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The Star Formation and Chemical Enrichment History of the Fornax dSph Galaxy

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Abstract

We present new deep color-magnitude diagrams (CMD) at two galactocentric distances, and Ca II triplet spectroscopy, of the Local Group dSph galaxy Fornax, obtained with the VLT and FORS1. These data are being used to reliably derive the star formation and chemical enrichment histories of this galaxy, and preliminary results are presented here: we discuss the characteristics of the stellar populations from the morphology of the CMD and describe the metallicity distribution of the individual stars. Finally, by combining these metallicities with the color of each star in the red-giant branch, we derive an age-metallicity relation for Fornax. The results are discussed in the context of the predictions of evolutionary models of dwarf galaxies.

1.1 Introduction

During the last decade, a number of CMDs reaching the oldest main-sequence turnoffs have beautifully shown the varied and complex star formation histories (SFH) among the Milky Way satellites. Among the dSph galaxies, which had once been considered predominantly old systems, there is extreme cases like Leo I, which has formed over 80% of its stars in the second half of the life of the Universe (Gallart et al. 1999), intermediate cases like Fornax (Stetson, Hesser & Smecker-Hane 1998; Buonanno et al. 1999; Gallart et al. 2004), with prominent intermediate-age populations, and predominantly old ($\simeq$ 10 Gyr old) systems like Ursa Minor (Mighell & Burke 1999; Carrera et al. 2002) or Draco (Aparicio, Carrera & Martínez-Delgado 2001). These CMDs, together with the available spectroscopy, confirmed early hints on the fact that the dSph galaxies satellites of the Milky Way had experienced more than one episode of star formation and nucleosynthesis (Zinn 1981, and references therein). But the very extended SFH 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 (Caldwell et al. 1998 and references therein): Leo I and Carina have low metallicities (Gallart et al. 1999; Smecker-Hane et al. 1999), 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. 2004; this paper). The metal content, therefore, seems to be not as much related to the SFH than to the ability of these systems to retain the produced metals, which may have to do with the effect on SNe on the interstellar medium and the depths of their potential wells (e.g., Mac-Low & Ferrara 1999; Ferrara & Tolstoy 2000).

The nearest galaxies, which evolution can be studied in great detail through the information given by their resolved stars, offer the opportunity of thoroughly testing these scenarios. Color-magnitude diagrams (CMD) reaching the oldest main-sequence turnoffs provide accurate SFH information (see Gallart 2000) while metallicities can be obtained from spectroscopy of the brightest stars. These metallicities, combined with photometry, provide insight on the chemical enrichment history. Indeed, the combination of both types of data is the most powerful tool to break the classical age-metallicity degeneracy in stellar populations and to derive reliable and accurate star formation and chemical enrichment histories.

In contrast with the wealth of high quality CMDs available for the nearest galaxies, spectroscopic studies providing detailed chemical abundances of the stars in them are scarce, due to the large investment of large-aperture telescope time required. An economical way of obtaining metallicity information involves low resolution spectroscopy. The Ca II triplet offers the possibility of obtaining global [Fe/H] values for individual stars with reasonable precision (≤ 0.2 dex), and this technique has developed into a popular way of using low-resolution spectra to estimate the abundances of stars in globular clusters and dSph galaxies.

We undertook a study of the star formation and chemical enrichment history of the Local Group dSph galaxy Fornax with the twofold approach mentioned above: we used the VLT with FORS1 to obtain photometry reaching the oldest main-sequence turnoffs and Ca II triplet spectroscopy of a sample of red giant branch (RGB) stars in the same fields.

1.2 Deep Color-Magnitude Diagrams

We obtained old main-sequence turnoff photometry in three fields at two galactocentric distances in the dSph Fornax, using FORS1 at the VLT. FORS1 has a field of view of $6.8 \times 6.8'$and $0.1''$pixels. The central field contains the globular cluster Fornax#4, while the two off-center fields were situated about 11 arcmin North of the center of the galaxy. Their position was chosen by considering the change in surface brightness across Fornax and then selecting fields that would provide measurements of similar numbers of stars in the central field and in the other two fields combined. The observations were performed in service mode in July 2000, with the requirement of seeing ≤ 0.6", which is key to perform photometry in fields affected by stellar crowding.

Figure 1 shows the CMDs at the two galactocentric distances, together with a published Fornax HST CMD (Buonanno et al. 1999), for comparison. The CMD in Figure 1a corresponds to the central field, while Figure 1b displays the combined CMD of the off-center fields. Isochrones from Bertelli et al (1994) have been superimposed. Note that the photometric quality of the ground-based data is comparable to the HST quality in terms of depth and photometric dispersion, while many more stars, in proportion to the larger area covered, are present in the ground based CMDs. This is key to measuring sufficient numbers of stars in parts of the CMD that are important for deriving the SFH, such as the subgiant branch and the horizontal branch. Since Fornax is one of the most distant Milky Way satellites, this shows that, for most of them, ground based observations with large telescopes under excellent seeing conditions, are superior to HST. HST is, however, essential for more distant Local Group galaxies.

Both the central and the outer Fornax CMDs imply a very extended SFH for this galaxy,

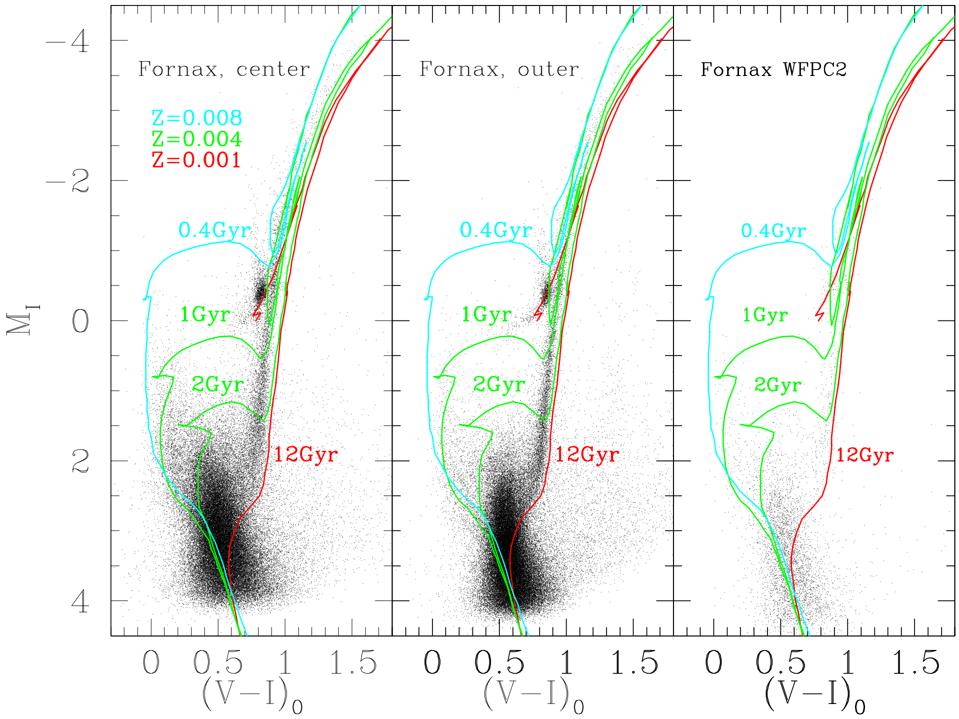

Fig. 1.1. a) CMD for a FORS1 field centered in Fornax (left panel); b) composite CMD for the two fields situated $\simeq$11 arcmin North from central field (central panel); c) HST WFPC2 CMD of a region in the central part of Fornax (right panel).

with star formation occurring from very early epochs to just 1 to 0.5 Gyr ago. No long periods of inactive star formation seem to have occurred. A gradient in the stellar populations is noticeable from the central to the outer fields, in the sense that the stars are younger on average in the central field. This can be noticed by comparing with the isochrones: in the outer field, the density of stars in the main sequence decreases quite sharply for stars younger than 2 Gyr (for Z=0.004), while the distribution of stars in the main sequence is very smooth in the CMD of the central field, where stars down to 0.4 Gyr are clearly present. The youngest star formation activity in the outer field, in contrast, seems to have ceased around 1 Gyr ago after a decrease 2 Gyr ago.

Our goal is to quantitatively derive the complete SFH in these fields, and characterize its spatial variation, using synthetic CMDs (as in Gallart et al. 1999) and the input on Z(t) from the Ca II triplet study (see below). These results will be presented in Gallart et al. (2004).

1.3 Stellar Metallicities from the Ca II Triplet

We obtained Ca II triplet spectroscopy for about 100 RGB stars in the central region of Fornax, using FORS1 at the VLT, in December 1999. We used grism GRIS-600I+15, resulting in a central wavelength near 7490 Å, a dispersion of 1.06 Å per pixel, and a

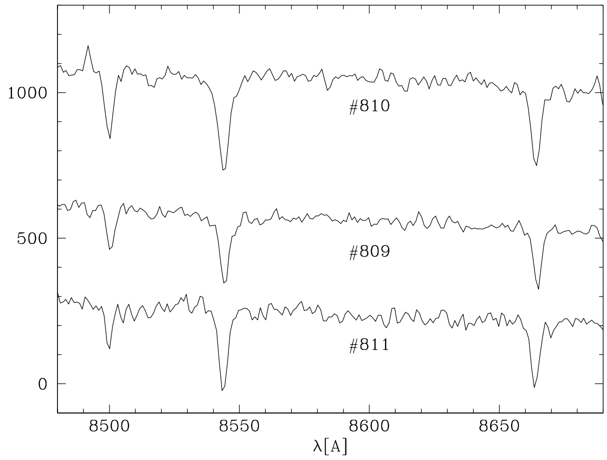

Fig. 1.2. Three representative spectra. **Top**: object with average metallicity ([Fe/H]~ -1). **Middle**: object with low metallicity ([Fe/H]~ -2). **Bottom**: spectrum that was considered too noisy to satisfy our quality criteria.

resolution R$\simeq$1530. The excellent seeing conditions during the observations -most of the time below 0.8" seeing- allowed us to use slitlet widths of 0.7 arcsec. We observed seven fields, with an average of 17 targets per field. For each, two 20-min exposures were acquired. The high quality of the resulting spectra is illustrated in Figure 1.2.

Pseudo equivalent widths were calculated from the spectra using passbands in and around the Ca II triplet lines. To place our measurements on the system of Rutledge, Hesser & Stetson (1999) (RHS hereafter), we followed closely their prescription for measuring the pseudo-equivalent widths. For the measurement of the combined equivalent width we used their definition of the weighted sum of the widths, ΣCa, which they defined as ΣCa$= 0.5w1 + w2 + 0.6w3$, where $w1, w2$ and $w3$ are the equivalent widths of individual Calcium lines (λ 8498, 8542, 8662 Å, respectively). We observed 19 red giants in the globular clusters NGC 2298, NGC 3201, and NGC 7099 for which values of ΣCa were measured by RHS or could be transformed to their system.

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. This quantity 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 much less clear that V-V(HB) is a 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. 2004) and have concluded that a calibration of ΣCa against M_I may produce more accurate results for the young populations present in Fornax (see Figure 1.3).

The mere location of the Fornax stars relative to the sequences of globular clusters of known metallicities in the ΣCa *vs.* M_I plane provides information on their metallicities that is completely unexpected from the position of the same stars in the [(V-I), M_I] CMD. In

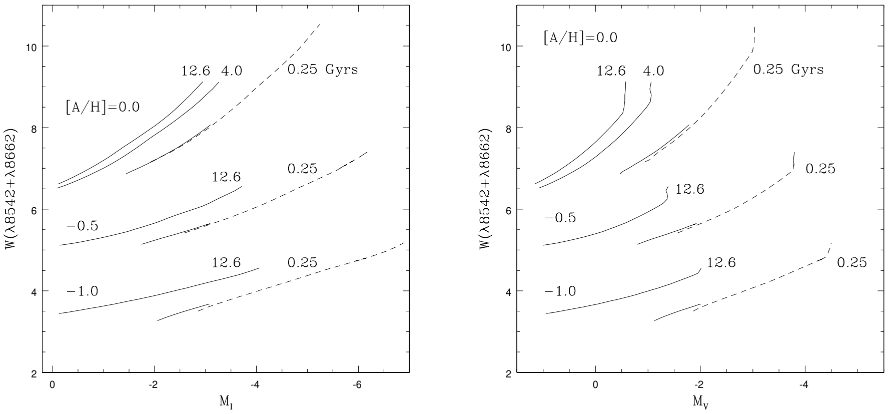

Fig. 1.3. Ca II line strength models for red giants in the M_I vs. EW (**left**), M_V vs EW (**right**) planes.

Figure 1.4a, the Fornax stars are plotted along with the RGB's of some of the clusters for which Ca II triplet data are available. The majority of the Fornax stars lie between the RGB's of M15 and NGC 1851. If all of these stars were very old, comparable in age to the globular clusters, then their metallicities should lie between [Fe/H]=–2 and −1.1, and their Ca II equivalent widths should lie between the sequences for these clusters. However, in the M_I - ΣCa plane (see Figure 1.4b), most of the Fornax stars lie above the line for NGC 1851, which indicates that a large fraction of the Fornax sample is more metal-rich than this cluster. Because these same stars are bluer than the RGB of NGC 1851 in the CMD (Figure 1.4a), they must be substantially younger stars. A sample of red giants in the metal-rich and young open cluster M11 stars are plotted (crosses) in these diagrams to illustrate the age effect: a metal-rich but young population is indistinguishable on the RGB from a metal-poor, old population. The relatively high metallicities of many of the young stars in Fornax was unexpected, and it constitutes the main result of our study.

We produced a calibration of W(Ca II) (the *reduced* equivalent width, defined as ΣCa at M_I=0) as a function of [Fe/H] using observations of the Ca II line strengths of 11 globular clusters and M67 from the literature, for which metallicities on the Carretta & Gratton (1997) scale were available. We used additional considerations that involve the comparison of the equivalent widths of the Fornax stars with those of better known systems such as the LMC or 47 Tuc to further constrain the metallicities of the metal-rich end of the Fornax population.

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 35% having abundances greater than 47 Tuc ([Fe/H]=–0.7) and up to [Fe/H] $\simeq -0.2$. The peak of the metallicity distribution occurs at [Fe/H] $\simeq -0.9$.

1.4 The Fornax Age-Metallicity Relation

The combination of the spectroscopic metallicity for each star with its color on the RGB provides a constraint on its age, and therefore, a well delineated age-metallicity relation can be obtained, especially for the more metal-rich, young stars: the colors of most

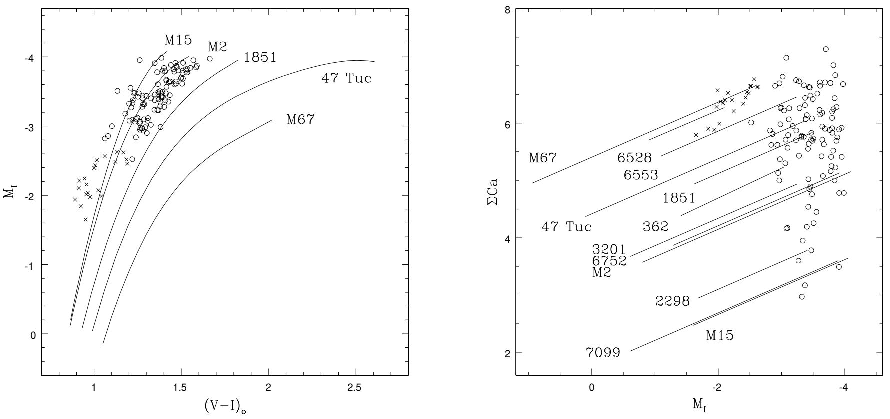

Fig. 1.4. a) The position of the red giants in Fornax and in M11 in the (V-I)–M_I CMD (left) and b) in a plot of ΣCa against absolute I magnitude (right). For comparison, the corresponding sequences of some clusters are plotted in the two diagrams. In the right hand diagram, the lengths of the lines indicate the span of M_I covered by the red giants in the clusters. These clusters were used to calibrate the diagram in terms of metallicity.

metal-rich RGB stars are much bluer than those of an old globular cluster of the same metallicity, and lead to the conclusion that they must be much younger. Indeed, while for each given metallicity, stars older than $\simeq$ 3 Gyr have a small range in color, the younger stars are substantially and increasingly bluer with decreasing age. In Figure 1.5 we display a preliminary version of the Fornax age-metallicity relation obtained by Pont et al. (2004). In the first few Gyr, the metal abundance of Fornax rose to [Fe/H]~ -1. A period of slower enrichment then ensued, with a more rapid increase to [Fe/H]~ -0.4 in the past $\sim$1-4 Gyr. More that half the sample seems to be constituted of star younger than $\sim$ 4 Gyr, thus indicating sustained recent star formation in Fornax.

1.5 Comparison with the Mac Low & Ferrara (1999) Predictions

It is interesting to compare the properties of Fornax with the predictions by Mac Low & Ferrara (1999, MF99). In order to identify where is Fornax in the MF99 parameter space, we will derive its baryonic mass, and an estimate of its likely SNe rate from data in the literature. The total (virial) mass of Fornax is $\sim 7 \times 10^7$ (Mateo 1998); by assuming the $(M/L)_{tot,V} = 4.4$ given in the same paper, and a baryonic $M/L \simeq 1.0$ (calculated for a population with constant star formation rate from 12 to 0.5 Gyr ago), this corresponds to a baryonic mass of $M_g = 1.6 \times 10^7 M_\odot$. For a constant star formation rate, it corresponds to a rate 1400 $M_\odot$ Myr^{-1}. For a Salpeter IMF, and this star formation rate, 146 $M_\odot$ Myr^{-1} of stars would be produced in the mass interval of SNe II progenitors, 10-100 $M_\odot$, with mean mass $\simeq 20 M_\odot$. These figures imply a rate of $\simeq$ 8.5 SNe/Myr, or a SNe luminosity $\simeq 2.5 \times 10^{38}$ ergs s^{-1}. If we input these data in 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.

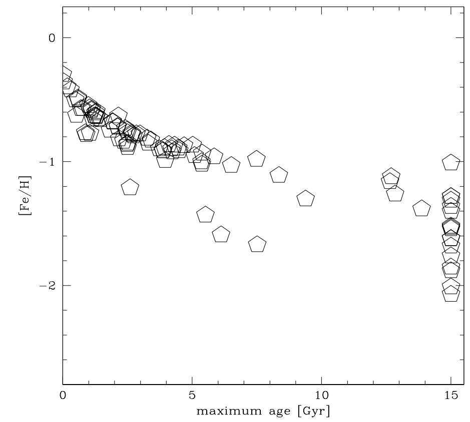

Fig. 1.5. Preliminary age-metallicity relation obtained for Fornax from Ca II triplet spectroscopy and RGB photometry.

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.

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