An abundance study of red-giant-branch stars in the Hercules
dwarf spheroidal galaxy

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ABSTRACT

Context. Dwarf spheroidal galaxies are some of the most metal-poor, and least luminous objects known. Detailed elemental abundance analysis of stars in these faint objects is key to our understanding of star formation and chemical enrichment in the early universe, and may provide useful information on how larger galaxies form.

Aims. Our aim is to provide a determination of [Fe/H] and [Ca/H] for confirmed red-giant branch member stars of the Hercules dwarf spheroidal galaxy. Based on this we explore the ages of the prevailing stellar populations in Hercules, and the enrichment history from supernovae. Additionally, we aim to provide a new simple metallicity calibration for Strömgren photometry for metal-poor, red giant branch stars.

Methods. High-resolution, multi-fibre spectroscopy and Strömgren photometry are combined to provide as much information on the stars as possible. From this we derive abundances by solving the radiative transfer equations through marcs model atmospheres.

Results. We find that the red-giant branch stars of the Hercules dSph galaxy are more metal-poor than estimated in our previous study that was based on photometry alone. From this, we derive a new metallicity calibration for the Strömgren photometry. Additionally, we find an abundance trend such that [Ca/Fe] is higher for more metal-poor stars, and lower for more metal-rich stars, with a spread of about 0.8 dex. The [Ca/Fe] trend suggests an early rapid chemical enrichment through supernovae of type II, followed by a phase of slow star formation dominated by enrichment through supernovae of type Ia. A comparison with isochrones indicates that the red giants in Hercules are older than 10 Gyr.

Key words. Galaxies:dwarf – Galaxies: evolution – Galaxies: individual: Hercules – Stars: abundances

1. Introduction

Over the past few years, the number of known dwarf spheroidal (dSph) galaxies orbiting the Milky Way has more than doubled through systematic searches in large photometric surveys such as the Sloan Digital Sky Survey (e.g., Zucker et al. 2006; Belokurov et al. 2007). These recently discovered dSph galaxies have much lower surface brightness than the previously known dSph galaxies. Typically, these systems have total luminosities $M_V > -6$ (e.g., Martin et al. 2008), so they are named ultra-faint (e.g., Koch 2009). Additionally, they are so faint that thus far they have only been detected around the Milky Way, but more sensitive surveys in the future may yield additional detections also at larger distances (Tollerud et al. 2008). These galaxies are also more metal-poor than the classical, more luminous dSph galaxies (e.g., Simon & Geha 2007; Kirby et al. 2008).

Very metal-poor stars have been found in the Galactic halo (e.g., Schöck et al. 2009). However, studies of the more luminous dSph galaxies (e.g., Koch et al. 2006; Helmi et al. 2006) have found a significant lack of stars with [Fe/H] $\leq -3$ when compared to the stars of the Milky Way halo. Since dSph galaxies may be the building blocks of parts of the Galactic halo (see Grebel & Gallagher 2004 for a discussion of the ages of stellar populations in the Galactic dSphs and halo), this result was considered a problem for our current understanding of the formation of large galaxies (Schöck et al. 2009). However, recent studies of the ultra-faint (e.g., Kirby et al. 2009b; Frebel et al. 2010b; Norris et al. 2010; Simon et al. 2010) and the classical (e.g., Starkenburg et al. 2010; Frebel et al. 2010a) dSph galaxies have discovered stars with [Fe/H] $\leq -3$, thus reigniting the discussion of the origin of the Galactic halo. Whether the metallicity distribution functions of the halo and of the dSph galaxies agree still remain to be determined. Additional abundance studies are needed for both halo and dSph stars, in order to rule out selection biases due to low number statistics.

Studies of [$\alpha$/Fe] in the stars in the more luminous dSph galaxies suggest that stars more metal-rich than [Fe/H] $> -2$ have lower [$\alpha$/Fe] ratios, whilst more metal-poor stars (from now taken to be stars with [Fe/H] $< -2$) have about the same enhancement in the $\alpha$-elements relative to iron as the stars in the halo and disk of the Milky Way (see, e.g., Shetrone et al. 2001; Geisler et al. 2007; Tolstov et al. 2009). This could be interpreted as support for an early accretion of dSphs. The discrepancy is poorly constrained for the recently discovered ultra-faint dSph galaxies, with notable exceptions for a few stars in these ultra-faint objects (Feltzing et al. 2009; Frebel et al. 2010b).

The Hercules dSph galaxy lies at a distance of $\sim 150$ kpc from us (Adén et al. 2009a) and it has a $V$-band surface brightness of only 27.2 $\pm$ 0.6 mag arcsec$^{-2}$ (Martin et al. 2008). Previous studies, based on photometry and the measurements of the near-infrared Ca ii triplet lines in red giant branch
the velocity distribution of the foreground dwarf stars, making it that the mean velocity of the Hercules dSph is very similar to members of the Milky Way. In Adén et al. (2009a) we showed that the system. This has implications for galaxy properties derived from such velocity dispersions, e.g., resulting in a lower mass.

### Table 1. Properties of the Hercules dSph galaxy

| Parameter | Footnote | Value |
|-----------|----------|-------|
| $\alpha_0$ | J2000 | 16 31 05.2 ± 2.5 a |
| $\delta_0$ | J2000 | +12 47 18 ± 17 a |
| $r_s$ | arcmin | 8.6 $^{+1.1}_{-1.0}$ a |
| $M_V$ | kpc | 6.6 ± 0.3 a |
| $E(B-V)$ | b | 0.062 b |
| $M_{500}$ | $M_\odot$ | 1.9$^{+1.1}_{-1.0}$ $\times$ 10$^6$ c |

a The centroid, $\alpha_0$ and $\delta_0$, half-light radius, $r_s$, and absolute magnitude are taken from Martin et al. (2008).
b The distance, $D$, and reddening, $E(B-V)$, are taken from Adén et al. (2009a).c The mass within the central 300 pc is taken from Adén et al. (2009a).

(RGB) stars, have found a mean metallicity of [Fe/H] $\sim$ −2.3 (Simon & Geha 2007; Adén et al. 2009a). In Table 1 we provide a list with additional properties of the Hercules dSph galaxy.

A study using spectrum synthesis of Fe I lines (Kirby et al. 2008b) found a lower mean metallicity of $-2.58 \pm 0.51$ dex, Koch et al. (2008b) found, using high-resolution spectroscopy of two Hercules RGB stars, that the hydrostatic burning $\alpha$-elements (e.g., Mg, O) are strongly enhanced, while the heavy (mainly) s-process elements (e.g., Sr, Ba, La) are largely depleted. The low [Fe/H] observed for the Hercules dSph galaxy suggests that star formation ceased relatively early after the formation of this galaxy. Thus, detailed elemental abundances for stars in the ultra-faint dSph galaxies are key to our understanding of star formation and chemical enrichment in the early universe.

In this study we will determine some of the elemental abundance trends in the ultra-faint Hercules dSph galaxy.

This paper is organised as follows: in Sect. 2 we describe the observations and the reduction of our spectra. In Sect. 3 we describe the determination of the stellar parameters for each star. Section 4 deals with the abundance analysis. In Sect. 5 we provide a comparison with abundances determined in other studies, in Sect. 6 we show and discuss our results and Sect. 7 concludes the article.

### 2. Observations, data reduction, and measurement of equivalent widths

#### 2.1. Selection of targets

Some of the new ultra-faint dSph galaxies are seen through a significant portion of the Milky Way disk. Moreover, sometimes they have systemic velocities very similar to the bulk motion of the stars in the Milky Way disk. This is the case for the Hercules dSph galaxy (Adén et al. 2009a). Thus, when studying systems like Hercules it is very important that the stars are members of the galaxy, and not foreground contaminating stars that belong to the Milky Way. In Adén et al. (2009a) we showed that the mean velocity of the Hercules dSph is very similar to the velocity distribution of the foreground dwarf stars, making it difficult to disentangle the dSph galaxy stars from the foreground dwarf stars using radial velocity measurements alone. We used the Strömgren $c_1$ index to identify the RGB stars that belong to the dSph galaxy and showed that a proper cleaning of the sample results in a smaller value for the velocity dispersion of the system. This has implications for galaxy properties derived from such velocity dispersions, e.g., resulting in a lower mass.

### Table 2. Data for the RGB stars in the Hercules dSph galaxy observed with FLAMES.

| ID | RA         | DEC        | $V$  | $(b - y)$ | S/N | Used |
|----|------------|------------|------|-----------|-----|------|
| 12175 | 247.81591  | 12.58238   | 18.72 | 0.83      | 35 * |      |
| 42241 | 247.73849  | 12.78898   | 18.72 | 0.82      | 36 * |      |
| 41082 | 247.84564  | 12.74666   | 19.05 | 0.78      | 23  |      |
| 42149 | 247.74718  | 12.79045   | 19.21 | 0.70      | 25 * |      |
| 41743 | 247.78386  | 12.80170   | 19.44 | 0.70      | 24 * |      |
| 42795 | 247.68541  | 12.82996   | 19.51 | 0.67      | 23  |      |
| 40789 | 247.87404  | 12.74030   | 19.52 | 0.67      | 20 * |      |
| 41460 | 247.80860  | 12.75741   | 19.60 | 0.69      | 21  |      |
| 42096 | 247.75261  | 12.82550   | 19.59 | 0.66      | 20  |      |
| 40993 | 247.85432  | 12.75811   | 19.73 | 0.67      | 20 * |      |
| 42324 | 247.73111  | 12.76968   | 19.72 | 0.62      | 13 * |      |
| 12729 | 247.78123  | 12.52606   | 19.84 | 0.67      | 12 * |      |
| 40222 | 247.93108  | 12.78307   | 20.01 | 0.62      | 11  |      |
| 42692 | 247.69607  | 12.75570   | 20.02 | 0.63      | 12  |      |
| 43688 | 247.59341  | 12.86022   | 20.04 | 0.61      | 8   |      |
| 43428 | 247.61721  | 12.75078   | 20.09 | 0.60      | 11  |      |
| 11239 | 247.87333  | 12.58958   | 20.11 | 0.61      | 9   |      |
| 41912 | 247.76877  | 12.77069   | 20.15 | 0.64      | 8   |      |
| 42008 | 247.76005  | 12.80071   | 20.21 | 0.61      | 9   |      |
| 41371 | 247.81831  | 12.83070   | 20.23 | 0.63      | 10  |      |

Column 1 lists the RGB star ID (Adén et al. 2009a). Columns 2 and 3 list the coordinates. Column 4 lists the $V$ magnitude and column 5 lists the $(b - y)$ colour. Column 6 lists estimates of the S/N in the final spectra and column 7 indicates whether the star was analysed in this work, compare Sect. 4.

#### 2.2. Observations

Our spectroscopy was carried out using the multiobject spectrograph Fibre Large Array Multi Element Spectrograph (FLAMES) at the Very Large Telescope (VLT) on Paranal. The observations, 18 observing blocks of 60 minutes each made in service mode, are summarised in Table 3. Operated in Medusa fibre mode, this instrument allows for the observation of up to 130 targets at the same time (Pasquini et al. 2002). 23 fibres were dedicated to observing blank sky. We used the GIRAFFE/HR13 grating, which provides a nominal spectral resolution of $R \sim 20000$ and a wavelength coverage from 6100 Å to 6400 Å. We verified the spectral resolution by measuring the full-width-half maximum of telluric emission lines in the combined sky spectrum.

#### 2.3. Data reduction and measurement of equivalent widths

The FLAMES observations were reduced with the standard GIRAFFE pipeline, version 2.8.1 (Blecha et al. 2000). This pipeline provides bias subtraction, flat fielding, dark-current subtraction, and accurate wavelength calibration from a ThAr lamp.
The 23 sky spectra were combined and subtracted from the object spectra with the task SKYSUB in the SPECRED package in IRAF.

Next, the object spectra from the individual frames were Doppler-shifted to the heliocentric rest frame and median-ockered, rejecting measurements deviating by more than 3 \( \sigma \) from the mean object spectrum with the task SKYSUB in the SPECRED package.

The object spectra were used an average sigma clipping algorithm, rejecting measurements deviating by more than 3 \( \sigma \), in order to remove cosmic rays. For accomodating for this, we set the continuum for each line individually when measuring the equivalent widths, \( W_t \).

Finally, we normalised the spectra with the task CONTINUUM in the ONEDSPEC package in IRAF. We used a Spline function of the 1st order. We note that the normalisation was not optimal over the entire wavelength range. To accomodate for this, we set the continuum for each line individually when measuring the equivalent widths, \( W_t \).

The \( W_t \) for the absorption lines were measured by fitting a Gaussian profile to each of the lines using the IRAF task SPLOT. However, for some of the weak lines with low S/N it was better to determine the \( W_t \) by integration of the pixel values using the "e" option in SPLOT. The \( W_t \) are listed in Table 3.

We were not able to identify any absorption lines in the continuum for stars fainter than \( V_0 \geq 19.80 \). The S/N for the spectra for these stars are about 10. Thus, 8 stars were discarded from the abundance analysis (compare Table 3). Additionally, we were not able to remove the sky emission for RGB star 41082 to a satisfying level, and the S/N was lower than expected from the stars magnitude, indicating that something may have gone wrong with the positioning of the fibre. Therefore, the spectrum for this star was discarded also, leaving us with spectra for 11 usable RGB targets.

### 3. Stellar parameters

The effective temperature \( T_{\text{eff}} \) is often determined by requiring that the abundances derived from individual Fe lines are independent of the excitation potential for the lines. This was not an option for us due to the small number of Fe i lines for each star. Instead, we calculated \( T_{\text{eff}} \) from the Str"omgren photometry using the calibration in Alonso et al. (1999). The photometry is from Adén et al. (2009a) and has been corrected for interstellar extinction using the dust maps by Schlegel et al. (1998). These maps give a reddening of \( E(B − V) = 0.062 \). We estimated the errors in \( T_{\text{eff}} \) using the uncertainties for the Str"omgren photometry. Since we are using deep photometry, and are only using stars at the brighter end of the luminosity function, the errors are essentially the same for the stars in the sample. We find a typical error of about 100 K for all stars.

Surface gravities, log \( g \), were estimated using an isochrone by VandenBerg et al. (2006) with [Fe/H] \( = −2.31 \) (most metal-poor isochrone available), an age of 12 Gyr, colour transformations by Clem et al. (2004), and no \( α \)-enhancement. Figure 1 shows the colour-magnitude diagram for the Hercules dSph galaxy with log \( g \) values indicated. The isochrone was shifted using the distance modulus derived in Adén et al. (2009a), \( (m − M) = 20.85 \pm 0.11 \).

To estimate how sensitive our value of log \( g \) is to the choice of the age for the isochrone, we repeated the above derivation for isochrones with an age of 8 and 18 Gyr, and [Fe/H] \( = −2.31 \). We find that the estimated value of log \( g \) deviated by a maximum of \( \sim 0.1 \) dex from the initial log \( g \) when the age was changed. Additionally, for comparison with an isochrone based on a different stellar evolutionary model, we compared with values of log \( g \) derived using the Dartmouth isochrones (Dotter et al. 2008), with colour transformations by Clem et al. (2004), and similar age and metallicity as for the isochrone by VandenBerg et al. (2006). We find that the values of log \( g \) estimated using the two sets of isochrones differ by about 0.1 dex.

Finally, we estimated the contribution to the error in log \( g \) from the uncertainty in the distance modulus and magnitude using 10^6 Monte Carlo realisations of the distance modulus and magnitude drawn from within the individual error bars on each parameter. We find that the values of log \( g \) deviated by a \( \sim 0.1 \) dex from the initial log \( g \). Based on these three error estimates, we define an upper limit to the error in log \( g \) of 0.35 dex to make sure that the error is not under-estimated.

In Sect. 4 we investigate how different values of log \( g \) affect the abundance analysis. We estimated the microturbulence, \( \xi_t \), using the \( \xi_t \) and log \( g \) for metal-poor halo stars from Andrievsky et al. (2010). These stars have about the same metallicity and log \( g \) as our Hercules RGB stars. A least-square fit to their data, in \( \xi_t \) vs. log \( g \) space (Fig. 2), of 35 giant stars yields

\[
\xi_t = −0.38(±0.06) \cdot \log g + 2.47(±0.1). 
\]

We estimated the errors in \( \xi_t \), using the uncertainties for the least-square fit (Eq. 1) and an uncertainty in log \( g \) of 0.3 dex. We find a typical error in \( \xi_t \) of \( \sim 0.2 \) km s^{-1}.

The final stellar parameters used in the abundance analysis are summarised in Table 3.

### 4. Abundance analysis

Model atmospheres were calculated for the programme stars with the code MARCS according to the procedures described in Gustafsson et al. (2008) and using the fundamental parameters in Table 3. Next a line list was compiled in the wavelength region 6120 – 6400 Å with spectral lines from neutral and singly ionised atoms from the VALD database (Piskunov et al. 1995; Ryabchikova et al. 1997; Kupka et al. 1999, 2000). Equivalent widths or synthetic spectra were then computed from radiative transfer calculations in spherical geometry in the model atmospheres using the Eqwi/Bsyn codes that share many subrou...
times and data files with M
c
terms of identifying absorption lines, the final elemental abundances are determined using a

\[ \epsilon \]

Table 4. Equivalent width measurements.

| Ion | \( \lambda \) | \( \log g_f \) | EP | \( W_i \) | \( W_j \) | \( W_k \) | \( W_l \) | \( W_m \) | \( W_n \) | \( W_o \) | \( W_p \) | \( W_q \) | \( W_r \) | \( W_s \) | \( W_t \) | \( W_u \) | \( W_v \) | \( W_w \) | \( W_x \) | \( W_y \) | \( W_z \) |
|-----|------|--------|---|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Ca I | 6122.22 | -0.386 | 1.886 | 46 | 89 | 44 | 66 | ... | 24 | 49 | 89 | 52 | 57 | ... |
| Ca I | 6162.17 | -0.167 | 1.899 | 72 | 122 | 35 | 96 | ... | 43 | ... | 70 | ... | 61 | 69 | ... |
| Fe I | 6137.69 | -1.403 | 2.588 | 41 | 148 | 48 | 65 | ... | 43 | ... | 66 | ... | 86 | ... | ... |
| Fe I | 6151.62 | -3.299 | 2.176 | ... | 62 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6173.34 | -2.880 | 2.223 | ... | 96 | ... | 52 | ... | ... | ... | ... | ... | ... | 65 | ... |
| Fe I | 6180.20 | -2.586 | 2.727 | ... | 38 | ... | 13 | ... | ... | ... | ... | ... | ... | 30 | ... |
| Fe I | 6200.31 | -2.437 | 2.608 | ... | 75 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6213.43 | -2.482 | 2.223 | ... | 92 | 25 | 35 | ... | ... | ... | ... | ... | ... | 49 | ... |
| Fe I | 6219.28 | -2.433 | 2.198 | ... | 111 | ... | 58 | ... | ... | ... | ... | 40 | ... | ... | ... |
| Fe I | 6232.64 | -1.223 | 3.654 | ... | 59 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6246.32 | -0.733 | 3.602 | ... | 87 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6252.56 | -1.687 | 2.404 | 50 | 149 | ... | 81 | ... | ... | ... | ... | ... | 71 | ... | ... |
| Fe I | 6265.13 | -2.550 | 2.176 | ... | 124 | ... | 83 | ... | ... | ... | ... | ... | 43 | ... | ... |
| Fe I | 6270.23 | -2.464 | 2.858 | ... | 42 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6301.50 | -0.718 | 3.654 | ... | 119 | ... | 42 | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6302.49 | -0.973 | 3.686 | ... | 57 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6322.69 | -2.426 | 2.588 | ... | 97 | ... | 40 | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6335.33 | -2.177 | 2.198 | 36 | 121 | ... | 91 | 27 | ... | ... | ... | 58 | 51 | ... | 50 |
| Fe I | 6336.82 | -0.856 | 3.686 | ... | 83 | ... | ... | ... | ... | ... | ... | ... | ... | ... | 33 |
| Fe I | 6355.03 | -2.350 | 2.845 | ... | 55 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6393.60 | -1.432 | 2.433 | 69 | 138 | ... | 109 | 35 | 39 | ... | 65 | 68 | ... | 85 |
| Fe I | 6355.03 | -2.177 | 2.198 | 36 | 121 | ... | 91 | 27 | ... | ... | ... | 58 | 51 | ... | 50 |
| Fe I | 6335.33 | -2.177 | 2.198 | 36 | 121 | ... | 91 | 27 | ... | ... | ... | 58 | 51 | ... | 50 |
| Fe I | 6322.69 | -2.426 | 2.588 | ... | 97 | ... | 40 | ... | ... | ... | ... | ... | ... | ... | ... |
| Fe I | 6335.33 | -2.177 | 2.198 | 36 | 121 | ... | 91 | 27 | ... | ... | ... | 58 | 51 | ... | 50 |
| Fe I | 6393.60 | -1.432 | 2.433 | 69 | 138 | ... | 109 | 35 | 39 | ... | 65 | 68 | ... | 85 |

Table 5. Photometry and model parameters used in the abundance analysis of the stars.

| ID | Other ID | \( V_0 \) | \( (b - y)_0 \) | [Fe/H] | \( T_{eff} \) | \( \log g \) | \( \xi \) | S/N |
|----|---------|--------|----------|-------|--------|--------|--------|-----|
| 12175 | Her-3 | 18.53 | 0.78 | -3.17 | 4370 | 0.78 | 2.17 | 35 |
| 42241 | Her-2 | 18.53 | 0.78 | -2.03 | 4270 | 0.78 | 2.17 | 35 |
| 41082 | Her-3 | 18.86 | 0.74 | -2.95 | 4520 | 1.19 | 2.02 | 24 |
| 42149 | ... | 19.25 | 0.66 | -2.42 | 4620 | 1.22 | ... | ... |
| 42795 | ... | 19.32 | 0.65 | -3.17 | 4620 | 1.22 | ... | ... |
| 40789 | ... | 19.33 | 0.63 | -2.88 | 4600 | 1.24 | ... | ... |
| 41460 | ... | 19.40 | 0.64 | -3.10 | 4590 | 1.27 | ... | ... |
| 42096 | ... | 19.40 | 0.62 | -2.60 | 4620 | 1.27 | ... | ... |
| 40993 | ... | 19.53 | 0.63 | -2.38 | 4600 | 1.33 | ... | ... |
| 42324 | ... | 19.53 | 0.57 | -2.70 | 4740 | 1.43 | ... | ... |
| 12729 | ... | 19.65 | 0.63 | -2.35 | 4640 | 1.40 | ... | ... |

Column 1 lists the RGB star ID (Adén et al. 2009a). Column 2 lists the ID from Koch et al. (2008a). Column 3 lists the \( V_0 \) magnitude and column 4 lists the \( (b - y)_0 \) colour. Column 5 lists the metallicity as determined in Sect. 4.2. Column 6 to 8 list the stellar parameters as determined in Sect. 4.2. Column 9 lists an estimate of the S/N.

4.1. Elemental abundance errors

For elements with more than four lines measured, the random errors in the elemental abundance ratios were calculated as

\[ \epsilon_{\text{rand}, \frac{X}{H}} = \frac{\sigma_X}{\sqrt{N}} \]  

where \( X \) is the element, \( \sigma \) is the standard deviation of the abundances derived from the individual \( W_i \), and \( N \) the number of lines for that element. For elements with two to four lines measured, the uncertainty in the measurement of \( W_i \), \( w_i \), was estimated using the relation in Cayrel (1988). The random errors in the elemental abundances were then estimated using 10^5 Monte Carlo realisations of \( W_i \), \( w_i \), drawn from within the probability distribution of \( W_i \) given \( w_i \). For each value of \( W_i \), we re-calculate an elemental abundance using the relation \( \log(A) = \log(W_i) \) where \( A \) is the elemental abundance. We note that the probability distribution of \( \log(A) \) is asymmetric. Thus, we adopt the standard deviation based on the sextiles (which is equivalent to 1σ in the case of a Gaussian distribution) as our final random error. For elements with less than two lines measured we performed a \( \chi^2 \)-
test between the stellar spectrum and a grid of synthetic spectra, to estimate the random errors in the elemental abundances (see Sect. 4.2 and 4.3). Note that none of the Ca abundances are estimated using more than two lines. Thus, the errors in [Ca/Fe] were derived using either a \( x^2 \)-test or by propagating \( \epsilon_{\text{rand}} \) as derived from \( \epsilon_{\text{sys}} \). The systematic errors were estimated from the error bars. As can be seen, [Fe/Fe] as derived from Fe I lines do not agree within the error bars. This discrepancy in the iron abundance could partially be caused by over-ionisation in Fe I lines. Ivans et al. (2001) argue that over-ionisation could cause an under-estimate of about 0.1 dex for RGB stars if Fe I lines are used.

Figure 3 shows the cumulative distribution functions (CDFs) for the measured Fe I lines. As can be seen, [Fe/Fe] derived from the \( W_i \) agrees well with a synthetic spectrum with an iron abundance close to the -2 dex value derived from the \( W_i \)s.
4.2.2. Low S/N spectra

RGB stars 42149, 41743, 42795, 40789, 42096, 40993 and 12729 have a lower S/N than 12175 and 42241. However, at least two Fe i lines were measurable for each of the stars. Since the S/N is much lower for these stars, we did the following test to ensure that the [Fe/H] derived from the equivalent widths are reasonable. For each of the stars, we generated a set of synthetic spectra with five different [Fe/H] values, separated by 0.2 dex, centred on the [Fe/H] derived from the equivalent widths. A plot of the stellar spectrum, with the synthetic spectra over-plotted, enabled us to verify that the [Fe/H] derived from the Wλs is a good estimate of the iron abundance of the star. We found that none of the stellar spectra deviated significantly from a synthetic spectrum with a similar [Fe/H] abundance. Figure 4 shows an example, for 41743. As can be seen, an [Fe/H] of ~ –2.4 dex is a reasonable estimate of the iron abundance for this star.

4.2.3. Difficult spectra

RGB stars 41460 and 42324 have low S/N (21 and 13, respectively) and are very metal-poor. Thus, it was difficult to identify the Fe i absorption lines in the spectra. However, we did see faint absorption signatures but the low S/N made it virtually impossible to measure the lines. Instead, we performed a χ²-test between the observed spectrum and a grid of synthetic spectra with 17 different [Fe/H] values, separated by 0.05 dex. Each synthetic spectrum yields a χ² value, and the best fit is found when χ² is minimised (χ²_min). We used a width of 3 σ, which covers about 99.7 per cent of the absorption feature, for each iron line in the line list (see Table 4). We investigated the sensitivity of the χ²-test region by varying it between 2 σ and 4 σ and found that it had negligible impact on the result. The continuum for each line was adjusted, as the average of the signal on each side of the absorption feature over 0.6 Å, to accommodate for the local deviations from the continuum normalisation in Sect. 2.3. The error for each pixel in the observed spectrum was approximated by the variance in the spectrum. The distribution enclosed by χ²_min + 1 corresponds to 1 σ for a normal distribution (Press et al. 1992). We used this as the measurement error.

4.3. Calcium

The mean [Ca/H] is determined on the scale where log εH = 12.00. The solar calcium abundance of 6.34 is adopted from Asplund et al. (2009). There are two Ca i lines, at 6122.22 Å and

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**Fig. 3. Left panels:** Portions of stellar spectra around four Fe i (b) and two Ca i (a) lines for RGB star 12175. • indicate the observed spectrum. The solid line indicates a synthetic spectrum with [Fe/H] = −3.1 and [Ca/H] = −2.8. The dotted lines in (a) indicate synthetic spectra with [Ca/H] ± 0.3 relative to the solid-line-synthetic spectrum. **Right panels:** Portions of stellar spectra around four Fe i (d) and two Ca i (c) lines for star 42241. • indicate the observed spectrum. The solid line indicates a synthetic spectrum with [Fe/H] = −2.0 and [Ca/H] = −2.6.

**Fig. 4.** Portions of stellar spectra around three Fe i lines for RGB star 41743. • indicate the observed spectra. The solid lines indicate synthetic spectra with [Fe/H] from −2.85 to −2.05 dex, top to bottom, separated by 0.2 dex each.
Lind et al. (2009) obtained high S five. A comparison with a high S/N RGB star are, in similar manner as done for Fe, discussed in the following sections.

4.3.1. Highest S/N spectra

For RGB star 12175 both Ca i lines were measured and they give \([\text{Ca}/\text{H}] = -2.9 \pm 0.1\). Figure 3 shows the stellar spectrum around the Ca i lines. As can be seen, [Ca/H] as measured from the \(W_i\) agree well with a synthetic spectrum with similar [Ca/H]. Additionally, Fig. 3 shows an example of two synthetic spectra with [Ca/H] \(\pm 0.3\).

For RGB star 42241 we find a [Ca/H] of \(-2.5 \pm 0.2\). This is significantly higher than [Ca/H] for RGB star 12175. Figure 3 shows the stellar spectrum of 42241 around the two Ca i lines. As can be seen, [Ca/H] as derived from the \(W_i\) agree well with a synthetic spectrum with a similar abundance.

4.3.2. Low S/N spectra

RGB stars 42149, 41743, 40789, 42096 and 42324 have a lower S/N than RGB stars 12175 and 42241. However, both of the Ca i lines were measurable in all four stars.

Since the S/N is lower we repeated the same test done for the iron abundance analysis (compare Sect. 4.2.2), generating a grid of synthetic spectra for each star, to see if the [Ca/H] as derived from the \(W_i\) were reasonable. We found that the synthetic spectrum of RGB star 40789, in comparison with the observed spectrum, indicates that the [Ca/H] determined from the measurement of the \(W_i\) was slightly, about 0.1 dex, over-estimated. Thus, we estimated the Ca i abundance for RGB star 40789 using the same method as for the spectra identified as difficult for the measurement of the Fe i lines (see Sect. 4.2.3). For all other stars in this category, the abundances from the measured \(W_i\) and those from the \(\chi^2\) comparison of synthetic spectra showed good agreement.

4.3.3. Difficult spectra

For RGB star 42795, 41460, and 40993 only one or none of the Ca i lines were measurable. However we did see a general decrease in the continuum at the wavelengths for the Ca i lines indicating the presence of Ca in the atmospheres of these metal-poor stars. Thus, we estimated the Ca i abundance using the same method as for the spectra identified as difficult for the measurement of the Fe i lines (see Sect. 4.2.3). The results from the analysis are summarised in Table 6.

We were not able to identify any Ca i absorption features for RGB star 12729. Thus, [Ca/H] remains unknown for this star.

5. A comparison with abundances determined in other studies

5.1. A comparison with a high S/N RGB star

Lind et al. (2009) obtained high S/N spectroscopy of several bright RGB stars in the Milky Way. They used the same instrument and grating (GIRAFFE/HR13) as in this study. Through private communication they provided us with a spectrum of one of their bright targets, star 17691, that has a S/N of about 300. We measured the \(W_i\) for the lines in Table 4 and performed an abundance analysis for this star as described in Sect. 2.3 and 4. The stellar parameters was adopted from Lind et al. (2009). We find an Fe abundance that is 0.01 dex more metal poor, and a Ca abundance 0.04 dex lower than given in Lind et al. (2009). Thus, \(\text{Ca}/\text{Fe}\) remains unknown for this star.

5.2. A comparison with earlier spectroscopic results

Koch et al. (2008b) obtained high resolution spectroscopy (\(R \sim 20000\)), with similar S/N and resolution as in this study, of two stars in the Hercules dSph galaxy, Her-2 and Her-3. These stars correspond to our RGB stars 42241 and 41082. However, RGB star 41082 was discarded from our sample (see Sect. 9). Koch et al. (2008b) find Fe/H] = \(-2.02 \pm 0.20\) and [Ca/Fe] = \(-0.13 \pm 0.05\) for RGB star 42241. Note, however, that Koch et al. (2008b) measured \(W_i\) values of lines over a broader wavelength range from 5500–8900 Å. Our estimates of [Fe/H] are in very good agreement, but [Ca/Fe] as derived by Koch et al. (2008b) is 0.4 dex higher.

Figure 5 shows our spectrum and the spectrum from Koch et al. (2008b) for RGB star 42241. In Table 7 we provide a comparison between \(W_{i5}\) as measured from our observed spectrum, and \(W_{i5}\) as measured from the spectrum obtained by Koch et al. (2008b), we note that, for the Ca i lines, the spectrum from Koch et al. (2008b) has deeper absorption. However, the overall absorption for the Fe i and blended lines are in good agreement, except for one weak Fe i line at \(\lambda = 6200.31\) Å that is more prominent in our observed spectrum. We note that the S/N at this line in the spectrum from Koch et al. (2008b) is low, making it difficult to distinguish such a weak line in the spectrum. There is a much brighter star, SDSS J163056.63+124737.5, located only ~12 arcsec from 42241. Thus, we investigate the possibility that the fibre allocated for 42241 has collected a significant amount of flux from SDSS J163056.63+124737.5. SDSS J163056.63+124737.5 is 6.7

Table 6. Derived elemental abundances for the RGB stars in the Hercules dSph galaxy.

| Star     | [Fe/H] | \(N\)  | [Ca/H] | \(N\) | [Ca/Fe] |
|----------|--------|-------|--------|------|--------|
| 12175    | \(-3.1\) \pm 0.14 | 4    | \(-2.89 \pm 0.15\) | 2 | 0.28 \pm 0.21 |
| 42241    | \(-2.03 \pm 0.14\) | 20   | \(-2.54 \pm 0.15\) | 2 | 0.51 \pm 0.21 |
| 42149    | \(-2.95 \pm 0.15\) | 2    | \(-3.08 \pm 0.16\) | 2 | 0.13 \pm 0.22 |
| 41743    | \(-2.42 \pm 0.15\) | 11   | \(-2.51 \pm 0.16\) | 2 | 0.09 \pm 0.22 |
| 42795    | \(-3.17 \pm 0.15\) | 2    | \(-3.11 \pm 0.17\) | 2 | 0.06 \pm 0.23 |
| 40789    | \(-2.88 \pm 0.17\) | 3    | \(-3.06 \pm 0.16\) | 2 | 0.18 \pm 0.23 |
| 41460    | \(-3.10 \pm 0.16\) | \(\chi^2\) | \(-2.78 \pm 0.15\) | \(\chi^2\) | 0.32 \pm 0.22 |
| 42096    | \(-2.60 \pm 0.17\) | 4    | \(-2.40 \pm 0.18\) | 2 | 0.20 \pm 0.25 |
| 40993    | \(-2.38 \pm 0.19\) | 8    | \(-2.68 \pm 0.15\) | \(\chi^2\) | \(-0.3 \pm 0.24\) |
| 42324    | \(-2.70 \pm 0.14\) | \(\chi^2\) | \(-2.60 \pm 0.28\) | 2 | 0.10 \pm 0.31 |
| 12729    | \(-2.35 \pm 0.17\) | 5    | ... | ... | ... |

Column 1 lists the RGB star ID. Column 2 and 4 list the [Fe/H] and [Ca/H], respectively, with total errors in the abundances as indicated. N indicates the number of lines measured for the determination of [Fe/H] and [Ca/H], as indicated, \(\chi^2\) indicates that the corresponding abundance was determined through a \(\chi^2\)-test using a grid of synthetic spectra (see Sect. 2.3.4 and 4.3.3). Column 6 lists [Ca/Fe].
magnitudes brighter in the SDSS r-filter, which is centred on our wavelength region of interest. The seeing for our observations was ∼ 1 arcsec. Based on this, we constructed a model of two Gaussian flux distributions with a full-width half-maximum of 1.5 arcsec and magnitudes that represent the brightness of the stars. We found that the amount of flux from SDSS J163056.63+124737.5 at the position of the fibre is negligible. A similar investigation was carried out for our spectrum obtained by Koch et al. (2008b), yielding the same conclusion. Thus, the origin of this discrepancy can not be due to a contamination by light from this nearby star. A more thorough investigation than this goes beyond the scope of this study. However, one could speculate that there is an unresolved binary present that was overlapped in one observation and out of phase in the other observation, or that it may be due to some differences in the reduction procedure.

Kirby et al. (2008b) studied 20 stars in the direction of the Hercules dSph galaxy. Their metallicities are based on a recently developed automated spectrum synthesis method that takes the information in the whole spectrum into account (Kirby et al. 2008b). The method was originally developed for globular clusters in the Milky Way and was then applied to ultra-faint dSph galaxies in Kirby et al. (2008b). We have 7 stars in common between our samples. Figure 6b shows the difference between our respective determinations of [Fe/H]. We find that our [Fe/H] is on average 0.07 dex more metal-rich, with a scatter of 0.09 dex. In conclusion, the agreement between the [Fe/H] determinations is very good.

### 5.3. A comparison with earlier photometric results

In a previous study of the Hercules dSph galaxy (Adén et al. 2009a) we estimated [Fe/H] using the Strömgren m1 index using the calibration from Calamida et al. (2007). Figure 6a shows a comparison between the photometric [Fe/H] as estimated in Adén et al. (2009a), [M/H]_{phot}, and [Fe/H] as determined from high-resolution spectroscopy in this study. We note that there is a strong trend such that [M/H] appears to be over-estimated in Adén et al. (2009a) for metal-poor stars.
difference of both metallicity scales such that $[\text{M}/\text{H}]_{\text{CA07}} > [\text{Fe}/\text{H}]_{\text{spec}}$. Taking into account the uncertainties of the least-squares fit and the correlation between the fitting parameters (Eq. 4), and the error in $m_{1,0}$ from Adén et al. (2009a) we find a typical error in $[\text{M}/\text{H}]_{\text{phot,new}}$ of 0.17 dex.

6. Results and discussion

6.1. Iron abundance and ages for the RGB stars in Hercules

The RGB stars analysed in this paper span a large range of iron abundances, from about $-3.2$ dex to $-2$ dex, indicating an extended period of chemical enrichment. It is somewhat fortuitous that the two brightest stars in our sample, RGB stars 12175 and 42241, bracket the full range of metallicities. Thus there is no doubt that the range of metallicities derived from high-resolution spectroscopy is real.

In Sect. 5.4 we provide a new Strömgren metallicity calibration. This calibration is valid for stars with $0.02 < m_{1,0} < 0.40$ and $-3.29 < [\text{Fe}/\text{H}] < 1.58$. Two of the 28 RGB stars from Adén et al. (2009a) have an $m_{1,0}$ less than the range for which the new metallicity calibration is valid. However, with an $m_{1,0}$ of 0.01, these stars are included in the sample as a slight extrapolation. In Fig. 8a, we show the resulting histogram of $[\text{M}/\text{H}]_{\text{phot,new}}$ for all the 28 RGB stars identified in Adén et al. (2009a). The bin size of 0.2 dex represents the typical error in $[\text{M}/\text{H}]_{\text{phot,new}}$ (see Sect. 5.4). Figure 8 shows the corresponding error-weighted metallicity distribution. For this plot, each star was assigned a Gaussian distribution with a mean of $[\text{M}/\text{H}]_{\text{phot,new}}$ and a dispersion equal to the typical error in $[\text{M}/\text{H}]_{\text{phot,new}}$ (0.17 dex). The Gaussians, one for each star, were then added to create the metallicity distribution function. We note that the distribution of $[\text{M}/\text{H}]_{\text{phot,new}}$ is shifted towards lower metallicities when the new calibration is applied, and that there is an abundance spread in the metallicity distribution for the RGB stars of at least 1.0 dex. Additionally, we note a more concentrated distribution.

Figure 9a and 9b show $V_0$ vs. $(v-y)_0$ for the stars with $[\text{Fe}/\text{H}]$ derived from high resolution spectroscopy. Additionally, in these plots, we show two isochrones with $[\text{Fe}/\text{H}]= -2.31$ (most metal-poor isochrone available) and $-2.14$ dex. As can be seen, the isochrones of a given metallicity become redder with increasing age. Since the isochrone with $[\text{Fe}/\text{H}]= -2.31$ is too metal-rich, compared to $[\text{Fe}/\text{H}]$ as derived from the spectroscopy, an even more metal-poor isochrone at the age of 8 Gyr would be even bluer, excluding an age of about 10 Gyr or younger. At an age of 14 Gyr, the isochrone with $[\text{Fe}/\text{H}]= -2.31$ is slightly redder than most of the stars more metal-poor than $[\text{Fe}/\text{H}]= -2.7$. Hence a more metal-poor isochrone would presumably represent the locus of these stars very well, arguing for an age older than about 10 Gyr for the Hercules dSph galaxy.

Figure 9c shows $V_0$ vs. $(v-y)_0$ for all the 28 RGB stars identified in Adén et al. (2009a).
Sextans (open stars), UMaII (filled triangles) and Hercules (filled squares). b) [M/H]_{phot,new} - [Fe/H] vs. $m_{1.0}$ to derive [M/H]. c) [M/H]_{phot,new} - [Fe/H] vs. $(v-y)_0$ using Eq. 4 to derive [M/H]. d) $[\alpha/Fe]$ vs. $(v-y)_0$ using the calibration by Calamida et al. (2007) to derive [M/H].

6.2. [Ca/Fe]

Figure 10 shows [Ca/Fe] as a function of [Fe/H]. We find a trend such that [Ca/Fe] is higher for more metal-poor stars, and lower for more metal-rich stars. Fortuitously, the most metal-rich and the most metal-poor star in the sample are both bright and have spectra with high S/N (see discussion in Sect. 3 and also Table 2). Thus we can be certain that the trend actually has this shape and we are not misinterpreting spectra of lower quality.

The production of alpha ($\alpha$)-elements, such as Ca, Si, Ti, Mg, and O, is correlated with the end stage of massive stars. Mg and O are created during the hydrostatic He burning in massive stars, and Si, Ca, and Ti are primarily produced during core-collapse supernovae (Woosley & Weaver 1995). On the other hand, less massive stars are able to produce significant amounts of Fe in SNe Ia. Thus, the ratio of $\alpha$-elements to iron is used to trace the time scale of the star formation in a stellar system. If the star formation rate is high, then the gas will be able to reach a higher [Fe/H] before the first SNe Ia occur. This can be observed in a plot of [Ca/Fe] vs. [Fe/H] as a "knee", where [Ca/Fe] decrease as [Fe/H] increase (McWilliam 1997). The fraction of stars at [Fe/H] less than the "knee" gives information on the star formation timescale.

The observed continuous downward trend, without a "knee", for [Ca/Fe] vs. [Fe/H] in Hercules can thus be interpreted as a brief initial burst of short-lived SNe II that enhanced the production of $\alpha$-elements. Since there are no stars at [Fe/H] less than the "knee", the star formation rate was very low. The subsequent continuous decline would be expected if contributions from long-lived SNe Ia were the dominant factor, decreasing [$\alpha$/Fe] while increasing [Fe/H]. This means that essentially no massive stars formed after the initial burst. Additionally, we interpret the relatively short range in [Fe/H] (no stars with [Fe/H] > -2 are seen in our sample) as a tentative evidence for a short duration of this low-efficiency star formation (for a discussion of continuous and bursty star formation histories and the role of SNe Ia see, e.g., Gilmore & Wyse 1991; Matteucci 2009). The classical dSph galaxies, such as Carina, Sculptor and Fornax, also show these types of trends for the $\alpha$-elements (e.g., Venn et al. 2004; Koch et al. 2008a; Tolstoy et al. 2009; Kirby et al. 2009). However, these dSph galaxies are more metal-rich and more massive than, e.g., Hercules. Only a few other ultra-faint dSphs have chemical element abundances published for only a handful of stars each.

Fig. 8. a) Metallicity histogram for RGB stars in the Hercules dSph galaxy. The shaded histogram shows the distribution of [M/H]_{phot,new}. For comparison, the dashed histogram shows the distribution of [M/H]_{phot} (Adén et al. 2009a). b) Corresponding error-weighted metallicity distribution.
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**Fig. 11.** A comparison of [Ca/Fe] as a function of [Fe/H] for stars in several dSph galaxies. • indicate Hercules (this study). Filled squares represent the ultra-faint dSph galaxies Ursa Major II, Coma Berenices, Boötes I and Leo IV (Feltzing et al. 2009; Frebel et al. 2010b; Norris et al. 2010; Simon et al. 2010). Open squares represent the classical dSph galaxies Draco, Sextans, Ursa Minor, Fornax, Carina and Sculptor (Sheetrone et al. 2001, 2003; Sadakane et al. 2004; Koch et al. 2008a; Cohen & Huang 2009; Aoki et al. 2009; Frebel et al. 2010a). The solid ellipses outline RGB stars in the classical dSph galaxy Fornax from Letarte et al. (2007).

Data from Fulbright (2002, 2000); Stephens & Boesgaard (2002); Bensby et al. (2003); Nissen & Schuster (1997); Hanson et al. (1998); Prochaska et al. (2000); Reddy et al. (2003); Edvardsson et al. (1993); McWilliam (1998); McWilliam et al. (1995); Johnson (2002); Burris et al. (2000); Ryan et al. (1999); Gratton & Sneden (1991, 1994, 1988). Thus, for example, the trend seen from our data in Hercules is the same as the overall trend seen for Draco. This is interesting and could be interpreted as that the Fe contribution from SNe Ia were the dominant factor for both Hercules and Draco. However, since Draco has many more stars with [Fe/H] > −2 it must have had a more integrated star formation than the Hercules dSph galaxy, as may be expected given its higher baryon content.

7. Conclusions

We have studied confirmed RGB stars in the ultra-faint Hercules dSph galaxy with FLAMES high-resolution spectroscopy. Abundances were determined by solving the radiative transfer calculations using the codes Eqwi/Bsyn in MARCS model atmospheres.

We find that the RGB stars of the Hercules dSph galaxy included in this study are more metal-poor than estimated in Adén et al. (2009a), however in good agreement with Kirby et al. (2008b), with a metallicity spread of at least 1 dex. Based on the position of the RGB stars in colour-magnitude diagrams, in comparison with isochrones, we conclude that there is no clear indication of a population younger than about 10 Gyr.

Additionally, we provide a first attempt at a new metallicity calibration for Strömgren photometry based on high-resolution spectroscopy for several dSph galaxies. With this new calibration, we find several RGB stars in the Hercules dSph galaxy that are more metal-poor than [Fe/H] = −3.0 dex.

Finally, we have determined the [Ca/Fe] for the RGB stars in this study. We found a trend such that [Ca/Fe] is higher for more metal-poor stars, and lower for more metal-rich stars. This trend is supported by our two brightest stars in the sample and is interpreted as a brief initial burst of SNe II during a very low star formation rate, followed by the enrichment of [Fe/H] by SNe Ia.

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References

Adén, D., Feltzing, S., Koch, A., et al. 2009a, A&A, 506, 1147
Adén, D., Wilkinson, M. I., Read, J. I., et al. 2009b, ApJ, 706, L150
Alonso, A., Arribas, S., & Martínez-Roger, C. 1999, A&AS, 140, 261
Andrievsky, S. M., Spite, M., Korotin, S. A., et al. 2010, A&A, 509, A88+
Aoki, W., Arimoto, N., Sadakane, K., et al. 2009, A&A, 502, 569
Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, A&A, 47, 481
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2007, ApJ, 654, 897
Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
Blecha, A., Cayatte, V., North, P., Royer, F., & Simons, G. 2000, in Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference, Vol. 4008, Proc. SPIE Vol. 4008, p. 467–474, Optical and IR Telescope Instrumentation and Detectors, Masanori Iye; Alan F. Moorwood; Eds., M. Iye & A. F. Moorwood, 467–474
Burris, D. L., Pilachowski, C. A., Armandroff, T. E., et al. 2000, ApJ, 544, 302
Calamida, A., Bono, G., Stetson, P. B., et al. 2007, ApJ, 670, 400
Calamida, A., Bono, G., Stetson, P. B., et al. 2009, ApJ, 706, 1277
Fig. 9. a) and b) Colour-magnitude diagrams for RGB stars with high-resolution spectroscopy of the Hercules dSph galaxy. • indicate RGB stars more metal-poor than [Fe/H] = −2.7. ○ represents RGB stars more metal-rich than, or equal to, [Fe/H] = −2.7. The filled square indicates the most metal-rich RGB star at [Fe/H] = −2.0. The solid and dashed lines represent isochrones with [Fe/H] = −2.31 and −2.14 dex, respectively, by VandenBerg et al. (2006) with colour transformations by Clem et al. (2004). c) Colour-magnitude diagram for the RGB stars in Adén et al. (2009a) with [M/H]_{phot,new} as determined in Sect. 5.4. • indicate RGB stars more metal-poor than [M/H] = −2.8. ○ indicate RGB stars more metal-rich than [M/H] = −2.8. Isochrones as in (b). The error bars on the right hand side in each figure represent the typical error in (v − y)_{o}.

Fig. 10. a) [Ca/Fe] as a function of [Fe/H]. Filled triangle and filled square indicate our two brightest RGB stars, RGB stars 12175 and 42241, respectively. The error-bars represent the error in [Ca/Fe] and [Fe/H], respectively. b) Same as a but with a compilation of the Milky Way disk and halo stars abundances from Venn et al. (2004), as indicated by small dots.

Kirby, E. N., Simon, J. D., Geha, M., Guhathakurta, P., & Frebel, A. 2008b, ApJ, 685, L43
Koch, A. 2009, Astronomische Nachrichten, 330, 675
Koch, A., Grebel, E. K., Gilmore, G. F., et al. 2008a, AJ, 135, 1580
Koch, A., Grebel, E. K., Wyse, R. F. G., et al. 2006, AJ, 131, 895
Koch, A., McWilliam, A., Grebel, E. K., Zucker, D. B., & Belokurov, V. 2008b, ApJ, 688, L13
Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, A&A, 338, 119
Kupka, F. G., Ryabchikova, T. A., Piskunov, N. E., Stempels, H. C., & Weiss, W. W. 2000, Baltic Astronomy, 9, 590
Letarte, B., Hill, V., & Tolstoy, E. 2007, in EAS Publications Series, Vol. 24, EAS Publications Series, ed. E. Emsellem, H. Wozniak, G. Massarotti, J.-F. Gonzalez, J. Devriendt, & N. Champenois, 33–38
Lind, K., Primas, F., Charbonnel, C., Grundahl, F., & Asplund, M. 2009, A&A, 503, 545
Martin, N. F., de Jong, J. A. T., & Rich, R. H. 2008, ApJ, 684, 1075
Matteucci, F. 2009, Memorie della Societa Astronomica Italiana, 80, 83
McWilliam, A. 1997, ARA&A, 35, 503
McWilliam, A. 1998, AJ, 115, 1640
McWilliam, A., Preston, G. W., Sneden, C., & Shectman, S. 1995, AJ, 109, 2736
Nissen, P. E., & Schuster, W. J. 1997, A&A, 326, 751
Norris, J. E., Yong, D., Gilmore, G., & Wyse, R. F. G. 2010, ApJ, 711, 350
Pasqui, L., Avila, G., Blecha, A., et al. 2002, The Messenger, 110, 1
Piskunov, N. E., Kupka, F., Ryabchikova, T. A., Weiss, W. W., & Jeffery, C. S. 1995, A&AS, 112, 525
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical recipes in FORTRAN. The art of scientific computing, ed. Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P.
Prochaska, J. X., Naumov, S. O., Carney, B. W., McWilliam, A., & Wolfe, A. M. 2000, AJ, 120, 2513
Reid, B. E., Tomkin, J., Lambert, D. L., & Allende Prieto, C. 2003, MNras, 340, 304
Ryabchikova, T. A., Piskunov, N. E., Kupka, F., & Weiss, W. W. 1997, Baltic Astronomy, 6, 244
Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254
Sadakane, K., Arimoto, N., Ikuho, C., et al. 2004, PASJ, 56, 1041
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schöck, T., Christlieb, N., Cohen, J. G., et al. 2009, A&A, 507, 817
Shetrone, M., Venn, K. A., Tolstoy, E., et al. 2003, AJ, 125, 684
Shetrone, M. D., Côté, P., & Sargent, W. L. W. 2001, ApJ, 548, 592
Simon, J. D., Frebel, A., McWilliam, A., Kirby, E. N., & Thompson, I. B., 2010, ApJ, 716, 446
Simon, J. D. & Geha, M. 2007, ApJ, 670, 313
Starkenburg, E., Hill, V., Tolstoy, E., et al. 2010, A&A, 513, A34+
Stephens, A. & Boesgaard, A. M. 2002, AJ, 123, 1647
Tollerud, E. J., Bullock, J. S., Strigari, L. E., & Willman, B. 2008, ApJ, 688, 277
Tolstoy, E., Hill, V., & Tosi, M. 2009, ARA&A, 47, 371
VandenBerg, D. A., Bergbusch, P. A., & Dowler, P. D. 2006, ApJS, 162, 375
Venn, K. A., Irwin, M., Shetrone, M. D., et al. 2004, AJ, 128, 1177
Walker, M. G., Mateo, M., Olszewski, E. W., et al. 2009, ApJ, 704, 1274
Woosley, S. E. & Weaver, T. A. 1995, ApJS, 101, 181
Zucker, D. B., Belokurov, V., Evans, N. W., et al. 2006, ApJ, 650, L41