PROCEEDINGS OF SCIENCE

Fornax dSph: star formation and s-process enrichment

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Dwarf spheroidal (dSph) galaxies in the Local Group are satellites of the Milky Way and provide the most neighbour laboratories for testing dynamical, nucleosynthesis and chemical evolution models. We present here the preliminary results studying chemical evolution in Fornax, for which a large number of spectroscopic observations and kinematic studies is now available. We highlight that a single star formation episode can not interpret the observed trend versus metallicity of both α and *s*-process elements. This agrees with recent detailed studies that determined more accurately the age of different stellar populations belonging to Fornax. In our first attempt two bursts of star formation are adopted, but we do not exclude the presence of three (or more).

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1. Introduction

The last generation of telescopes (wide-field CCD imagers and large ground-based telescopes as VLT/FLAMES, Keck, HET and Magellan, as well as the Hubble Space Telescope, HST) has enabled detailed studies of stars in Galactic and extra-galactic systems. Several survey projects (VLT/Giraffe, HET/HRS surveys, DART survey at ESO) have revolutionised our understanding of the chemical evolution and star formation history of the Milky Way and her satellites. Among extra-galactic objects, galaxies fainter than $M_B \leq -16$ and more spatially extended than globular clusters were defined dwarf galaxies. Each dwarf galaxy shows different properties, including velocity dispersion and luminosity, stellar ages, metallicities, star formation episode(s), chemical enrichment, interstellar gas and dark matter contents (see review by [10, 21] and references therein). Among dwarf galaxies, dwarf spheroidals (dSphs) are the most studied systems of the last years. The spectroscopic analysis of several elements (including neutron capture elements) has provided direct instruments for examining the chemical contribution from different stellar generations. Moreover, dSphs host some of the most metal-poor stars known, which represent the chemical imprint of the early epoch of star formation (e.g., [17]).
We focus our analysis on Fornax, one of the most luminous, massive and well studied dSphs in the Local Group. Recent studies have revealed a complex dynamical, chemical and evolutionary history (see e.g., [5, 13, 9, 4, 2] and references therein). Starting from the spectroscopic observations by [9, 17], we investigate its star formation and the nucleosynthesis processes occurred in this system. We have made a first attempt to derive the best-fit to the observations of Mg (Section 2.1) and neutron capture elements (Ba, La, Eu and Y; Section 2.2).
The chemical enrichment history of Fornax is simulated using a modified version of the Galactic chemical evolution (GCE) code described by [22, 24, 14]. Unlike dSphs, the Milky Way has three zones (halo, thick and thin disk) showing different dynamical and chemical properties. GCE model accounts for these zones and their interaction. We adapted the chemical evolution (CE) code to the description of small systems as dSphs, including the possibility of outfall or infall of material. Indeed, Supernovae (SNe) II exploding in low mass galaxies as dSph may drive important outflows of metal-rich material, because of the low gravitational bound due to the small mass of the system with respect to our Galaxy. Moreover, dSph may interact with closer interstellar clouds or galaxies (e.g., the Milky Way) and the gas stripping can efficiently remove the metal-enriched gas from the system. Preliminary results are presented in the following Section.

2. Results

2.1 Mg and star formation rate

The behaviour of [Mg/Fe] vs [Fe/H] provides a key information about the star formation. Since Mg is mainly synthesised by short-lived SNII, and under the hypothesis that Fe is mostly produced by long-lived SNIa ($\sim$1/3 by SNII and $\sim$2/3 by SNIa), the presence of a 'knee' in the trend of [Mg/Fe] vs [Fe/H] indicates the delayed contribution to iron by SNIa. Moreover, the level of [Mg/Fe] before the knee constrains the efficiency of the contribution by SNII. We adopted the yields by Rauscher et al. (2002) and Travaglio et al. (2004b) for SNe II and Ia, respectively.

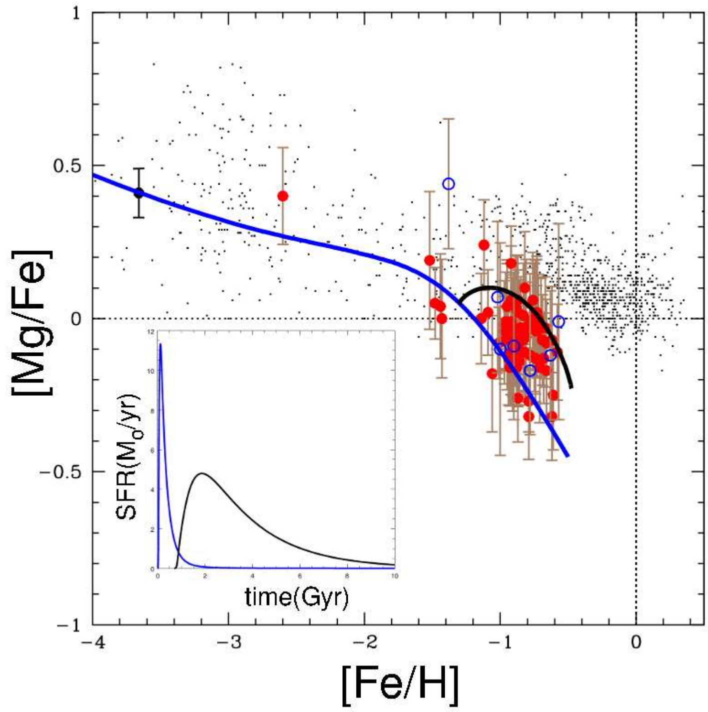

Figure 1: Spectroscopic observations of [Mg/Fe] versus [Fe/H] for Fornax dSph. Symbols correspond to stars detected by [9] (red filled circles) and [17] (black circle). We adopt different symbols for seven stars with a larger uncertainty by [9] (blue empty circles). Galactic stars at different metallicities are also included for comparison (black small circles) from the compilation by [7]. Two lines represent the results of CE model under the hypothesis of the two star formation episodes shown in the inset panel. *Inset panel:* The adopted star formation rate (SFR) versus time is shown. Two bursts of star formation are needed to interpret the observations belonging to different stellar populations (see text): the first short burst (blue line) last up to ∼2 Gyr with an efficient star formation rate. A second slower burst of star formation (black line; major contribution within ∼6 Gyr) occurs before the end of the first burst, when the iron enrichment reach a metallicity [Fe/H] ~ -1.3, explaining the younger stellar population at [Fe/H] ~ -1. *See the electronic paper for a colour version of this and the following figures.*

Lifetimes of stars are the same adopted by Travaglio et al. (2004) to study chemical evolution of our Galaxy.

As highlighted by previous studies, Fornax shows an [Mg/Fe] in average lower than that observed in our Galaxy, with an anticipated change of slope (likely close to [Fe/H] ~ -1.2; see Fig. 1). Spectroscopic observations are collected from [9] (red filled circles; as well as seven blue empty circles corresponding to stars with larger uncertainty) and [17] (black circle)[1]. Galactic field stars are shown for comparison (black small circles from the compilation by [7]). In Fig. 1 (bottom left panel) we also show the two star formation bursts (versus time) adopted in this preliminary analysis. Unfortunately, only a limited number of stars is available at low metallicities ([Fe/H] $\lesssim -1.2$), which results in poor star formation constraints during the first evolutionary epochs. How-

[1]Note that [9] overcome previous studies by [20, 15]: these older data are not included in this analysis. Medium-resolution Mg observations by [8] are generally consistent with [9] determinations, and are not shown in Fig. 1.

ever, as claimed by many studies, we confirm that a single burst of star formation is not sufficient to interpret the different stellar populations observed in Fornax (dominated by $\sim$1 to $\sim$8 Gyr old stars). The presence of a very old stellar population ($\gtrsim$8 Gyr) implies that a first short burst of star formation took place (blue line; $\sim$2 Gyr of duration). The young stellar population (around $\sim$3 Gyr), with averaged metallicity around [Fe/H] ~ -1, strengthens the occurrence of an additional slower burst of star formation (black line; major contribution within $\sim$6 Gyr). These results are in agreement (within the errorbars) with the metallicity distribution observed ([2, 9, 5], and references therein). The reasons of this second burst are still not clear. Several hypotheses have been recently proposed in literature and investigated through dynamical models (see e.g., [13, 26, 1]).

2.2 Neutron capture elements

Heavy elements beyond the iron peak are synthesised by neutron captures through the s (slow) and the r (rapid) processes. The s-process occurs when the intervals between neutron captures are much longer than the β-decay time-scale of unstable isotopes. It is not an unique process as three components are needed to reproduce the solar s-abundances. The s-process nuclei below the Sr peak receive a contribution by the weak s-process component, occurring in advanced evolutionary phases of massive stars [11]. Stars with low initial mass during their thermally pulsing asymptotic giant branch (TP-AGB) phase are the major responsible for the s-process production of elements from Sr to Pb/Bi (main and strong components; [22, 23]). It is worth mentioning here the elements belonging to the first two s-peaks at the neutron magic numbers N = 50 (e.g., Y) and 82 (e.g., Ba, La), which have been observed in Fornax with high-resolution spectroscopy.
Despite a clear description of the r-process site is still not available, it is believed to occur during explosive SNII phases ([16, 18] and references therein), which extreme physical environments allow neutron fluxes sufficiently high to capture another neutron before decaying. Among the r-process elements, Eu is the most representative.
In this section we present the results of CE model for Y, La and Eu, obtained by adopting the two bursts of star formation described in Section 2.1. We compute a detailed analysis of the s-process elements, by including the s-process yields averaged over a range of s-process efficiencies, masses and metallicities [6, 3, 24]. The r-process yields are deduced by subtracting the solar s-process contribution to the solar abundances, following the analytic approach described by [22]. This simple approximation provides the first estimation of the r-contribution for heavier elements, e.g., La and Eu. We consider SNII in the mass range 8–10 $M_\odot$ to contribute to the r-process Eu, as hypothesised for our Galaxy (following the assumption adopted in [22]). Actually, an additional primary process has been postulated to interpret the abundances of light neutron capture elements, e.g., Y, observed in our Galaxy (LEPP, [24]). There is a general consensus about the need of this extra process, even if its source is still under debate (see e.g., [7]). Because the observations at present available in Fornax do not provide strong constraints about the need or not of LEPP, we adopt the same hypothesis discussed by [24] for the Milky Way.
In Fig. 2, left panel, we show [La/Fe] and [Y/Fe] versus [Fe/H]. We have considered La among the elements of the second s-process peak. Ba gives clear indications to be affected by larger uncertainties or systematic effects showing a spread of about 1 dex in the [La/Ba] ratio not predicted by s-process calculations. The increasing [La/Fe] trend for [Fe/H] > -1 attests an s-contribution to La from AGB stars. Note that for [Y/Fe], a decreasing trend of the blue line starting from [Fe/H] < -2

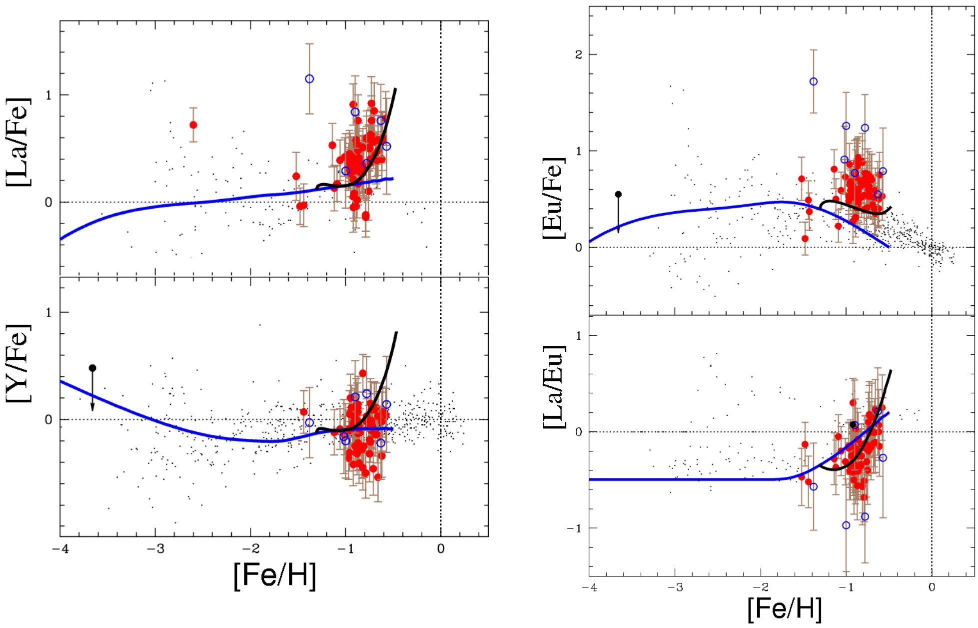

Figure 2: The same as in Fig. 1, but for [La/Fe] versus [Fe/H] (top left panel), [Y/Fe] versus [Fe/H] (bottom left panel), [Eu/Fe] versus [Fe/H] (top right panel) and [La/Eu] versus [Fe/H] (bottom right panel).

would be obtained by excluding LEPP contribution. The observed [Y/Fe] is almost flat for [Fe/H] > -1.5, while no information is available at lower metallicities. The second burst of star formation (black line) provided in this preliminary analysis slightly overestimates [Y/Fe] (+0.4 dex) for few stars with [Fe/H] ~ -0.6. Additional theoretical investigations are in program.

In Fig. 2, right panel, [Eu/Fe] and [La/Eu] vs [Fe/H] provide information about the r-process contribution. Indeed, given that ∼30% of solar La and ∼94% of solar Eu are produced by the r-process, respectively, a pure r-contribution predicts $[\mathrm{La/Eu}]_r = -0.5$. The star at [Fe/H] = -1.38 (BL147) shows a high r-process enhancement ([Eu/Fe] = 1.72; [La/Eu] = -0.6), in agreement with peculiar r-rich stars also found in our Galaxy. This star may likely have experienced an additional local pollution by neighbour SNII explosions. The star at [Fe/H] = -2.6 (BL085) has [La/Fe] = 0.72 (much higher than CE predictions); however, as no Eu is detected, we do not have information about possible r-process enhancement. Both stars show the evidence for confined nucleosynthesis processes, which deviate from the general chemical evolution process of Fornax. Further investigations would be helpful. Moreover, an increase of the spectroscopic observations in the metal-poor region with [Fe/H] $\lesssim -1.3$ would significantly constrain the first burst of star formation, and the nucleosynthesis of early stars.

Finally, in Fig. 3 we also show the ratios of Mg over La and over Y. Because Mg is mainly produced by SNII, while La and Y mostly by AGB stars, [Mg/La] and [Mg/Y] vs [Fe/H] indicate the time-scale contribution of SNII versus AGB stars during the Fornax history.

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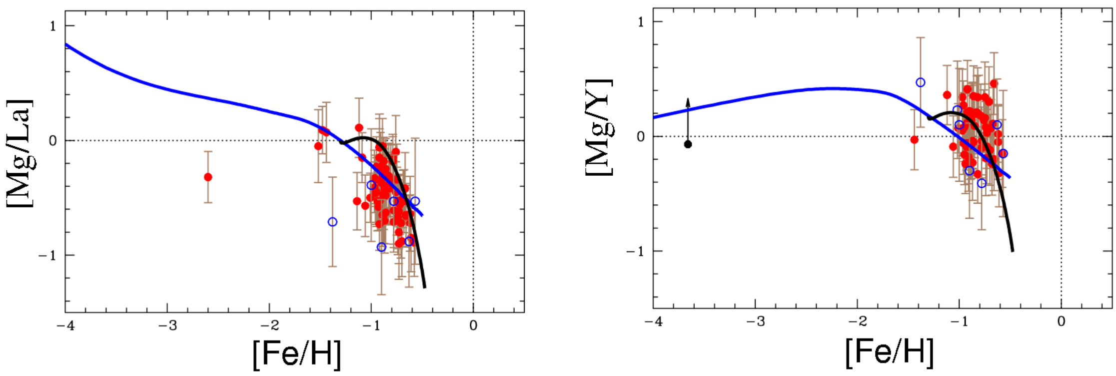

Figure 3: The same as in Fig. 1, but for [Mg/La] versus [Fe/H] (left panel) and [Mg/Y] versus [Fe/H] (right panel).

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