 2005

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Abstract

The ancient Large Magellanic Cloud (LMC) globular cluster NGC 2005 has recently been reported to have an ex situ origin, thus, setting precedents that the LMC could have partially formed from smaller merged dwarf galaxies. We here provide additional arguments from which we conclude that is also fairly plausible an in situ origin of NGC 2005, based on the abundance spread of a variety of chemical elements measured in dwarf galaxies, their minimum mass in order to form globular clusters, the globular cluster formation imprints kept in their kinematics, and the recent modeling showing that explosions of supernovae are responsible for the observed chemical abundance spread in dwarf galaxies. The present analysis points to the need for further development of numerical simulations and observational indices that can help us to differentiate between two mechanisms of galaxy formation for the LMC; namely, a primordial dwarf or an initial merging event of smaller dwarfs.

Unified Astronomy Thesaurus concepts: Large Magellanic Cloud (903); Globular star clusters (656)

1. Introduction

Mucciarelli et al. (2021) recently reported that the Large Magellanic Cloud (LMC) old globular cluster NGC 2005 is the unique surviving relic of a low star formation efficiency dwarf galaxy that merged into the LMC in the past. The ex situ origin of NGC 2005 was claimed from its deficient abundance of some chemical species—forming from different nucleosynthesis channels—with respect to those of five LMC old globular clusters of similar metallicities ($-1.75 < \mathrm{[Fe/H]}$[7]< -1.69). A Fornax-like progenitor of NGC 2005 was suggested by arguing that such a dwarf spheroidal galaxy matches the peculiar chemical composition of NGC 2005. NGC 2005 is a 13.77 ± 4.90 Gyr old globular cluster (Wagner-Kaiser et al. 2017), with a overall metallicity $\mathrm{[Fe/H]} = -1.75 \pm 0.10$ (Suntzeff et al. 1992; Beasley et al. 2002; Mucciarelli et al. 2010), and a total mass of $\log(M/M_\odot) = 5.49 \pm 0.16$ (Mackey & Gilmore 2003).

While the proposed scenario for the formation of NGC 2005 results plausible in the context of the hierarchical assembly of galaxies according to the standard cosmological model (e.g., Moore et al. 1999), there are a couple of inferences made by Mucciarelli et al. (2021) in order to conclude on the ex situ origin of NGC 2005 that may allow another interpretation.

Precisely, this work aims to introduce them so that they can trigger further analysis. The arguments in this work imply that the Mucciarelli et al. (2021)' results would not be conclusive but greatly enrich the debate on the NGC 2005 origin. The possible in situ or ex situ formation of NGC 2005 points to the need for a better understanding of galaxy formation. Particularly, whether the LMC partly formed through the accretion of smaller galactic systems or from a purely gaseous outside-in formation scenario (Carrera et al. 2011; Piatti & Geisler 2013) is still under debate. Furthermore, the analysis of the origin of NGC 2005 can shed light on some distinctive features that an LMC-like galaxy formed as a primordial dwarf should have with respect to an LMC-like galaxy partially built from the accretion and merging of smaller subunits. In this context, it is worth studying whether there is a minimum mass budget to differentiate the above two modes of galaxy formation. As far as we are aware, there are no simulations testing whether it is possible to distinguish both modes of galaxy formation.

In this work, we gathered relevant works available in the literature about mechanisms of nucleosynthesis that take place during the early life of galaxies in order to show that there exists an alternative interpretation for the origin of NGC 2005 to that suggested by Mucciarelli et al. (2021). The present results do not discredit the possible ex situ origin of this ancient LMC globular cluster but pose the issue in a broader context. These results point to the need for detailed simulations exploring the space of similarities and differences of galaxy formation processes for different galaxy masses. In order to provide a conclusive answer about the origin of NGC 2005, further spectroscopic observation campaigns of LMC field stars are needed, as well as globular cluster formation modeling in the context of galaxy formation with higher resolution and precision of the orbital integration. Nevertheless, the present somehow qualitative arguments shed light on a more comprehensive analysis of the origin of NGC 2005.

2. Analysis

The first piece of analysis that led us to support a possible in situ origin of NGC 2005 is a rigorous statistical treatment of the abundances used by Mucciarelli et al. (2021) to conclude on the ex situ origin. Mucciarelli et al. (2021) showed that 13 chemical abundances measured in NGC 2005 are

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[7] $\mathrm{[A/B]} = \log_{10}(N_\mathrm{A}/N_\mathrm{B}) - \log_{10}(N_\mathrm{A}/N_\mathrm{B})_\odot$, where N_A and N_B are the number densities of elements A and B, respectively.

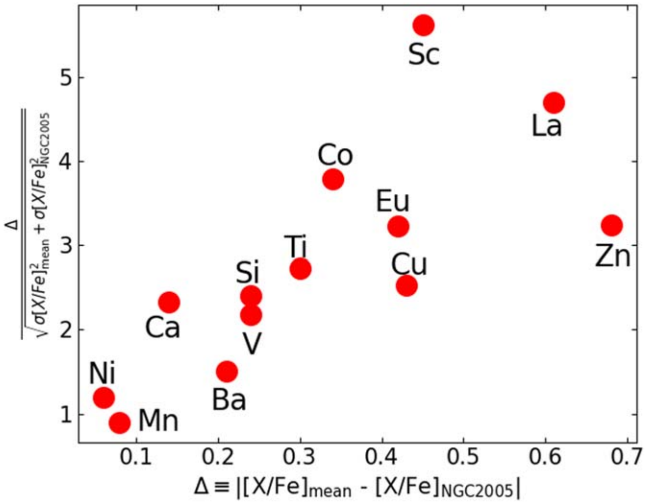

Figure 1. Diagnostic diagram built to illustrate the quality of the measurements of different chemical abundances ratios in Mucciarelli et al. (2021).

Table 1
[X/Fe] Values from Mucciarelli et al. (2021)

[X/Fe]	NGC 2005	⟨LMC⟩	Δ	σ	η
Si	0.08 ± 0.09	0.32 ± 0.05	0.24	0.10	2.40
Ca	0.01 ± 0.05	0.15 ± 0.03	0.14	0.06	2.33
Sc	−0.39 ± 0.07	0.06 ± 0.04	0.45	0.08	5.62
Ti	−0.06 ± 0.10	0.24 ± 0.04	0.30	0.11	2.73
V	−0.34 ± 0.10	−0.10 ± 0.04	0.24	0.11	2.18
Mn	−0.61 ± 0.09	−0.53 ± 0.02	0.08	0.09	0.89
Co	−0.29 ± 0.08	0.05 ± 0.03	0.34	0.09	3.78
Ni	−0.07 ± 0.05	−0.01 ± 0.02	0.06	0.05	1.20
Cu	−1.10 ± 0.14	−0.67 ± 0.09	0.43	0.17	2.53
Zn	−0.80 ± 0.20	−0.12 ± 0.07	0.68	0.21	3.24
Ba	0.09 ± 0.09	0.30 ± 0.11	0.21	0.14	1.50
La	−0.22 ± 0.07	0.39 ± 0.11	0.61	0.13	4.69
Eu	0.28 ± 0.06	0.70 ± 0.11	0.42	0.13	3.23

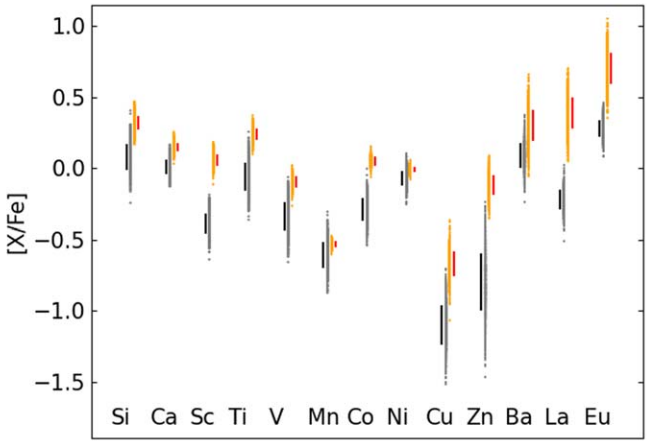

Figure 2. [X/Fe] ratios derived by Mucciarelli et al. (2021; see Table 1) for NGC 2005 (gray points) and the other five LMC globular clusters (orange dots), respectively. Each [X/Fe] ratio is represented by 1000 points following a Gaussian distribution. For the seek of the reader we included the corresponding 1σ error bars represented by black and red segments, respectively.

systematically lower than the values for five LMC globular clusters (NGC 1786, 1835, 1916, 2210, 2257) with metallicities ([Fe/H]) similar to that of NGC 2005. However, if the uncertainties are taken into account, those differences change as a function of the chemical element.

Figure 1 shows a more comprehensive picture in this respect. In order to build it, we first computed the difference (Δ, absolute value) in abundance ratios between the mean abundance ratios for the aforementioned five LMC globular clusters ($[X/Fe]_{mean}$) and that of NGC 2005 ($[X/Fe]_{NGC\,2005}$), using values kindly provided by A. Mucciarelli. We note that Mucciarelli et al. (2021) only included the values for [Si/Fe], [Ca/Fe], [Cu/Fe], and [Zn/Fe] in their Table 1, because they focused on elements with predictions of stellar yields that are representative of different nucleosynthesis channels. Particularly, they rely their analysis on the [Zn/Fe] ratio, for which they found the largest mean difference (0.68 dex).

For completeness purposes, we included in Table 1 all the [X/Fe] ratios used in that work. Then, we added in quadrature their respective uncertainties $\sigma[X/Fe]_{mean}$ and $\sigma[X/Fe]_{NGC\,2005}$, and calculated $\eta = \Delta / \sqrt{\sigma[X/Fe]^2_{mean} + \sigma[X/Fe]^2_{NGC\,2005}}$, which we plotted in Figure 1 as a function of Δ, and included them in Table 1. As can be seen, [Sc/Fe], [Co/Fe], [La/Fe], [Zn/Fe], and [Eu/Fe] ratios show differences Δ larger than 3 times the sum of their respective uncertainties, which means these chemical element abundances in NGC 2005 and the other five globular clusters are different. We note that η values < 3 do not warrant a real difference so that the conclusion on distinctive chemical patterns between NGC 2005 and the other five LMC globular clusters for [Si/Fe], [Ca/Fe], and several other chemical abundances should be taken with caution. Therefore, if only some chemical elements show real abundance differences between NGC 2005 and five LMC globular clusters, both ex situ and in situ formation scenarios are feasible.

Figure 1 shows that the 13 different chemical abundances in NGC 2005 and the other five LMC clusters would not seem to be equally distinguishable, and those differences are only exhibited for a couple of the 13 chemical species analyzed by Mucciarelli et al. (2021). The unavoidable question arises: what does the difference in these few chemical species mean? Mucciarelli et al. (2021) argued that NGC 2005 formed in a Fornax-like dwarf galaxy that was accreted onto the LMC. According to them, the Fornax-like dwarf galaxy would have left negligible consequences in the LMC in the form of relics (galaxy mass ratio < 0.01), except only NGC 2005. The different chemical abundance features would be a signature that NGC 2005 formed ex situ the LMC.

However, the global chemical pattern of NGC 2005 is not statistically peculiar compared to that of the LMC. In order to quantify this, we figured out that we measured 1000 times the abundance of each of the 13 elements of Table 1 in NGC 2005 and in the other five LMC globular clusters; then we gathered the 1000 measurements of each element, and looked at the obtained distributions. We assume, as expected, that this experimental exercise will provide normal distribution functions, so that we represented them by generating 1000 points following a Gaussian distribution for each element in NGC 2005 and in the other five LMC globular clusters. In order to do this, we used the *random.normal* library within Numpy[8] using the mean values and errors quoted in Table 1 as *loc* and *scale* parameter values, respectively (see Figure 2). Note that most of the points are concentrated within 1σ. As can be seen, there are some elements in NGC 2005 and in the five

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[8] https://www.numpy.org/

Table 2
Mean [X/Fe] Values in dex at the NGC 2005 Metallicity ([Fe/H] = −1.75 ± 0.10 dex) for the Observed [X/Fe] vs. [Fe/H] Distributions (References in Parenthesis)

X	LMC	Fornax	Sagittarius	Sextants	Sculptor	Ursa Minor
Si	0.17 ± 0.03 (1)		0.17 ± 0.04 (1)			
Ca	0.12 ± 0.05 (1)		0.02 ± 0.07 (1)			
Sc		−0.07 ± 0.15 (2)	−0.10 ± 0.02 (2)	−0.28 ± 0.17 (2)	0.00 ± 0.10 (2)	−0.30 ± 0.10 (2)
Ti		0.25 ± 0.10 (2)	0.25 ± 0.10 (2)	0.25 ± 0.15 (2)	0.20 ± 0.25 (2)	0.25 ± 0.15 (2)
V						
Mn		−0.60 ± 0.10 (2)	−0.75 ± 0.15 (2)	−0.55 ± 0.10 (2)	−0.35 ± 0.10 (2)	−0.70 ± 0.05 (2)
Co						
Ni	−0.03 ± 0.03 (1)	0.00 ± 0.05 (2)	−0.03 ± 0.04 (1) −0.05 ± 0.06 (2)	0.00 ± 0.10 (2)	−0.10 ± 0.13 (2)	−0.10 ± 0.07 (2)
Cu						
Zn			−0.03 ± 0.12 (2)		−0.25 ± 0.20 (2)	−0.20 ± 0.19 (2)
Ba		−0.10 ± 0.07 (2)	0.01 ± 0.04 (2)	0.00 ± 0.20 (2)	−0.10 ± 0.20 (2)	−0.05 ± 0.15 (2)
La						
Eu			0.50 ± 0.05 (2)	0.55 ± 0.05 (2)	0.45 ± 0.04 (2)	0.50 ± 0.04 (2)

References. (1) Hasselquist et al. (2021); (2) Reichert et al. (2020).

LMC globular clusters whose point distributions totally overlap (Mn, Ni); other elements with a partial overlap (e.g., Ca, V, Ba), and a few ones which look different (Sc, La). The total overlap of the point distributions for some chemical elements means that any possible measure of that element in NGC 2005 can also be obtained for the other five LMC globular clusters, or role reversal. A similar reasoning can be used for those elements with a partial or null overlap, respectively. We note that the comparison of these distributions for each element in NGC 2005 and in the five LMC globular clusters is more meaningful than the use of the respective η values (see Table 1), although the latter has the advantage of providing a quantitative measure.

If we considered altogether the 13 element distributions of NGC 2005 and compared it with that of the five LMC globular clusters, we would obtain a measure of the level of similitude between them. We then considered the 13 chemical elements together using the 26,000 points of Figure 2; most of the points distributed within 1σ as provided by the normal distribution law. We built two tables, one for NGC 2005 and another for the five LMC globular clusters containing the respective 13,000 generated previously. Then we statistically estimated the similarity between these two tables—in a scale from 0 to 1, where 0 means totally different and 1 means totally equals—between the 13 chemical abundances in NGC 2005 (gray points in Figure 2) and the LMC (orange points in Figure 2) using different statistical methods; namely, Jaccard similarity (0.47); cosine distance (0.59); Sørensen–Dice statistic (0.64); Levenshtein, Hamming, Jaro, and Jaro–Winkler distances (0.52); Pearson correlation (0.83); Spearman correlation (0.81). We used Python language v3.8.10,[9] and the following packages: Numpy (Harris et al. 2020) and Scipy (Virtanen et al. 2020).[10] The Appendix shows the Python scripts used in order to applied the aforementioned statistics. The resulting similarities between both samples are given within parenthesis above, following the name of the respective method. As can be seen, the general consensus of these statistics is that the chemical abundance pattern of NGC 2005 can partially overlap that of the other five LMC globular clusters.

In order to explore such a possibility more deeply, we first thoroughly searched the literature for [X/Fe] ratios measured in the LMC. Hasselquist et al. (2021) used APOGEE abundances (Majewski et al. 2017) to uncover the chemical abundance patterns in massive Milky Way satellites, including the LMC. They carefully selected galaxy stars based on APOGEE data quality cuts and proper motions. For Si, Ca, and Ni (the only three elements overlapping those in Mucciarelli et al. 2021), they obtained the median abundances and $\pm 1\sigma$ uncertainties listed in Table 2. When comparing these values with those of five LMC globular clusters in Table 1, we found that abundances of Ca and Ni are less than 1η and that of Si is different at 2.5η level. We assume that this result supports that both metallicity scales are similar within the quoted uncertainties, inhomogeneities and/or systematic effects, if present, being smaller. We carried out the same statistical comparison for the values of NGC 2005, and found that abundances of Si and Ni are less than 1η, but Ca is different at 1.6η. They suggest that these chemical elements in NGC 2005 and the LMC have similar abundances.

We also derived the mean values of different chemical elements of dwarf galaxies using the homogenized analysis carried out by Reichert et al. (2020), which is, as far as we are aware, the largest compilation of these quantities for this type of object. The calculated values are listed in Table 2. As can be seen, the abundance of Ni in Sagittarius is in excellent agreement with that of Hasselquist et al. (2021) so that we assumed that both results are in the same scale within the quoted uncertainties.

For the chemical elements showing $\eta > 3$ in Figure 1 (Sc, Zn, and Eu), we repeated the statistical analysis described above by comparing the values in Table 1 with those in Table 2. We found that: (1) the five LMC globular clusters have $\eta < 3$ for Sc, Zn, and Eu with respect to all the dwarfs included in Table 2, with the exception of Sc for Sagittarius and Ursa Minor; (2) NGC 2005 has only Sc abundance different from Sagittarius and Sculptor and Zn abundance different from Sagittarius. The above results show that chemical element abundances that appear to be different in NGC 2005 with respect to LMC are also found to be different, unevenly, between the LMC and other dwarfs, as well as between NGC 2005 and other dwarfs.

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[9] http://www.python.org/

[10] https://scipy.org

Note that we performed this statistical analysis based on chemical abundances derived by the different sets of analysis, i.e., we adopt chemical abundances of Mucciarelli et al. (2021) and Hasselquist et al. (2021). On the other hand, Mucciarelli et al. (2021)' chemical abundances were derived with the same analysis. This difference may introduce additional inhomogeneity and systematic effects.

We would expect that if NGC 2005 formed in a dwarf (Fornax-like) galaxy as proposed by Mucciarelli et al. (2021), their chemical abundance patterns should be similar. Mucciarelli et al. (2021) compiled from the literature abundances for Si, Ca, Cu, and Zn in Fornax (see their supplementary Figure 5). Unfortunately, none of these chemical elements are in the compilation by Reichert et al. (2020) to compare one to the other. Nevertheless, we found that Letarte et al. (2006) measured Ba, Ni, and Ti abundances for Fornax's globular clusters. When extrapolating their [X/Fe] versus [Fe/H] relationships up to $[\mathrm{Fe/H}] = -1.75$, we found that the values for Ba and Ni are similar to those in Table 2, while that for Ti is somewhat different. Therefore, according to the compilation by Reichert et al. (2020), the chemical element abundances in NGC 2005 and Fornax would not seem to be clearly different. We note that it would be worth performing further measurements for more chemical elements in the LMC and other dwarfs to make a more comprehensive comparison with the values obtained for NGC 2005.

3. Discussion

In this study, we explore whether a scenario of in situ formation of NGC 2005 is still allowed. We have shown that most elements show η between 2 and 3, meaning that the probability that the difference in chemical abundance is real is more than 95%, it cannot be considered insignificant. Although this argument would suffer from systematics in different observations, the following discussion of chemo-dynamical properties of NGC 2005 could support the in situ formation scenario.

3.1. Chemical Abundances

The analysis of chemical abundances and their production channels support a possible in situ origin of NGC 2005 even if chemical abundances in NGC 2005 and other LMC's globular clusters are different. Dispersion of the [Zn/Fe] ratios in dwarf galaxies can be caused by the inhomogeneity of the interstellar medium. Hirai et al. (2018) performed a series of chemo-dynamical simulations of dwarf galaxies with the Zn enrichment. Their models assume that Zn is synthesized by electron-capture supernovae and hypernovae, while Fe is from core-collapse supernovae (CCSNe) and type Ia supernovae (SNe Ia). They found that scatters of [Zn/Fe] for $[\mathrm{Fe/H}] > -2.5$ reflect the inhomogeneity of [Zn/Fe] ratios caused by SNe Ia. As shown in their Figures 9 and 11, several stars with $[\mathrm{Fe/H}] > -2$ have $[\mathrm{Zn/Fe}] < -1$. These stars are formed from gas clouds heavily enriched by SNe Ia. These results mean that inhomogeneity caused by SNe Ia could produce low [X/Fe] ratios at relatively high metallicity in dwarf galaxies.

Characteristics of the [X/Fe] in NGC 2005 suggest that it was formed from the gas cloud heavily affected by the ejecta of SNe Ia. Since they synthesize a large amount of Fe, star clusters formed in gas containing ejecta of SNe Ia tend to show low [X/Fe] ratios if these types of supernovae do not largely synthesize the element X. A notable example is [Eu/Fe], which shows $\Delta = 0.42$. Eu is almost entirely synthesized by the r-process, which does not occur in SNe Ia (e.g., Hirai et al. 2015, 2017; Wanajo et al. 2021).

On the other hand, the difference of the [X/Fe] for elements synthesized by SNe Ia tends to be smaller. The double detonation (CSDD-L) model of sub-Chandrasekhar (sub-M_{Ch}) white dwarfs in Lach et al. (2020) synthesizes a large amount of Ca, Mn, and Ni but not much for Co, Cu, and Zn. As shown in Figure 1, Δ of [Ca/Fe], [Mn/Fe], and [Ni/Fe] are relatively small compared to [Co/Fe], [Cu/Fe], and [Zn/Fe]. de los Reyes et al. (2022) found the possible contribution of sub-M_{Ch} SNe Ia to the Sculptor dwarf galaxy from [Mn/Fe] ratios. These results mean that NGC 2005 could be formed from the gas cloud heavily affected by the ejecta of SNe Ia.

The lack of well-mixed gas during the formation of the LMC is documented in the case of Fe by the extensive range of [Fe/H] values of the 15 LMC globular clusters and field stars ($-2.0 \leqslant [\mathrm{Fe/H}] \leqslant -1.3$), all of them formed in a relatively short timescale (Δ(age) ~ 2 Gyr; Piatti & Geisler 2013; Piatti & Mackey 2018; Piatti et al. 2018). Since SNe Ia can be occurred in $\sim$1 Gyr (e.g., Strolger et al. 2020), this timescale is enough to cause SNe Ia in the progenitors of the LMC.

Among the 15 LMC globular clusters, four are metal-poorer than NGC 2005; five are of comparable metallicity, and other five clusters are metal-richer; the whole globular cluster population spanning the [Fe/H] range from -2.0 up to -1.3 (Piatti et al. 2019). If we considered the gas cloud metallicities similarly distributed as the metallicity distribution of the LMC globular clusters (27% metal-poorer, 40% similar, and 33% metal-richer than $[\mathrm{Fe/H}] = -1.75$), then we would find that $\sim$27%, 40% and 33% of the whole gathered gas cloud was metal-poorer, with similar metallicity, and metal-richer than NGC 2005, respectively. The portion of the gas cloud out of which the five globular clusters with metallicities ([Fe/H]) similar to that of NGC 2005 and NGC 2005 itself were formed (40% of the whole gas cloud), should also have the 13 chemical elements analyzed by Mucciarelli et al. (2021) distributed similarly as these six globular clusters, i.e., five sharing a similar pattern and NGC 2005 with a somewhat different one. This means that 1/6 of that gas cloud portion ($40\%/6 \approx 6\%$ of the whole cloud, $\sim 12 \times 10^6 M_\odot$) should have had the chemical abundance pattern found in NGC 2005. This percentage explains that only NGC 2005 has a different chemical abundance from other globular clusters.

This estimate is consistent with the gas mass affected by SNe Ia around dwarf galaxies formed in a cosmological zoom-in simulation. Here we analyze the high-resolution cosmological zoom-in simulation of a Milky-Way-like galaxy in Hirai et al. (2022). This simulation assumes the initial mass function of Chabrier (2003) from 0.1 $M_\odot$ to 100 $M_\odot$ with the nucleosynthesis yields of Nomoto et al. (2013) for CCSNe and the N100 model of Seitenzahl et al. (2013) for SNe Ia. They also adopt a turbulence-induced metal mixing model to compute chemical inhomogeneity correctly (Hirai & Saitoh 2017). We pick up the most massive satellite dwarf galaxy from this simulation with a total stellar mass of $2.1 \times 10^7 M_\odot$ at $z = 0$. Although this simulation does not have LMC-mass systems, this satellite is large enough to discuss the inhomogeneity caused by the SNe Ia. As shown in Reichert et al. (2020), Fornax dwarf spheroidal galaxy, which has a similar mass to this galaxy, also has significant variations of chemical abundances.

We then compute a gas affected by SNe Ia at the lookback time of 11.5 Gyr within the virial radius of the progenitor of this galaxy. By this analysis, we found that $2.6 \times 10^7\,M_\odot$ of gas shows $-2 < [\mathrm{Fe/H}] < -1$ and $[\mathrm{Mg/Fe}] < 0$, which indicates these gas clouds are affected by SNe Ia. The total gas mass of this galaxy in this epoch is $8.8 \times 10^7\,M_\odot$. Since globular clusters are collisional systems, galaxy formation simulations assuming collisionless systems cannot correctly resolve the formation and evolution of globular clusters. Even though there are such numerical difficulties, this result suggests that there is enough gas around a dwarf galaxy to form a globular cluster affected by SNe Ia together with globular clusters with different chemical abundances.

In addition to the analysis of the cosmological zoom-in simulation, we estimate the star formation rates (SFRs) and the number of SNe Ia (N_{Ia}) to explain the chemical abundances obtained by Mucciarelli et al. (2021). Here we estimate the SFRs and N_{Ia} using closed box chemical evolution model (Hirai & Saitoh 2017). In this model, we adopt exponentially declining SFR, i.e., SFRs are proportional to $\exp(-t/\tau)$, where $\tau = 2 \times 10^9$ yr. The initial gas mass of this system is $5 \times 10^9 M_\odot$. These values result in a model consistent with the LMC's metallicity distribution and star formation timescale. Since this model is to roughly estimate SFRs and N_{Ia}, we ignore gaseous inflow and outflow. For nucleosynthesis yields, we adopt Nomoto et al. (2013) for CCSNe and the W7 model of Iwamoto et al. (1999) for SNe Ia. Since this yield set tends to overproduce Si and Ca, the resulting [Si/Fe] and [Ca/Fe] are shifted -0.2 dex (Timmes et al. 1995; Prantzos et al. 2018). This shift is done within the uncertainties of nucleosynthesis.

According to this model, SFRs for $\lesssim$1 Gyr are $1\ M_\odot\ \mathrm{yr}^{-1}$ while they are decreased to $10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$ at 13.8 Gyr. The final stellar mass of this system is $3 \times 10^9 M_\odot$, consistent with the stellar mass of the LMC. Mucciarelli et al. (2021) also estimated that the LMC globular clusters were formed with 1–1.5 $M_\odot\ \mathrm{yr}^{-1}$ in the early phase.

We have counted the number of type Ia supernovae in this model. When the system's metallicity is $[\mathrm{Fe/H}] = -1.75$, the system is polluted by 5.5×10^5 of SNe Ia. At this time, [Si/Fe] and [Ca/Fe] are 0.36 and 0.11, respectively. These values are consistent with the average [X/Fe] values in LMC (Table 1).

We further estimate N_{Ia} to explain [Si/Fe] ratios of NGC 2005 by the scenario of the local inhomogeneity. We assume that NGC 2005, with the stellar mass of $3 \times 10^5 M_\odot$ was formed from the gas cloud of $5 \times 10^7 M_\odot$. This assumption is based on the average star formation efficiency (0.006) of the giant molecular cloud (Murray 2011). By adopting the solar system abundance of Asplund et al. (2009), we estimate that there are 1200 $M_\odot$ of Fe and Si in the cloud with $[\mathrm{Fe/H}] = -1.75$ and $[\mathrm{Si/Fe}] = 0.32$. To decrease the [Si/Fe] to the value of NGC 2005 ($[\mathrm{Si/Fe}] = 0.08$), we estimate that $dM_{\mathrm{Fe}} = 860\ M_\odot$ of Fe should be added to the cloud. We then apply the Fe yield ($Y_{\mathrm{Fe}} = 0.75\ M_\odot$ for each SNIa) of the W7 model of Iwamoto et al. (1999) and ignore the production of Si in SNe Ia. By dividing dM_{Fe} by Y_{Fe}, N_{Ia} required to reproduce [Si/Fe] in NGC 2005 is 1100. This number is only 0.2% of the total number of SNe Ia in the whole region.

This result means that if there is a region around LMC enriched slightly excess in the ejecta of SNe Ia, a globular cluster with alpha-element abundance similar to NGC 2005 could be formed. Since this is a simple estimation, we ignore the increase of [Fe/H] by additional SNe Ia. We also refrain from doing this estimate on other elements due to the significant uncertainties of nucleosynthesis.

3.2. Kinematics

Kinematics of globular clusters let us consider an in situ origin for NGC 2005. Indeed, the kinematics of Milky Way globular clusters have been used to disentangle different accretion events (Kruijssen et al. 2019; Massari et al. 2019) since their motions have kept along their lifetimes' imprints of their origins (Piatti 2019). Similarly, Bennet et al. (2022) performed a 6D phase-space analysis from multiple independent analysis techniques of 31 LMC globular clusters using Gaia EDR3 (Gaia Collaboration et al. 2021) and Hubble Space Telescope data. They found that the system of globular clusters rotates like in a stellar disk with one-dimensional velocity dispersions of order 30 km s^{-1}, similar to that of the LMC old stellar disk population. From these results, they argued that most, if not all, LMC globular clusters formed through a single formation mechanism in the LMC disk, albeit their significant dispersion in age and metallicity, any accretion signature being absent within the involved uncertainties. Similarly to outer halo Milky Way globular clusters, which are associated with dwarf galaxy accretion events (e.g., Sagittarius, Gaia-Enceladus, Sequoia, etc.; Forbes 2020), the LMC halo globular cluster should be those with more chances to have an ex situ origin, but at present, there is no chemical signature hinting at it. Note that NGC 2005 is placed in the inner LMC disk.

Several recent studies support the in situ scenario. Shao et al. (2021) showed that accreted globular clusters in the Milky Way and Fornax are less centrally concentrated than those formed in situ. Moreover, globular clusters that escape dwarf satellites of the Milky Way are found orbiting the latter (Rostami Shirazi et al. 2022). Piatti et al. (2019) derived mean proper motions of the 15 LMC globular clusters, and from existent radial velocities, they computed their velocity vectors. They found that LMC globular clusters are distributed in two different kinematics groups, namely: those moving in the LMC disk and others in a spherical component. Since globular clusters in both kinematicstructural components share similar ages and metallicities, they concluded that their origin occurred through a fast collapse that formed a halo and disk concurrently. NGC 2005 resulted in being a disk globular cluster, while among the other five LMC clusters, three and two are in the disk and halo, respectively.

In addition to kinematics, the mass required to form globular clusters would support the in situ formation scenario. Eadie et al. (2022) estimated a minimum galaxy stellar mass required to form globular clusters of $\sim 10^7 M_\odot$. We found from Table 3 that only Sagittarius and Fornax could form globular clusters. Carina, Draco, and Ursa Minor do not have globular clusters (either formed in situ or ex situ). With a total galaxy stellar masses of $\sim 10^{5.4} M_\odot$ it is probable that these galaxies are primordial dwarfs, i.e., they did not form from the merger of smaller galaxies.

We also computed the LMC mass for a lookback time of 11.5 Gyr, when all its globular clusters formed (Piatti et al. 2019), using the SFRs derived by Mazzi et al. (2021) and Massana et al. (2022). We obtained an LMC mass of $\sim 10^8 M_\odot$. Thus, the preenriched gas cloud out of which the LMC globular clusters formed could have been a gathering of smaller pieces, each with a particular chemical enrichment history.

Table 3
Stellar Mass of Dwarf Galaxies using the Absolute M_V Magnitudes Compiled by Drlica-Wagner et al. (2020) and Interpolating them in Figure 5 of Georgiev et al. (2010)

Name	M_V (mag)	log(stellar mass/$M_\odot$)
Carina	−9.43	$5.6^{+0.3}_{-0.2}$
Draco	−8.71	$5.3^{+0.3}_{-0.2}$
Fornax	−13.46	$7.4^{+0.3}_{-0.2}$
Sagittarius	−13.50	$7.4^{+0.3}_{-0.2}$
Sextants	−8.72	$5.3^{+0.3}_{-0.2}$
Sculptor	−10.82	$6.2^{+0.2}_{-0.1}$
Ursa Minor	−9.03	$5.4^{+0.3}_{-0.2}$

Following these discussions, we anticipate that stars with chemical abundances similar to NGC 2005 would be formed if there are gas clouds with enough mass ($\sim 10^7\,M_\odot$) enriched by SNe Ia larger than the other region. On the other hand, in Mucciarelli et al. (2021)’ scenario, NGC 2005 would be formed around a Fornax-like dwarf galaxy and later accreted to the LMC. Our discussion suggests that NGC 2005 could be formed in situ without imposing unphysical assumptions.

4. Conclusions

The present analysis shows that the 13 chemical elements employed by Mucciarelli et al. (2021) to claim an ex situ origin of NGC 2005 are not all of the same accuracy. Consequently, they cannot be used indistinctly to support abundance differences between the [X/Fe] values derived for NGC 2005 and for five LMC globular clusters with similar metallicities. Nevertheless, the abundance differences measured for some chemical elements ($>3\sigma$) are yielded by SNe Ia. Different dwarf galaxies with studied chemical enrichment histories show abundances spread of the considered chemical elements that encompass the mean values of NGC 2005, which means that NGC 2005 could have been born in any of these galaxies, including the LMC. The five LMC globular clusters with [Fe/H] values similar to that of NGC 2005 belong to the inner disk (3) and the outer halo (2) of the LMC, and they have similar individual [X/Fe] ratios. The LMC globular clusters span a wide range of metallicities, and that range is verified from those populating the kinematically different disk and halo substructures, respectively (Piatti et al. 2019). Therefore, the presence of NGC 2005 in the inner LMC disk should not catch our attention to differentiate it from the remaining LMC globular cluster population. Recent modeling has also shown a widespread abundance of chemical species at the metalicity level of NGC 2005 can be produced by supernova explosions, as has also been probed in the LMC.

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Appendix
Python Scripts used to Perform Different Statistics

In what follows y1 and y2 represent values of the 13 element abundances in NGC 2005 and in the five LMC globular clusters, respectively (see text for details).

```
# Spearman correlation


spearman = stats.spearmanr(y1,y2, axis = 0)
print (spearman)

# Sørensen–Dice statistic


def dice(a, b):_
a = set(a)_
b = set(b)
return (2*len(_a.intersection(_b))) / (len(_a) + len(_b))
dice = dice(y1, y2)
print (dice)

# Jaccard similarity


def jaccard_similarity(x,y):
intersection_cardinality = len(set.intersection(*[set(x),
set(y)]))
union_cardinality = len(set.union(*[set(x), set(y)]))
return intersection_cardinality/float(union_cardinality)
jaccard = jaccard_similarity(y1,y2)
print (jaccard)

# Cosine similarity


def square_rooted(x):
return round(np.sqrt(sum([a*a for a in x])),3)
def cosine_similarity(x,y):
numerator = sum(a*b for a,b in zip(x,y))
denominator = square_rooted(x)*square_rooted(y)
return round(numerator/float(denominator),3)
cosine = cosine_similarity(y1,y2)
print (cosine)

# Pearson correlation


my_rho = np.corrcoef(y1,y2)
print (my_rho)

# Levenshtein distance


import Levenshtein as lev
ratio = lev.ratio(y1,y2)
jaro = lev.jaro(y1,y2)
jw = lev.jaro_winkler(y1,y2)
ham = lev.hamming(y1,y2)
```

```
print (ratio, jaro, jw, ham)
```

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References

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, ARA&A, 47, 481
Beasley, M. A., Hoyle, F., & Sharples, R. M. 2002, MNRAS, 336, 168
Bennet, P., Alfaro-Cuello, M., del Pino, A., et al. 2022, ApJ, 935, 149
Carrera, R., Gallart, C., Aparicio, A., & Hardy, E. 2011, AJ, 142, 61
Chabrier, G. 2003, PASP, 115, 763
de los Reyes, M. A. C., Kirby, E. N., Ji, A. P., & Nuñez, E. H. 2022, ApJ, 925, 66
Drlica-Wagner, A., Bechtol, K., Mau, S., et al. 2020, ApJ, 893, 47
Eadie, G. M., Harris, W. E., & Springford, A. 2022, ApJ, 926, 162
Forbes, D. A. 2020, MNRAS, 493, 847
Luri, X., Chemin, L., et al. 2021, A&A, 649, A7
Georgiev, I. Y., Puzia, T. H., Goudfrooij, P., & Hilker, M. 2010, MNRAS, 406, 1967
Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Natur, 585, 357
Hasselquist, S., Hayes, C. R., Lian, J., et al. 2021, ApJ, 923, 172
Hirai, Y., Beers, T. C., Chiba, M., et al. 2022, MNRAS, 517, 4856
Hirai, Y., Ishimaru, Y., Saitoh, T. R., et al. 2015, ApJ, 814, 41
Hirai, Y., Ishimaru, Y., Saitoh, T. R., et al. 2017, MNRAS, 466, 2474
Hirai, Y., & Saitoh, T. R. 2017, ApJL, 838, L23
Hirai, Y., Saitoh, T. R., Ishimaru, Y., & Wanajo, S. 2018, ApJ, 855, 63
Iwamoto, K., Brachwitz, F., Nomoto, K., et al. 1999, ApJS, 125, 439
Kruijssen, J. M. D., Pfeffer, J. L., Reina-Campos, M., Crain, R. A., & Bastian, N. 2019, MNRAS, 486, 3180
Lach, F., Röpke, F. K., Seitenzahl, I. R., et al. 2020, A&A, 644, A118
Letarte, B., Hill, V., Jablonka, P., et al. 2006, A&A, 453, 547
Mackey, A. D., & Gilmore, G. F. 2003, MNRAS, 338, 85
Majewski, S. R., Schiavon, R. P., Frinchaboy, P. M., et al. 2017, AJ, 154, 94
Massana, P., Ruiz-Lara, T., Noël, N. E. D., et al. 2022, MNRAS, 513, L40
Massari, D., Koppelman, H. H., & Helmi, A. 2019, A&A, 630, L4
Mazzi, A., Girardi, L., Zaggia, S., et al. 2021, MNRAS, 508, 245
Moore, B., Ghigna, S., Governato, F., et al. 1999, ApJL, 524, L19
Mucciarelli, A., Massari, D., Minelli, A., et al. 2021, NatAs, 5, 1247
Mucciarelli, A., Origlia, L., & Ferraro, F. R. 2010, ApJ, 717, 277
Murray, N. 2011, ApJ, 729, 133
Nomoto, K., Kobayashi, C., & Tominaga, N. 2013, ARA&A, 51, 457
Piatti, A. E. 2019, ApJ, 882, 98
Piatti, A. E., Alfaro, E. J., & Cantat-Gaudin, T. 2019, MNRAS, 484, L19
Piatti, A. E., & Geisler, D. 2013, AJ, 145, 17
Piatti, A. E., Hwang, N., Cole, A. A., Angelo, M. S., & Emptage, B. 2018, MNRAS, 481, 49
Piatti, A. E., & Mackey, A. D. 2018, MNRAS, 478, 2164
Prantzos, N., Abia, C., Limongi, M., Chieffi, A., & Cristallo, S. 2018, MNRAS, 476, 3432
Reichert, M., Hansen, C. J., Hanke, M., et al. 2020, A&A, 641, A127
Rostami Shirazi, A., Haghi, H., Khalaj, P., Asl, A. F., & Hasani Zonoozi, A. 2022, MNRAS, 513, 3526
Seitenzahl, I. R., Ciaraldi-Schoolmann, F., Röpke, F. K., et al. 2013, MNRAS, 429, 1156
Shao, S., Cautun, M., Frenk, C. S., et al. 2021, MNRAS, 507, 2339
Strolger, L.-G., Rodney, S. A., Pacifici, C., Narayan, G., & Graur, O. 2020, ApJ, 890, 140
Suntzeff, N. B., Schommer, R. A., Olszewski, E. W., & Walker, A. R. 1992, AJ, 104, 1743
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261
Wagner-Kaiser, R., Mackey, D., Sarajedini, A., et al. 2017, MNRAS, 471, 3347
Wanajo, S., Hirai, Y., & Prantzos, N. 2021, MNRAS, 505, 5862