Chemical analysis of the Fornax Dwarf galaxy
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The object of this thesis has been to determine detailed chemical abundances of individual stars in the nearby Fornax dwarf spheroidal galaxy, based on high resolution observations with the VLT spectrographs UVES and FLAMES. Fornax, is one of the few dwarf galaxies to have an extensive population of globular clusters (with 5), and it has also had a complex field star formation history dominated by a star formation at intermediate ages. For this thesis, samples of individual stars were studied in both the globular clusters and in the field star populations of Fornax.

7.1 New Data Reduction and Analysis Techniques

UVES is an Echelle spectrograph for which classical observations of single stars followed by careful data reduction and analysis star by star is possible. FLAMES is a powerful new multiplexing spectrograph that was more challenging to use. It required new techniques to be developed, from the preparation of the observing run to the last steps of getting the stellar abundances. In the case of FLAMES the 100+ fibres that were typically allocated to scientific targets made a high degree of automating very important. Another important aspect was the relatively low resolution (of the HR mode) of GIRAFFE and also the limited wavelength coverage. This required careful adjustments and testing of the usual approach applied to UVES data.

An important achievement of this thesis is the method developed to analyse approximately one hundred stellar spectra in a consistent and statistically robust manner, using tools that are typically used on spectra with twice the resolution and larger wavelength coverage. This required bringing together several complex tasks, including accurate stellar atmospheric models, atomic data for the absorption lines, codes of line formation, $EW$ measurements and signal extraction methods, all of which need to be properly included and treated in order to obtain accurate results. We developed a pipeline that delivers stellar parameters and abundances in a controlled manner. This involved developing error analysis and diagnostics to carefully test the robustness of the results.
7.2 The Fornax Globular Clusters

The Fornax dSph contains five globular clusters with a range of properties such as metallicity, central concentration and Horizontal Branch structure. Using VLT/UVES we have taken the first high resolution spectra of individual stars in the Fornax globular clusters. We obtained detailed chemical abundances for 9 individual RGB stars in 3 of the 5 Fornax globular clusters. This makes the Fornax globular clusters some of the very few extra-galactic globular clusters that have been studied in this detail. From my results it is clear that Clusters 1, 2 and 3 were formed promptly and early in the history of Fornax dSph. They are over abundant in $\alpha$-elements (O, Mg, Ca) at a similar level to Galactic clusters at identical [Fe/H], and the heavy element abundances (Y, Ba, Eu) in the 3 clusters are compatible with dominant $r$-process enrichment. In addition, Cluster 1 is found to be the most metal-poor globular cluster known, although the difference in metallicity between Cluster 1 and M 92 or M 15 in the Milky Way is small.

Thus, despite their very different mass, morphology and global star formation history, the abundance patterns of individual stars in the Fornax GCs are almost identical to those found in the Milky Way globular clusters. This extends to the ubiquitous deep-mixing patterns found among globular cluster members that were detected in two stars of Cluster 1 and Cluster 3, and the rare anomalies like the Eu-rich stars of Cluster 3 for which the only Galactic counterpart known to date is M15. This suggests that all globular clusters, regardless of their host galaxy, were formed with the same initial conditions at their epoch of formation, namely the same pre- or self-enriched processes and identical nucleosynthesis patterns.

7.3 Fornax Field stars

Thanks to the multi-fibre capability of FLAMES we have been able to make detailed abundance measurements of a large sample of 81 RGB stars in the central part of Fornax. This is a significant, even dramatic, improvement on the previous UVES sample of 3 individual field stars. Our abundance ratios provide detailed information as to what were the chemical enrichment processes in Fornax, and how they differ from the MW.

We find that Fornax field stars exhibit unusually low $\alpha$-element ratios, as well as Ni and Na abundances. The $[\alpha/{\rm Fe}]$ dependence on $[\rm Fe/H]$ is different from the Milky Way, meaning that there has been a different efficiency of chemical enrichment of the ISM. Fornax field stars are clearly predominantly enriched by s-process elements, showing the strong role of (metal poor) AGB stars. This is clearly seen from the high $[\rm Ba/Y]$ ratios, compared to the Milky Way.

Our sample, which was randomly chosen from the entire breadth of the RGB, is dominated by a relatively young, relatively metal rich population (see Figure 7.1). This means that we have obtained the most detailed picture of the chemical enrichment of Fornax during the last $\sim 4$ Gyrs. There is only one field star in our sample which appears to be old and metal poor, and its properties are almost indistinguishable from the globular clusters in Fornax, and also from Galactic halo stars at the same [Fe/H]. Figure 7.1 shows the main abundance results (alpha, Ba, and Eu) versus time. The ages were determined
Figure 7.1: Here we show the result of our abundance analysis for alpha elements, and an s- and an r-process element compared to the ages of the individual stars observed in Fornax field star population. Representative error bars are shown on the bottom left corner of each panel.

from a colour-magnitude diagram finding the appropriate isochrone using the detailed spectroscopic abundances (Fe, and alpha). This allows us to determine how the different abundances vary with time.

The $[\alpha/\text{Fe}]$ ratios were higher in the past and have gradually decreased towards more recent times. This is a sign that SN Ia are becoming increasingly important with time, similar to what we were able to deduce from the $[\alpha/\text{Fe}]$ versus $[\text{Fe/H}]$ plot of chapter 6. It is clear that the s-process abundances (e.g., $[\text{Ba/Fe}]$) show a slow increase in the contribution with increasing time (and $[\text{Fe/H}]$). This means that as the stellar population
becomes more metal rich there has been a steady rise in the Ba abundance, and the ages of the stars show that this rise began about 2-4 Gyr ago. The s-process is a much stronger contributor to the chemical evolution of Fornax than it is to the MW, or the Sculptor dSph. This suggests that stellar winds (e.g., from AGB stars) have played a uniquely important role in the (recent, 2-4 Gyr ago) enrichment history of Fornax. There is no such trend in r-process, shown in the [Eu/Fe] panel of Figure 7.1. With the exception of the Eu-rich Cluster 3 points, all the observed stars in Fornax have a more or less constant [Eu/Fe].

Our detailed abundance studies confirm and deepen the difficulties found in earlier more limited surveys in understanding the role (if any) of dwarf galaxies, such as Fornax in the build up of our Milky Way. These results also challenge our understanding of basic nucleosynthetic processes, with for example, ratios of [Ni/Fe] that are well below what was typically thought possible.

Further work on Fornax will be to investigate the different regions of this surprisingly complex dwarf galaxy in more detail, and specifically to increase our sample of high resolution abundances for metal poor stars in Fnx.