Mem. S.A.It. Vol. 94, 173

Memorie della

The assembly history of the Local Group: the case of the Large Magellanic Cloud

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Received: 17-11-2022; Accepted: 28-11-2022

Abstract. The assembly history of the satellites of the Milky Way is still an unexplored field of research. The Large Magellanic Cloud is expected to have a number of satellites of different masses, the only one firmly recognised being the Small Magellanic Cloud. In the search of these missing "satellites of satellites" the investigation of the chemical composition is a key tool to identify tracers of past merger events. We discuss the state of the art about this search and the recent discovery of a globular cluster accreted by the Large Magellanic Cloud in a past merger with a disrupted small satellite, probably with a mass similar to those of dwarf spheroidal galaxies. This is the first evidence obtained from high-resolution spectroscopy that the process of hierarchical assembly occurred also in our closest satellite.

1. Introduction

The Λ-cold dark matter cosmological model provides a widely accepted framework to understand how galaxies form and evolve (White & Rees 1978). In this scenario, galaxy formation proceeds hierarchically via a chain of mergers. The most massive galaxies that we observe today in the Universe have built up to their current size by accreting smaller galaxies during past merging events. The Milky Way (MW) is no exception, the latest phases of this long-standing process being strikingly exemplified by the ongoing cannibalisation of the Sagittarius dwarf spheroidal galaxy (Sgr dSph, Ibata et al. 1994).

In this sense, the novel view of the MW and its history as revealed by the ESA *Gaia* mission dominates the scene of Galactic astrophysics. In the lapse of just a few years, our understanding of the process of galaxy formation is radically changed and a scientific revolution is in progress. The field of Galactic Archaeology is particularly flourishing as tens of relics from the hierarchical build-up of the MW are being discovered (Helmi 2020).

This hierarchical process should occur on all mass scales. This implies that also the satellites of the MW should have had their own satellites. The search for these "satellites of satellites" is very challenging. In fact, on the one hand these small galaxies are often too faint to be easily detected. On the other hand, some of these satellites should now be completely dissolved into their parent galaxy after a merger event. Where are these satellites of satellites today?

In the search of these systems, the Large Magellanic Cloud (LMC) plays the role of the main actor. In fact, according to its mass ($\sim 3 \cdot 10^9 M_\odot$, van der Marel et al. 2002) it should be surrounded by a system of satellites (Lynden-Bell 1976; D'Onghia & Lake 2008; Li & Helmi 2008). For instance, Sales et al. (2013) predicted for the LMC up to about 40 satellites, covering the entire range of masses of the realm of the dwarf galaxies. In particular, one of the LMC satellites should have a mass a factor of 10 smaller than the LMC, while the other systems should have smaller masses, comparable to those of the ultra-faint dwarf galaxies. Up to now, the only confirmed satellite of the LMC is the close Small Magellanic Cloud with a mass that nicely matches that expected in Λ-cold dark matter theory. Some of the ultra-faint dwarf galaxies discovered using the *Gaia* data release 2 have been proposed to be possible satellites of the LMC (Kallivayalil et al. 2018; Erkal & Belokurov 2020; Battaglia et al. 2022).

2. The chemical-DNA of stars as tracer of merger events

Most of the answers that we look for are written in the chemical composition that we measure on the stellar surfaces, that thus acts as a cosmic-DNA. In fact, apart from a few exceptions, stars keep a memory of the chemical composition of the gas out of which they formed. The chemical enrichment in galaxies is driven by the yields from stars of different initial mass and metallicity, that pollute the interstellar medium on different time scales when they die. The chemistry of stellar populations in different systems thus depends on how the environment in which they form is enriched prior to their birth, which, in turn, depends on the duration and efficiency of the star formation, on any inflow and/or outflow of gas, on the shape of the stellar initial mass function, and on the stellar yields. Proper chemical evolution models have to take all of these ingredients into account.

The reading of stellar spectra allows us to map the chemical heritage of the parent galaxies, even if the latter have already totally dissolved after a merging event. This is our best opportunity to study these destroyed progenitors, because the information about their chemical-DNA is preserved. Once a set of bona-fide stellar yields is fixed, the most important property that differentiates the chemistry of stellar populations born in different galaxies is their star-formation rate. The faster a galaxy formed its stars, the more intense the contribution to the chemical enrichment by hypernovae, Type II supernovae or electron-capture supernovae is. Different star-formation/chemical-evolution histories leave different chemical imprinting in the stellar atmosphere. This is why chemistry can discriminate among different formation environments, notably between progenitor galaxies of different mass and star formation efficiency.

The chemical composition of stars and globular clusters (GCs) thus provides a powerful tool to identify surviving witnesses of accretion events even when applied to extragalactic environments, where the kinematical information is not accurate enough to shed light on their assembly history as in the case of the MW (Massari et al. 2019; Kruijssen et al. 2020).

3. An innovative approach for Stellar Archaeology

To identify accreted stars (and therefore the relics of past merger events) by using their chemical DNA, we proposed an innovative tool that takes advantage of the chemical abundances of some poorly investigated iron-peak elements (Sc, V and Zn, Minelli et al. 2021b).

By performing an homogeneous comparison between the chemical composition of LMC, the Sgr dwarf spheroidal and MW stars, we found that the largest differences between the two dwarf galaxies (LMC/Sgr) and the MW in the metal-rich regime ([Fe/H]>-1) occur just in these three abundances ratios, reaching up to 0.5/0.7 dex for [Zn/Fe].

[Zn/Fe] thus turns out to be the most sensitive chemical diagnostic to distinguish in-situ from external stars at these metallicities. The likely reason is that Zn is produced mainly by hypernovae (associated to stars more massive than $\sim 25-30M_{\odot}$). without a significant contribution by Type Ia Supernovae (Romano et al. 2010; Kobayashi et al. 2020). Hence, the [Zn/Fe] abundance ratio is expected to significantly decrease in galaxies with a low star formation rate, where the contribution by massive stars is poor (Yan et al. 2017; Jeřábková et al. 2018), even at relatively large [Fe/H].

The prediction power and the robustness of this tool as a diagnostic to discriminate between accreted and in-situ GCs has been further demonstrated by Minelli et al. (2021a). In this work, we measured the abundances of Sc, V and Zn for four metal-rich GCs: two of them (namely NGC 5927 and NGC 6496) were unambiguously recognised as in-situ clusters according to their dynamics (Massari et al. 2019), while the other two (namely NGC 6388 and NGC 6441) had dynamical properties that made their classification uncertain. From the analysis of Sc, V and Zn, NGC 6388 and NGC 6441 turned out to have abundance ratios significantly lower (by ~0.5 dex) than those measured in the in-situ clusters NGC 5927 and NGC 6496. These differences led to the conclusion that both NGC 6388 and NGC 6441 should have formed from a gas poorly enriched by massive stars, as is likely the case of the environment of dwarf galaxies. This chemical tool thus demonstrated the different origin of the two pairs of clusters: NGC 5927 and NGC 6496 formed in-situ, as already suggested by their dynamics, while NGC 6388 and NGC 6441 must have formed in an external dwarf galaxy, only later accreted by the MW. The chemical abundances of Sc, V and Zn thus provide an extraordinarily efficient tool to discriminate between the in-situ and the accreted origin of metal-rich clusters when their dynamical properties are not sufficient to do so.

4. NGC 2005: the relic of a past merger event in the LMC

In Mucciarelli et al. (2021) we exploited the chemical tagging method (with particular focus on the abundances of these new chemical diagnostics) to study the chemistry of the LMC. We analysed high-resolution spectra, obtained with UVES@VLT, FLAMES@VLT and MIKE@Magellan, for stars in 11 old LMC GCs, and compared them with a reference sample of 15 MW GCs, analysed in the same homogeneous way. This enabled an extremely accurate comparison between the chemical composition of LMC and MW clusters, that did not suffer for the most typical systematic errors arising from the spectroscopic analysis (i.e. the choice of model atmospheres, temperature and gravity scales, atomic data, solar reference abundances, etc.).

Among the LMC clusters we could identify a very clear outlier, the cluster NGC 2005. In fact, this cluster exhibits chemical patterns that are significantly different from those of the other LMC clusters at similar metallicity (5 in our sample), its chemical abundances being systematically lower for each of the analysed chemical elements. Most of the elements, for instance α-elements, Sc, Co, Zn, La and Eu show discrepancies at a high level of significance (3-5σ, see Figure 1). Even if some individual abundance ratios show a marginally significant difference, it is appropriate to say that the global chemical pattern of NGC 2005 is unique and totally inconsistent with that of the other LMC clusters at similar metallicity, which instead behave all in the same homogeneous way.

Therefore, these findings suggest that NGC 2005 followed a different chemical evolutionary path, compared to that homogeneously followed by its five LMC siblings of similar metallicity. The very similar chemical composition of the other LMC clusters with the same [Fe/H] of NGC 2005 suggests that the LMC has experienced an experienced an homogeneous chemical enrichment history. This enforces that differences with the chemistry of NGC 2005. In particular, we are able to reproduce the LMC GCs chemical patterns with chemical evolutionary models assuming a star formation rate of $\sim 1-1.5M_{\odot}$ / yr. On the other hand, the chemical abundance ratios measured for NGC 2005 can only be reproduced by assuming a significantly lower star formation rate, $\sim 10^{-4}M_{\odot}$ / yr. This evidence clearly points towards the fact that NGC 2005 was born in a galaxy that formed its stars with a much less efficient star formation com-

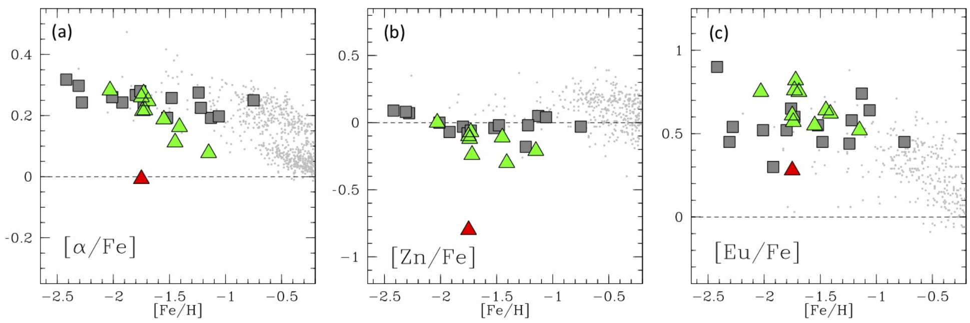

Fig. 1. Behaviour of [α/Fe], [Zn/Fe] and [Eu/Fe] abundance ratios as a function of [Fe/H] (panel a, b and c, respectively) for the LMC clusters (green triangles), the anomalous cluster NGC 2005 (red triangle), the reference MW GCs (grey squares) and literature MW field stars (grey points).

pared to the LMC, namely in a low-mass dwarf galaxy, that was once a former satellite of the LMC, and is now totally disrupted as a result of the merger process that has left NGC 2005 as part of its debris. This progenitor should have had a mass comparable with that of some dwarf spheroidal galaxies populating the Local Group and characterised by chemical patterns similar to those observed in NGC 2005.

As a final remark, we stress once again the key role that the iron-peak elements (in particular Sc, V and Zn) played in recognising the chemical peculiarity of this cluster. For instance, [Zn/Fe] is extremely useful to identify stars formed in environments that have been poorly enriched by massive stars. The Sculptor dwarf spheroidal galaxy is a perfect example, as it exhibits [Zn/Fe] abundance ratios significantly lower than those of Milky Way stars at similar metallicities (Skúladóttir et al. 2017), even if affected by large uncertainties.

5. Conclusions

The turbulent evolution history of the Magellanic Clouds has been the subject of a renewed interest in the last years, as demonstrated by several dedicated photometric and spectroscopic surveys. One of the most fundamental open questions about these galaxies is the search for the satellites of the LMC, predicted to exist by the Λ-cold dark matter theory. Using chemical abundance ratios of different species (in particular of poorly investigated iron-peak elements) and taking advantage of a homogeneous and accurate comparison with other clusters of the same galaxy, we have identified the relic of a past merger event occurring between the LMC and one of its past satellites. This result opens a new route to approach the complex research of the missing satellites of the LMC using the chemical tagging and the measure of iron-peak elements.

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