Mem. S.A.It. Vol. 75, 134

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The chemical history of the Fornax dSph galaxy

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Abstract. The metallicity distribution of stars in the Fornax dwarf spheroidal galaxy is studied with infrared Ca II triplet spectroscopy for 117 red giants, obtained with FORS1 on the VLT. The results reveal a very wide distribution of metallicities in Fornax, including a surprising abundance of young, relatively metal-rich stars ([Fe/H]> −0.7). By combining these metallicities with the position of the stars in the colour-magnitude diagram, we derive an age-metallicity relation for Fornax, characterized by sustained star formation and chemical enrichement in the past few Gyrs. The results are discussed in the context of the predictions of evolutionary models of dwarf galaxies.

Key words. Dwarf spheroidal galaxies. Chemical evolution. Abundances

1. Introduction

Until the last decade, the dwarf spheroidal galaxies surrounding the Milky Way were though to be globular-cluster-like systems with a uniformly old population, despite early hints on the fact that they had experienced more than one episode of star formation and nucleosynthesis (Zinn 1981, and references therein). On closer inspection, these galaxies have revealed a surprising variety of star formation histories, ranging from extreme cases like Leo I, which has formed over 80% of its stars in the second half of the life of the Universe, through intermediate cases like Fornax, with prominent intermediate-age populations, to predominantly old ($\simeq$ 10 Gyr old) systems like Ursa Minor or Draco (see references in Gallart et al. 2003).

The extention of the star formation history in several of these galaxies seems to be independent of their total mass: Carina and Leo I are among the least massive dSph in the Milky Way system, with virial masses around $2 \times 10^7 M\odot$, while Fornax is the most massive one, with $7 \times 10^7 M\odot$ (see Mateo 1998). Their metal content, however, is directly related to their total luminosity, and presumably, to their total mass: Leo I and Carina have low metallicities, while Fornax seems to have a relatively high metallicity and a large metallicity dispersion (Saviane, Held & Bertelli 2000; Tolstoy et al. 2001; Pont et al. 2003; this paper). The metal content, therefore, seems to be related less to the star formation history than to the ability of these systems to retain the produced metals, which may have to do with the

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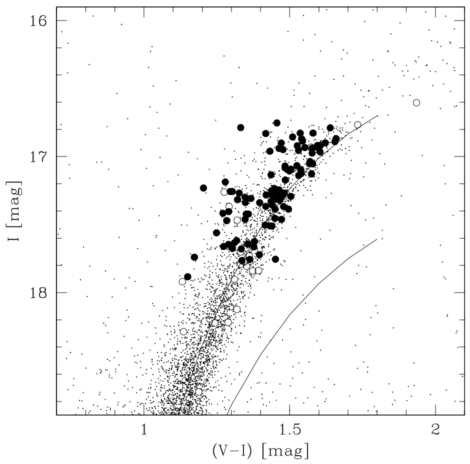

Fig. 1. Upper colour-magnitude diagram for the Fornax dwarf spheroidal galaxy, with our spectroscopy targets indicated as large symbols (open symbols for targets with lower signal-to-noise or suspected non-members).The lines show the sequences of globular clusters and [Fe/H]=−1.1 and [Fe/H]=−0.7 dex.

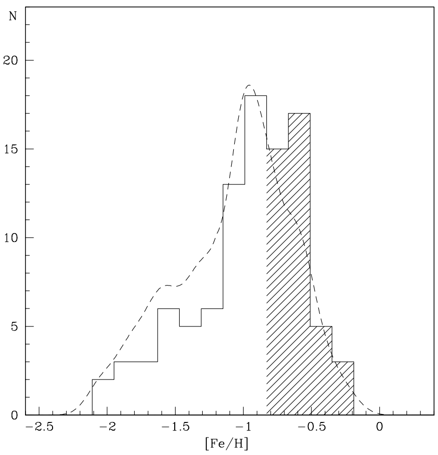

Fig. 2. Histogram : metallicity distribution of our red giant sample in Fornax. The shaded part shows the regions where the metallicity calibration was extrapolated. Dotted line: smoothed distribution inferred for the underlying population

effect of SNe on the interstellar medium and the depths of their potential wells (e.g., Mac-Low & Ferrara 1999).

In contrast with the wealth of high quality CMDs available for the nearest galaxies, spectroscopic metallicity measurements of individual stars are scarce, due to the large investment of telescope time required. The infrared Ca II triplet offers the possibility of obtaining [Fe/H] estimates for individual stars with reasonable precision (≤ 0.2 dex) from low-resolution spectra, and this technique has developed into a popular way of estimating the abundances of stars in globular clusters and dSph galaxies.

2. Stellar metallicities from the Ca II triplet

We obtained Ca II triplet spectroscopy for 117 RGB stars in the central region of Fornax, using FORS1 at the VLT. The position of our targets in the colour-magnitude diagram of Fornax is shown in Figure 1. The combined equivalent widths of the three Ca II lines, ΣCa, were computed as defined in Rutledge, Hesser & Stetson (1998).

Most previous investigations that used ΣCa as a metallicity indicator have plotted it against V-V(HB) because this quantity is independent of the reddening and the distance modulus of the system. V-V(HB) works fine for very old stellar populations that have well-defined horizontal branches and small or virtually non-existent internal metallicity spreads, such as most globular clusters. It is a much less useful parameter for a galaxy like Fornax that possesses wide ranges in age and metallicity. For this reason, with the aid of theoretical models, we have investigated the behavior of ΣCa as a function of absolute magnitude, both M_V and M_I (see Pont et al. 2003), and have concluded that a calibration of ΣCa against M_I may produce more accurate results for the young populations present in Fornax .

The actual metallicity distribution that we derive for Fornax (see Figure 2) reveals the presence of a large proportion of relatively metal-rich stars. Stars more metal-rich than

[Fe/H]$\sim$ -0.7 dex were totally unexpected from the CMD of Fornax. In fact, the Ca II equivalent width of many red giants in our Fornax sample is so large that none of the calibrating clusters reach the same position in luminosity, colour and metallicity. Consequently, the higher end of our metallicity calibration for Fornax depends on an extrapolation from the cluster data. We have used Ca II measurements in the LMC by Cole et al. (2000) as an empirical check of the extrapolation.

Our main results can be summarized as follows: we find a large metallicity dispersion in Fornax, with about 20% of the objects having low abundances ($-2.5 \leq$ [Fe/H] ≤ -1.3), and about a third having abundances greater than 47 Tuc ([Fe/H]$=-0.7$) and up to [Fe/H] $\simeq -0.4$. The peak of the metallicity distribution occurs at [Fe/H] $\simeq -0.9$.

3. The Fornax age-metallicity relation

Once the metallicity of a red giant is determined, its position in the CMD gives an indication of its age. Stellar evolution models predict that the red giant branch gets progressively redder with age, first evolving rapidly in colour then settling asymptotically on the "infinite age" red giant branch, corresponding in practice to the loci of the oldest globular clusters. Therefore, the position of a given red giant blueward of the old globular cluster sequence for its metallicity indicates its age. This indication gets progressively more precise as the age gets younger, because the colour of the red giant branch changes more quickly.

Most red giants in the Fornax sample are much bluer than globular clusters of similar metallicity (see Fig. 1). It also implies that they are much younger, with ages of a few Gyr at most. Fig. 3 shows the computed ages as a function of metallicity for our sample.

The most salient feature is a rapid increase of the metallicity up to [Fe/H]$\sim$ -0.4 in the past $\sim$1-4 Gyr. Overall, the outlined age-metallicity relation is compatible with a typical closed-box model. Moreover, more that half the sample is constituted of star younger than $\sim$ 4 Gyr, thus indicating sustained recent star formation in Fornax.

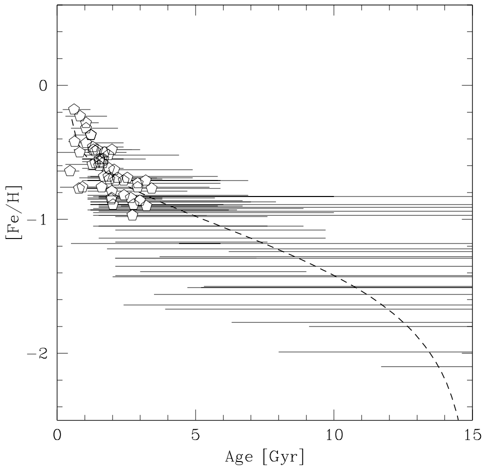

Fig. 3. Age-metallicity relation obtained for Fornax from Ca II triplet spectroscopy and photometry. Ages computed by comparison with Girardi et al. (2000) stellar evolution models. The bars show the 95% confidence intervals in age. The points are plotted only when this interval is lower than 5 Gyr. The dotted line is the prediction of a closed-box model with constant IMF and remaining gas fraction 0.0018 at t = 0.5 Gyr.

These results also imply that the Fornax RGB is subject to the age-metallicity degeneracy to a surprising degree: the relatively low dispersion of its RBG is due to the chance superposition of populations with a wide range of age and metallicity (from [Fe/H]$\sim$ -2.0 and t $\sim$12 Gyr to [Fe/H]$\sim$ -0.4 and t $\leq$1 Gyr) obeying a tight age-metallicity relation.

A global analysis of the CMD of Fornax confirms the coherence of this picture with other regions of the CMD (see Gallart et al. 2003). In particular, the inclusion of young and metal-rich populations in synthetic CMDs also produces a better fit to the Fornax data in the region of the main-sequence.

4. Metal ejection efficiency in Fornax

The high metallicities reached by the youngest stars in Fornax (only slightly lower than the youngest populations in the LMC) indicate that this galaxy was able to retain a large fraction of the heavy elements that its stars produced, despite the relative shallowness of its gravitational potential well. It is interesting to compare the properties of Fornax with the predictions by Mac Low & Ferrara (1999, MF99) about the capacity of dwarf galaxies to conserve metals in their interstellar medium. Using data from the literature about the virial and bayonic mass of Fornax and the frequency of SNe II, and Tables 2 and 3 of MF99, we find that the mass ejection efficiency expected for Fornax would be modest, $\simeq 1 \times 10^{-2}$, while all the metals should be ejected. The fact that there is a substantial metal enrichment in Fornax seems to be in contradiction with these models, and would indicate that the metal ejection efficiency must be in some way overestimated in them.

One possible reason for the apparent overestimate of metal ejection efficiency in the MF99 models is the fact that they consider that all the mass injection occurs in the central 100 pc of the galaxy. As MF99 discuss, several small bubbles distributed in a larger area must be less effective in blowing away the interstellar medium than a single central cluster. The core radius of Fornax is 460 pc. Since dwarf irregular galaxies have widely dispersed sites of star formation, it is possible that the assumption of one large central site for the dSph galaxies is also incorrect.

Acknowledgements. This research is part of a Joint Project between Universidad de Chile and Yale University, funded partially by the Fundación Andes. C.G. acknowledges partial support from Chilean CONICYT through FONDECYT grant number 1990638. R.Z. was supported by NSF grant AST-9803071 and F.P. by the Swiss National Science Fund and FONDECYT grant number 3000056.

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