VLT/UVES ABUNDANCES IN FOUR NEARBY DWARF SPHEROIDAL GALAXIES. II. IMPLICATIONS FOR UNDERSTANDING GALAXY EVOLUTION

Eline Tolstoy
Kapteyn Institute, University of Groningen, P.O. Box 800, NL-9700 AV Groningen, Netherlands

Kim A. Venn
Macalester College, 1600 Grand Avenue, Saint Paul, MN, 55105; University of Minnesota, 116 Church Street, S.E., Minneapolis, MN 55455

Matthew Shetrone
McDonald Observatory, University of Texas, HC75 Box 1337-L, Fort Davis, TX 79734

Francesca Primas
European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

Vanessa Hill
Observatoire de Paris-Meudon, GEPI, Place Jules Janssen 2, F-92195 Meudon Cedex, France

AND

Andreas Kaufer and Thomas Szeifert
European Southern Observatory, Alonso de Cordova 3107, Santiago 19, Chile

Received 2002 August 19; accepted 2002 November 5

ABSTRACT

We have used the Ultraviolet Visual-Echelle Spectrograph (UVES) on Kueyen (UT2) of the Very Large Telescope to take spectra of 15 individual red giant stars in the centers of four nearby dwarf spheroidal galaxies (dSph's): Sculptor, Fornax, Carina, and Leo I. We measure the abundance variations of numerous elements in these low-mass stars with a range of ages (1–15 Gyr old). This means that we can effectively measure the chemical evolution of these galaxies with time. Our results show a significant spread in metallicity with age, but an overall trend consistent with what might be expected from a closed- (or perhaps leaky-) box chemical evolution scenario over the last 10–15 Gyr. We make comparisons between the properties of stars observed in dSph's and in our Galaxy's disk and halo, as well as globular cluster populations in our Galaxy and in the Large Magellanic Cloud. We also look for the signature of the earliest star formation in the universe, which may have occurred in these small systems. We notice that each of these galaxies show broadly similar abundance patterns for all elements measured. This suggests a fairly uniform progression of chemical evolution with time, despite quite a large range of star formation histories. It seems likely that these galaxies had similar initial conditions, and that they evolve in a similar manner with star formation occurring at a uniformly low rate, even if at different times. With our accurate measurements we find evidence for small variations in abundances, which seem to be correlated to variations in star formation histories between different galaxies. The α-element abundances suggest that dSph chemical evolution has not been affected by very high mass stars (>15–20 M☉). The abundance patterns we measure for stars in dSph's are significantly different from those typically observed in the disk, bulge, and inner halo of our Galaxy. This means that, as far as we can tell from the (limited) data available to date, it is impossible to construct a significant fraction of our disk, inner halo, or bulge from stars formed in dSph's such as we see today, which subsequently merged into our own. Any merger scenario involving dSph's has to occur in the very early universe while they are still gas-rich, so the majority of mass transfer is gas and few stars.

Key words: galaxies: abundances — galaxies: dwarf — galaxies: individual (Sculptor, Fornax, Carina, Leo I) — stars: abundances

1 INTRODUCTION

With high-resolution spectrographs on 8 m class telescopes, such as UVES on VLT/UT2, we can take detailed spectra of individual stars in nearby dwarf galaxies and start to seek answers to detailed questions about the enrichment history of a variety of different elements in galaxies other than our own. It is critical to our understanding of galaxy evolution to accurately measure how the fraction of heavy elements in a galaxy builds up over time. It is impossible to accurately analyze a color-magnitude diagram (CMD) and extract a unique star formation history (SFH) without independent information on the metallicity of the stars and how this may have changed with time. The oldest stars we find in the nearby universe are of an age similar to, if not greater than, the look-back time of the most distant galaxies found in the highest-redshift galaxies known.

There are many theories as to how the chemical enrichment of subsequent generations of stars may occur in dwarf galaxies (e.g., Silk, Wyse, & Shields 1987; Pagel 1997), and there are also a significant number of measurements of nebular abundances and young stars today that undoubt-

1 Based on Ultraviolet-Visual Echelle Spectrograph observations collected at the European Southern Observatory, proposals 66.B-0320, 65.N-0378, 62.N-0653, and 61.A-0275.
edly carry the imprint of past enrichment patterns (e.g., Matteucci & Tosi 1985; Pagel & Tautvaišienė 1998; Venn et al. 2001). However, extracting unique chemical evolution scenarios from these data is very difficult. The only way to accurately determine absolute abundances at different ages in the history of a galaxy is to take high-resolution spectra of old low-mass stars with a range in age (color and luminosity). With extragalactic stars in nearby galaxies we are forced to look at the brightest stars we can, the red giant branch (RGB) stars, which were formed during the last 1–15 Gyr. The abundances of different elements provide an indication of the number and type of supernovae enrichments that have preceded the formation of these stars. Thus, we can measure the evolution of these galaxies in great detail from the earliest times up to the epoch of last star formation. From previous studies there are well-established techniques for detailed abundance analysis (e.g., Shetrone, Bolte, & Stetson 1998; Shetrone, Côte, & Sargent 2001a, hereafter SCS01; Hill et al. 2000, hereafter H00), which we can apply to the same type of stars in our sample of southern dwarf spheroidals.

Dwarf spheroidal galaxies (dSph’s) are intriguing systems. They are our nearest neighbors, and so we can study them in great detail. Within the Local Group they are mostly satellites of larger galaxies, such as our own Galaxy and M31 (e.g., van den Berg 2000). Originally, all dSph’s were believed to be essentially old systems similar to globular clusters, although there were hints to the contrary from the RR Lyrae stars and anomalous Cepheids, which suggested that their underlying stellar populations were fundamentally different from those of globular clusters (e.g., Baade 1963; Zinn 1980). Zinn suggested that the difference was due to the dSph systems being on average younger than globular clusters. Subsequent deep photometric observations of the main-sequence turnoffs (MSTOs) in these galaxies confirmed the presence of intermediate-age populations in some galaxies and always an age spread at the earliest times, completely unlike most globular clusters. The dSph’s are typically small, faint, and diffuse, non-nucleated systems, and yet they have complex SFHs. For most of these systems the SFHs have been accurately measured from main-sequence–turnoff photometry. These galaxies have typically no associated ISM, no H i gas (in the center), although there have been tentative detections of gas in the outlying regions of a few nearby dSph’s (e.g., Carignan et al. 1998).

Despite considerable efforts with 4 m class telescopes, many of the most basic questions remain unanswered for most of the Local Group dSph’s. How and when were they formed? Are they left over building blocks of our Galaxy? How has environment affected their evolution? To have a hope of addressing these complex and difficult questions, we need to first answer such mundane ones as the following: What is the total range in [Fe/H] for stars within a given dSph? Does the [Fe/H] match that of our halo populations (globular clusters or field stars)? Do the elemental ratios (particularly [α/Fe] and [r- and s-process/Fe] ratios) in dSph stars track those seen in the metal-poor field or the globular clusters? In addition, there is strong evidence for a difference in the ratios of C, N, O, Na, Mg, and Al to Fe between field Population II giants and globular cluster giants (e.g., Pilachowski, Sneden, & Kraft 1996; Shetrone 1998). This difference is presumably related to the extent to which deep dredging occurs in giants, but if (and how) this is ultimately caused by variations in environment between globular cluster and field stars remains a mystery. However, if the dSph’s are “globular cluster-like” in this regard, it would present a problem for the idea that the Galactic halo is composed of dispersed dSph galaxies (e.g., Zinn 1993; Shetrone 1998).

Detailed studies of the abundance patterns of stars in dSph’s can constrain the effects of discrete star formation episodes and different SFHs on chemical evolution (e.g., McWilliam 1997). UT2+UVES provides a unique opportunity (in the southern hemisphere) to extend detailed stellar abundance work to stars in external galaxies. This kind of study has only been possible so far with HIRES on Keck (e.g., Shetrone et al. 1998; SCS01), where it has been clearly shown that detailed abundance analysis of stars in nearby galaxies is feasible and can place important constraints on metallicity dispersions and what they mean for the metallicity evolution of nearby galaxies. We looked at samples of stars in four nearby dwarf spheroidal galaxies: Sculptor, Fornax, Carina, and Leo I. We also looked at four stars in three well-studied Galactic globular clusters (M30, M55, M68), to check that at least our calibrations put us on the same abundance scale as previous studies. Globular clusters also serve as an interesting comparison to the observations of stars in dSph’s.

In Sculptor and Fornax there are recently published low-resolution Ca ii triplet (CaT) spectra of a sample of RGB stars (Tolstoy et al. 2001, hereafter T01). These UVES data thus provide a detailed check of the CaT method, which has been used to estimate iron abundances in RGB stars, based on calibrations in the Galaxy (e.g., Armandroff & Da Costa 1991; Rutledge, Hessler, & Stetson 1997).

From our high-resolution spectra the most basic measurement that we can make is the iron abundance ([Fe/H]) in the atmospheres of these RGB stars. Iron is the typical element used to define the fundamental metallicity of a system. From high-resolution spectra we typically have nearly 70 lines of Fe i and around 15 of Fe ii, which allows the determination of an exceptionally secure value for [Fe/H] independent of the usual caveats and uncertainties accompanying the determination of abundance from a single line, and especially all the additional problems of measuring a different element (such as Ca or Mg) and converting this to [Fe/H]. From high-resolution spectra there are also a host of other elements for which an accurate abundance can be obtained. These give us additional insights into the details of past star formation processes in these galaxies (see McWilliam 1997 and references therein).

Light elements (e.g., O, Na, Mg, Al) allow us to trace “deep-mixing” abundance patterns in RGB stars. This is a very distinctive pattern of abundances that are markedly different in globular cluster giants and field stars. There are also the group of α-elements (e.g., O, Mg, Si, Cu, Ti), elements with even Z. The production of these elements is dominated by Type II supernovae (SNe II). They affect the age estimates based on RGB isochrones, as lower α-tracks are bluer than high α-tracks. The α-abundance limits the number of SN II explosions that can have polluted the gas from which the star was made and, thus, contains estimates of the fraction of lost ejecta and/or IMF variations in the stellar populations of a galaxy through time. The iron peak elements (e.g., V, Cr, Mn, Co, Ni, Cu, Zn) are mostly believed to be the products of explosive nucleosynthesis. The level of the iron peak can (in principle) limit the most
massive progenitor that can have exploded in the galaxy (e.g., Woosley & Weaver 1995). Cu has been thought to be primarily produced in Type Ia supernovae (SNe Ia), and hence [Cu/α] could be an indicator of the ratio SNe Ia/SNe II. However, there is no physical basis for this assumption. It is also possible to account for Cu evolution in the halo using metallicity-dependent SN II yields (e.g., Timmes, Woosley, & Weaver 1995). Heavy metals (Z > 30, e.g., Y, Ba, Ce, Sm, Eu) enable a distinction to be made between the fraction of s-process and r-process elements in a star, and this again puts detailed constraints on the number and type of past SN explosions. The [Ba/Eu] ratio can be considered an indicator of the contribution of AGB stars to the chemical evolution process. One has to be a bit careful, since some stars can self pollute their [Ba/Eu] ratio (but usually they stand out as having very large Ba/Fe ratios). Since AGB stars have a several gigayear timescale for chemical contamination of the ISM they provide yet another type of clock.

By looking at dSph’s we are studying an environment which is metal-poor ([Fe/H] < −1.0) and often with complex SFH. This describes the properties of the galaxies found to dominate deep redshift surveys and hence the Universe (e.g., Madau, Pozzetti, & Dickinson 1998). Indeed, if the standard models of galaxy formation are to be believed, small dwarf galaxies are the oldest structures in the universe (e.g., White & Rees 1978; Moore et al. 1999; Klypin et al. 1999). Because dSph stars are relatively easy to age date from a CMD if (at least) [Fe/H] is known (more accuracy is obtained if [α/Fe] is also known), and given that dSph’s always contain ancient stellar populations, there are potentially stars carrying the nucleosynthetic signature of the earliest epochs of star formation in the universe (e.g., Abel, Bryan, & Norman 2002; Bromm, Coppi, & Larson 2002; Heger & Woosley 2002). We make a comparison with the abundance patterns we observed in the oldest stars in the dSph’s with theoretical predictions of the formation of the first star(s).

2. OBSERVATIONS

We observed 15 individual RGB stars in four nearby southern dSph galaxies which we can add to the 17 RGB stars previously observed in three northern dSph’s with Keck/HIRES by SCS01 (see Table 1). We selected RGB stars to cover as much range in color as possible in each galaxy to sample the diversity in [Fe/H] and age and thus gain an insight into how stellar abundances have varied over the history of the galaxies (∼1–15 Gyr).

Our observations were obtained in visitor mode, with UT2/UVES (Dekker et al. 2000) on two separate visitor runs on Paranal, one in 2000 August, and one in 2001 January. We used the red arm of UVES, CD No. 3, centered at 580 nm, which results in a wavelength range of 480–680 nm. We obtained a resolution of ∼40,000 and average S/N ∼ 30 pixel⁻¹. The integrations varied from 2–4 hr depending upon the brightness of the target and sky conditions. The details of the individual observations and the data reduction are contained in Shetrone et al. (2003, hereafter Paper I).

Covering the wavelength range 480–680 nm, we detected a range of elements, including Fe i, Fe ii, O i, Na i, Mg i, Ca i, Sc ii, Ti i, Ti ii, Cr i, Ni i, Y ii, Ba ii, Eu ii, La ii, Zn ii, Cu i, Mn i (see Paper I for complete tables). This allowed us to achieve the comprehensive abundance analysis described in Paper I. We are able to make especially reliable abundance measurements because we determine abundances from more than one line for several elements, most crucially Fe ii. The error analysis in abundance determinations from high resolution spectra is complex and difficult, and the procedures and checks we carried out are described in detail in Paper I.

3. RESULTS

3.1. Calibration Globular Clusters

We observed four previously studied stars in three globular clusters to verify our data reduction techniques and confirm that our abundances are consistent with previous measurements of the same stars with different instruments and telescopes (see Paper I). We have also compiled from the literature observations of other Galactic globular clusters (from SCS01), and also LMC star clusters (from H00; Hill & Spite 2001; Hill et al. 2003) to compare the elemental abundance patterns typical in globular clusters with those found in dSph’s.

The LMC clusters are in many ways the most reliable measures of abundance variations with time due to galaxy scale evolution because of the relative ease to age date globular cluster stars and the spread of ages in LMC clusters. The data set of H00 is a useful comparison with our results. Care should be taken in understanding the uncertainties in a few specific cases (see H00). Also direct comparisons between globular cluster and field star age-metallicity relationships are a little uncertain, because it is well known that the properties of star clusters do not always transfer readily to the field star population (e.g., Shetrone 1996). Nevertheless, the LMC star clusters provide an age-metallicity range with which to compare our results. Recent CaT measure-

| Object         | l      | b      | (m–M)₀     | B–V         | Mᵥ     | Σ₀     | vₛ     | Mₜₐₓ (10⁶ M☉) |
|----------------|--------|--------|------------|-------------|--------|--------|--------|----------------|
| Sculptor ...... | 287.5  | −83.2  | 19.54 ± 0.08 | 0.02 ± 0.02 | −11.1  | 23.7 ± 0.4 | 110 ± 3 | 6.4            |
| Carina .......  | 260.1  | −22.2  | 20.03 ± 0.09 | 0.025 ± 0.02 | −9.3   | 25.5 ± 0.4 | 224 ± 3 | 13             |
| Leo I .......... | 226.0  | +49.1  | 21.99 ± 0.20 | 0.01 ± 0.01  | −11.9  | 22.4 ± 0.3 | 286 ± 2 | 22             |
| Fornax ........ | 237.1  | −65.7  | 20.70 ± 0.12 | 0.03 ± 0.01  | −13.2  | 23.4 ± 0.3 | 53 ± 3  | 68             |
| Draco .......... | 86.4   | +34.7  | 19.58 ± 0.15 | 0.03 ± 0.01  | −8.8   | 25.3 ± 0.5 | −293 ± 2 | 22             |
| Ursa Minor ..... | 105.0  | +44.8  | 19.11 ± 0.10 | 0.03 ± 0.02  | −8.9   | 25.5 ± 0.5 | −248 ± 2 | 23             |
| Sextans ....... | 243.5  | +42.3  | 19.67 ± 0.08 | 0.03 ± 0.01  | −9.5   | 26.2 ± 0.5 | 227 ± 3 | 19             |

Note.—All these data are taken from Mateo 1998.
ments of a large sample of field stars in the LMC (Cole et al. 2003) suggest that the LMC field star population follows the same age-metallicity relationship as the clusters (without the gaps).

3.2. The Dwarf Galaxies

For each of the four dSph’s we used imaging taken at the NTT (Tolstoy et al. 2003) and supplemented by VLT archival images to select and determine the color of individual stars as targets for spectroscopic observation, and where possible we found radial velocity information about our targets from previous studies, which helps to a priori determine membership of stars in the dwarf galaxies.

From our UVES spectra we obtain an accurate [Fe/H] measurement for each star which allows us to compare its color and [Fe/H] with the appropriate isochrone set to determine the age. The previous age determinations for the stars in Sculptor and Fornax from the CaT observations of T01 used Padua isochrones (Bertelli et al. 1994), which assume $\alpha$-enhanced abundances ($[\alpha/Fe] = +0.5$), and as our high-resolution measurements suggest that in the mean dSph stars have roughly solar $\alpha$ abundance we have redone the CaT age determinations using the new Yale-Yonsei isochrones (Yi et al. 2001), which assume solar $\alpha$ abundance. This results in a small shift to older ages on average, but the trend (such as it is) does not seem to change markedly compared to T01. For our UVES spectra we have used exclusively the new Yale-Yonsei isochrones of Yi et al. to age date the stars observed (Table 2). Comparisons were made with Bergbusch & VandenBerg (2001) and Bertelli et al. (1994), see also Tolstoy (2002), and although there were differences no other set of tracks was significantly better (or worse) than another. We chose Yale-Yonsei because they went down to very young ages (unlike Bergbusch & VandenBerg) and they covered a range of $\alpha$-values down to zero. We also used the Yale-Yonsei isochrones to determine the ages of the dSph stars observed by SCS01 (see Table 3).

There is a marked degree of uncertainty in the ages determined from the RGB tracks, and an additional uncertainty coming from the errors on the measurement of [Fe/H]. There are some stars which do not fit any of the isochrones of the appropriate (observed) [Fe/H] for a star. Typically they are too red (or too old) for any of the tracks, but sometimes too blue. This makes it clear that a simple global offset (e.g., absolute photometric offset, reddening) does not solve the problem. It might be that there is more differential reddening in some of these galaxies than is realized. It is also possible that some of the stars which are on the blue side of RGB are in fact unidentified AGB stars (e.g., in Sculptor), and the stars on the red side of the isochrones are weak CH stars (e.g., Shetrone, Coè, & Stetson 2001b found large numbers in Sculptor), and the stars unidentified AGB stars (e.g., in Sculptor), and the stars

| Galaxy    | Star ID | Age (Gyr) | [Fe/H]       | [O/Fe]      | [Mg/Fe]    | [Ca/Fe]    | $[\alpha/Fe]$ |
|-----------|---------|-----------|--------------|-------------|------------|------------|-------------|
| Sculptor  | H459    | 15$^{+1}_{-2}$ | $-1.66 \pm 0.02$ | $0.12 \pm 0.15$ | $0.36 \pm 0.13$ | $0.24 \pm 0.05$ | 0.18         |
|           | H479    | 15$^{+1}_{-2}$ | $-1.77 \pm 0.02$ | $0.38 \pm 0.11$ | $0.26 \pm 0.16$ | $0.17 \pm 0.05$ | 0.13         |
|           | H461    | 15$^{+1}_{-2}$ | $-1.56 \pm 0.02$ | $0.34 \pm 0.16$ | $0.18 \pm 0.11$ | $0.22 \pm 0.06$ | 0.13         |
|           | H482    | 10$^{+2}_{-1}$ | $-1.24 \pm 0.02$ | $0.08 \pm 0.18$ | $0.09 \pm 0.13$ | $0.06 \pm 0.06$ | $-0.01$      |
|           | H400    | 15$^{+1}_{-2}$ | $-1.98 \pm 0.03$ | ...          | $0.37 \pm 0.12$ | $0.38 \pm 0.09$ | 0.23         |
| Fornax    | M12     | 15$^{+1}_{-2}$ | $-1.60 \pm 0.02$ | $0.12 \pm 0.18$ | $0.09 \pm 0.07$ | $0.23 \pm 0.06$ | 0.12         |
|           | M25     | 10$^{+1}_{-2}$ | $-1.21 \pm 0.02$ | $0.07 \pm 0.11$ | $0.02 \pm 0.09$ | $0.21 \pm 0.06$ | 0.03         |
|           | M21     | 8$^{+1}_{-2}$  | $-0.67 \pm 0.03$ | $0.02 \pm 0.17$ | $0.20 \pm 0.12$ | $0.23 \pm 0.08$ | 0.27         |
| Leo I     | M5      | 8$^{+0.5}$    | $-1.52 \pm 0.02$ | $0.43 \pm 0.13$ | $0.12 \pm 0.12$ | $0.15 \pm 0.06$ | 0.13         |
|           | M2      | 11$^{+1}_{-2}$ | $-1.59 \pm 0.02$ | $0.12 \pm 0.09$ | $0.26 \pm 0.09$ | $0.14 \pm 0.04$ | 0.14         |
| Carina    | M4      | 10$^{+2}_{-1}$ | $-1.65 \pm 0.02$ | $-0.06 \pm 0.12$ | $-0.27 \pm 0.12$ | $-0.10 \pm 0.06$ | $-0.26$      |
|           | M3      | 10$^{+2}_{-1}$ | $-1.60 \pm 0.02$ | $0.34 \pm 0.12$ | $0.23 \pm 0.10$ | $0.20 \pm 0.05$ | 0.17         |
|           | M2      | 10$^{+2}_{-1}$ | $-1.41 \pm 0.02$ | $0.07 \pm 0.10$ | $0.24 \pm 0.10$ | $0.12 \pm 0.05$ | 0.13         |
|           | M0      | 10$^{+2}_{-1}$ | $-1.94 \pm 0.02$ | $-0.02 \pm 0.19$ | $0.06 \pm 0.11$ | $-0.02 \pm 0.05$ | 0.05         |
example of the problems we have encountered in Sculptor and Fornax are plotted in Figures 1 and 2. There were not such severe problems in determining the ages of stars in the Carina and Leo I stars, as they fall into the expected color range of the appropriate theoretical stellar isochrones, but given the problems in Fornax and Sculptor all the isochrone ages should still be viewed with some caution.

We checked the Galactic Na i interstellar absorption line in all our spectra to try and understand how reliable the reddening estimates we have used might be. There is clearly evidence for variation in line width between all the galaxies and also between individual stars in each galaxy. These variations could be interpreted as evidence for differential reddening, but the correlation between Na i line width and $E(B-V)$ is a very uncertain and complex problem (e.g., Munari & Zwitter 1997; Andrews, Meyer, & Lauroesch 2001). The variations we find fall broadly into the scatter of this relationship.

Looking at where our spectroscopic targets lie in a CMD and comparing them to globular cluster RGB fiducials (Da Costa & Armandroff 1990) we found that globally speaking the more metal-rich stars are to the red of the more metal-poor, consistent with what you would expect from a population where the older stars have the lower metallicity. However, going from a determination of relative ages to absolute ages requires accurate isochrones. Our problems with isochrones suggest that perhaps there are more factors than age, $[\text{Fe/H}]$ and $[\alpha/\text{Fe}]$ that are required to uniquely define the correct isochrones for stars in dSph’s. This might be due to differences in stellar evolution in globular clusters from galaxies (e.g., different mixing lengths, rotation rates, binary fractions, etc.), or perhaps more simply the theoretical stellar evolution models are not able to take into account the different abundance patterns in nonglobular cluster stars (e.g., $\alpha$-elements, and also the light elements). For example, Na is (along with K) by far the most important $e^{-}$ donor in the atmosphere of an RGB star, and $[\text{Na}/\text{Fe}]$ is depleted in
dSph stars relative to stars in most globular clusters. It seems that all isochrones have difficulty determining the ages of stars in galaxies, but this is not a problem in globular clusters (e.g., Tolstoy 2002).

There are main-sequence–turnoff star formation histories for all these galaxies, so we know which age range to expect, but it is clear that the only way to resolve these problems with isochrones in galaxies fully is to get more spectra and see if a pattern emerges. Not only in understanding the star formation processes at the formation epoch, but also in understanding the problems in matching low-metallicity stellar evolution tracks to stars in these galaxies.

The previous CaT results from T01 are plotted in the following sections as small pink circles, and a representative error bar is also shown on the plot. No individual error bars are plotted for the CaT values, because they are too large, and make the plot unreadable (see T01). The new UVES results are plotted as symbols with individual error bars. The error bars are determined from the equivalent width measurement errors in the UVES spectra and the resulting uncertainty of this error on the age determination based on the range of isochrones within the [Fe/H] error bars. We also plot for comparison other observations of age and [Fe/H] for stars in the Galactic disc from Edvardsson et al. (1993, hereafter E93) as small black dots, and the UVES study of the LMC clusters from H00 as light blue star symbols.

The dashed line(s) in the metallicity evolution figures describe the most simple (closed-box) chemical evolution model (as first described by Searle & Sargent 1972). Searle & Sargent define a yield as the ratio of the rate at which an element is produced by nucleosynthesis and ejected into the ISM to the rate at which hydrogen is removed from the interstellar gas by star formation. We assume that these dSph galaxies have used up all their gas forming stars at the time of the last star formation in the galaxy. The [Fe/H] they achieved in doing so is the metallicity of the most recent star formation. This allows us to determine the value of the yield as defined by Searle & Sargent for each galaxy, and, assuming it is constant, we can work back to how [Fe/H] has varied over time by assuming that the star/gas ratio has been changing at the star formation rate determined from

**Fig. 2.**—Same as Fig. 1, but for imaging of and targets in Fornax.
CMD analysis. This is ad hoc, but it provides a basic estimate of how [Fe/H] may have varied as a result of the SFH of each dSph.

We also plot in each metallicity evolution figure as a dotted line the LMC age-metallicity relation as determined by the bursting model of Pagel & Tautvaisené (1998).

The Galactic disk age-metallicity observations are included only as a broad based comparison, they have of course been differently determined coming from spectra of main-sequence–turnoff stars. These have different errors and uncertainties from the RGB spectra we use. Reassuringly, abundance measurements of giants and subgiants in Galactic globular NGC 6397 (Castilho et al. 2000) find similar results to a study of main-giants and subgiants in Galactic globular NGC 6397 spectra we use. Reassuringly, abundance measurements of these have different errors and uncertainties from the RGB abundances we include only as a broad based comparison, they have of course been differently determined coming from spectra of main-sequence–turnoff stars.

3.3. Sculptor Dwarf Spheroidal

From the NTT CMD (Fig. 3) we selected stars bright enough to be observed by UVES, and where possible we found radial velocity information about our targets from previous studies (Queloz, Dubath, & Pasquini 1995; Schweitzer et al. 1995). The UVES targets and the stars previously observed with FORS1 to measure the CaT metallicity are marked on Figure 3.

3.3.1. Star Formation History

The first attempt to piece together an accurate star formation history determined from a CMD reaching down to globular cluster age main-sequence turnoffs was made by Da Costa (1984). He noted that the intrinsic width of the RGB was probably caused by a 0.5 dex spread in abundance (from [Fe/H] = −2.1 to −1.6), and a population of “blue stragglers” (in globular cluster terminology), which could be interpreted as main-sequence–turnoff stars as young as 5 Gyr old. Kaluzny et al. (1995) made a careful study of the central region of Sculptor and found no main-sequence stars (m_V < 21), ruling out any star formation over the last 2 Gyr. Using WFPC2, Monkiewicz et al. (1999) have made the deepest CMD of Sculptor to date, although they cover a tiny fraction of the entire galaxy. Their accurate photometry in this region allowed them to conclude that the mean age of Sculptor is similar to that of a globular cluster, but that there was probably a spread in age during this epoch of at least 4 Gyr.

Sculptor is known to contain a small number (eight) of intermediate-age carbon stars (e.g., Frogel et al. 1982; Azzopardi, Lequeux, & Westerlund 1986), of which only one is a bona fide AGB star; the other seven have been identified as CH stars (M. Groenewegen 2002, private communication). There is thus very little evidence for a significant metal-poor intermediate-age stellar populations (e.g., Aaronson et al. 1984). Sculptor shows tantalizing evidence on its horizontal branch (HB) for an unusual enrichment history (Majewski et al. 1999; Hurley-Keller, Mateo, & Grebel 1999).

Carignan et al. (1998) found evidence for small amounts of HI gas in and around Sculptor, although this has recently been found to be part of a large scale complex, presumably Galactic HVC and unlikely to be associated to Sculptor (L. Young 2002, private communication).

The SFH resulting from previous studies of the stellar population is plotted in Figure 4. Sculptor is the only predominantly old galaxy in our sample. It has thus much in common with the northern dwarf galaxy sample previously looked at with HIRES on Keck (SCS01).

3.3.2. Metallicity Evolution

From the CaT results of T01 it was suggested that the RGB stars across Sculptor contain a mean metallicity, ⟨[Fe/H]⟩ = −1.5, with a significant spread δ[Fe/H] = 0.9, larger than that predicted from photometry ⟨[Fe/H]⟩ = −1.8 ± 0.3 (Kaluzny et al. 1995; Da Costa 1984). The histogram plot shows a fairly sharp cut off in the upper [Fe/H] boundary for Sculptor, with a shallow tail extending to low [Fe/H]. The highest metallicity observed was [Fe/H] = −1.3, and there are a few objects around [Fe/H] = −2.1, but the majority are clustered between [Fe/H] = −2.0 and −1.3. There is no evidence for any spatial effect in the central region of Sculptor and found no main-sequence stars (m_V < 21), ruling out any star formation over the last 2 Gyr. Using WFPC2, Monkiewicz et al. (1999) have made the deepest CMD of Sculptor to date, although they cover a tiny fraction of the entire galaxy. Their accurate photometry in this region allowed them to conclude that the mean age of Sculptor is similar to that of a globular cluster, but that there was probably a spread in age during this epoch of at least 4 Gyr.

Sculptor is known to contain a small number (eight) of intermediate-age carbon stars (e.g., Frogel et al. 1982; Azzopardi, Lequeux, & Westerlund 1986), of which only one is a bona fide AGB star; the other seven have been identified as CH stars (M. Groenewegen 2002, private communication). There is thus very little evidence for a significant metal-poor intermediate-age stellar populations (e.g., Aaronson et al. 1984). Sculptor shows tantalizing evidence on its horizontal branch (HB) for an unusual enrichment history (Majewski et al. 1999; Hurley-Keller, Mateo, & Grebel 1999).

Carignan et al. (1998) found evidence for small amounts of HI gas in and around Sculptor, although this has recently been found to be part of a large scale complex, presumably Galactic HVC and unlikely to be associated to Sculptor (L. Young 2002, private communication).

The SFH resulting from previous studies of the stellar population is plotted in Figure 4. Sculptor is the only predominantly old galaxy in our sample. It has thus much in common with the northern dwarf galaxy sample previously looked at with HIRES on Keck (SCS01).

3.3.2. Metallicity Evolution

From the CaT results of T01 it was suggested that the RGB stars across Sculptor contain a mean metallicity, ⟨[Fe/H]⟩ = −1.5, with a significant spread δ[Fe/H] = 0.9, larger than that predicted from photometry ⟨[Fe/H]⟩ = −1.8 ± 0.3 (Kaluzny et al. 1995; Da Costa 1984). The histogram plot shows a fairly sharp cut off in the upper [Fe/H] boundary for Sculptor, with a shallow tail extending to low [Fe/H]. The highest metallicity observed was [Fe/H] = −1.3, and there are a few objects around [Fe/H] = −2.1, but the majority are clustered between [Fe/H] = −2.0 and −1.3. There is no evidence for any spatial effect in the central region of Sculptor and found no main-sequence stars (m_V < 21), ruling out any star formation over the last 2 Gyr. Using WFPC2, Monkiewicz et al. (1999) have made the deepest CMD of Sculptor to date, although they cover a tiny fraction of the entire galaxy. Their accurate photometry in this region allowed them to conclude that the mean age of Sculptor is similar to that of a globular cluster, but that there was probably a spread in age during this epoch of at least 4 Gyr.

Sculptor is known to contain a small number (eight) of intermediate-age carbon stars (e.g., Frogel et al. 1982; Azzopardi, Lequeux, & Westerlund 1986), of which only one is a bona fide AGB star; the other seven have been identified as CH stars (M. Groenewegen 2002, private communication). There is thus very little evidence for a significant metal-poor intermediate-age stellar populations (e.g., Aaronson et al. 1984). Sculptor shows tantalizing evidence on its horizontal branch (HB) for an unusual enrichment history (Majewski et al. 1999; Hurley-Keller, Mateo, & Grebel 1999).

Carignan et al. (1998) found evidence for small amounts of HI gas in and around Sculptor, although this has recently been found to be part of a large scale complex, presumably Galactic HVC and unlikely to be associated to Sculptor (L. Young 2002, private communication).

The SFH resulting from previous studies of the stellar population is plotted in Figure 4. Sculptor is the only predominantly old galaxy in our sample. It has thus much in common with the northern dwarf galaxy sample previously looked at with HIRES on Keck (SCS01).
distribution of stars of different \([\text{Fe}/\text{H}]\). The dispersion is too large to be consistent with all the stars being similarly old. H400 is lying in a position in the CMD (see Fig. 3), which might cause concern as to whether it is an RGB or an AGB star.

The CaT results, along with the new UVES results and the comparison observations described in § 3.2 are plotted in Figure 5. There is, broadly speaking, an agreement between the UVES results and the CaT results. The observations suggest that Sculptor has had quite a similar metallicity evolution to that found for the old LMC star clusters of H00 in its earliest times, but not evolving so rapidly during the last 10–15 Gyr, consistent with very little star formation in Sculptor after this time. At 4–5 Gyr ago the star formation in Sculptor appears to have stopped altogether and contrary increased rapidly in the LMC, and this is the period of largest deviation in the comparison between the UVES results and the CaT results. The observa-
tions (red triangles with error bars) are in good agreement with the CaT measurements. LMC star cluster iron abundances by H00 (blue stars) are offset from the LMC bursting model, but have similar iron abundances as the Sculptor stars at the oldest ages. The numerous small dots show the iron abundances in Galactic disk stars by E93.

3.4. Fornax Dwarf Spheroidal

From the NTT CMD (Fig. 6) we selected stars bright enough to be observed by UVES, and we supplemented this list with targets from a previous spectroscopic study to determine radial velocities of stars in Fornax (Mateo et al. 1991). The UVES targets, and the stars previously observed with FORS1 to measure the CaT metallicity are marked on Figure 6.

3.4.1. Star Formation History

Fornax is larger and more metal-rich, in the mean, than the other galaxies in our sample. It also has (unusually for dSph galaxies and uniquely in our sample) globular clusters. The extended sequence of main-sequence turnoffs in the Fornax CMD indicates a long history of star formation (e.g., Beauchamp et al. 1995; Stetson, Hesser, & Smecker-Hane 1998; Buonanno et al. 1999), which has only recently ceased. The luminosity of the brightest blue stars show that Fornax cannot contain any stars younger than 100 Myr (Stetson et al. 1998). The numerous (~120) carbon stars with a significant age spread in the range 2–8 Gyr ago (e.g., Azzopardi et al. 1999; Aaronson & Mould 1980, 1985) testify to extensive intermediate-age star formation. This is supported by a well-populated intermediate-age subgiant branch and a red clump, which require a significant population with an age of 2–4 Gyr. Most recently, an HST study sampling the main-sequence turnoffs of the intermediate-age and old populations in the center of Fornax was carried out by Buonanno et al. (1999), and they found evidence for a highly variable SFH starting at the epoch of globular cluster formation (~15 Gyr ago) and continuing until 0.5 Gyr ago. An ancient population is present as demonstrated by detection of a red horizontal branch, slightly fainter than the red clump (Buonanno et al. 1999), and of RR Lyrae variables (Stetson et al. 1998). There is also a weak, blue horizontal branch, so Fornax clearly must contain only a small old, metal-poor component (despite having a globular cluster population). Young (1999) looked for neutral hydrogen in and around Fornax and found none, to the column density limit of \(4 \times 10^{13} \text{cm}^{-2}\) in the galaxy center, and \(10^{19} \text{cm}^{-2}\) out to the tidal radius.

The SFH resulting from these previous studies of the stellar population is plotted in Figure 7. Fornax appears to have been forming stars until 2 Gyr ago and to be dominated by an intermediate-age (4–7 Gyr old) population, and it has evidence for only a small number of globular cluster–age stars in its field population.

3.4.2. Metallicity Evolution

From the CaT results of T01, the RGB stars selected across Fornax contain a mean metallicity, \([\text{Fe}/\text{H}] = -1.0\)
and a significant spread of $\delta[\text{Fe/H}] = 1.0$, which is slightly larger than that predicted from photometry $\langle [\text{Fe/H}] \rangle = -1.3 \pm 0.6$ (Beauchamp et al. 1995; Buonanno et al. 1985). In contrast to Sculptor, Fornax has more of a sharp cutoff in the $[\text{Fe/H}]$ distribution at low $[\text{Fe/H}]$, with a tail of values going out to higher values. This suggests different evolutionary influences. The highest $[\text{Fe/H}]$ observed is nearly solar, and there are few objects at $[\text{Fe/H}] < -1.4$, with the majority clustered between $[\text{Fe/H}] = -0.9$ and $-1.3$, with no evidence for any spatial effect in the distribution of stars of different $[\text{Fe/H}]$.

The CaT results, along with the new UVES results and the comparison observations described in § 3.2 are plotted in Figure 8. There is, broadly speaking, an agreement between the UVES results and the CaT results. Fornax looks like it has had quite a similar metallicity evolution to that found for the LMC star clusters of H00. Of course, with so few measurements in both samples, it is difficult to say how close the similarities are. It looks like our CaT data at the oldest epochs contain a larger spread of $[\text{Fe/H}]$ than is seen in the LMC sample. Perhaps there should be more concern in the Fornax RGB for contamination by weak CH stars, given the large number of identified carbon stars in the galaxy. This might result in an over estimate of the ages of the oldest stars and explain the rather high $[\text{Fe/H}]$ (apparently) observed in the oldest stars (in both CaT and UVES results). From the CMD analysis it is not expected that Fornax should have a very high star formation rate at oldest times, which makes it surprising that we apparently see quite a few old stars in the CaT sample. This is consistent with the hypothesis that we may have contamination of the RGB with weak CH stars.

The closed box chemical evolution model plotted on Figure 8 shows reasonable agreement with the $[\text{Fe/H}]$ measurements going back to about 10 Gyr ago. Before this period, during the epoch of earliest star formation in Fornax $[\text{Fe/H}]$ is somewhat higher than might be expected. This could be due to the inherent uncertainty in determining the star formation rates at the oldest times. It resembles the G-dwarf problem known in our Galaxy (e.g., Pagel 1997)—there is an apparent lack of low-$[\text{Fe/H}]$ stars in Fornax, which is hard to explain within a simple enrichment model, starting from a zero-metallicity protogalaxy.

### 3.5. Carina Dwarf Spheroidal

From our NTT CMD we selected stars bright enough to be observed by UVES, and we supplemented this list with targets from a previous spectroscopic study to determine radial velocities of stars in Carina (Mateo et al. 1993). These stars had the advantage of known radial velocities. The UVES targets are marked on Figure 9, which is a VLT/FORS1 CMD made from archival data.

#### 3.5.1. Star Formation History

Carina was the first dSph galaxy to benefit from deep imaging in the early days of modern CCD detectors (Mould & Aaronson 1983) and remains one of the more spectacular examples of a dSph galaxy with significant variations in star formation rate with time and a dominant intermediate-age population (Mighell 1990, 1997; Smecker-Hane et al. 1994; Hurley-Keller, Mateo, & Nemec 1998; Hernandez, Gilmore, & Valls-Gabaud 2000; Dolphin 2002). The bulk of the stellar population in Carina has ages ranging from about 4 to 7 Gyr, though older (RR Lyr variables, Saha, Seitzer, & Monet 1986) and younger stars (or blue stragglers: Hurley-Keller et al.) are also clearly present.
The most recent quantitative star formation histories for Carina (from two different data sets) are plotted in Figure 10. There are obvious differences between the three different SFHs. It is hard to normalize the absolute star formation rates between the three different determinations, so this has been done in an arbitrary fashion. The main difference is that Hurley-Keller et al. (1998), in contrast to Hernandez et al. (2000) and Dolphin (2002) see discrete bursts of star formation. This might be because Hurley-Keller et al. are better able to resolve such details as they cover a much larger area of the galaxy and hence all the main-sequence turnoffs are better populated than in the tiny HST field used by the other two studies. Also Dolphin and Hurley-Keller et al. find evidence of ancient star formation (as expected from the RR Lyr population found by Saha et al. 1986), whereas Hernandez et al. do not. Another difference is the assumed [Fe/H], not only the absolute value, but the spread. Dolphin finds [Fe/H] = −1.2 ± 0.4, where as Hurley-Keller et al. assumes [Fe/H] = −2.1 ± 0.1 and Hernandez et al. [Fe/H] = −2.0 ± 0.2. In comparison with our results here, it looks like Dolphin is a little too metal-rich, and the other two studies a little too metal-poor. These different assumptions significantly affect the star formation history determinations, and particularly the age of the peak(s) in the star formation rate.

3.5.2. Metallicity Evolution

The photometry of Carina from wide-field imaging reveals a very thin giant branch (e.g., Hurley-Keller et al. 1998). Given the large age spread measured from main-sequence–turnoff photometry in this galaxy, a metallicity spread has always been thought necessary to compensate and produce the observed narrow RGB. Our UVES results for five stars give an average abundance, <[Fe/H]> = −1.6, with a spread δ[Fe/H] = 0.5. This is different from previous determinations from CMDs, which gave [Fe/H] = −2.0 and a spread δ[Fe/H] < 0.1 (Mould & Aaronson 1983; Smeecker-Hane et al. 1994; Hurley-Keller et al. 1998). CaT spectroscopy of 15 giants in Carina (Da Costa 1994) resulted in a narrow average [Fe/H] = −1.9 ± 0.1, with one giant more metal-poor ([Fe/H] = −2.2). This is significantly more metal-poor than our UVES results, but similar to our results they found a very small spread in [Fe/H].

We plotted the [Fe/H] versus age measurements as blue star symbols in Figure 11. The several (different) SFHs (shown in Fig. 10) are represented by a series of lines, all consistent with a very small spread in [Fe/H]. There is no resolvable difference between the three predictions. They are broadly speaking in agreement with the UVES results, with one outlier (M10) at lower [Fe/H] than might be expected. This star is comparable to the previous CaT determinations and may represent a small population at this metallicity (similar to the old LMC cluster metallicity) that we do not sample very well.

Carina is the faintest galaxy in our sample, although its mass and average [Fe/H] are similar to Sculptor (see Table 1). There is only evidence for fairly mild evolution (very small spread) in [Fe/H], but the number of stars observed is still very small. Unlike Sculptor and Fornax, in Carina the metallicity evolution looks significantly different from the LMC measurements of H00. Carina has a metallicity evolution that is consistently lower than the LMC clusters. The one star (M10) that is more metal-poor than might be expected from the amount of star formation creates a spread in [Fe/H] at the oldest ages. The [Fe/H] values from the independently determined SFHs suggest that the older stars in Carina should have [Fe/H] similar to the older LMC clusters. However, our results suggest (as do those of Da Costa 1994) that at least a small fraction of stars in Carina are of very low [Fe/H]. This may represent the “shot noise” in the self-enrichment of this galaxy at the earliest epochs of star formation, or it might be a result of the highly variable SFH in Carina. The number of high-resolution observations we have is still too small to quantify this accurately, but the hints are tantalizing (see also Paper I).

3.6. Leo I Dwarf Spheroidal

From the previous spectroscopic study of Leo I (Mateo et al. 1998) we selected stars bright enough to be observed by UVES. These stars had the advantage of known radial velocities. The UVES targets are marked on Figure 12, which is a VLT/FORS1 CMD made from archival data.

3.6.1. Star Formation History

Leo I is the most distant galaxy in our sample and this, along with the proximity on the sky of the bright Galactic star Regulus, have made photometric studies difficult. The earliest observations of Leo I indicated a significant intermediate age stellar population; Hodge & Wright (1978) observed an unusually large number of anomalous Cepheids; carbon stars were found by Aaronson, Olszewski, &
Hodge (1983) and Azzopardi, Lequeux, & Westerlund (1985, 1986). High-quality CMDs have recently revealed a horizontal branch well populated from blue to red in Leo I (Held et al. 2000), and subsequent observations were made of RR Lyr variable stars (Held et al. 2001) predicted from the detection of the horizontal-branch population. Held et al. estimated a mean metallicity for Leo I RR Lyr stars of $[\text{Fe/H}] = -1.8$, using the relation derived by Sandage (1993) between the average period of the RRab variable stars in the Milky Way globular clusters and their metallicity. This might suggest that the oldest populations in Leo I ($>10$ Gyr) have a mean metallicity close to this value.

Sophisticated modeling of main-sequence turnoffs in a deep HST CMD by Gallart et al. (1999) has given the most accurate information on the SFH of Leo I to date. The SFH they derived is plotted in Figure 13. Also plotted is a more recent determination by Dolphin (2002) based on the same data set. The Gallart et al. analysis suggests a smoothly varying metallicity evolution of the stellar population between $[\text{Fe/H}] = -1.4$ and $[\text{Fe/H}] = -2.3$ (consistent with the mean determined by Held et al.). Dolphin, on the other hand, found much higher metallicities, $[\text{Fe/H}]$ between $-0.8$ and $-1.2$ dex. This discrepancy shows the inherent uncertainties in determining $[\text{Fe/H}]$ from the color of the RGB for a galaxy with a significant intermediate or young stellar population. Surprisingly, the SFHs look very similar from both studies. Similarly to the case of Carina, our high-resolution $[\text{Fe/H}]$ measurements seem to fall somewhat intermediate to the two photometric determinations.

3.6.2. Metallicity Evolution

The Leo I CMD reveals an RGB, which, based on photometry, can (and has been) suggested to be either indicative of a broad range of metallicity in the galaxy ($[\text{Fe/H}] = -1.9 \pm 0.5$ dex; Gallart et al. 1999) or a narrower range of higher metallicity stars ($[\text{Fe/H}] = -1.1 \pm 0.2$ dex; Dolphin 2002). Our UVES results are only for two stars, which makes any statistical analysis difficult. The abundances are $[\text{Fe/H}] = -1.06 \pm 0.2$ and $[\text{Fe/H}] = -1.52 \pm 0.2$, which falls somewhat intermediate between the two CMD analyses, but with only two stars it is impossible to be conclusive. Clearly more spectroscopic data are needed for this to be confirmed.

We plotted the $[\text{Fe/H}]$ versus age measurements as triangles with circles in Figure 14. There is no resolvable difference between the two chemical evolution scenarios, and they both, broadly speaking, agree with the UVES results, although the (young) high $[\text{Fe/H}]$ point is slightly above what might be expected.

It is very difficult to say anything detailed about the metallicity evolution in Leo I with just two measurements. In comparison to the trend of the LMC star clusters from H00, there appears to have been no rise in enrichment levels at intermediate ages ($\sim 8$ Gyr ago), consistent with a galaxy dominated by star formation occurring in the last 5 Gyr (Fig. 13). The metallicity evolution in Leo I may be similar to that observed in Carina, with very little spread until quite recent times.

4. OTHER ELEMENTS

There is much more information in a high-resolution spectrum than the iron abundance of a star. There are a host of lines from other elements, which can be interpreted in terms of how the chemical state of the interstellar medium...
from which stars are made has varied over time (see Tables 3 and 4). There are four broad categories into which elements are distributed depending upon their properties: light elements, α-elements, iron peak elements, and heavy elements. All provide pieces of the overall story of the chemical evolution history of the stellar populations in a galaxy.

Our sample of dSph galaxies has a very broad range of ages of stars, and this makes studies of the abundance variations with time possible. Most of the diverse (and complex) aspects involved in interpreting these kinds of measurements are covered Paper I. However here we would like to summarize those aspects we consider most crucial for gaining a clearer understanding of the global star formation properties of these galaxies and how they may have formed and evolved through time.

### 4.1. The α-Elements

The “α-elements” is a common collective term for some even-Z elements (e.g., O, Mg, Si, S, Ca, and Ti) that are predominantly dispersed into the ISM in SN II explosions. They are typically overabundant in globular clusters and halo stars relative to (solar) disk stars. The traditional interpretation of the trend of [α/Fe] decreasing with time is that this is due to the time delay between SN II and SN Ia (e.g., Tinsley 1979; Gilmore & Wyse 1991). In principle the mixture of different α abundances can provide a clue as to the mixture of SN explosions that must have produced the enrichment seen in a star (e.g., Woosley & Weaver 1995), because different mass SNe produce different proportions of α-elements.

We define an average α in the same way as SCS01, namely, as an average of Mg, Ca, and Ti abundances ([α/Fe] = 1/3([Mg/Fe] + [Ca/Fe] + [Ti/Fe]). There are different ways to define this because, since O, Mg, and Si dominate by mass and relative abundance, they can also dominate the α-effects on chemical evolution models and isochrones. In Figure 15 we compare the distribution of α-elements in our data (red and blue symbols, as defined in the caption) and the Keck measurements made by SCS01 of northern dSph RGB stars (Draco, Ursa Minor, and Sextans), as green triangles with similar measurements of disk stars (E93, black crosses); halo stars (McWilliam et al. 1995, open squares); Galactic globular cluster measurements (this work and SCS01, blue crosses); LMC star cluster measurements (H00, blue stars). SCS01 did not work out ages for their dSph stars, and so we have made estimates based on the [Fe/H] and color of the stars they observed (see Table 3).

We have plotted the α abundances both in the “traditional” manner, against [Fe/H] in the top panel of Figure 15 and against age in the bottom panel. Both provide differing insights as to how these galaxies may be evolving with time and also how our observations compare with those of other galaxies. Plotting against age is more useful from the point of view of understanding chemical evolution, but it is not easy to find suitable measurements to compare our results with, as it is difficult to determine accurate ages for halo or bulge stars.

The dSph α abundances, when plotted against age in the bottom panel of Figure 15, appear to follow the same distribution as those for the disk and the star clusters. However, if we look at the plot of [α/Fe] versus [Fe/H] in the top panel of Figure 15, the properties of dSph’s are clearly significantly different from the disk in the sense that, although the levels and the variation with stellar age of [α/Fe] are similar between the disk and the dSph’s, this is all occurring...
at much lower [Fe/H] in the dSph’s. The top panel of Figure 15 also shows that the properties of the dSph’s differ from those typical of halo stars. There is overlap in [Fe/H] values, but the \([\alpha/Fe]\) of the halo stars are typically higher, although there is a population of low \([\alpha/Fe]\) halo stars which could conceivably be accreted satellite galaxies (e.g., Nissen & Schuster 1997). The star cluster measurements follow the upper envelope of dSph values, although most of the cluster stars show a deep mixing abundance pattern. Thus, the properties of \([\alpha/Fe]\) in dSph’s do not match globular clusters or the disk or the majority of the halo.

4.1.1. The Evolution of \([\alpha/Fe]\) Due to Star Formation

In Figure 16 we plot \([\alpha/Fe]\) for each dSph separately; overplotted is an illustrative estimate of the variation of \([\alpha/Fe]\) for each galaxy given the star formation rate variation. There really are not sufficient data on these galaxies to be certain that we are seeing direct evidence of evolution in \([\alpha/Fe]\), but the results are highly suggestive. The dashed lines are not derived from the SFH directly, but a knowledge of the SFH is used to find the most likely pattern with time in the \([\alpha/Fe]\) abundances. Carina has the most impressive evidence for evolution of abundances due to variations in star formation rates with time. The variations seen in \([\alpha/Fe]\) are supported by consistent variations in Ba, La, Nd, and Eu (see Paper I). With the exception of Carina, the star formation histories inferred from \([\alpha/Fe]\) are consistent with the CMD SFH described in § 3. In Carina it is possible that, because of the incorrect metallicity evolution assumed in all the CMD SFH determinations described in § 3.5.1, the SFH has not been well determined. Figure 16 suggests that there has been an ancient epoch of star formation (13–15 Gyr ago) followed by a hiatus, then another epoch of star formation 9–11 Gyr ago. More data are clearly required to quantify this interpretation of these data.

One curious point is that in all our observations \([\alpha/Fe]\) is roughly solar for the oldest stars. This might be a remnant of the initial enrichment of the dSph gas in the early universe, by a process which is quite different from the star formation processes that we see today. This is certainly not consistent with what would be expected for stars switching on in a zero (or close) metallicity environment. It ought to take time for the \([\alpha/Fe]\) to get to zero (e.g., Pagel & Tautvaisiené 1998).

4.1.2. Comparison with Common “Metallicity” Determinants

In Figure 17 we plot three elements of particular interest against age, using the same symbol definitions as in Figure 15. We choose to look at \([O/Fe]\) against age in the top panel because O is so abundant and thus arguably the best “metallicity” tracer. The high-resolution measurement of the \([Ca/Fe]\) abundance is a useful test of the reliability of the conversion between CaT observations and \([Fe/H]\). Another common tracer of \([Fe/H]\) from low-resolution spectra is \([Mg/Fe]\), which we plot in the bottom panel of Figure 17. We also plot in all the panels of Figure 17 the E93 disk abundances as black crosses.

There is quite a large scatter in the \([O/Fe]\), especially at the earliest times. It follows the same trend as the disk abundances, but the scatter is somewhat larger than seen in the disk at earlier times, often similar to the halo enhancement. The relatively young (~2 Gyr old) LMC star cluster NGC 1978 appears to have a very high oxygen abundance, but this is a very insecure measurement (see H00).

The \([Mg/Fe]\) results look very similar to the \([Ca/Fe]\), with slightly greater spread in the \([Mg/Fe]\) values. These values are also fairly similar to the results from the disk stars. They are very close to solar, with little or no discernible trend, although in common with \([O/Fe]\) the dSph measurements...
circles are a selection from the new sample of disk and halo obtained from the literature (e.g., Sneden, Gratton, & son, are compilations of \([Zn/Fe]\) for disk and halo stars defined in Figure 15. Also plotted in Figure 18, for comparison, are compilations of \([Zn/Fe]\) for disk and halo stars obtained from the literature (e.g., Sneden, Gratton, & Crocker 1991), plotted as black stars, and the black open circles are a selection from the new sample of disk and halo.

4.1.3. Interpretation of \([\alpha/Fe]\) Observations

The low \([\alpha/Fe]\) values found in the disk stars of our Galaxy have been interpreted as evidence for star formation in material with a large fraction of SN Ia ejecta. This is perhaps not surprising for our disk, with high metallicity and typical predictions of fairly recent formation (from enriched material). It is not clear that the same assessment can be made of the similarly low \([\alpha/Fe]\) in dSph galaxies. Everything we know about dwarf galaxies suggests that they have never had very high rates of star formation. The stars in dSph's typically have much lower \([Fe/H]\) and \([O/H]\) than in our disk. A low star formation rate may explain the low \([\alpha/Fe]\) values, because the SN II products may predominately come from low-mass SNe II (8–12 M\(_\odot\) progenitors), which result in lower \(\alpha\) yields than their higher mass cousins (e.g., Woosley & Weaver 1995). This is (unfortunately) effectively a truncated IMF, but it is motivated by the likelihood that, in the physical conditions to be found in small galaxies, the probability of forming high-mass molecular clouds (and thus high-mass stars) is low. The variations in \([\alpha/Fe]\) shown in Figure 16 suggest that \([\alpha/Fe]\) does vary with star formation rate, but more data are needed to confirm and quantify this.

4.2. Iron Peak Elements

The iron peak elements (e.g., Cr, Mn, Co, Ni, Cu, Zn) are the highly stable end products of the nucleosynthesis sequence by nuclear fusion, and they provide the seeds that capture neutrons and produce heavy elements. It is hard to find suitable comparison samples with known ages for heavy-element abundances, because it seems that none of the observations of these elements have been made of stars of known age. Generally speaking, it seems that dSph stars have halo-like iron peak abundance patterns (see Paper I and Table 4). Two important iron peak elements with regard to understanding galaxy evolution and also making the connection between galaxies observed in the nearby and more distant universe are Zn and Cu.

4.2.1. Zinc

Zn plays a pivotal role in interpreting the abundance patterns of the damped Ly\(\alpha\) (DLA) systems, so it is interesting to compare it with the values measured in the nearby universe. In Figure 18 \([Zn/Fe]\) is plotted versus \([Fe/H]\). The dSph observations are plotted using the same symbols defined in Figure 15. Also plotted in Figure 18, for comparison, are compilations of \([Zn/Fe]\) for disk and halo stars obtained from the literature (e.g., Sneden, Gratton, & Crocker 1991), plotted as black stars, and the black open circles are a selection from the new sample of disk and halo star measurements from Primas et al. (2000). Also plotted are the values measured in DLA absorption systems at cosmological distances by Pettini et al. (2000), as black circles with purple error bars. The DLA \([Zn/Fe]\) measurements at high redshift are, on average, higher than anything else observed in the Local Group (see Fig. 18). This is largely due to depletion of Fe onto dust grains. In fact, these particular DLAs were selected by Pettini et al. as those that showed the lowest dust depletions, such that the gas phase Zn results should represent the total Zn abundance quite well. The fact that they are quite homogeneous could imply that the Zn abundances are quite uniform in these DLA systems, but of course the uncertainties in the dust corrections complicates the interpretation. Also, the DLA measurements are very different from all others in Figure 18, coming from the absorption of quasar light in the interstellar gas of an intervening galaxy.

The nucleosynthetic origin and history of Zn is not well understood (see Paper I). Traditionally, Zn has been thought to be produced by \(s\)-process neutron capture reactions, but then it should decrease with metallicity (e.g., Matteucci et al. 1993). Another possible site of Zn production is explosive Si burning in SNe II. Recent computations (Umeda & Nomoto 2002) suggest that the over-solar \([Zn/Fe]\) values found in the most metal-poor stars of our Galaxy are the result of deep mixing of complete Si-burning material and significant fall back in SNe II. It is clear that Zn is a key element to further constrain the physics of SN II explosions, but more data will be needed (also of other elements) to be able to discern among the different possible solutions (e.g., Primas et al. 2003, from the VLT Key Programme 165.N-0276).

4.2.2. Copper

In the case of Cu, it has been suggested that the most significant production occurs in SNe Ia (e.g., Matteucci et al. 1993). Cu is clearly underabundant with respect to Fe in all our observations of dSph’s (e.g., Fig. 19). They resemble the halo star iron peak abundance patterns, which might suggest a lack of SN Ia enrichment of the dSph ISM, but given that dSph’s also show lower \(\alpha\) abundances relative to metal-poor halo stars (Fig. 15), interpreted as a low SN II rate (relative to SNe Ia), it is not clear that this simple explanation is valid here. In Paper I we suggest that Cu is not produced...
readily in low-metallicity SNe Ia. Another possible explanation is that dSph galaxies rarely form very massive stars (i.e., >15 $M_\odot$; see § 4.1). SN II explosions at the low-mass end of the possible mass range agree with the solar [$\alpha$/Fe] measurements and also with the apparent underproduction of heavy elements. It is also possible to invoke metal-dependent SN yields (e.g., Timmes et al. 1995; see discussion in Paper I).

[Cu/$\alpha$] has been supposed to be a good indicator of the ratio of SNe Ia/SNe II, assuming that Cu is predominantly made in SNe Ia and $\alpha$-elements are predominantly SN II products. Our data do not support this though. [Cu/$\alpha$] is very low (halo-like) in all of the dSph stars (with the exception of the most metal-rich star in Fornax; see Fig. 19). Also, [Cu/$\alpha$] is remarkably constant with age. This again suggests that Cu is not significantly produced in the low-metallicity SNe Ia, like $\alpha$-elements, especially given the star formation histories in these galaxies and the expected SN Ia contributions before 5 Gyr, when the Cu abundance begins to increase.

4.3. The Heavy Elements

The heavy elements are defined as those elements beyond the iron peak ($Z > 31$). Heavy elements can only be synthesized by repeated neutron captures onto to iron peak elements followed by $\beta$ decay. This can happen either slowly, with respect to the time for $\beta$ decay ($s$-process) or rapidly ($r$-process), and these two processes are the result of different neutron sources and lead to different abundance patterns.

Ba is thought to be a predominantly $r$-process element, which is thought to mainly occur in low-mass ($1–3 M_\odot$) AGB stars (e.g., Truran 1981; Busso et al. 1995; Lambert et al. 1995). Eu is a nearly pure $r$-process element and thought to be produced only in SNe II. It is typically enhanced in the stars measured in dSph’s (see Table 4), as it is in our halo. This is also true for all but the oldest of the LMC star clusters. This is perhaps somewhat at odds with the relatively low $\alpha$ abundance measured in the dSph stars, but consistent with our interpretation of $\alpha$-element and iron peak abundances being predominantly from low-mass SNe II (predominantly $8–12 M_\odot$) in dSph’s, as discussed in §§ 4.1 and 4.2.

In Figure 20 we have plotted the [Ba/Eu] abundances, with the symbols and the comparison data the same as in Figure 15 (§ 4.1). As in previous figures we plotted the same data twice, once in the more traditional manner against [Fe/H], in the top panel of Figure 20, and again versus age to put the data directly in an evolutionary context, in the bottom panel. Examination of these two figures gives us an idea of the mix of $s$- and $r$-process products in the stars in our sample, which allows us to assess the contribution of AGB stars to the chemical evolution of dSph’s as compared with low-mass SNe II. In the bottom panel of Figure 20 we can see that, with the exception of one star (in Ursa Minor, which is clearly $s$-process contaminated, with a huge over-abundances of the $s$-process elements compared with Eu), the older stars in our sample show predominantly $r$-process heavy elements. This is similar to the older disk stars and appears to evolve with time to include more and more $s$-process heavy elements. In the top panel of Figure 20 we can see that the same domination of $r$-process elements is present in the halo and bulge stars, although there is some scatter. The LMC star cluster results plotted in the top panel of Figure 20 show either a balance of $r$- and $s$-process elements or perhaps a slight enhancement of $s$-process elements. This is different from the Galactic globular clusters.
and the halo stars (in the mean) and more similar to the younger disk stars (see also the bottom panel in Fig. 20).

The heavy elements in the oldest stars in the universe must come from the r-process, because AGB stars have not yet had time to evolve and contribute to the ISM (which takes at least ~1 Gyr). In both panels of Figure 20 we see a trend of increasing contribution of s-process elements with increasing [Fe/H] (and age) across the disk, halo, and also the dSph sample, consistent with the interpretation that it takes a few gigayears for the low-mass stars created in the earliest star formation epochs to start producing enough s-process elements to influence subsequent generations of stars. Our data allow us to constrain this delay in our sample of dSph galaxies until about ~10 Gyr ago. It is at this time that s-process contributions start to match those of r-process elements, at least in Fornax, Sculptor, and Carina. It does not look like Leo I ever reached this stage; nor did Draco. But, as for all our conclusions, this is uncertain due to the small number statistics.

5. IMPLICATIONS FOR UNDERSTANDING GALAXY EVOLUTION

Having such detailed information, albeit on very few stars, it is interesting to try and put our results into a context that can be understood in terms of the implications for our understanding of galaxy evolution. This has been termed “chemical tagging” by Freeman & Bland-Hawthorn (2002) and is probably the only way to accurately disentangle the different phases in a galaxy’s evolution back to the epoch of formation, tagged by the ever increasing enrichment of an interstellar medium by elements produced in stars and liberated in supernovae explosions or stellar winds. The galaxies we are concentrating on, dSph’s, are arguably very simple objects with regard to chemical evolution. They are like a single-cell star-forming entity. They have small potentials in orbit around a much larger one and are thus unlikely to accrete much (if any) extraneous matter during their lifetime (either intergalactic gas or galaxies) because they will typically lose the competition with our Galaxy. Their evolution is going to be influenced, maybe strongly, by the presence of our Galaxy. They will permanently lose gas to our Galaxy if it is expelled too far from their centers, and the dynamical friction of the orbit may have a strong influence on the rate of star formation at any given time in these galaxies.

5.1. Similar Abundance Patterns: Consistent Star Formation Mode

One aspect of these dSph RGB abundances that clearly stands out is how uniform they appear to be in general, despite a range of different star formation histories, and also how different they are from the properties of stars observed in the disk and halo of our Galaxy (e.g., α abundances, Fig. 15). It is as if all stars know the mass of the potential in which they are forming.

Figure 16 suggests that with our UVES results we can trace the variation of [α/Fe] with time caused by varying (but always low) star formation rates at different times. This is the first time it has been possible to directly measure the [α/Fe] evolution of a stellar population over gigayear timescales, back from the earliest epoch of formation to the most recent star formation. The range of variation of α-elements is quite small (which means accurate measurements are required to observe it), and it never reaches the parameter space where the disk and halo are stars predominantly to be found. So, probably, star formation, when it occurs, always occurs at similarly low levels in these small galaxies. Perhaps this is not surprising as it is the mass of cool H i gas in conjunction with the ability of the gravitational potential to compress it that determines the size and number of molecular cloud complexes that can form stars in a galaxy. It seems very unlikely that dwarf galaxies have ever experienced a very high star formation rate, and they have thus had very few (if any) SNe II of masses more than 15–20 M☉.

Thus, it seems as if the classical interpretation of [α/Fe] as applied to the disk and halo of our Galaxy does not work when applied to dSph’s. It is possible to produce solar [α/Fe] values from very low star formation rates. Assuming a Salpeter IMF and using the predicted yields from Woosley & Weaver (1995), an event that forms 2500 M☉ of stars (over 10 yr; SFR ~ 2.5 × 10⁻⁴ M☉ yr⁻¹) reduces O and Mg by a small amount (~0.1–0.15 dex) and has no net effect on Si. However, for an event that forms only 1000 M☉ stars (SFR ~ 10⁻⁴ M☉ yr⁻¹) the affect on O, Mg, and Si is significant (~0.5–0.6 dex). This means that a low star formation rate can explain the low [α/Fe] we observe in these galaxies. It also means that [α/Fe] will not be a good indicator of SN Ia rates in systems with few massive SNe II.

5.2. Chemical Evolution: Evidence for Infall or Outflow

It is somewhat uncertain whether these systems were (or are) small enough to lose significant mass (and metals) in SN explosions. This is partly due to problems determining the total mass of these small galaxies, both today and in terms of ascertaining what they may have been in the past. If we believe current estimates (e.g., Mateo 1998 and references therein), these galaxies are currently of low enough mass that they are easily in the mass range where supernova explosions ought to result in a significant metal-enriched blow-away, (e.g., Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000; Mori, Ferrara, & Madau 2002). Blow-away means that it is unlikely that these galaxies would easily lose their entire interstellar medium in this fashion, but they may suffer metal-enriched winds, where the metals may leave the system but the gas probably will not. Even if the metal-enriched winds escape the central regions of the galaxy, it seems likely that they will continue to exist in a bubble surrounding the galaxy (e.g., Ferrara, Pettini, & Shchekinov 2000; Mori et al. 2002), and therefore may still play a role in future star formation episodes. If dwarfs have a more extended dark matter halo than currently thought (e.g., Kleyna et al. 2002), these metal-rich bubbles will be smaller and more likely to collapse back into the central potential. None of the dSph’s around our Galaxy contain evidence for any particularly violent or intense star formation episodes in their past, so the typically high (simultaneous) SN rates assumed in simulations modeling the blowout properties are unlikely to occur in dSph’s (e.g., Mori et al. assume a SFR = 0.03 M☉ yr⁻¹, which is much higher than is thought to be typical for small dwarfs: ~10⁻⁴ M☉ yr⁻¹). However, it is difficult to distinguish between low yields due to a low star formation rate and low yields due to mass loss. Another possible explanation is that the products of more massive (>20 M☉) SNe II are predominantly lost to these galaxies, but it is hard to find any plausible reason why this might be so.
With the exception of the earliest times, all abundance properties in these dSph’s are consistent with closed-box evolution as inferred from the star formation histories (Figs. 5, 8, 11, and 14). Our data are not sufficient to rule out a leaky-box scenario, where some (small) fraction of the metals are lost. The implication is that outflows (and inflows) of metals are not necessary to explain the chemical evolution observed through most of the history of any of these systems. Gas and metals may flow out from the galaxy (e.g., Mac Low & Ferrara 1999; Mori et al. 2002) but, with the possible exception of the initial burst of star formation, there is a chance that they will return on a timescale (~1–2 Gyr) compatible with the evolutionary timescale of star formation in these galaxies.

It is possible that the large-scale differences we see in star formation histories of dSph’s result from their differing orbits around our Galaxy (e.g., Oh, Lin, & Aarseth 1995). Tidal perturbations can significantly affect star formation, either compressing the ISM and increasing the star formation rate or inhibiting it by stripping the galaxy or even stripping the ISM altogether and thus stopping star formation for good, independent of the star formation rate in the galaxy. Some galaxies apparently lost (or used up) all of their gas very quickly (in a few Gyr), and others have managed to continue forming stars until very recently; but all seem to maintain similar chemical abundance patterns across time, until perhaps the last few gigayears. This suggests that the properties of star formation have not changed significantly over time. There is evidence for slow evolution in both the SNe Ia/SNe II ratio and the increasing contribution of α-process elements over time. There is no significant evidence for large discrepancies in abundances such as might be expected from gas renewal at some point in the life of a galaxy from a pristine source. But more data are required to make more firm conclusions.

5.3. Building Large Galaxies from Smaller Ones

One of the fundamental pillars of cold dark matter (CDM) theory is that small galaxies are the building blocks of larger ones (e.g., Navarro, Frenk, & White 1995). The timescale on which this buildup of material occurs has been a matter of some discussion between the classical approach to modeling within the CDM paradigm, which results in the prediction that galactic disks and halos (such as our own) have relatively recently experienced significant accretions of smaller galaxies (e.g., Steinmetz & Navarro 2002; Kauffmann, White, & Guiderdoni 1993), and those approaches that, independent of assumptions from CDM, utilize observations of our Galaxy and the nearby universe to place limits on the star formation rates for all the different components in our Galaxy over a Hubble time (e.g., Prantzos & Silk 1998; Rocha-Pinto et al. 2000).

Our results unequivocally show that the stars observed in dSph galaxies today (many of which are extremely old) cannot be used to make up the majority of stellar mass in our Galaxy, either in the disk or in the inner halo (or the bulge), because their nucleosynthetic signatures are not compatible. This places a limit on the age at which the majority of the merging of small halos can have occurred, if it is to have occurred. This is, of course, assuming that these small halos are similar to the dwarf galaxies we see today. The majority of these kinds of mergers must have occurred very early, in the first few gigayears of structure formation, because this is the only way to ensure that the large potentials accreted mostly gas and very few stars, and so the majority of star formation will occur in a much larger potential than a dwarf galaxy with a lot more influence from massive SNe II, which is required to explain the abundance patterns seen in our Galaxy but not found in dSph’s. In this scenario there still remains the mismatch in the \( M/L \) between dwarf and giant galaxies; dwarf galaxies are frequently dark matter–dominated, unlike large spiral galaxies.

Of course, our dSph results do not place any limits on the effect of significantly larger accretions, (e.g., LMC-like objects). The detailed abundance measurements of old and intermediate-age stars in the Magellanic Clouds are rather sparse, and so the conclusions are inherently uncertain, but there are suggestions that the abundance patterns of the stellar population observed in the Clouds and nearby dwarf irregulars do not resemble our Galaxy anymore than the dSph’s do (e.g., Hill 1997; H00; Venn et al. 2003).

The only component of our Galaxy that could plausibly contain a significant contribution from stars formed in accreted dwarf galaxies is the halo, and it contains only about 1% of the stellar mass of our Galaxy (e.g., Morrison 1993), and only a fraction of this, the outer halo (\(~10\%\)), could plausibly include stars accreted from dwarf galaxies (e.g., Unavane, Wyse, & Gilmore 1996). The outer-halo stars typically have different properties from the inner-halo stars, which include relatively lower \( \alpha \) abundances, more consistent with those observed in dwarf galaxies (Nissen & Schuster 1997). However, the kinematic properties of these stars are not always consistent with what we see in satellite galaxies today (e.g., Gilmore & Wyse 1998). The samples of well-studied halo stars are still too small to be reliably quantitative or conclusive on any of these issues.

5.4. Did the “First Stars” Form in dSph’s?

In CDM cosmology dwarf galaxy–size objects are the first structures to collapse in the early universe. These first objects, arguably protogalaxies, are predicted to have a total mass (dark + baryonic matter) of \(~10^6 \, M_\odot\) (White & Rees 1978; Tegmark et al. 1997). Within the CDM paradigm most of these small structures will merge to form much larger galaxies, such as our own, but a fraction may be supposed to survive until today in something like their original form. Within these first objects the first generation of stars in the universe may form (zero metallicity), perhaps as one massive star (Abel, Bryan, & Norman 2002; Bromm et al. 2002). So far it has been difficult to constrain the final mass of the “first” stars. Current predictions place them between 30 and 300 \( M_\odot \). Such a large uncertainty makes reliable nucleosynthetic predictions difficult.

These first collapsed proto galaxies at \(~10^6 \, M_\odot\) have a mass that, in most models, is very close to the limit, where star formation results in significant blowout and disruption of the ISM and the total blow-away of all the gas in the galaxy in a SN explosion (e.g., Larson 1974; Dekel & Silk 1986; Mac Low & Ferrara 1999; Ferrara & Tolstoy 2000; Mori et al. 2002). Thus, the formation (and subsequent SN explosion) of high-mass stars (of order 100 \( M_\odot \)) in such small halos in the early universe has also been recently invoked as a convenient way to pollute the early universe with metals (e.g., Madau, Ferrara, & Rees 2001), and explain the relatively high abundance of metals in the IGM at quite high
The initial enrichment of the ISM in these galaxies is likely to develop extremely quickly as a result of the first star(s) formation. The timescale for SNe II is of order less than 10^7 yr, so the initial enrichment timescale of the ISM is well beyond the time resolution of our CMD analysis. Since we are only looking at two to five stars per galaxy we are not very likely to find a sample that represents the earliest, most-rapid phases of ISM enrichment. We need to observe abundances for a much larger sample of stars in these dSph’s to build up an accurate picture of how the early enrichment may have progressed on the very short time-scales of the initial enrichment. It is possible, at least for dSph’s, that varying rates of loss of gas and metals in SN driven winds in the earliest starburst phase of formation make our understanding of the abundance patterns in the oldest stars very complex.

6. CONCLUSIONS

We have obtained high-resolution VLT UVES spectra for 15 RGB stars in Sculptor, Fornax, Carina, and Leo I dSph galaxies. Adding this to the previous Keck HIRES observations of 17 RGB stars in Draco, Ursa Minor, and Sextans dSph’s by SCS01, we have a sizable sample of stars with which to study the chemical evolution of our smallest neighbors. We have measured abundances for more than 20 different elements in all these stars and used these many different indicators to try and constrain our understanding of chemical evolution in dwarf galaxies back to the earliest times.

Our results, similar to SCS01, show a very uniform abundance pattern across all these galaxies. This is evidence for very similar chemical evolution histories in all dSph galaxies, similar initial conditions, and a similar IMF. It was initially a surprise that the abundance patterns were so similar, since these galaxies have often quite different star formation histories and all of the galaxies have evidence for fairly large spreads in [Fe/H] (see Table 5). The fact that these galaxies have always had very small (but variable) rates of star formation is consistent the patterns we see in the α-, iron peak, and heavy-element abundances. These variations are fairly well behaved. We also find that the global increase in [Fe/H] with time does not require (or indicate) any significant infall or outflow of gas or metals from these systems, but this is very dependent on the accuracy of the models used to determine yields.

A small star formation rate could also have the effect of limiting the impact of massive SNe II on the chemical evolution of these galaxies, effectively truncating the IMF, which could account for the marked difference between the abundance patterns seen in dSph stars and those found in our Galaxy. This data set allows us to infer more clearly the effects of AGB star mass loss and low-mass SNe II on the chemical evolution of a galaxy. In our Galaxy detailed signatures of this kind of enrichment may often be “washed out” over time, possibly because the chemical properties of a system that has high-mass SNe II will (not surprisingly) be totally dominated by them. It might also be possible to explain the abundance patterns in terms of mass (and metal) loss in dwarf galaxies, but for this (admittedly small) data set this appears to be a contrived solution as, from current models, this would have to preferential mass loss of massive star (>20 M☉) SN II products.

redshift, remove the G-dwarf problem in our Galaxy, and even to reionize the universe (e.g., Oh et al. 2001).

As a means of testing the idea that very massive stellar objects (VMOs) may have exploded at early times in small dwarf galaxy–like objects that have survived until the present day as dSph’s, we look for their nucleosynthetic signature in the spectra of the oldest stars our sample, as predicted by Heger & Woosley (2002). We are not looking directly for Population III objects, but we are looking for any sign that the stars we observe were polluted by VMOs in the early universe. In Figure 21 we plot the comparison of the abundances we observe in the only predominantly old galaxy in our sample, the Sculptor dSph, with the predictions of Heger & Woosley for the SN products of a zero-metallicity VMO. We also plot as a comparison the average abundance pattern seen in the metal-poor halo stars (in the range −3 < [Fe/H] < −4, from McWilliam et al. 1995).

The Sculptor dSph abundance patterns are very halo-like, despite having significantly higher [Fe/H] and lower average α/Fe not obvious in this plot, where all abundances are relative to α-element, Mg. Comparing the Sculptor abundance patterns with those predicted by the VMO pair-production SN (progenitor masses between 140 and 260 M☉) models of Heger & Woosley we cannot find a good match. It is likely that all the stars in our sample have been enriched by more than one SN, although perhaps not many more (see Paper I). Most critically we always find elements heavier than Zn in all our spectra, which are absent in the Heger & Woosley VMO pair-production SNe. This does place limits on the models that anticipate only one zero-metallicity SN per protogalaxy, but a lot more data are required to be conclusive.
The observations we have presented here also add to the evidence suggesting that the abundance patterns observed in stars in small nearby galaxies are markedly different from those observed in our Galaxy. This makes it difficult for a significant proportion of the stars observed in our Galaxy to have been formed in small galaxies that subsequently merged to form the Milky Way. This is true of the disk, the bulge, and the inner halo of our Galaxy from the (limited) data available to date. The only component of our Galaxy with some similarity to the stellar populations found in dwarf galaxies is the outer halo, which contains a very small fraction by mass of stars in our Galaxy.

With our accurate measurements of a range of different elements we have found that we can plot the enrichment of the ISM in these galaxies due to the observed star formation rate variations directly. This is especially evident in the α elements (see Fig. 16). This is the first time such a direct measurement has been made of the chemical evolution of a galaxy over nearly a Hubble time. Currently, the number of stars observed in each dSph is too small to be able to make concrete statements, but it is clear that larger samples coming from instruments such as FLAMES are going to have a dramatic impact upon our understanding of the chemical evolution of galaxies. These larger samples will also allow us to be more definite in our interpretation of the nucleosynthetic origin of the elements used to trace SN II and SN Ia masses and rates, as well as the timescales and effect of AGB stars.

There are many good arguments to suggest that star formation has occurred in these small objects back to the earliest times in the universe. There are also suggestions that the first stars were formed in dwarf galaxy-size objects. Nonetheless, we can find no evidence that any of the stars we observed were formed from an ISM enriched by the single zero-metallicity stars proposed in the literature.

The absolute ages of the oldest stars can still not be determined very accurately; a reasonable error of ~2 Gyr is the time elapsed between $z = 6$ and $z = 2$. But with abundances we can measure the enrichment of the gas in a galaxy, which provides enough information to allow us to determine a more accurate absolute timescale. The galaxy must produce SNe at a rate consistent with the star formation history. We have taken this approach here, for a limited sample of stars, with promising results, and we look forward to significantly extending our sample in the not too distant future.

We thank the Paranal Observatory staff for the excellent support we received during both of our visitor runs. We also acknowledge useful discussions with Tom Abel, Andrea Ferrara, Alex Heger, Sally Oey, Evan Skillman, Rosie Wyse, and Sukyoung Yi. We also thank the anonymous referee for helpful comments. E. T. gratefully acknowledges support from a fellowship of the Royal Netherlands Academy of Arts and Sciences and PATH travel support from the University of Oxford. K. A. V. would like to thank the National Science Foundation for support through a CAREER award, AST-99-84073.

### References

Aaronson M., & Mould J. R. 1980, ApJ, 240, 804
Aaronson M., Mould J. R. 1985, ApJ, 290, 191
Aaronson, M., Olszewski, E. W., & Hodge P. W. 1983, ApJ, 267, 271
Aaronson, M., Da Costa, G. S., Hørstok, M., Mould, J. R., Norris, J., & Stockman, H. S. 1984, ApJ, 277, L9
Abel, T., Bryan, G. L., & Norman, M. L. 2002, Science, 295, 93
Andrews, S. M., Meyer, D. M., & Lauroesch, J. T. 2001, ApJ, 552, L73
Armandroff, T. E., & Da Costa, G. S. 1991, AJ, 101, 1329
Azzopardi, M., Breysacher, J., Muratorio, G., & Westerlund, B. E. 1999, in IAU Symp. 192, The Stellar Content of Local Group Galaxies, ed. P. A. Whitelock & R. D. Cannon (San Francisco: ASP), 9
Azzopardi, M., Lequeux, J., & Westerlund, B. E. 1985, A&A, 144, 388
———. 1986, A&A, 161, 232
Baade, W. 1963, Evolution of Stars and Galaxies, ed. C. H. P. Payne-Gaposchkin (Cambridge: MIT Press)
Beaucamp, D., Hardy, E., Suntzeff, N. B., & Zinn, R. 1995, AJ, 109, 1628
Bergbush, P. A., & VandenBerg, D. A. 2001, ApJ, 556, 322
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&A, 106, 275
Bromm, V., Coppi, P. S., & Larson, R. B. 2002, ApJ, 564, 23
Buonanno, R., Corsi, C. E., Castellani, M., Marconi, G., Fusie Pecci, F., & Zinn, R. 1999, AJ, 118, 1671
Buonanno, R., Corsi, C. E., Fusie Pecci, F., Hardy, E., & Zinn, R. 1985, A&A, 152, 65

### Table 5

| Galaxy      | Photometric ([Fe/H]) | Spectroscopic ([Fe/H]) | Ref.     |
|-------------|----------------------|------------------------|----------|
|            | $\delta$[Fe/H]       | $\delta$[Fe/H]         |          |
| Ursa Minor  | $-2.2$               | $-1.9$                 | SC01     |
| Draco       | $-2.1$               | $-2.0$                 | SC01     |
| Carina      | $-2.0$               | $-1.6$                 | This work |
| Sculptor    | $-1.8$               | $-1.5$                 | This work |
| Sextans     | $-1.7$               | $-2.1$                 | SC01     |
| Leo I       | $-1.5$               | $-1.3$                 | This work |
| Fornax      | $-1.3$               | $-1.2$                 | This work |

There are many good arguments to suggest that star formation has occurred in these small objects back to the earliest times in the universe. There are also suggestions that the first stars were formed in dwarf galaxy-size objects. Nonetheless, we can find no evidence that any of the stars we observed were formed from an ISM enriched by the single zero-metallicity stars proposed in the literature.

The absolute ages of the oldest stars can still not be determined very accurately; a reasonable error of ~2 Gyr is the time elapsed between $z = 6$ and $z = 2$. But with abundances we can measure the enrichment of the gas in a galaxy, which provides enough information to allow us to determine a more accurate absolute timescale. The galaxy must produce SNe at a rate consistent with the star formation history. We have taken this approach here, for a limited sample of stars, with promising results, and we look forward to significantly extending our sample in the not too distant future.

We thank the Paranal Observatory staff for the excellent support we received during both of our visitor runs. We also acknowledge useful discussions with Tom Abel, Andrea Ferrara, Alex Heger, Sally Oey, Evan Skillman, Rosie Wyse, and Sukyoung Yi. We also thank the anonymous referee for helpful comments. E. T. gratefully acknowledges support from a fellowship of the Royal Netherlands Academy of Arts and Sciences and PATH travel support from the University of Oxford. K. A. V. would like to thank the National Science Foundation for support through a CAREER award, AST-99-84073.
