New cluster members and halo stars of the Galactic globular cluster NGC 1851

Colin A. Navin1, Sarah L. Martell2, and Daniel B. Zucker1,3
1Department of Physics & Astronomy, Macquarie University, Sydney 2109, Australia
2Department of Optics & Astrophysics, University of New South Wales, Sydney 2052, Australia
3Australian Astronomical Observatory, PO Box 296, Epping, NSW 2121, Australia

ABSTRACT
NGC 1851 is an intriguing Galactic globular cluster, with multiple stellar evolutionary sequences, light and heavy element abundance variations and indications of a surrounding stellar halo. We present the first results of a spectroscopic study of red giant stars within and outside of the tidal radius of this cluster. Our results identify nine probable new cluster members (inside the tidal radius) with heliocentric radial velocities consistent with that of NGC 1851. We also identify, based on their radial velocities, four probable extratidal cluster halo stars at distances up to \( \sim 3.1 \) times the tidal radius, which are supportive of previous findings that NGC 1851 is surrounded by an extended stellar halo. Proper motions were available for 12 of these 13 stars and all are consistent with that of NGC 1851. Apart from the cluster members and cluster halo stars, our observed radial velocity distribution agrees with the expected distribution from a Besançon disk/N-body stellar halo Milky Way model generated by the Galaxia code, suggesting that no other structures at different radial velocities are present in our field. The metallicities of these stars are estimated using equivalent width measurements of the near infrared calcium triplet absorption lines and are found, within the limitations of this method, to be consistent with that of NGC 1851. In addition we recover 110 red giant cluster members from previous studies based on their radial velocities and identify three stars with unusually high radial velocities.

Key words: globular clusters: general; globular clusters: individual: NGC 1851; stars: kinematics and dynamics; techniques: spectroscopic; techniques: radial velocities

1 INTRODUCTION

Until relatively recently globular clusters (GCs) were considered as examples of single stellar populations (SSPs), with all the cluster stars having the same age, helium abundance and overall [Fe/H] metallicity. In reality all GCs that have been thoroughly studied have multiple stellar populations (with the possible exception of Ruprecht 106, but the sample size was small\cite{Villanova13}). Evidence comes from many photometric studies showing multiple branches on colour-magnitude diagrams (CMDs), and high resolution spectroscopic studies showing that all globular clusters exhibit significant star-to-star abundance variations in light elements (such as C, N, O and Na). In addition a few clusters (typically the most massive) also show overall [Fe/H] metallicity variations and variations in neutron capture elements.

Globular clusters are, therefore, more complex than originally thought, and in fact contain multiple generations of stars (for a review see \cite{Gratton12}). This was first discovered for the more massive globular clusters and for the brightest red giant branch (RGB) and asymptotic giant branch (AGB) sequences. Now many globular clusters with a wide range of masses have been shown to exhibit these features, and various studies have shown multiple sequences in the fainter main sequences (MS), sub giant branches (SGB) and horizontal branches (HB).

The abundances of light elements of stars in GCs exhibit various relations, in particular C-N and O-Na anticorrelations. The origin of these patterns is believed to be hot hydrogen burning in either AGB stars, fast rotating massive stars, massive binaries or supermassive stars (\cite{Gratton12}). However there are indications that the C-N and O-Na anti-correlations are not perfectly coupled. \cite{Pancino10} measured CN and CH band strengths for MS stars in 12 GCs with well-characterized RGB abundances and found that the frequency of C-poor, N-rich MS stars does not match the frequency of O-poor, Na-rich RGB stars reported for those same clusters in \cite{Carretta09}. They sug-
suggested that enrichment in C and N may not match enrichment in O and Na because the CN cycle, the full CNO bicycle and the Ne-Na cycle are each responsible for a different part of the light element abundance pattern, and each requires a different temperature to operate.

NGC 1851 is an unusual Galactic globular cluster. It is one of four globular clusters (along with NGC 1904, NGC 2298 and NGC 2808) all physically located within a sphere of radius 6 kpc (Bellazzini et al. 2004). It has been proposed that they form a group associated with the putative Canis Major Major dwarf galaxy stream (Martin et al. 2004). NGC 1851 exhibits the common features of multiple evolutionary sequences and star-to-star abundance dispersions in the light elements, but it also has some features not ordinarily found in other globular clusters, as detailed below.

1.1 Photometry

Stetson (1981) detected peculiarities in the HB with a dense clump of stars at the red end and a hint of another clump at the blue end. Walker (1992) confirmed the split nature of the HB in the cluster, clearly shown in the right panel of Fig. 8. A double SGB was announced in Milone et al. (2008b); they postulated two populations with similar overall [Fe/H] metallicity but an age difference of ∼1 Gyr, while Cassisi et al. (2008) suggested an alternative two coeval populations with different C+N+O abundance mixtures. Han et al. (2009) also detected a split RGB using UI photometry. These studies strongly suggest that a second generation of higher overall [Fe/H] metallicity stars formed after an early episode of metal enrichment.

1.2 Spatial extent

There have been a number of photometric and spectroscopic studies (detailed below) that indicate that NGC 1851 has a surrounding stellar halo outside the tidal radius. The nature of this halo is not yet clear - they may be stars stripped by tidal or disk shocking. Alternatively, modelling has shown that it is possible that NGC 1851 is the nuclear star cluster of a now disrupted dwarf galaxy, with the halo stars representing the remnant of that galaxy.

The tidal radius $r_t$ calculated by different dynamical models such as King (King 1966), Wilson (Wilson 1975) and power-law templates can vary considerably, and various studies have adopted different values. The current version of the Harris (2010 edition) catalogue does not tabulate $r_t$ values, but instead lists the structural parameters core radius $r_c = 0.09$ arcmin and central concentration $c = 1.86$ arcmin from McLaughlin & van der Marel (2005). The central concentration $c$ is given by:

$$c = \log \frac{r_c}{r_t}$$

From this the tidal radius $r_t$ is calculated as 6.5 arcmin. The Wilson (1975) model $r_t$ as calculated by McLaughlin & van der Marel (2005) is 44.7 arcmin. Carballo-Bello et al. (2012) looked at the number density profiles of 19 Galactic globular clusters and found power-law templates to be a better representation for about 2/3 of their sample, including NGC 1851 for which their calculated tidal radius is 11.7 arcmin. Allen et al. (2006) calculated the Jacobian (or Roche) radius as 17 arcmin, although this is strongly dependent on the adopted Galaxy gravitational potential and cluster orbital parameters. For results discussed in this introduction, we quote the tidal radius adopted by the authors in the paper where applicable. For our own study we adopt the value of Carballo-Bello et al. (2012) of 11.7 arcmin.

Wide field photometric star-count analyses carried out by Leon et al. (2000) show a symmetric stellar structure out to ∼20 arcmin and extensions to ∼45 arcmin that are roughly aligned towards the Galactic center. Photometric studies by Olszewski et al. (2009) also show indications of a stellar halo extending up to 75 arcmin, ∼6.5 times beyond their adopted tidal radius of 11.7 arcmin. This halo has a mass of ∼1 per cent of the dynamical mass of NGC 1851, but there was no evidence for any substructure or tidal stream formation. Carballo-Bello & Martínez-Delgado (2010) reported a distinct MS of a metal-poor stellar overdensity with a sky projected size $15.7^\circ$ in the area surrounding NGC 1851 and NGC 1904.

A possible tidal tail was reported by Sollima et al. (2012) in a spectroscopic survey of 107 stars from 12 arcmin to 33 arcmin around the cluster centre. They not only found a significant fraction of stars outside their adopted tidal radius of 11.7 arcmin, but also an interesting hint of a kinematically cold stellar stream, albeit with a peak in the heliocentric radial velocity ($V_r$) distribution of $\sim$180 km s$^{-1}$, compared with 320.5 ± 0.6 km s$^{-1}$ Harris (2010 edition) for NGC 1851. Marino et al. (2014) carried out a spectroscopic analysis of 23 stars in the halo of NGC 1851 and found stars at distances up to ∼2.5 times their adopted tidal radius of 11.7 arcmin. However they did not find convincing evidence for the tidal tail of stars reported by Sollima et al. (2012) at $\sim$180 km s$^{-1}$. Kunder et al. (2014) reported nine RAVE stars up to 10$^2$ away from NGC 1851 that may be associated with the cluster.

Bekki & Yong (2012) simulated the dynamical evolution of a dwarf galaxy with a stellar nucleus in the tidal field of the Galaxy. They showed that a diffuse stellar halo around NGC 1851 would be produced after stripping the dark matter halo and stellar envelope, and that the remnant nucleus was consistent with an object like NGC 1851. They also showed that mergers of globular clusters in host dwarf galaxies were possible, which in the case of NGC 1851 could explain its multiple stellar populations.

1.3 Chemistry

NGC 1851 exhibits the typical GC light element star-to-star abundance dispersions and relations that are believed to result from multiple star formation episodes. Even for GC systems with multiple stellar populations it is unusual in being one of a handful of clusters that show evidence (detailed below) of variations in overall [Fe/H] metallicity and C+N+O abundances. It shows some similarities to $\omega$ Cen-tauri, which exhibits large star-to-star abundance variations in all elements (Lee et al. 1999 and Bedin et al. 2004), but also some similarities to clusters like NGC 6752 that have no [Fe/H] variation but show light element abundance variations (Yong et al. 2013). However, some results have been conflicting, especially the question of whether there is a scat-
ter in the sum of the C+N+O abundances and whether this sum correlates with the metallicities or heavy-element abundances.

Eight bright giant member stars analysed by Yong & Grundahl (2008) (hereafter YG08) showed abundance variations of the s-process elements Zr and La that were correlated with Al and anticorrelated with O. There was a hint that these s-process element abundances clustered around two values, but the sample size was small. An analysis of high-resolution spectroscopic data for four of the YG08 RGB stars was reported in Yong et al. (2009). These stars showed a large C+N+O abundance variation that correlated with the light elements Na and Al, and also with the s-process elements Zr and La.

The largest extant high resolution spectroscopic study of NGC 1851 stars, Carretta et al. (2010, 2011) (hereafter C10), obtained spectra of 124 RGB stars and found a measurable [Fe/H] spread of 0.06 to 0.08 dex. A division into metal-rich and metal-poor groups based on [Fe/H] and [Ba/H] also shows many differences in various abundance correlations and anti-correlations. They proposed that NGC 1851 is the product of a merger of two globular clusters, with an age difference of ~1 Gyr and different Fe and α-capture element abundances, that formed in a now disrupted dwarf galaxy.

There have been several other spectroscopic studies of NGC 1851 stars. Lardo et al. (2012) obtained C and N abundances in 64 SGB and MS stars and found significant anti-correlations in [C/H] and [C/N] and significant variations in C, N and total C+N content when divided into fainter and brighter samples. Villanova et al. (2010) studied a sample of 15 red giant branch (RGB) stars in NGC 1851. Their analysis did not show variations in iron-peak elements or total C+N+O content. In contrast, Yong et al. (2015) found a large (~0.6 dex) spread in the sum of the C+N+O abundances in AGB and RGB stars, providing support for the idea of coeval SGB populations with different C+N+O content.

While there has been a large-scale study of C and N in SGB and MS stars (Lardo et al. 2012), and a smaller study in RGB stars (Villanova et al. 2010), C and N abundances have not been measured for a large sample of RGB stars, and not for stars with measured light element abundances. This study was specifically aimed at expanding the set of abundance information available for the RGB stars in the C10 studies. In particular we aimed to carry out a thorough survey of C and N abundances for the same stars, which can be determined from moderate-resolution blue spectra. Combined with the proton-capture (O, Na, Mg, Al), α-capture (Si, Ca, Ti) and s-process (Y, Zr, Ba, La) element abundances obtained in their study, this will enable us to assess the evidence for the conclusions drawn in the C10 study.

This study was specifically aimed at expanding the set of literature, and not for stars with measured light element abundances.

## 2 Sample Selection, Observations and Initial Data Reduction

We used the AAOmega spectrograph on the Anglo-Australian Telescope (AAT) at Siding Spring Observatory in two degree field (2dF) fibre positioner multi-object spectrograph (MOS) mode to obtain the spectra. The target list was made up of the 124 RGB stars from the C10 study and four of the giant stars analysed by YG08 (the main targets of our study), plus a third field sample made up of stars with similar 2MASS Skrutskie et al. (2006) photometry to that of NGC 1851 RGB stars. The latter were selected with the aim of allowing for serendipitous discovery of new cluster members, extratidal cluster halo stars or of field stars with unusual abundance patterns. Observing details are listed in Table 1.

The red channel spectra were used for determination of stellar heliocentric radial velocities ($V_r$) and metallicities [Fe/H]. We used the standard 2dF data reduction (2dFdr) pipeline, as well as the IRAF task aplot to remove skylines. A total of 1876 spectra were obtained. Spectra with low signal-to-noise ratio (SNR) and/or bad columns or other artefacts were discarded leaving a total of 1730 spectra for the analysis. Because of the selection algorithm of the 2dF configuration software, 541 stars were observed more than once in different pointings. In total the useable spectra of 1149 unique stars were obtained, including 106 stars from the C10 study and the four stars from YG08. In the vicinity of the CaT in the red channel, the median SNR of spectra obtained was ~28. Spectra of the star used as a template for calculation of $V_r$ and of one of our probable new member stars are shown in Fig. 1 to illustrate the quality of our data and the similarity of the spectra in our observations.

## 3 Heliocentric Radial Velocities

We used the IRAF task fxcor to derive the $V_r$ of observed stars using the C10 star [CLG2011] 30965 (2MASS ID 05142874–4003159) in our sample as a template star. Mean $V_r$ values were calculated for the 541 stars with multiple observations by weighting their fxcor $V_r$ values with their respective fxcor $V_r$ errors.

Multiple observations of the same target were also used to estimate the $V_r$ errors for stars. An estimate of the standard deviation of $V_r$ ($\sigma_v$) was calculated using the simplified statistics for small number of observations methods of Dixon & Massey (1951). These $\sigma_v$ for multiple observations

1 Manual and technical details at http://www.aao.gov.au/2dF/aomega
were then compiled as a function of the median continuum level of the spectrum between the two strongest CaT lines. The values of the mean \( \sigma_v \) for each bin for stars with multiple observations were then used as the errors \( \Delta V_r \) for stars with single observations as a function of their continuum level. For stars with \( N \) observations, \( \Delta V_r \) was calculated by dividing \( \sigma_v \) by \( \sqrt{N} \).

We compared our \( V_r \) values for the stars in common with the C10 study. Fig. 2 shows the \( V_r \) of all observed C10 stars compared to our \( V_r \) measurements of the same stars. The solid black line is the linear best fit to our data, the solid green line shows the one-to-one relationship and the dashed green lines show \( \pm \sigma \) of the one-to-one relationship.

Selection as a probable new member was based on the \( V_r \) range of the recovered C10 and YG08 groups. The minimum and maximum measured \( V_r \) for stars in these groups was 308.0 km s\(^{-1}\) and 328.9 km s\(^{-1}\) respectively. We found 13 stars in our field sample with \( V_r \) within this range.

Fig. 3 shows the \( V_r \) distribution of observed stars. The left panel shows all the observed stars, with the predicted \( V_r \) distribution of the Milky Way model generated by the Galaxia code (Sharma et al. (2011), see Sect. 6) overplotted as a grey histogram. The distribution shows two prominent peaks: i) a peak with a mean \( V_r \) \( \sim 40 \) km s\(^{-1}\) consisting of 1015 stars with a spread in radial velocity from \(-100 \) km s\(^{-1}\) to \( 200 \) km s\(^{-1}\) that we identify as Galactic disc or halo field stars (non cluster members), and ii) a peak with a mean \( V_r \) \( \sim 320 \) km s\(^{-1}\) containing 123 stars that we identify as members of NGC 1851. In the follow-

### Table 1. Observing details.

| Date       | Start Time | Field name      | Magnitude | Exposures | Seeing | Airmass |
|------------|------------|-----------------|-----------|-----------|--------|---------|
| 2012 Dec 17| 11:30      | bright-f1       | \( V < 14.5 \) | 3 x 540  | 1.4    | 1.10    |
| 2012 Dec 17| 12:30      | faint-f1-long   | \( V > 14.5 \) | 2 x 2700 | 1.5    | 1.05    |
| 2012 Dec 17| 14:21      | faint-f1-short  | \( V > 14.5 \) | 1 x 2700 | 1.3    | 1.11    |
| 2012 Dec 17| 15:44      | faint-f2-long   | \( V > 14.5 \) | 2 x 2700 | 1.5    | 1.14    |
| 2012 Dec 18| 10:51      | faint-f2-short  | \( V > 14.5 \) | 1 x 2700 | 1.6    | 1.24    |
| 2012 Dec 18| 15:34      | faint-f3-long   | \( V > 14.5 \) | 2 x 2700 | 1.4    | 1.24    |

### Figure 1. Example spectra.

- **Top panel:** red channel spectrum of the star used as the template for \( V_r \) measurements - C10 Simbad reference [CLG2011] 30965; 2MASS identification 05142874-4003159. The Calcium II triplet absorption lines are indicated.
- **Bottom panel:** red channel spectrum of one of our probable new member stars - 2MASS identification 05141398-4000194. Note: flux scales are different on each plot.

### Figure 2. \( V_r \) of all observed C10 stars compared to our \( V_r \) measurements of the same stars. The solid black line is the linear best fit to our data, the solid green line shows the one-to-one relationship and the dashed green lines show \( \pm \sigma \) of the one-to-one relationship.
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Figure 3. Left panel: $V_r$ distribution of all observed stars with the predicted $V_r$ distribution of the Milky Way model generated by the Galaxia code (Sharma et al. 2011) overplotted as a grey histogram. Right panel: Expanded $V_r$ distribution of cluster member and cluster halo stars. Blue denotes known C10 members, green known YG08 members and red are stars that are probable new cluster members or cluster halo stars. The vertical dashed line shows the Harris 1996 (2010 edition) catalogue $V_r$ of 320.5 km s$^{-1}$.

Table 2. Probable members based on $V_r$. [Fe/H] values marked with * are derived using a $V$ magnitude estimated from 2MASS $J$ and $K_s$ magnitudes. $R$ = radial distance from cluster centre. Status: m = probable new cluster member star, h = probable extratidal cluster halo star.

| 2MASS ID | RA     | Dec    | $V_r$ (km s$^{-1}$) | $\Delta V_r$ (km s$^{-1}$) | [Fe/H] | $\Delta$[Fe/H] (dex) | $\mu_\alpha\cos(\delta)$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $R$ (arcmin) | Status |
|----------|--------|--------|---------------------|---------------------------|--------|----------------------|---------------------------------|---------------------------------|-------------|--------|
| 05111553-4018102 | 5:11:15.54 | -40:18:10.25 | 318.7 | 2.7 | -1.27 | 0.09 | -0.1 | 0.7 | 36.1 | h |
| 05135811-3956592 | 5:13:58.11 | -39:56:59.25 | 324.7 | 1.1 | -1.08* | 0.06 | -1.3 | -0.1 | 6.0 | m |
| 05140637-4024514 | 5:14:06.37 | -40:24:51.40 | 321.3 | 1.6 | -1.02* | 0.05 | -8.5 | -2.9 | 22.1 | h |
| 05140736-4000020 | 5:14:07.36 | -40:00:02.04 | 312.7 | 1.6 | -1.15* | 0.05 | -10.8 | 13.0 | 2.8 | m |
| 05141174-4002180 | 5:14:11.74 | -40:02:18.07 | 319.0 | 1.6 | -0.90* | 0.03 | - | - | 1.1 | m |
| 05141359-4001109 | 5:14:13.59 | -40:01:10.98 | 314.9 | 1.6 | -1.56* | 0.07 | -0.3 | 4.7 | 2.1 | m |
| 05141398-4000194 | 5:14:13.98 | -40:00:19.39 | 321.6 | 1.6 | -1.44 | 0.06 | -1.7 | 12.1 | 2.8 | m |
| 05142006-4005116 | 5:14:20.06 | -40:05:11.69 | 315.2 | 2.2 | -1.19 | 0.06 | 3.3 | 0.3 | 3.5 | m |
| 05142068-4055477 | 5:14:20.89 | -40:55:47.74 | 318.8 | 1.3 | -1.21* | 0.05 | -2.1 | 2.1 | 4.0 | m |
| 05142994-4000251 | 5:14:29.95 | -40:00:25.08 | 318.3 | 1.3 | -1.08 | 0.04 | -4.6 | 1.3 | 5.0 | m |
| 05153906-3947485 | 5:15:39.06 | -39:47:48.52 | 318.6 | 1.3 | -1.08 | 0.04 | 0.2 | -1.9 | 23.2 | h |
| 05162438-4019326 | 5:16:24.38 | -40:19:32.62 | 317.9 | 1.1 | -1.10 | 0.04 | -1.5 | -0.4 | 31.2 | h |

The mean and standard deviation of the $V_r$ distribution of cluster members and cluster halo stars is 319.3 km s$^{-1}$ and 4.4 km s$^{-1}$, which is similar to previous estimates for NGC 1851 (320.5 ± 0.6 km s$^{-1}$ from Harris 1996 (2010 edition). The $V_r$ of these stars strongly suggests that all these targets are likely cluster members or cluster halo stars, and, where available, is supported by their positions, proper motions, metallicities (Sect. 5) and positions on the

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colour-magnitude diagrams (Sect. 7). Details of these stars are listed in Table 2.

There are no indications of an overdensity at \( \sim 180 \text{ km s}^{-1} \) in our observed distribution that might correspond to the tidal tail at this \( V_c \) reported by Sollima et al. (2012). However the number of stars for comparison is small, especially if we exclude the number of stars that are predicted by the Milky Way model generated by the Galaxia code distribution to be in this range of \( V_c \). Therefore our observations do not provide additional support for the existence of a stellar stream at \( \sim 180 \text{ km s}^{-1} \).

4 SPATIAL DISTRIBUTION AND PROPER MOTIONS

Figure 4 shows the spatial (RA and Dec) distribution of observed stars. Of the 13 stars classified as probable new cluster members or cluster halo stars on the basis of \( V_c \), nine are within our adopted Carballo-Bello et al. (2012) tidal radius of 11.7 arcmin and are identified as probable current members of NGC 1851. A further four are outside at distances up to \( \sim 3.1 \) times the adopted tidal radius. Members of a stellar halo of NGC 1851 are expected to share its distinctive \( V_c \) signature, so these are identified as probable extratidal cluster halo stars. The identification of these cluster halo stars provides further evidence of the existence of a stellar halo surrounding NGC 1851. Details of these stars are listed in Table 2.

The absolute proper motions of 106 of the C10 stars, nine out of ten of the probable new cluster members and all four probable new cluster halo stars of NGC 1851 were available in the UCAC4 catalogue (Zacharias et al. 2013). The proper motion of NGC 1851 (\( \mu_\alpha\cos(\delta) = 1.28 \pm 0.68 \text{ mas yr}^{-1}, \mu_\delta = 2.39 \pm 0.65 \text{ mas yr}^{-1} \)) was obtained from Dinescu et al. (1999). Figure 5 shows a plot of the absolute proper motions of the observed C10 stars (only 20 stars are plotted to avoid overcrowding) and 12 of the 13 probable new cluster members or cluster halo stars of NGC 1851. The proper motion of NGC 1851 is shown by the intersection of the dashed lines. It is interesting to note that 15 of the 106 C10 stars have UCAC4 catalogue proper motions in RA and/or Dec greater than 50 mas yr\(^{-1}\) and 34 have proper motions in RA and/or Dec greater than 25 mas yr\(^{-1}\). This scatter in proper motion values may simply reflect the difficulty of making proper motion measurements in crowded stellar fields. The proper motions of the probable new cluster members and cluster halo stars are listed in Table 2 and all are consistent with the proper motion of NGC 1851.

5 METALLICITY FROM THE Ca TRIPLET LINES

Applying the method of Armandroff & Da Costa (1991) we used measurements of the equivalent widths (\( EW \)) of the Ca\( T \) lines to calculate stellar metallicity ([Fe/H]). A number of Ca\( T \) empirical relations have been proposed by different authors. They connect a linear combination of the equivalent widths of the Ca\( T \) lines and the luminosity of the star (usually the \( V \) magnitude of the star relative to the HB of the cluster: \( V - V_{\text{HB}} \)) to its [Fe/H] value.

We used the IRAF task splot to measure the \( EWs \) of the Ca\( T \) lines (8498 \( \Rightarrow \) EW\( 8498 \), 8542 \( \Rightarrow \) EW\( 8542 \) and 8662 \( \Rightarrow \) EW\( 8662 \)) in the red channel spectra of the known C10 and YG08 members plus the probable new cluster members and cluster halo stars. Gaussian profiles were fitted to these lines to measure the \( EWs \).

The calibration procedure is valid for \( V - V_{\text{HB}} \) brighter than \( \sim 0.0 \) and for a range \( \sim 2 \) in \( V - V_{\text{HB}} \) luminosities. To include all 13 of the probable new cluster members and cluster halo stars, a faint limit of \( V - V_{\text{HB}} < 0.3 \) and a bright limit of \( -1.7 < V - V_{\text{HB}} < 2.0 \) were chosen. These criteria were also applied to the C10 and YG08 stars to select a comparison sample. 64 of the 106 stars in the C10 group matched these criteria, but the YG08 stars are somewhat brighter and did not fit within the limits.

Fig. 6 shows the sum of the measured \( EWs \) of the Ca\( T \) lines (EW\( 8542 \) + EW\( 8662 \)) of the 13 new cluster members and cluster halo stars plus the 64 C10 stars, plotted against the magnitude difference from the horizontal branch \( V - V_{\text{HB}} \).

To calibrate the \( EWs \) in terms of [Fe/H] we adopted the empirical calibration equation of Yong et al. (2014):

\[
[\text{Fe/H}] = 0.59(\pm 0.04)W' - 2.81(\pm 0.16)
\]

where the reduced equivalent width \( W' \) is:

\[
W' = EW_{8542} + EW_{8662} + 0.60(\pm 0.02)(V - V_{\text{HB}})
\]

\( V \) magnitudes were listed in the catalogue for all 64 of the C10 stars. \( V \) magnitudes were available from APASS (Henden et al. 2009) for seven of the 13 probable new cluster members and cluster halo stars. For the remaining six stars, an estimate \( V_{J,K_s} \) was made from 2MASS \( J \) and \( K_s \) magnitudes. The calibration formula used was that used to calculate \( V \) magnitudes for the GALAH survey input catalogue (De Silva et al. 2015):

\[
V_{J,K_s} = K_s + 2(J - K_s + 0.14) + 0.382_e((J-K_s-0.3)/0.50)
\]

There are differences of up to \( \pm \sim 0.5 \) mag when \( V \) magnitudes obtained with this calibration are compared with literature values for C10 stars, which translates into an error of \( \pm 0.4 \) dex in [Fe/H]. Given this, the values of [Fe/H] for these stars are best regarded as indicative values only.

Details of the [Fe/H] of the 13 probable new cluster members and cluster halo stars are listed in Table 2, with the [Fe/H] of stars obtained using an estimated \( V \) magnitude marked with an asterisk.

Fig. 7 shows the [Fe/H] distribution of the 13 probable new cluster members and cluster halo stars and the 64 C10 members of NGC 1851, with the predicted [Fe/H] distribution of the Milky Way model generated by the Galaxia code (Sharma et al. 2011), see Sect. 6) overplotted as a grey histogram. The model distribution is normalised to the number of observed known members (64) plus the number of probable new cluster members and cluster halo stars (13). The distribution shows a prominent peak with a mean [Fe/H] = -1.10 that we identify as members of NGC 1851. This group includes the 64 homogeneously selected RGB stars from the C10 group and the 13 probable new cluster members or cluster halo stars of NGC 1851.

The mean and standard deviation of the observed [Fe/H] distribution are -1.10 and 0.11 respectively. Seven of our probable new cluster members or cluster halo stars lie within \( \pm 1 \sigma \) of the [Fe/H] metallicity of NGC 1851 and

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Figure 4. Left panel: Spatial distribution of observed stars for the complete 2° field of 2dF/AAOmega. Right panel: Expanded version showing the observed stars inside the tidal radius. The green cross and circle show the Harris 1996 (2010 edition) catalogue centre position and the tidal radius of 11.7 arcmin. Grey crosses show non members, blue circles denote known C10 members, green squares are known YG08 members and red triangles are probable new cluster members or cluster halo stars.

Figure 5. Absolute proper motions of 20 of the observed C10 stars (blue) and 12 of the probable new cluster members or cluster halo stars of NGC 1851 (red). The proper motion of NGC 1851 is shown by the intersection of the dashed lines.

Figure 6. The sum of the EWs of the CaT lines plotted against the magnitude difference from the horizontal branch $V - V_{HB}$. Blue circles indicate known C10 cluster members, red triangles are probable new cluster members and cluster halo stars with V magnitudes from APASS and red stars are probable new cluster members and cluster halo stars with V magnitudes estimated from J and K magnitudes.

10 within $\pm 2\sigma$, so most of these stars have metallicities that are consistent with that of NGC 1851.
that the cluster stars are not reproduced by the models in either the $V_r$ or the [Fe/H] distributions. We then performed a Kolmogorov-Smirnov (K-S) test for the null hypothesis that the model $V_r$ and [Fe/H] distributions and the observed $V_r$ and [Fe/H] distributions are drawn from the same continuous distributions.

For the $V_r$ distribution, this was done in the $V_r$ range from 250 to 400 km s$^{-1}$ to compare NGC 1851 member stars with the average Milky Way model distribution. The mean and standard deviation of the observed $V_r$ distribution were 319.3 km s$^{-1}$ and 4.5 km s$^{-1}$ respectively, compared with 306.7 km s$^{-1}$ and 40.1 km s$^{-1}$ for the average model distribution. The $p$ value calculated by comparing the observed and model distributions with the K-S test was $3 \times 10^{-35}$. For [Fe/H] the mean and standard deviation of the observed distribution were $-1.108$ and $0.097$ respectively, compared with $-0.309$ and $0.373$ for the average model distribution. The $p$ value calculated by comparing the distributions with the K-S test was $9.4 \times 10^{-43}$.

The $p$ values for comparing the observed and model $V_r$ distributions are effectively zero, hence it is unlikely that the observed and predicted $V_r$ samples are drawn from the same distributions. The Milky Way model generated by the Galaxia code predicts just three stars within the same spatial, colour, magnitude, and [Fe/H] ranges as the observed stars. Similarly, the $p$ value for the [Fe/H] distribution is effectively zero, hence it is unlikely that the observed and predicted [Fe/H] samples are drawn from the same distributions. The model predicts just six stars within the same spatial, colour, magnitude and [Fe/H] ranges as the C10 stars. Most stars in the observed distributions are thus either current members, probable new cluster members or cluster halo stars of NGC 1851.

7 COLOUR-MAGNITUDE DIAGRAMS

Fig. 8 shows 2MASS and optical CMDs ($J$ vs $J - K_s$ and $V$ vs $V$) of target stars. The left panel clearly shows the 2MASS selection limits of the third group of target stars ($0 < J - K_s < 1.2$ and $13 < J < 14.5$). The right panel shows the $V$ vs $V - V$ CMD of all the known C10 and YG08 cluster members and probable new cluster members and cluster halo stars (with directly measured $B$ and $V$ magnitudes). The stars from the photometric study of Walker (1992) are also plotted and the split nature of the HB in the cluster is obvious. The C10 stars, three of the four YG08 stars and seven of the probable new cluster members and cluster halo stars that had directly measured $B$ and $V$ magnitudes all nicely follow the RGB ridge line of the cluster population.

8 HIGH $V_r$ STARS

There are eight stars with $V_r$ between 200 km s$^{-1}$ and the $V_r$ of NGC 1851 as listed in Table 3. These stars are likely not cluster members so their distance and luminosity are unknown. Any $V - V_{H_B}$ measurements would be invalid, so metallicities could not be calculated for these stars. Proper motions obtained from the UCAC4 catalogue (Zacharias et al. 2013) are also tabulated. The proper motion of NGC 1851 is $\mu_\alpha \cos(\delta) = 1.28 \pm 0.68$ mas yr$^{-1}$.
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Figure 8. Left panel: 2MASS ($J$ vs $J - K_s$) CMD. The grey crosses show observed non member stars, blue circles indicate known C10 members, green squares known YG08 members and red triangles denote stars that are probable new cluster members and cluster halo stars. Right panel: $V$ vs $B - V$ CMD. Here the grey crosses show Walker (1992) stars, other symbols are the same as for the left panel except that only the seven probable new cluster members and cluster halo stars with directly measured $B$ and $V$ magnitudes are plotted.

Table 3. Other stars with high $V_r$. Stars above the line are those with $V_r$ between 200 km s$^{-1}$ and the lower $V_r$ membership limit for NGC 1851 of 308 km s$^{-1}$, those below the line have $V_r$ greater than the $V_r$ of NGC 1851. $R$ = radial distance from cluster centre.

| 2MASS identification | RA      | Dec     | $V_r$ (km s$^{-1}$) | $\Delta V_r$ (km s$^{-1}$) | $\mu_{\alpha}\cos(\delta)$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | $R$ (arcmin) |
|----------------------|---------|---------|---------------------|-----------------------------|---------------------------------|----------------------------|-------------|
| 05122418-4051596      | 5:12:24.18 | -40:51:59.53 | 210.3              | 1.6                         | 9.3                               | -18.4                   | 52.9        |
| 05130199-3931439      | 5:13:02.00 | -39:31:43.90 | 283.6              | 1.2                         | 13.7                               | -1.8                    | 33.5        |
| 05134950-4013007      | 5:13:49.50 | -40:13:00.77 | 201.5              | 1.1                         | 35.2                               | -23.8                   | 10.7        |
| 05141567-4001444      | 5:14:15.68 | -40:01:44.39 | 301.1              | 1.6                         | 5.9                                | 6.2                     | 2.0         |
| 05152527-4012529      | 5:15:25.27 | -40:12:52.94 | 243.7              | 1.3                         | 16.4                               | 8.7                     | 18.1        |
| 05162712-3931579      | 5:16:27.12 | -39:31:57.95 | 213.6              | 0.9                         | -1.9                               | 8.3                     | 41.0        |
| 05163977-4039434      | 5:16:39.77 | -40:39:43.39 | 288.0              | 2.2                         | 60.4                               | -0.9                    | 47.0        |
| 05182129-4006551      | 5:18:21.30 | -40:06:55.15 | 292.4              | 1.3                         | 1.8                                | 3.7                     | 49.1        |

$\mu_\delta = 2.39 \pm 0.65$ mas yr$^{-1}$ (Dinescu et al. 1999). Several stars have proper motions that are quite different, but as mentioned in Sect 4 there are also significant numbers of C10 stars in the UCAC4 catalogue with proper motions that are considerably different from that of NGC 1851. One star, 2MASS 05122418-4051596, is located just 2 arcmin from the cluster centre, has a proper motion similar to NGC 1851 and a $V_r$ of 301.1 km s$^{-1}$ which is just outside the $V_r$ criteria we adopted for membership, so it could conceivably be a cluster member. If cluster membership is assumed, the [Fe/H] calculated using the methods of Sect 5 using an estimated $V_{J,K_s}$ from 2MASS $J$ and $K_s$ magnitudes, is -0.41. This is high for a cluster member, even allowing for errors in calculating [Fe/H] with estimated $V$ magnitudes (discussed above in Sect 5). Therefore this star was not included in the list of probable members in Table 2.

There are also three stars with $V_r \sim$50 to 75 km s$^{-1}$ higher than that of NGC 1851 (05133314-4100160 at 371.8, 05135111-3958381 at 388.8 and 05184308-4027077 at 394.8 km s$^{-1}$) listed in Table 3. As these stars are also likely not cluster members, metallicities could not be calculated for them. Based on the similarity of their $V_r$ and proper motions we speculate that the stars might be associated. None of the GCs that are also possibly associated with the Canis Major dwarf galaxy (NGC 1904, NGC 2298 and NGC 2808) have a $V_r$ that is consistent with these stars, in fact there are no GCs in that area of the sky that have a similar $V_r$. Without further information, at this stage we tentatively identify all three as high velocity Galactic halo stars.
9 SUMMARY AND CONCLUSIONS

We report the first results of a spectroscopic survey of NGC 1851 and its surroundings, with good quality spectra of 1149 unique stars. Based on \( V_r \) obtained from Fourier cross-correlation of the wavelength range around the near infrared calcium triplet absorption lines, we identify

1. nine probable new cluster members inside the tidal radius
2. four probable extratidal cluster halo stars at distances up to \( \sim 3.1 \) times the tidal radius
3. 106 red giant cluster stars in the Carretta et al. (2010, 2011) study
4. four red giant cluster stars observed in the Yong & Grundahl (2008) study
5. eight stars with \( V_r \) values intermediate between those of the Galactic field stars and NGC 1851
6. three stars with very high radial velocities of 371.8, 388.8 and 394.8 \( \text{km s}^{-1} \), and
7. 1015 non-member Galactic disc or halo field stars with \( -100 \text{ km s}^{-1} < V_r < 200 \text{ km s}^{-1} \)

Proper motions were available for eight of the nine probable new cluster members and the four probable extratidal cluster halo stars and all are consistent with that of NGC 1851. The four extratidal cluster halo stars provide further confirmation of the findings of Olszewski et al. (2009), Carballo-Bello & Martínez-Delgado (2010), Marino et al. (2014) and Kunder et al. (2014) that NGC 1851 is surrounded by a stellar halo system and does not have a classical tidally-limited profile. Apart from the cluster and halo stars our observed radial velocity distribution agrees with the expected distribution from the Besançon disk/N-body stellar halo Milky Way model generated by the Galaxia code, and the probability that the \( V_r \) distribution of the cluster and halo stars are drawn from the same distribution as the model is effectively zero. In particular there are no indications of an overdensity at \( \sim 180 \text{ km s}^{-1} \) in our observed distribution that might correspond to the tidal tail at this \( V_r \) reported by Sollima et al. (2012), however the number of observed stars in our sample with comparable \( V_r \) is small.

The metallicities of the Carretta et al. (2010, 2011) stars and the probable new cluster members and cluster halo stars were estimated using equivalent width measurements of the calcium triplet absorption lines. Within the limitations of this method discussed above, the metallicities of most of the probable new cluster members and cluster halo stars were found to be consistent with that of NGC 1851. As with the \( V_r \) distribution, the probability that the [Fe/H] distribution of the cluster and halo stars are drawn from the same distribution as the model is effectively zero.

We also identified three stars with unusually high \( V_r \) \( \sim 50 \) to 75 \( \text{km s}^{-1} \) higher than that of NGC 1851. As the velocity separation is large it is likely that they are not associated with NGC 1851. Based on the similarity of their \( V_r \) and proper motions we speculate that the stars might be associated and tentatively identify them as high velocity Galactic halo stars.

In our second paper (in preparation) we will address the determination of C and N abundances using the blue channel of the spectra and discuss the questions of the relationship of the C-N and O-Na anticorrelations, whether there is a scatter in the sum of the C+N+O abundances and whether the sum correlates with metallicities or heavy-element abundances.

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REFERENCES

Allen C., Moreno E., Pichardo B., 2006, ApJ, 652, 1150
Armandroff T. E., Da Costa G. S., 1991, AJ, 101, 1329
Bedin L. R., Piotto G., Anderson J., Cassisi S., King I. R., Mon- mony Y., Carraro G., 2004, ApJ, 605, L125
Bekki K., Yong D., 2012, MNRAS, 419, 2063
Bellazzini M., Ibata R., Ferraro F. R., 2004, in Prada F., Martínez Delgado D., Mahoney T. J., eds, Astronomical Society of the Pacific Conference Series Vol. 327, Satellites and Tidal Streams. p. 220 (arXiv:astro-ph/0307547)
Bullock J. S., Johnston K. V., 2005, ApJ, 635, 931
Carballo-Bello J., Martínez-Delgado D., 2010, in Diego, Jose M. and Goicoechea, Luis J. and González-Serrano, J. Ignacio and Gorgas, Javier ed., Astrophysics and Space Science Proceedings, Highlights of Spanish Astrophysics V. Springer Berlin Heidelberg, p. 383, doi:10.1007/978-3-642-11250-8_40
Carballo-Bello J. A., Gieses M., Sollima A., Koposov S., Martínez-Delgado D., Peñarrubia J., 2012, MNRAS, 419, 14
Carretta et al., 2009, A&A, 595, 117
Carretta E., et al., 2010, ApJ, 722, L1
Carretta E.,Lucatello S., Gratton R. G., Bragaglia A., D'Orazi V., 2011, A&A, 533, A69
Cassisi S., Salaris M., Pietrinferni A., Piotto G., Milone A. P., Bedin L. R., Anderson J., 2008, ApJ, 672, L115
De Silva G. M., et al., 2015, MNRAS, 449, 2604
Dinescu D. I., Girard T. M., van Altena W. F., 1999, AJ, 117, 1792
Dixon W. J., Massey F. J., 1951, Introduction to statistical analysis. McGraw-Hill, New York
Gratton R. G., Carretta E., Bragaglia A., 2012, A&A, 20, 50
Han S., Lee Y., Joo S., Sohn S., Yoon S., Kim H., Lee J., 2009, ApJ, 707, L190
Harris W. E., 1996, AJ, 112, 1487

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Henden A. A., Welch D. L., Terrell D., Levine S. E., 2009, in American Astronomical Society Meeting Abstracts 14. p. 407.02

King I. R., 1966, AJ, 71, 64

Kunder A., et al., 2014, A&A, 572, A30

Lardo C., et al., 2012, A&A, 541, A141

Lee Y.-W., Joo J.-M., Sohn Y.-J., Rey S.-C., Lee H.-C., Walker A. R., 1999, Nature, 402, 55

Leon S., Meylan G., Combes F., 2000, A&A, 359, 907

Marino A. F., et al., 2014, MNRAS, 442, 3044

Martin N. F., Ibata R. A., Conn B. C., Lewis G. F., Bellazzini M., Irwin M. J., McConnachie A. W., 2004, MNRAS, 355, L33

McLaughlin D. E., van der Marel R. P., 2005, ApJS, 161, 304

Milone A. P., Piotto G., Bedin L. R., Sarajedini A., 2008a, Mem. Soc. Astron. Italiana, 79, 623

Milone A. P., et al., 2008b, ApJ, 673, 241

Olszewski E. W., Saha A., Knezek P., Subramaniam A., de Boer T., Seitzer P., 2009, AJ, 138, 1570

Pancino E., Rejkuba M., Zoccali M., Carrera R., 2010, A&A, 524, A44

Robin A. C., Reylé C., Derrière S., Picaud S., 2003, A&A, 409, 523

Sharma S., Bland-Hawthorn J., Johnston K. V., Binney J., 2011, ApJ, 730, 3

Skrutskie M. F., et al., 2006, ApJ, 131, 1163

Sollima A., Gratton R. G., Carballo-Bello J. A., Martínez-Delgado D., Carretta E., Bragaglia A., Lucatello S., Peñarrubia J., 2012, MNRAS, 426, 1137

Stetson P. B., 1981, AJ, 86, 687

Villanova S., Geisler D., Piotto G., 2010, ApJ, 722, L18

Villanova S., Geisler D., Carraro G., Moni Bidin C., Muñoz C., 2013, ApJ, 778, 186

Walker A. R., 1992, PASP, 104, 1063

Wilson C. P., 1975, AJ, 80, 175

Yong D., Grundahl F., 2008, ApJ, 672, L29

Yong D., Grundahl F., D’Antona F., Karakas A. I., Lattanzio J. C., Norris J. E., 2009, ApJ, 695, L62

Yong D., et al., 2013, MNRAS, 434, 3542

Yong D., et al., 2014, MNRAS, 441, 3396

Yong D., Grundahl F., Norris J. E., 2015, MNRAS, 446, 3319

Zacharias N., Finch C. T., Girard T. M., Henden A., Bartlett J. L., Monet D. G., Zacharias M. I., 2013, AJ, 145, 44

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