

The Oldest Stars in the Galaxy – Searching for Metal-Poor Stars in the Galactic Bulge

Louise Margaret Howes

A thesis submitted for the degree of
Doctor of Philosophy
of the Australian National University



Australian
National
University

Research School of Astronomy & Astrophysics

Submitted 5th August 2015

Accepted 4th April 2016

To all the SkyMapper students who came before me...

Disclaimer

I hereby declare that the work in this thesis is that of the candidate alone, except where indicated below or in the text of the thesis. The work was undertaken between November 2011 and August 2015 at the Australian National University, Canberra. It has not been submitted in whole or in part for any other degree at this or any other university.

Chapter 2 is a standalone chapter detailing the EMBLA Survey. The SkyMapper observations discussed were taken by the SkyMapper team and the data reduced by Stefan Keller, all work thereafter was completed by the candidate. All observations on the AAT were taken by the candidate.

Chapter 3 is the paper '*The Gaia-ESO Survey: the most metal-poor stars in the Galactic bulge*', published in *Monthly Notices of the Royal Astronomical Society* by L. M. Howes et al. in November 2014, volume 445, pg. 4241. This paper was published as part of the Gaia-ESO Survey, and as such was bound by the survey's publication policy. This mandated the inclusion of a required list of authors, despite this, the paper was written entirely by the candidate. Observations and data reduction were controlled by the survey.

Chapter 4 is the paper *The EMBLA Survey - Metal-poor stars in the Galactic bulge*, submitted to *Monthly Notices of the Royal Astronomical Society* by L. M. Howes et al. in July 2015. Alan Alves Brito and Anna Frebel obtained the observations discussed in the paper. The paper was written entirely by the candidate.

Chapter 5 is the paper '*Extremely Metal-Poor Stars from the Cosmic Dawn in the Milky Way Bulge*', published in *Nature* by L. M. Howes et al. in November 2015, volume 527, pg. 484. The proper motions were obtained through observations taken by the OGLE Survey, and were processed by Radek Poleski. All other observations were taken by the candidate, and the paper was written entirely by the candidate.



Louise Margaret Howes

1st April 2016

Acknowledgments

I came to Australia in November 2011, not knowing a single person in the country. Since then, I have met so many kind people who have made my time in Canberra some of the best years of my life. My aim is to thank all of them here – please forgive me if I don't succeed.

I must first thank the one person who made this all possible. Without him, there would have been no Ph.D., no time in Australia, no thesis. I will be forever grateful to Martin Asplund for inviting me to come to Canberra and taking me on as his Ph.D. student, even if I still don't quite know why he did. Once I arrived, he immediately made me feel like I had someone looking out for me. Beyond those initial first weeks, Martin has been a fantastic supervisor. Always ready with new and exciting plans, his passion for research has inspired me throughout these past years. His unflappable nature has proven to be an excellent counter to my frequent (and unnecessary) worries, with which he has dealt with great patience, and he has been kind, generous, and encouraging.

I have been fortunate to have a great team as my supervisory panel. Thanks to Mike Bessell, Stefan Keller, and also Brian Schmidt, for teaching me so many invaluable lessons about both astronomy, and a career in research. The final member of my supervisory panel, Dave Yong, deserves extra thanks for the time and effort he put into answering all of my "stupid questions" (and there were many!), always assuring me that there were no stupid questions. He taught me all I needed to know about observing, data reduction, analysis of high-resolution spectroscopy, and of course his secrets of frequent international travel.

I have worked with a large group of astronomers throughout my Ph.D., too many to list here individually – the author lists of my papers can inform you of all their names. But there are more than a few that I would like to thank further. Karin Lind, despite being on the other side of the world, has been so generous with her time. Thank you Karin, for letting me visit you (twice) and for all your wise words and friendly emails. I hope that in a few years I can be half as good a researcher, and as kind a person, as you. Andy Casey has been generous with his time and code, without which much of this work would have taken many years! Thanks also to Alan Alves Brito, Luca Casagrande, Remo Collet, Gary Da Costa, Gerry Gilmore, Amanda Karakas, David Nataf, Melissa Ness, Katie Schlesinger, Richard Stancliffe, and Clare Worley - your doors were always open to me, and I appreciated all your advice and encouragement.

Thanks to Chris Owen for being a great observing partner on those first runs to Siding Spring. The rain and fog tried to dampen my spirit, but alongside Angel Lopez Sanchez (the best support astronomer in the world), you managed to cheer me up!

I have shared my time at Stromlo with so many fantastic fellow students, a community I am proud to belong to. Cherie Fishlock, thank you for sharing an office with me for a whole year - for all the laughs, advice, knitting, and tea! You always managed to brighten my day

and make me smile, I'm going to miss our chats and your cookies. Thanks to George Zhou, for introducing me to IRAF and sharing my office grumbles. Shaheen Iqbal and Tammy Roderick, it's been so much fun to share the Woolley basement with you, thank you for the tea-breaks. There have been many more students who have become friends, I hope to stay in touch with you all. Thanks especially to Anish Amarsi, Michele Bannister, Pete Kuzma, Sarah Leslie, Fan Liu, Chris Nolan, Fréd Vogt, Marc White, and Bonnie Zhang.

I've been fortunate to meet a great number of people outside of Stromlo who between them managed to keep me sane. Claire Bruen and Michael Richards were always the best at this, I don't know how I would have made it without them. Thanks guys for being such my best friends, you will always be welcome at my house, wherever I end up! I'm going to miss you both so much.

Thanks to all the other lovely friends I made through St. Johns; Shawn Liew, Pierre and Suzanne (and Hannah) Grobler, Kaz Lummis, Bec Veness, Margaret Campbell, Carl and Lilina Zimmerman, Lydia Fisher, Dave McLennan, Kirsten Mackerras, and many others. Thanks to the St. Johns Choir for all the singing! Special thanks to Joan Nicholls, Rosemary and Peter Thwaites, and Michelle Xue, for taking such good care of me in my first few months here.

On the topic of singing, thanks also to Helen Swan and the Resonants. I have so many special memories of singing with you in some places I would never have thought possible, you kept my love of choral music going strong. Extra thanks to the altos, for proving that once again, we are the coolest section of any choir.

I want to thank Cherie again, for introducing me to her netball team, and the rest of team Jinxd for letting me join. I can't believe I had fun whilst doing some physical exercise!

Thank you to Edlyn, Sinead, Fitz, and Duncan for being the best housemates ever.

Thanks to Philippa Borrill and Laura Searle who, despite being so far away, kept reminding me that I have best friends for life. And to Phil Adsley, for keeping me amused with one line emails.

I want to thank Luke Shingles for all his patience and wise words during my Ph.D. The journey was a long and occasionally difficult one, but I really loved your company on the way. I hope life in Belfast goes well for you.

My final and biggest thanks go to my family, who have supported me throughout not only my time in Australia, but my whole life. I definitely wouldn't be finishing this Ph.D. if it weren't for them, and I can't wait to live a bit closer to them. They gave me so much; not only the means to study a subject I love for so long, but also the love of learning which I inherited from them. Thank you so much for your understanding and support, even though that meant supporting me as I moved to the other side of the world.

One postscript to these acknowledgements - I would also like to thank Paul McMillan for soothing all my anxieties between submitting the thesis and hearing back from the examiners!

Abstract

The nature of the first generations of stars that formed after the Big Bang is one of the major topics in contemporary astrophysics and cosmology. Such stars formed out of gas that was relatively free of elements heavier than helium, during a time before generations of supernovae had polluted the environment. Previous hunts have found many of these ‘old’ stars in the Galactic halo. However, not all parts of the Milky Way evolved at the same rate. Cosmological models of galaxy formation have drawn the conclusion that, due to the "inside-out" formation of galaxies like the Milky Way, the oldest stars should today preferentially reside close to the centre of the Galaxy – in or near the Galactic bulge.

This thesis documents the initial results of the EMBLA Survey, the first successful search for ancient and metal-poor stars in the bulge of the Milky Way. By utilising the metallicity indicator provided by SkyMapper photometry, we were able to search through more than five million bulge stars, looking for those rare objects with extremely low iron abundances. The AAOmega spectrograph on the AAT gave us the opportunity to obtain intermediate-spectroscopy of approximately 350 stars simultaneously; during 24 nights of observing spread over three years, we observed more than 14,000 candidate metal-poor stars to spectroscopically confirm the photometric metallicity estimates.

We found that 49% of the stars observed with the AAT had metallicities below $[\text{Fe}/\text{H}] = -1.0$, and around 1,000 stars with $[\text{Fe}/\text{H}] < -2.0$. This is a remarkable achievement given that previous searches had only found a total of 21 stars with metallicities that low.

Thirty-seven of the most metal-poor stars were then observed with high-resolution spectroscopy using 8 m telescopes like Magellan and the Very Large Telescope (VLT), to determine their detailed chemical compositions. As part of the Gaia-ESO Survey, four stars were observed in 2012 on the VLT, with metallicities of $-2.72 \leq [\text{Fe}/\text{H}] \leq -2.48$. We then observed a further ten stars with the MIKE spectrograph at Magellan in 2012, and in 2014 we observed a final 23 targets.

We have found the first EMP stars in the bulge; nine of our stars have $[\text{Fe}/\text{H}] < -3.0$, and one has $[\text{Fe}/\text{H}] = -4.0$. We compared the abundances found in our sample with stars of the same metallicities found in the Galactic halo, and found in general similar trends. Unexpectedly, however, we only found one carbon-enhanced metal-poor (CEMP) star (3%) while 20% of halo stars with $[\text{Fe}/\text{H}] < -2.0$ are CEMP stars. In order to verify the predicted old ages of our stars, we also investigated their kinematics. We found that half the stars examined have tightly bound orbits; remaining within the inner Galaxy rather than being merely halo stars passing through the bulge region. This is crucial, as the oldest stars are predicted to have the lowest binding energies. The two most metal-poor stars in our sample have binding energies low enough that there is a 50% chance they formed at redshifts of $z > 12$, which would make them the oldest known objects in the Universe.

Contents

List of Figures	xiii
List of Tables	xxi
1 Introduction	1
1.1 Metal-Poor Stars	1
1.1.1 The First Stars	1
1.1.2 The Age of a Star	3
1.1.3 Astronomical Implications	4
1.2 Searching for Metal-Poor Stars	6
1.2.1 Proper Motion Astrometry	6
1.2.2 Objective-Prism Spectroscopy	7
1.2.3 Modern Day Low-Resolution Spectroscopy	7
1.2.4 Photometry Based Searches	8
1.2.5 Metal-Poor Stars in Dwarf Satellite Galaxies	8
1.3 The Galactic Bulge	9
1.3.1 Description	9
1.3.2 Where are the Oldest Stars Now?	10
1.3.3 Observational Evidence of Metal-Poor Stars in the Bulge	13
1.4 The EMBLA Survey	14
1.4.1 The SkyMapper EMP Hunt	14
1.4.2 Outline of the Thesis	15
1.4.3 A Note on Presentation	16
2 Hunting Metal-Poor Stars with the EMBLA Survey: An Outline	17
2.1 Introduction	17
2.2 The SkyMapper Telescope	17
2.2.1 A Specially Designed Filter Set	18
2.3 Selection of Metal-Poor Stars	21

2.3.1	The Photometry Observed	21
2.3.2	Finding the Candidates	23
2.3.3	The Problem with Reddening	26
2.3.4	Improving the Selection in 2013	28
2.4	Intermediate-Resolution Spectroscopy with AAOmega	29
2.4.1	Three Years of Observations	29
2.4.2	Processing the Survey Data	34
2.5	Initial Results	36
2.5.1	The Metallicity Distribution Function	36
2.5.2	Levels of Contamination from Foreground Dwarfs	39
2.6	Stars Chosen for High-Resolution Follow-up	42
2.6.1	The Gaia-ESO Survey	42
2.6.2	Magellan Observations	43
2.6.3	Further Observations	43
3	The Gaia-ESO Survey: the Most Metal-Poor Stars in the Galactic Bulge	45
3.1	Introduction	46
3.2	Observations	47
3.3	Stellar Parameters and Chemical Abundances	49
3.4	Discussion	51
3.4.1	Bulge membership	51
3.4.2	Chemical Composition	53
3.5	Conclusions	54
4	The EMBLA Survey – Metal-poor Stars in the Galactic Bulge	57
4.1	Introduction	58
4.2	Observations	59
4.2.1	Photometry from SkyMapper	59
4.2.2	Medium resolution spectroscopy with AAOmega on the AAT	60
4.2.3	High resolution spectroscopy with MIKE on Magellan	62
4.3	Analysis	64
4.3.1	Data Reduction and Radial Velocities	64
4.3.2	Atmospheric Parameters	65
4.3.3	Chemical Abundances	69
4.3.4	Distances to the stars	70
4.4	Analysis of previously studied stars	70
4.5	Results	75
4.5.1	Positions and Kinematics	75
4.5.2	Stellar Parameters	78
4.5.3	Chemical Abundances	78
4.6	Conclusions	88
5	Extremely Metal-Poor Stars from the Cosmic Dawn in the Milky Way Bulge	91

5.1	Introduction	91
5.2	Results	92
5.3	Methods	98
5.3.1	Observations	98
5.3.2	Parameter and Abundance Determination	98
5.3.3	Distances and Orbital Parameters	100
6	Final Results and Conclusions	103
6.1	Introduction	103
6.2	Metallicities of the EMBLA Stars	104
6.3	Kinematics of the EMBLA Stars	105
6.4	Chemistry of the EMBLA Stars	110
6.4.1	Carbon	111
6.4.2	Light Elements	114
6.4.3	Alpha-capture Elements	115
6.4.4	Connections between Chemistry and Kinematics	117
6.5	Conclusions	119
6.5.1	Future Plans for the EMBLA Survey	121
6.5.2	Metal-Poor Bulge Stars in the Next Decade	123
	Bibliography	125
	Appendix A Online Data Tables	137
A.1	Tables from Chapter 4	137
A.2	Tables from Chapter 5	144

List of Figures

1.1	Figure 5 from Greif et al. (2012), showing models of the evolution of protostellar systems. Each panel shows the density projection in a cube of side length 10 au, each row corresponds to a different minihalo, evolving from left to right. The discs around the initial protostar split into several smaller protostars, some of which fall back into the centre, whilst others gain enough angular momentum to escape and form a smaller mass star.	2
1.2	Figure 1 from Aoki et al. (2006) showing the differences between high-resolution spectra of stars with iron abundances of $[\text{Fe}/\text{H}] = 0, -3.2$ and -5.6 (since reassessed to be -5.4).	5
1.3	Photograph of the Galactic centre, including the bulge region. Credit: ESO/C. Malin	9
1.4	MDF of the Galactic bulge, taken from the ARGOS Survey (Ness et al. 2013a)	10
1.5	Figure 12 from Ness et al. (2013a), showing the MDF of the bulge at three locations along its minor axis. Overplotted are the gaussian decompositions of the MDF, shown as populations A-E.	11
1.6	Figure 4 from Salvadori et al. (2010), showing the average formation redshift of dark matter particles that host stars with $[\text{Fe}/\text{H}] < -1.0$, throughout the model galaxy. Those particles which formed at redshifts of $z < 10$ all lie within the innermost 5 - 10 kpc of the model galaxy.	12
1.7	Figure 15 from Tumlinson (2010), showing a map of the sky in Galactic coordinates. The sky has been split into bins, each bin shows the percentage of stars with $[\text{Fe}/\text{H}] \leq -3.0$ that formed prior to $z = 15$	12
1.8	An overview of the SkyMapper search for EMP stars, incorporating the halo search (in blue) and the EMBLA survey (in red). The numbers on the arrows show the approximate number of stars at each stage. See text for an explanation of all the nodes.	14

2.1	Figure 1 from Murphy et al. (2009), the throughput of the SkyMapper filters (solid lines) compared to the <i>ugriz</i> filters of SDSS (dashed lines).	18
2.2	Figure 13 from Keller et al. (2007), showing a version of the metallicity gradient; $(v - g) - 0.9(g - i)$, for stars of solar metallicity but different surface gravities (black, solid lines), and for stars of decreasing metallicity with $\log g = 4$ (red, dashed lines). On top of this are the computed colours for one of the most metal-poor stars known (with $[\text{Fe}/\text{H}] = -5.4$), HE 1327-2326 (star symbol, Frebel et al. 2005), and the EMP star sample from Cayrel et al. (2004) (circles).	19
2.3	An example of a colour-colour plot used to select stars for follow-up in the EMP halo search. The grey points are the data from SkyMapper, and the coloured points are taken from the EMP follow-up data, where all metallicities have been determined spectroscopically. In this diagram, the <i>u</i> band has been used to maximise the metallicity separation between stars. Credit: Stefan Keller/ANU.	20
2.4	An image taken with SkyMapper of one of the bulge fields. Credit: Chris Owen/ANU.	21
2.5	The position of all SkyMapper fields observed (green rectangles) and those followed up in intermediate resolution spectroscopy with the AAT (circles: blue were observed in 2012, purple in 2013, and orange in 2014). The size of each circle and rectangle matches the field-of-view of each instrument.	22
2.6	The $v, v - i$ colour magnitude diagrams of raw photometry from one field, observed twice by SkyMapper. Left: The photometry from the 2012 observations, containing $\sim 16,000$ stars. Right: The photometry from the 2013 observations, containing $\sim 537,000$ stars. The magnitudes shown are not calibrated to a universal system, and are indicated only to relate the two figures.	23
2.7	An example of the cut used to eliminate extended objects from the photometry by evaluating the difference between two aperture cuts, g_2 (larger) and g_3 (smaller). The areas outside the two blue lines were rejected.	24
2.8	An example of the colour-colour plots used to make the selection of metal-poor candidates. Like Figure 2.3, data from one SkyMapper field is shown in black, with the spectroscopic data from the corresponding ARGOS field shown in colour. Additionally, the closest EMBLA field has also been overplotted, with $[\text{Fe}/\text{H}]$ values from the intermediate-resolution AAOmega spectroscopy. The red outline shows the selection box used in this field, whilst the arrow indicates the reddening vector.	25
2.9	Figure 3 from Gonzalez et al. (2012), showing the extinction map of part of the Galactic bulge covered by the VVV survey (Minniti et al. 2010). This figure saturates at 1.5 mag of extinction, when in fact the extinction in the inner regions reaches 3.5 mag.	26

2.10	The colour-colour diagrams of two bulge fields, both observed in 2013. Left: Field 1029, with Galactic coordinates $(l,b)=(10.4, 9.0)$. Right: Field 1890, $(l,b)=(1.1, -3.1)$	27
2.11	The $g, g - i$ colour magnitude diagram from an example field. The red box shows the selection that was made on this field to limit our sample to stars on the giant branch, and hence in the bulge region rather than the foreground.	28
2.12	An example of the spectra obtained using AAOmega/2dF (in black), along with the model spectra generated using <code>sick</code> (blue). Top: Part of the blue arm, used for the analysis. Bottom: The whole of the red arm of the spectrum.	34
2.13	Screenshot from the original version of <code>sick</code> , used to analyse the 2012 data and choose targets for follow-up in 2012/13.	35
2.14	An example of a corner plot output by <code>sick</code> , showing the convergence of the code to four of the modelled parameters, T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$.	36
2.15	The MDF of all the stars observed in 2012/13 with converged solutions from <code>sick</code> (green), compared to the total MDF of bulge stars from the unbiased ARGOS survey (Ness et al. 2013a) (blue).	38
2.16	The percentage of stars in each field that a) had a convergent solution in <code>sick</code> (blue points), b) had $[\text{Fe}/\text{H}] < -1.0$ (red points), and c) had $[\text{Fe}/\text{H}] < -2.0$ (green points). The corresponding lines are linear fits to the data points to show the overall trend of the points.	39
2.17	The HR diagram for all stars successfully analysed by <code>sick</code> . On top of this are three Dartmouth isochrones (Dotter et al. 2008) to demonstrate where we roughly expect the stars to lie. All three isochrones are 14 Gyr in age, have $[\alpha/\text{Fe}] = 0.2$, and have $[\text{Fe}/\text{H}] = -1$ (continuous line), -2 (dotted line), and -3 (dashed line).	40
2.18	Histograms of the distribution of $\log g$ values throughout the survey. The blue histogram shows the distribution of stars observed in 2012, the red in 2013.	41
3.1	Two-colour plot using the g, v , and i bands of SkyMapper to demonstrate the metallicity dependence on the $(v - g) - 2(g - i)$ colour. The coloured circles are data taken from both EMBLA and the ARGOS survey (Ness et al. 2013a), with $[\text{Fe}/\text{H}]$ determined spectroscopically (field at $(l,b)=(0,-10)$). The red trapezium shows our selection criteria for metal-poor candidates. The arrow represents the mean reddening vector in this field, $E(B - V)=0.17$ (Schlegel et al. 1998).	48
3.2	Raw metallicity distribution function, without accounting for selection effects, of the first 8,611 spectra from the EMBLA survey (red), compared to the MDF of the ARGOS bulge survey (blue). Both are normalised to have the same area.	48
3.3	Comparison of the the FLAMES/UVES spectrum of Bulge-1 (black) and Bulge-3 (green), with the Gaia benchmark metal-poor halo giant (Jofre et al. 2014) HD 122563 (red), over the Mg triplet wavelength region.	49

3.4	The four bulge stars plotted onto Figure 1 of Shen et al. 2010, which shows the face-on and side-on views of the bulge constructed from their N-body model of the BRAVA survey data. The position of the sun is marked with a cross on the x-axis. Underneath, the position of the bulge stars as viewed from the Sun's location.	52
3.5	Comparison of the abundances in our bulge stars (blue circles), and the metal-poor halo stars from Gaia-ESO (red circles). Also shown are bulge stars from Bensby et al. (2013) (light green triangles), Alves-Brito et al. (2010) (dark green triangles), APOGEE (García Pérez et al. (2013), purple squares), as well as halo stars from Yong et al. (2013a) (black dots).	54
4.1	Positions of all the fields observed by SkyMapper in the bulge, shown as green rectangles, superimposed on an image of the bulge region of the sky (credit: OGLE). The blue circles show the fields that have been followed up with spectroscopy from AAOmega.	60
4.2	Two-colour plot using the g , v , and i bands of SkyMapper to demonstrate the metallicity dependence on the $(v - g) - 2(g - i)$ colour. The coloured circles are data taken from both EMBLA and the ARGOS survey (Ness et al. 2013a), with $[\text{Fe}/\text{H}]$ determined spectroscopically. The red trapezium shows our selection criteria for metal-poor candidates. The arrow represents the mean reddening vector in this field, $E(B - V)=0.17$ (Schlafly & Finkbeiner 2011).	61
4.3	The red-arm spectra showing the Ca II triplet ($R=10,000$) of three of the stars observed with AAOmega. The three stars have been chosen from the same field $(l, b)=(-1.5, -8.8)$ and with a range of metallicities to demonstrate the notable difference in the spectra with varying metallicity. The stellar parameters (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$) are labelled underneath each spectrum.	62
4.4	Raw MDF of the first 9,000 spectra from the EMBLA Survey (green) observed in 2012 and 2013, compared to the MDF of the ARGOS bulge survey (blue). Both are normalised to have the same area, and the EMBLA histogram has been truncated at $[\text{Fe}/\text{H}]=-3.0$ as the low resolution stellar analysis breaks down below this.	64
4.5	The spectra of the first five stars at both the $\text{H}\beta$ and $\text{H}\alpha$ lines, from which a synthetic spectrum was fitted to derive the effective temperatures. The yellow shaded regions show the spectral windows used for the fit. Three synthetic spectra have been overplotted; one with the fitted temperature (blue), one with $T_{\text{eff}} + 200$ K (purple), and one with $T_{\text{eff}} - 200$ K (green). The fits for SMSS J182600.09-332531.0 were not used to derive the T_{eff} of this star, see text for details.	67
4.6	Same as Fig. 4.5 for the remaining five stars. The fits for SMSS J183128.71-341018.4 were not used to derive the T_{eff} of this star, see text for details.	69

4.7	Comparison of the stellar parameters of the four GES stars (blue dots), along with seven halo stars from the literature (red dots). The parameters are derived in this paper, compared with those from Howes et al. (2014), and the literature values (Yong et al. 2013a).	74
4.8	A diagram showing the positions of our stars in the Milky Way, viewed from above and from the side, with the Galactic centre at (0,0) and the Sun at (−8.5, 0), shown as the purple diamond. The purple circle represents a 3.5 kpc sphere around the centre of the Galaxy. Each star is coloured according to its Galactocentric velocity, with the error bars calculated in the projection plane from the distance uncertainties. The GES stars are shown as diamond symbols.	76
4.9	Plots comparing the Galactocentric velocity to both Galactic longitude and latitude. Our sample is shown as purple circles, compared with the bulge dwarf stars of Bensby et al. (2013) (grey circles), and the velocity dispersions of certain ARGOS fields (Ness et al. 2013b) at similar latitudes and longitudes (green lines).	77
4.10	The HR diagram for all 14 stars discussed, given different colours to indicate their metallicity. Also shown are three 14 Gyr Dartmouth isochrones (Dotter et al. 2008), at metallicities of $[\text{Fe}/\text{H}] = -1$ (solid line), -2 (dotted line), and -3 (dashed line). All three are α -enhanced, with $[\alpha/\text{Fe}] = 0.4$	79
4.11	Abundance trends of elements C to Ti, with respect to $[\text{Fe}/\text{H}]$. Both the Magellan data (red circles) and Gaia-ESO data (orange circles) are shown. For comparison, we show the literature samples of both bulge (triangles) and halo (dots) stars, taken from Bensby et al. 2013 (turquoise), Alves-Brito et al. 2010 (blue), García Pérez et al. 2013 (green), Roederer et al. 2014 (grey), and Yong et al. 2013a (purple).	81
4.12	Abundance trends for the iron-peak elements, symbols as in Figure 4.11.	82
4.13	Abundance trends for the neutron capture elements, symbols as in Figure 4.11.	82
4.14	The α abundance trends of the 14 stars, compared to literature values (symbols as in Fig. 4.11). Here $[\alpha/\text{Fe}] = ([\text{Mg}/\text{Fe}] + [\text{Ca}/\text{Fe}] + [\text{Ti}/\text{Fe}])/3$	85
4.15	$[\text{Sr}/\text{Ba}]$ with respect to $[\text{Ba}/\text{Fe}]$, compared to literature values (symbols as in Fig. 4.11).	87
4.16	$[\text{Y}/\text{Ba}]$ with respect to $[\text{Fe}/\text{H}]$, compared to literature values (symbols as in Fig. 4.11).	87
4.17	$\log \epsilon (\text{La}/\text{Eu})$ with respect to $[\text{Fe}/\text{H}]$, compared to values from Roederer et al. (2010) (grey circles), and the solar value (Asplund et al. 2009, orange circle). The blue dashed line shows the predicted solar system total value, and the purple dashed lines show the published r-process prediction range. Both these lines are taken from Sneden et al. (2008).	88

- 5.1 Extracts of the spectrum of the lowest metallicity star in our sample. Top: A section of the spectrum of SMSS J181609.62-333218.7 (black line), the most metal-poor bulge star known. In blue is the predicted spectrum with the inferred stellar parameters (effective temperature $T_{\text{eff}} = 4809$ K, $\log g = 1.93$ dex [cgs], $[\text{Fe}/\text{H}] = -3.94$, $[\text{Mg}/\text{Fe}] = 0.20$), and the red and green lines show spectra with all abundances scaled to ± 0.15 dex respectively. All three were created using the 1D local thermodynamic equilibrium (LTE) spectrum synthesis programme, *MOOG* (Snedden et al. 2012). Bottom: The $\text{H}\beta$ line of the same star, compared to three synthetic spectral line profiles (Barklem et al. 2000) computed with $T_{\text{eff}} = 4640$ K (red, dash-dot), 4800 K (purple, continuous), and 4960 K (blue, dashed). 93
- 5.2 The Galactic positions and orbits of the 23 stars observed at high resolution. Top: Surface density map of a model of the Galactic bulge projected onto the X-Z (top) and X-Y (bottom) planes (Ness et al. 2014), where X, Y, and Z are Cartesian coordinates with the origin at the Galactic Centre and Z perpendicular to the plane of the Galaxy. Plotted over this (filled black circles) are the 23 stars of this study, with distance uncertainties shown as error bars, and a circle of radius 3.43 kpc (white: the cutoff radius of the inner bulge determined from 2MASS data (Robin et al. 2012)). The position of the Sun is shown with a red diamond, at 8.5 kpc from Galactic Centre. Bottom: Projections of the orbit of the lowest metallicity star, SMSS J181609.62-333218.7, both in the (R, Z) plane (right), where R is the radial direction, and in the plane of the orbit itself (left). 94
- 5.3 Chemical abundances of the 23 stars observed at high resolution. Top: The abundance ratio of carbon versus iron ($[\text{C}/\text{Fe}]$), with respect to metallicity ($[\text{Fe}/\text{H}]$) measured in the observed stars (filled red circles, red arrow for an upper limit). The dotted lines represent the solar abundance. Also shown for comparison are literature metal-poor halo giants (small black dots, Yong et al. 2013a) and more metal-rich bulge stars (filled blue triangles, Ryde et al. 2010). Bottom: The chemical abundance pattern of SMSS J181609.62-333218.7, for elements X, where X is displayed at the top of the figure. Each determined abundance is shown as an open black star. These abundances are compared to three synthetic supernovae yields; a pair-instability supernova of $170 M_{\odot}$ (PISN; blue, short dash, Umeda & Nomoto 2002), a core-collapse supernova of $15 M_{\odot}$ (SN; green, long dash, Kobayashi et al. 2014), and a hypernova of $40 M_{\odot}$ (HN; red, solid, Kobayashi et al. 2014). Dotted arrows represent expected non-LTE corrections, solid arrows represent measurements where only an upper or lower limit was possible. The error bars in parts a and b are estimates of the uncertainties in our measurements, calculated as described in Section 5.3.2. 96

5.4	The C-H band of SMSS J181609.62-333218.7. The C-H band used to derive an upper limit for C in our most metal-poor star, SMSS J181609.62-333218.7. Synthetic spectra with abundances of $[C/Fe] = 0.06$ (blue) and $[C/Fe] = 0.56$ (red) are shown for comparison.	97
6.1	The metallicities of all 37 stars observed in high-resolution.	104
6.2	Projections of the orbits of five of the ten stars. Left: projected onto the plane of the orbit, and Right: projected onto the (R, z) plane. From top to bottom: SMSS J182048.26-273329.2, SMSS J184656.07-292351.5, SMSS J181406.68-313106.1, SMSS J181609.62-333218.7, and SMSS J175746.58-384750.0.	107
6.3	Same as Figure 6.2, for the other five stars. From top to bottom: SMSS J184201.19-302159.6, SMSS J181219.68-343726.4, SMSS J181634.60-340342.5, SMSS J175544.54-392700.9, and SMSS J175455.52-380339.3.	108
6.4	Figure 13 from Tumlinson (2010), showing the distribution of the numbers of stars in his model which formed at certain redshifts ($z > 3, 6, 10, 12$, and 15) with respect to their binding energies. The first panel contains all stars with $[Fe/H] < -2$, the second contains all stars with $[Fe/H] < -2.5$, and so on. Note that for the bottom two panels, the curves for $z > 3, z > 6$, and $z > 10$ overlap. The red lines overplotted show the binding energies of the stars in the EMBLA sample, plotted on the appropriate figure for their metallicities.	109
6.5	Chemical abundance plots showing all 37 stars observed in high-resolution, for the light elements Li, C, Na, Al, and K. All are plotted as red circles, with error bars, and as a ratio of Fe abundance (i.e. $[X/Fe]$), except for Li, which is shown as an absolute abundance $A(Li)$. The linear fit to the data is shown (black solid line), and printed in each plot is the slope of the line. For comparison literature samples of bulge stars (Bensby et al. (2013) - turquoise triangles, Alves-Brito et al. (2010) - blue triangles, and Ryde et al. (2010) - sand triangles), and metal-poor halo stars (Yong et al. (2013a) - purple dots, and Roederer et al. (2014) - grey dots).	111
6.6	Comparing the C abundances between the EMBLA stars (red circles), and the seven most metal-poor stars known (blue stars), with abundances taken from Frebel & Norris (2015). SMSS J031300.36-670839.3 is plotted off the figure, with $[Fe/H] < -7.3$ and $[C/Fe] > 4.9$. Also shown are lines representing two criteria for a star to be considered a CEMP star, $[C/Fe] > 1.0$ (Beers & Christlieb 2005, green dashed line), and $[C/Fe] > 0.7$ (Aoki et al. 2007, purple dashed line).	112
6.7	Chemical abundance plots showing all 37 stars observed in high-resolution, for the α -elements O, Mg, Si, Ca, and Ti, symbols as in Figure 6.5, except the green triangles (García Pérez et al. 2013). No linear fit has been shown for O, due to the lack of measurements.	115
6.8	The combined alpha abundances of the sample, using the same symbols as in Figure 6.5. $[\alpha/Fe] = [Mg/Fe] + [Ca/Fe] + [Ti/Fe]$	116

6.9	The orbital binding energies of the ten stars with kinematic information plotted against their metallicity, $[\text{Fe}/\text{H}]$	118
6.10	The orbital binding energies of the ten stars compared to various elemental abundances, $[\text{X}/\text{Fe}]$	118

List of Tables

2.1	SkyMapper fields observed in 2012 on the AAT. Given are the coordinates of each field in both equatorial and Galactic format. Star count gives the number of stars observed in the SkyMapper field in at least the g band. Priority 1 and 2 list the numbers of stars observed at the AAT out of the total selected for that priority. The date and no. of stars observed refers to the date the field was observed and how many stars in each field were observed at the AAT. The star count for field 2025 is not known as the original photometry has been lost.	31
2.2	SkyMapper fields observed in 2013 on the AAT. Columns as in Table 2.1. . .	32
2.3	SkyMapper fields observed in 2014 on the AAT. Columns as in Table 2.1 with the addition of the "New data?" column. This indicates whether the SkyMapper photometry used for each field came from the newer observations taken in 2013.	33
2.4	The results from the fields observed in 2012/13.	37
3.1	Stellar parameters for the four bulge stars and ten halo stars observed as part of the Gaia-ESO Survey in May and August 2012. The SkyMapper naming convention is SMSS J(RA2000)+(Dec2000).	50
3.2	Chemical abundances of the four bulge stars.	53
4.1	Details of the observations of the 10 stars. The SkyMapper naming convention is SMSS J(RA2000)+(Dec2000).	63
4.2	Atomic data. The full table can be found in Appendix Table A.1.	65
4.3	Stellar parameters for the 10 bulge stars.	68
4.4	Details of the four stars originally published in Howes et al. (2014).	71
4.5	Comparison of the new parameters with the GES recommended parameters. The ξ_t uncertainty is ± 0.2 in both cases.	72

4.6	Chemical abundances for all 14 stars. The full table can be found in Appendix Table A.2.	75
4.7	The slope of the linear fit made to the abundance data for each element and the associated error. For comparison, the linear fits from the giant stars in Yong et al. (2013a) are given. No slope could be calculated for [O/Fe] as there are only two measurements.	80
6.1	The fraction of CEMP stars found in the Milky Way halo at certain metallicity ranges. Literature data taken from Placco et al. (2014).	113
6.2	The numbers of CEMP stars found in the EMBLA survey.	113
A.1	Full list of the lines measured including atomic data.	137
A.1	Full list of the lines measured including atomic data.	138
A.1	Full list of the lines measured including atomic data.	139
A.1	Full list of the lines measured including atomic data.	140
A.2	Chemical abundances for all 14 stars.	141
A.2	Chemical abundances for all 14 stars.	142
A.2	Chemical abundances for all 14 stars.	143
A.3	Coordinates and 2MASS photometry of the 23 stars observed. RA, right ascension; Dec., declination; l and b , Galactic longitude and latitude, respectively.	144
A.4	Stellar parameters of the 23 stars observed. V_{helio} , heliocentric velocity; $d_{\odot}$, distance from the Sun to the star; T_{eff} , effective temperature; $\log g$, stellar surface gravity; ξ_t , microturbulence; $[\alpha/Fe] = ([Mg/Fe] + [Ca/Fe] + [Ti/Fe])/3$. Average uncertainties: velocity, 1.0 km s^{-1} ; distance, 3.0 kpc; temperature, 160 K; microturbulence, 0.2 dex; $\log g$, 0.14 dex; [Fe/H], 0.09 dex; $[\alpha/Fe]$, 0.13 dex.	145
A.5	Chemical abundances measured for each star (Li to Ca). A(Li) is the logarithmic abundance of lithium. All abundances are derived using LTE, except for Li, Na, Mg, and Ca, where non-LTE corrections have been applied. Average uncertainties: Li, 0.20; C, 0.25; Na, 0.20; Mg, 0.16; Al, 0.22; Si, 0.21; K, 0.17; Ca, 0.12.	146
A.5	Chemical abundances measured for each star (Li to Ca). A(Li) is the logarithmic abundance of lithium. All abundances are derived using LTE, except for Li, Na, Mg, and Ca, where non-LTE corrections have been applied. Average uncertainties: Li, 0.20; C, 0.25; Na, 0.20; Mg, 0.16; Al, 0.22; Si, 0.21; K, 0.17; Ca, 0.12.	147
A.6	Chemical abundances measured for each star (Sc to Cu). All abundances are derived using LTE. Average uncertainties: Sc, 0.10; Ti, 0.10; Cr, 0.21; Mn, 0.25; Co, 0.23; Ni, 0.19; Cu, 0.25.	148
A.6	Chemical abundances measured for each star (Sc to Cu). All abundances are derived using LTE. Average uncertainties: Sc, 0.10; Ti, 0.10; Cr, 0.21; Mn, 0.25; Co, 0.23; Ni, 0.19; Cu, 0.25.	149

A.7	Chemical abundances measured for each star (Zn to Eu). All abundances are derived using LTE. Average uncertainties: Zn, 0.10; Sr, 0.20; Y, 0.12; Zr, 0.12; Ba, 0.17; La, 0.15; Eu: 0.16.	150
A.7	Chemical abundances measured for each star (Zn to Eu). All abundances are derived using LTE. Average uncertainties: Zn, 0.10; Sr, 0.20; Y, 0.12; Zr, 0.12; Ba, 0.17; La, 0.15; Eu: 0.16.	151
A.8	Orbital Parameters. $\mu_\alpha \cos \delta$ and μ_δ are the proper motions in equatorial coordinates. r_{peri} and r_{ap} are the pericentric and apocentric radii of the orbit, respectively, Z_{max} is the maximum distance the orbit reaches above/below the Galactic plane, and E_{tot} is the total energy of the orbit. All values given here are the mean values from the Monte Carlo simulation of 1,000 orbits. .	152

CHAPTER 1

Introduction

For my part I know nothing with any certainty, but the sight of the stars makes me dream...

– Vincent van Gogh¹

1.1. Metal-Poor Stars

1.1.1. The First Stars

The first stars in the Universe formed roughly 100-200 million years after the Big Bang (Bromm 2013), corresponding to redshifts of $z = 15 - 25$, in dark matter minihaloes with masses of around $10^6 M_{\odot}$. Prior to this point no elements other than those that formed during the Big Bang existed: hydrogen ($\sim 75\%$ by mass), helium ($\sim 25\%$) and trace amounts of lithium. These first stars brought about the end of the cosmic "dark ages" by heralding the start of the epoch of reionisation, and produced the first elements heavier than lithium through stellar nucleosynthesis. Generations of star formation and recycling of stellar material over the 13.8 Gyr lifetime of the Universe have led to the Cosmos as we know it today, enriching our own Solar System.

These generations of stars have been grouped into three broad categories labelled Populations I, II, and III. Population I and II stars (originally defined in Baade (1944)) refer to stars in the disc of the galaxy, and older stars, such as those found in globular cluster systems,

¹In a letter to his brother, Theo

respectively. Population III stars are those from the very first generation – formed out of the initial gas clouds. Traditional models of star formation (e.g., Abel et al. 2002, Bromm et al. 2002, O’Shea & Norman 2007) have predicted that at early times the initial mass function (IMF) would have been top-heavy, i.e. dominated by larger mass stars. This is due to the high temperatures of the gas clouds, and lack of cooling agents heavier than H_2 , forcing the clouds to have larger Jeans masses. This implies that the stars that formed were all massive (of the order of $100 M_\odot$), and hence short lived. For a first generation star to still exist today, however, it would need to have a mass of $\leq 0.8 M_\odot$.

This picture of Population III star formation has altered over the past decade for two main reasons. Firstly, extremely massive stars with $M \gtrsim 150 M_\odot$ are expected to die in so-called pair-instability supernovae (PISN, Heger & Woosley 2002), and these would imprint a noticeable signature onto the next generation of stars formed. This signature has not been convincingly observed in any of the Galactic halo stars observed to date. Secondly, star formation models have been created at higher numerical resolutions than previously possible (examples of these models are shown in Figure 1.1), and these show signs of disc-instability which could lead to the sorts of fragmentation required to create lower mass Population III stars (Clark et al. 2011, Greif et al. 2012).

To date, no Population III stars have been observed. Instead, surveys have yielded a small number of stars that formed from the ejecta of the first stellar generation, from the remnants of the original Pop. III stars. The first stars would have undergone different varieties of core-collapse supernovae at the end of their lives, polluting the interstellar medium (ISM) with the elements formed. These elements are still observable in the atmospheres of the stars that were subsequently created. Finding one of these second generation stars helps to not only describe the previous generation of stars, but also to piece together the change in the IMF from early times to the IMF of today, which peaks at $< 1 M_\odot$ (e.g., Chabrier 2003; Krumholz 2014).

1.1.2. The Age of a Star

To find the oldest stars in the Galaxy, we must first agree on a method of age-determination. Estimating the age of a star is no easy task. Age is not observable directly, we can only derive it from those stellar parameters that are inferred from observations. There are several methods we can use to do this; the most common method involves fitting to stellar evolution models. The atmospheres of stars have several determinable parameters, with which we can classify the star. Effective temperature (T_{eff}), surface gravity ($\log g$, a proxy for the star’s luminosity), iron abundance, and abundance of alpha-capture elements such as Mg, Ca, and Ti, can all be measured through spectroscopy and/or photometry of the star. Isochrones – curves on the Hertzsprung-Russell diagram connecting stars of different masses but the same age and chemical composition, created from stellar models – can then be fitted to these parameters to estimate the age of the star (e.g. Serenelli et al. 2013) As this method depends

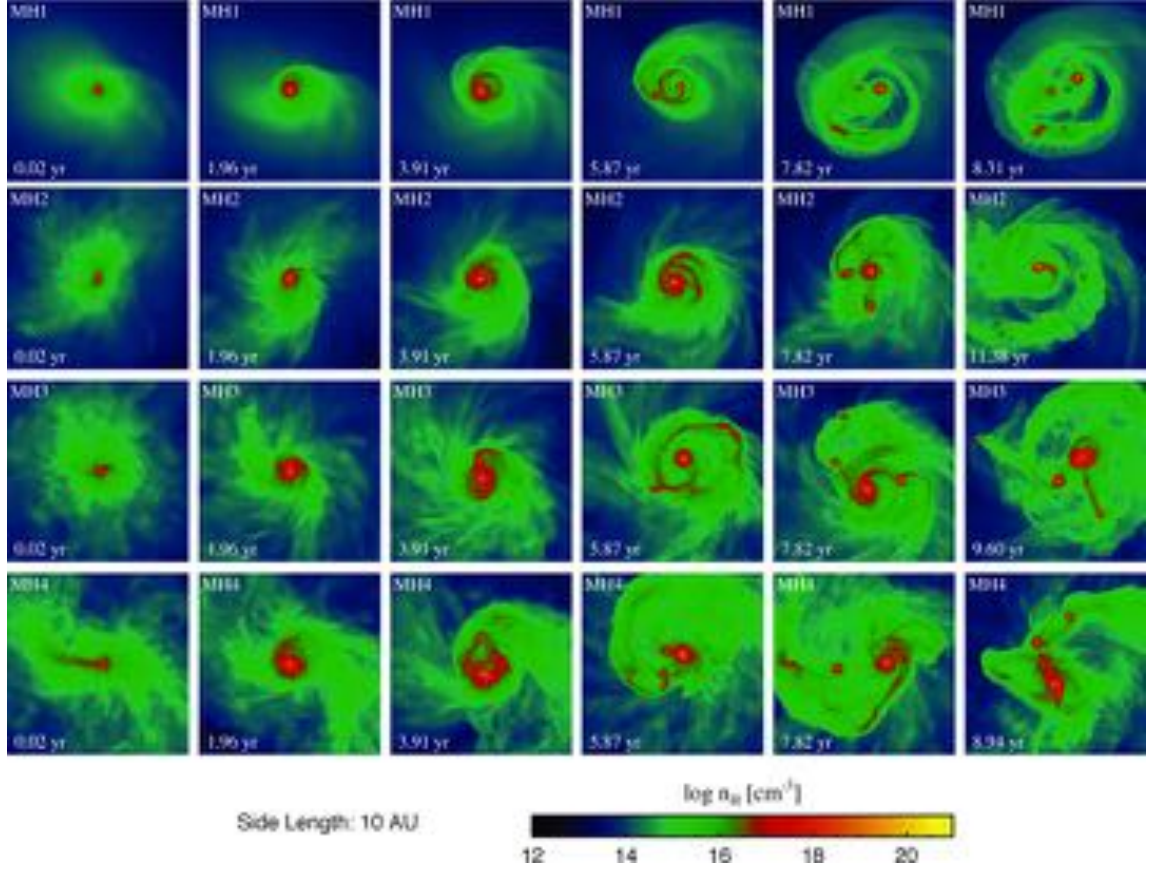


Figure 1.1 Figure 5 from Greif et al. (2012), showing models of the evolution of protostellar systems. Each panel shows the density projection in a cube of side length 10 au, each row corresponds to a different minihalo, evolving from left to right. The discs around the initial protostar split into several smaller protostars, some of which fall back into the centre, whilst others gain enough angular momentum to escape and form a smaller mass star.

on the stellar parameters derived, typically large uncertainties are involved, leading to ages with uncertainties greater than 1 Gyr. Isochrone fitting only works for main-sequence stars, as stellar tracks become degenerate once a star reaches the red giant branch (RGB) phase.

More recently, the techniques of gyrochronology and asteroseismology have been developed for ageing a star. Gyrochronology entails using the rotation period of the star to estimate its age. All low-mass, main-sequence stars like the Sun lose angular momentum over time, slowing down their rotation period. Calibrating this to stars of known ages, we can use the technique to age stars for which we can derive their rotation period (Soderblom et al. 1993; Barnes 2003; Meibom et al. 2015), however so far this has only been shown to work for young stars on the main-sequence. Asteroseismology uses the pulsations of a star to derive information about its interior, and when combined with scaling relations, this can provide ages for stars on either the main-sequence, or the red giant branch (Chaplin & Miglio 2013). This technique hasn't been used to search for the oldest stars, as the age estimates are also uncertain, providing accuracies of 10-15%.

Establishing accurate ages, therefore, is often not possible for many stars; instead, we rely on the age-metallicity relation. By comparing a star's atmosphere to the contents of the local

Universe at different times, we can estimate the age of the Universe when the star formed. As the Universe has evolved, generations of stars have formed, created elements, died and polluted the ISM with the metals formed. Therefore generally speaking, old stars formed at a time when the gas clouds had been through fewer episodes of chemical enrichment. Stars found to be lacking in metals are labelled ‘metal-poor’ and are generally considered synonymous with the oldest stars. This age-metallicity relation is dubious, however, because stars in various parts of the Galaxy with the same metallicities have been found to have very different ages.

Quantifying metallicity is another tricky task. The precise definition of an object’s metallicity is the fraction of elements other than hydrogen or helium in its composition. This value, Z (frequently referred to relative to the solar metallicity, $Z_{\odot}$ e.g., Asplund et al. 2009) is difficult to observe, so frequently metallicity is discussed in terms of the object’s $[\text{Fe}/\text{H}]$ value. Using the bracket notation $[A/B] = \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_{\odot}$, where N_A is the number of atoms of element A, this implies that the star’s abundance of iron relative to hydrogen is given by $[\text{Fe}/\text{H}] = \log_{10}(N_{\text{Fe}}/N_{\text{H}})_* - \log_{10}(N_{\text{Fe}}/N_{\text{H}})_{\odot}$. Iron is used as a proxy for total metallicity due to the large number of iron absorption lines in the spectra of stars - it is easier than most heavy elements to measure accurately. Figure 1.2 shows example spectra at different metallicities, demonstrating how iron lines are affected and hence why we can use $[\text{Fe}/\text{H}]$ as a reasonable substitute for a metallicity value.

Nomenclature

Throughout this thesis, I will use ‘metallicity’ and ‘iron abundance’ interchangeably. I will be using the naming conventions originally set out in Beers & Christlieb (2005) and summarised usefully in Table 1 of Frebel & Norris (2013). This will predominantly involve the use of MP to mean a metal-poor star with $[\text{Fe}/\text{H}] < -1.0$ and EMP an extremely metal-poor star with $[\text{Fe}/\text{H}] < -3.0$.

1.1.3. Astronomical Implications

The study of the first stars of the Universe has long been considered fascinating research in its own right, however the predominant reason for finding these stars lies in the application of their data to a wide range of astronomical interests. Listed here are five such examples, ranging from large-scale cosmological concerns to individual stellar evolution.

- To constrain the products formed through Big Bang Nucleosynthesis (BBNS), and understand the progress of the Universe thereafter. As already discussed, the original stars formed out of gas clouds containing only elements that were created in the primordial Universe; studying the abundances of ancient stars can help to constrain the original BBNS products usually studied through means like the WMAP (Komatsu

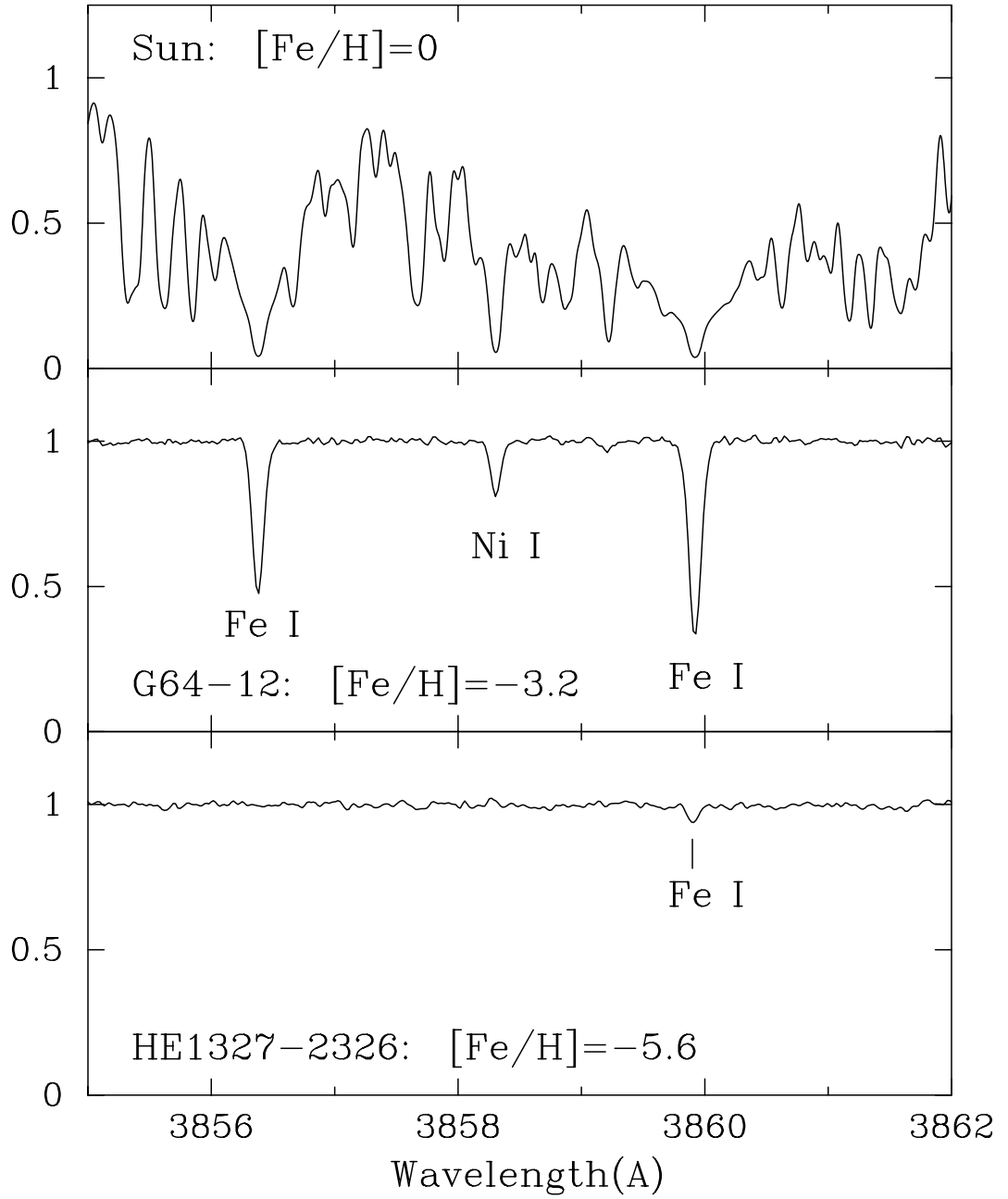


Figure 1.2 Figure 1 from Aoki et al. (2006) showing the differences between high-resolution spectra of stars with iron abundances of $[\text{Fe}/\text{H}] = 0$, -3.2 and -5.6 (since re-assessed to be -5.4).

et al. 2011) and Planck (Planck Collaboration et al. 2014) surveys. One such example is the study of lithium, where the abundances found in old stars is much lower than that predicted by WMAP and Planck; there have been numerous attempts to explain why (e.g., Spite & Spite 1982; Asplund et al. 2006; Sbordone et al. 2010; Meléndez et al. 2010).

- To study the relationships between the kinematics and the chemistry of Galactic components. Stellar populations formed at the same time and in the same environment should have similar chemistry, even if their kinematics have long been altered. By

studying the chemistry of old stars, we can attempt to trace the initial populations of the Galaxy, even after the populations have dispersed (Freeman & Bland-Hawthorn 2002; Mitschang et al. 2014). This forms the basic premise of the ongoing GALAH survey (De Silva et al. 2015), which hopes to identify the original star-forming regions of stars with the same chemistry, but different kinematics.

- To understand the formation process of the Milky Way. Currently it is not possible to gain detailed chemical abundances of individual stars outside our own galaxy and a few nearby dwarf galaxies, so we are limited to the populations within the local group. However the formation of the Galaxy is by no means a simple picture, and the debate into the origin of its components (the thick/thin disc, the halo, and the bulge) continues. This is particularly relevant in the central regions of the Galaxy, the Galactic bulge, where two competing theories of formation – major merger (Abadi et al. 2003) or disk instability (Kormendy & Kennicutt 2004) – pose convincing arguments.
- To establish an accurate picture of the IMF at early times. It has already been discussed that an original top-heavy IMF was likely, however its exact nature remains unknown (Bromm 2013). Does the IMF flatten at low masses and leave room for a rare Population III star to survive to the present day? At what time in the Universe's development did the IMF change to be the low-mass dominated IMF of today's star forming regions? These questions, and others about the cooling mechanisms required to form early stars (Klessen et al. 2012; Stacy et al. 2013) have still to be resolved.
- To understand further the processes involved in chemical enrichment, particularly in core-collapse supernovae. The search for the "second generation" stars is largely driven by the desire to find the remnants of the first supernovae. Giant stars of order $\sim 100 M_{\odot}$ would have undergone massive core-collapse SN explosions at the end of their short lives, and discovering which elements were formed in these explosions helps to probe the processes involved and guide future theory work into supernovae (e.g., Heger & Woosley 2002, Kobayashi et al. 2014, Ishigaki et al. 2014).

1.2. Searching for Metal-Poor Stars

Until the second half of the 20th century, stars were generally assumed to contain an identical mix of elements, and any differences were due to physical conditions in stellar atmospheres. However this idea was dismissed with the discovery of the chemical abundances of two stars with $[\text{Fe}/\text{H}] = -0.8$ and $[\text{Fe}/\text{H}] = -1.0$ by Chamberlain & Aller (1951). In the following years a variety of surveys have been carried out in order to find objects of lower metallicity than those discovered previously. Stars become increasingly rare with decreasing metallicity, requiring the most modern observational techniques to find new record-holders as time has progressed. The most important surveys and the methods used are discussed below.

1.2.1. Proper Motion Astrometry

Proper motion surveys of stars in the Milky Way have been taking place for more than a century. The velocities of stars are linked to the component of the Milky Way that they belong to; typically metal-poor stars belong to the Galactic halo, and so can be found in a selection of stars with the correct proper motions. This technique was used in searches such as that by Ryan & Norris (1991a). However in recent times it has been used less frequently, as it is only useful in selecting stars of a certain Galactic component, which provides little information about a star's chemistry. Even the stars of the metal-poor halo have an average $[\text{Fe}/\text{H}]$ of only approximately -2.0 (Roederer 2009), so finding very metal-poor stars is not guaranteed. Fewer than 10% of the stars in catalogues using this method have $[\text{Fe}/\text{H}] < -2$ (Beers & Christlieb 2005).

1.2.2. Objective-Prism Spectroscopy

By far the most prolific method of finding metal-poor objects to date has been the use of wide-angle intermediate-resolution spectrographs, with spectral resolving powers of around 1,000. Historically this has been achieved on Schmidt telescopes with objective prisms and photographic plates, although advances in technology now make this possible on those telescopes fitted with multi-fibre spectrographs and CCDs. Arguably the two most important EMP surveys in the last few decades, the HK survey and the Hamburg-ESO survey, used this technique. Key results from these surveys are summarised here.

The HK Survey

The HK survey covered 2800 deg^2 in the Northern hemisphere, and 4100 deg^2 in the Southern hemisphere, using 0.6 m Schmidt telescopes, and discovered approximately 100 EMP stars (Beers 1999). A selection of 10,000 candidates was made using the strength of the Ca II K spectral features, and follow-up intermediate-resolution and high-resolution spectroscopy continues on these. The details of the survey can be found in Beers et al. (1985), but the summary presented in Beers & Christlieb 2005 states that at the time of writing, 1000 stars had been confirmed with $[\text{Fe}/\text{H}] < -2$.

The Hamburg-ESO Survey

This survey, initially designed to search for QSOs (Wisotzki et al. 2000), reaches apparent depths of almost two magnitudes fainter than the HK Survey and covers additional regions of the sky (the total southern extragalactic sky is included). Observed on the ESO 1 m Schmidt telescope, again the Ca II K feature is examined and from this $\sim 21,000$ candidates

were selected (Christlieb et al. 2000). The follow-up is still ongoing, but according to the summary presented in Frebel & Norris (2013), the number with subsequent spectroscopy taken by 2013 was $\sim 5,200$. The two stars with the lowest $[\text{Fe}/\text{H}]$ values known at the time and for a decade after were found through this survey; HE 1327–2326 (Frebel et al. 2005) with $[\text{Fe}/\text{H}] = -5.4$ and HE 0107-5240 (Christlieb et al. 2002) with $[\text{Fe}/\text{H}] = -5.2$.

1.2.3. Modern Day Low-Resolution Spectroscopy

With the arrival of the SDSS SEGUE-I survey, a new era of large scale stellar surveys began. SEGUE-I (Yanny et al. 2009) observed around 240,000 stars with a low-resolution spectrograph ($R = 2,000$) on the 2.5 m SDSS telescope at Apache Point Observatory, providing stellar parameters for thousands of stars spread over three-quarters of the sky. By observing such a large number of stars, the survey was able to find a significant number of metal-poor stars (Caffau et al. 2011b). SEGUE-I was extended into SEGUE-II, and since then the BOSS survey has also observed many thousands of stellar spectra using the same telescope, and the search for extremely metal-poor candidates with these spectra continue (see for example, the ToPoS survey Caffau et al. 2013). SEGUE-I led to the discovery of SDSS J102915+172927, a star with $[\text{Fe}/\text{H}] = -4.89$ and very few detections of other elements (Caffau et al. 2012). It does not appear to be enhanced in the elements C, N, or O, like the other stars found at such low metallicities ($[\text{Fe}/\text{H}] < -4.5$), making it truly the most metal-poor star known, rather than the most iron-poor.

The latest generation survey of this type, the LAMOST survey, has recently started hunting for metal-poor stars. With the capability of obtaining spectra for 4,000 stars at once, the numbers of stars that LAMOST observed in its first year of operation stands at more than one million (Luo et al. 2012). With the ability to observe so many stars simultaneously, preselecting for the most metal-poor is almost unnecessary. The early results of the metal-poor search are published in Li et al. (2015), detailing the first five EMP stars discovered, with the most metal-poor star having $[\text{Fe}/\text{H}] = -3.7$.

1.2.4. Photometry Based Searches

Photometry taken from several wavelength bands of the stellar flux can also be used to determine a rough estimate of metallicity. Metallic line blanketing influences the overall flux in specific wavelength regions, so by observing in bands placed at the right part of the spectrum, and comparing the star's colours, a relative estimate of metallicity can be made. This option has the advantage of being able to observe millions of stars in each field, simultaneously, and can go to much fainter magnitudes than spectroscopy. The first major survey to employ this technique is the SkyMapper EMP survey, of which this thesis is a part. More detail about the methods employed and the results of the survey into the bulge

will be presented in later chapters. The halo part of the survey has already proved very successful, a summary of the EMP stars observed with SkyMapper until November 2013 has been recently published (Jacobson et al. 2015). In particular, the survey has discovered a star with no observable iron lines, placing an upper limit on its iron abundance at a remarkable $[\text{Fe}/\text{H}] < -7.52$ (Keller et al. 2014; Bessell et al. 2015)

1.2.5. Metal-Poor Stars in Dwarf Satellite Galaxies

The vast majority of extremely metal-poor stars found to date have been discovered in the Galactic halo. The halo is a complex component of the Milky Way, perhaps composed of two separate populations – first suggested in Searle & Zinn (1978), recent work into the chemistry of the halo seems to confirm this (Nissen & Schuster 2010). There is heated discussion on the relative positions and dynamics of the two populations (Carollo et al. 2010; Schönrich et al. 2011; Beers et al. 2014; Schönrich et al. 2014). It seems clear, however, that at least one of these populations is composed of α -poor stars that used to belong to dwarf satellite galaxies of the Milky Way. The metallicity of the halo is on average metal-poor – the peak of its metallicity distribution function (MDF) is at about $[\text{Fe}/\text{H}] = -2.0$ (Roederer 2009) – if these stars came from dwarf satellite galaxies, perhaps the surviving satellites contain metal-poor stars too. Initial searches into the known satellites of the Milky Way found only stars with $[\text{Fe}/\text{H}] > -3.0$ (Helmi et al. 2006), but with the discovery of ultra-faint dwarf satellites around the Milky Way (Belokurov et al. 2007; Irwin et al. 2007), eventually, EMP stars were also found (Kirby et al. 2008; Tafelmeyer et al. 2010; Frebel et al. 2010). The recent discovery of many new ultra-faint dwarf spheroidals in the southern sky (Koposov et al. 2015) could result in more EMP stars being found in these satellites, and could provide us with answers about how the first small galaxies formed.

1.3. The Galactic Bulge

1.3.1. Description

Situated in the centre of the Milky Way, the bulge describes the bar-like structure that lies approximately 8.5 kpc away from the Sun, within a radius of about 3.5 kpc. The bulge, combined with the halo and the thick and thin discs, make up the entirety of the Milky Way, although how well understood these individual structures are varies enormously (Freeman & Bland-Hawthorn 2002). The bulge, due to its large distance from the Sun and the presence of dust clouds obscuring our view of it, is one of the least studied parts of the Galaxy. In recent years, much of the work on the bulge has focused around the question of how it formed - by a classical merger history (e.g. Wyse & Gilmore 1992; Kauffmann 1996; Bournaud & Elmegreen 2009), or disk instability (Combes et al. 1990; Kormendy &



Figure 1.3 Photograph of the Galactic centre, including the bulge region. Credit: ESO/C. Malin

Kennicutt 2004; Athanassoula 2005). Bulges forming via disk instability are ‘boxy’ in shape and have a cylindrical rotation profile - a feature of the Milky Way which has been confirmed observationally (Howard et al. 2009). Classical bulges have spheroidal rotation profiles, and also should have noticeable radial metallicity gradients due to rapid bursts of star formation - another feature which has been observed in the Milky Way multiple times over the past 20 years (Minniti et al. 1995; Zoccali et al. 2008; Ness et al. 2013a; Gonzalez et al. 2013). Recently, the idea that there is both a boxy-peanut bulge component, and a smaller classical spheroid component, has grown in popularity.

Part of the evidence for suggesting multiple populations in the bulge is due to its MDF. Stellar iron abundances in the bulge have been measured many times in the past 25 years (e.g., Rich 1988; Ibata & Gilmore 1995; Sadler et al. 1996; Ramirez et al. 2000; Zoccali et al. 2008), but arguably the most detailed study of the MDF in recent history was the ARGOS survey (Freeman et al. 2013). The MDF for the bulge is shown in Figure 1.4, taken from the 28,000 stars observed as part of the survey (Ness et al. 2013a). Ness et al. (2013a) suggest that the bulge is composed of as many as five separate populations, including two metal-weak populations (populations D and E in Figure 1.5). Component D is attributed to the metal-weak thick disc, and component E, with the fewest stars of all, to the inner Galactic halo. Studies of bulge stars have also used higher-resolution spectra to infer details about the chemical composition of the bulge, for example Lecureur et al. (2007); Hill et al. (2011), who looked into the Mg abundance spread, and numerous studies into enhanced O abundances (Zoccali et al. 2006; Lecureur et al. 2007). Meléndez et al. (2008) looked into C and O in bulge stars compared to disc stars, and Ryde et al. (2010) found enhanced levels of O, Si,

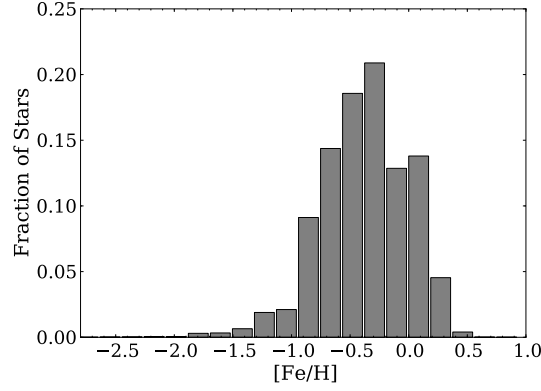


Figure 1.4 MDF of the Galactic bulge, taken from the ARGOS Survey (Ness et al. 2013a)

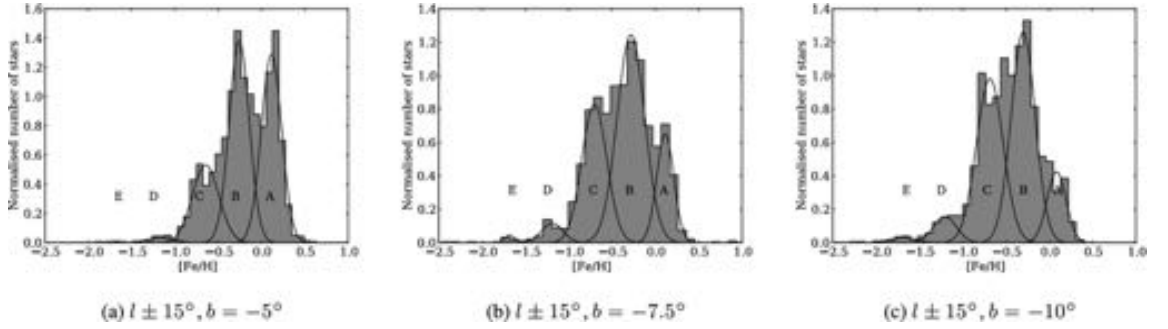


Figure 1.5 Figure 12 from Ness et al. (2013a), showing the MDF of the bulge at three locations along its minor axis. Overplotted are the gaussian decompositions of the MDF, shown as populations A-E.

and S, whereas Fulbright et al. (2007) found that, along with O and Si, Ca and Ti were also enhanced with respect to the disc.

1.3.2. Where are the Oldest Stars Now?

The long-held assumption that the most metal-poor stars were also the oldest began to be examined by theorists around the turn of the Millennium. Attempts to model the formation of the Milky Way in order to determine where those initial building blocks of the Galaxy now lie began with dark matter models of galaxy formation. As the first stars were predicted to have formed in the largest overdensities of dark matter, by following the evolution of these overdensities through time, it would be possible to determine where the remnants of the first stars would now lie.

One of the first attempts to use models to determine where the oldest stars should be is detailed in White & Springel (2000). Their models predicted that the oldest stars should be found at the centre of rich galaxy clusters, for example in the galaxy M87. On a smaller scale, there was no evidence to suggest that metallicity was the best indicator of the age of the star. But the classic monolithic collapse theory of galactic formation indicates that the oldest stars in our Galaxy would be found in the bulge or inner halo regions. Continuing this work, Diemand et al. (2005) used high resolution N-body cosmological simulations to

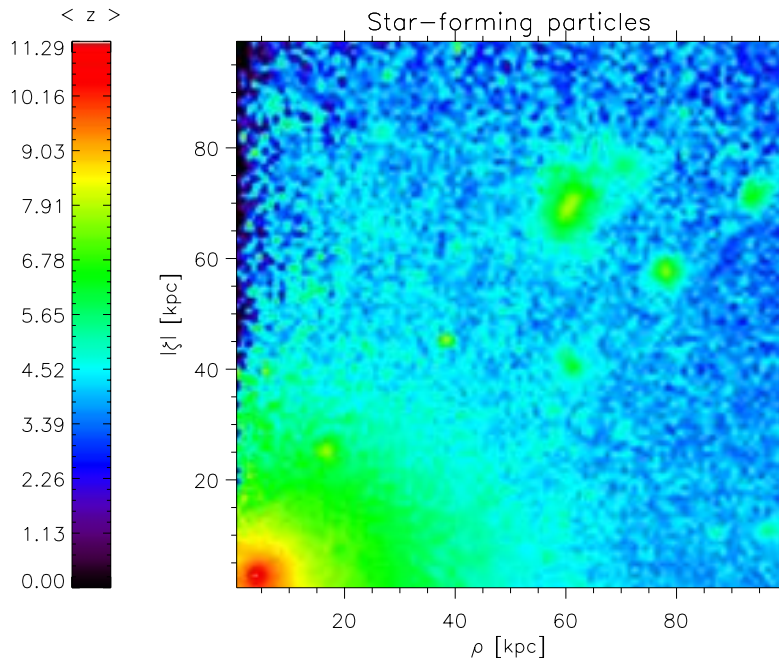


Figure 1.6 Figure 4 from Salvadori et al. (2010), showing the average formation redshift of dark matter particles that host stars with $[\text{Fe}/\text{H}] < -1.0$, throughout the model galaxy. Those particles which formed at redshifts of $z < 10$ all lie within the innermost 5 - 10 kpc of the model galaxy.

analyse the distribution of dark matter particles in galaxy haloes at the present time. They predicted that if any first stars were to survive today, 33-59% of them would lie within the inner 3 kpc of the Galaxy. These stars should also have more radial orbits than stars which formed later. Scannapieco et al. (2006) combined an N-body cosmological simulation with a semi-analytic model of metal enrichment, and found that the redshift of formation increased with decreasing distance from the Galactic centre. Figure 1.6 comes from Salvadori et al. (2010), which extended the work from Scannapieco et al. (2006) by taking the N-body model and combining it with a new semi-analytic model of galaxy formation, tracing the evolution of gas and stars within the model. Again, Salvadori et al. (2010) found that the oldest stars populate the innermost regions of their theoretical galaxies.

Tumlinson (2010) combined a similar cosmological N-body model of dark matter with Galactic chemical evolution calculations into a merger-tree representation of the Milky Way, in order to show that the Milky Way did indeed contain stars from the epoch of reionisation, and to characterise the nature of the relationship between metallicity and redshift of formation. Tumlinson modelled the current spatial distribution of all stars with $[\text{Fe}/\text{H}] < -3.0$ that formed prior to $z = 15$, and this distribution is shown as a global map of the Galaxy in Figure 1.7. Each bin considers all the stars found with $[\text{Fe}/\text{H}] < -3.0$ in that space, and gives the percentage of them which formed at redshifts of $z > 15$. The figure shows very clearly that the largest population of the oldest stars should now be found in the central regions of the Galaxy. He also argues that, dynamically, these stars should have weaker binding energies than their younger counterparts - old stars should have tightly bound orbits, and that any chemical differences found between EMP stars in the bulge and

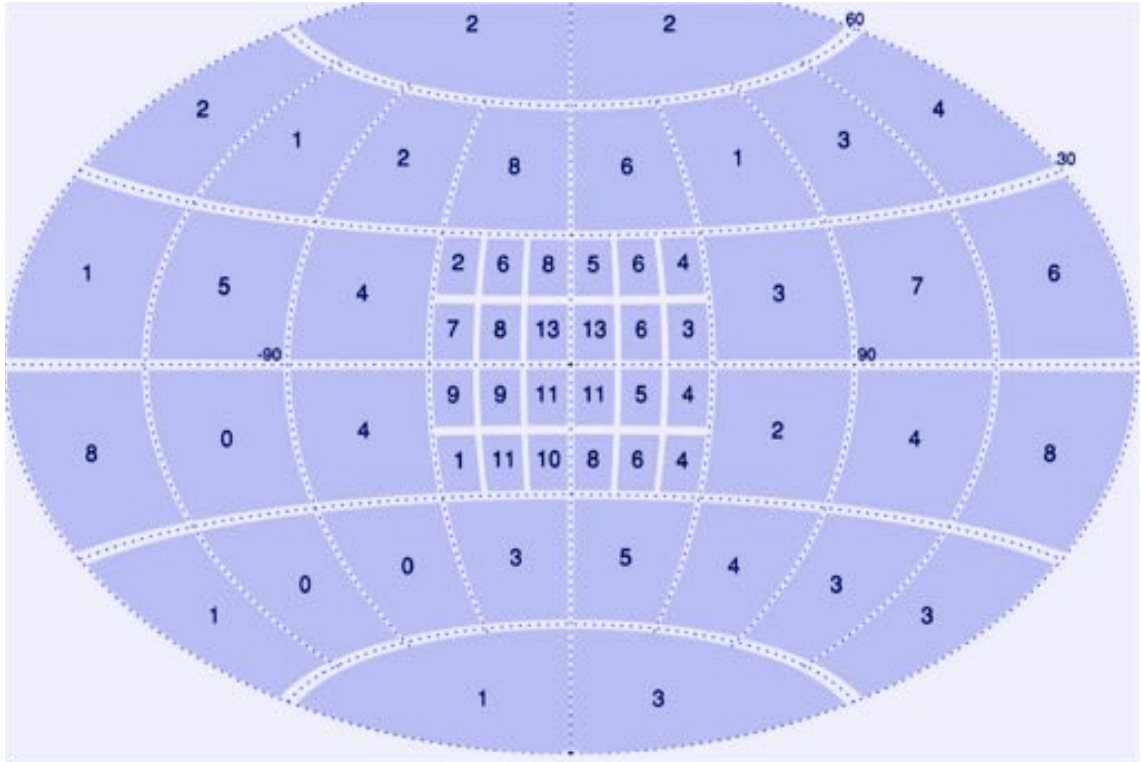


Figure 1.7 Figure 15 from Tumlinson (2010), showing a map of the sky in Galactic coordinates. The sky has been split into bins, each bin shows the percentage of stars with $[\text{Fe}/\text{H}] \leq -3.0$ that formed prior to $z = 15$.

in the halo could be due to the different time of formation.

1.3.3. Observational Evidence of Metal-Poor Stars in the Bulge

The theoretical argument for searching the bulge for EMP stars seems to be clear - if they can be found, there is a high chance they will be much older than halo stars of the same metallicity. Prior to the EMBLA survey, however, there has been no dedicated successful search for these stars. How can this be?

There are several reasons why no search for metal-poor stars in the bulge had previously taken place, and all are due to the practicalities of such a search. As mentioned earlier, the bulge is some distance away; it is only with the advent of 8 m-class telescopes that getting detailed abundances of any star in the bulge has been possible across the whole bulge region. Even with these, we are still limited to a subset of the stars, as dwarf stars are too faint to observe at such a distance (unless they are serendipitously observed as part of a microlensing event - one such survey makes use of this technique (Bensby et al. 2013), providing the only chemical information we have about dwarfs in the bulge).

Secondly, there is a large amount of dust obscuring our view of the central regions of the Galaxy. This creates a large amount of extinction - up to 50 magnitudes worth in the V band in the direction of the Galactic centre (Nishiyama et al. 2008; Nataf et al. 2013). Such high levels of extinction not only mean that spectroscopy is harder to obtain, but

that photometry too is affected by the disproportionate effect that extinction has on bluer wavelengths, causing reddening. This has meant that, over the years, often a successful method of surveying the bulge has been to use infrared wavelengths.

Finally, the largest problem with finding metal-poor stars in the bulge is the issue of overcrowding. The bulge is a densely populated region of stars, more so than any other component in the Galaxy. And the overall metallicity of the bulge is quite metal-rich - as the MDF in Figure 1.4 shows, the peak metallicity in the bulge is roughly $[\text{Fe}/\text{H}] = -0.3$ (Ness et al. 2013a). The effect of such a large number of stars, which are overwhelmingly metal-rich, means that finding the metal-poor stars becomes like searching for a needle in a haystack. The results from the ARGOS survey reveal that, in an unbiased survey of the bulge, one would need to search through 10,000 stars in order to find just 10 with $[\text{Fe}/\text{H}] < -2.0$. The survey found no stars with $[\text{Fe}/\text{H}] < -3.0$. Clearly, a targeted approach is required in order to find these rare objects.

There have, however, been several fortuitous discoveries of stars in the bulge with low metallicities. As mentioned, the ARGOS survey found several stars with $[\text{Fe}/\text{H}] < -2.0$, although as yet these have not been studied in greater detail. The microlensing bulge study of Bensby et al. (2013) found one star with $[\text{Fe}/\text{H}] = -1.9$. The APOGEE survey first targeted the bulge in 2011, and found in the initial 2,403 bulge stars observed, five with very low metallicities (with $-2.1 < [\text{Fe}/\text{H}] < -1.6$).

1.4. The EMBLA Survey

1.4.1. The SkyMapper EMP Hunt

It is clear from the theoretical studies into the distribution of the first stars that, in order to probe the earliest times in the formation of the Milky Way, we must look in the bulge. The difficulties in doing this, however, mean that many of the techniques mentioned in Section 1.2 are not feasible. The best chance of finding these objects is to use a photometric based search, where millions of stars can be observed very quickly. The SkyMapper telescope was built with exactly this sort of project in mind (Keller et al. 2007). The telescope was designed with a specific filter set to optimise the study of stellar populations (Bessell et al. 2011). More details about the telescope and the photometry observed will be given in Chapter 2, but in brief, the v filter serves as a metallicity indicator for each star, allowing the observer to distinguish in each field between more metal-rich and more metal-poor stars.

The telescope was built in order to complete the SkyMapper Southern Sky Survey, aiming to observe the entire southern sky in all six bandpasses. This led to the development of the SkyMapper EMP team, and importantly for this thesis, the EMBLA² Survey. This thesis

²In Nordic mythology, Embla was the first woman, born in the middle of the world from the remains of

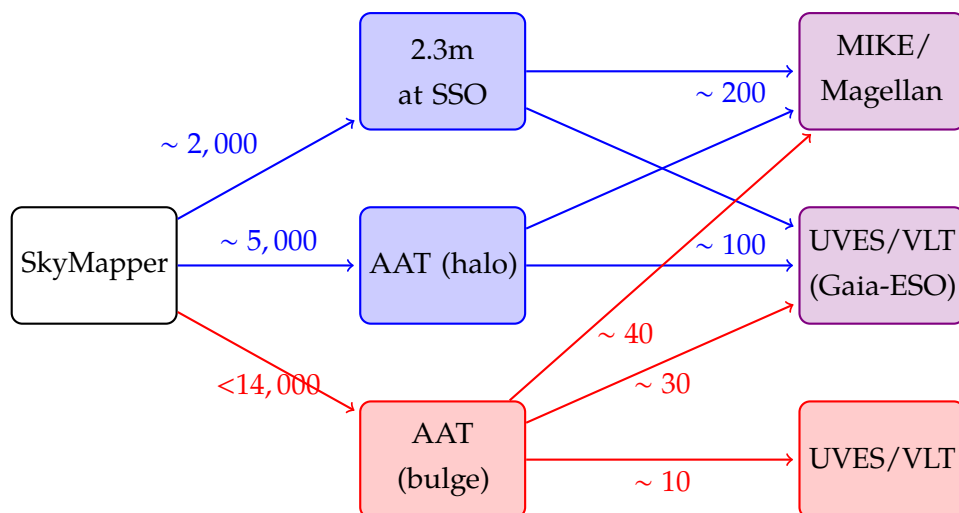


Figure 1.8 An overview of the SkyMapper search for EMP stars, incorporating the halo search (in blue) and the EMBLA survey (in red). The numbers on the arrows show the approximate number of stars at each stage. See text for an explanation of all the nodes.

details the structure, operation, and initial scientific results of EMBLA (which stands for Extremely Metal-poor BuLge stars with AAOmega), carried out during my Ph.D. between 2011 and 2015. Parallel to our work on EMBLA has been the halo EMP hunt with SkyMapper (Jacobson et al. 2015), which has proven very successful – discovering amongst other things, the most iron-poor object known to date (Keller et al. 2014).

Figure 1.8 shows a schematic of the two surveys and the telescopes used at each stage. The SkyMapper photometry is used to select the most metal-poor stars in each field, which are then followed up using the multi-object spectrograph AAOmega on the 4m Anglo-Australian Telescope. Most of the halo fields contain only a few candidates, so some of these sparser fields are followed up instead on the WiFeS spectrograph on the ANU’s 2.3m telescope at Siding Spring Observatory. The low-resolution spectra then allow the stellar parameters of the stars to be determined accurately, and the most interesting stars are observed by 8m telescopes to get spectra in high-resolution. High-resolution spectra allow us to determine the detailed chemistry of the stars through measuring spectral absorption features created in the atmospheric layers of the stars. The surveys make use of two 8m class telescopes; firstly the 6.5m Magellan-Clay telescope, using the MIKE spectrograph, and secondly one of the four 8m VLT telescopes, using the UVES spectrograph. The next chapter will provide more details on all the observations completed so far as part of the survey.

1.4.2. Outline of the Thesis

This thesis comprises three papers detailing results on the EMBLA survey, all are either published, or submitted for publication in the main refereed journals. As well as these three papers, the thesis also contains a methods section, and some final results that will be published in the near future.

Chapter 2 gives more details about the methods and observations of the EMBLA survey, especially regarding the photometry and low-resolution spectra. The details in this chapter will be published in a future article, however it is written as a standalone chapter and is not in the style of a particular journal.

The first paper on the EMBLA survey is presented in Chapter 3; entitled *The Gaia-ESO Survey: The most metal-poor stars in the Galactic bulge*. This paper is written as part of our collaboration with the Gaia-ESO survey (Gilmore et al. 2012), and introduces the first stars observed in high-resolution for EMBLA. This paper was published in November 2014 in the *Monthly Notices of the Royal Astronomical Society (MNRAS)* journal.

Chapters 4 and 5 present the results from observations on the Magellan telescope in 2012 (Chapter 4) and 2014 (Chapter 5). The paper in Chapter 4 - *The EMBLA Survey - Metal-poor stars in the Galactic bulge* - explores the detailed chemistry of these stars, and was submitted to *MNRAS* in July 2015. Chapter 5 was published in the journal *Nature* in November 2015 as a letter titled *Extremely Metal-Poor Stars in the Milky Way Bulge from the Cosmic Dawn*, and highlights our findings from the high-resolution studies to date whilst combining this data with results from the OGLE survey (Udalski et al. 2015) on the kinematics of these stars.

In the final chapter of the thesis, Chapter 6, the results published in the three chapters previous will be collated together in a discussion of what has been uncovered through the EMBLA Survey to date. The thesis will then finish with a brief conclusions section that shall include some discussion on the future for both EMBLA and the study of metal-poor bulge stars in general. The results and discussion in this chapter have yet to be published in a journal article, however a paper is in preparation. That future paper may overlap with some of the work of this chapter.

1.4.3. A Note on Presentation

Chapters 3 to 5 of the thesis were written in the style of the journal they were submitted to, including individual abstracts, introductions, and conclusions. Due to this, there is some unavoidable repetition of the introductory material. This thesis is written in British English throughout, as required by the journals the papers were submitted to.

CHAPTER 2

Hunting Metal-Poor Stars with the EMBLA Survey: An Outline

2.1. Introduction

In this chapter I will give a brief description of the methodology used in the EMBLA survey, focussing on the initial photometry and low-resolution spectroscopy taken. This research has yet to be published in a journal; results from the low-resolution studies will be published in the future once the final processing of the data has taken place.

In 2011, with the imminent arrival of data from the commissioning period of SkyMapper, Prof. Martin Asplund led the first successful proposal for time on the Anglo-Australian Telescope to observe metal-poor candidates in the Milky Way bulge region, which became the EMBLA Survey. I began my Ph.D. in November 2011, with the EMBLA Survey as my thesis subject.

2.2. The SkyMapper Telescope

In late 2002, a team at the ANU led by Prof. Brian Schmidt were granted funding from the Australian Research Council to complete an optical all-southern-sky survey in six wavelength bands on the Great Melbourne Telescope at Mount Stromlo Observatory, Canberra. Unfortunately the January 2003 Canberra bush-fires destroyed all telescopes at the observatory, including the Great Melbourne. In order to carry out the survey that had been proposed, a new telescope had to be built, this time at the Siding Spring Observatory in New South Wales.

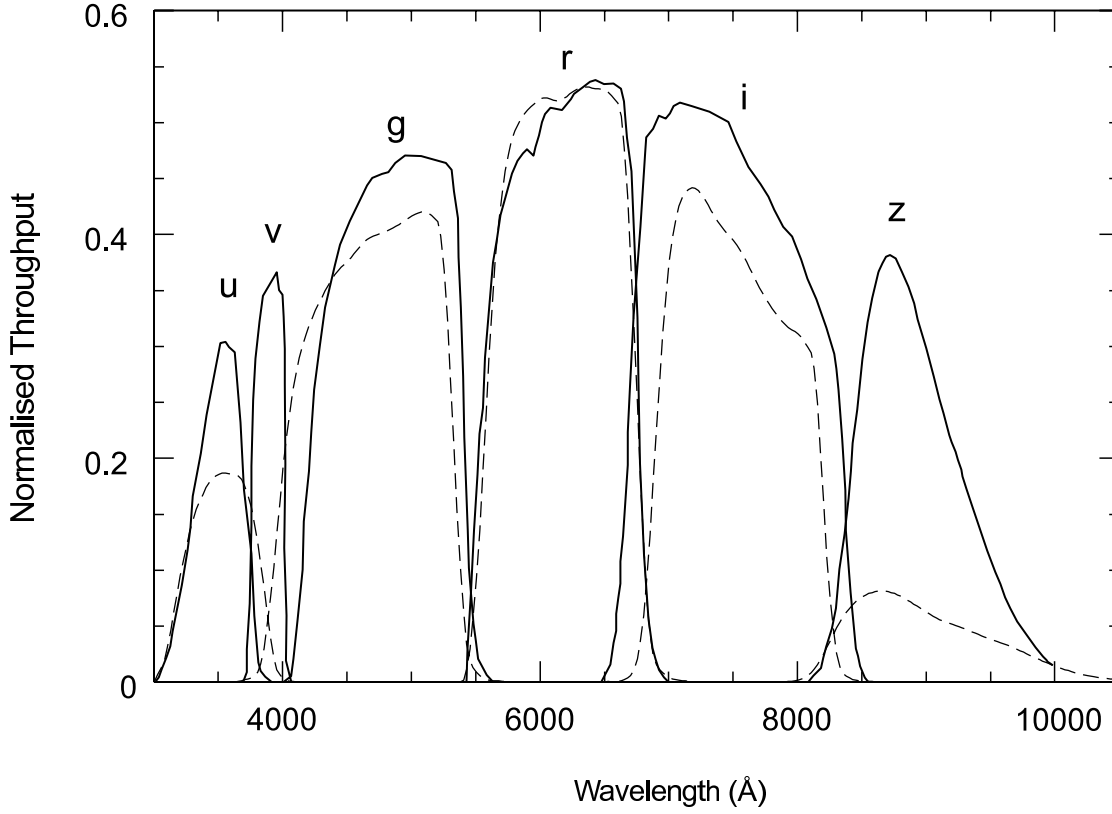


Figure 2.1 Figure 1 from Murphy et al. (2009), the throughput of the SkyMapper filters (solid lines) compared to the *ugriz* filters of SDSS (dashed lines).

SkyMapper is a 1.33 m telescope with a 5.7 square degree field-of-view and an imager composed of 32 2048x4096 CCDs (Keller et al. 2007). The primary aim of the telescope is to perform the SkyMapper Southern Sky Survey, a multi-epoch, six-band survey. The telescope saw first light in 2007, and the survey officially began 2014. Over the seven years of commissioning, the aims of the survey changed to adapt to the telescope’s capabilities, however some of the core objectives of the telescope have remained. These include using the main survey to observe blue horizontal branch stars, in order to trace substructure in the Galactic halo, and the SkyMapper Supernova Survey, which is aiming to observe approximately 100 SNe Ia each year.

2.2.1. A Specially Designed Filter Set

The filter set of SkyMapper (Bessell et al. 2011) is a modified version of the *ugriz* filter set of the Sloan Digital Sky Survey (SDSS) telescope (York et al. 2000). SDSS successfully surveyed the majority of the northern sky, using the five photometry passbands to derive approximate stellar parameters for the stars observed. The SDSS Survey, however, was primarily extragalactic, and so by modifying the filters the SkyMapper team was able to maximise the stellar information accessible using just optical photometry (Fig. 2.1). The red passbands, *r*, *i*, and *z* were left largely unchanged, as they are already optimized for the discovery of high-redshift QSOs; instead the *u* and *g* bands were shortened in order

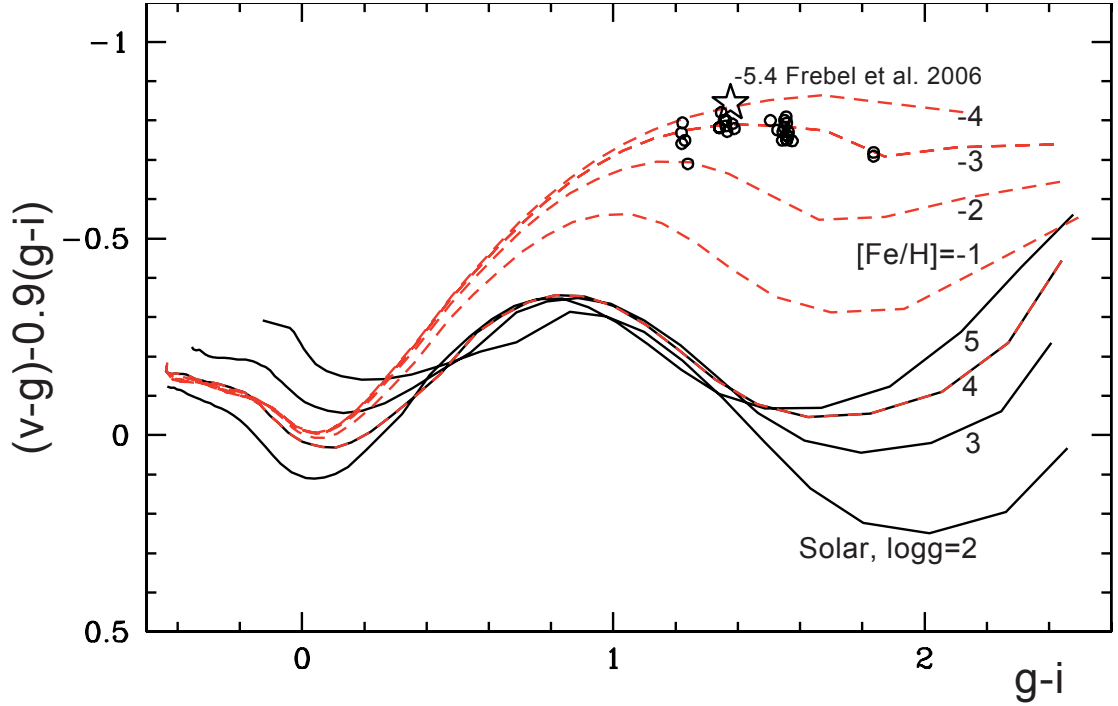


Figure 2.2 Figure 13 from Keller et al. (2007), showing a version of the metallicity gradient; $(v - g) - 0.9(g - i)$, for stars of solar metallicity but different surface gravities (black, solid lines), and for stars of decreasing metallicity with $\log g = 4$ (red, dashed lines). On top of this are the computed colours for one of the most metal-poor stars known (with $[\text{Fe}/\text{H}] = -5.4$), HE 1327-2326 (star symbol, Frebel et al. 2005), and the EMP star sample from Cayrel et al. (2004) (circles).

to fit a thin v passband in between. By cutting the u -band short, its power to discriminate stellar gravities is improved. The v -band proves to be most useful for surveys like EMBLA - by covering a narrow region in the spectrum with high metal line-blanketing especially from the CaII H and K lines, the photometry in this band becomes highly sensitive to stellar metallicity.

One of the key scientific goals of the SkyMapper Southern Sky Survey has been to use the data to search for EMP stars in the Milky Way halo. In Keller et al. (2007), the usefulness of the SkyMapper filters to find stars of very low metallicities is shown in a modified colour-colour plot (Fig. 2.2), where $g - i$ (a proxy for effective stellar temperature) is plotted against $(v - g) - 0.9(g - i)$. Other colour combinations can also be used to do this; in particular when combined with the u band (Fig. 2.3), the separation can be improved further.

The search for halo EMP stars began in 2012, and has so far published 38 newly discovered stars with $[\text{Fe}/\text{H}] < -3$ (Jacobson et al. 2015) using these colour combinations. The work to date has used commissioning data from SkyMapper; due to this the photometry has not been optimal. Despite this, the search has already uncovered a star with at least 30 times less iron than any previously known star (Keller et al. 2014). To date, no iron lines have been observed in SMSS J031300.362670839.3, meaning that the upper limit on its iron abundance is $[\text{Fe}/\text{H}] < -7.5$ (Bessell et al. 2015). The hunt for EMP stars in the halo continues - it is expected that once the Southern Sky Survey is complete, approximately 1,000 stars will be

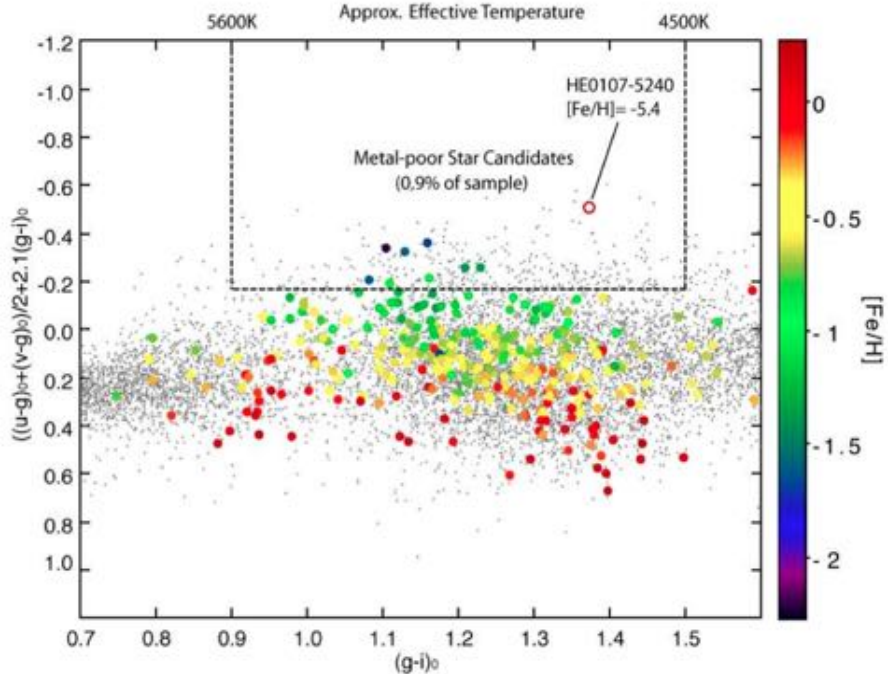


Figure 2.3 An example of a colour-colour plot used to select stars for follow-up in the EMP halo search. The grey points are the data from SkyMapper, and the coloured points are taken from the EMP follow-up data, where all metallicities have been determined spectroscopically. In this diagram, the u band has been used to maximise the metallicity separation between stars. Credit: Stefan Keller/ANU.

found in the halo with $[\text{Fe}/\text{H}] < -4$ (Keller et al. 2007).

The success of the halo EMP search highlights the power of the SkyMapper filter set in distinguishing metallicity. With this in mind, we began the hunt for metal-poor stars in the bulge, using the same techniques.

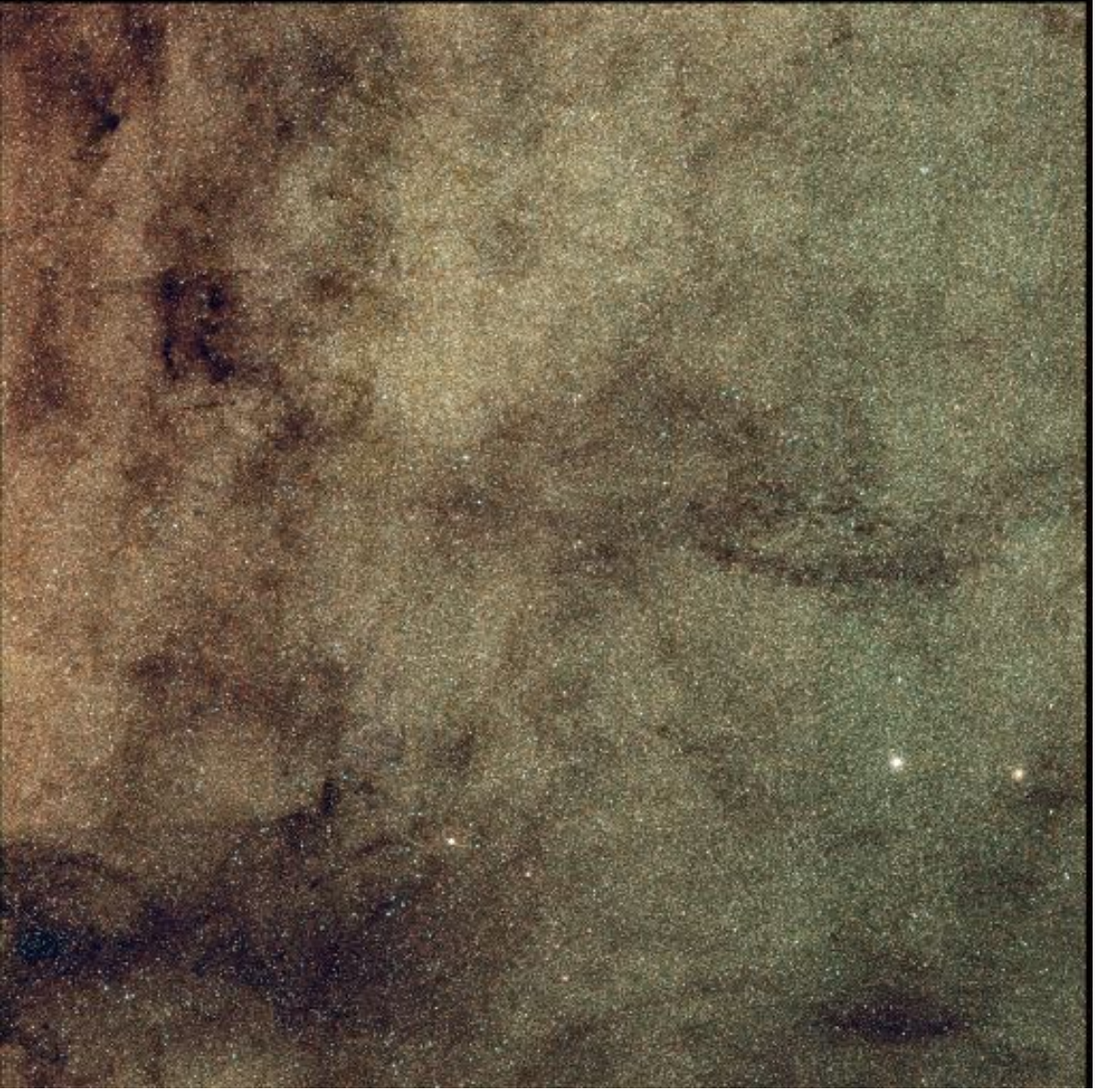


Figure 2.4 An image taken with SkyMapper of one of the bulge fields. Credit: Chris Owen/ANU.

2.3. Selection of Metal-Poor Stars

2.3.1. The Photometry Observed

The data for the EMBLA survey began to be taken on the SkyMapper telescope in August 2011, and by late 2012 we had photometry of more than 70 fields covering the bulge region. Following the lead of the ARGOS survey (Freeman et al. 2013), we restricted the area observed to roughly a $20^\circ \times 20^\circ$ region surrounding the Galactic centre, with coordinates $(l, b) = (0, 0)$ (Fig. 2.5).

In 2011, SkyMapper was still in commissioning, and had had more than a few teething difficulties. In particular, the telescope had some vibration issues, blurring the images and limiting the exposure time available for each frame. Due to this, the depth which could be reached in each filter was somewhat reduced, and it became impossible for us to obtain data

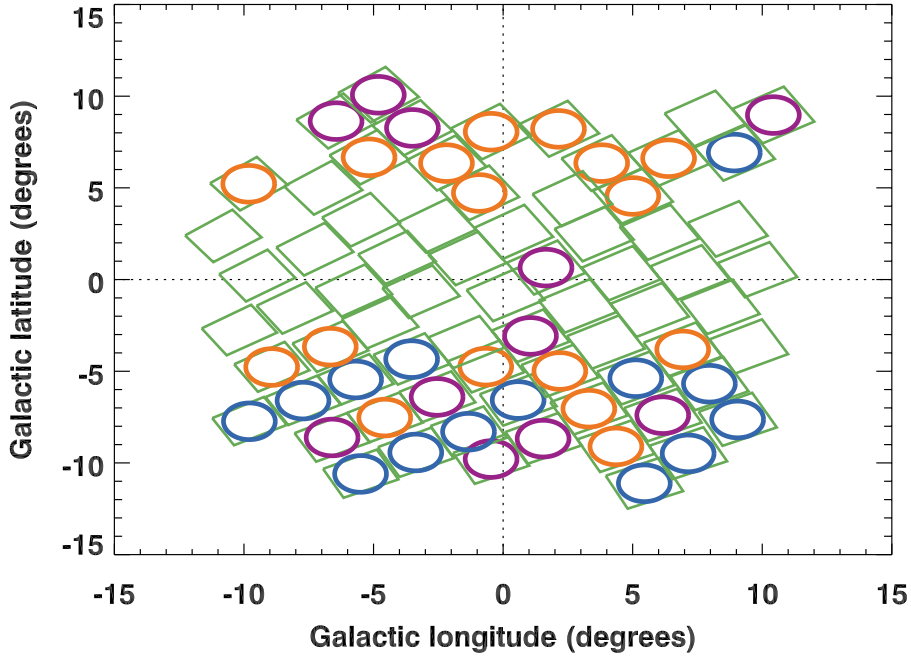


Figure 2.5 The position of all SkyMapper fields observed (green rectangles) and those followed up in intermediate resolution spectroscopy with the AAT (circles: blue were observed in 2012, purple in 2013, and orange in 2014). The size of each circle and rectangle matches the field-of-view of each instrument.

in the u band at an appropriate depth to cover the stars in the bulge. As mentioned in the previous section, the u band can be used to improve the selection of metal-poor stars, but a reliable selection can still be made using just the v , g , and i filters. Therefore we continued the EMBLA survey using these three bands. The g band was observed for 9 s per field (3x3 s exposures), the i band for 6 s per field (3x2 s exposures) and the v band for 15 s per field (5x3 s exposures).

The entire $20^\circ \times 20^\circ$ was covered by SkyMapper during this time, although Figure 2.5 shows that there are several gaps in the coverage. The frames observed in these fields had various problems associated with the continuing issues of the telescope (most notably, there were problems with the telescope’s sky tracking and associating the frames with WCS coordinates) and unfortunately did not successfully make it through the data reduction pipeline.

During the course of the EMBLA Survey, the majority of SkyMapper’s commissioning problems were solved, and so by 2013 it was possible to observe fields for longer and with more precision. This improvement led to another round of photometry taken in the bulge region, covering those areas not yet followed up with intermediate spectroscopy. From May to October, another 45 fields were observed, and the difference in the photometry derived from the observations was significant. Figure 2.6 shows the colour magnitude diagrams (CMDs) of two sets of observations of the same field in the v band, where the biggest improvement was achieved. These second set of observations led to photometry of 33 times more stars than the original observations, reaching almost two magnitudes deeper.

Despite these improvements, problems persisted and for the majority of the 45 fields, the

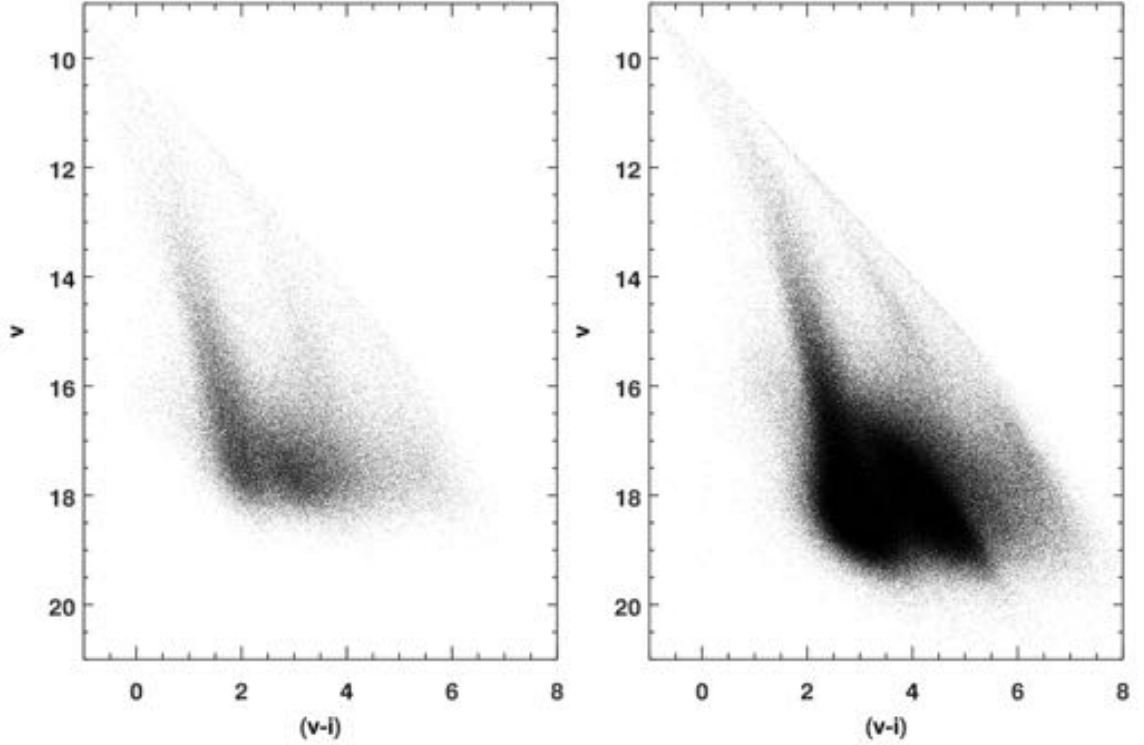


Figure 2.6 The v , $v - i$ colour magnitude diagrams of raw photometry from one field, observed twice by SkyMapper. Left: The photometry from the 2012 observations, containing $\sim 16,000$ stars. Right: The photometry from the 2013 observations, containing $\sim 537,000$ stars. The magnitudes shown are not calibrated to a universal system, and are indicated only to relate the two figures.

telescope’s tracking problems proved too extreme to extract the photometry. Twenty-one fields were processed, and many were used in the spectroscopic observations of 2014. Table 2.3 lists which of those fields observed in 2014 used new photometry.

One of the main problems in using the photometry throughout the survey has been the lack of calibration to universal standards. It is important to note that in all figures where photometry is shown, the magnitudes of the stars are only relative to other stars in the same field - the magnitudes do not reliably correspond to any universal system. Furthermore, each of the 32 CCD chips were not calibrated to each other, leaving small offsets between stars on different chips. Because of this, reconstructing the selection effects of our survey may prove to be an impossible task; however these offsets were small enough not to affect the selection of metal-poor stars, the main aim of the survey. In order to assess necessary exposure times in follow-up observations, the rough equivalence of SkyMapper $g + 0.5 =$ Strömgren v has been used.

2.3.2. Finding the Candidates

Once the fields were observed by SkyMapper, and the images processed by the reduction pipeline, we received the photometry in order to select our targets. Before the metallicity selection could be made, several cuts were made in order to weed out photometric noise,

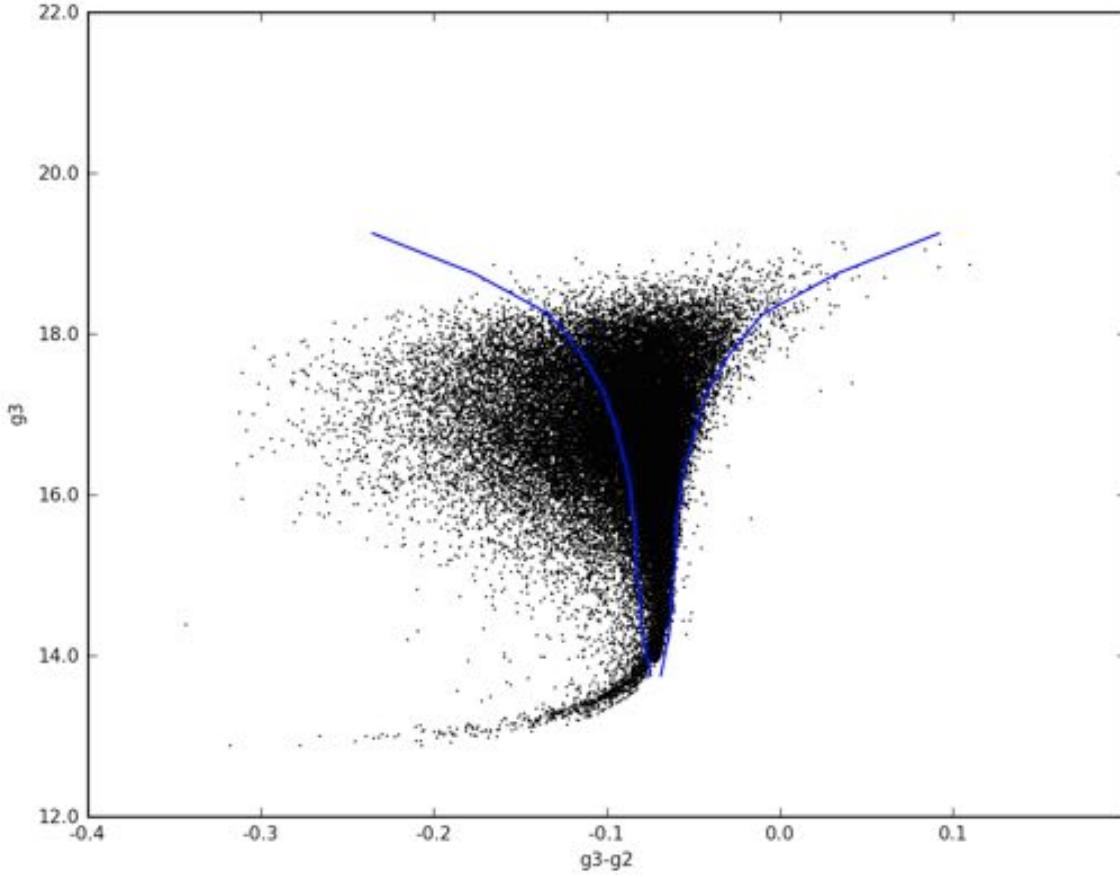


Figure 2.7 An example of the cut used to eliminate extended objects from the photometry by evaluating the difference between two aperture cuts, g_2 (larger) and g_3 (smaller). The areas outside the two blue lines were rejected.

non-stellar objects, and bright foreground stars.

The first selection made was to limit the field to the 2° diameter field-of-view of the AAO-mega/2dF instrument. Known non-stellar objects were then removed by matching the photometry catalogue to SIMBAD (Wenger et al. 2000), and foreground objects with very high proper motions ($> 500 \text{ mas yr}^{-1}$) were also removed by cross matching with the PPMXL catalogue (Roeser et al. 2010). Extended objects were removed by using two different aperture cuts in the g band, and restricting the difference between these cuts to reasonable values (see Figure 2.7). Finally, stars with photometry outside reasonable ranges were cut to eliminate very bright foreground objects, or objects that were too faint to observe reliably.

At this point, we made the selection based on the metallicity indicator. As mentioned in the previous section, the u band was not observed for most of our fields, so we made use of a diagnostic composed solely of v , g , and i . Several versions of the diagnostic were tested in halo observations, and the agreed upon final indicator is $\text{mod}(v - g) = (v - g) - 2(g - i)$. I have demonstrated how this works in Figure 2.8, which shows one of the fields we observed in 2012.

To make the selection, a box was created around the most metal-poor stars in the $g - i$ vs. $\text{mod}(v - g)$ plane. The $g - i$ cut acts to limit our selection to stars of the right temperatures;

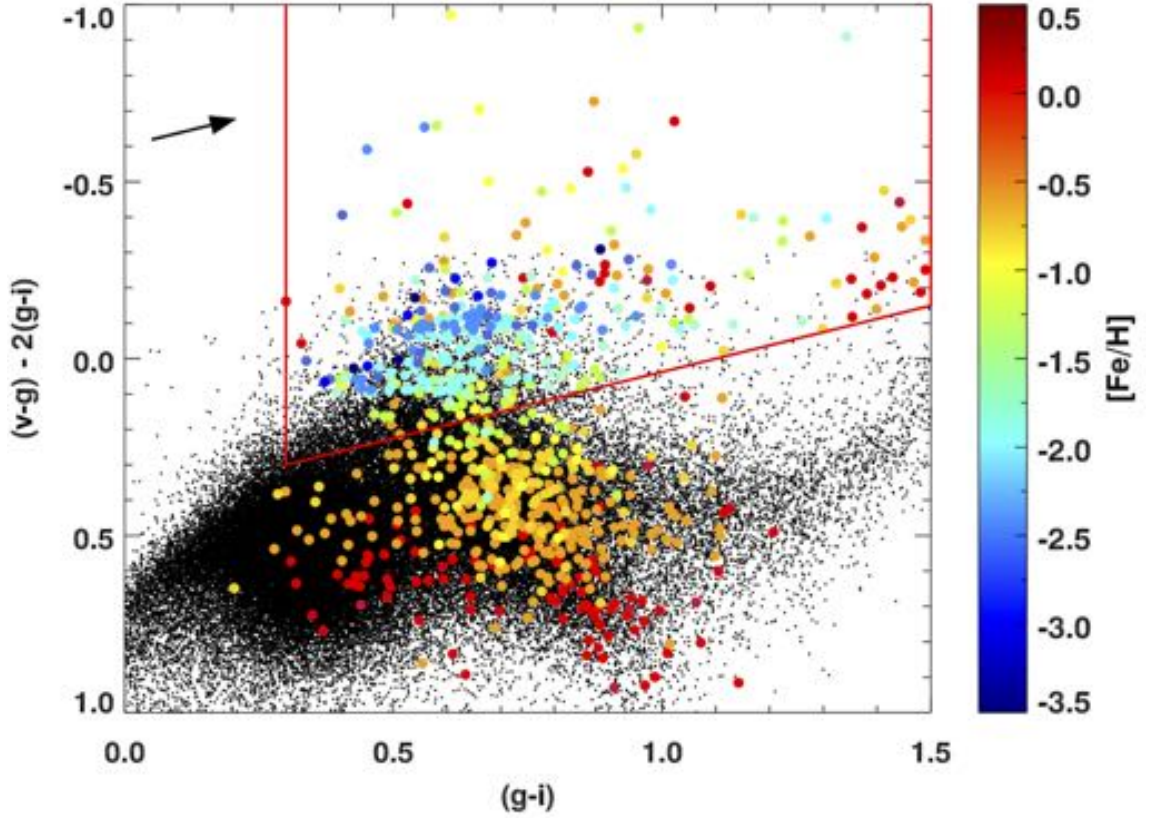


Figure 2.8 An example of the colour-colour plots used to make the selection of metal-poor candidates. Like Figure 2.3, data from one SkyMapper field is shown in black, with the spectroscopic data from the corresponding ARGOS field shown in colour. Additionally, the closest EMBLA field has also been over-plotted, with $[Fe/H]$ values from the intermediate-resolution AAOmega spectroscopy. The red outline shows the selection box used in this field, whilst the arrow indicates the reddening vector.

too low and the star would be hotter than giant stars, too high and the star would be too cool. In Figure 2.8, instead of a horizontal cut with respect to $\text{mod}(v - g)$, the cut has been altered to account for reddening effects - this is discussed further in the next section.

Once the selection box has been created, 200 stars are selected, starting at the top of the box and working down towards higher values of $\text{mod}(v - g)$. These stars are classed as Priority 1 targets, chosen as the targets most likely to be EMP stars. Priority 2 targets are selected as the next 500 stars in the box¹. The reason for discriminating between the two sets of targets is to provide two different samples when the stars are followed up with spectroscopy. Due to the design of the 2dF robot, hundreds of targets can be provided for a field, from which the software configures the plate to provide the right number of guide stars, sky fibres, and object fibres. The targets can be awarded priorities, such that the software will endeavour to select as many top priority targets as possible, before selecting targets with the next priority. We experimented with the numbers of targets assigned to Priority 1 and 2, and found that 200 was the largest number we could label Priority 1 and still get $\sim 95\%$ of those 200 observed. A larger number would have resulted in more of the most promising targets missing out on observation. The Priority 2 targets then represent a random selection

¹Some of the fields observed early during our first observing run in June 2012 had 700 Priority 2 stars.

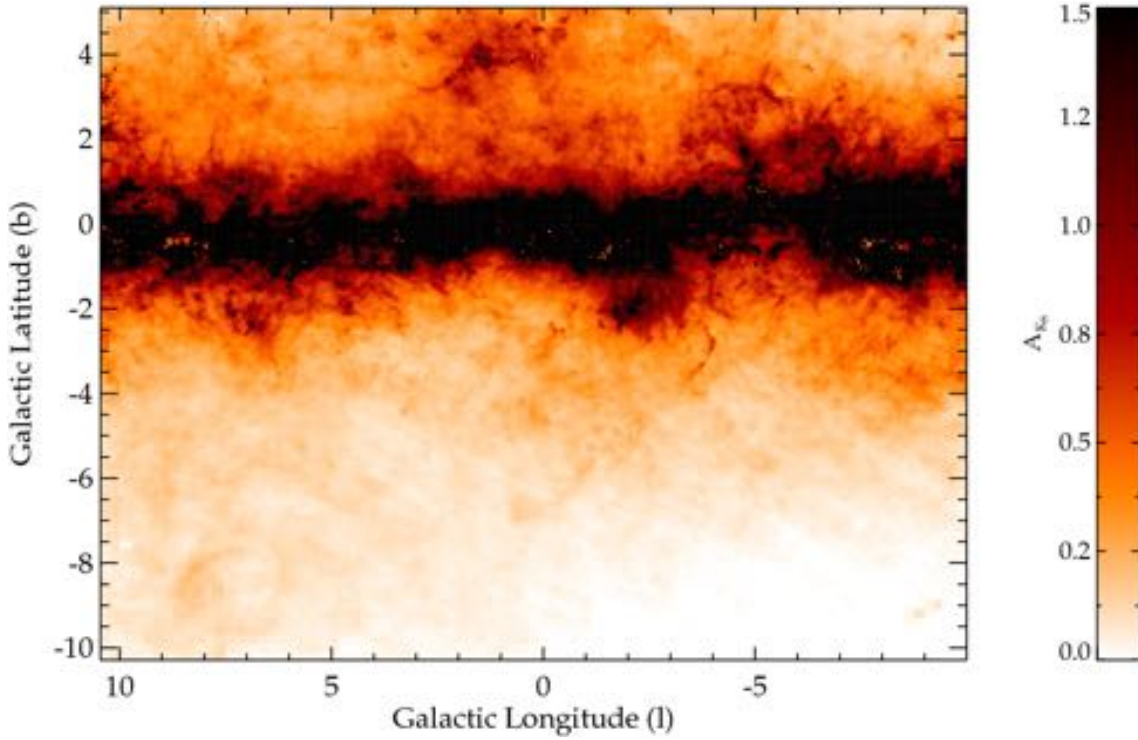


Figure 2.9 Figure 3 from Gonzalez et al. (2012), showing the extinction map of part of the Galactic bulge covered by the VVV survey (Minniti et al. 2010). This figure saturates at 1.5 mag of extinction, when in fact the extinction in the inner regions reaches 3.5 mag.

of the metal-poor population of the field, from which we hope to recreate the tail end of the bulge MDF, and tie in with the literature studies towards understanding the entire bulge population. The numbers of stars observed in each of the priority bins can be found in Tables 2.1, 2.2, and 2.3.

2.3.3. The Problem with Reddening

The process of selecting metal-poor stars using SkyMapper photometry was created in order to find stars in the Galactic halo. As described in the Introduction, the halo makes up the outer regions of the Galaxy, the least dense areas of stars and gas in the Milky Way. Therefore the lines-of-sight to the target stars are clear and free of dust extinction, and the effect of reddening is minimal. The bulge, however, is a different story. Figure 2.9 shows the high levels of extinction caused by gas clouds between us and the central regions of the Galaxy. When we turned the selection process to the bulge, we were unsure as to how extinction and reddening would affect the process.

Figure 2.9 also makes clear that the extinction across the bulge is very non-uniform. Ten degrees from the plane has very little reddening, whereas by four degrees from the plane, the extinction has reached 1 mag. This difference is also clearly observed in our photometry. Figure 2.10 shows the colour-colour plots for two fields, both observed in 2013. Field 1029 lies 9° from the plane, and so has very little sign of reddening - the figure looks very similar

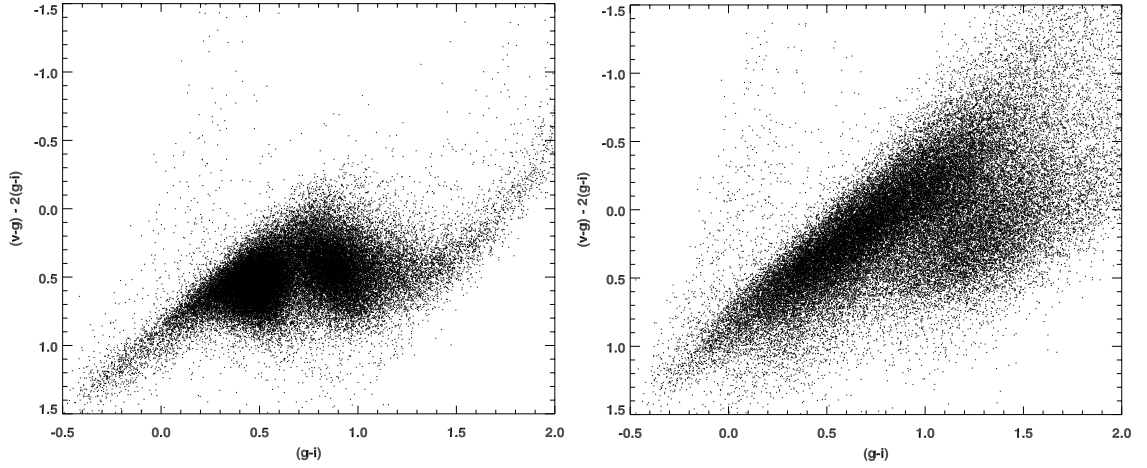


Figure 2.10 The colour-colour diagrams of two bulge fields, both observed in 2013. Left: Field 1029, with Galactic coordinates $(l,b)=(10.4, 9.0)$. Right: Field 1890, $(l,b)=(1.1, -3.1)$.

to what we would expect in a halo field, the only difference being the two central clumps (one for foreground dwarfs, one for bulge giants) instead of one. Field 1890, however, is only 3° from the plane, and here the typical shapes expected have been smeared beyond recognition. Looking at this figure, it is almost impossible to see where the selection box should be placed.

It became clear that in order to observe closer than about 8° from the plane, something would have to be done about the reddening in these fields. In 2012, we attempted to de-redden the photometry, using the OGLE reddening maps (Nataf et al. 2013), but instead this exacerbated the problem. The stars in our fields lie scattered throughout the disc and bulge of the Galaxy, somewhere between 1 kpc and 15 kpc from the Sun. Because of this, they all have varying line-of-sight reddening effects; some stars lie in front of the bulk of the gas and dust of the Galaxy, some behind, and many more in the middle of it. Reddening maps describe the reddening at infinity, and as such can not be used to effectively de-redden our fields.

In 2014, we again tried to de-redden the photometry by cross-matching our stars to both the 2MASS (Skrutskie et al. 2006) and OGLE (Szymański 2005) photometry catalogues. A version of the metallicity indicator, this time making use of the NIR bands of 2MASS (extinction is much less of a problem in the NIR), was created. However, in the time available, no indicator could be created which was "reddening-free" - when tested, all attempts failed.

Sadly this restricted the area we could cover in the EMBLA survey. As is clear in Figure 2.5, the majority of our fields followed up with spectroscopy lie more than 4° from the plane. In order to counter the effects of reddening between 4° and 10° , we adjusted the metallicity selection cut to lie in the same direction as the reddening vector (shown by the arrow in Figure 2.8). This adjustment worked fairly well - as discussed in Section 2.5.1, we still found significant numbers of metal-poor stars in the fields closer to the plane. However, the workaround was not perfect, and when tested at $(l,b)=(1.7, 0.7)$ (Field 1752),

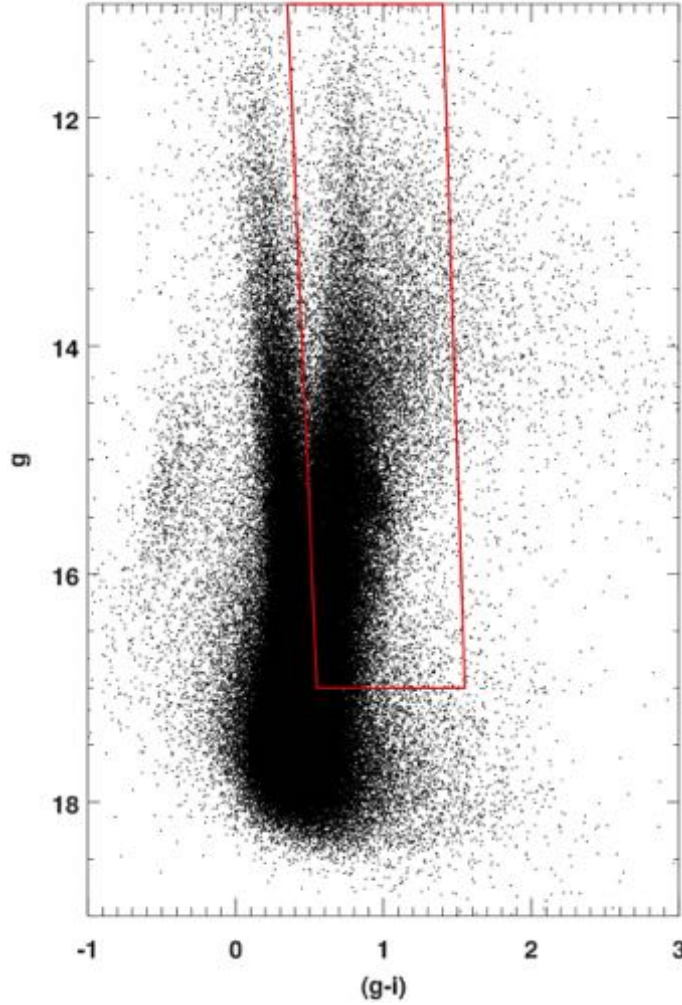


Figure 2.11 The $g, g - i$ colour magnitude diagram from an example field. The red box shows the selection that was made on this field to limit our sample to stars on the giant branch, and hence in the bulge region rather than the foreground.

the numbers of metal-poor stars picked up was significantly reduced, and the field was heavily contaminated by hot, A-type stars. For this reason, we chose to remain more than 4° from the plane.

2.3.4. Improving the Selection in 2013

After our first year of observations, the results were very promising. We were, however, concerned about the number of foreground metal-poor disc stars we may be picking up, so we introduced an extra step into our selection process. Before creating the colour-colour plot from which metal-poor candidates were selected, we plotted the $g, g - i$ CMD, an example of which is shown in Figure 2.11.

The figure shows two "prongs", the left, bluer prong and the right, redder prong. We could then restrict our selection to the red prong - essentially choosing stars that are bulge giants, rather than foreground dwarfs which make up the blue prong. The figure also shows a g

cut of about 17 - in practise this was not needed, as the availability of v photometry would limit how deep we could realistically reach in g anyway.

This new selection produced a lower contamination rate, as discussed in Section 2.5.2. The selection also meant that in the colour-colour diagram, we had a much narrower range to choose from. In Figure 2.8, it is clear that the selection box went too far into the red, a much better cut would have been $0.3 < (g - i) < 1.0$. By imposing the CMD cut first, we essentially make this cut before we reach the colour-colour plot, eliminating the far-red contaminants.

2.4. Intermediate-Resolution Spectroscopy with AAOmega

2.4.1. Three Years of Observations

The EMBLA Survey was awarded a total of 24.5 nights on the 3.9 m Anglo-Australian Telescope, with the AAOmega spectrograph (Saunders et al. 2004) coupled to the 2dF fibre positioner (Lewis et al. 2002; Sharp et al. 2006), enabling the observation of up to 392 stars (+8 guide stars) per field. These nights were spread over three (southern hemisphere) winters, from 2012 to 2014.

After selecting the stars from photometry, the 700 candidates in each field were fed into the Configure software², which uses a simulated annealing algorithm to assign candidates to available fibres. This was done at the telescope on the afternoon prior to observing, in order to have the most up-to-date information on the fibres available. The software allows you to set the number of sky fibres required for data reduction; for the survey we chose the standard number of 25. We selected guide stars by choosing stars from the SkyMapper photometry that were brighter than 12.5 mag in the g band, although often there were not enough to cover all eight guide fibres, so this was extended to 13.5 mag. Once the software assigned all 400 fibres, this information was fed to the 2dF fibre positioner system and one of the two available plates was configured to our specifications.

Following the success of the ARGOS survey in observing bulge giants with AAOmega/2dF (Ness et al. 2013a), we used a similar setup at the telescope (Freeman et al. 2013). The 1700D grating choice for the red arm gave us coverage of the Ca II triplet region (840 – 880 nm) with a resolving power of approximately 10,000. For the blue arm, we chose the 580V grating, which covers 370 – 580 nm with a resolving power of 1,300. The blaze wavelengths were set throughout at 500 and 860 nm, and the central wavelength for the red arm was also fixed at 860 nm throughout. We used a central wavelength of 480 nm for the blue arm in 2012, for optimal wavelength coverage, however in 2013 we altered this to 521 nm. When the central wavelength was set to 480 nm, many of the stars' H- β lines fell on bad pixels on the blue CCD, so by moving the central wavelength, we could ensure that this important

²<http://www.aao.gov.au/science/software/configure>

spectral feature was observed in all stars. Moving the central wavelength resulted in a shorter wavelength region observed; 414 – 580 nm, as we shifted the wavelength range, but the dichroic crossover is at 570 nm, limiting the red end of the spectrum. In 2014, we reverted to the original central wavelength, as the blue CCD had been replaced and there were no longer any bad pixels lying on important parts of the spectrum.

We took calibration fields throughout the night with which we could then reduce the data. These consisted of 20 bias frames (at the start of the evening), a 6 s flat frame using the quartz lamp, and two 30 s wavelength calibration frames (taken before each new configuration). One of the two wavelength calibration frames was taken with all lamps turned on (FeAr, CuAr, He, Ne, and ThAr), and one with all lamps except for ThAr. The ThAr lamp creates many weak lines in the spectra, and is useful for calibrating the higher resolution red arm data, but impedes the reduction of lower resolution data using the blue arm.

Freeman et al. (2013) found that in order to observe red clump stars at a distance of 8.5 kpc (roughly the distance to the centre of the Galaxy), 120 min of exposure time was needed. The stars we hoped to observe were similar in luminosity to red clump stars, so we also observed our fields for 120 mins, in 4x30 min exposures.

Our observing time was scheduled in June or July to maximise the hours spent observing the bulge; with perfect weather we would have observed four fields a night. Originally intending to spend two years on the survey, with the time we were allocated this would have led to 70 fields of data. Unfortunately, due to frequent bad weather at Siding Spring Observatory, we observed for only three nights in 2012, and a further three in 2013. This encouraged us to apply for a third and final year of observations, and in 2014 we were able to obtain an extra 3.5 nights of observations. Tables 2.1, 2.2, and 2.3 list in full all the fields we have observed for the survey. Comparing the tables reveals that, on average, each field contained ~ 42 more stars in 2013/4 than in 2012. This is because the fibres were replaced on the instrument, including a large number of broken fibres, between our observing runs in 2012 and 2013.

Figure 2.5 shows the coverage completed each year. Patchy coverage of the available SkyMapper fields in the northern half of the bulge meant that we decided to attempt full coverage of the southern outer bulge (between $b = -4^\circ$ and -10°), before moving on to any available northern fields. Choosing to focus on the southern bulge also aligned our observations with the planned observations of the Gaia-ESO survey (Gilmore et al. 2012; Randich et al. 2013), which we collaborated with in order to follow up any interesting metal-poor stars found in high-resolution with the VLT (see section 2.6.1 for details).

Table 2.1 SkyMapper fields observed in 2012 on the AAT. Given are the coordinates of each field in both equatorial and Galactic format. Star count gives the number of stars observed in the SkyMapper field in at least the g band. Priority 1 and 2 list the numbers of stars observed at the AAT out of the total selected for that priority. The date and no. of stars observed refers to the date the field was observed and how many stars in each field were observed at the AAT. The star count for field 2025 is not known as the original photometry has been lost.

Field	RA (2000)	Dec (2000)	l ($^{\circ}$)	b ($^{\circ}$)	Star count	Priority 1	Priority 2	Date observed	No. of stars observed
1178	265.039	-17.730	8.9	6.9	75,950	185/200	133/500	9-Jul	318
1616	276.316	-24.774	8.0	-5.7	229,000	180/200	138/500	21-Jul	318
1617	278.769	-24.689	9.0	-7.6	69,601	114/200	209/700	14-Jul	323
1755	274.569	-27.139	5.1	-5.4	116,454	174/200	130/700	16-Jul	304
1757	279.690	-27.200	7.1	-9.5	405,672	179/200	140/700	16-Jul	319
1894	280.544	-29.389	5.5	-11.1	750,148	181/200	133/500	20-Jul	314
2025	273.350	-31.691	0.6	-6.6	?	187/200	127/500	16-Jul	314
2154	268.666	-34.190	356.5	-4.3	258,169	194/200	120/700	16-Jul	314
2156	274.126	-34.170	358.7	-8.3	140,851	199/200	125/500	18-Jul	324
2281	268.521	-36.611	354.3	-5.5	313,012	191/200	132/500	9-Jul	323
2283	274.237	-36.480	356.6	-9.4	88,674	191/200	128/500	19-Jul	319
2404	268.512	-38.928	352.3	-6.6	280,524	196/200	122/500	15-Jul	318
2406	274.370	-38.874	354.5	-10.6	218,653	191/200	127/500	15-Jul	318
2523	268.456	-41.273	350.2	-7.7	198,663	181/200	137/500	9-Jul	318

Table 2.2 SkyMapper fields observed in 2013 on the AAT. Columns as in Table 2.1.

Field	RA (2000)	Dec (2000)	l (°)	b (°)	Star count	Priority 1	Priority 2	Date observed	No. of stars observed
1029	264.032	-15.390	10.4	9.0	310,927	187/200	177/500	5-Jul	364
1747	253.915	-27.171	355.2	10.1	343,606	110/200	252/500	3-Jun	362
1747-2	253.915	-27.171	355.2	10.1	343,606	108/200	245/500	2-Jul	353
1748	256.417	-27.223	356.5	8.3	237,149	192/200	172/500	3-Jul	364
1752	266.750	-27.184	1.7	0.7	164,178	192/200	171/500	3-Jun	363
1756	277.112	-27.145	6.2	-7.4	51,798	196/200	168/500	2-Jul	364
1757	279.690	-27.200	7.1	-9.5	405,672	183/200	178/500	16-Jun	361
1884	254.085	-29.321	353.6	8.6	269,406	190/200	180/500	3-Jul	370
1890	270.056	-29.588	1.1	-3.1	297,413	197/200	166/500	3-Jun	363
2026	276.065	-31.804	1.5	-8.7	143,113	198/200	166/500	8-Jul	364
2155	271.418	-34.344	357.5	-6.4	105,907	194/200	168/500	8-Jul	362
2157	276.203	-34.073	359.5	-9.8	754,852	128/200	234/500	3-Jun	362
2405	271.465	-38.930	353.4	-8.6	186,523	194/200	168/500	5-Jul	362

Table 2.3 SkyMapper fields observed in 2014 on the AAT. Columns as in Table 2.1 with the addition of the "New data?" column. This indicates whether the SkyMapper photometry used for each field came from the newer observations taken in 2013.

Field	RA (2000)	Dec (2000)	l (°)	b (°)	Star count	New data?	Priority 1	Priority 2	Date observed	No. of stars observed
1324	263.917	-20.033	6.4	6.6	460,458	y	195/200	163/500	25-Jun	358
1467	260.011	-22.693	2.1	8.2	318,369	y	192/200	134/500	25-Jun	326
1468	262.683	-22.341	3.8	6.3	295,625	y	195/200	163/500	26-Jun	358
1469	265.012	-22.288	5.0	4.6	639,949	y	195/200	163/500	26-Jun	358
1609	258.558	-24.899	359.5	8.1	114,821	y	191/200	167/500	26-Jun	358
1615-1	273.967	-24.809	6.9	-3.8	574,980	y	199/200	159/500	23-Jun	358
1615-2	273.967	-24.809	6.9	-3.8	574,980	y	183/200	167/500	23-Jun	350
1749	259.027	-27.284	357.8	6.3	675,839	y	192/200	166/500	25-Jun	358
1750	261.338	-27.163	359.1	4.7	607,891	y	193/200	165/500	26-Jun	358
1885	256.765	-29.510	354.8	6.7	986,757		194/200	164/500	25-Jun	358
1892	275.294	-29.505	3.3	-7.0	513,928	y	195/200	163/500	23-Jun	358
1893	277.941	-29.505	4.4	-9.1	891,529	y	200/200	158/500	25-Jun	358
2149	254.837	-34.062	350.2	5.2	535,663	y	193/200	165/500	24-Jun	358
2280	265.986	-36.532	353.3	-3.7	512,096	y	197/200	164/500	26-Jul	361
2282	271.458	-36.644	355.4	-7.5	132,534		192/200	169/500	26-Jul	361

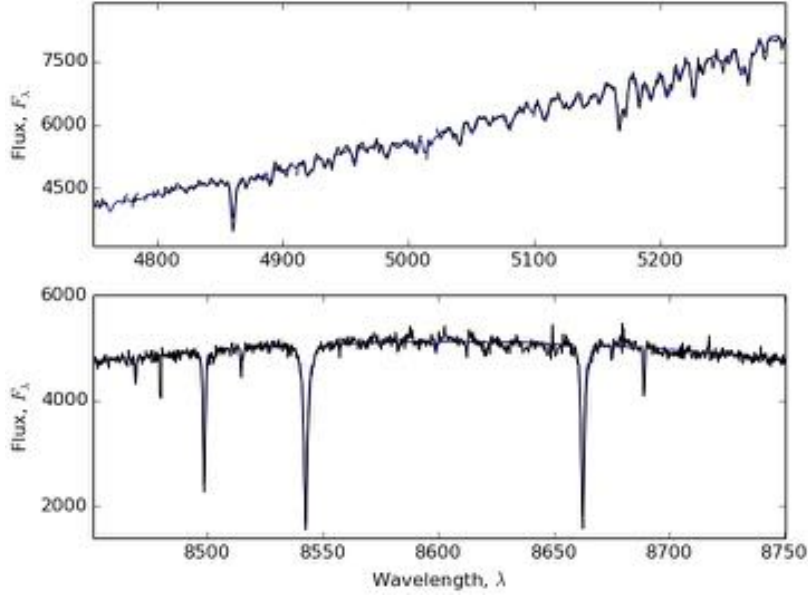


Figure 2.12 An example of the spectra obtained using AAOmega/2dF (in black), along with the model spectra generated using `sick` (blue). Top: Part of the blue arm, used for the analysis. Bottom: The whole of the red arm of the spectrum.

2.4.2. Processing the Survey Data

Data Reduction

All data taken at the AAT were reduced using the `2dfdr` software package³. The software automatically performs all the data reduction steps without requiring any manual input. We set up `2dfdr` to create a master bias frame, subtract this from the blue arm data (a bias subtraction is not needed for the red arm), reduce the flat field and arc frames, re-reduce the flat field with the arc wavelength solution, and finally reduce and combine the science frames, subtracting the sky contribution using the sky fibres. The end product is two multi-fits files, a blue and a red, with the spectra of all 400 fibres. An example of an output spectrum for both arms can be seen in Figure 2.12.

Analysis with `sick`

In order to find the most metal-poor stars in each field, we analysed the spectra using a Python code called `sick` (the spectroscopic inference crank; Casey 2014). The code was written alongside the EMBLA survey, and our data was used in the testing process. `sick` combined the normalisation of the spectra along with determining the important parameters of the stars - v_{rad} , T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$.

The first incarnation of `sick` in 2012 - which was called SCOPE - was a very different code from the final analysis code. SCOPE first normalised the spectra using the `IRAF` routine

³<http://www.aao.gov.au/science/instruments/AAOmega/reduction>

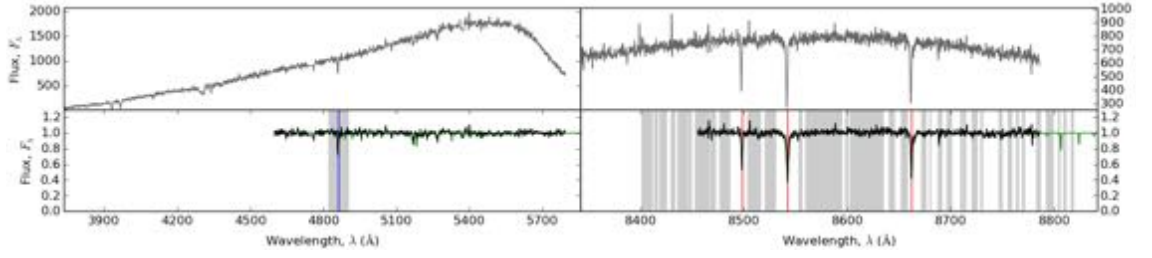


Figure 2.13 Screenshot from the original version of *sick*, used to analyse the 2012 data and choose targets for follow-up in 2012/13.

FXCOR (Tody 1993, 1986), then matched small sections of the spectra to a set of interpolated model data, using a χ^2 minimisation. The small sections used were different for each parameter. Figure 2.13 shows a screenshot from SCOPE, with example spectra. The grey regions on the normalised spectra are the regions used in the minimisation; in the blue arm the only feature used was the H- β line, whereas many features were used in the red arm. This led to problems with those spectra missing the H- β line due to the bad pixels on the CCD. However, as the problem only affected around a dozen spectra per field, and we were only using the output of SCOPE in order to choose targets to follow-up with high-resolution studies, it was possible to visually inspect the candidate spectra and rule out those with missing H- β lines.

After the observations in 2013, SCOPE was rewritten, and renamed *sick*. *sick* has developed since then, however its main premise remains the same; it infers both the stellar parameters and other parameters affecting the spectrum (for example the continuum placement, instrumental broadening, and data outliers) simultaneously. It does this by interpolating between grids of model spectra and matching to the observed spectra using a three step method. For our analysis, we used the grid of AMBRE model stellar spectra (de Laverny et al. 2012). First, *sick* samples the multi-parameter space with a scattered approach, to uniformly sample across all possible solutions. The best solution is then taken as an initial guess from which a numerical optimisation is then employed. Finally a Monte Carlo Markov Chain (MCMC) algorithm is used to converge on the final solution for all of the parameters. We used 1000 samples in the scattered phase, plus 200 steps to converge in the MCMC phase. *sick* produces several plots for each star which we used to verify the parameters derived, the most important being the observed spectrum with the interpolated model (such as that shown in Figure 2.12), and the corner plot of the convergence of the parameters. An example of this, showing only four of the parameters, is shown in Figure 2.14.

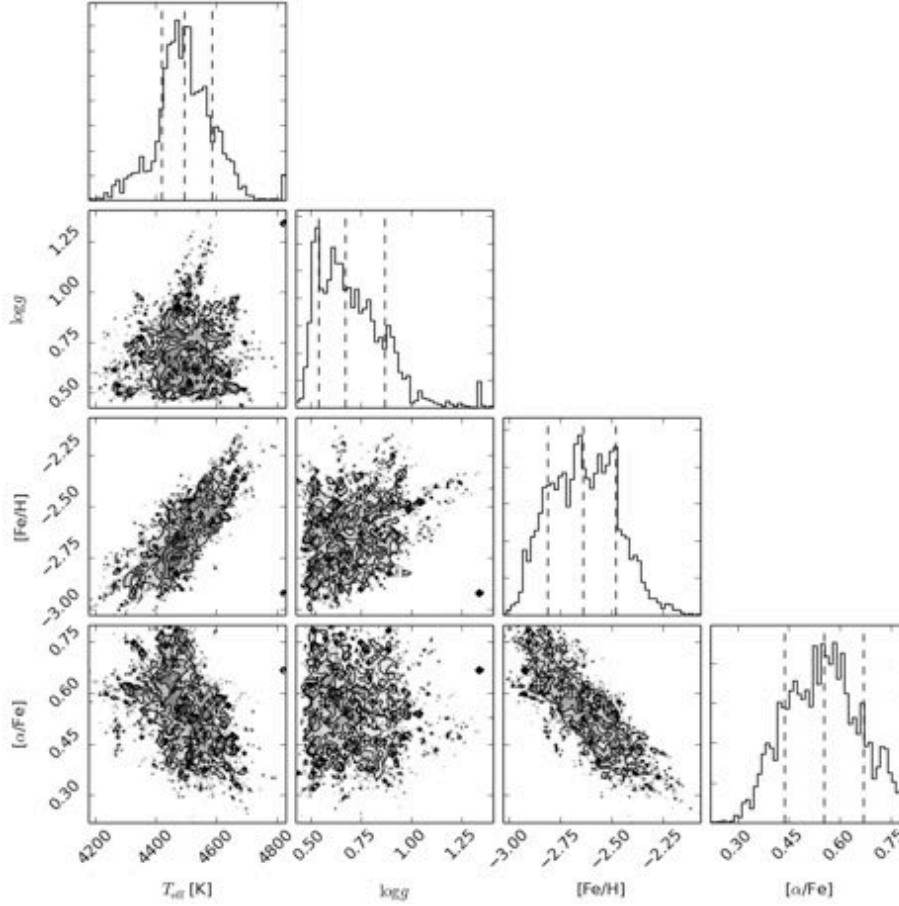


Figure 2.14 An example of a corner plot output by *sick*, showing the convergence of the code to four of the modelled parameters, T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$.

2.5. Initial Results

The fields observed in 2012 and 2013 were analysed by *sick* in the months following the observations. As yet, fields observed in 2014 have not been analysed, so here I will discuss the preliminary results discovered from the 2012/13 data. 9,158 stars were observed over the two years, the results of which are summarised in Table 2.4.

2.5.1. The Metallicity Distribution Function

Figure 2.15 shows the MDF for the EMBLA survey data of 2012/13. This MDF contains all stars that have a converged solution from *sick*, a total of 8,563, or 93% of the stars. The MDF cuts off at $[\text{Fe}/\text{H}] < -3.0$ due to the unreliability of *sick* to accurately predict metallicities below this. 318 stars were given $[\text{Fe}/\text{H}]$ values of less than -3.0 , all of which have been visually inspected, and the majority of which are false positives. These false positives were caused by a number of things, the most common reasons being the spectra having too low S/N, the star was too hot ($T_{\text{eff}} > 8,000$ K), or the star was a double-lined spectroscopic binary. Future versions of *sick* are aiming to reduce the number of false

Table 2.4 The results from the fields observed in 2012/13.

Year	Field	Number observed	Number analysed [*]	Percentage [Fe/H]< -1	Percentage [Fe/H]< -2	Followed up [†]
2013	1029	364	351	50.8	3.3	1
2012	1178	318	295	29.2	4.1	0
2012	1616	318	293	30.8	6.3	0
2012	1617	323	306	33.4	10.5	0
2013	1747 (1&2)	715	687	75.4	19.7	0
2013	1748	364	349	62.1	12.6	1
2013	1752	363	307	16.5	8.0	0
2012	1755	304	233	24.3	4.6	1
2013	1756	364	357	48.9	7.4	0
2012	1757	319	299	58.3	18.2	5
2013	1757	361	346	53.2	5.0	0
2013	1884	370	357	59.5	5.4	0
2013	1890	363	340	33.1	4.4	0
2012	1894	314	291	68.5	33.1	3
2012	2025	314	293	58.6	12.1	2
2013	2026	364	347	49.5	4.9	0
2012	2154	314	311	30.3	5.7	0
2013	2155	362	342	40.9	5.2	1
2012	2156	324	287	74.1	30.9	6
2013	2157	362	348	47.2	8.0	0
2012	2281	323	293	43.7	9.9	1
2012	2283	319	307	40.8	6.0	0
2012	2404	318	308	53.8	14.2	3
2013	2405	362	347	61.6	2.8	0
2012	2406	318	271	67.9	27.4	3
2012	2523	318	298	57.2	13.8	7

^{*} Number of stars for which the analysis converged on a solution.

[†] Number of stars that were followed up in high-resolution.

positives at low metallicity; in the meantime for the general MDF we can consider only those stars with $[\text{Fe}/\text{H}] > -3.0$.

Despite this, it is clear that EMBLA has succeeded in observing a significantly more metal-poor population than the average bulge sample. The peak of our MDF is $[\text{Fe}/\text{H}] = \sim -1.0$,

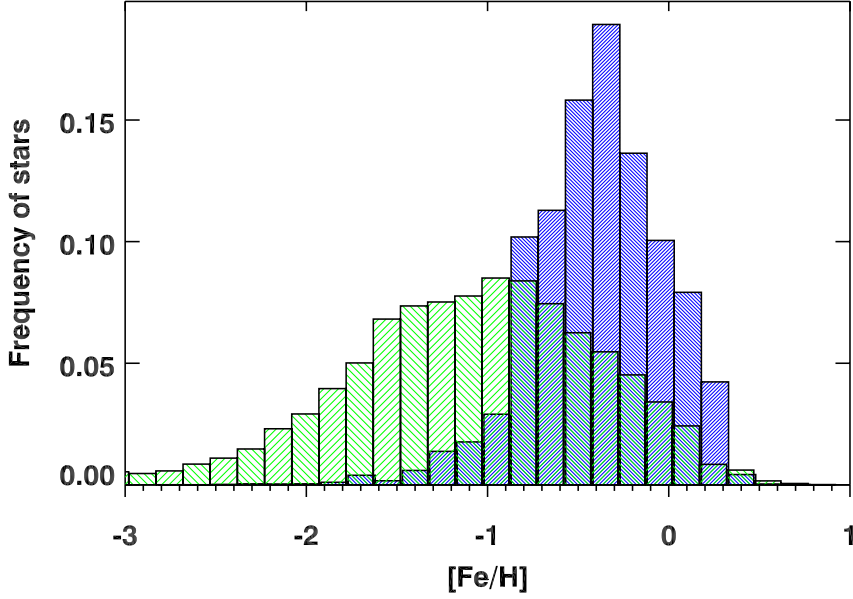


Figure 2.15 The MDF of all the stars observed in 2012/13 with converged solutions from *sick* (green), compared to the total MDF of bulge stars from the unbiased ARGOS survey (Ness et al. 2013a) (blue).

which is significantly lower than the peak in the ARGOS survey (representative of an unbiased sample of bulge stars) at $[\text{Fe}/\text{H}] = -0.3$ (Ness et al. 2013a). In total, 49% of the EMBLA stars have $[\text{Fe}/\text{H}] < -1.0$, compared to only 5% in the ARGOS survey. This is a remarkable improvement, and reveals the power of the SkyMapper selection technique, even in the highly reddened bulge region.

Furthermore, the MDF extends down beyond $[\text{Fe}/\text{H}] < -2.0$, with 11% (a total of 999 stars) having metallicities below this. Even allowing for a percentage of false positives, this is still a huge number. The ARGOS survey found 16 stars with $[\text{Fe}/\text{H}] < -2.0$. Before the EMBLA survey took place, only two stars had been observed in high-resolution in the bulge with such low metallicities (García Pérez et al. 2013), we have increased the number available for detailed chemical analysis 500-fold.

Breaking down these results by individual fields reveals some interesting trends. The numbers of low metallicity stars found in each field varies enormously, for example field 1752 had only 16% with $[\text{Fe}/\text{H}] < -1.0$, whereas field 1747 had 75%. Figure 2.16 shows the percentage of stars with converged solutions, with $[\text{Fe}/\text{H}] < -1.0$, and with < -2.0 , for each field as a function of distance from the Galactic plane. This figure reveals a strong correspondence with the fields' distance from the plane. There is a slight positive increase in the percentage of spectra successfully analysed with increasing distance. This is intuitive; the closer a field is to the plane, the more dust will obscure the view, meaning the bulge giants will be fainter and our spectra will have lower S/N. The more noticeable trend is in the number of low metallicity stars, however. This striking difference could be caused by two effects. Firstly, there is a known negative metallicity gradient in the bulge (Gonzalez et al. 2013; Ness et al. 2013a; Rojas-Arriagada et al. 2014), where the outer regions of the bulge are more metal-poor than the centre. Perhaps our stars, despite being very different

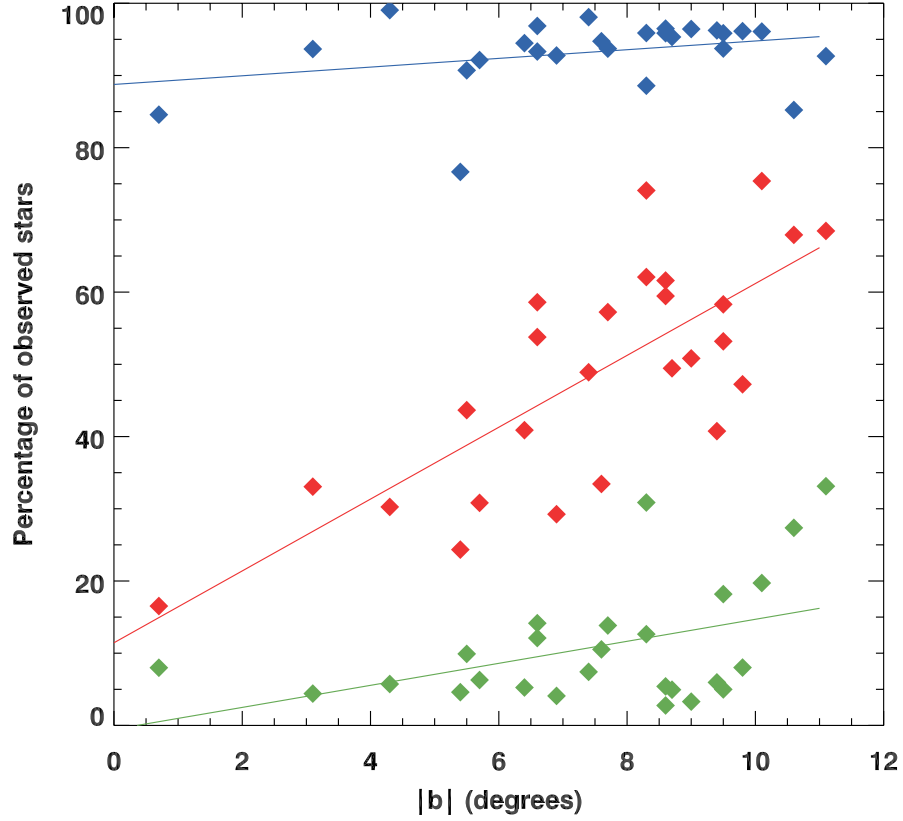


Figure 2.16 The percentage of stars in each field that a) had a convergent solution in `sick` (blue points), b) had $[\text{Fe}/\text{H}] < -1.0$ (red points), and c) had $[\text{Fe}/\text{H}] < -2.0$ (green points). The corresponding lines are linear fits to the data points to show the overall trend of the points.

from the average metallicity of bulge stars, also follow this trend. Secondly, we are likely seeing the effect of reddening on our selection. As shown in Section 2.3.3, the photometry is badly affected by extinction and reddening, and we were unable to completely solve this problem, instead employing an empirical correction to counter the reddening as best we could. Figure 2.16 could well be confirming that this empirical correction was not fully successful in removing contamination from the selection box. It is encouraging that, despite this, the number of stars with $[\text{Fe}/\text{H}] < -2$ remains above 5% even in the fields closest to the plane. We are searching for the metal-poor stars that are closest to the centre, as these are predicted to be the oldest.

2.5.2. Levels of Contamination from Foreground Dwarfs

The aim of the survey was to observe only metal-poor bulge giants, and not the foreground dwarf stars of the disc. As discussed in Section 2.3.4, in our first year of observations, we did not use a cut on the CMD to do this, we instead relied solely on the $g - i$ restraints on our metallicity selection box. In the following two years, we imposed a cut on the CMD to select stars red enough to be bulge giants (Fig. 2.11).

Currently the stellar parameters from the AAOmega intermediate-resolution spectroscopy

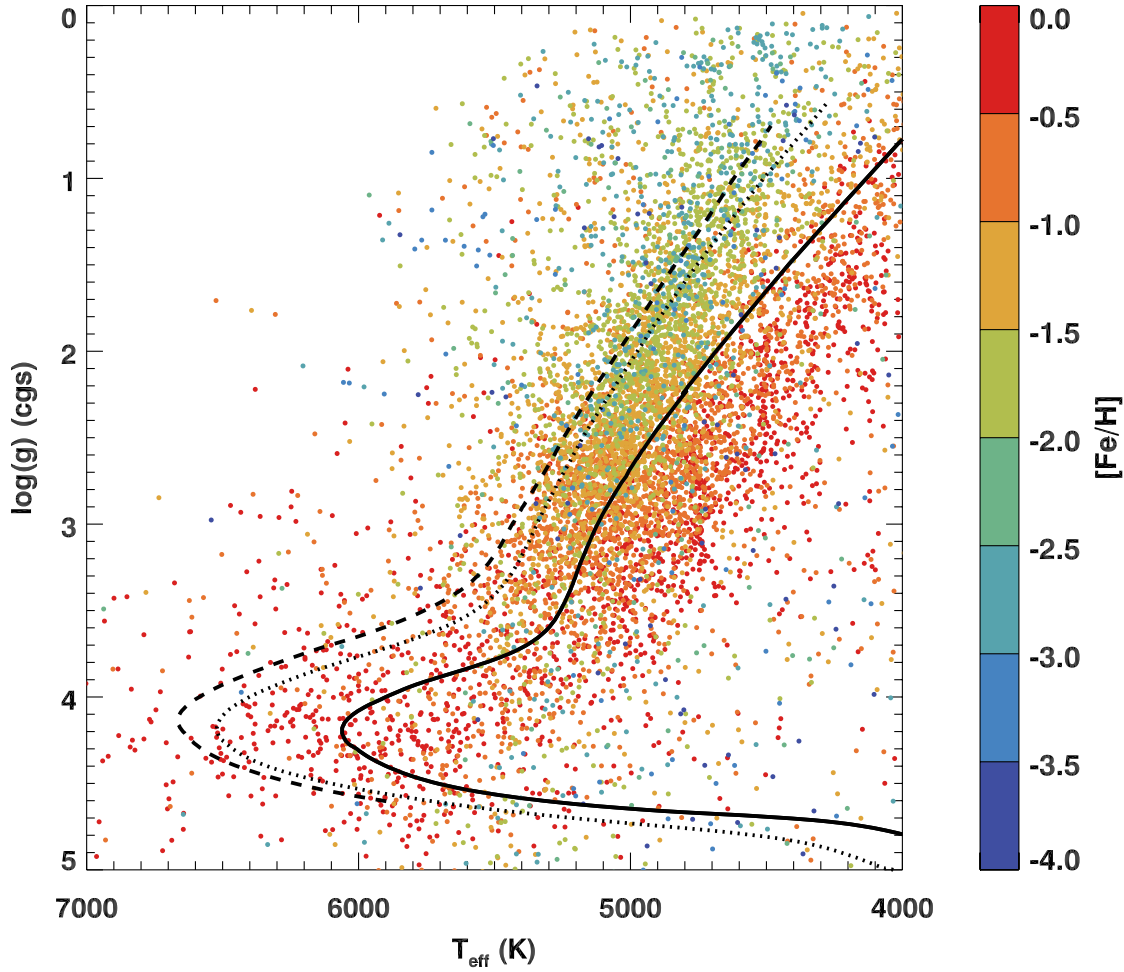


Figure 2.17 The HR diagram for all stars successfully analysed by *sick*. On top of this are three Dartmouth isochrones (Dotter et al. 2008) to demonstrate where we roughly expect the stars to lie. All three isochrones are 14 Gyr in age, have $[\alpha/\text{Fe}] = 0.2$, and have $[\text{Fe}/\text{H}] = -1$ (continuous line), -2 (dotted line), and -3 (dashed line).

are too uncertain to derive accurate distances for the stars, so we cannot use distance as our criteria for assessing the levels of contamination in the fields. Future versions of *sick* will aim to reduce these uncertainties. In the meantime, it is worthwhile examining the distribution of stars on the Hertzsprung-Russell (HR) diagram (Fig. 2.17).

The resulting HR diagram reveals that indeed the majority of our stars lie on the RGB, and we have succeeded in mostly targeting giant stars. There are a number of turn-off and main-sequence stars, although the numbers are not much higher than the background noise of stars with poorly-constrained parameters. In total, 5,938 of the stars have $\log g < 3.0$ (an approximate indicator of a star being a giant), which is 69% of stars with parameters. With the improvements to *sick*, we would hope to reduce the number of stars analysed as having poorly-constrained parameters, so 69% could be considered a lower bound to the percentage of giants. Looking at the distribution of $[\text{Fe}/\text{H}]$ across the diagram, the giant stars show the typical metallicity spread with effective temperature, which provides further confirmation that our stellar parameters are correct. The dwarf contaminants are nearly all metal-rich.

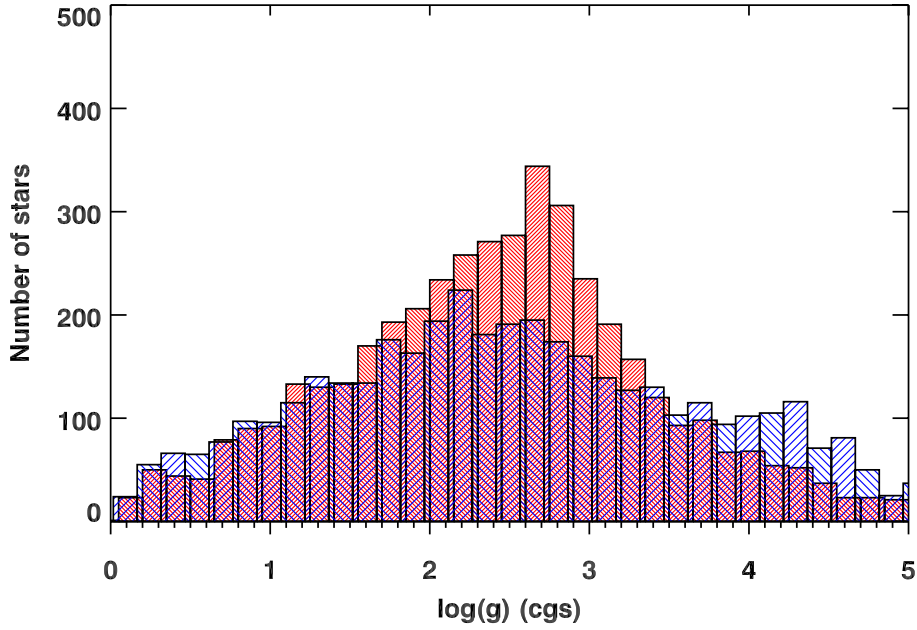


Figure 2.18 Histograms of the distribution of $\log g$ values throughout the survey. The blue histogram shows the distribution of stars observed in 2012, the red in 2013.

We have also examined how effective the 2013 CMD cut was in reducing the number of contaminants. Figure 2.18 shows the distribution of $\log g$ values, separated into the year they were observed. The blue histogram, showing stars observed without a CMD cut, is fairly uniform, but peaks at around $\log g = 2.0$, whereas the red histogram has a much more normal distribution. The peak in the red is higher, around $\log g = 2.7$, but it has fewer stars with $\log g > 3.5$, showing the cut was successful in reducing the number of dwarfs observed. In terms of percentages, 66% of stars analysed from 2012, whilst 73% from 2013, have $\log g < 3.0$. The 7% increase in the number of giants is not a huge change, confirming that the 2012 selection already did a pretty good job at limiting contamination.

For such a small improvement, was the CMD cut worth it? Looking at the $[\text{Fe}/\text{H}]$ values observed in 2012 and 2013 separately, we can see that there was very little difference in the metallicity spread. Of the stars observed in 2012, 48% had $[\text{Fe}/\text{H}] < -1$, compared to 50% in 2013; overall we slightly improved our numbers of metal-poor stars. There does appear to be a downside, however, in that in 2012, 14% of stars had $[\text{Fe}/\text{H}] < -2$, whereas only 7% did in 2013. The Galactic latitudes of the fields observed in 2012 and 2013 were similar, although in 2013 we observed two fields very close to the plane, so this may have had an impact on the number of metal-poor stars we observed. The expected reason, however, is that by making a cut between the dwarfs and giants on the CMD, it is possible that the bluest giants would have been selected out, and these are likely to be the most metal-poor. To attempt to rectify this problem, in 2014 we were more generous with our $g - i$ cut. When the data from 2014 is analysed, we anticipate that there will be a slightly higher contamination rate than the 2013 observations, but hopefully the numbers of stars with $[\text{Fe}/\text{H}] < -2$ will be similar to that found in 2012.

2.6. Stars Chosen for High-Resolution Follow-up

Once we had derived stellar parameters for the stars observed in intermediate resolution in 2012, we visually inspected all those with $[\text{Fe}/\text{H}] < -2.8$, in order to find candidates for the most metal-poor stars. Through collaborating with the Gaia-ESO Survey, and applying for our own time on 8 m-class telescopes, we were able to follow-up these most interesting objects with high-resolution spectra. These stars merited obtaining further spectra, in order to observe many weaker lines only visible at the highest resolutions and with good S/N. These weaker lines can be measured for many different elements, revealing a variety of different nucleosynthetic pathways that went into creating these stars' outer atmospheres. By making a detailed chemical analysis of the most metal-poor stars, we can begin to understand the gas that went into forming them, and consequently how the very first stars of the Galaxy ended their lives.

The next three chapters of the thesis reveal the discoveries made from these high-resolution spectra, published or submitted for publication in leading astronomy journals. Before this, I will quickly describe the high-resolution observations that have taken place.

2.6.1. The Gaia-ESO Survey

The Gaia-ESO survey (GES) (Gilmore et al. 2012; Randich et al. 2013) is a large public spectroscopic survey run by the European Southern Observatory (ESO), designed to observe 100,000 stars across the Milky Way over five years. Using the FLAMES multi-object spectrograph (Pasquini et al. 2002) on the VLT, 128 stars are observed per field in intermediate-resolution, and 8 stars are observed in high-resolution, using a fibre feed to the UVES spectrograph (Dekker et al. 2000). The survey is targeting all areas of interest in the Galaxy: halo, thin and thick discs, bulge, and many open and globular clusters. Both the SkyMapper EMP halo search and the EMBLA Survey have joined GES, in order to provide metal-poor targets for observation on the UVES fibres. By assigning one or two fibres in the bulge fields to the EMBLA Survey, GES obtains the full metallicity range in their bulge sample, and we get high-resolution observations of targets we find interesting.

To date, approximately 15 stars have been observed by GES for EMBLA, most of which were observed in July and August of 2014. Six targets were observed in 2012, and the observations and subsequent analysis of these can be found in Chapter 3. The survey is ongoing, we expect that over the next two years, another 15 targets may be observed, providing us with a large sample of detailed chemical information of these stars.

2.6.2. Magellan Observations

Simultaneously, we have been observing stars with the MIKE spectrograph (Bernstein et al. 2003) on the Magellan Clay 6.5 m telescope. In 2012, ten stars were observed as part of various observing programs. Eight of these were not targets from the EMBLA intermediate-resolution data, but instead were taken directly from SkyMapper photometry, from early observing runs of the SkyMapper halo EMP search. They were observed in May 2012 by Prof. Anna Frebel, who then gave the data to us to analyse. A further two stars were observed as back-up targets during Prof. Alan Alves Brito's observing runs; these targets were both taken from EMBLA fields observed in 2012. The details of these stars are published in Chapter 4.

We were awarded three nights observing with MIKE/Magellan in June 2014, where we followed up our most exciting targets from 2012/13. Excellent weather meant that we were able to observe 23 stars, and these were first published in 2015 (Chapter 5).

2.6.3. Further Observations

We have since also observed more targets (from all three years of AAT data) in high-resolution, using both UVES/VLT and MIKE/Magellan. Time constraints surrounding my Ph.D. mean that these targets will not feature in this thesis, but will be published in future EMBLA Survey papers, along with the as yet unpublished GES targets.

CHAPTER 3

The Gaia-ESO Survey: the Most Metal-Poor Stars in the Galactic Bulge

This chapter has been previously published as ‘The Gaia-ESO Survey: the most metal-poor stars in the Galactic bulge’, Howes, L. M., Asplund, M., Casey, A. R., Keller, S. C., Yong, D., Gilmore, G., Lind, K., Worley, C. C., Bessell, M. S., Casagrande, L., Marino, A. F., Nataf, D. M., Owen, C. I., Da Costa, G. S., Schmidt, B. P., Tisserand, P., Randich, S., Feltzing, S., Vallenari, A., Allende Prieto, C., Bensby, T., Flaccomio, E., Korn, A. J., Pancino, E., Recio-Blanco, A., Smiljanic, R., Bergemann, M., Costado, M. T., Damiani, F., Heiter, U., Hill, V., Hourihane, A., Jofré, P., Lardo, C., de Laverny, P., Magrini, L., Maiorca, E., Masseron, T., Morbidelli, L., Sacco, G. G., Minniti, D., Zoccali, M., 2014, MNRAS, 445, 4241. The work is presented exactly as published.

Abstract

We present the first results of the EMBLA survey (Extremely Metal-poor BuLge stars with AAOmega), aimed at finding metal-poor stars in the Milky Way bulge, where the oldest stars should now preferentially reside. EMBLA utilises SkyMapper photometry to pre-select metal-poor candidates, which are subsequently confirmed using AAOmega spectroscopy. We describe the discovery and analysis of four bulge giants with $-2.72 \leq [\text{Fe}/\text{H}] \leq -2.48$, the lowest metallicity bulge stars studied with high-resolution spectroscopy to date. Using FLAMES/UVES spectra through the Gaia-ESO Survey we have derived abundances of twelve elements. Given the uncertainties, we find a chemical similarity between these bulge stars and halo stars of the same metallicity, although the abundance scatter may be larger, with some of the stars showing unusual $[\alpha/\text{Fe}]$ ratios.

3.1. Introduction

The first stars in the Universe (referred to as Population III stars) have been extensively searched for, both in the local Universe (Frebel & Norris 2013 and references therein) and at high redshift (e.g., Bromm & Loeb 2006, Cooke et al. 2012), but despite massive efforts no true Population III star has yet been found. There is an argument that no such stars should remain today: models of their formation indicate that they would have been massive and short-lived (Nakamura & Umemura 2001; Abel et al. 2002). Recent simulations however have suggested that disc fragmentation could have produced smaller mass stars, some of which may have survived to the present day (Clark et al. 2011).

Surveys focusing on the discovery of these old and metal-poor stars have almost exclusively targeted the Galactic halo (e.g., Christlieb et al. 2008), although some more recent studies have looked at dwarf galaxies of the Local Group (e.g., Frebel et al. 2010). The halo is known to be on average more metal-poor than other Galactic components, and some of these halo stars pass through the solar neighbourhood, making them relatively uncomplicated to observe. The number of metal-poor halo stars discovered has been growing, and there are now chemical abundances for > 400 metal-poor stars with $[\text{Fe}/\text{H}] < -2.5$ (Norris et al. 2013a).

It is not obvious though that the halo is the ideal place to look for the first stars. Using Λ CDM simulations, Diemand et al. (2005) predicted that if any were to survive to the present day, 30-60% of them would reside within the inner 3 kpc of the Galaxy, a population density of first stars that would be 1000 times greater than that of the solar neighbourhood. Tumlinson (2010) has modelled the current spatial distribution of all stars with $[\text{Fe}/\text{H}] < -3.5$ that formed prior to $z = 15$, and shown that, because of the inside-out construction of dark-matter haloes, the oldest as well as the most metal-poor stars should be more frequent in the central regions of the Galaxy. In other words, even if these stars may have originated elsewhere, they are now most likely to be located within the central regions of the Galaxy.

Few, if any, dedicated attempts have been made to search the Galactic bulge for extremely metal-poor stars. The bulge is known to be metal-rich, with a metallicity distribution function (MDF) peaking at $[\text{Fe}/\text{H}] \sim +0.3$ (e.g., Ness et al. 2013a; Gonzalez et al. 2013). Furthermore, the huge number of stars in the bulge, the distance to the bulge, and the high degree of extinction in the Galactic plane make it practically very difficult to find metal-poor stars there. The ARGOS survey (Ness et al. 2013a) spectroscopically studied 28,000 stars in the bulge at $R \approx 10,000$, identifying only 16 stars with $-2.8 \leq [\text{Fe}/\text{H}] \leq -2.0$, outlining the extent of the problem of finding metal-poor stars in a metallicity unbiased survey of the bulge. Similar results were found in the BRAVA survey (Kunder et al. 2012). The APOGEE survey found five new metal-poor stars (García Pérez et al. 2013) with $-2.1 \leq [\text{Fe}/\text{H}] \leq -1.6$ from 2400 observed bulge stars. To date, no bulge star with $[\text{Fe}/\text{H}] < -2.1$ has been exposed to a high-resolution abundance analysis.

This paper is the first in a series of papers exploring the results of the EMBLA¹ (Extremely Metal-poor BuLge stars with AAOmega) survey, which aims to find the most metal-poor stars in the bulge. Here we present the results of our initial observations, from which we have analysed four bulge stars with $[\text{Fe}/\text{H}] < -2$.

3.2. Observations

Our observations are conducted in three stages. We first acquire *uvgriz* photometry from the SkyMapper telescope, identifying metal-poor candidates that we then confirm spectroscopically with the AAOmega multi-object spectrograph. Finally we analyse the most interesting stars using high-resolution spectra obtained with 8m class telescopes.

The SkyMapper telescope is a 1.3m telescope capable of imaging in six bandpasses with a 5.7-square-degree field of view (Keller et al. 2007). The filters have been designed to optimise both stellar and extragalactic astronomy; in particular the narrow *v*-band filter centred on the CaII K line provides a useful stellar metallicity indicator. We have obtained SkyMapper photometry, taken during commissioning, for more than 100 deg² of the bulge, with each field containing on the order of 10⁶ stars, ranging from 12th to 18th magnitude. From $(v - g) - 2(g - i)$, $(g - i)$ two-colour diagrams we are able to select the most metal-poor candidates (Figure 3.1). Figure 3.1 shows our selection ‘box’, which accounts for the effects of reddening.

The AAOmega spectrograph on the AAT provides spectra of ≈ 350 stars (plus ≈ 50 sky and guide fibres) simultaneously over a 2 degree field-of-view (Sharp et al. 2006). Approximately 8500 bulge stars were observed in 2012 and 2013. All of these observations were taken using the 1700D grating for the red arm, and the 580V grating for the blue arm, providing a resolving power of about 10,000 over the 845-900 nm and of 1,300 over the 370-580 nm region. The data were reduced using *2dfdr*, and analysed with the *sick* pipeline (Casey 2014) to measure radial velocities, and to determine the stellar parameters (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$).

Figure 3.2 shows the raw MDF of the EMBLA survey, uncorrected for selection biases. In comparison to the relatively unbiased ARGOS MDF (Ness et al. 2013a), the average metallicity is approximately 0.8 dex lower with a significant tail of stars down into the extremely metal-poor regime. More than 300 stars have been found with $[\text{Fe}/\text{H}] < -2$. The full details of the EMBLA survey will be presented in future works.

From the first 3,600 stars observed in April and July 2012, ten were immediately identified as very metal-poor candidates. Six of these targets were observed with FLAMES/UVES on

¹In Nordic mythology, Embla was the first woman, born in the middle of the world from the remains of giants.

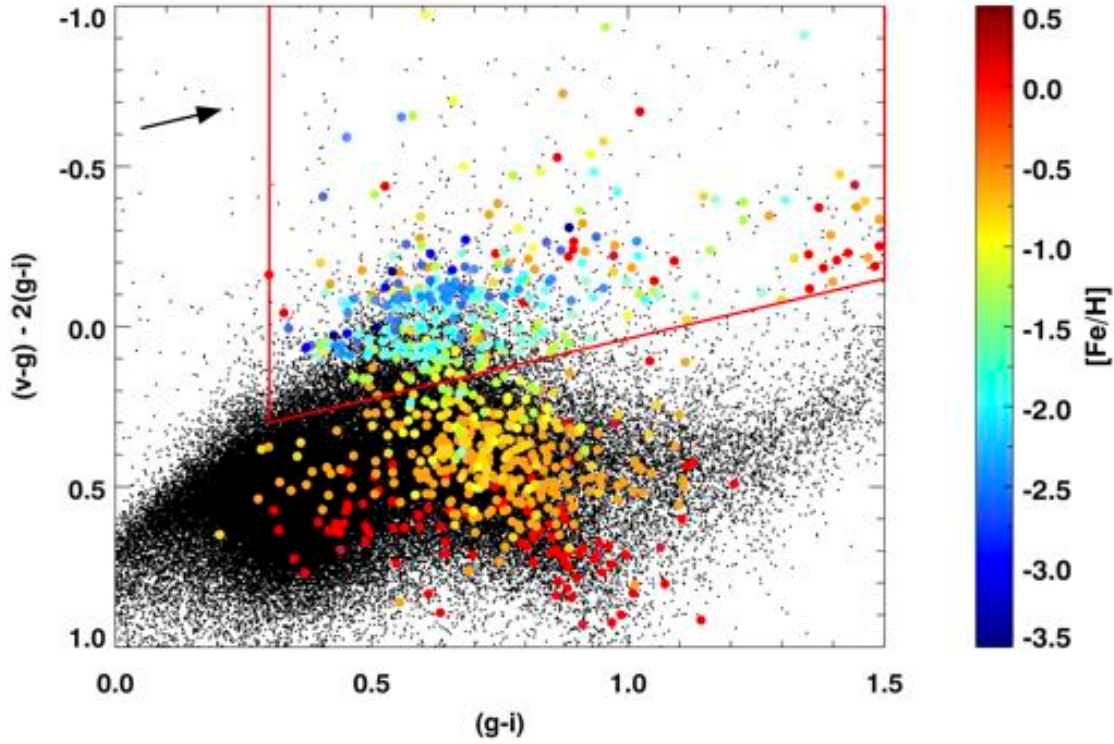


Figure 3.1 Two-colour plot using the g , v , and i bands of SkyMapper to demonstrate the metallicity dependence on the $(v - g) - 2(g - i)$ colour. The coloured circles are data taken from both EMBLA and the ARGOS survey (Ness et al. 2013a), with $[\text{Fe}/\text{H}]$ determined spectroscopically (field at $(l, b) = (0, -10)$). The red trapezium shows our selection criteria for metal-poor candidates. The arrow represents the mean reddening vector in this field, $E(B - V) = 0.17$ (Schlegel et al. 1998).

the VLT (Dekker et al. 2000) as part of the Gaia-ESO Survey (Randich et al. 2013) in May and August of 2012. The UVES observations have a resolving power of 47,000, using the 580nm setup. The data reduction of the FLAMES/UVES data in the survey is described in detail in Sacco et al. (2014). Of these six stars, the signal-to-noise ratios of two were too poor to be able to gain any useful analysis from ($S/N \leq 8$). The other four had average S/N per pixel values ranging from 14 to 73, sufficient for the derivation of stellar parameters and chemical abundances. The spectra of two of the stars are shown in Figure 3.3, where they are compared to the Gaia-ESO benchmark metal-poor giant star, HD 122563 ($[\text{Fe}/\text{H}] = -2.64$, Jofre et al. 2014), which has similar stellar parameters. In addition, ten halo EMP candidates, similarly selected from SkyMapper photometry and intermediate resolution spectroscopy, were observed through Gaia-ESO.

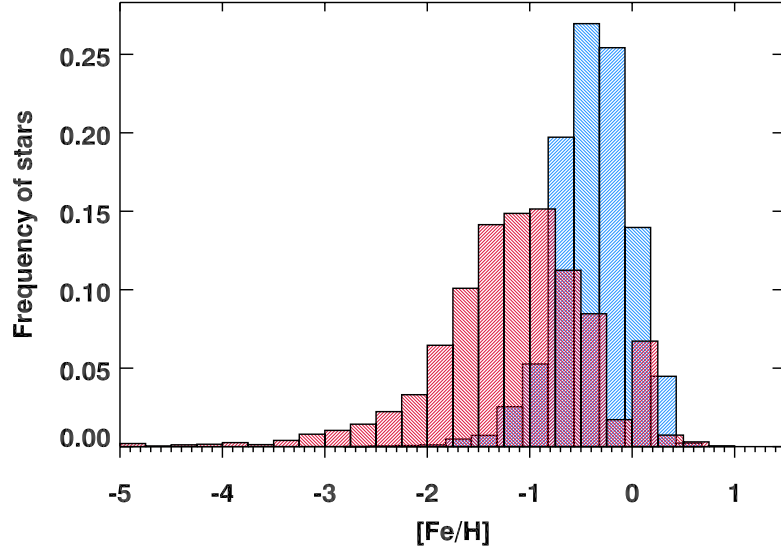


Figure 3.2 Raw metallicity distribution function, without accounting for selection effects, of the first 8,611 spectra from the EMBLA survey (red), compared to the MDF of the ARGOS bulge survey (blue). Both are normalised to have the same area.

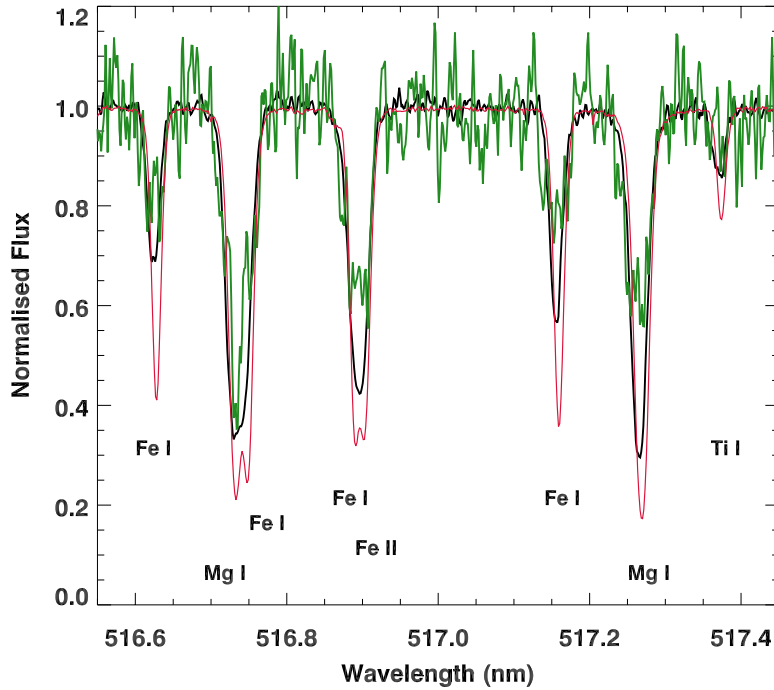


Figure 3.3 Comparison of the the FLAMES/UVES spectrum of Bulge-1 (black) and Bulge-3 (green), with the Gaia benchmark metal-poor halo giant (Jofre et al. 2014) HD 122563 (red), over the Mg triplet wavelength region.

3.3. Stellar Parameters and Chemical Abundances

The FLAMES/UVES spectra of the Gaia-ESO Survey are analysed by 13 different nodes (Smiljanic et al. 2014), each using the same MARCS model atmospheres (Gustafsson et al. 2008) and line-lists (Heiter et al. in preparation), but different analysis techniques. Due to the

Table 3.1 Stellar parameters for the four bulge stars and ten halo stars observed as part of the Gaia-ESO Survey in May and August 2012. The SkyMapper naming convention is SMSS J(RA2000)+(Dec2000).

Star	l (°)	b (°)	V_{GC} (km s^{-1})	d (kpc)	S/N*	T_{eff} (K)	$\log(g)$ (cgs)	[Fe/H] (dex)	ξ_t (km s^{-1})
SMSS J182153.85-341018.8 (Bulge-1)	359.2	-9.3	-237.68	7.0 $\pm$ 3.2	73	4947 $\pm$ 85	1.41 $\pm$ 0.49	-2.60 $\pm$ 0.31	2.3 $\pm$ 0.2
SMSS J183617.33-270005.3 (Bulge-2)	7.1	-8.9	-129.48	5.3 $\pm$ 1.9	37	4926 $\pm$ 137	1.97 $\pm$ 0.35	-2.72 $\pm$ 0.28	2.4 $\pm$ 0.2
SMSS J175510.50-412812.1 (Bulge-3)	350.2	-8.0	-48.28	12.4 $\pm$ 4.4	14	5187 $\pm$ 59	2.23 $\pm$ 0.31	-2.57 $\pm$ 0.19	2.0 $\pm$ 0.2
SMSS J175652.43-413612.8 (Bulge-4)	350.2	-8.4	216.46	5.4 $\pm$ 2.8	14	5035 $\pm$ 196	2.65 $\pm$ 0.54	-2.48 $\pm$ 0.23	1.5 $\pm$ 0.2
SMSS J094755.04-102724.7 (Halo-1)	246.8	31.8	309.16	2.1 $\pm$ 1.1	112	5258 $\pm$ 195	2.96 $\pm$ 0.61	-2.80 $\pm$ 0.17	1.8 $\pm$ 0.2
SMSS J100915.77-412715.5 (Halo-2)	273.1	11.8	383.89	3.6 $\pm$ 1.8	59	5266 $\pm$ 200	2.72 $\pm$ 0.55	-2.42 $\pm$ 0.18	1.9 $\pm$ 0.2
SMSS J101427.85-405250.3 (Halo-3)	273.6	12.9	284.67	2.0 $\pm$ 0.9	142	5136 $\pm$ 123	2.64 $\pm$ 0.50	-1.99 $\pm$ 0.20	1.6 $\pm$ 0.2
SMSS J105806.38-154239.0 (Halo-4)	266.9	39.1	519.06	8.0 $\pm$ 2.6	54	4907 $\pm$ 58	2.02 $\pm$ 0.32	-2.39 $\pm$ 0.12	2.3 $\pm$ 0.2
SMSS J110053.36-132808.2 (Halo-5)	266.0	41.3	-73.40	9.4 $\pm$ 4.6	10	5194 $\pm$ 125	2.92 $\pm$ 0.56	-2.30 $\pm$ 0.40	2.3 $\pm$ 0.2
SMSS J125551.46-450734.2 (Halo-6)	303.8	17.7	496.02	4.3 $\pm$ 3.1	54	4957 $\pm$ 215	2.00 $\pm$ 1.00	-2.62 $\pm$ 0.19	2.6 $\pm$ 0.2
SMSS J131358.51-460012.3 (Halo-7)	307.0	16.7	284.04	8.5 $\pm$ 3.2	109	4744 $\pm$ 62	1.37 $\pm$ 0.38	-2.34 $\pm$ 0.22	2.5 $\pm$ 0.2
SMSS J133013.60-434632.3 (Halo-8)	310.3	18.5	314.65	11.2 $\pm$ 3.6	86	4558 $\pm$ 54	0.93 $\pm$ 0.31	-2.42 $\pm$ 0.08	2.7 $\pm$ 0.2
SMSS J142148.60-440839.9 (Halo-9)	319.6	15.8	232.93	12.5 $\pm$ 4.8	44	4761 $\pm$ 65	1.47 $\pm$ 0.40	-2.42 $\pm$ 0.18	2.4 $\pm$ 0.2
SMSS J144100.90-400741.3 (Halo-10)	324.7	18.1	-138.96	6.9 $\pm$ 2.7	99	4921 $\pm$ 93	1.61 $\pm$ 0.41	-2.45 $\pm$ 0.17	2.2 $\pm$ 0.2

* Median S/N per pixel calculated across total wavelength range.

metal-poor nature of the stars, and with most pipelines being optimised for solar-metallicity stars, not all analysis nodes were able to establish robust parameters of the bulge and halo stars as well as the two metal-poor benchmark stars, HD 122563 (giant) and HD 140283 (subgiant). However three nodes provided accurate parameters for the majority of these metal-poor stars; the nodes IACAIP and Nice both used global fitting codes, while ULB used line-by-line analysis (Smiljanic et al. 2014). In addition, we included the results of two further methods: firstly a modified version of the Lumba node pipeline used in the Smiljanic et al. analysis that uses the *sME* code (Valenti & Piskunov 1996) for primarily H and Fe lines to determine stellar parameters, and secondly a similar analysis to that used in other SkyMapper EMP analyses (e.g., Keller et al. 2014) using the *smH* code (Casey 2014) in 1D LTE but with the Gaia-ESO line lists and atmospheres, and effective temperatures (T_{eff}) measured from H lines instead. The final parameters were evaluated by taking weighted averages of these five results. The here derived stellar parameters, abundances and radial velocities have been adopted by the Gaia-ESO survey as the recommended values. The uncertainties quoted are the calculated standard errors of the five parameter sets.

Abundances for twelve elements were derived using the *smH* code (Table 3.2). The uncertainties are formed from standard deviation of the line measurements taken in quadrature with the abundances differences due to stellar parameter uncertainties. Some elements (Mg, Ca, Ti and Ni) were measured in all four bulge stars, however some of the elements could not be detected in the stars with lower S/N, while some elements were not detected at the lowest [Fe/H]. Additionally barium abundances were calculated from synthesis of the Ba lines rather than from equivalent widths, taking into account hyperfine splitting and isotopic shifts.

3.4. Discussion

3.4.1. Bulge membership

All four stars were specifically taken from fields in the outer, southern part of the bulge ($-10^\circ < l < 8^\circ$, $b \approx -8.5^\circ$). Distances have been estimated by calculating absolute luminosities based on our derived T_{eff} , $\log g$ and assuming $M_* = 0.8M_\odot$, then fitting synthetic model fluxes from the T_{eff} , $\log g$, [Fe/H] and $E(B - V)$ (Schlegel et al. 1998) of each star, from which the correction factor used to reconstruct the bolometric luminosities from 2MASS JHK_S photometry is derived using the methodology described in Casagrande et al. (2006) and Casagrande et al. (2012). The derived distances are given in Table 3.1. Assuming a distance to the Galactic centre of 8.5 kpc and a bulge radius of 3 kpc, all but one are located inside the bulge. When considering the more complex bar structure of the bulge, and given the large distance uncertainties, Bulge-3 is also consistent with residing in the bulge. This is seen in Figure 3.4, where the locations of all four stars have been projected onto an N-body

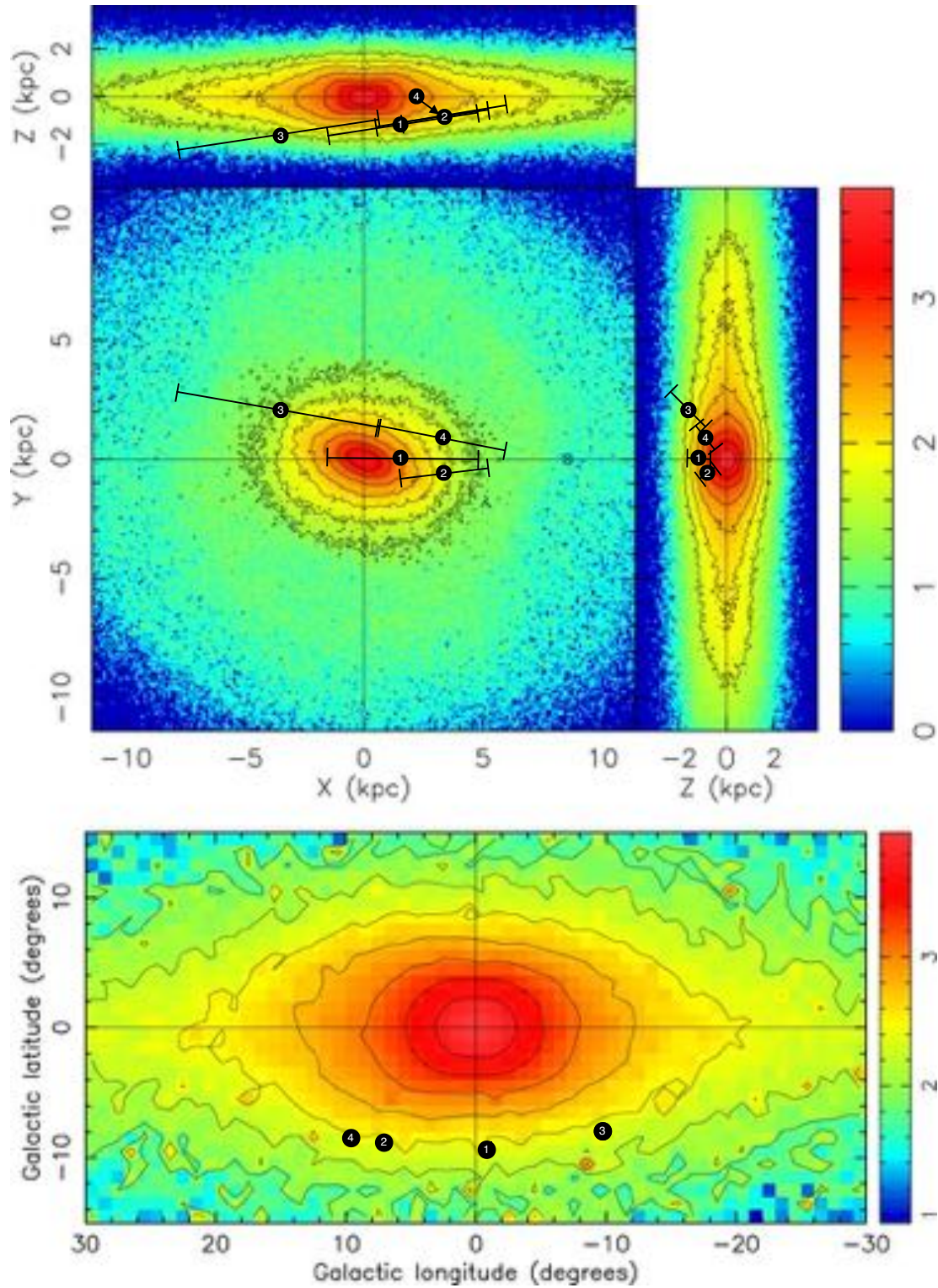


Figure 3.4 The four bulge stars plotted onto Figure 1 of Shen et al. 2010, which shows the face-on and side-on views of the bulge constructed from their N-body model of the BRAVA survey data. The position of the sun is marked with a cross on the x-axis. Underneath, the position of the bulge stars as viewed from the Sun's location.

Table 3.2 Chemical abundances of the four bulge stars.

Element	Bulge-1	Bulge-2	Bulge-3	Bulge-4
[Na I/Fe]	0.65 $\pm$ 0.23			0.15 $\pm$ 0.17
[Mg I/Fe]	0.62 $\pm$ 0.19	0.23 $\pm$ 0.16	-0.03 $\pm$ 0.10	-0.07 $\pm$ 0.20
[Si I/Fe]	0.50 $\pm$ 0.06			
[Ca I/Fe]	0.40 $\pm$ 0.07	0.24 $\pm$ 0.06	0.29 $\pm$ 0.18	0.32 $\pm$ 0.09
[Sc II/Fe]	0.20 $\pm$ 0.16	0.22 $\pm$ 0.15		
[Ti II/Fe]	0.38 $\pm$ 0.16	0.41 $\pm$ 0.14	0.38 $\pm$ 0.12	0.84 $\pm$ 0.27
[Cr I/Fe]	-0.20 $\pm$ 0.06	-0.27 $\pm$ 0.06		-0.24 $\pm$ 0.10
[Mn I/Fe]	-0.50 $\pm$ 0.04			
[Ni I/Fe]	0.02 $\pm$ 0.03	0.19 $\pm$ 0.06	0.11 $\pm$ 0.25	0.44 $\pm$ 0.07
[Zn I/Fe]	0.45 $\pm$ 0.06			
[Y II/Fe]	-0.43 $\pm$ 0.15	0.34 $\pm$ 0.14		
[Ba II/Fe]	-0.32 $\pm$ 0.13	0.41 $\pm$ 0.12	-0.07 $\pm$ 0.15	-0.06 $\pm$ 0.26

model taken from Shen et al. 2010.

The radial velocities of our stars split them into two groups: those with velocities similar to that of the bulk of bulge stars, and those with larger velocities. According to Ness et al. (2013b), the velocity dispersion of the bulge in the region of our stars is $\sigma = 75.1 \text{ km s}^{-1}$. Bulge-3 has a galactocentric velocity that would therefore be typical of a bulge star, but Bulge-1 and Bulge-4 have much larger velocities (-237.68 and 216.46 km s^{-1} , respectively), and Bulge-2 lies in between the two groups. These velocities are more characteristic of halo stars, and may indicate that although these stars are presently in the bulge, they are actually halo stars passing through. We intend to return to the important issue of kinematics for a much larger sample of stars in a future, detailed, analysis. For the time being we continue to refer to all four stars as bulge stars, given their location, but recognise that they may well have different origins from the typical bulge stars.

3.4.2. Chemical Composition

All four program stars are confirmed (based on high-resolution spectroscopy) to have lower metallicities ($[\text{Fe}/\text{H}] < -2.4$) than any previously published metal-poor bulge star. We compare our four bulge stars in Figure 3.5 to metal-poor halo stars also identified by SkyMapper and observed as part of the Gaia-ESO Survey, as well as other published bulge and halo stars. The ten halo stars also observed with the Gaia-ESO Survey have similar metallicities to the bulge stars, and all were analysed in an identical manner.

Our abundance analysis reveals that all four bulge stars are significantly α -enhanced (Fig. 3.5), with average abundance ratios of $[\text{Mg}/\text{Fe}] = 0.19$, $[\text{Si}/\text{Fe}] = 0.50$ (one star), $[\text{Ca}/\text{Fe}] = 0.34$, and $[\text{Ti}/\text{Fe}] = 0.50$. This enhancement is in line with the plateau shown in less metal-poor bulge stars of García Pérez et al. (2013), Alves-Brito et al. (2010), and Bensby et al. (2013). However, one obvious difference in this limited sample of metal-poor bulge stars is the intrinsic scatter in abundance, specifically in Mg and Ti. Whereas the $[\text{Ca}/\text{Fe}]$ ratios are all similar, matching the metal-poor halo stars and the more metal-rich bulge stars, for Mg and Ti the scatter is larger. Two stars have $[\text{Mg}/\text{Fe}] < 0.0$, and one of those is very overabundant in Ti ($[\text{Ti}/\text{Fe}] = 0.84$). The scatter for these elements is comparable to that for the halo stars analysed here, although in some cases the bulge stars may have larger scatter (noticeable in Mg, for example). Compared to the larger sample of halo stars from Yong et al. (2013a), given the limited statistics and remaining abundance uncertainties, our bulge and halo stars appear quite similar in $[\alpha/\text{Fe}]$.

Due to the wavelength region (480-680nm) and S/N of our spectra, it was only possible to measure Y and Ba in two of our bulge stars. In these stars, both neutron-capture elements are under-abundant and similar to our sample of halo stars. Again, the scatter is larger than for the more metal-rich bulge stars, although this is expected for neutron capture elements as seen in halo stars (Francois et al. 2007). There appear to be no obvious chemical differences in either neutron-capture or α abundances between those stars with very different velocities, although we caution that more stars are needed to confirm this.

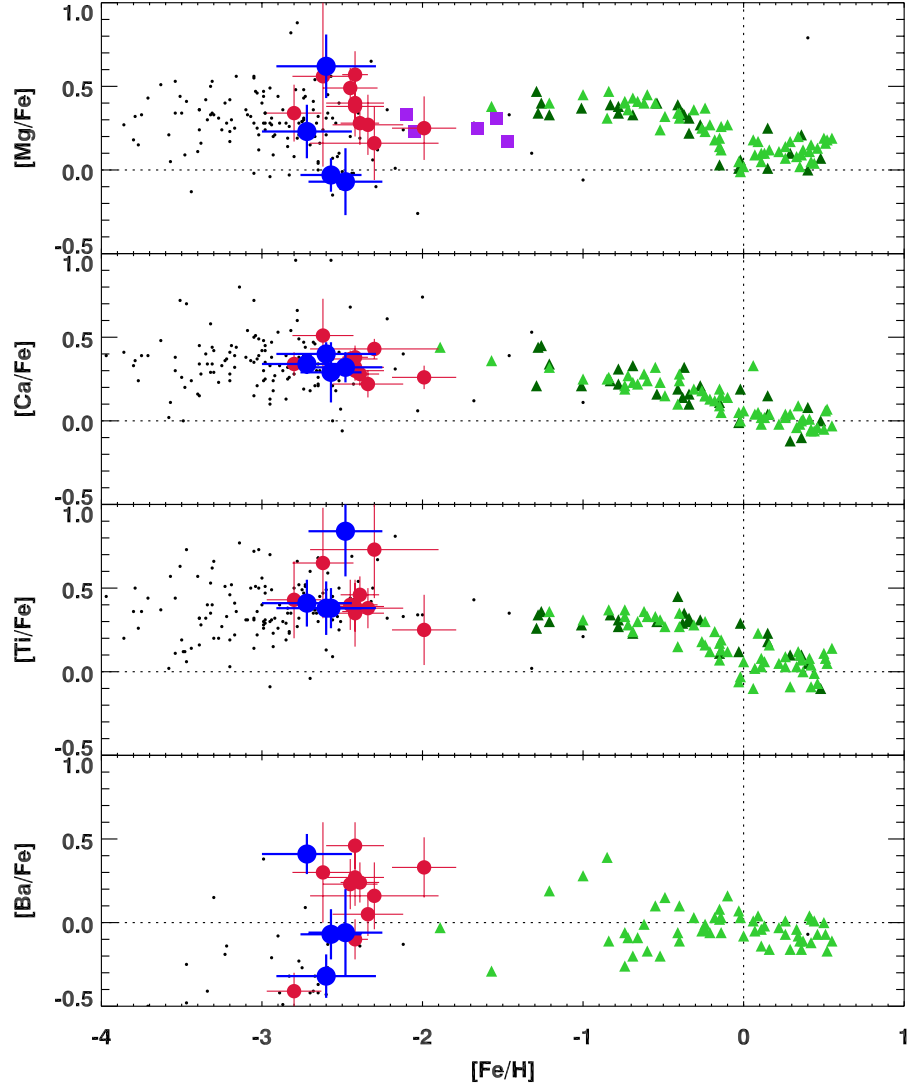


Figure 3.5 Comparison of the abundances in our bulge stars (blue circles), and the metal-poor halo stars from Gaia-ESO (red circles). Also shown are bulge stars from Bensby et al. (2013) (light green triangles), Alves-Brito et al. (2010) (dark green triangles), APOGEE (García Pérez et al. (2013), purple squares), as well as halo stars from Yong et al. (2013a) (black dots).

3.5. Conclusions

Using the unique photometric capabilities of the SkyMapper telescope, and the large field-of-view, high multiplexing AAOmega spectrograph on the AAT, the EMBLA survey has already found more than 300 stars spectroscopically confirmed to have $[\text{Fe}/\text{H}] < -2.0$. We have presented an abundance analysis of four of these, observed in high-resolution as part of the Gaia-ESO Survey. These four are all considerably more metal-poor than any previously studied bulge star ($-2.72 < [\text{Fe}/\text{H}] < -2.48$) and are chemically similar to metal-poor halo stars at similar $[\text{Fe}/\text{H}]$. The four stars are the first of many which will be studied at high-resolution by the EMBLA survey using Magellan and VLT, which will allow us to study the metal-poor tail of the bulge's MDF, make a detailed comparison with the halo and study the oldest stars in the Universe, many of which would have formed at $z \approx 15$.

Acknowledgements

We greatly acknowledge generous funding from the Australian Research Council (grants FL110100012 and DP120101237). T.B. was funded by grant No. 621-2009- 3911 from The Swedish Research Council. Support from the Swedish National Space Board is acknowledged. Based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 188.B-3002. This work was partly supported by the European Union FP7 programme through ERC grant number 320360 and by the Leverhulme Trust through grant RPG-2012-541. We acknowledge the support from INAF and Ministero dell' Istruzione, dell' Universita' e della Ricerca (MIUR) in the form of the grant "Premiale VLT 2012". The results presented here benefit from discussions held during the Gaia-ESO workshops and conferences supported by the ESF (European Science Foundation) through the GREAT Research Network Programme. MZ acknowledges support from Fondecyt Regular 1110393, the BASAL CATA PFB-06 and by the Chilean Ministry for the Economy, Development, and Tourism's Programa Iniciativa Científica Milenio through grant IC12009, awarded to the Millennium Institute of Astrophysics.

CHAPTER 4

The EMBLA Survey – Metal-poor Stars in the Galactic Bulge

This chapter has been previously submitted for publication as 'The EMBLA Survey – Metal-poor stars in the Galactic bulge', Louise M. Howes, Martin Asplund, Stefan C. Keller, Andrew R. Casey, David Yong, Karin Lind, Anna Frebel, Austin Hays, Alan Alves-Brito, Michael S. Bessell, Luca Casagrande, Anna F. Marino, David M. Nataf, Christopher I. Owen, Gary S. Da Costa, Brian P. Schmidt, Patrick Tisserand. The work is presented exactly as submitted for publication, except where the examiners have requested changes, which have been made.

Abstract

Cosmological models predict the oldest stars in the Galaxy should be found closest to the centre of the potential well, in the bulge. The EMBLA Survey successfully searched for these old, metal-poor stars by making use of the distinctive SkyMapper photometric filters to discover candidate metal-poor stars in the bulge. Their metal-poor nature was then confirmed using the AAOmega spectrograph on the AAT. Here we present an abundance analysis of 10 bulge stars with $-2.8 < [\text{Fe}/\text{H}] < -1.7$ from MIKE/Magellan observations, in total determining the abundances of 22 elements. Combining these results with our previous high-resolution data taken as part of the Gaia-ESO Survey, we have started to put together a picture of the chemical and kinematic nature of the most metal-poor stars in the bulge. The chemistry of these bulge stars deviates from that found in halo stars of the same metallicity. Two notable differences are the absence of carbon-enhanced metal-poor bulge stars, and the alpha-element abundances exhibit a large intrinsic scatter and include stars which are underabundant in these typically enhanced elements.

4.1. Introduction

Studies of the most metal-poor stars have for many years provided insights into the early Universe and the formation of the Galaxy. These stars allow us to place constraints on our understanding of the first supernovae, the early initial mass function, and the evolution of the Milky Way. Individual metal-poor stars have led to theories on the formation of the first stars (e.g., Klessen et al. 2012, Schneider et al. 2012, Ishigaki et al. 2014) and ideas about the chemical enrichment of the galaxy thereafter (e.g., Norris et al. 2007, Karlsson et al. 2013, Frebel & Norris 2015).

The first stars in the Universe (referred to as Population III stars) are predicted to have formed within the first few hundred million years after the Big Bang (e.g. Bromm 2013, and references therein), corresponding to redshifts of $z > 10$. Until recently it was thought that these stars were all massive, and therefore short-lived (Nakamura & Umemura 2001; Bromm & Larson 2004). A lack of metals in the giant gas clouds would make the cooling needed for fragmentation into smaller clouds difficult, possibly preventing the formation of low mass stars. However with the introduction of higher-resolution numerical simulations, it appears that accretion disc fragmentation may allow stars of around a solar mass to emerge, and with that the possibility of one surviving to the present day becomes plausible (e.g., Clark et al. 2011, Greif et al. 2012, Bromm 2013).

There have been numerous extensive searches for metal-poor stars in the Milky Way. Surveys like the HK survey (Beers et al. 1985), Hamburg-ESO survey (Christlieb 2003), and SDSS/SEGUE (Caffau et al. 2011b) have extended our knowledge of this area immeasurably, producing a significant number of stars with $[\text{Fe}/\text{H}]^1 < -3.5$ (Norris et al. 2013a) and a few stars with $[\text{Fe}/\text{H}] < -5.0$ (e.g., Christlieb et al. 2002; Frebel et al. 2005, 2008; Caffau et al. 2011a; Keller et al. 2014). In the future, large-scale spectroscopic surveys like LAMOST and 4MOST will increase the number of metal-poor stars known tenfold (Li et al. 2015; de Jong et al. 2012). These surveys have primarily targeted the Galactic halo, which is known to be on average more metal-poor than any other Galactic component. More recently this has been extended to dwarf satellite galaxies of the Milky Way (Tafelmeyer et al. 2010; Frebel et al. 2010; Starkenburg et al. 2013), finding stars down to $[\text{Fe}/\text{H}] = -4.0$.

According to theoretical modelling within the cold dark matter framework, however, the Milky Way halo is not the optimal place to look for the most metal-poor and oldest stars. White & Springel (2000) first predicted that the oldest stars in the Milky Way should mostly be in the bulge or inner halo, a conclusion which was reinforced by e.g. Brook et al. (2007). Salvadori et al. (2010) suggested that any stars found with $[\text{Fe}/\text{H}] < -1$ within the inner few kpc of the Galaxy would have formed at $z > 10$. Tumlinson (2010) combined models of Λ CDM halo formation with baryonic gas budgets and star formation histories, to mimic the

¹Using the standard notation, where $[A/B] \equiv \log_{10}(N_A/N_B)_* - \log_{10}(N_A/N_B)_\odot$, and $\log_{10}\epsilon(B) = A(B) \equiv \log_{10}(N_B/N_H) + 12.00$, for elements A and B.

formation of the Milky Way. He showed that, of all the stars with $[\text{Fe}/\text{H}] < -3.0$, those found in the central regions of the Galaxy were more likely to have formed before $z = 15$ than in any other location. He writes that the oldest and most metal-poor stars, which formed as early as $z \approx 20$ according to his model, “are in the bulge, but not of the bulge”.

Despite these simulations suggesting the bulge to be the best location to find the oldest stars today, very few attempts have been made to search the bulge for metal-poor stars. It is much easier to search the Galactic halo, where the majority of stars are of a low metallicity (the peak of the metallicity distribution function (MDF) of the halo is around $[\text{Fe}/\text{H}] = -1.6$; Laird et al. 1988; Ryan & Norris 1991b; Schörck et al. 2009). The bulge, on the other hand, is the most metal-rich component of the Milky Way, containing some of the most metal-rich stars known, and with an MDF ranging from $[\text{Fe}/\text{H}] \approx -1.5$ to $[\text{Fe}/\text{H}] = +0.5$ (Zoccali et al. 2008; Ness et al. 2013a; Gonzalez et al. 2013). Indeed, the metallicity unbiased ARGOS survey (Freeman et al. 2013) showed that of 14,150 stars identified as lying in the bulge, only 16 had $[\text{Fe}/\text{H}] \leq -2.0$ (Ness et al. 2013a). Furthermore, the bulge is also a heavily crowded region and with high extinction due to dust, making it practically very difficult to find metal-poor bulge stars. The large distance to the bulge (around 8.5 kpc) means that only red giant stars can be targeted without amplification from microlensing (Bensby et al. 2013).

Very recently, the first very metal-poor stars in the bulge have been discovered. García Pérez et al. (2013) found five new metal-poor stars with $[\text{Fe}/\text{H}]$ ranging from -1.6 to -2.1 based on infrared spectroscopy of $\sim 2,400$ bulge stars. Recent work combining data from near-infrared surveys with optical photometry have also started to find metal-poor bulge stars, with three discovered having $-3.0 < [\text{Fe}/\text{H}] < -2.7$ (Schlaufman & Casey 2014).

This paper, the third in a series of papers concerning the EMBLA² spectroscopic survey (Extremely Metal-poor BuLge stars with AAOmega), describes the findings of our initial observations, following the results published in Howes et al. (2014) as part of the Gaia-ESO Survey, and those published in Howes et al. (2015a) based on observations taken in 2014.

4.2. Observations

4.2.1. Photometry from SkyMapper

The SkyMapper telescope is a 1.3 m telescope capable of imaging in six bandpasses with a 5.7-square-degree field of view (Keller et al. 2007). It has primarily been designed to perform the Southern Sky Survey, a multi-epoch photometric survey of the whole of the southern sky, which commenced regular science operations in 2014. We have acquired complete coverage of the bulge with SkyMapper, taken during telescope commissioning

²In Nordic mythology, Embla was the first woman, born in the middle of the world from the remains of giants.

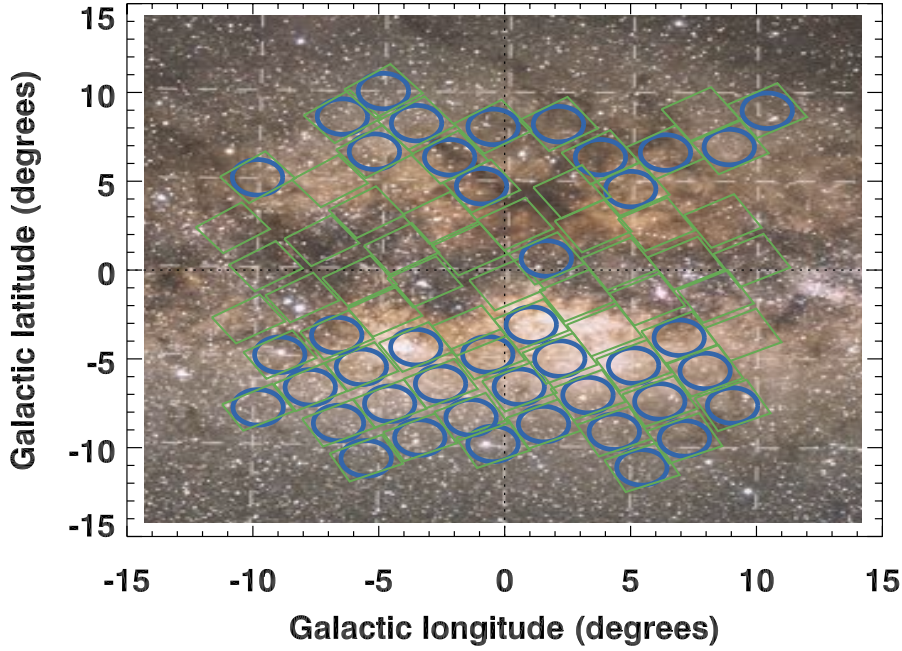


Figure 4.1 Positions of all the fields observed by SkyMapper in the bulge, shown as green rectangles, superimposed on an image of the bulge region of the sky (credit: OGLE). The blue circles show the fields that have been followed up with spectroscopy from AAOmega.

during 2012-2014. The distribution of these fields is shown in Figure 4.1. Each bulge field contains on the order of 10^6 stars, ranging roughly from 12th to 19th magnitude in the Strömgren v band.

The filters in SkyMapper have been chosen specifically to enhance important spectral features in both stellar and extra-galactic research (Bessell et al. 2011); in our case in particular the v band provides an important stellar metallicity indicator. We first select stars on the giant branch of the bulge from a $g-i$, g colour-magnitude diagram. This is necessary to limit our selection to stars that are in the bulge, and not foreground dwarfs. Then we move on to the metallicity selection, plotting $(v-g) - 2(g-i)$ against $g-i$ to create a selection box. In Figure 4.2 we show an example two-colour diagram, revealing its powerful ability to identify low metallicity stars. We have overlaid the SkyMapper photometry with spectroscopic $[\text{Fe}/\text{H}]$ data taken from both a metallicity unbiased ARGOS field, and an EMBLA field, centred at $(l, b) = (0, -10)$. From the selection region, a box of the first 200 stars from the top downwards were identified as the highest priority candidates, followed by a box containing 500 lower priority candidates from which ~ 150 are chosen at random at the fibre configuration stage of the spectroscopic follow-up. This second selection is designed to provide us with a random sample of the metal-poor stars in the field, from which we aim to recreate the tail end of the metallicity distribution function (MDF) of the bulge to be presented in a later paper.

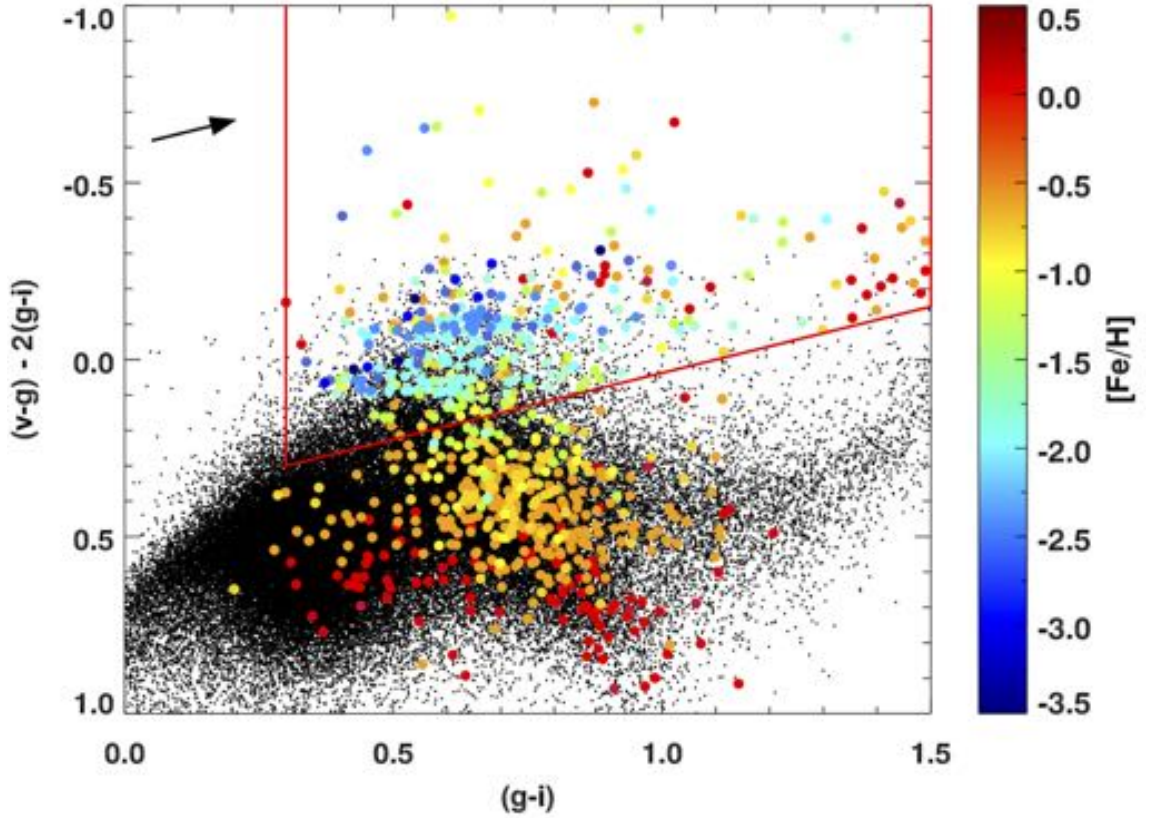


Figure 4.2 Two-colour plot using the g , v , and i bands of SkyMapper to demonstrate the metallicity dependence on the $(v - g) - 2(g - i)$ colour. The coloured circles are data taken from both EMBLA and the ARGOS survey (Ness et al. 2013a), with $[\text{Fe}/\text{H}]$ determined spectroscopically. The red trapezium shows our selection criteria for metal-poor candidates. The arrow represents the mean reddening vector in this field, $E(B - V)=0.17$ (Schlafly & Finkbeiner 2011).

4.2.2. Medium resolution spectroscopy with AAOmega on the AAT

With the capability of selecting so many candidate metal-poor stars, an efficient means to spectroscopically confirm their metal-poor nature is necessary. The AAOmega spectrograph combined with the 2dF fibre positioner on the Anglo-Australian Telescope (AAT) (Sharp et al. 2006) provides spectra of up to 392 stars at once with a circular field-of-view of 2° diameter. Over 24.5 nights on the AAT between 2012 and 2014 we have observed more than 14,000 stars in the fields shown in Figure 4.1. All observations were taken using the 1700D grating for the red arm, and the 580V grating for the blue arm, which provides a spectral resolving power of 10,000 in the Ca II triplet region and of 1,300 over 370 - 580 nm. The data were reduced using the 2dfdr pipeline³, and examples of reduced spectra from field 2156 ($(l, b)=(-1.5, -8.3)$) can be seen in Figure 4.3, showing a range of metallicities.

The AAOmega spectra have been analysed using *sick* (Casey 2014), a Python code that forward models spectroscopic data from which we can ascertain the standard astrophysical parameters of the stars: v_{rad} , T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and $[\alpha/\text{Fe}]$. *sick* relies on the AMBRE

³<http://www.aao.gov.au/science/software/2dfdr>

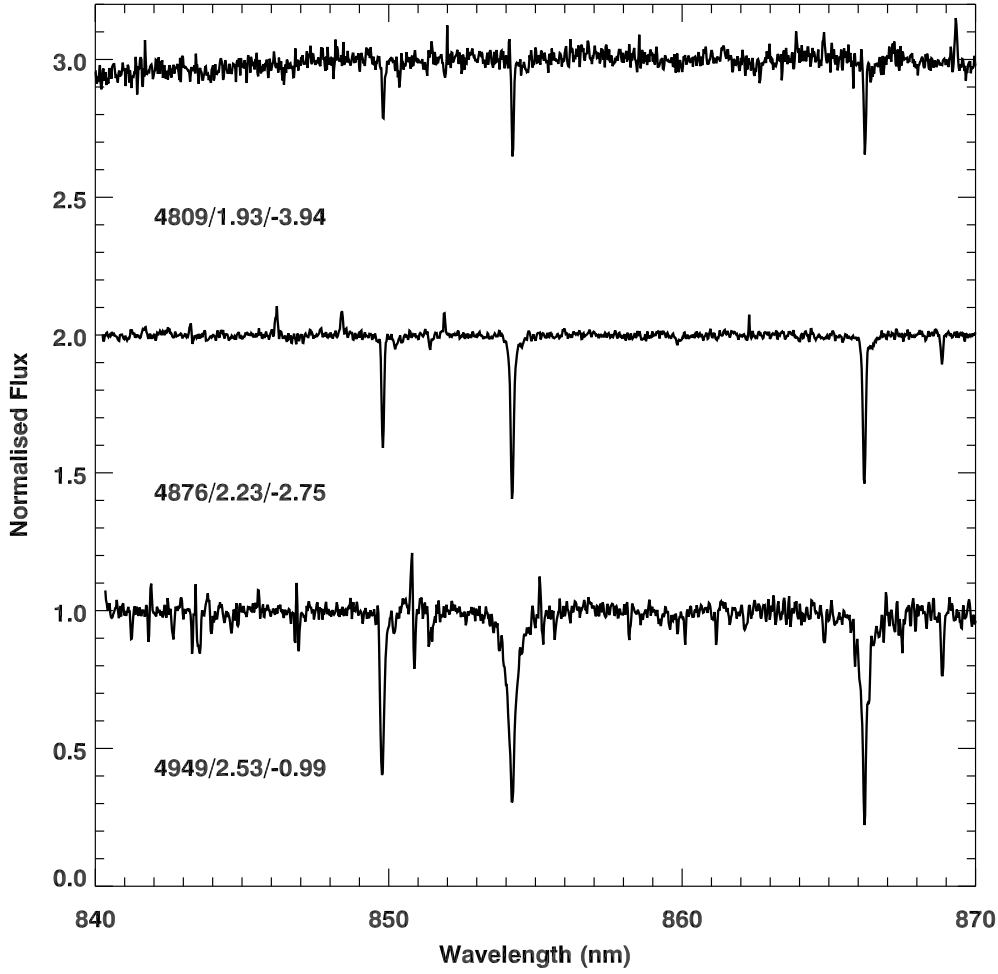


Figure 4.3 The red-arm spectra showing the Ca II triplet ($R=10,000$) of three of the stars observed with AAOmega. The three stars have been chosen from the same field ($l, b = (-1.5, -8.8)$) and with a range of metallicities to demonstrate the notable difference in the spectra with varying metallicity. The stellar parameters (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$) are labelled underneath each spectrum.

grid of synthetic stellar spectra (de Laverny et al. 2012). From these results, we have calculated the raw MDF of the data (Fig. 4.4), which demonstrates the overall success of the photometric selection process. When compared to all bulge stars from the ARGOS survey (shown in blue), the peak of our MDF is ~ 0.6 dex lower, and we have a significant number of stars reaching down to the lowest metallicities. The fields observed span a range of locations in the bulge (as seen in Fig. 4.1), which will allow us to complete a detailed breakdown of the metal-poor stellar population across the bulge. We note that as expected, the SkyMapper photometric selection of metal-poor stars is less successful in the heavily and differentially reddened bulge region than for the halo (Jacobson et al. 2015) but on the other hand the spectroscopic confirmation stage is far more efficiently carried out using the high multiplexing of AAOmega.

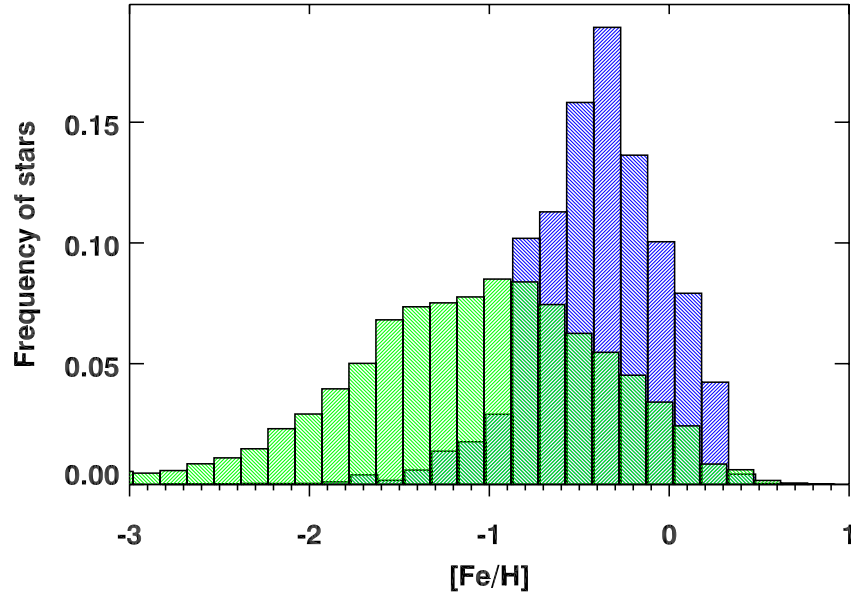


Figure 4.4 Raw MDF of the first 9,000 spectra from the EMBLA Survey (green) observed in 2012 and 2013, compared to the MDF of the ARGOS bulge survey (blue). Both are normalised to have the same area, and the EMBLA histogram has been truncated at $[\text{Fe}/\text{H}] = -3.0$ as the low resolution stellar analysis breaks down below this.

4.2.3. High resolution spectroscopy with MIKE on Magellan

In order to discover the detailed chemical composition of some of the most metal-poor stars found in the survey, we have observed at both Magellan (?) and the VLT (Howes et al. 2014) over the course of the three years of the survey. This paper focuses on high-resolution data taken at Magellan in 2012, immediately after the first fields were observed on the AAT. As they were observed early in the course of the survey, these are not the most metal-poor stars we have discovered, rather a range of stars with metallicities originally estimated as $[\text{Fe}/\text{H}] < -2$.

Ten stars were observed using the MIKE high-resolution spectrograph (Bernstein et al. 2003) on Magellan's 6.5m Clay telescope. The observations took place between April and June of 2012, and all make use of the full wavelength coverage offered by MIKE, with the spectra covering 370-890 nm. All except the first star were configured with a 1.0" slit, resulting in resolving powers of 22,000 in the blue and 28,000 in the red, and were binned by two in both the spatial and spectral directions. The first star (SMSS J182637.10-342924.2), which was observed in April as part of a different set of observations, used a slit with width of 0.35", and no spatial or spectral binning. This provided resolving powers of 83,000 and 65,000, in the blue and red respectively. We note that although the higher resolving power provides extra detail in our spectra, the lower resolving powers are sufficient to be able to measure the elements of relevance at these modest signal-to-noise values of metal-poor stars. Details of the exact S/N acquired, along with exposure times and wavelength range can be found in Table 4.1.

Table 4.1 Details of the observations of the 10 stars. The SkyMapper naming convention is SMSS J(RA2000)+(Dec2000).

Star (SMSS)	l ($^{\circ}$)	b ($^{\circ}$)	Date Observed (2012)	Exposure time (s)	Wavelength range (nm)	Slit width ($''$)	S/N per pixel at 450nm
J182637.10-342924.2	-0.68	-10.31	April 28	14,400	340-890	0.35	35
J182600.09-332531.0	0.24	-9.72	May 15	1,200	333-941	1.0	20
J182601.24-332358.3	0.26	-9.72	May 15	2,700	333-941	1.0	20
J182753.81-334607.7	0.10	-10.23	May 15	1,200	333-941	1.0	13
J183000.36-333919.3	0.40	-10.58	May 15	1,350	333-941	1.0	24
J182922.48-335559.4	0.09	-10.58	May 15	3,600	333-941	1.0	28
J182930.47-335958.3	0.04	-10.63	May 15	1,850	333-941	1.0	17
J183225.29-334938.4	0.46	-11.10	May 15	1,350	333-941	1.0	16
J183128.71-341018.4	0.06	-11.07	May 15	900	333-941	1.0	14
J182948.48-341053.9	-0.10	-10.77	June 25	3,600	370-890	1.0	26

4.3. Analysis

4.3.1. Data Reduction and Radial Velocities

The stars were all reduced with the CarPy data reduction pipeline⁴ (Kelson 2003). The spectra were normalised using `SMH` (Casey 2014). Radial velocities for the stars were determined using both `IRAF` and `SMH`. Both methods make use of cross-correlation with the spectrum of a known metal-poor subgiant (HD140283), and their respective velocities were found to have on average less than 1.0 km s^{-1} difference. The `SMH` values are used throughout, and converted to heliocentric radial velocities using `IRAF` to be published here. The radial velocities are all single epoch measurements, leaving open the possibility that some fraction of the stars are in binary systems.

4.3.2. Atmospheric Parameters

Equivalent Widths

The strength of atomic absorption lines were measured in all 10 stars using a line list compiled for the EMBLA Survey, listed in Table 4.2 along with the adopted atomic data. This line list was extracted from the Gaia-ESO line list (Heiter et al. in prep.), specifically utilising the best lines available in metal-poor stars, and supplemented with lines outside the wavelength regions of Gaia-ESO with lines primarily from Norris et al. (2013a). In particular, 66 Fe I lines and 24 Fe II lines have been included, in order to robustly measure $[\text{Fe}/\text{H}]$ and other atmospheric parameters. The lines were measured automatically using `SMH`, which determines the local continuum and then iteratively fits a Gaussian profile to the line. All lines were then checked by eye, removing any spurious results, and rejecting any line with an equivalent width greater than 120 mÅ in order to restrict our equivalent width measurements to the linear part of the curve of growth. For the most metal-poor star in the sample (SMSS J182601.24-332358.3), 18 Fe I lines and 8 Fe II lines were measurable. In some cases, where there are no other lines available for a particular element, lines stronger than 120 mÅ have been used.

Effective Temperature

The atmospheric parameters for the stars were calculated using an iterative process, where the initial parameters were taken from those derived from the low-resolution spectra. T_{eff} values were found for each star by interpolating between a grid of precomputed synthetic $\text{H}\alpha$ and $\text{H}\beta$ lines, taken from Barklem et al. (2000), and matching to suitable wavelength

⁴<http://code.obs.carnegiescience.edu/mike>

Table 4.2 Atomic data. The full table can be found in Appendix Table A.1.

Ion	λ (nm)	χ (eV)	$\log gf$
Li I	670.776	0.000	0.174
O I	630.030	0.000	-9.715
O I	636.378	0.000	-10.190
Na I	588.995	0.000	0.108
Na I	589.592	0.000	-0.194
Na I	818.326	2.102	0.237
Na I	819.482	2.104	0.492
...	...	...	...

regions of the observed spectra using a χ^2 minimisation (Figures 4.5 and 4.6). This method has been preferred over the excitation potential balance method, due to the latter producing significantly lower temperatures in metal-poor stars than any other method (Cayrel et al. 2004; Lai et al. 2008; Frebel et al. 2013). Alternate temperatures were also derived using excitation balance, followed by an empirical correction of +325 K, decided upon after analysing both the metal-poor Gaia benchmark stars (Heiter et al. 2015) and the larger sample of stars in Howes et al. (2015a) (25 stars in total). In general, these alternate temperatures were used solely to confirm that our temperatures from the Balmer lines were accurate, however due to the uncertain normalisation of the hydrogen wings in two of the stars (SMSS J182600.09-332531.0 and SMSS J183128.71-341018.4), the corrected excitation balance T_{eff} values were used instead for those two stars.

Surface Gravity, Metallicity, and Microturbulence

After the effective temperatures were determined, these values were entered into `SMH` (which provides a user interface for the 1D LTE stellar synthesis software `MOOG` (Snedden et al. 2012)), and the remaining atmospheric parameters were measured, using the 1D MARCS model atmospheres (Gustafsson et al. 2008). The $\log g$ values were determined first by forcing the mean Fe I and Fe II abundances to be equal (within 0.01 dex). Similarly, the microturbulence was calculated by forcing a zero gradient between the Fe I abundances and the reduced equivalent widths, with a maximum value set at $\xi_t = 2.5 \text{ km s}^{-1}$. The adopted [Fe/H] values are the mean Fe II abundances from the line measurements. Non-LTE effects in the measurements of the Fe I lines were considered using the calculations of Lind et al. (2012). As our stars are both metal-poor and giants, the non-LTE corrections were typically quite large: the average correction applied to the sample was 0.14 dex. These new parameters were then used to re-calculate the effective temperatures, and the process repeated until the

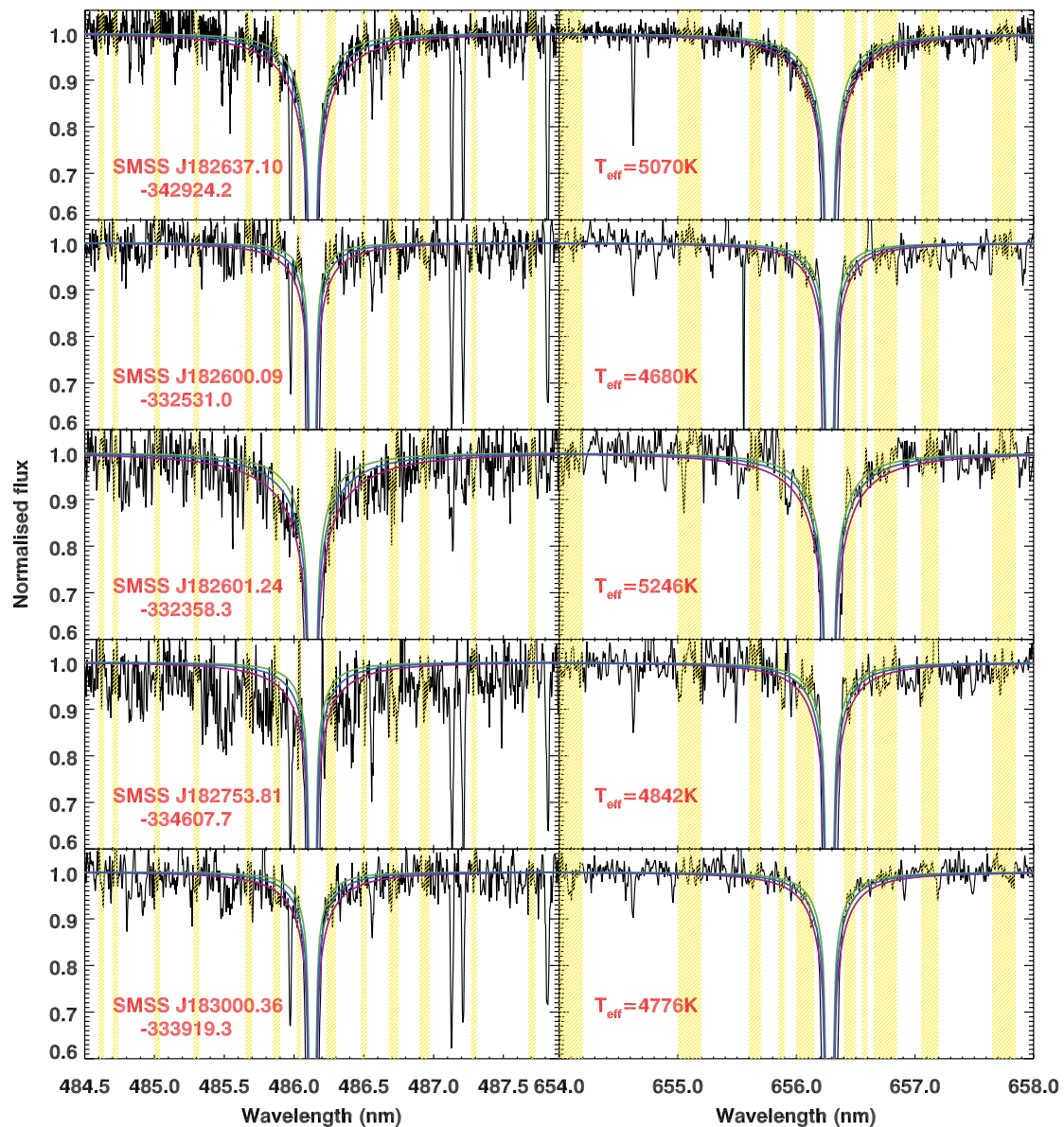


Figure 4.5 The spectra of the first five stars at both the $H\beta$ and $H\alpha$ lines, from which a synthetic spectrum was fitted to derive the effective temperatures. The yellow shaded regions show the spectral windows used for the fit. Three synthetic spectra have been overplotted; one with the fitted temperature (blue), one with $T_{\text{eff}} + 200$ K (purple), and one with $T_{\text{eff}} - 200$ K (green). The fits for SMSS J182600.09-332531.0 were not used to derive the T_{eff} of this star, see text for details.

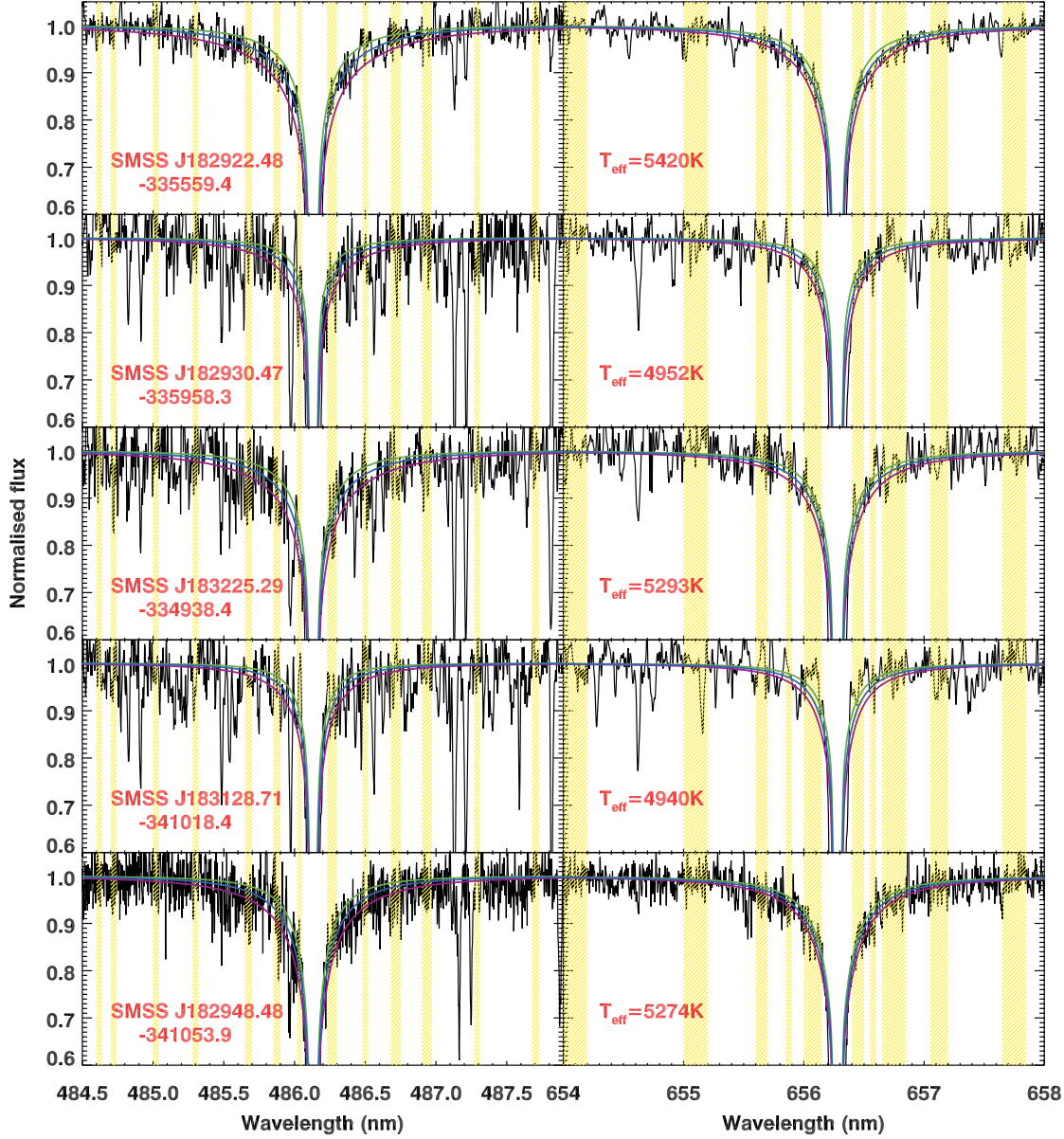


Figure 4.6 Same as Fig. 4.5 for the remaining five stars. The fits for SMSS J183128.71-341018.4 were not used to derive the T_{eff} of this star, see text for details.

process had converged. The final parameters are listed in Table 4.3.

Uncertainties in the Parameters

The statistical uncertainties of the χ^2 minimisation employed in the determination of the effective temperatures were typically 20 K for the stars. The uncertainties are heavily dominated by systematic errors, which have been estimated to be ~ 100 K (Barklem et al. 2000). The $\log g$ uncertainties are assumed to be composed of the standard errors of both the Fe I and Fe II abundances, and an added term of 0.12 dex, half the size of the average $\log g$ correction from non-LTE effects, to encompass the uncertainty in that correction. For microturbulence, an uncertainty of 0.2 km s^{-1} is assumed throughout. The metallicity uncertainties were

Table 4.3 Stellar parameters for the 10 bulge stars.

Star (SMSS)	V_{GC} (km s ⁻¹)*	$d_{\odot}$ (kpc)	T_{eff} (K)	$\log g$ (cgs)	[Fe/H] (dex)	ξ_t (km s ⁻¹)
J182637.10-342924.2	-44.7	8.1 $\pm$ 2.2	5070 $\pm$ 100	2.50 $\pm$ 0.12	-1.97 $\pm$ 0.08	1.3 $\pm$ 0.2
J182600.09-332531.0	-213.2	10.6 $\pm$ 3.2	4680 $\pm$ 100	1.36 $\pm$ 0.14	-2.53 $\pm$ 0.09	2.4 $\pm$ 0.2
J182601.24-332358.3	-323.3	10.5 $\pm$ 3.5	5246 $\pm$ 100	1.65 $\pm$ 0.16	-2.83 $\pm$ 0.11	2.5 $\pm$ 0.2
J182753.81-334607.7	-270.3	12.3 $\pm$ 3.5	4842 $\pm$ 100	1.53 $\pm$ 0.13	-2.31 $\pm$ 0.07	2.5 $\pm$ 0.2
J183000.36-333919.3	124.2	10.4 $\pm$ 3.0	4776 $\pm$ 100	1.55 $\pm$ 0.13	-2.63 $\pm$ 0.07	2.5 $\pm$ 0.2
J182922.48-335559.4	-54.0	9.9 $\pm$ 2.9	5420 $\pm$ 100	1.94 $\pm$ 0.13	-2.77 $\pm$ 0.07	2.5 $\pm$ 0.2
J182930.47-335958.3	-218.8	16.9 $\pm$ 5.3	4952 $\pm$ 100	1.25 $\pm$ 0.15	-1.97 $\pm$ 0.13	2.3 $\pm$ 0.2
J183225.29-334938.4	-147.4	9.2 $\pm$ 2.8	5293 $\pm$ 100	2.35 $\pm$ 0.14	-1.74 $\pm$ 0.09	1.8 $\pm$ 0.2
J183128.71-341018.4	-35.0	3.3 $\pm$ 0.9	4940 $\pm$ 100	2.15 $\pm$ 0.13	-1.83 $\pm$ 0.10	2.0 $\pm$ 0.2
J182948.48-341053.9	-71.7	6.0 $\pm$ 2.0	5274 $\pm$ 100	2.82 $\pm$ 0.16	-2.47 $\pm$ 0.11	2.2 $\pm$ 0.2

* Galactocentric velocity, calculated using equation 4.3.

calculated by summing in quadrature the effects of the uncertainties from T_{eff} , $\log g$, and ξ_t , as well as the standard error of the Fe II abundance.

4.3.3. Chemical Abundances

It was possible to measure the chemical abundances of up to 21 elements additional to Fe from the spectra. Equivalent widths were measured for 19 elements, using the lines listed in Table 4.2. These elements covered include light (Na, Al, K), alpha (O, Mg, Si, Ca, Ti), iron group (Sc, Mn, Cr, Co, Ni, Zn), and neutron-capture (Sr, Y, Zr, La, Eu). C abundances were derived from synthesising the CH bands at 431.3 nm (430.5 - 431.9 nm) and 432.3 nm (431.9 - 432.9 nm). The Ba lines were also synthesised in order to account for isotopic and hyperfine splitting, again taking atomic data from the Gaia-ESO line list.

The inferred abundances are listed in the form of $[X/\text{Fe}]$ in Table 4.6, calculated relative to the solar values given in Asplund et al. (2009). The Fe abundances used in these calculations were the Fe II-based values, apart from for the iron-peak elements Cr, Mn, Co, Ni, and Zn, as these neutral species should behave more similarly to Fe I for example in terms of their non-LTE effects (e.g., Asplund 2005, Bergemann et al. 2012) and dependence on stellar parameters, especially $\log g$. The uncertainties given for $[X/\text{Fe}]$ are calculated by summing in quadrature the offsets due to the uncertainties in T_{eff} , $\log g$, ξ_t , and $[\text{Fe}/\text{H}]$, as well as the standard error across the individual line abundances. For elements where only one line was measurable, 0.10 dex has been used to represent this standard error. Besides Fe, we have implemented line-by-line non-LTE corrections for Na (Lind et al. 2011), Mg, and Ca (Lind et al. in preparation).

4.3.4. Distances to the stars

Distances to the stars have been estimated by calculating the distance modulus from the absolute and apparent magnitudes. The SkyMapper photometry that we used in the initial selection was taken early on in the telescope’s commissioning period, and as such was not calibrated to other magnitude systems. Therefore we chose to use 2MASS J , H , and K_S bands, from which we reconstructed the bolometric flux of the stars, fitting synthetic model fluxes to the stellar parameters of the stars and reddening values taken from Schlafly & Finkbeiner (2011). As the majority of the ten stars analysed here lie more than 10° away from the plane, they are not covered by the more recently published bulge reddening maps such as OGLE (Nataf et al. 2013) and VVV (Gonzalez et al. 2011) and instead the Schlafly & Finkbeiner (2011) reddening map has been employed. The process of reconstructing the bolometric fluxes is documented in Casagrande et al. (2006) and Casagrande et al. (2012). Absolute magnitudes were calculated from the Stefan-Boltzmann relation, specifically using

$$M_{\text{bol}} = M_{\text{bol},\odot} - 2.5 \log \frac{L_*}{L_\odot}, \quad (4.1)$$

where

$$L_* = \frac{4\pi\sigma T_{\text{eff}}^4 M_* G}{10^{\log g_*}}. \quad (4.2)$$

We have assumed a stellar mass of $M_* = 0.8 \pm 0.2 M_\odot$ throughout. This is appropriate for the very old, metal-poor stars studied here; the mass range includes stars of ages ranging from 10 up to ~ 36 billion years old (estimated using the mass-luminosity relation for main-sequence stars). Nearly all bulge stars found to date have been shown to have ages greater than 10 billion years (Bensby et al. 2013), with only some metal-rich dwarfs found with younger ages, so this age limit doesn't impose any realistic assumption on our distances.

4.4. Analysis of previously studied stars

This study follows on from the chemical abundance results published in the first paper of the EMBLA Survey (Howes et al. 2014). It is important to include those stars published in Howes et al. (2014) as part of the Gaia-ESO Survey (GES, Gilmore et al. 2012; Randich et al. 2013) when analysing the sample described here for a fair comparison. Full details of the observations and original analysis of the GES stars can be found in Howes et al. (2014) and corresponding survey papers, but we will briefly outline it here. A further 23 stars have been analysed in Howes et al. (2015a), and a chemical analysis of those results will be the subject of a forthcoming paper.

Table 4.4 Details of the four stars originally published in Howes et al. (2014).

Star (SMSS)	l (°)	b (°)	V_{GC} (kms ⁻¹)	S/N* (kpc)
J182153.85-341018.8	359.2	-9.3	-237.68	73
J183617.33-270005.3	7.1	-8.9	-129.48	37
J175510.50-412812.1	350.2	-8.0	-48.28	14
J175652.43-413612.8	350.2	-8.4	216.46	14

* Median S/N per pixel calculated across total wavelength range.

The Gaia-ESO Survey is a public spectroscopic survey taking place on the VLT, aiming to observe approximately 100,000 stars in the Galaxy. All major components of the Milky Way are being covered, including the bulge. The stars are observed using the FLAMES multi-object spectrograph (Dekker et al. 2000), which combines both GIRAFFE and UVES to observe up to 138 targets at once. As part of a collaboration between the SkyMapper and GES teams, EMP targets are observed with the UVES fibres in both halo and bulge fields. In 2012, six bulge targets were observed for the EMBLA Survey, resulting in spectra covering the region of 480-680 nm at a resolving power of 47,000. Unfortunately, two of the spectra had an average S/N lower than 10, and were unable to be analysed, but

four spectra were processed (Table 4.4). The data were reduced and normalised along with the rest of the survey data (Sacco et al. 2014), but the analysis was separate from the standard GES UVES analysis (Smiljanic et al. 2014) due to the metal-poor nature of the stars. Four of the analysis nodes provided accurate atmospheric parameters for the Gaia metal-poor benchmark stars (Jofre et al. 2014), and so their parameters for the EMBLA stars were combined in a weighted average along with our own analysis. This analysis was the alternate method using excitation balance along with an empirically calibrated offset, as described in Section 4.3.2. The uncertainties were calculated as the standard errors between the five different analysis methods.

In order to compare the results from these stars with the stars observed with Magellan, we have also analysed them using the same methods described in Section 4.3.2. Unfortunately the S/N in two of these stars was too low to ascertain sensible T_{eff} estimates. Instead for these two stars, we again used the alternate temperatures derived from excitation-balance, offset by +325 K in a similar determination to that of SMSS J182600.09-332531.0 and SMSS J183128.71-341018.4 using the Magellan spectra described above. The parameters from both Gaia-ESO and this paper are compared in Table 4.5, and the new abundances calculated are listed in Table 4.6.

In general, the two sets of parameters are very similar, and provide confidence in our method of determination. The average temperature offset (all offsets described are written as Gaia-ESO - new parameters) between the four stars is -13 ± 24 K, well within the predicted systematic uncertainties. Due to the wide variety of S/N between the four stars, and the differences in temperature determinations, it would perhaps be better to consider separately the two stars with high S/N, and the two with low S/N. In this case, the temperature offset for the "high-S/N" stars is +68 K, but for the "low-S/N" stars -93 K. The differences between the $\log g$ and $[\text{Fe}/\text{H}]$ values for the two sets of analysis are also minor, well within the uncertainties. The average $\log g$ offset is $+0.03 \pm 0.10$ dex. The average $[\text{Fe}/\text{H}]$ offset is -0.08 ± 0.03 dex, and all four stars have individual differences of less than 0.25 dex.

There are large differences in the uncertainties quoted for each analysis. The statistical uncertainties used in the GES analysis, whilst indicative of the size of the differences between the several nodes' analyses, do not accurately reflect the difference in uncertainty caused by the large variation in S/N of the spectra. In particular, the quoted uncertainties for SMSS J175510.50-412812.1 are smaller than for the other three stars, despite the low S/N of that star.

These differences in parameters have led to offsets in the estimated distances to the stars, particularly for the low-S/N pair. The average offset is -2.0 kpc, the average for the high-S/N stars is only -0.4 kpc, well within the rather large distance uncertainties. Both low-S/N stars have very different distances - altering their position in the Galaxy from both being consistent with being in the bulge (as shown in Figure 4 of Howes et al. (2014)) to most likely not being in the bulge.

Table 4.5 Comparison of the new parameters with the GES recommended parameters. The ξ_t uncertainty is ± 0.2 in both cases.

Star (SMSS)	Gaia-ESO parameters						New parameters			
	$d_\odot$	T_{eff}	$\log g$	[Fe/H]	ξ_t	$d_\odot$	T_{eff}	$\log g$	[Fe/H]	ξ_t
J182153.85-341018.8	7.0 $\pm$ 3.2	4947 $\pm$ 85	1.41 $\pm$ 0.49	-2.60 $\pm$ 0.31	2.3	7.6 $\pm$ 2.1	4896 $\pm$ 100	1.33 $\pm$ 0.12	-2.51 $\pm$ 0.07	1.9
J183617.33-270005.3	5.3 $\pm$ 1.9	4926 $\pm$ 137	1.97 $\pm$ 0.35	-2.72 $\pm$ 0.28	2.4	5.5 $\pm$ 1.6	4842 $\pm$ 100	1.93 $\pm$ 0.14	-2.80 $\pm$ 0.10	2.1
J175510.50-412812.1	12.4 $\pm$ 4.4	5187 $\pm$ 59	2.23 $\pm$ 0.31	-2.57 $\pm$ 0.19	2.0	21.9 $\pm$ 12.4	5266 $\pm$ 100	1.75 $\pm$ 0.32	-2.36 $\pm$ 0.32	2.3
J175652.43-413612.8	5.4 $\pm$ 2.8	5035 $\pm$ 196	2.65 $\pm$ 0.54	-2.48 $\pm$ 0.23	1.5	3.1 $\pm$ 1.1	5142 $\pm$ 100	3.15 $\pm$ 0.17	-2.39 $\pm$ 0.13	1.1

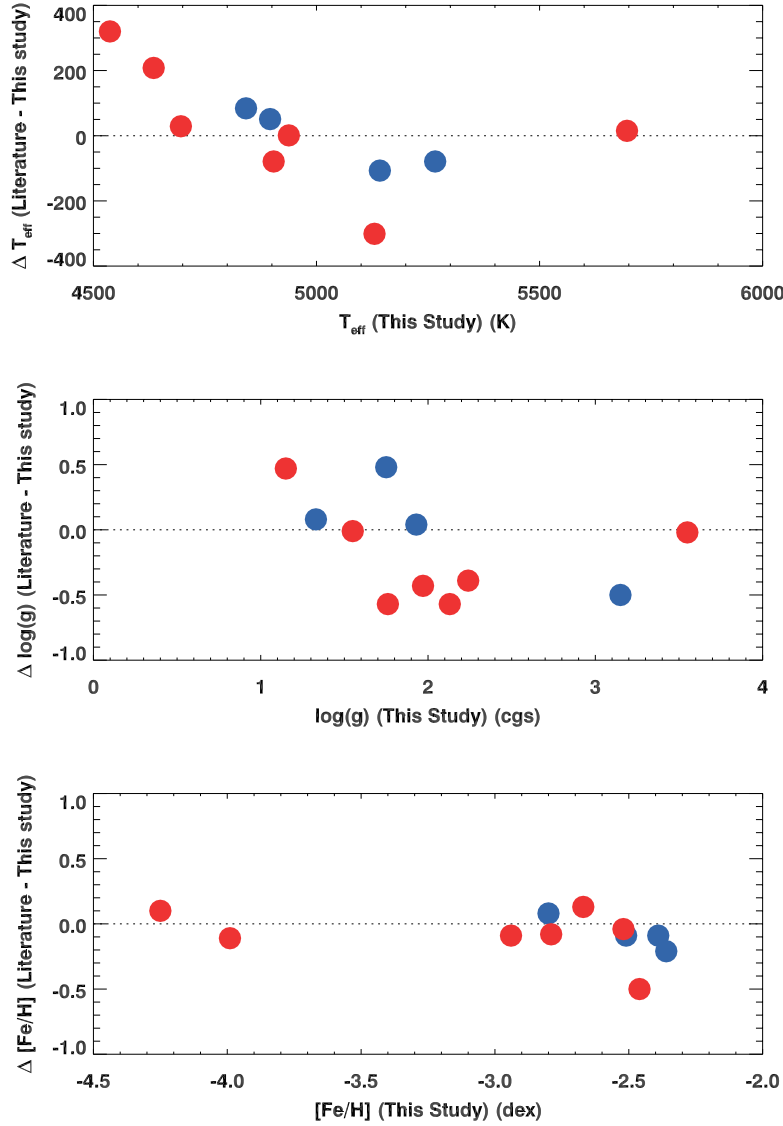


Figure 4.7 Comparison of the stellar parameters of the four GES stars (blue dots), along with seven halo stars from the literature (red dots). The parameters are derived in this paper, compared with those from Howes et al. (2014), and the literature values (Yong et al. 2013a).

To further investigate the reliability of our methodology for determining stellar parameters, we have also derived parameters for seven literature stars. We took five halo stars from Yong et al. (2013a), where the spectra were also observed using MIKE on Magellan. Furthermore we analysed the two Gaia benchmark metal-poor stars HD122563 and HD140283, using the publicly available UVES-POP spectra (Bagnulo et al. 2003), but have taken the parameters for these stars from Yong et al. (2013a), for consistency. The results of this comparison are shown in Figure 4.7, which reveals no obvious trends in the offsets between the two parameter sets, with our $[\text{Fe}/\text{H}]$ measurements in very good agreement with the literature values. The mean offset for $[\text{Fe}/\text{H}]$ is -0.08 dex, and the standard error of the mean, 0.03 dex, which is well within the levels of the reported uncertainties. For $\log g$ the average difference is -0.22 , with a standard error of the mean of 0.06 . The differences in T_{eff} are more noticeable, particularly at low temperatures. Of the two stars with the lowest T_{eff} values in our analysis,

Table 4.6 Chemical abundances for all 14 stars. The full table can be found in Appendix Table A.2.

Star (SMSS)	[C/Fe]	[O/Fe]	[Na/Fe]	...
J182637.10-342924.2	0.68 ± 0.20	-	-0.36 ± 0.14	...
J182600.09-332531.0	-0.41 ± 0.22	-	-0.10 ± 0.18	...
J182601.24-332358.3	0.32 ± 0.20	-	0.27 ± 0.18	...
J182753.81-334607.7	-0.41 ± 0.25	-	-0.40 ± 0.14	...
...	...	...	...	...

one is HD122563. The Balmer line temperature we find for that star is 4635 K, whereas the value in Yong et al. (2013a) is 4843 K (from photometry). Other literature analyses for this star give temperatures of 4665 K (Bergemann et al. 2012, a non-LTE analysis) and 4608 K (temperatures taken from interferometry), which are much closer to our value. The coolest star, CD -38° 245 ([Fe/H] = -4.0), has a difference of 300 K between our two methods, but it is not clear why. On average, however, there is only a mean separation between our temperatures of +28 K, with a standard error of 28 K. We thus conclude that our stellar parameters are on a scale consistent with other state-of-the-art analyses of metal-poor stars.

4.5. Results

4.5.1. Positions and Kinematics

All the stars were originally chosen from the SkyMapper bulge fields shown in Fig. 4.1, covering roughly a $20^\circ \times 20^\circ$ area centred on the Galactic centre. The stars analysed here were chosen after the first observing runs in 2012, which is why the majority are all from one field, close to $(l, b) = (0, -10)$. Combining their positions with the derived distances, we can confirm that the majority of the stars in the sample are situated within the Milky Way bulge. Figure 4.8 shows the positions of each of the stars as viewed from the side of the Galaxy, with the Sun positioned at $(-8.5, 0)$ (Bovy et al. 2012). A circle of 3.43 kpc demonstrates the simplest criteria on bulge membership (Robin et al. 2012), although we note here that the bulge is actually a more complex bar shape, extending further out into the plane along the Y axis, and reaching above the plane into a "peanut" shape, as seen in recent work matching models to bulge data (Shen et al. 2010; Wegg & Gerhard 2013; Ness et al. 2014; Nataf et al. 2015). Nine out of the 14 stars analysed here lie within this 3.5 kpc radius, and another three lie just outside the circle (two in the foreground, one in the background), which, when considering the stellar parameters uncertainties and a more realistic bulge, could well be members also. The distance uncertainty for the two stars seemingly located furthest away are so large that they are also consistent with residing in the bulge.

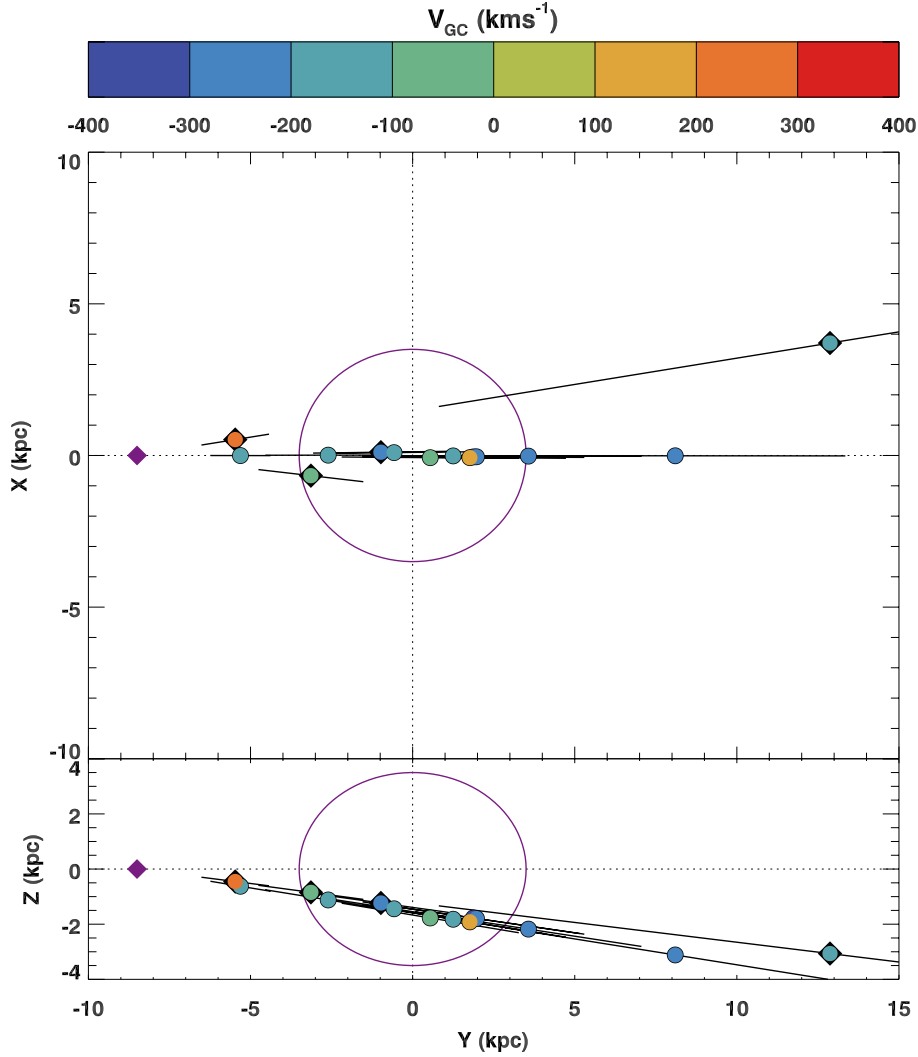


Figure 4.8 A diagram showing the positions of our stars in the Milky Way, viewed from above and from the side, with the Galactic centre at (0,0) and the Sun at (−8.5, 0), shown as the purple diamond. The purple circle represents a 3.5 kpc sphere around the centre of the Galaxy. Each star is coloured according to its Galactocentric velocity, with the error bars calculated in the projection plane from the distance uncertainties. The GES stars are shown as diamond symbols.

A key component of the assertion that metal-poor stars in the bulge are truly among the oldest stars surviving in the Milky Way is the question of whether these stars are "true" bulge stars, or merely halo stars just passing through the bulge region on eccentric orbits. Currently, this is a question that cannot be easily answered due to the lack of published, reliable proper motions and thus meaningful orbit information of these metal-poor stars. There are proper motions for these 14 stars in existing catalogues, but the large uncertainties of approximately 5 mas yr^{-1} mean that any orbits derived are very uncertain and open to the possibility of being either bulge or halo orbits. Until the publication of new proper motion catalogues of the outer bulge, such as OGLE-IV (Udalski et al. 2015) or VVV (Minniti et al. 2010), we cannot eliminate either possibility that these stars have bulge-like or halo-like orbits. Accurate distances would also improve the levels of uncertainties for the orbits; here parallaxes from Gaia should be helpful in the near future.

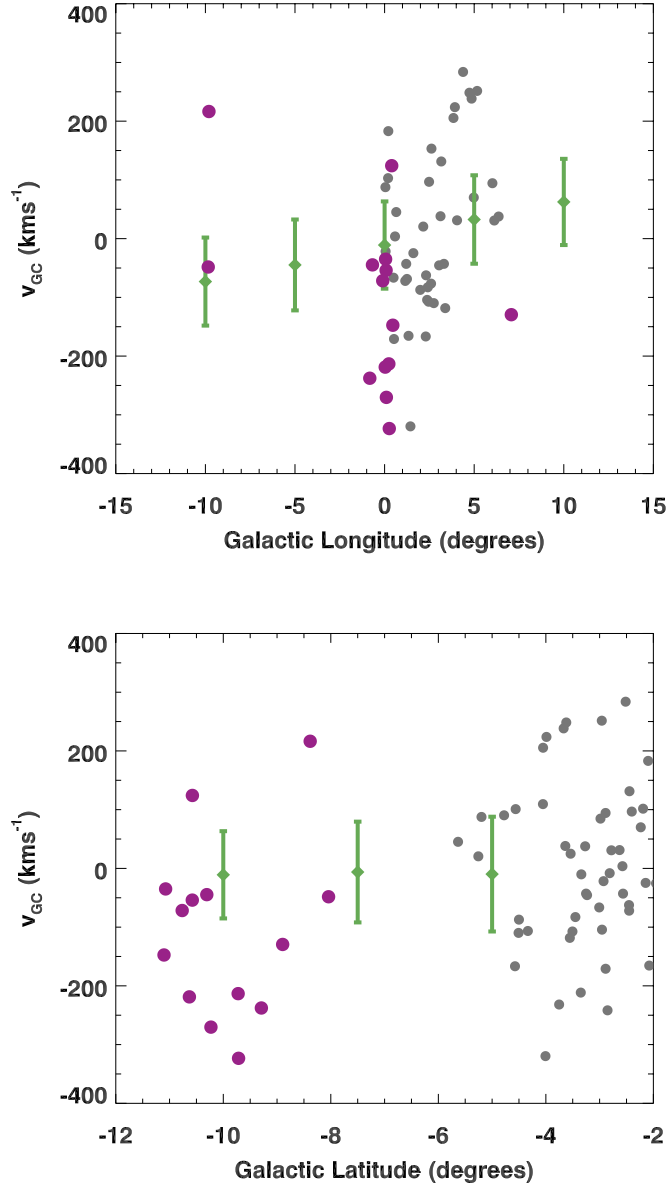


Figure 4.9 Plots comparing the Galactocentric velocity to both Galactic longitude and latitude. Our sample is shown as purple circles, compared with the bulge dwarf stars of Bensby et al. (2013) (grey circles), and the velocity dispersions of certain ARGOS fields (Ness et al. 2013b) at similar latitudes and longitudes (green lines).

A potentially good, independent tracer of the relevant stellar population are RR Lyrae, as they are old, metal-poor, and have standardisable distances. The BRAVA-RR survey of Galactic bulge RR Lyrae stars has found that the fraction of RR Lyrae stars toward the bulge with orbits more consistent with a halo-rather-than-bulge dynamical origin may be as low as 1% (Kunder et al. 2015).

We can consider the radial velocities of the stars - which we have determined from their spectra to an accuracy of $\sim 1 \text{ km s}^{-1}$ - to help constrain their possible dynamics. To compare the velocities to other samples of bulge stars, they have been converted into Galactocentric velocities, which correct for the solar motion around the Galaxy. To do this we have used

the equation originally from Mihalas & Binney (1981), given in Ness et al. (2013b):

$$V_{GC} = V_{helio} + 220 \sin l \cos b + 16.5(\sin b \sin 25 + \cos b \cos 25 \cos [l - 53]), \quad (4.3)$$

where V_{helio} is the star's heliocentric velocity, and l and b are the Galactic coordinates in degrees. The velocity dispersion amongst these 14 stars is quite large – $\sigma = 149.6 \text{ km s}^{-1}$ – compared to the velocity dispersion found by the ARGOS survey (Ness et al. 2013b) in the closest field to our sample at $(l, b) = (0, -10)$ of $\sigma = 74.3 \text{ km s}^{-1}$. Whilst the velocity dispersion of the EMBLA stars is more characteristic of a halo population, the small number of stars involved makes it difficult to say anything meaningful about this quantity. Instead, we have compared our sample of stars to the microlensing sample of Bensby et al. (2013) (Figure 4.9). It is clear that both samples have a wide range in velocities, spanning more than 700 km s^{-1} , and that for a small sample, the EMBLA stars do not appear more dispersed than the Bensby et al. (2013) stars. There is a positional offset between the two groups; the Bensby et al. (2013) stars are found closer to the Galactic plane, $b \leq -6$, whereas the EMBLA stars are at high negative latitudes, $b < -8$. This offset could make a difference to what we expect dynamically of the two sets.

4.5.2. Stellar Parameters

As part of the photometric selection for EMBLA, we attempted to limit the stars to those on the RGB using the colour-magnitude diagram (CMD). However, those stars observed in high-resolution here were all selected from early fields observed at the AAT during our pilot observations. At that time, the CMD cut had not been introduced into our selection process. Therefore the numbers of dwarfs that were observed is much higher than in fields observed later. Despite this, the stars chosen for high-resolution follow-up were confirmed spectroscopically as giants (as displayed on the HR diagram in Figure 4.10), and as mentioned previously, mostly contained within the bulge region.

The metallicities of the stars in our sample are some of the lowest found in the Galactic bulge. Schlafman & Casey (2014) detail the discovery of three stars with metallicities of $[\text{Fe}/\text{H}] = -3.02, -2.84$, and -2.70 , around the same metallicities as the most metal-poor stars here. Between the EMBLA results (Howes et al. 2014, 2015a), the APOGEE metal-poor bulge stars (García Pérez et al. 2013), and the Casey & Schlafman (2015) stars, a total of 37 stars have now been studied in high-resolution with $[\text{Fe}/\text{H}] < -2.0$, providing the observational evidence that metal-poor stars do exist in the central regions of the Galaxy. Those metal-poor stars with the lowest binding energies would be more likely to have formed at redshifts $z > 15$ (Salvadori et al. 2010), making the need for further detailed work into these stars' kinematics vital.

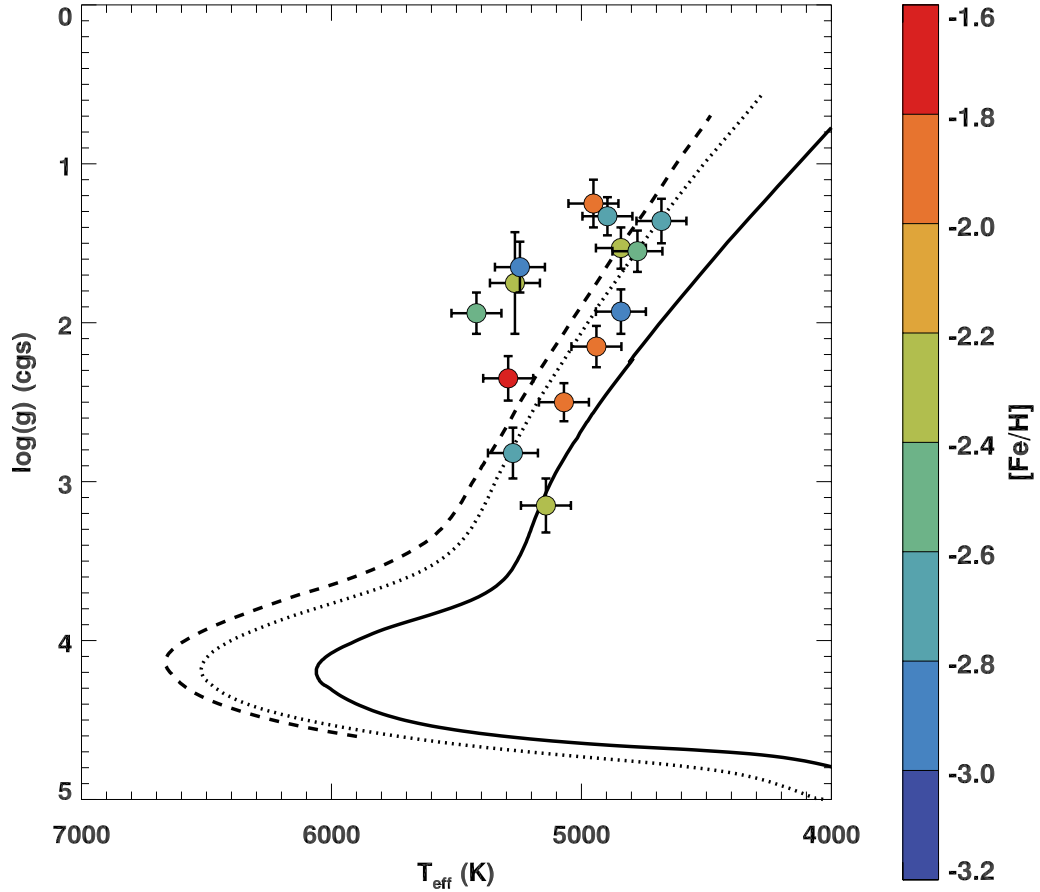


Figure 4.10 The HR diagram for all 14 stars discussed, given different colours to indicate their metallicity. Also shown are three 14 Gyr Dartmouth isochrones (Dotter et al. 2008), at metallicities of $[\text{Fe}/\text{H}] = -1$ (solid line), -2 (dotted line), and -3 (dashed line). All three are α -enhanced, with $[\alpha/\text{Fe}] = 0.4$.

4.5.3. Chemical Abundances

The elemental abundances that have been measured are displayed in Figures 4.11, 4.12, and 4.13, shown with respect to their $[\text{Fe}/\text{H}]$ values. Also shown are bulge and halo samples taken from the literature (Bensby et al. 2013; Alves-Brito et al. 2010; García Pérez et al. 2013; Roederer et al. 2014; Yong et al. 2013a). In case there are any noticeable differences between the sample observed as part of GES or the sample observed on MIKE, perhaps caused by systematic differences between the two methods of observation, they are shown as different colours - however, there does not appear to be any significant difference. In an attempt to identify any trends in the abundance data, Table 4.7 shows the slope of linear fits to $[X/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$. It is not presumed that a linear trend is the most appropriate fit to the data, only that this provides a first attempt to identify trends across different elements, and that there is limited consensus in the literature on a better method to do this. Table 4.7 also gives the same linear slopes calculated in Yong et al. (2013a) from the giant stars, as a comparison. Notably the errors given for the Yong et al. (2013a) slopes are smaller than those calculated for the stars in this paper; this is likely a consequence of our much smaller sample size.

Table 4.7 The slope of the linear fit made to the abundance data for each element and the associated error. For comparison, the linear fits from the giant stars in Yong et al. (2013a) are given. No slope could be calculated for [O/Fe] as there are only two measurements.

Abundance Ratio	Linear Slope (this paper)	Linear Slope (Yong et al. 2013a)
[C/Fe]	-0.10 ± 0.17	
[Na/Fe]	-0.29 ± 0.17	0.24 ± 0.07
[Mg/Fe]	-0.19 ± 0.12	-0.03 ± 0.04
[Al/Fe]	-0.13 ± 0.19	0.11 ± 0.06
[Si/Fe]	-0.14 ± 0.15	-0.30 ± 0.18
[K/Fe]	0.09 ± 0.20	
[Ca/Fe]	-0.14 ± 0.10	0.02 ± 0.03
[Sc/Fe]	0.00 ± 0.08	0.08 ± 0.05
[Ti/Fe]	0.03 ± 0.08	0.14 ± 0.04
[Cr/Fe]	-0.03 ± 0.16	0.15 ± 0.03
[Mn/Fe]	0.44 ± 0.20	0.33 ± 0.06
[Co/Fe]	-0.44 ± 0.20	-0.38 ± 0.04
[Ni/Fe]	-0.13 ± 0.14	-0.02 ± 0.04
[Zn/Fe]	-0.49 ± 0.13	
[Sr/Fe]	0.18 ± 0.17	0.89 ± 0.21
[Y/Fe]	-0.18 ± 0.09	
[Zr/Fe]	-0.07 ± 0.13	
[Ba/Fe]	0.59 ± 0.14	0.38 ± 0.22
[La/Fe]	0.98 ± 0.35	
[Eu/Fe]	0.16 ± 0.16	

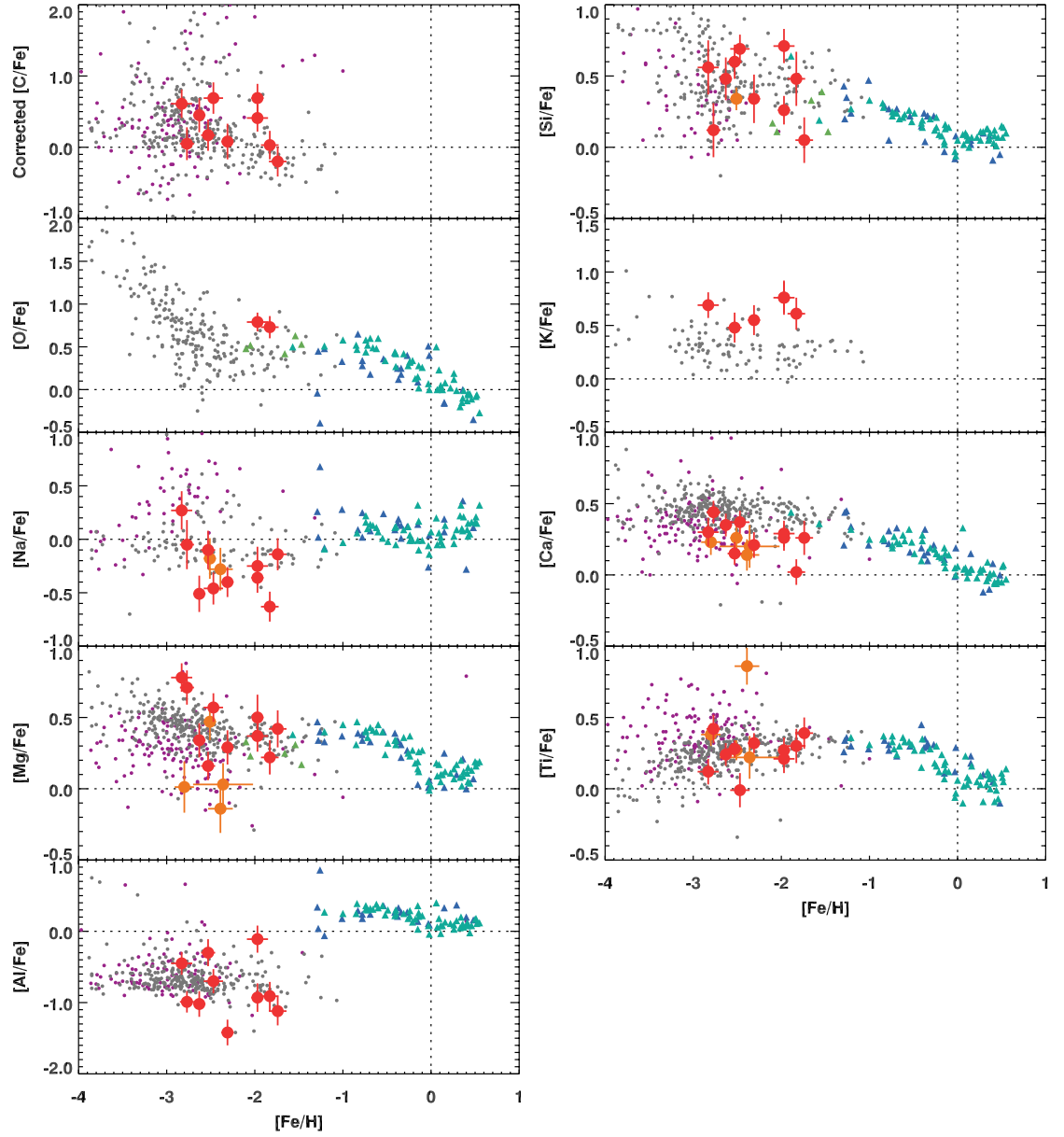


Figure 4.11 Abundance trends of elements C to Ti, with respect to $[\text{Fe}/\text{H}]$. Both the Magellan data (red circles) and Gaia-ESO data (orange circles) are shown. For comparison, we show the literature samples of both bulge (triangles) and halo (dots) stars, taken from Bensby et al. 2013 (turquoise), Alves-Brito et al. 2010 (blue), García Pérez et al. 2013 (green), Roederer et al. 2014 (grey), and Yong et al. 2013a (purple).

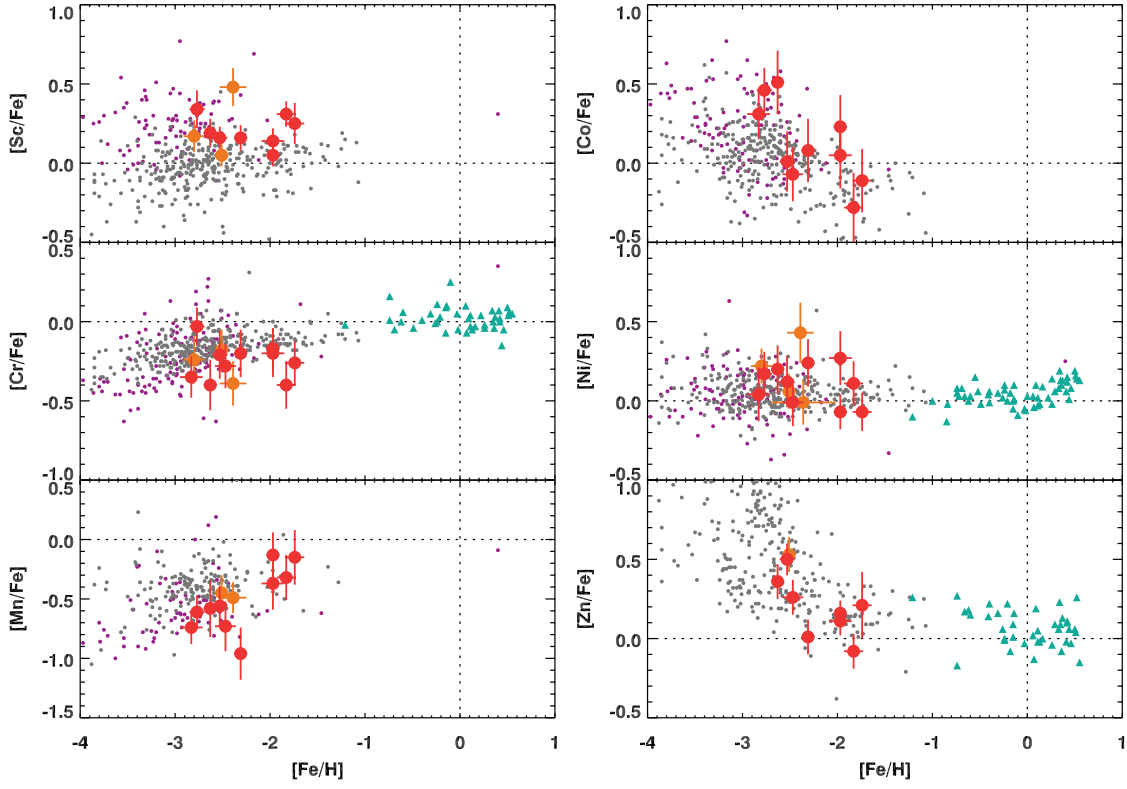


Figure 4.12 Abundance trends for the iron-peak elements, symbols as in Figure 4.11.

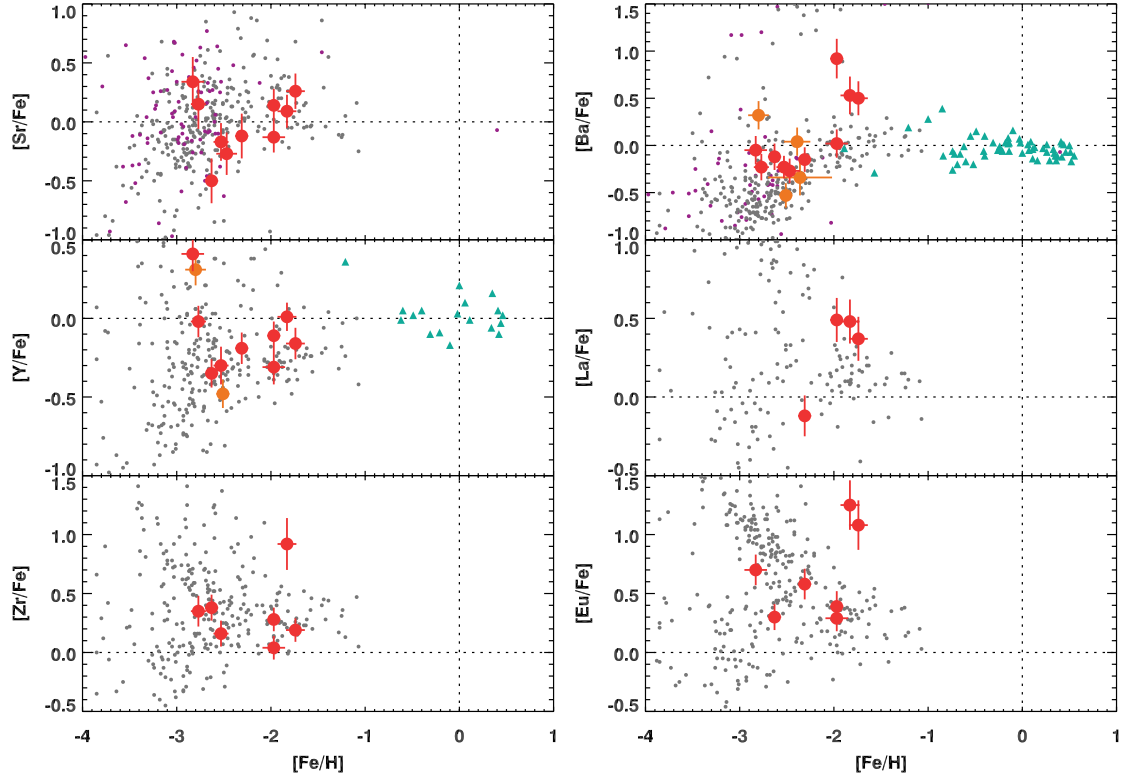


Figure 4.13 Abundance trends for the neutron capture elements, symbols as in Figure 4.11.

Carbon

The carbon abundances in the sample have a wide range, covering values from as low as $[C/Fe] = -0.41$, up to 0.68. This wide scatter is typical of metal-poor stars, like those found in the halo. Interestingly, however, is the lack of stars with much higher C abundances. For some time now, it has been accepted that metal-poor stars broadly fit into two categories; the C-normal stars and the C-enhanced (CEMP) stars (first categorised in Beers & Christlieb (2005); Norris et al. (2013b) present a recent discussion on the differences between the two populations). Whether one considers the criterion for a carbon-enhanced star to be $[C/Fe] > 1.0$ (Beers & Christlieb 2005) or $[C/Fe] > 0.7$ (Aoki et al. 2007), none of these bulge stars make the grade. There are several reasons this could be, firstly, as the stars have already started to evolve up the red giant branch, their photospheric C abundances may have become depleted due to envelope mixing. We have applied theoretical corrections for this (taken from Placco et al. 2014) and displayed the result in Figure 4.11, which shows the C levels the stars would have been born with, rather than that observed now. Whilst these corrections have decreased the number of stars with sub-solar C levels, the stars with the higher C abundances have been largely unaffected, as their surface gravities imply they are less evolved. Even with the correction, none of the bulge stars have $[C/Fe] \geq 0.7$.

A second reason for a lack of CEMP stars in our sample could be a selection bias introduced by our SkyMapper photometric selection. A recent paper on the SkyMapper halo EMP search (Jacobson et al. 2015) has found no CEMP stars with $[C/Fe] \geq 2$, and suggested that, due to the strong CH absorption of such stars, photometric colours may have been affected, placing them outside the selected region in the colour-colour diagram (Fig. 4.2). Jacobson et al. (2015) do not describe a lack of CEMP stars, however, finding 20% of their sample have $[C/Fe] \geq 0.7$, in line with the values expected from previous studies. Therefore, whilst possible that the EMBLA Survey could have missed stars with extremely large C enhancements due to selection effects, stars with mild C enhancements should still have been found.

Perhaps the most likely explanation for the lack of CEMP stars is small number statistics. This sample contains 10 stars with measured C abundances; the literature suggests that 21% of stars with $[Fe/H] < -2.0$ should have $[C/Fe] \geq 1.0$ (Lucatello et al. 2006), so we would only expect to find approximately two CEMP stars. Only with a larger sample can we confirm that there are no, or very few, CEMP stars in the bulge. If this is confirmed, it would have wide ranging implications for the studies of first star formation. Overabundances of C have been frequently cited as the observational evidence that C and O are required to provide the cooling mechanisms needed for early gas clouds to condense into stars at the very lowest iron abundances (Frebel et al. 2007). Tumlinson (2010) suggested that the number of CEMP stars should increase with increasing age of the population studied - indicating that the CEMP fraction should be larger in the bulge than the halo - the opposite of our current results, while mindful of the relatively small number statistics.

Light Elements - O, Na, Al, K

We measured O in those stars where the forbidden line at 630.0 nm was detectable, but unfortunately due to the metal-poor nature of the stars, this was only possible for two of them, both with $[\text{Fe}/\text{H}] \approx -2.0$. The two measurements we have are unusually high - averaging 0.76 whereas the APOGEE sample (García Pérez et al. 2013) at approximately the same metallicity average 0.52 across five stars. This difference could be due to the different lines measured; the APOGEE spectra are in the infrared with the oxygen abundances measured from OH lines.

The Na abundances have been corrected for non-LTE effects using Lind et al. (2011), as have the abundances for the stars in the Roederer et al. (2014) sample (grey circles), and on the whole, our abundances match well, perhaps our Na abundances are slightly lower. As the Yong et al. (2013a) sample have not been corrected for non-LTE effects, it is not surprising that those stars do not match our data, nor the overall trend as shown in Table 4.7. Like Na, the Al abundances are predominately sub-solar. Non-LTE effects have not been considered for our stars nor the literature sample, it is expected that these corrections would bring the abundances closer to the solar $[\text{Al}/\text{Fe}]$ value (Andrievsky et al. 2008). It appears that the dispersion in our Al abundances is larger than the Roederer et al. (2014) sample, similar to that found in the alpha elements. The linear trend in our Al values varies in direction from the Yong et al. (2013a) (-0.13 compared to 0.11), although the large error in our computed slope may explain this. Our K abundances are noticeably higher than those in the halo literature (Roederer et al. 2014), although ours have not been corrected for non-LTE effects, whereas the literature stars have (using Takeda et al. 2002) and note that the corrections resulted in lower abundances than before.

Alpha Elements

One of the most intriguing results found in Howes et al. (2014) was the intrinsic scatter in the α -elements (particularly in Mg and Ti), a marked difference from literature metal-poor halo stars. This is now confirmed with a larger dataset. Furthermore, it is clear that Si is also affected - the dispersion of Mg, Si and Ti are respectively $\sigma = 0.26, 0.22$, and 0.19. The average measurement uncertainties for these elements are 0.13, 0.14, and 0.10; the dispersion cannot be explained by the size of the uncertainties. Compared to halo stars of the same metallicity the abundances found in the EMBLA sample are much more dispersed: the dispersion of Mg in the Yong et al. (2013a) giant sample about a linear fit is $\sigma = 0.13$, and for those stars with $[\text{Fe}/\text{H}] > -3.0$ in Roederer et al. (2014), the dispersion of Mg is $\sigma = 0.12$. There are several examples of bulge stars with extreme differences between the different elements, for example SMSS J182948.48-341053.9, which has $[\text{Si}/\text{Fe}] = 0.69$ and $[\text{Ti}/\text{Fe}] = -0.01$, and SMSS J175652.43-413612.8 with $[\text{Mg}/\text{Fe}] = -0.18$ and $[\text{Ti}/\text{Fe}] = 0.86$. Only a couple of stars with large variations in their α abundances have been found in the halo, such as HE 2136-6030

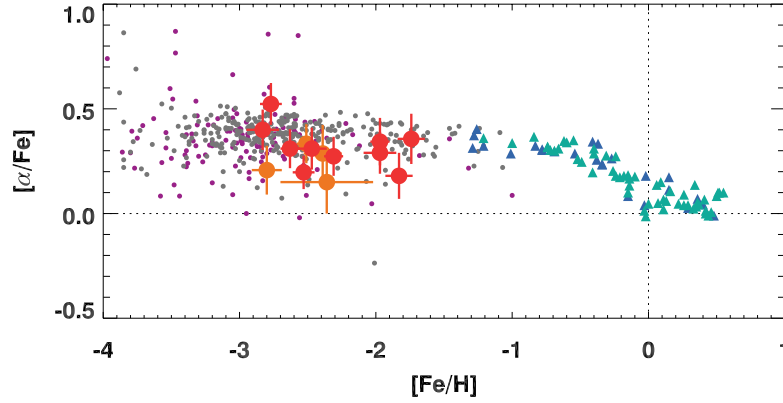


Figure 4.14 The α abundance trends of the 14 stars, compared to literature values (symbols as in Fig. 4.11). Here $[\alpha/\text{Fe}] = ([\text{Mg}/\text{Fe}] + [\text{Ca}/\text{Fe}] + [\text{Ti}/\text{Fe}])/3$.

(Yong et al. 2013a) with $[\text{Si}/\text{Fe}] = 1.20$ but $[\text{Mg}/\text{Fe}] = 0.08$. These large differences perhaps suggest inhomogeneous mixing at the time of formation, indicative that these stars were formed early in the life of the Universe.

The caveat to this story of a wide scatter between different α -elements and different stars is Ca. The fourteen stars show a much tighter trend in $[\text{Ca}/\text{Fe}]$, with a dispersion of only $\sigma = 0.11$, and they appear to plateau in a similar way to halo stars and stars from the thick disc. Averaging over the alpha elements (Figure 4.14), we find they are at the level we would expect for metal-poor stars - that is, α -enhanced, suggesting the gas they were formed from was polluted by fairly massive core-collapse supernovae. It is interesting to note that, for three of the four α -elements, the level of enhancement is slightly lower than that seen in the halo (noticeable in $[\text{Ca}/\text{Fe}]$ when compared to the Roederer et al. (2014) sample), which was similarly noted in the previous study of metal-poor bulge stars by García Pérez et al. (2013). The average values and uncertainties of the four compared to the giants of the Yong et al. (2013a) sample in parentheses are $[\text{Mg}/\text{Fe}] = 0.35 \pm 0.13$ (0.30), $[\text{Si}/\text{Fe}] = 0.42 \pm 0.14$ (0.57), $[\text{Ca}/\text{Fe}] = 0.25 \pm 0.10$ (0.32), and $[\text{Ti}/\text{Fe}] = 0.31 \pm 0.10$ (0.32) (bearing in mind that we correct both Mg and Ca for non-LTE effects). A larger sample of stars is needed to disentangle any trend from the measurement uncertainties.

The linear fits to the Mg, Si, and Ca element plots are very similar - all negative and between -0.1 and -0.2 , suggesting a positive trend with declining metallicity, albeit a small one. Only Ti has a flat trend, 0.03 , which is expected of metal-poor alpha elements. Compared to the slope values of Yong et al. (2013a), our values appear quite different, in contrast to the appearance of the figures. For both Mg and Ca, our gradients are 0.16 dex lower than the gradients of Yong et al. (2013a), a value that is very similar to the magnitude of the slope. Yong et al. (2013a) has nearly flat trends for both of these elements. These results are unsurprising, at the $[\text{Fe}/\text{H}]$ values of both samples of stars we would expect to see a flat gradient / the sample in this paper is much smaller though, and likely suffers from small number statistics. For Si, however, our value is 0.16 less negative than the -0.30 slope found in Yong et al. (2013a), a more surprising outcome. Perhaps this difference is explained by

the differences in the metallicity ranges covered in the two samples - the majority of the Yong et al. (2013a) stars have $[\text{Fe}/\text{H}] < -3$, unlike our stars. It must also be remembered that a linear fit to the trends shown in these plots is only a first approximation at understanding them, and unlikely to reveal the true picture.

Iron-peak Elements

All iron-peak elements measured in this work match well when compared to the literature values in the halo. It is expected that both Cr and Mn have large positive NLTE corrections (Bergemann & Cescutti 2010), which, when applied would bring them close to the solar values (the halo literature stars have also been measured with LTE assumptions, so would have similar NLTE corrections). Unlike in Casey & Schlafman (2015), no unusually low abundances of Sc or Mn are found in these stars. In particular, the normal abundance of Sc found in our stars is of interest due to the predictions that stars originating from material produced in Pop. III supernovae would have particularly low abundances of odd-Z elements like Sc (Heger & Woosley 2010). Models have been produced, however, which enhance the amount of Sc produced in Pop. III stars (Umeda & Nomoto 2005), provided the densities of matter in the supernovae explosions are lowered for some reason.

Neutron-capture Elements

In general, the abundances of the neutron-capture elements measured here match the trends found in halo metal-poor stars. The overriding feature of these elements in halo stars is a very large scatter; this has been found in all studies of metal-poor stars to date (McWilliam et al. 1995; Francois et al. 2007; Yong et al. 2013a; Roederer et al. 2014), and there have been numerous attempts to explain the various abundance patterns seen (e.g., Travaglio et al. 2004, Roederer et al. 2010). One such explanation is the introduction of yields from fast-rotating massive stars (or spinstars), which would produce elements formed through the s-process (Maeder & Meynet 2012). Typically the s-process occurs in AGB stars, which are less massive than the stars that undergo core-collapse supernovae, and so it occurs on longer timescales (Busso et al. 1999). Therefore fast-rotating massive stars provide a theoretical reason why s-process elements are found in metal-poor stars; works such as Cescutti et al. (2013) and Cescutti & Chiappini (2014) have explained the trends seen in the halo.

Previous studies of bulge stars have also attempted to find the signatures of spinstars (Barbuy et al. 2014) at higher metallicities than those studied here. Cescutti et al. (2013) show that incorporating spinstar models into the chemical evolution model leads to a larger scatter of α -elements, as we have found. However, one of the key indicators of these spinstars is a high $[\text{Sr}/\text{Ba}]$ ratio, (> 0.5), which is not borne out in our data (Figure 4.15).

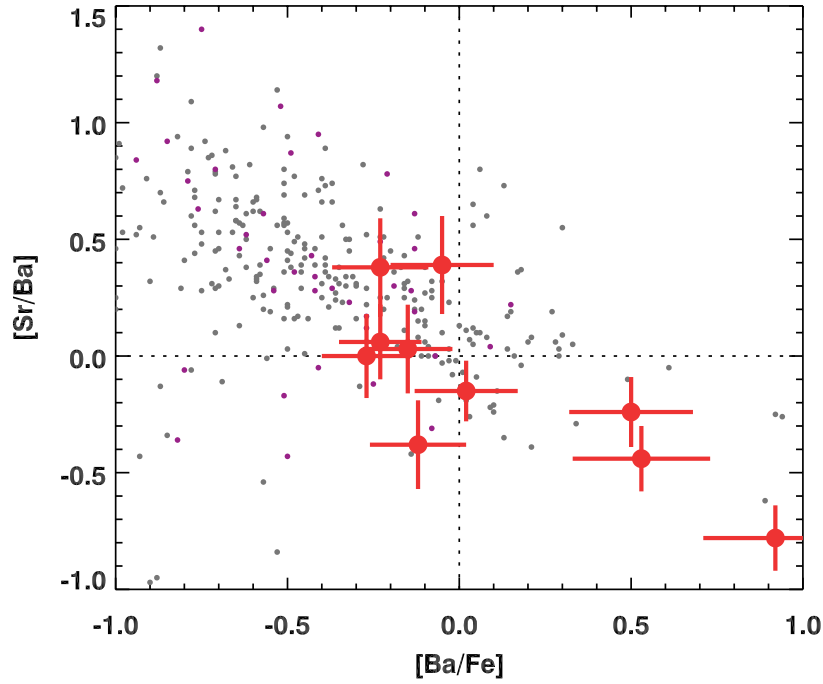


Figure 4.15 $[\text{Sr}/\text{Ba}]$ with respect to $[\text{Ba}/\text{Fe}]$, compared to literature values (symbols as in Fig. 4.11).

Another key indicator is high Y abundances, particularly when compared to Ba, and again our data show the opposite of this (Fig. 4.16). Our bulge stars have relatively low abundances of both Sr and Y. The Ba abundances too are predominately sub-solar, but there is one star (SMSS J182637.10-342924.2) with a high Ba abundance ($[\text{Ba}/\text{Fe}] = 0.92$). This star has a very low $[\text{Sr}/\text{Ba}]$ ratio, more so than any of the rest of the sample, and of many of the literature comparison stars. Studies into such "low-Sr/Ba" stars have suggested two explanations (Spite et al. 2014); stars in a binary system where the other star has evolved past the AGB phase and polluted the stellar atmosphere through mass transfer, or stars which themselves have started to undergo the mixing involved in the AGB. The parameters of the star ($T_{\text{eff}} = 5070 \text{ K}$, $\log g = 2.50$) would make it highly unlikely that the star is an AGB star (Fig. 4.10), making the binary hypothesis more likely. Interestingly the star's C abundance is the highest of all the stars in the sample ($[\text{C}/\text{Fe}] = 0.68$), close to the limit categorising it as a CEMP star. The star has a high ratio of $\log \epsilon (\text{La}/\text{Eu}) = 0.68$, indicative of s-process enriched material (Snedden et al. 2008), further suggesting that the star has received AGB pollution from a companion. Studies into possible radial velocity variations in the star would be needed to confirm the binarity.

The $\log \epsilon (\text{La}/\text{Eu})$ ratio is used as a strong indicator of s- and r- process enrichment, as shown in Figure 12a of Sneden et al. (2008), which we have recreated to include our data in Figure 4.17. Besides from SMSS J182637.10-342924.2, we have only been able to measure La in three other stars, as the lines are too weak at these metallicities. All three stars have very low $\log \epsilon (\text{La}/\text{Eu})$ values, -0.12 , -0.13 , and -0.19 . Not only is this value well below that expected for s-process enrichment, it is also below the predicted values for r-process

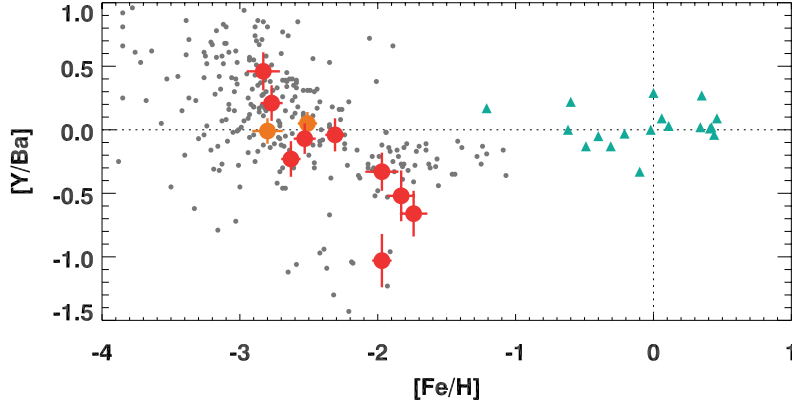


Figure 4.16 $[Y/Ba]$ with respect to $[Fe/H]$, compared to literature values (symbols as in Fig. 4.11).

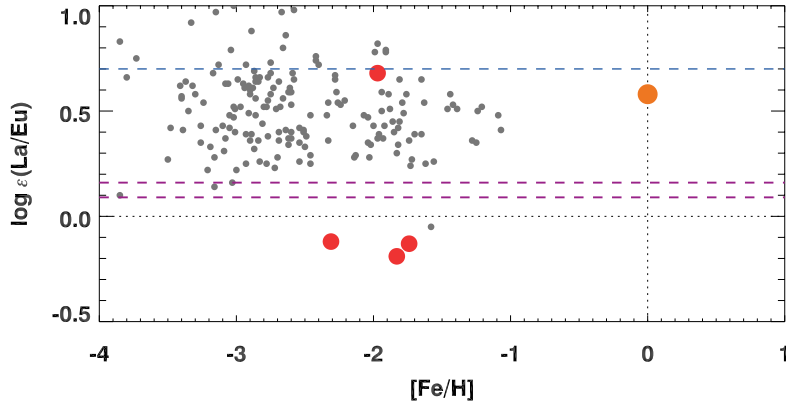


Figure 4.17 $\log \epsilon(La/Eu)$ with respect to $[Fe/H]$, compared to values from Roederer et al. (2010) (grey circles), and the solar value (Asplund et al. 2009, orange circle). The blue dashed line shows the predicted solar system total value, and the purple dashed lines show the published r-process prediction range. Both these lines are taken from Sneden et al. (2008).

enhanced stars. Roederer et al. (2010) calculated this ratio in a sample of 88 metal-poor halo stars, and the star with lowest value had $\log \epsilon(La/Eu) = -0.01$; all three of our stars appear to have even smaller amounts of s-process material in their atmospheres. As s-process enrichment occurs on much longer timescales than r-process enrichment, this could be further evidence that the metal-poor bulge stars formed at earlier times than their halo counterparts.

Tumlinson (2010) suggested that bulge metal-poor stars would show a wide scatter in r-process elemental abundances, even wider than that seen in halo stars at the same metallicity. The best r-process indicator element we have observed is Eu, and we do see a large scatter amongst our data points. Unfortunately, due to the Eu lines being quite weak in metal-poor stars, it was only observable in seven stars. No heavily r-process enhanced star has been uncovered. A greater number of metal-poor bulge stars would be needed to confirm the large $[Eu/Fe]$ scatter.

The stars in this study appear to show no evidence of s-process enhancement, or pollution from a generation of spinstars, which has been seen in the halo literature. There could be a

significant difference between the neutron-capture composition of bulge and halo metal-poor stars. Table 4.7 shows the linear trends for two neutron-capture elements measured in Yong et al. (2013a) compared to the linear trends computed for our stars. The difference between the slopes of $[\text{Sr}/\text{Fe}]$ in the two data sets is very large (0.71), larger than for any other element, and many times larger than the errors associated with the fits. Unfortunately we can only compare one other neutron-capture element in common with the Yong et al. (2013a) sample, Ba, which also shows a difference larger than that of many of the other elements. Further work into the trends shown in neutron-capture elements in both halo and bulge metal-poor stars will be essential to understanding which nucleosynthetic channels were operating during the earliest stages of the evolution of the Universe.

4.6. Conclusions

The EMBLA survey is in the first dedicated search for metal-poor stars in the Milky Way bulge. In this paper we have presented an abundance analysis of 10 stars observed with high-resolution spectroscopy using MIKE/Magellan in 2012; we have also reanalysed the four stars observed as part of Gaia-ESO, originally discussed in Howes et al. (2014), to enable a homogeneous comparison. Ten of these have been confirmed spectroscopically as having metallicities of $[\text{Fe}/\text{H}] < -2.0$, and this increases the number of such stars known in the bulge to 15. Models of the formation of the Milky Way predict that the oldest stars should now be found in the Galaxy's most central regions (e.g. Salvadori et al. 2010; Tumlinson 2010), suggesting that the stars presented in this paper could be the oldest known.

We have confirmed that the majority of the observed stars lie within the bulge region, given the distance uncertainties involved. Further, despite the lack of accurate proper motions of stars at these distances in the bulge, we have been able to show that the range of Galactocentric velocities shown by these stars is not dissimilar from other published bulge star samples. With the publication of upcoming data from OGLE, VVV, and ultimately Gaia, we will be able to confirm definitively whether these metal-poor bulge stars lie on tightly-bound orbits, as predicted by Tumlinson (2010), instead of merely being halo stars that are passing through the bulge region

The abundances of the stars do not deviate largely from those observed in the halo; however there are a few potentially crucial differences. All the stars have $[\text{C}/\text{Fe}] < 0.7$, and this lack of carbon enhanced stars in the sample is unexpected. It can not be explained by internal mixing processes occurring due to the stars' evolved state, but perhaps could be due to mix of selection effects (a study into the SkyMapper EMP survey and the lack of stars with $[\text{C}/\text{Fe}] < 2.0$ will investigate this further), and the small sample size presented here.

In Howes et al. (2014), we discovered that the bulge stars may have a larger scatter in α abundances than expected, and this result is confirmed with our analysis here. The

dispersion of Mg, Si and Ti are all approximately double that found in either more metal-rich bulge samples (Bensby et al. 2013), or halo samples of similar metallicity (Yong et al. 2013a). The Ca abundances, however, do not show the same scatter. We also find that for all four elements, the $[\alpha/\text{Fe}]$ values in these stars are slightly lower than for corresponding halo stars.

Wide scatter is seen in both r- and s-process elements, but the ratios of Y and Sr to Ba do not support any signs of a previous generation of fast-rotating massive stars (Cescutti et al. 2013). Furthermore, the ratios of La to Eu hint that there is less s-process enrichment in these stars than in halo metal-poor stars. Despite the small sample size, there are several stars with anomalous abundance results. One such star has $[\text{Sr}/\text{Ba}] = -0.78$, as well as the highest C abundance of the sample, $[\text{C}/\text{Fe}] = 0.68$. Potentially this star could be in a binary system, where mass from a partner AGB star has been transferred. Other stars have anomalously high and low α abundances, for example, one star with $[\text{Mg}/\text{Fe}] = -0.18$ and $[\text{Ti}/\text{Fe}] = 0.86$.

It is clear from these initial findings that the metal-poor stars in the bulge do have some chemical differences from those found in the halo, providing evidence for having formed at a different time in the history of the Universe. Crucially, in order to confirm that these stars are different from halo metal-poor stars, better kinematic data are required. If bulge-like orbits can be confirmed, these stars could give us a look at the earliest epochs in the life of the Milky Way.

Acknowledgments

L.M.H. and M.A. have been supported by the Australian Research Council (grant FL110100012). A.R.C. acknowledges support from the European Union FP7 programme through ERC grant number 320360. DY is supported through an Australian Research Council Future Fellowship (FT140100554). Research on metal-poor stars with SkyMapper is supported through Australian Research Council Discovery Projects grants DP120101237 and DP150103294 (PI: Da Costa). This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

CHAPTER 5

Extremely Metal-Poor Stars from the Cosmic Dawn in the Milky Way Bulge

This chapter has been previously published as 'Extremely metal-poor stars from the cosmic dawn in the bulge of the Milky Way', L. M. Howes, A. R. Casey, M. Asplund, S. C. Keller, D. Yong, D. M. Nataf, R. Poleski, K. Lind, C. Kobayashi, C. I. Owen, M. Ness, M. S. Bessell, G. S. Da Costa, B. P. Schmidt, P. Tisserand, A. Udalski, M. K. Szymański, I. Soszyński, G. Pietrzyński, K. Ulaczyk, Ł. Wyrzykowski, P. Pietrukowicz, J. Skowron, S. Kozłowski, & P. Mróz. The work is presented exactly as published.

5.1. Introduction

The first stars are predicted to have formed within 200 million years after the Big Bang (Bromm et al. 2009), initiating the cosmic dawn. A true first star has not yet been discovered, although stars (Christlieb et al. 2002; Caffau et al. 2011a; Keller et al. 2014) with tiny amounts of elements heavier than helium ('metals') have been found in the outer regions ('halo') of the Milky Way. The first stars and their immediate successors should, however, preferentially be found today in the central regions ('bulges') of galaxies, because they formed in the largest over-densities that grew gravitationally with time (Tumlinson 2010; Salvadori et al. 2010). The Milky Way bulge underwent a rapid chemical enrichment during the first 1-2 billion years (Feltzing & Gilmore 1999), leading to a dearth of early, metal-poor stars (García Pérez et al. 2013; Howes et al. 2014). Here we report the observations of extremely metal-poor stars in the Milky Way bulge, including one star with an iron abundance about 10,000 times lower than the solar value without noticeable carbon enhancement. We confirm that most of the metal-poor bulge stars are on tight orbits around the Galactic Centre, rather than

being halo stars passing through the bulge, as expected for stars formed at redshifts greater than 15. Their chemical compositions are in general similar to typical halo stars of the same metallicity although intriguing differences exist, including lower abundances of carbon.

5.2. Results

Stars with a low content of heavy elements have distinct spectral flux distributions, which are reflected in their colours. Using the photometric filter system on the SkyMapper telescope operated by the Australian National University, it is possible to identify metal-poor candidate stars (Keller et al. 2007) in the Galactic halo (Keller et al. 2014) and bulge (Howes et al. 2014). We have observed $\sim 14,000$ bulge stars preselected from SkyMapper photometry using the AAOmega spectrograph on the AAT, which enables the acquisition of 400 simultaneous stellar spectra over a 2-degree field of view. More than 500 stars with an iron abundance less than 1/100th of the solar value have been identified, making our survey the first to successfully target metal-poor stars in the Milky Way bulge. Twenty-three of these stars, preferentially targeting the most metal-poor ones based on the intermediate resolution spectra (Appendix Table A.3), were observed in June 2014 with the MIKE high-resolution spectrograph on the 6.5m Magellan Clay telescope (Bernstein et al. 2003) to enable a comprehensive determination of their chemical compositions (Fig. 5.1).

The stars' effective temperatures were derived through fitting the observed hydrogen lines with theoretical spectra, while neutral and ionized iron lines provided measurements of the surface gravities and metallicities in the framework of 1D stellar atmosphere models (Gustafsson et al. 2008) and non-equilibrium spectral line formation (Lind et al. 2012) (Appendix Table A.4). All 23 stars were found to have $[\text{Fe}/\text{H}] \leq -2.3$, including nine stars with $[\text{Fe}/\text{H}] < -3$ (here $[A/B] = \log_{10}(\frac{N_A}{N_B})_* - \log_{10}(\frac{N_A}{N_B})_\odot$, where $\frac{N_A}{N_B}$ refers to the number ratio of atoms of elements A and B in the star (*) and the Sun ($\odot$)). The most metal-poor star, SMSS J181609.62-333218.7, has $[\text{Fe}/\text{H}] = -3.94 \pm 0.16$. The abundances of an additional 22 elements were determined spectroscopically, including the α -elements Mg, Si, Ca, and Ti, and the neutron capture elements Y, Zr, and Ba (Appendix Tables A.5, A.6, A.7).

To confirm their bulge membership, the distances and orbits of the stars have been determined. Using the spectroscopic temperatures and surface gravities, and an assumed mass of $0.8 M_\odot$, distances were inferred, which in nearly all cases are consistent with them being located within the bulge (Fig. 5.2). We have measured velocities for ten of our stars using observations taken by the OGLE-IV survey (Udalski et al. 2015), from which orbits around the Galaxy have been determined in combination with their distances and velocities (Appendix Table A.8); the remaining stars fall outside the OGLE footprint while other sources of kinematic information are too uncertain to constrain the orbits sufficiently. Seven out of the ten stars with accurate kinematics are shown to have tightly bound orbits, placing them in the inner regions of the Milky Way (Fig. 5.2). In particular, using a cutoff radius of

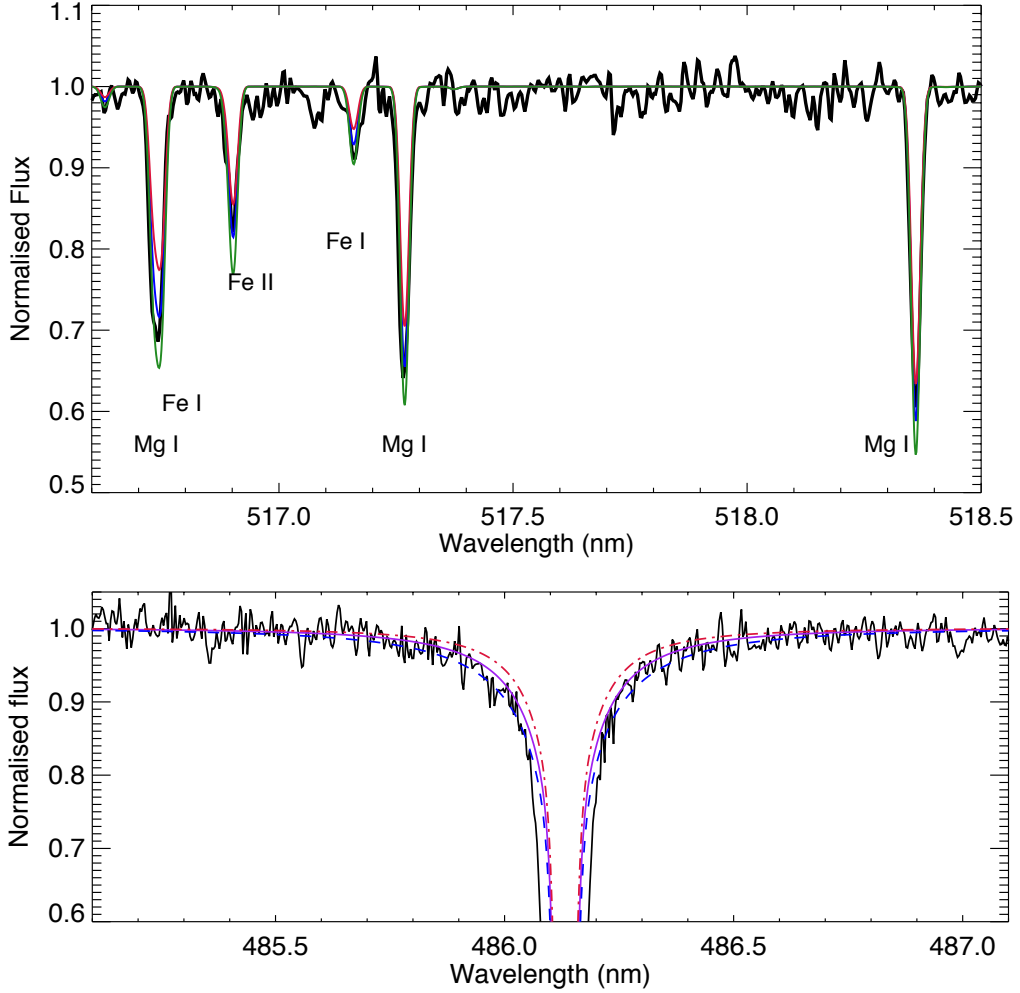


Figure 5.1 Extracts of the spectrum of the lowest metallicity star in our sample. Top: A section of the spectrum of SMSS J181609.62-333218.7 (black line), the most metal-poor bulge star known. In blue is the predicted spectrum with the inferred stellar parameters (effective temperature $T_{\text{eff}} = 4809$ K, $\log g = 1.93$ dex [cgs], $[\text{Fe}/\text{H}] = -3.94$, $[\text{Mg}/\text{Fe}] = 0.20$), and the red and green lines show spectra with all abundances scaled to ± 0.15 dex respectively. All three were created using the 1D local thermodynamic equilibrium (LTE) spectrum synthesis programme, *MOOG* (Sneden et al. 2012). Bottom: The $\text{H}\beta$ line of the same star, compared to three synthetic spectral line profiles (Barklem et al. 2000) computed with $T_{\text{eff}} = 4640$ K (red, dash-dot), 4800 K (purple, continuous), and 4960 K (blue, dashed).

3.43 kpc as the radius of the bulge component (Robin et al. 2012), the most metal-poor star SMSS J181609.62-333218.7 has an orbit entirely contained within the bulge. Only two out of the ten stars are on much larger orbits, being merely halo stars currently passing through the bulge region. Extending these numbers to the whole sample, we can expect ~ 14 of the 23 bulge stars analysed here to have orbits fully within the central regions of the Milky Way; with the imminent arrival of kinematic data from the Gaia satellite, accurate orbits for all of the bulge stars will be able to be determined.

The very first stars are predicted to have brought about the cosmic dawn by forming in the centres of the largest dark matter mini-halos, which subsequently accreted material to become the inner regions of the largest galaxies (Greif et al. 2012). The typical redshift of formation for stars in the bulge with $[\text{Fe}/\text{H}] < -1$ is $z \approx 10$, in contrast to $z \approx 5$ for halo stars. Of the stars with $[\text{Fe}/\text{H}] < -3$, approximately 15% are expected to have formed at $z > 15$ (Tumlinson 2010; Salvadori et al. 2010). Of the ten stars with accurate orbit information, half of them have binding energies $E_{\text{tot}} < -8 \times 10^{-4} \text{ km}^2 \text{ s}^{-2}$, which is consistent with a formation redshift of $z > 15$ (Tumlinson 2010). Low binding energies imply that the stars have been in the Galactic potential well for some time and it is very unlikely they have been accreted from a recent dwarf spheroidal merger. Their low metallicities, orbits and binding energies make these stars prime candidates for being direct descendants of the very first stars, probing a cosmic epoch otherwise completely inaccessible currently. Direct age determinations of these ancient and extremely metal-poor bulge stars from comparison with stellar evolutionary tracks or radioactive U or Th dating are currently not possible but asteroseismic ages could possibly be inferred with the extended Kepler mission or future satellites.

Given their extremely low metallicities and large formation redshifts, these stars are likely to have formed from gas polluted by ejecta from a single or at most a few supernovae of the first stellar generation. A chemical composition analysis has been carried out to search for tell-tale nucleosynthetic signatures and possible differences from halo stars at the same metallicities. For most elements, the chemical compositions of the 23 bulge stars are consistent with typical halo stars, suggesting enrichment by similar supernovae in spite of the distinct environments and formation redshifts. Subtle differences do exist however, most notably in terms of the carbon abundances. None of the 23 stars have the large observed carbon enhancements that occur frequently in halo stars. Applying evolutionary corrections to the surface carbon abundance to counter the mixing that occurs with material processed by H-burning through CNO-cycling at late stages of the stellar lifetime (Placco et al. 2014), still only one of the stars would have had a natal $[\text{C}/\text{Fe}] > 1$. In the halo, the percentage of stars that are carbon-enhanced increases dramatically at lower metallicities - from 27% of stars with $[\text{Fe}/\text{H}] < -2$ up to 69% with $[\text{Fe}/\text{H}] < -4$ (Placco et al. 2014). From the literature data on halo stars with similar iron abundances to our stars (Placco et al. 2014), the probability of selecting at most one carbon-enhanced star out of 23 halo stars is only 0.2%. Carbon-enhanced stars come in two varieties; those with and those without large excesses

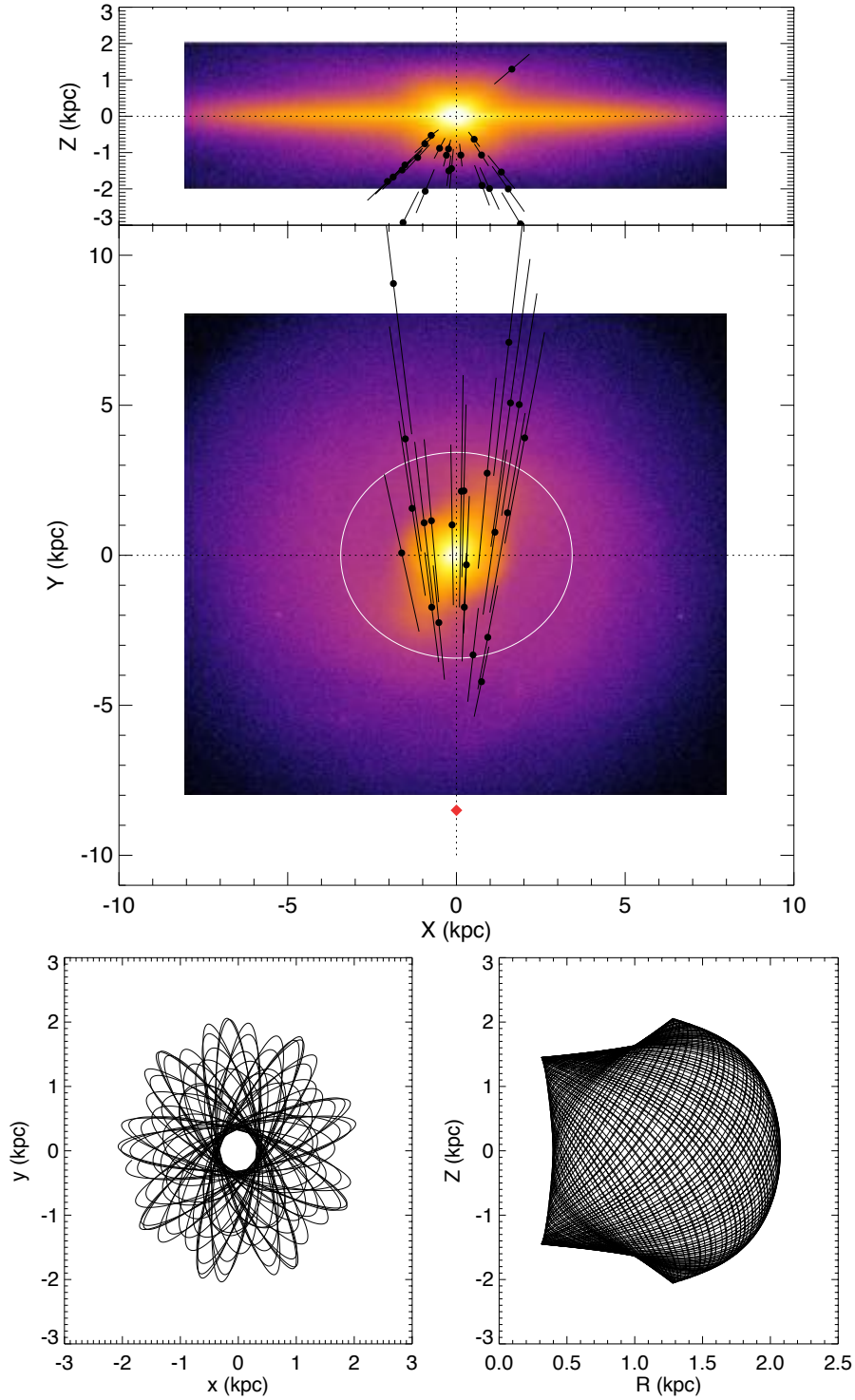


Figure 5.2 The Galactic positions and orbits of the 23 stars observed at high resolution. Top: Surface density map of a model of the Galactic bulge projected onto the X-Z (top) and X-Y (bottom) planes (Ness et al. 2014), where X, Y, and Z are Cartesian coordinates with the origin at the Galactic Centre and Z perpendicular to the plane of the Galaxy. Plotted over this (filled black circles) are the 23 stars of this study, with distance uncertainties shown as error bars, and a circle of radius 3.43 kpc (white: the cutoff radius of the inner bulge determined from 2MASS data (Robin et al. 2012)). The position of the Sun is shown with a red diamond, at 8.5 kpc from Galactic Centre. Bottom: Projections of the orbit of the lowest metallicity star, SMSS J181609.62-333218.7, both in the (R, Z) plane (right), where R is the radial direction, and in the plane of the orbit itself (left).

of neutron-capture elements. The former are most likely to have been formed by mass-transfer from a binary companion that underwent the asymptotic giant branch phase. Those carbon-enhanced stars with neutron capture excesses occur most frequently at metallicities of $[\text{Fe}/\text{H}] > -3$, whereas those without do not appear to have binary companions, and are more common at the very lowest metallicities. As none of our bulge stars are classified as having large abundances of neutron capture elements, the likelihood of finding one such carbon-enhanced star out of 23 is 7% if the frequency is the same for the bulge as for the halo. A lower frequency of carbon-enhanced stars in the bulge relative to the halo is contrary to theoretical predictions; the expected dependence of the initial mass function on the cosmic microwave background (Tumlinson 2007) would result in a greater number of carbon-enhanced stars near the centre of the Galaxy.

The most metal-poor bulge star, SMSS J181609.62-333218.7 is at least an order of magnitude more iron-deficient than previously found low-metallicity bulge stars (Howes et al. 2014; Schlafman & Casey 2014). We have not been able to detect C in its spectrum, instead finding only an upper limit to the star's C abundance (Figure 5.4). This makes the upper limit on its total metallicity, $[Z/\text{H}] \sim -3.8$ (total mass fraction of $Z \sim 2.1 \times 10^{-6}$), where Z represents the sum of all metals, placing it amongst the four most metal-poor stars known, along with the halo star SDSS J102915+172927 (Caffau et al. 2011b). The low C measured in both these stars fall below the predicted metallicity limit for formation of low-mass stars due to metal line cooling (Frebel et al. 2007).

We have compared the detailed chemical abundance pattern of SMSS J181609.62-333218.7 to primordial supernovae yields (Kobayashi et al. 2014; Umeda & Nomoto 2002) (Fig. 5.3). In particular, the low Mg and Ca abundance, but higher Si abundance, and the absence of a pronounced odd-even abundance pattern rule out the possibility of enrichment by a pair-instability supernova resulting from a primordial star of $140 - 250 M_{\odot}$. Low abundances of Cr and Mn and of α -elements, combined with the higher abundance of Co, indicate that the polluting supernova was most likely to have been a primordial hypernova – an extremely energetic kind of supernova releasing ten times the kinetic energy of regular core-collapse supernovae, possibly due to the forming black hole having larger angular momentum (Nomoto et al. 2003). Good agreement is found for a $40 M_{\odot}$ hypernova; a more stringent Zn limit would further constrain the mass range. Unusual abundance ratios have been found in small numbers of stars in the halo – 4% of halo stars with low carbon abundances have chemical peculiarities in at least two elements (Yong et al. 2013b) - but none so far appear to have been polluted by a $40 M_{\odot}$ hypernova. A low $[\alpha/\text{Fe}]$ ratio (0.14 dex) at such low $[\text{Fe}/\text{H}]$ is consistent with an inhomogeneous enrichment from such supernovae (Karlsson et al. 2013), while stars with higher $[\alpha/\text{Fe}]$ formed from more well-mixed gas due to a longer time delay in forming the second generation of stars.

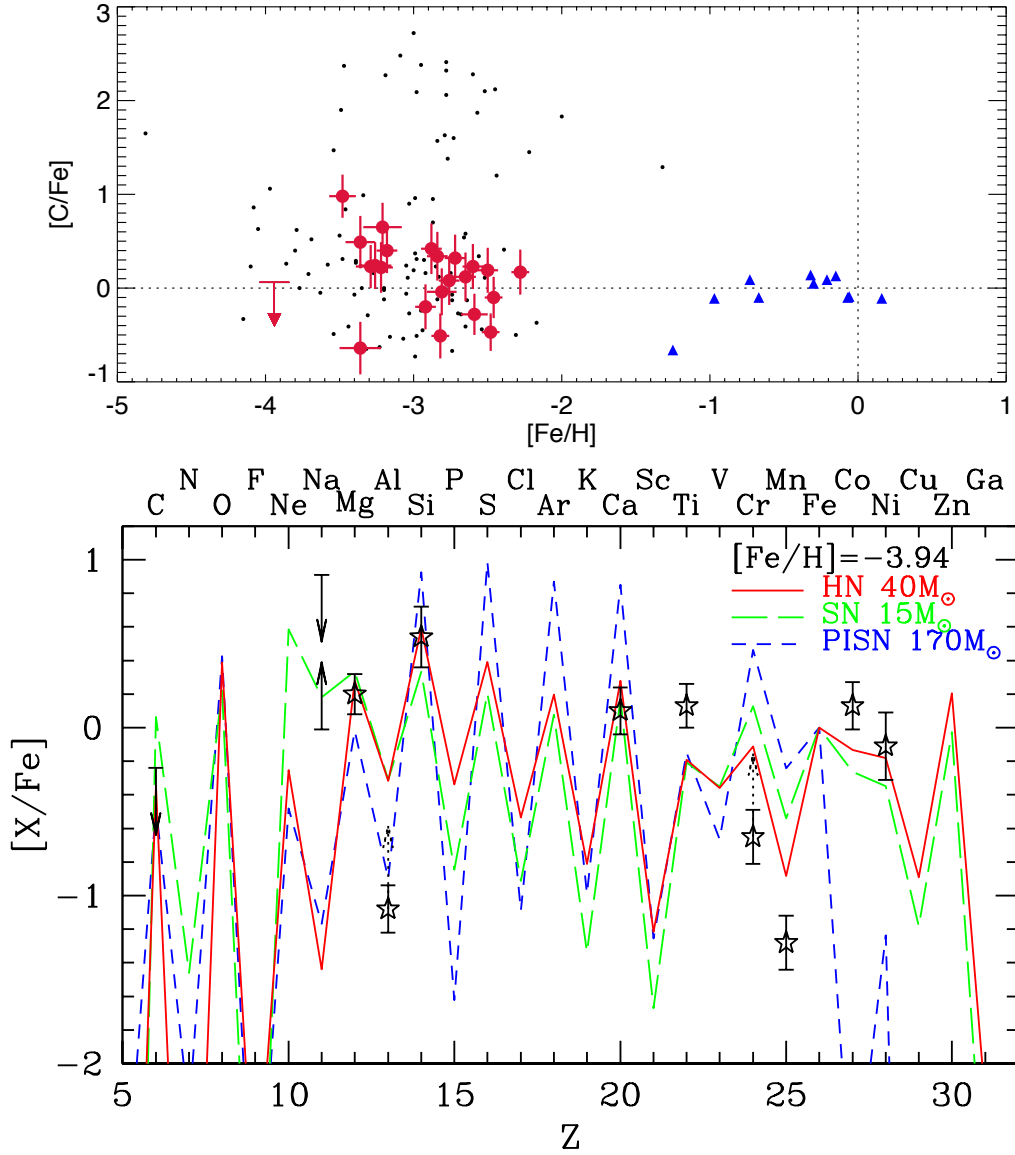


Figure 5.3 Chemical abundances of the 23 stars observed at high resolution. Top: The abundance ratio of carbon versus iron ($[C/Fe]$), with respect to metallicity ($[Fe/H]$) measured in the observed stars (filled red circles, red arrow for an upper limit). The dotted lines represent the solar abundance. Also shown for comparison are literature metal-poor halo giants (small black dots, Yong et al. 2013a) and more metal-rich bulge stars (filled blue triangles, Ryde et al. 2010). Bottom: The chemical abundance pattern of SMSS J181609.62-333218.7, for elements X, where X is displayed at the top of the figure. Each determined abundance is shown as an open black star. These abundances are compared to three synthetic supernovae yields; a pair-instability supernova of $170 M_{\odot}$ (PISN; blue, short dash, Umeda & Nomoto 2002), a core-collapse supernova of $15 M_{\odot}$ (SN; green, long dash, Kobayashi et al. 2014), and a hypernova of $40 M_{\odot}$ (HN; red, solid, Kobayashi et al. 2014). Dotted arrows represent expected non-LTE corrections, solid arrows represent measurements where only an upper or lower limit was possible. The error bars in parts a and b are estimates of the uncertainties in our measurements, calculated as described in Section 5.3.2.

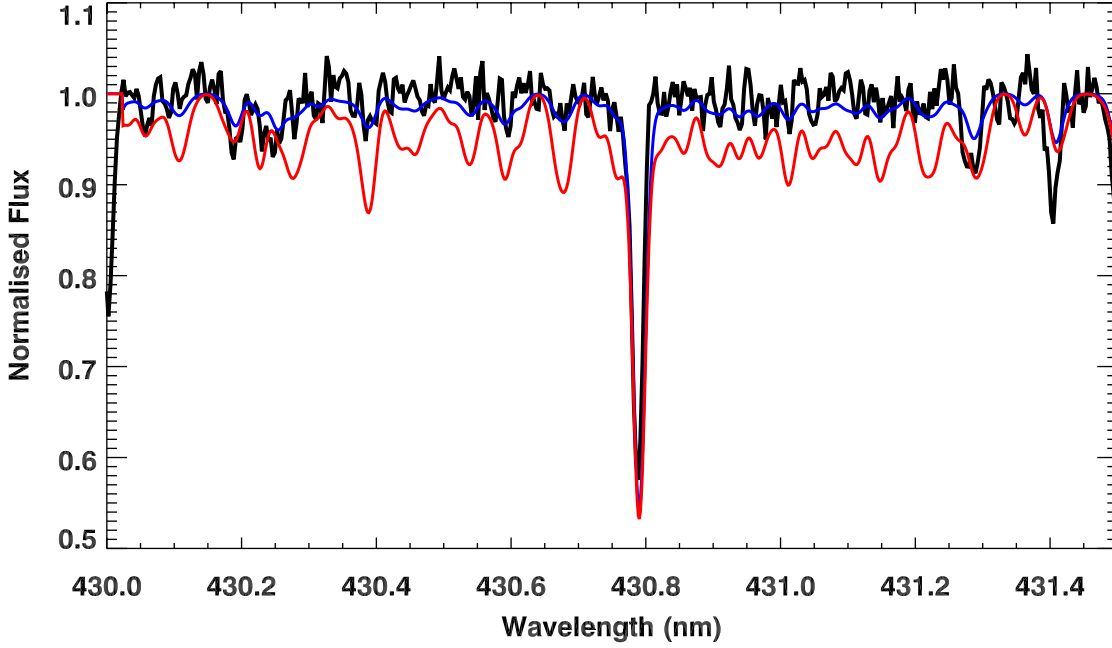


Figure 5.4 The C-H band of SMSS J181609.62-333218.7. The C-H band used to derive an upper limit for C in our most metal-poor star, SMSS J181609.62-333218.7. Synthetic spectra with abundances of $[C/Fe] = 0.06$ (blue) and $[C/Fe] = 0.56$ (red) are shown for comparison.

5.3. Methods

5.3.1. Observations

Photometry of the Milky Way bulge was acquired for the EMBLA survey (Howes et al. 2014) during the commissioning period of the SkyMapper telescope in 2012 and 2013. Stars were selected from the photometry using a combination of the g , i , and v bandpasses, designed to give a reliable metallicity indicator (Keller et al. 2007).

Spectroscopic follow-up observations took place during 2012-14, making use of the AAO-mega+2dF multi-object spectrograph (Sharp et al. 2006) on the Anglo-Australian Telescope. With between 350 and 400 stars observed in each field, spectra of more than 14,000 bulge stars have been obtained. The gratings used have a spectral resolving power of 1,300 in the blue (370-580 nm) and 10,000 in the red (840-885 nm). The data were reduced using the standard 2dFDR pipeline. Stellar spectra were fitted using a generative model that simultaneously accounts for stellar parameters (by interpolating from the AMBRE grid (de Laverny et al. 2012)), continuum, spectral resolution and radial velocity.

From the first two years of spectroscopic data, more than 50 stars were identified as having $[Fe/H] < -2.5$. The high-resolution spectroscopic data of 23 stars presented in this Letter are the result of observations using the MIKE spectrograph at the Magellan Clay telescope (Bernstein et al. 2003) on the 15-17 June 2014. All observations were taken using a slit width of $0.7''$, resulting in a resolving power of 35,000 in the blue and 31,000 in the red. The data

were reduced using the CarPy data reduction pipeline ¹, before they were normalised and summed together using the SMH software (Casey 2014). The final spectra cover 330-890 nm.

5.3.2. Parameter and Abundance Determination

The stellar parameters (Appendix Table A.4) were calculated iteratively, using the original parameters from the low-resolution spectra as initial guesses. First, effective temperatures were derived by fitting the wings of the Balmer H α and H β lines with a synthetic profile (Fig. 5.1). These profiles were created by linearly interpolating between a grid of synthetic spectra (Barklem et al. 2000). The best lines were fit by a χ^2 -minimisation, using a weighted average of the two lines - weighting was double on the H β line, due to predicted LTE effects being larger for H α (Barklem 2007). The difference between the temperatures calculated for each line was on average only 26 K. The $\log g$, microturbulence ξ_t , and [Fe/H] were then derived for that temperature, by forcing the FeI abundance to remain constant with respect to reduced equivalent width, and equilibrium between the FeI and FeII abundances. FeI and FeII abundances were measured from the equivalent widths of a maximum of 66 FeI lines and 24 FeII lines (in the case of the most metal-poor star, SMSS J181609.62-333218.7, these numbers are reduced to 10 FeI lines and 4 FeII lines). Finally a non-LTE correction is applied to the FeI abundance, calculated by taking the average of the line-by-line corrections (Lind et al. 2012). This correction forces an offset between the FeI and FeII abundances, thus replacing the initial equilibrium. This process is repeated until the parameters converge on a solution. Throughout we use the 1D MARCS model atmospheres (Gustafsson et al. 2008), and a shortened version of the Gaia-ESO line list, with extra lines supplemented from Norris et al. (2013a) due to our wider wavelength coverage. The stellar abundances are referenced to the solar abundances of Asplund et al. (2009). This analysis method was tested on seven halo stars from the literature (Yong et al. 2013a), and the offsets found were $T_{\text{eff}} = +28\text{K}$, $\log g = -0.2$, and [Fe/H] = -0.08 (literature values - our values).

The abundances were measured using the equivalent widths of atomic lines (that were all on the linear part of the curve-of-growth), except in the case of C (measured from the CH molecular bands at 431.3 nm and 432.3 nm) and Ba (synthesised in order to account for hyperfine splitting). Non-LTE corrections were calculated for Li (Lind et al. 2009), Na (Lind et al. 2011), Mg, and Ca, and applied to the individual line abundances. The literature halo abundances of Mg and Ca (Yong et al. 2013a) shown in Figure 5.3 have also had a NLTE correction applied, in order to ensure a fair comparison. 3σ upper limits were derived for some elements in those stars where the lines were too weak to be detected (Appendix Tables A.5, A.6, A.7). The abundance offsets compared to the literature values averaged 0.10 ± 0.19 across those elements measured in common. Due to wavelengths covered in the SkyMapper metallicity filter, it is possible that stars with extremely high C abundances appeared to be more metal-rich, and so weren't selected. However, a similar study of

¹<http://code.obs.carnegiescience.edu/mike>

metal-poor stars discovered in the halo with SkyMapper (Jacobson et al. 2015) found the fraction of C-enhanced stars was identical to that reported in previous surveys (Lucatello et al. 2006). Furthermore, we followed up 14,000 stars with intermediate resolution spectra, and determined metallicities using those spectra. The majority of the stars observed had $[\text{Fe}/\text{H}] \approx -1.0$ and included some that had solar metallicities, so it is highly unlikely that we missed any C-enhanced EMP star in our selection.

The systematic uncertainties in the temperature determinations were estimated to be ± 100 K, and the statistical uncertainties averaged ± 125 K, so combined in quadrature we conclude the total uncertainty to be ± 160 K. The ξ_t uncertainties are estimated to be ± 0.2 , mostly due to systematics. The standard errors of the individual line abundances of FeI and FeII were combined in quadrature to evaluate the $\log g$ uncertainties. The differences between the $[\text{Fe}/\text{H}]$ values when varying the temperature, surface gravity, and microturbulence by their respective errors were combined in quadrature with the standard error of the FeII lines to produce the $[\text{Fe}/\text{H}]$ uncertainties. The individual abundance errors were also calculated using this method, using the standard error of the individual abundances for the lines of that particular element.

For SMSS J181609.62-333218.7, which has $[\text{Fe}/\text{H}] = -3.94$, a measurement of Na was not possible, due to the 818.3 nm and 819.4 nm lines being too weak, and the Na D lines (588.9 nm and 589.5 nm) being partly blended with interstellar Na lines. We have derived a range of possible values for this star, taking the upper limit from the non-detection at 819.4 nm, and the lower limit from fitting a Gaussian to the Na D lines, taking into account the interstellar Na.

5.3.3. Distances and Orbital Parameters

Distances to the stars were calculated by comparing the absolute and apparent bolometric magnitudes. The absolute magnitudes were recovered from the relation

$$M_* = M_\odot - 2.5 \log \frac{L_*}{L_\odot}, \quad (5.1)$$

where the luminosities are calculated using

$$\frac{L_*}{L_\odot} = \frac{4\pi\sigma T^4 M_* G}{10^{\log g_*}}, \quad (5.2)$$

taking $M_* = 0.8 \pm 0.2 M_\odot$ for all stars. The apparent bolometric magnitudes are reconstructed from the 2MASS JHK_s magnitudes (Appendix A.3), assuming reddening (Schlafly & Finkbeiner 2011) (as no more recent reddening catalog covers all 23 stars), via the methodology of Casagrande et al. (2006). The proper motions are based on I band images taken during the OGLE-IV (Udalski et al. 2015) observations of the Galactic bulge. Relative proper motions were derived from multiple epochs of data for each field (Poleski et al. 2013), and the uncertainties are a combination of statistical and systematic (estimated to be $\sim 0.4 \text{ mas yr}^{-1}$).

These were converted into absolute proper motions by adding the predicted average bulge motion for each field, calculated using the Besançon Galaxy model (Robin et al. 2003). The orbits were calculated using the python package `galpy`² and the galactic potential assumed in these calculations was a 3-component Milky Way-like potential (Bovy 2015). To model the uncertainty distributions, we sampled 1,000 orbits using a Monte Carlo simulation, assuming a normal distribution for the uncertainties of the input parameters. The results of this are included in Extended Data Table A.8. One star, SMSS J175455.52-380339.3, has an unbound E_{tot} and impractically large orbital parameters, suggesting that one or more of our input parameters need to be changed.

Code Availability

All codes used to analyse the data presented are publicly available. In particular, the 1D LTE analysis used was made possible with the line analysis and spectrum synthesis code MOOG (Snedden et al. 2012).

Acknowledgements

This paper includes data gathered with the 6.5 meter Magellan Telescopes located at Las Campanas Observatory, Chile. Australian access to the Magellan Telescopes was supported through the Collaborative Research Infrastructure Strategy of the Australian Federal Government. L.M.H. and M.A. have been supported by the Australian Research Council (FL110100012). A.R.C. acknowledges support from the European Union FP7 programme through ERC grant number 320360. Research on metal-poor stars with SkyMapper is supported through Australian Research Council Discovery Projects grants DP120101237 and DP150103294 (PI: Da Costa). The OGLE project has received funding from the NSC, Poland, MAESTRO grant (2014/14/A/ST9/00121 to A.U.).

²<http://github.com/jobovy/galpy>

CHAPTER 6

Final Results and Conclusions

Why, I ask myself, should the shining dots of the sky not be as accessible as the black dots on the map of France?

– Vincent van Gogh¹

6.1. Introduction

The observational search for the evidence of the first stars has led us to stars in the outskirts of the Milky Way, finding stars with for example no detectable iron (Keller et al. 2014), and overall metallicities lower than it was predicted low mass stars could form (e.g., Frebel et al. 2007; Caffau et al. 2012). From such stars, details of the lives of the very first stars have been deduced, such as how massive they were and in what sort of explosion they died (e.g., Heger & Woosley 2010; Klessen et al. 2012; Komiya et al. 2015; Bessell et al. 2015). But whilst these metal-poor stars give us details of how stars formed from pristine gas and evolved until their deaths, they do not necessarily give us glimpses of the Universe at the very earliest times. The results from theoretical models of the formation of the Galaxy are clear; stars in the low-density periphery of the Milky Way are not the oldest stars, having formed at redshifts of $z < 8$ (Salvadori et al. 2010). To find out what the Galaxy looked like at its birth, and to probe times as early as the epoch of reionisation, one must search in the highest density regions to find the oldest stars. Those stars may have formed at redshifts of $z > 15$, in the largest overdensities that with time grew to become the central regions of the Galaxy, and remained there whilst the rest of the Milky Way formed around them.

¹In a letter to his brother, Theo

By utilising the distinctive ability of the SkyMapper telescope to efficiently probe the metallicities of stars, the EMBLA survey has searched through more than 5 million stars in the Galactic bulge. Hunting for those ancient, low metallicity giants predicted by the theoretical models, we chose $\sim 14,000$ stars to follow-up with intermediate-resolution spectroscopy. From those, we chose the most promising candidates to study in high-resolution, and searched for the most accurate kinematical data measured to date. The results of 37 of these stars have been discussed in each of the three papers compiled in this thesis, here I will elaborate on the sample as a whole.

6.2. Metallicities of the EMBLA Stars

Of the 37 stars analysed in high-resolution so far, four have $-1 < [\text{Fe}/\text{H}] < -2$, 24 have $-2 < [\text{Fe}/\text{H}] < -3$, and 9 have $[\text{Fe}/\text{H}] < -3$. The MDF of the high-resolution data is shown in Figure 6.1, considering that some of our targets were based on pilot observations, the low metallicity of our sample is encouraging. More EMPs are waiting to be discovered in the survey data; between the analysis of the 2014 AAT observations, and the improvements in the data analysis pipeline `sick`, there are opportunities for further discoveries.

One measure of the survey's success will be the number of discoveries made compared to previous surveys of the bulge. As discussed in the introduction, other surveys of the bulge have had serendipitous discoveries of metal-poor stars, such as the five found by APOGEE (García Pérez et al. 2013), where two stars have $[\text{Fe}/\text{H}] \approx -2.1$, or the 16 found by ARGOS with $-3 < [\text{Fe}/\text{H}] < -2$ (Ness et al. 2013a). However, in the process of finding these stars, APOGEE observed $\sim 4,700$ stars, and ARGOS acquired 28,000 intermediate-resolution spectra. Some of these ARGOS stars have been observed with UVES/VLT in high-resolution but the analysis has not been completed, so the exact $[\text{Fe}/\text{H}]$ values of these stars are unclear (Ness et al. in preparation). We observed 9,000 spectra in the first two years of observations, uncovering 500-1000 stars with $[\text{Fe}/\text{H}] < -2$. The success of using photometry to select metal-poor candidates has been picked up on by others. Schlafman & Casey (2014) have

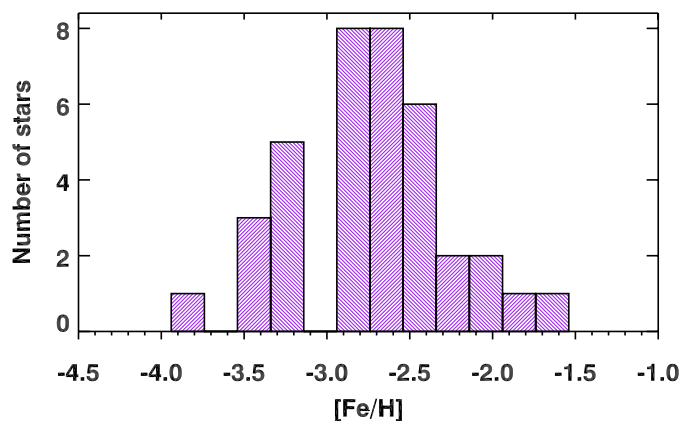


Figure 6.1 The metallicities of all 37 stars observed in high-resolution.

found three stars in the bulge with $[\text{Fe}/\text{H}] \leq -3$, but as yet the existing publicly available photometry of the bulge is not deep enough at the wavelengths they use to find anything but the brightest of metal-poor bulge stars.

We have also found the first star in the bulge with $[\text{Fe}/\text{H}] \approx -4$: SMSS J181609.62-333218.7. This star is remarkable in its lack of elements usually over-abundant in stars; we estimate its total metallicity to be $[\text{Z}/\text{H}] = -4.17$, amongst the lowest of any star ever discovered. This lack of metals poses problems for theories about how the first low mass stars formed. Frebel et al. (2007) predicted that in order for low mass stars to form, enough C and O would be needed to cool the gas through fine structure line cooling. They proposed a lower limit on the amount of these two elements needed:

$$D_{\text{trans}} \equiv \log(10^{[\text{C}/\text{H}]} + 0.3 \times 10^{[\text{O}/\text{H}]}) > -3.5 \pm 0.2. \quad (6.1)$$

Assuming the C abundance of SMSS J181609.62-333218.7 to be its upper limit of $[\text{C}/\text{Fe}] = 0.06$, and that $[\text{O}/\text{Fe}] = 0.14$ (in most stars, O has a similar abundance to other α -elements, and we know $[\alpha/\text{Fe}] = 0.14$), we calculate that for SMSS J181609.62-333218.7, $D_{\text{trans}} = -3.75$. According to the models of Frebel et al. (2007), in order for this star to have formed, there must have been other fragmentation methods in the early Universe. These methods could have been dust-induced fragmentation; Klessen et al. (2012) showed that SDSS J1029151+172927 (the star with the lowest $[\text{Z}/\text{H}]$ known) could have formed this way. Interestingly, Klessen et al. (2012) suggest that SDSS J1029151+172927 could have been ejected from the bulge. Alternatively, Clark et al. (2011) and Greif et al. (2012) show that molecular H and disc fragmentation could lead to smaller stars forming in binaries or higher order systems around more massive stars.

In any case, the formation of SMSS J181609.62-333218.7 with so little metals and so close to the Galactic centre surely makes it a prime candidate for the oldest star known. According to Tumlinson (2010), stars with $[\text{Fe}/\text{H}] < -3$ found in the inner $30^\circ \times 30^\circ$ of the Galaxy have on average a 12% chance of having formed at redshifts of $z > 15$. We found 9 such stars, so there is a $1 - 0.88^9 \approx 68\%$ chance that one of them formed at such early times. We can constrain this further by looking at the kinematics; below, I will discuss how their Galactic orbits provide further evidence for their old age.

6.3. Kinematics of the EMBLA Stars

The kinematics of these stars provide a vital clue to the understanding of the importance of these stars. For example, if they were all on very large orbits, spending most of their lives in the halo of the Galaxy, but we just happened to observe them as they passed through the bulge region, it would be very hard to argue that they were anything other than halo metal-poor stars, like those found in large numbers previously. On the other hand, if we could prove that these stars have tightly bound orbits, circling within the bulge of the Galaxy,

then we would have found prime candidates for the very oldest stars that Tumlinson (2010) had predicted. To quote from that paper: "as stars become more tightly bound, the mean redshift of star formation and the earliest redshift of star formation both shift to earlier times." By calculating the orbits of these stars, we derive their binding energies, and can predict their mean redshifts of formation.

Unfortunately, positional and kinematic data for these stars is not easily available. We have their sky coordinates from SkyMapper, which have been confirmed with 2MASS (Skrutskie et al. 2006), however their distances could only be estimated using the distance modulus between their apparent and absolute magnitudes. To do that, we had to assume a stellar mass, and use their T_{eff} and $\log g$ values, all of which introduced significant uncertainties in the calculations. The resulting uncertainties meant we only know their distances to an approximate accuracy of 30%. This level of accuracy is particularly troublesome in the bulge, where the uncertainties mean we cannot constrain on which side of the Galactic centre some of our stars lie, radically altering their predicted orbits.

But the biggest problem we faced in deriving orbits for the stars was a lack of reliable, accurate proper motions. All-sky proper motion catalogues that are publicly available, such as UCAC4 (Zacharias et al. 2013) and SPM4 (Girard et al. 2011), have extremely large uncertainties in their bulge measurements – for our stars, the errors were between 3 and 20 mas yr^{-1} . When we factored that level of uncertainty into our calculations (using the methods described in Chapter 5), we could not constrain our stars' orbits to within any specific region of the Milky Way. Typical uncertainties on r_{ap} (the apocentric radius of the orbit) were in the region of 1000 kpc.

We knew of two ongoing projects to measure bulge proper motions, OGLE and VVV (Minniti et al. 2010). OGLE have already released catalogues for some regions of the bulge (Sumi et al. 2004), but not in the areas where our stars reside. Their future catalogue, OGLE-IV (Udalski et al. 2015), however, does cover a region containing some of our stars. We collaborated with the OGLE team, who were able to provide us with proper motions for 10 of our stars, this time with uncertainties that averaged 0.9 mas yr^{-1} . With these, we were able to calculate orbits that had reasonable uncertainties, as described in Chapter 5, and listed in Appendix Table A.8.

In Figures 6.2 and 6.3, I show projections of all ten orbits, using their absolute orbital values, rather than the mean values given in Appendix Table A.8. For ease of plotting, Figure 6.2 shows the five smallest orbits, and Figure 6.3 shows the five largest.

From these results, we have found three stars that always stay within a 3.5 kpc radius, which is roughly the radius of the bulge. This includes our $[\text{Fe}/\text{H}] = -4$ star, SMSS J181609.62-333218.7. A further four stars remain within 10 kpc of the Galactic centre, some of which could be considered bulge or disc stars. Only two have distinctly halo-type orbits, with mean apocentric radii of 17.3 and 29.3 kpc. The final star, SMSS J175455.52-380339.3, has extremely

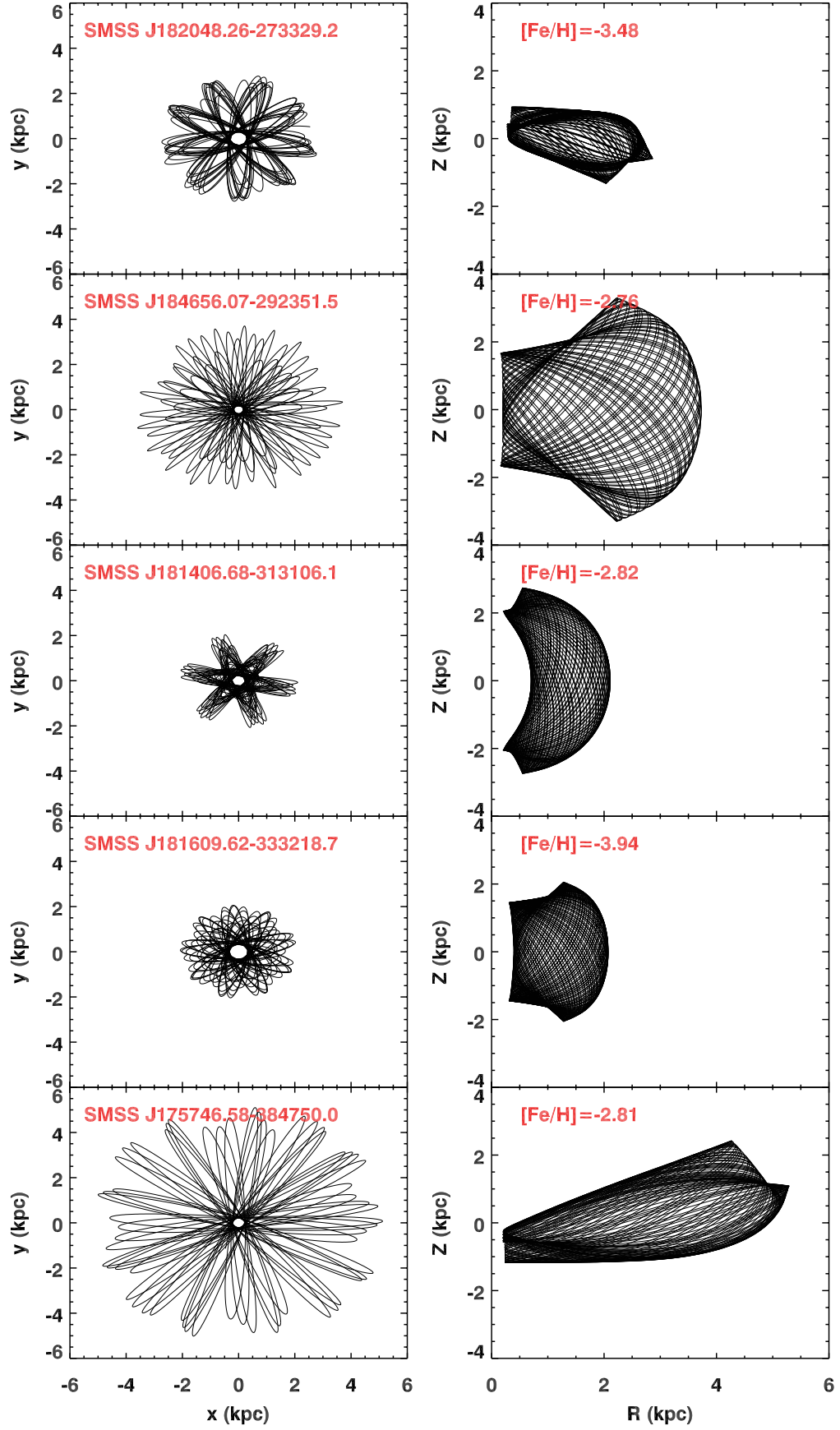


Figure 6.2 Projections of the orbits of five of the ten stars. Left: projected onto the plane of the orbit, and Right: projected onto the (R, z) plane. From top to bottom: SMSS J182048.26-273329.2, SMSS J184656.07-292351.5, SMSS J181406.68-313106.1, SMSS J181609.62-333218.7, and SMSS J175746.58-384750.0.

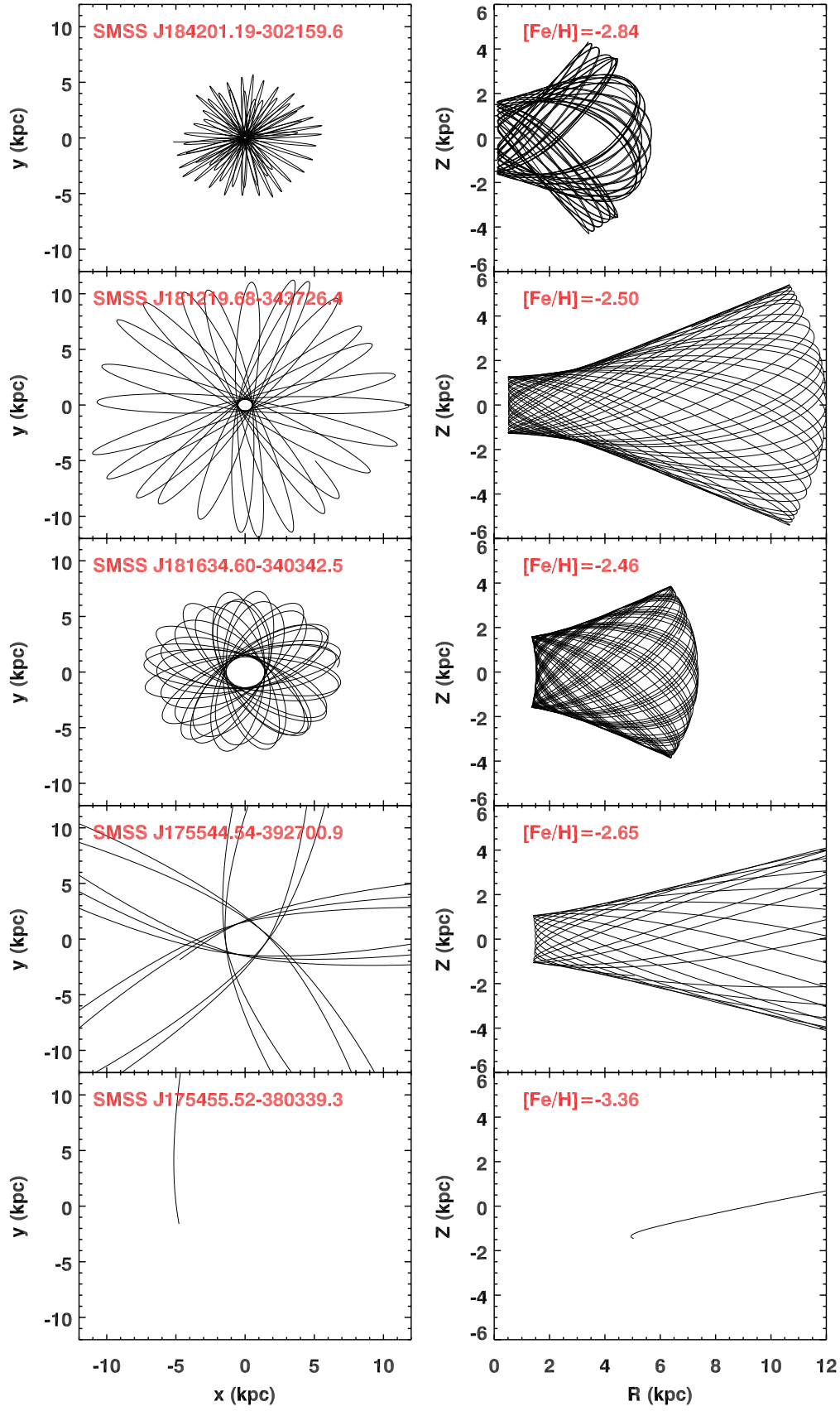


Figure 6.3 Same as Figure 6.2, for the other five stars. From top to bottom: SMSS J184201.19-302159.6, SMSS J181219.68-343726.4, SMSS J181634.60-340342.5, SMSS J175544.54-392700.9, and SMSS J175455.52-380339.3.

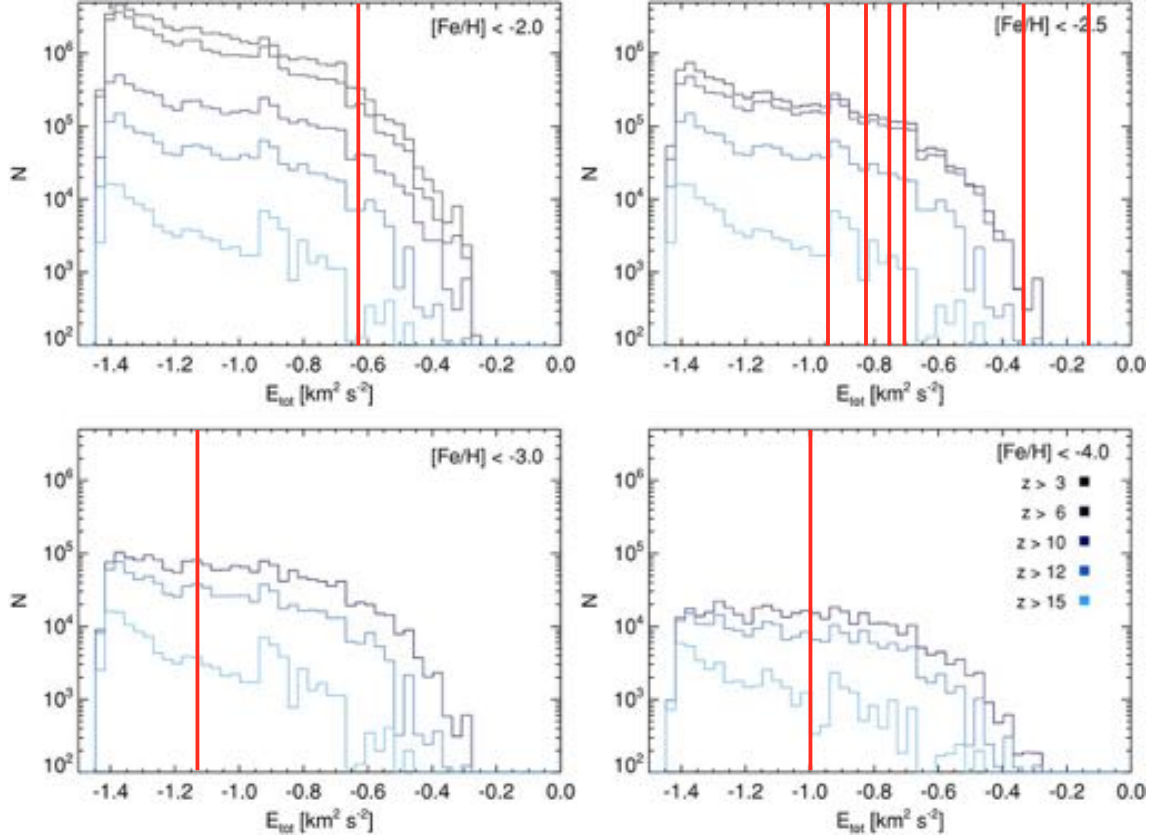


Figure 6.4 Figure 13 from Tumlinson (2010), showing the distribution of the numbers of stars in his model which formed at certain redshifts ($z > 3, 6, 10, 12$, and 15) with respect to their binding energies. The first panel contains all stars with $[\text{Fe}/\text{H}] < -2$, the second contains all stars with $[\text{Fe}/\text{H}] < -2.5$, and so on. Note that for the bottom two panels, the curves for $z > 3$, $z > 6$, and $z > 10$ overlap. The red lines overplotted show the binding energies of the stars in the EMBLA sample, plotted on the appropriate figure for their metallicities.

unlikely orbital parameters – as seen at the bottom of Figure 6.3, the star appears to be on a trajectory heading straight out of the Galaxy. Its velocity is not enormous; $v_{tot} = 330 \text{ km s}^{-1}$, but it has an unfeasible positive total binding energy of $E_{tot} = 6.9 \times 10^4 \text{ km}^2 \text{s}^2$. This suggests that either the distance or the velocity parameters are wrong. The distance from the Sun that we calculated for this star is $d_{\odot} = 13.5 \pm 4.8 \text{ kpc}$; the large uncertainties could well explain the unfeasible orbital parameters and the star is likely not at 13.5 kpc . For this reason, I will ignore this star’s orbital parameters in the discussion.

Tumlinson (2010) predicts that the oldest stars will be the ones with tightly bound orbits. In particular, he lists three particular cases. Stars with $E_{tot} \approx -4 \times 10^4 \text{ km}^2 \text{s}^2$, like most halo stars, will have formed at $z < 10$. Stars with $E_{tot} \approx -8 \times 10^4 \text{ km}^2 \text{s}^2$ have more tightly bound orbits and formed at a variety of redshifts – perhaps as early as $z \approx 20$, but also as late as $z \approx 5$. Finally, stars with $E_{tot} \approx -13 \times 10^4 \text{ km}^2 \text{s}^2$ would have formed before and during the epoch of reionisation, at redshifts $z > 14$, perhaps even at $z > 20$. It is clear that these stars with the lowest binding energies are the oldest stars we should be looking for. Figure 6.4 gives this information graphically, separated into four different metallicity ranges.

Whilst we do not have any stars with binding energies as low as $E_{tot} \approx -13 \times 10^4 \text{ km}^2 \text{s}^2$, of

the nine EMBLA stars that we have binding energies for (ignoring SMSS J175455.52-380339.3, as mentioned above), one star has $E_{tot} = -11.3 \times 10^4 \text{ km}^2 \text{ s}^2$. This star, SMSS J182048.26-273329.2, has a metallicity of $[\text{Fe}/\text{H}] = -3.48$, making it a candidate for the oldest star in our sample. Using the lower left panel of Figure 6.4 as a guide, we can estimate that there is a roughly 50% chance that the star formed at $z > 12$. Similarly, the most metal-poor star in our sample, SMSS J181609.62-333218.7, has a binding energy of $E_{tot} = -9.9 \times 10^4 \text{ km}^2 \text{ s}^2$. From the lower right panel of Figure 6.4, we can also estimate there is $\approx 50\%$ chance that the star formed before $z = 12$.

Two other stars have binding energies of $E_{tot} < -8 \times 10^4 \text{ km}^2 \text{ s}^2$, and a further two have $E_{tot} \approx -7 \times 10^4 \text{ km}^2 \text{ s}^2$, implying that they might have formed at very early times; all four of these stars have metallicities of $[\text{Fe}/\text{H}] \approx -2.8$. One additional star has $E_{tot} \approx -6 \times 10^4 \text{ km}^2 \text{ s}^2$, while only two stars have binding energies of $E_{tot} > -4 \times 10^4 \text{ km}^2 \text{ s}^2$ (these are the two mentioned previously as having halo-like orbits). Interestingly, the three stars with the highest binding energies also have the highest metallicities of the ten stars with orbital parameters.

It should be repeated that these probabilities of formation redshift rely on the models of Tumlinson (2010), which we assume are reasonable models of the formation of the Milky Way halo. They are, however, only models, and therefore our probabilities are only speculative. Many processes involved in the evolution of the Galaxy have not been included in these models, and the reader must bear this in mind.

The fact that we only have ten stars with orbital information limits us in what conclusions we can draw about the sample as a whole, however we have shown that there are candidates in our sample for the oldest stars known in the Galaxy. Given that the most distant GRBs and star forming galaxies observed to date all have redshifts of $z < 11$ (Cucchiara et al. 2011; Ellis et al. 2013; Pirzkal et al. 2015), the EMBLA sample most likely contains the oldest known objects in the Universe.

6.4. Chemistry of the EMBLA Stars

Having shown how the metallicities and kinematical information of the EMBLA stars combine to provide evidence for these being the oldest known stars in the Galaxy, we are left to work out whether these stars have any different chemical patterns compared to their younger halo counterparts. Have the differences in the time of formation or environment led to specific elemental differences? Can we distinguish differences in the Population III stars which would have exploded and polluted the gas which made these stars, from gas which formed the halo stars later on?

To consider these questions, we have measured the abundances of up to 23 elements additional to iron, using the methods described in the previous chapters. In this section I

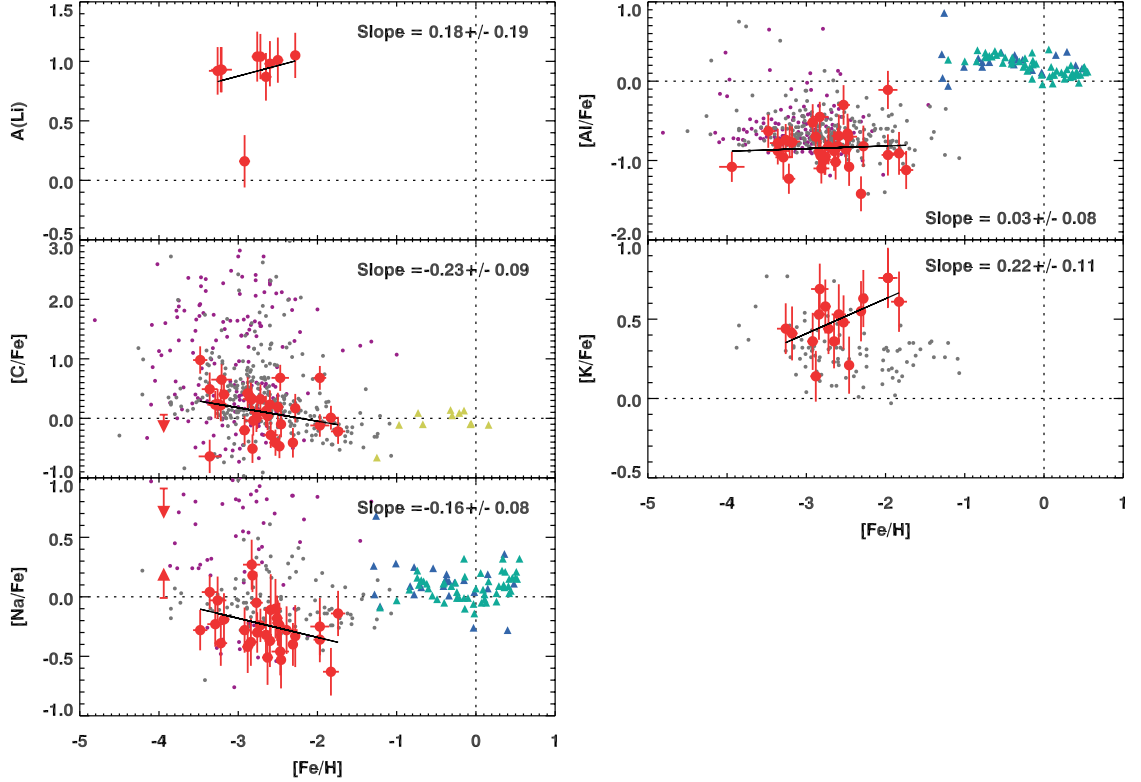


Figure 6.5 Chemical abundance plots showing all 37 stars observed in high-resolution, for the light elements Li, C, Na, Al, and K. All are plotted as red circles, with error bars, and as a ratio of Fe abundance (i.e. $[X/\text{Fe}]$), except for Li, which is shown as an absolute abundance $A(\text{Li})$. The linear fit to the data is shown (black solid line), and printed in each plot is the slope of the line. For comparison literature samples of bulge stars (Bensby et al. (2013) - turquoise triangles, Alves-Brito et al. (2010) - blue triangles, and Ryde et al. (2010) - sand triangles), and metal-poor halo stars (Yong et al. (2013a) - purple dots, and Roederer et al. (2014) - grey dots).

will go into detail about ten of these elements, shown in Figures 6.5 and 6.7, in particular what we have found different between the bulge and halo metal-poor stars. The figures show the results of a linear fit to our data, similar to that presented in Chapter 4, although with considerably smaller errors now that our sample is three times larger. These can be compared to the linear fits to the giant stars in the Yong et al. (2013a) analysis, given in Table 4.7. Again, we must bear in mind that a linear fit is unlikely to be the ideal parameterisation of the abundance data, but may give us insight into the overall trends displayed.

6.4.1. Carbon

As reported in the previous chapters, we have discovered that the number of stars with enhanced carbon abundances in our bulge metal-poor sample is unusually low. This is perhaps the biggest difference between the chemistry of halo EMP stars and bulge EMP stars that we have found. It has been known for some time that halo metal-poor stars appear to fall into two groups, the so-called "C-normal" stars, and the carbon enhanced (CEMP) stars. The percentages of CEMP stars are fairly low at $[\text{Fe}/\text{H}] \approx -2$, about 20% (Lucatello et al. 2006), but increase dramatically for more metal-poor stars; six out of seven of the stars

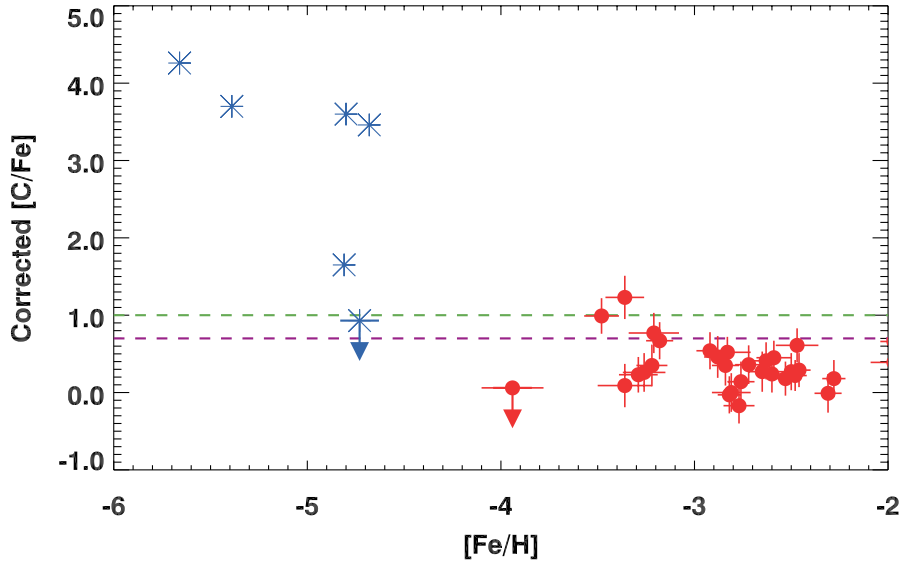


Figure 6.6 Comparing the C abundances between the EMBLA stars (red circles), and the seven most metal-poor stars known (blue stars), with abundances taken from Frebel & Norris (2015). SMSS J031300.36-670839.3 is plotted off the figure, with $[\text{Fe}/\text{H}] < -7.3$ and $[\text{C}/\text{Fe}] > 4.9$. Also shown are lines representing two criteria for a star to be considered a CEMP star, $[\text{C}/\text{Fe}] > 1.0$ (Beers & Christlieb 2005, green dashed line), and $[\text{C}/\text{Fe}] > 0.7$ (Aoki et al. 2007, purple dashed line).

known with $[\text{Fe}/\text{H}] < -4.5$ are strongly carbon enhanced.

We found that in both our 2012 Magellan sample Howes et al. (2015b) and the 2014 Magellan sample (Howes et al. 2015a), there was a lack of CEMP stars. Using the Beers & Christlieb (2005) threshold to be considered a metal-poor star, $[\text{C}/\text{Fe}] > 1.0$, none of the 33 stars with C measurements or upper limits can be considered a CEMP star. Even by the standards of the more recent threshold, $[\text{C}/\text{Fe}] > 0.7$ (Aoki et al. 2007), only one star can be classified as a CEMP star.

We cannot compare directly the observed C abundances of EMBLA stars to many of the EMP halo abundances, because we know that the surface C abundance is reduced once a star reaches the upper parts of the RGB (Gratton et al. 2000). The EMBLA survey has solely observed giant stars, as the bulge dwarfs are too faint to observe, so our stars may currently have lower surface C abundances than they were born with. Many of the most metal-poor stars in the halo are dwarfs, with their original C abundances in tact. In order to account for this in comparisons with halo metal-poor stars, we have employed the evolutionary C abundance corrections of Placco et al. (2014). With these corrected abundances, we now find that one star has $[\text{C}/\text{Fe}] > 1.0$, and two stars have $0.7 < [\text{C}/\text{Fe}] < 1.0$. The corrected abundances are plotted in Figure 6.6.

Figure 6.6 also shows the C abundances of the seven most metal-poor stars known, and it is clear from this why the most metal-poor EMBLA star SMSS J181609.62-333218.7 has a much lower $[\text{Z}/\text{H}]$ ratio than all but one of these stars. Four out of the seven halo metal-poor stars have huge C abundances of $[\text{C}/\text{Fe}] > 3.0$. The only star out of the six which is not a CEMP star is SDSS J1029151+172927, which has an upper limit of $[\text{C}/\text{Fe}] = 0.93$. This

Table 6.1 The fraction of CEMP stars found in the Milky Way halo at certain metallicity ranges. Literature data taken from Placco et al. (2014).

[Fe/H]	Observed [C/Fe]> 1.0	Observed [C/Fe]> 0.7	Corrected [C/Fe]> 1.0	Corrected [C/Fe]> 0.7
-2.25 <[Fe/H]< -2.75	0.21	0.25	0.21	0.25
-2.75 <[Fe/H]< -3.25	0.23	0.27	0.26	0.31
-3.25 <[Fe/H]< -3.75	0.27	0.37	0.34	0.50
-3.75 <[Fe/H]< -4.25	0.42	0.54	0.50	0.58

Table 6.2 The numbers of CEMP stars found in the EMBLA survey.

[Fe/H]	Total Number	Observed [C/Fe]> 1.0	Observed [C/Fe]> 0.7	Corrected [C/Fe]> 1.0	Corrected [C/Fe]> 0.7
-2.25 <[Fe/H]< -2.75	12	0	0	0	0
-2.75 <[Fe/H]< -3.25	11	0	0	0	1
-3.25 <[Fe/H]< -3.75	5	0	1	1	2
-3.75 <[Fe/H]< -4.25	1	0	0	0	0

corresponds to an absolute C abundance of $A(C) < 4.6$, whereas SMSS J181609.62-333218.7 has an absolute abundance of $A(C) < 4.55$. The most metal-poor star found in the bulge appears to be very different from most of metal-poor stars found in the halo, it is most similar to SDSS J1029151+172927.

To assess the probability of observing this many metal-poor C-normal stars at the same metallicities as our stars, if the fractions of CEMP stars were the same in the halo and the bulge, we have taken data of the CEMP fractions in the halo from Placco et al. (2014), who have collated the data on known metal-poor halo stars. They have calculated all the abundance corrections required in order to assess the percentages of stars that are observed as C enhanced compared to the percentages that were born as CEMP stars. The fractions of CEMP stars in the halo covering the range of metallicities found by EMBLA, and considering all possible criteria for CEMP classification, are listed in Table 6.1. Similarly, the numbers of stars found in the EMBLA survey for those same ranges are listed in Table 6.2. Since Placco et al. (2014) only considers stars with $[Fe/H] < -2$, we have limited the sample to the 29 bulge stars that have measured C abundances and $[Fe/H] < -2$.

Using the fractions in Table 6.1, we have assessed the probability of obtaining the distribution found in Table 6.2 from a random selection of 29 halo stars. Those probabilities are as follows; 0.0004 (Observed $[C/Fe] > 1.0$), 0.0002 (Observed $[C/Fe] > 0.7$), 0.0005 (Corrected $[C/Fe] > 1.0$), and 0.0007 (Corrected $[C/Fe] > 0.7$). These probabilities are tiny - even for the

most stringent criteria (Corrected $[C/Fe] > 0.7$), there is only a 0.07% chance of observing our distribution at random in the halo.

These probabilities confirm that, even with the relatively small sample size of the EMBLA stars, the distribution of carbon abundances observed in the bulge is distinct from that of the halo. The gas produced from Population III supernovae that created these metal-poor bulge stars would have had to have much less carbon than the gas which formed the halo stars at a later time. As discussed in Chapter 5, for the case of SMSS J181609.62-333218.7, a $40 M_{\odot}$ hypernova produces less C than other potential progenitors, and could explain the lack of C seen in our sample. Studies of the existing Fe-poor, C-rich halo stars suggest that faint supernovae may be their progenitors (Ishigaki et al. 2014); where the amount of fall-back during the explosion is very high, limiting the amount of Fe-peak elements that escape into the gas. It would appear that such supernovae do not fit the abundances found in the bulge.

This result casts doubt on one particular theory of early star formation. Tumlinson (2007) explains how, at early times, the higher temperature of the CMB may have played a role in preventing many low mass stars from forming. Many CEMP stars are predicted to have been affected by binary mass transfer. If low mass star formation was suppressed due to the CMB at early times, and CEMP stars are mostly the result of binaries, then the number of stars in binaries with higher mass stars would be greater at earlier times, creating the required conditions for more CEMP stars to be discovered. In which case, the oldest and most metal-poor stars of the bulge should have a higher fraction of CEMP stars compared with the younger halo metal-poor stars. This is not borne out in our observations. Binary companions have not been found for many of the lowest metallicity CEMP stars, and so it is likely that the assumption that all CEMP stars form in binaries is not realistic.

6.4.2. Light Elements

We observed four other light elements: Li, Na, Al, and K (Fig. 6.5). Of these four, the most hotly debated element is Li, due to the discrepancy between the observed Li abundances in metal-poor stars (e.g., Spite & Spite 1982; Asplund et al. 2006; Sbordone et al. 2010; Meléndez et al. 2010), and the primordial Li abundance of the Universe predicted from Big Bang nucleosynthesis and detected using satellites such as WMAP (Komatsu et al. 2011) and Planck (Planck Collaboration et al. 2014). A summary of the debate can be found in Frebel & Norris (2015). We have measured Li in a number of our stars, using the 670.7 nm line and correcting for non-LTE effects (Lind et al. 2009), and found that the majority have very low Li abundances: $A(\text{Li}) \approx 1.0$. This is to be expected, however, as all of our stars have evolved off the main-sequence. Whilst moving up the RGB, a star's convective layer extends further in towards the core, where the temperatures are hotter. The Li is therefore mixed in to higher temperature regions, where it is destroyed through proton fusion. The abundances found in our stars match the abundances expected for their evolutionary state,

and do not appear to differ from abundances found in similar halo giants. Because of these evolutionary effects, the linear fit presented in Figure 6.5 of $A(\text{Li})$ with respect to $[\text{Fe}/\text{H}]$ is most likely misleading as the stars are not all at the same point in their evolution. In order to probe the initial Li abundance of the oldest stars in the bulge, main-sequence dwarfs would need to be observed, which is not possible with the current technology in all but the most serendipitous occasions due to, for example, microlensing events (Bensby et al. 2013).

We find that out of the three other elements, both Na and Al have very similar abundances to the comparison halo stars. Na matches well with the Roederer et al. (2014) sample, which like our sample have also been corrected for non-LTE effects. The Yong et al. (2013a) sample has not been corrected, and this is evident as these stars seem all more abundant in Na in Figure 6.5, and the linear fit to the Yong et al. (2013a) sample is quite different (Table 4.7). The linear fit to our data shows a slight positive trend with decreasing metallicity, meaning the most metal-poor are closest to the solar $[\text{Na}/\text{Fe}]$ value. Unlike Na, non-LTE corrections have not been applied to the Al abundances in either our sample or the literature samples. Non-LTE corrections for Al predict that the average abundance will increase, bringing it closer to the solar $[\text{Al}/\text{Fe}]$ value (Andrievsky et al. 2008). Our abundances are very similar to those of the halo stars, displaying a similar lack of obvious trend with metallicity (compare the slope of our trend; 0.03, with the Yong et al. (2013a) trend of 0.11).

Our K abundances are mostly consistent with the Roederer et al. (2014) halo stars, especially considering theirs have been corrected for non-LTE effects (Takeda et al. 2002); if the same were applied to our stars, we would expect our abundances to fall by a small amount, and the fairly strong trend that we currently see to disappear.

6.4.3. Alpha-capture Elements

Combining the stars observed in 2012 and 2014 (Figure 6.7), the trends reported in earlier chapters remain. In Chapters 3 and 4, we reported a large spread in the measurements of Mg, Si, and Ti. With the addition of the 2014 sample, the spread still appears larger than that found in halo stars, although its significance has reduced slightly. Certainly in Figure 6.5, both Mg and Si appear to be spread over more than 0.8 dex, with dispersions of $\sigma = 0.19$ dex (Mg) and 0.17 dex (Si). This is quite different from the dispersions found in Roederer et al. (2014) and Yong et al. (2013a), which, for example for Mg, are 0.12 dex and 0.13 dex respectively. Ti also shows a high dispersion ($\sigma = 0.17$ dex), however in the figure we can see a downward trend, with one anomalously high value. Removing that value from the dispersion calculation reduces it to $\sigma = 0.14$ dex, closer to the level of the expected uncertainties.

As noted previously, Ca does not appear to have quite the same abundance spread as the other α -elements. Again, its dispersion is only $\sigma = 0.11$ dex, identical to the Ca dispersion found in the halo giants of Yong et al. (2013a). We have also been able to measure the

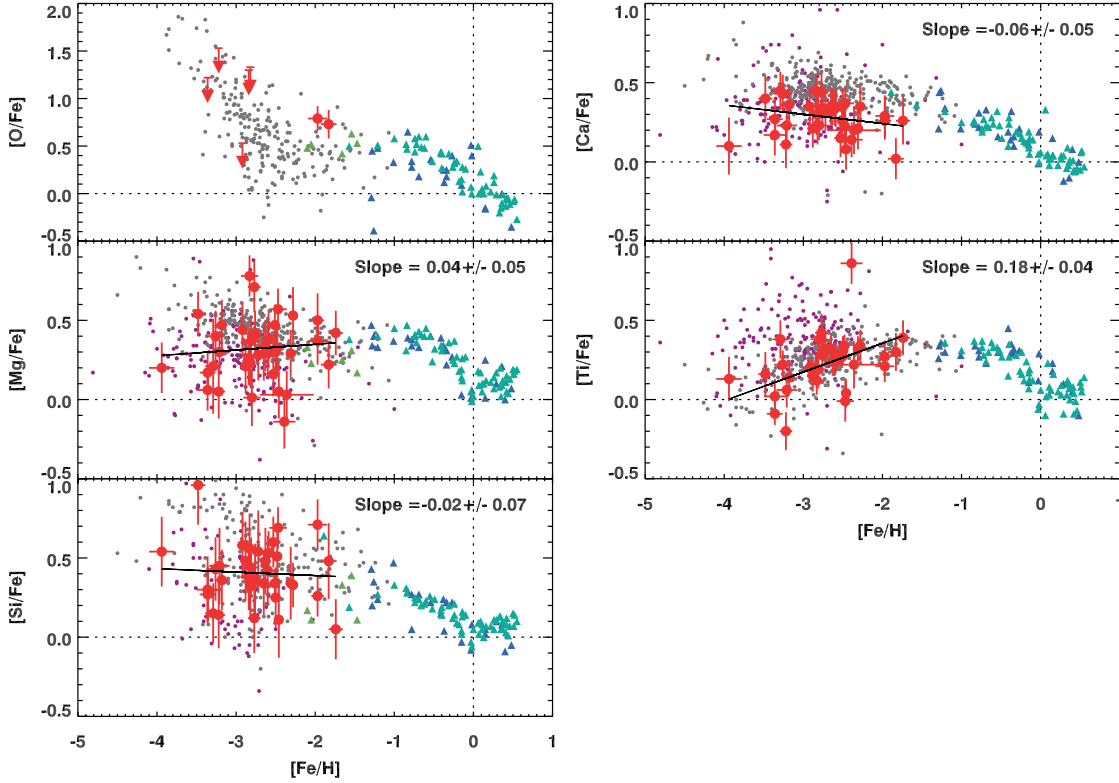


Figure 6.7 Chemical abundance plots showing all 37 stars observed in high-resolution, for the α -elements O, Mg, Si, Ca, and Ti, symbols as in Figure 6.5, except the green triangles (García Pérez et al. 2013). No linear fit has been shown for O, due to the lack of measurements.

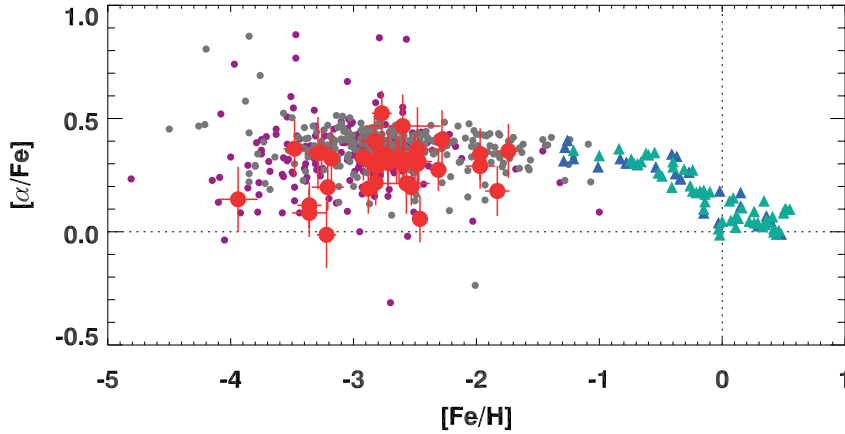


Figure 6.8 The combined alpha abundances of the sample, using the same symbols as in Figure 6.5. $[\alpha/\text{Fe}] = [\text{Mg}/\text{Fe}] + [\text{Ca}/\text{Fe}] + [\text{Ti}/\text{Fe}]$.

forbidden O line at 630.0 nm in two of the stars, but the line is too weak to be detected in the vast majority of the sample. We have measured some upper limits, shown in Figure 6.7, but the majority are too high to be meaningful.

We continue to report a slight offset in the mean α abundances between the EMBLA bulge stars and the halo. The mean values for the EMBLA sample are lower than those from halo samples, although at levels which are too small to separate from the uncertainties. This slight offset can be seen in Figure 6.8, where we calculate the average of Mg, Ca, and Ti for each star. The mean $[\alpha/\text{Fe}]$ value calculated by this method is 0.27 dex. As we have corrected

for non-LTE effects in both Mg and Ca, it is hard to get a true comparison with the literature values, which do not have these corrections. There is a more noticeable difference in the Si abundances, for which non-LTE corrections do not yet exist; they average 0.40 dex in our sample, compared to 0.57 dex in the Yong et al. (2013a) sample. For such small differences, a larger sample is really needed in order to ascertain how real they are. Further observations for the EMBLA survey will help with this, and hopefully in the near future these trends will be able to be confirmed.

The linear fits shown in Figure 6.7 confirm the continuation of the α -plateau at lower metallicities, identified previously in the bulge, for example in the samples of both Bensby et al. (2013) and Alves-Brito et al. (2010), and in the disc components of the Milky Way (Bensby et al. 2014). Mg, Si, and Ca all have trends that, within the errors, are flat. The halo data also show this trend, with both Mg and Ca having flat trends in the Yong et al. (2013a) data (Table 4.7). There is a discrepancy with the Si trends, with Yong et al. (2013a) reporting an increase in Si abundance with decreasing metallicity (the linear fit to the data gives a value of -0.3). That trend appears to be peculiar to the Yong et al. (2013a) sample, the rest of the literature doesn't find similar. As mentioned previously, our Ti abundances show a downward trend, which is apparent in the slope of our linear fit, 0.18 ± 0.04 . Yong et al. (2013a) also report a slope of 0.14 ± 0.04 , although it is noted that this trend is only seen for giant stars, and not for dwarfs.

There are still a number of stars with unusual combinations of α abundances, as mentioned in Chapter 4. In addition to those mentioned there, we also particularly note the star SMSS J182048.26-273329.2, which has a large overabundance of Si ($[\text{Si}/\text{Fe}] = 0.96$), higher levels of Mg and Ca than the average ($[\text{Mg}/\text{Fe}] = 0.54$, $[\text{Ca}/\text{Fe}] = 0.40$), but a lower Ti abundance than expected ($[\text{Ti}/\text{Fe}] = 0.16$). These anomalous differences are particularly interesting, as this star has the second lowest metallicity, $[\text{Fe}/\text{H}] = -3.48$, but also has the highest observed C abundance of $[\text{C}/\text{Fe}] = 0.98$. This star also has the lowest binding energy, and was discussed in the Section 6.3 as having a 50% chance of having formed at $z > 12$. It may be fruitful in the future to study the exact chemical signature of this star and compare it to the lowest metallicity star SMSS J181609.62-333218.7, calculating what sort of supernova progenitor led to its creation.

6.4.4. Connections between Chemistry and Kinematics

In Section 6.3, the orbits of ten of the stars in the EMBLA high-resolution sample were discussed, and in particular the idea that those stars with the lowest orbital binding energies have the highest probabilities of having formed at an early time. It makes sense, therefore, to question whether the chemical abundances of the stars correlate in any meaningful way with the orbital binding energies. Ideally, we would want to compare these trends with those of similar halo stars. Unfortunately, due to a lack of reliable proper motions and distances for extremely metal-poor stars in the literature, this task is currently not possible.

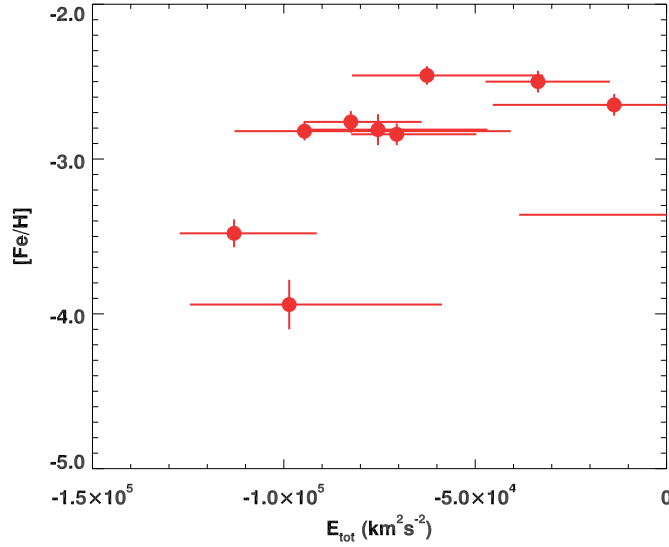


Figure 6.9 The orbital binding energies of the ten stars with kinematic information plotted against their metallicity, $[\text{Fe}/\text{H}]$.

With the arrival of data from the *Gaia* satellite in 2016 and the following years, it will soon be easy to make comparisons of the orbits of halo and bulge metal/poor stars.

In the mean time, we can examine the trends of the ten stars for which we have accurate kinematic data. As shown in Figure 6.9, despite the large error bars associated with E_{tot} , the trend does appear to be towards lower $[\text{Fe}/\text{H}]$ at lower binding energies. The error bar shown entering the plot on the right hand side is that of SMSS J175455.52-380339.3, the star discussed previously as most likely having faulty orbital parameters; this plot summing up the large uncertainty introduced with the lack of precise distances. Within its error bars, there is still a plausible range of E_{tot} values. In fact, the large error bars associated with all ten stars, along with the small sample size, lead to large caveats on the idea of a trend between $[\text{Fe}/\text{H}]$ and E_{tot} .

Figure 6.10 plots E_{tot} against six abundance ratios. These six elements were chosen from the range of those plotted in previous sections, due having a reasonable number of measurements amongst the ten stars. For example, only three of the ten have measured Li abundances, so Li has not been plotted.

The clear trend from this plot is the lack of any noticeable correlation between abundances and orbital energy. Clearly shown in the plots of $[\text{Ca}/\text{Fe}]$ and $[\text{Ti}/\text{Fe}]$, the abundances remain constant with some scatter over the range of E_{tot} values, similarly for $[\text{Na}/\text{Fe}]$, with a larger scatter. The $[\text{C}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$ and $[\text{Si}/\text{Fe}]$ plots also show this, when considering all stars except for SMSS J182048.26-273329.2, which is more abundant in all three than the other stars, as discussed previously. This star has a high chance of having formed at very high redshifts, which is perplexing, considering it appears quite chemically dissimilar to SMSS J181609.62-333218.7, the star with the lowest metallicity and second-lowest binding energy. Currently it would appear that there is no distinct chemical trend to associate with

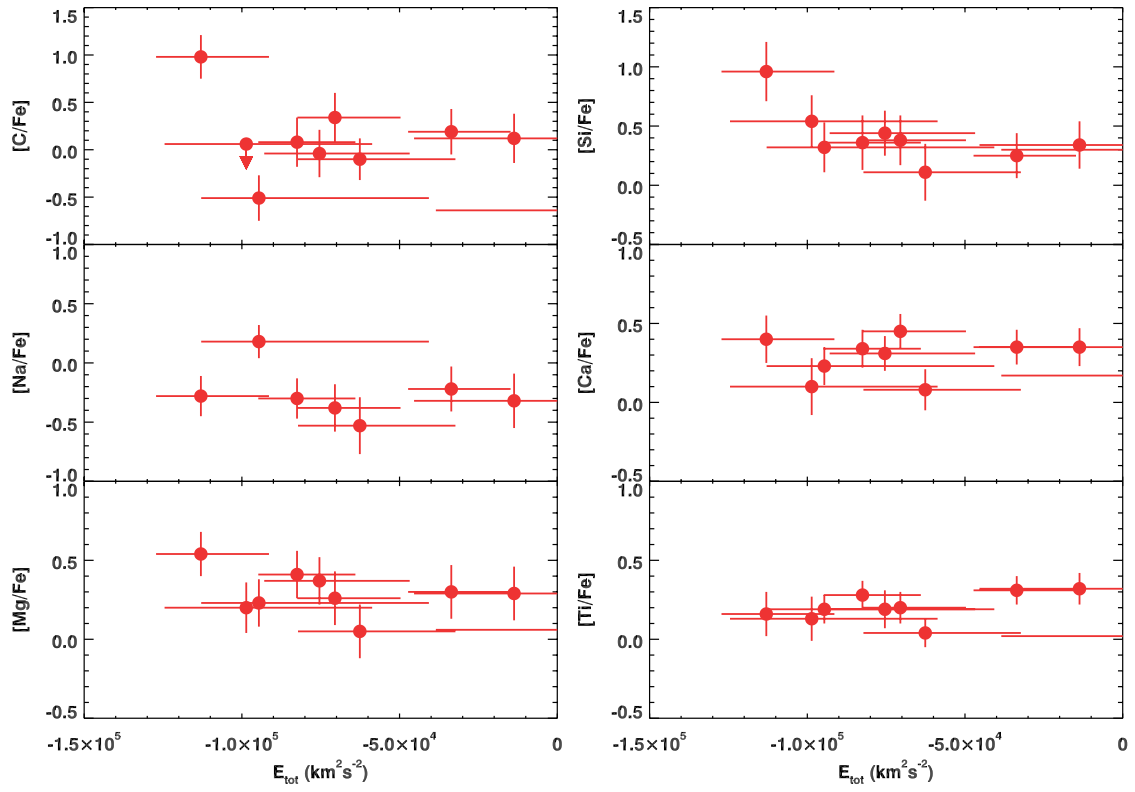


Figure 6.10 The orbital binding energies of the ten stars compared to various elemental abundances, $[X/\text{Fe}]$.

the stars that have the highest chance of having formed at the earliest times.

6.5. Conclusions

In this work, I have detailed the design, progress, and first results of the EMBLA Survey. The survey has proven to be highly successful, making use of the new filters available on the SkyMapper telescope to observe 5 million bulge stars, and selecting 14,000 as potentially metal-poor. From those 14,000 stars observed with AAOmega on the AAT, we have found just under half of these have metallicities lower than $[\text{Fe}/\text{H}] = -1$, probing a population that makes up less than 5% of the bulge (Ness et al. 2013a). Not all parts of the bulge were equally prosperous; closer to the plane we suffered badly due to the effects of extinction and reddening caused by dust. We also know that the bulge in general has a negative metallicity gradient, and it is still not clear whether this is one of the reasons why we observed fewer metal-poor stars close to the Galactic plane. Further work examining the distribution of metal-poor stars in the individual fields, and a universal calibration of the SkyMapper filter set will be needed in order to address this question.

Crucially, in our hunt for the very oldest stars, our spectra revealed hundreds of stars with $[\text{Fe}/\text{H}] < -2$. From these, we were able to pick out the most interesting spectra to follow up with high-resolution spectroscopy from 8 m-class telescopes. Our first high-resolution data came from the 8 m VLT as part of the Gaia-ESO survey, in 2012 (Howes et al. 2014; Chapter 3). The four stars studied were the amongst the most metal-poor stars known in the bulge, with metallicities in the range of $-2.72 < [\text{Fe}/\text{H}] < -2.48$. Probing their elemental abundances, we found they appeared to be mostly in line with stars found in the halo, although the α abundances showed a large range, with some unusual results. Two of the four had $[\text{Mg}/\text{Fe}] < 0$, whilst one of these also had $[\text{Ti}/\text{Fe}] = 0.85$. Studies of α -elements in halo stars had found that generally, different α -elements show little variation in an individual star, so this initial discovery was quite unexpected, and perhaps gave us some evidence of inhomogeneous mixing in the early Galaxy.

We continued observing early EMP candidates in 2012 with ten stars observed using the MIKE instrument on the Magellan Clay 6.5 m telescope (Howes et al. 2015b; Chapter 4). These ten had a wide range of metallicities ($-2.8 < [\text{Fe}/\text{H}] < -1.7$), and when combined with the four GES stars, provided us with the opportunity to properly assess the chemistry of bulge stars with metallicities between -1.5 and -3 . In this sample, we found the first sign of a very peculiar trend – a lack of stars with large carbon enhancements in their stellar atmospheres. The large wavelength range of MIKE spectra enabled us to measure the CH bands in all ten stars, and found that none of them showed the carbon enhancements found in halo CEMP stars.

Other interesting chemical features were also emerging from this data set. In particular, the spread of α abundances seen in the GES sample was also noticed here. The wide scatter seen in the neutron-capture elements, on the other hand, was consistent with that found in the halo. We found the EMBLA stars lacked high Y or Sr abundances that are required to

indicate that these stars had been polluted by a previous generation of fast rotating massive stars. In fact the ratio of $A(\text{La})$ to $A(\text{Eu})$ in our stars indicated less s-process enrichment than that found in the halo. Unfortunately, a lack of La lines strong enough in the stars to be able to measure meant that we only had four measurements of this indicator. We found one star which had chemistry consistent with having accreted material from an AGB binary companion; it had the highest C levels in the whole group and had a very low $[\text{Sr}/\text{Ba}]$ ratio, similar in composition to the CEMP-s category of halo metal-poor stars. It will be fascinating to investigate the trends of the neutron-capture elements for stars in the bulge with $[\text{Fe}/\text{H}] < -3$, in order to track the levels of s-process enrichment at the earliest epochs of the Galaxy.

Finally, we observed a further 23 stars in high-resolution using MIKE/Magellan (Howes et al. 2015a, Chapter 5). These stars more than doubled the number we had in high-resolution, and importantly broke through the $[\text{Fe}/\text{H}] = -3$ barrier to new, lower metallicities. Nine of the stars were classed as EMP, with one of these nine having a confirmed metallicity of $[\text{Fe}/\text{H}] = -3.94$. We were unable to measure any C in the spectrum of this star, and so combined with low Mg, we gave this star a total metallicity of $[\text{Z}/\text{H}] < -4.17$, which makes it among the most metal-poor stars known, along with SDSS J1029151+172927 (Caffau et al. 2012). We measured a total of 12 detected elements in this star's spectrum, and placed upper limits on a further seven. When we calculated the most likely supernova progenitor to this star, we found a good match to a $40 M_{\odot}$ hypernova. Hypernovae have been linked to the GRBs seen in the high-redshift Universe, but the signature of one has yet to be found in metal-poor halo stars. In contrast, the most metal-poor halo stars have been associated with low-energy supernovae with low levels of mixing (Heger & Woosley 2010; Bessell et al. 2015). These differing results could be due to the very different environments that halo and bulge metal-poor stars would have evolved from.

The last, important step in recognising these stars as potentially the oldest in the Galaxy came through establishing orbital parameters for them. Working together with the OGLE team, we used proper motions for 10 of the 23 stars to derive orbits. Seven of these were confined to the inner Galaxy, and in particular three stars had orbits that were entirely within the bulge. Extrapolating this information to our larger sample, we can expect that perhaps 33% of our stars have bulge-like orbits. We also used their kinematics to calculate the stars' total binding energies, E_{tot} . When comparing these to the models of Tumlinson (2010), we found that five of the stars had energies low enough to mean they could have formed as far back as $z \approx 20$. Two of the stars – the two most metal-poor stars in the sample – have a $\approx 50\%$ chance each at having formed before $z \sim 12$, if true, it would make them the oldest known objects in the cosmos.

So far, we have combined the information from these three samples of high-resolution data to draw the first conclusions on the chemistry of metal-poor bulge stars. With C measurements for 33 stars, and only one confirmed CEMP star, we can deduce that the lack of C enhanced stars is a feature that distinguishes the bulge region from the halo

region chemically. Combined with the information that these stars are very likely older than corresponding halo stars, this casts doubt onto the idea that CEMP stars are older than C-normal stars, which is considered a possibility. There is still a good chance that these stars have larger scatter in their α abundances compared to halo stars, with each individual star showing wider variation than that seen in the halo. This sort of pattern could well be indicative of inhomogeneous mixing, which is to be expected at the earliest epochs of star formation (Karlsson et al. 2013).

In summary, the EMBLA Survey has been the first to find and study in detail extremely metal-poor stars in the bulge region. There is a wealth of information from the intermediate-resolution data that is yet to be explored, with hundreds of stars classified as $[\text{Fe}/\text{H}] < -2$. The initial work into studying these stars in high-resolution has led to extraordinary discoveries of EMP stars with bulge-like kinematics and distinctive chemical patterns. With this new information, we may have found the first signatures of the birth of the Milky Way.

6.5.1. Future Plans for the EMBLA Survey

Clearly, the EMBLA Survey still has a significant amount of existing data that has not been fully explored yet, and we expect that over the course of the next couple of years, further observations may also help to answer some of the questions opened up by the initial findings. Listed here are the main goals of the survey in the immediate future:

- Further investigation is needed into the chemistry of our high-resolution sample. In this thesis, we have described the findings of the 37 stars analysed, in particular looking at the carbon and the α -elements. However, it is clear that the neutron-capture elements may hold interesting trends that we have yet to find. Initial work into this was done in Howes et al. (2015b), where we analysed the neutron capture results of the 14 stars studied to date, but it will be interesting to see how well those trends discovered extend to the larger sample.
- This investigation will be aided by further high-resolution observations that have already taken place. In July 2014, nine stars were observed using the UVES instrument (Dekker et al. 2000) on the VLT. In June 2015, another 15 stars were also observed using MIKE on Magellan. Adding these to the sample discussed here, we expect to publish the full details of their chemistry and kinematics in an upcoming paper. Further targets have been observed as part of GES, and will continue to be observed over the next two years.
- Now that `sick` – the pipeline used to analyse the 14,000 intermediate-resolution spectra – has been fully developed, we intend to reanalyse all of the stars observed. This will enable us to put together a final MDF of the survey, and discover the true numbers of metal-poor stars that we have found. We will be able to break down the

analysis by field position, to discover the full variation of metallicity with each field - both in terms of latitude, as was done in Chapter 2, but also longitude. The dust in the bulge region varies with respect to longitude as well as latitude - hopefully by comparing the MDFs at different positions, we will be able to tell whether the variation in our MDFs has been created due to the reddening issues, or due to the intrinsic metallicity gradient of the bulge.

- The unexpected result of a lack of carbon enhanced stars in our high-resolution data will push us to investigate the carbon levels at all the metallicities covered by EMBLA. Fortunately, the blue arm of the AAOmega spectra covers the CH bands around 430 nm. Although the resolution is low in the blue arm ($R \approx 1,500$), the C abundance for all of our stars will be approximately determined. This will enable us to deduce how carbon varies across the metallicity range, and also get some idea of variation with location in the bulge. This will directly test theories of first-star formation and the possible existence of a critical metallicity for the formation of low-mass stars.
- As mentioned in the Introduction, it is possible to derive the age of a star from asteroseismology. Currently, no space-based missions have observed bulge stars in order to obtain asteroseismic information, however the K2 mission plans to observe a bulge field for three months in the middle 2016 (Howell et al. 2014). The footprint of the bulge field has been made publicly accessible, so we have obtained observations using AAOmega of ~ 300 stars within the footprint; unfortunately the majority of EMBLA stars are located further from the Galactic plane than the K2 Campaign 9 footprint. The K2 team will be making a call for applications for Directors Discretionary Targets, and we intend to apply for these with the results of the observations taken in that field. Whilst the ages we can derive from asteroseismology will only be accurate to perhaps 10%, if we can obtain the ages of 100 stars with $[\text{Fe}/\text{H}] < -2$, we aim to constrain their average age statistically to the level of 100 million years - at which point we will have direct confirmation of whether these stars are indeed the oldest known. The K2 observations will also enable a direct comparison of asteroseismic ages for bulge and halo stars with the same $[\text{Fe}/\text{H}]$, with the expectation that the bulge stars will be older.

In the long term, there is the possibility of extending the original EMBLA survey. With the arrival of new, deep, and calibrated SkyMapper photometry from the Southern Sky Survey within the next few years, it will be possible to re-assess the fields we observed originally, to see if better candidates can be found. The advantage of a fully calibrated photometry set may be that we also can derive alternate methods of de-reddening, in which case probing the inner regions of the bulge will surely be a priority. Investigations by the APOGEE team into stars within one degree of the Galactic centre have revealed that there could be an overdensity of metal-poor stars in that region (Ness et al., in preparation). It will be fascinating to see if this tentative result can be confirmed by SkyMapper photometry, particularly as the age of metal-poor stars are predicted to be even older if they are found

closer to the centre. It will also be possible to combine the newly calibrated photometry from SkyMapper with infrared photometry from publicly available surveys, using similar techniques to Schlafman & Casey (2014). A second round of observations on the AAT to follow-up the improved SkyMapper photometry would lead to many new metal-poor stars being found.

6.5.2. Metal-Poor Bulge Stars in the Next Decade

There are several large-scale surveys and missions planned for the coming decade which are bound to enhance the study of metal-poor stars in the bulge. Most important of these will be Gaia (Perryman et al. 2001; Lindegren et al. 2008), which will bring us distances and proper motions of more than a billion stars in the Galaxy. With such accurate positional and kinematic data, we will be able to derive precise orbital information, discovering the binding energies of all the stars in the EMBLA survey, and beyond. We will be able to find the best candidates in terms of both chemistry and kinematics for the oldest stars in the Galaxy. We will also be able to get an accurate picture of the kinematics of all the stars surveyed – will the metal-poor population follow the orbital trends of the more metal-rich bulge stars? Do they align with the possible existence of the spherical, classical bulge?

The metal-poor stars observed as part of the Gaia-ESO survey will provide an important link to the chemistry of the rest of the bulge. By the time of its completion, GES will have observed close to 500 bulge stars with FLAMES/UVES, providing the largest sample of high-resolution bulge spectra ever observed. The advantage of having one sample, covering the entire metallicity range, is that the sample will be homogeneously observed and analysed. It will be possible to get a detailed chemical history of the bulge, we will be able to compare the ~ 30 metal-poor EMBLA stars surveyed with the more metal-rich population, to see exactly how the abundances of many elements changed over time, without fear of systematic offsets obscuring the trends. As GES is also surveying the other Galactic components, we will also be able to compare directly to the populations of the thick and thin discs, and crucially, metal-poor halo stars. A similar survey is taking place with the HERMES instrument on the AAT (Sheinis et al. 2014), where some targets from EMBLA with metallicities of $-2 < [\text{Fe}/\text{H}] < -1$ have been included, in order to probe the chemical abundances of all metallicities in the bulge (Duong et al. in preparation).

The numbers of spectra obtained in the bulge will be dwarfed, however, with the next generation of large scale surveys. One example of these, 4MOST (de Jong et al. 2012), plans to observe hundreds of thousands of bulge stars at a resolving power of $R \sim 20,000$. The evolution of many elements throughout the history of the Galaxy will be traced accurately, and allowing many more metal-poor stars to be found.

Finally, within the next decade we will see the arrival of the first of the extremely large telescopes, the ELTs. With (segmented) primary mirrors of 24 m+, these telescopes will

be able to obtain spectra of stars in the bulge that are currently too faint to observe. High-resolution, high-S/N spectra of many of these stars will be feasible, providing us with much more chemical information than we can currently obtain from bulge spectra.

The study of metal-poor stars has only just opened up to those in the bulge. Prior to the EMBLA survey, the lowest confirmed metallicity found was only $[\text{Fe}/\text{H}] = -2.1$. We have now pushed back that lower bound to $[\text{Fe}/\text{H}] = -3.94$, and with the future analysis of the data taken in 2014, we may find even lower.

Now that the first metal-poor stars have been found in the bulge, hopefully with the same time and effort that has been used to search the halo, further breakthroughs will occur in the bulge. As models of Population III stars have advanced in recent years, there have been frequent explanations put forth for how a low mass star could have formed. Perhaps, finally, a surviving Population III star will be found.

Bibliography

- Abadi, M. G., Navarro, J. F., Steinmetz, M., & Eke, V. R. 2003, *The Astrophysical Journal*, 597, 21
- Abel, T., Bryan, G. L., & Norman, M. L. 2002, *Science*, 295, 93
- Alves-Brito, A., Meléndez, J., Asplund, M., Ramírez, I., & Yong, D. 2010, *Astronomy & Astrophysics*, 513, 35
- Andrievsky, S. M., Spite, M., Korotin, S. A., Spite, F., Bonifacio, P., Cayrel, R., Hill, V., & Francois, P. 2008, *Astronomy & Astrophysics*, 481, 481
- Aoki, W., Beers, T. C., Christlieb, N., Norris, J. E., Ryan, S. G., & Tsangarides, S. 2007, *The Astrophysical Journal*, 655, 492
- Aoki, W., et al. 2006, *The Astrophysical Journal*, 639, 897
- Asplund, M. 2005, *Annual Review of Astronomy & Astrophysics*, 43, 481
- Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, *Annual Review of Astronomy & Astrophysics*, 47, 481
- Asplund, M., Lambert, D. L., Nissen, P. E., Primas, F., & Smith, V. V. 2006, *The Astrophysical Journal*, 644, 229
- Athanassoula, E. 2005, *Celestial Mechanics and Dynamical Astronomy*, 91, 9
- Baade, W. 1944, *The Astrophysical Journal*, 100, 137
- Bagnulo, S., Jehin, E., Ledoux, C., Cabanac, R., Melo, C., Gilmozzi, R., & Team, E. P. S. O. 2003, *The Messenger*, 114, 10
- Barbuy, B., et al. 2014, *Astronomy & Astrophysics*, 570, A76
- Barklem, P. S. 2007, *Astronomy & Astrophysics*, 466, 327

- Barklem, P. S., Piskunov, N., & O'Mara, B. J. 2000, *Astronomy & Astrophysics*, 363, 1091
- Barnes, S. A. 2003, *The Astrophysical Journal*, 586, 464
- Beers, T. C. 1999, *Astrophysics and Space Science*, 265, 105
- Beers, T. C., & Christlieb, N. 2005, *Annual Review of Astronomy & Astrophysics*, 43, 531
- Beers, T. C., Norris, J. E., Placco, V. M., Lee, Y. S., Rossi, S., Carollo, D., & Masseron, T. 2014, *The Astrophysical Journal*, 794, 58
- Beers, T. C., Preston, G. W., & Shectman, S. A. 1985, *The Astronomical Journal*, 90, 2089
- Belokurov, V., et al. 2007, *The Astrophysical Journal*, 654, 897
- Bensby, T., Feltzing, S., & Oey, M. S. 2014, *Astronomy & Astrophysics*, 562, A71
- Bensby, T., et al. 2013, *Astronomy & Astrophysics*, 549, 147
- Bergemann, M., & Cescutti, G. 2010, *Astronomy & Astrophysics*, 522, A9
- Bergemann, M., Lind, K., Collet, R., Magic, Z., & Asplund, M. 2012, *Monthly Notices of the Royal Astronomical Society*, 427, 27
- Bernstein, R., Shectman, S. A., Gunnels, S. M., Mochnacki, S., & Athey, A. E. 2003, *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*. Edited by Iye, 4841, 1694
- Bessell, M., Bloxham, G., Schmidt, B., Keller, S., Tisserand, P., & Francis, P. 2011, *Publications of the Astronomical Society of the Pacific*, 123, 789
- Bessell, M. S., et al. 2015, *The Astrophysical Journal Letters*, 806, L16
- Bournaud, F., & Elmegreen, B. G. 2009, *The Astrophysical Journal Letters*, 694, L158
- Bovy, J. 2015, *The Astrophysical Journal Supplement*, 216, 29
- Bovy, J., et al. 2012, *The Astrophysical Journal*, 759, 131
- Bromm, V. 2013, *Reports on Progress in Physics*, 76, 112901
- Bromm, V., Coppi, P. S., & Larson, R. B. 2002, *The Astrophysical Journal*, 564, 23
- Bromm, V., & Larson, R. B. 2004, *Annual Review of Astronomy & Astrophysics*, 42, 79
- Bromm, V., & Loeb, A. 2006, *The Astrophysical Journal*, 642, 382
- Bromm, V., Yoshida, N., Hernquist, L., & McKee, C. F. 2009, *Nature*, 459, 49
- Brook, C. B., Kawata, D., Scannapieco, E., Martel, H., & Gibson, B. K. 2007, *The Astrophysical Journal*, 661, 10

- Busso, M., Gallino, R., & Wasserburg, G. J. 1999, *Annual Review of Astronomy & Astrophysics*, 37, 239
- Caffau, E., et al. 2011a, *Nature*, 477, 67
- . 2011b, *Astronomy & Astrophysics*, 534, 4
- . 2012, *Astronomy & Astrophysics*, 542, A51
- . 2013, *Astronomy & Astrophysics*, 560, A71
- Carollo, D., et al. 2010, *The Astrophysical Journal*, 712, 692
- Casagrande, L., Portinari, L., & Flynn, C. 2006, *Monthly Notices of the Royal Astronomical Society*, 373, 13
- Casagrande, L., Ramírez, I., Meléndez, J., & Asplund, M. 2012, *The Astrophysical Journal*, 761, 16
- Casey, A. R. 2014, *arXiv.org*, 1405.5968
- Casey, A. R. 2014, *The Astrophysical Journal*, submitted
- Casey, A. R., & Schlafman, K. C. 2015, *The Astrophysical Journal*, 809, 110
- Cayrel, R., et al. 2004, *Astronomy & Astrophysics*, 416, 1117
- Cescutti, G., & Chiappini, C. 2014, *Astronomy & Astrophysics*, 565, A51
- Cescutti, G., Chiappini, C., Hirschi, R., Meynet, G., & Frischknecht, U. 2013, *Astronomy & Astrophysics*, 553, A51
- Chabrier, G. 2003, *The Publications of the Astronomical Society of the Pacific*, 115, 763
- Chamberlain, J. W., & Aller, L. H. 1951, *The Astrophysical Journal*, 114, 52
- Chaplin, W. J., & Miglio, A. 2013, *Annual Review of Astronomy & Astrophysics*, 51, 353
- Christlieb, N. 2003, *The Cosmic Circuit of Matter*, 16, 191
- Christlieb, N., Bessell, M. S., Beers, T. C., & Gustafsson, B. 2002, *Nature*, 419, 904
- Christlieb, N., Reimers, D., Wisotzki, L., Reetz, J., Gehren, T., & Beers, T. C. 2000, in *The First Stars: Proceedings of the MPA/ESO Workshop Held at Garching, Hamburger Sternwarte, Germany* (Springer Berlin Heidelberg), 49–50
- Christlieb, N., Schörck, T., Frebel, A., Beers, T. C., Wisotzki, L., & Reimers, D. 2008, *Astronomy & Astrophysics*, 484, 721
- Clark, P. C., Glover, S. C. O., Smith, R. J., Greif, T. H., Klessen, R. S., & Bromm, V. 2011, *Science*, 331, 1040

- Combes, F., Debbasch, F., Friedli, D., & Pfenniger, D. 1990, *Astronomy & Astrophysics*, 233, 82
- Cooke, R., Pettini, M., & Murphy, M. T. 2012, *Monthly Notices of the Royal Astronomical Society*, 425, 347
- Cucchiara, A., et al. 2011, *The Astrophysical Journal*, 736, 7
- de Jong, R. S., et al. 2012, in *Ground-based and Airborne Instrumentation for Astronomy IV. Proceedings of the SPIE, Leibniz-Institut für Astrophysik Potsdam (Germany) (International Society for Optics and Photonics)*
- de Laverny, P., Recio-Blanco, A., Worley, C. C., & Plez, B. 2012, *Astronomy & Astrophysics*, 544, A126
- De Silva, G. M., et al. 2015, *Monthly Notices of the Royal Astronomical Society*, 449, 2604
- Dekker, H., D’Odorico, S., Kaufer, A., Delabre, B., & Kotzlowski, H. 2000, *Proc. SPIE*, 4008, 534
- Diemand, J., Madau, P., & Moore, B. 2005, *Monthly Notices of the Royal Astronomical Society*, 364, 367
- Dotter, A., Chaboyer, B., Jevremovic, D., Kostov, V., Baron, E., & Ferguson, J. W. 2008, *The Astrophysical Journal Supplement Series*, 178, 89
- Ellis, R. S., et al. 2013, *The Astrophysical Journal Letters*, 763, L7
- Feltzing, S., & Gilmore, G. 1999, *Astrophysics and Space Science*, 265, 337
- Francois, P., et al. 2007, *Astronomy & Astrophysics*, 476, 935
- Frebel, A., Casey, A. R., Jacobson, H. R., & Yu, Q. 2013, *The Astrophysical Journal*, 769, 57
- Frebel, A., Collet, R., Eriksson, K., Christlieb, N., & Aoki, W. 2008, *The Astrophysical Journal*, 684, 588
- Frebel, A., Johnson, J. L., & Bromm, V. 2007, *Monthly Notices of the Royal Astronomical Society: Letters*, 380, L40
- Frebel, A., Kirby, E. N., & Simon, J. D. 2010, *Nature*, 464, 72
- Frebel, A., & Norris, J. E. 2013, *Planets*, 55
- . 2015, *Annual Review of Astronomy & Astrophysics*, 53, 631
- Frebel, A., et al. 2005, *Nature*, 434, 871
- Freeman, K., & Bland-Hawthorn, J. 2002, *Annual Review of Astronomy & Astrophysics*, 40, 487
- Freeman, K., et al. 2013, *Monthly Notices of the Royal Astronomical Society*, 428, 3660

- Fulbright, J. P., McWilliam, A., & Rich, R. M. 2007, *The Astrophysical Journal*, 661, 1152
- García Pérez, A. E., et al. 2013, *The Astrophysical Journal Letters*, 767, L9
- Gilmore, G., et al. 2012, *The Messenger*, 147, 25
- Girard, T. M., et al. 2011, *The Astronomical Journal*, 142, 15
- Gonzalez, O. A., Rejkuba, M., Zoccali, M., Valent, E., Minniti, D., & Tobar, R. 2013, *Astronomy & Astrophysics*, 552, 110
- Gonzalez, O. A., Rejkuba, M., Zoccali, M., & Valenti, E. 2012, *Astronomy & Astrophysics*, 543, 13
- Gonzalez, O. A., Rejkuba, M., Zoccali, M., Valenti, E., & Minniti, D. 2011, *Astronomy & Astrophysics*, 534, 3
- Gratton, R. G., Sneden, C., Carretta, E., & Bragaglia, A. 2000, *Astronomy & Astrophysics*, 354, 169
- Greif, T. H., Bromm, V., Clark, P. C., Glover, S. C. O., Smith, R. J., Klessen, R. S., Yoshida, N., & Springel, V. 2012, *Monthly Notices of the Royal Astronomical Society*, 424, 399
- Gustafsson, B., Edvardsson, B., Eriksson, K., Jørgensen, U. G., Nordlund, Å., & Plez, B. 2008, *Astronomy & Astrophysics*, 486, 951
- Heger, A., & Woosley, S. E. 2002, *The Astrophysical Journal*, 567, 532
- . 2010, *The Astrophysical Journal*, 724, 341
- Heiter, U., Jofre, P., Gustafsson, B., Korn, A. J., Soubiran, C., & Thévenin, F. 2015, *Astronomy & Astrophysics*, 582, A49
- Helmi, A., et al. 2006, *The Astrophysical Journal*, 651, L121
- Hill, V., et al. 2011, *Astronomy & Astrophysics*, 534, 80
- Howard, C. D., et al. 2009, *The Astrophysical Journal Letters*, 702, L153
- Howell, S. B., et al. 2014, *Publications of the Astronomical Society of the Pacific*, 126, 398
- Howes, L. M., et al. 2014, *Monthly Notices of the Royal Astronomical Society*, 445, 4241
- . 2015a, *Nature*, 527, 484
- . 2015b, *Monthly Notices of the Royal Astronomical Society*, submitted
- Ibata, R. A., & Gilmore, G. F. 1995, *Monthly Notices of the Royal Astronomical Society*, 275, 605
- Irwin, M. J., et al. 2007, *The Astrophysical Journal Letters*, 656, L13

- Ishigaki, M. N., Tominaga, N., Kobayashi, C., & Nomoto, K. 2014, *The Astrophysical Journal Letters*, 792, L32
- Jacobson, H. R., et al. 2015, *The Astrophysical Journal*, 807, 171
- Jofre, P., et al. 2014, *Astronomy & Astrophysics*, 564, 133
- Karlsson, T., Bromm, V., & Bland-Hawthorn, J. 2013, *Reviews of Modern Physics*, 85, 809
- Kauffmann, G. 1996, *Monthly Notices of the Royal Astronomical Society*, 281, 487
- Keller, S. C., et al. 2007, *Publications of the Astronomical Society of Australia*, 24, 1
- . 2014, *Nature*, 506, 463
- Kelson, D. D. 2003, *The Publications of the Astronomical Society of the Pacific*, 115, 688
- Kirby, E. N., Simon, J. D., Geha, M., Guhathakurta, P., & Frebel, A. 2008, *The Astrophysical Journal Letters*, 685, L43
- Klessen, R. S., Glover, S. C. O., & Clark, P. C. 2012, *Monthly Notices of the Royal Astronomical Society*, 421, 3217
- Kobayashi, C., Ishigaki, M. N., Tominaga, N., & Nomoto, K. 2014, *The Astrophysical Journal Letters*, 785, L5
- Komatsu, E., et al. 2011, *The Astrophysical Journal Supplement*, 192, 18
- Komiya, Y., Suda, T., & Fujimoto, M. Y. 2015, *The Astrophysical Journal Letters*, 808, L47
- Koposov, S. E., Belokurov, V., Torrealba, G., & Evans, N. W. 2015, *The Astrophysical Journal*, 805, 130
- Kormendy, J., & Kennicutt, R. C. J. 2004, *Annual Review of Astronomy & Astrophysics*, 42, 603
- Krumolz, M. R. 2014, *Physics Reports*, 539, 49
- Kunder, A., Rich, R. M., Hawkins, K., & Poleski, R. 2015, *The Astrophysical Journal Letters*, 808, L12
- Kunder, A., et al. 2012, *The Astronomical Journal*, 143, 57
- Lai, D. K., Bolte, M., Johnson, J. A., Lucatello, S., Heger, A., & Woosley, S. E. 2008, *The Astrophysical Journal*, 681, 1524
- Laird, J. B., Carney, B. W., Rupen, M. P., & Latham, D. W. 1988, *The Astronomical Journal*, 96, 1908
- Lecureur, A., Hill, V., Zoccali, M., Barbuy, B., Gomez, A., Minniti, D., Ortolani, S., & Renzini, A. 2007, *Astronomy & Astrophysics*, 465, 799

- Lewis, I. J., et al. 2002, *Monthly Notices of the Royal Astronomical Society*, 333, 279
- Li, H.-N., Zhao, G., Christlieb, N., Wang, L., Wang, W., Zhang, Y., Hou, Y., & Yuan, H. 2015, *The Astrophysical Journal*, 798, 110
- Lind, K., Asplund, M., & Barklem, P. S. 2009, *Astronomy & Astrophysics*, 503, 541
- Lind, K., Asplund, M., Barklem, P. S., & Belyaev, A. K. 2011, *Astronomy & Astrophysics*, 528, A103
- Lind, K., Bergemann, M., & Asplund, M. 2012, *Monthly Notices of the Royal Astronomical Society*, 427, 50
- Lindgren, L., et al. 2008, *Proceedings of the IAU*, 3, 217
- Lucatello, S., Beers, T., Christlieb, N., Barklem, P., Rossi, S., Marsteller, B., Sivarani, T., & Lee, Y. S. 2006, *The Astrophysical Journal Letters*, 652, L37
- Luo, A. L., et al. 2012, *Research in Astronomy and Astrophysics*, 12, 1243
- Maeder, A., & Meynet, G. 2012, *Reviews of Modern Physics*, 84, 25
- McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, *The Astronomical Journal*, 109, 2757
- Meibom, S., Barnes, S. A., Platais, I., Gilliland, R. L., Latham, D. W., & Mathieu, R. D. 2015, *Nature*, 517, 589
- Meléndez, J., Casagrande, L., Ramírez, I., Asplund, M., & Schuster, W. J. 2010, *Astronomy & Astrophysics*, 515, L3
- Meléndez, J., et al. 2008, *Astronomy & Astrophysics*, 484, L21
- Mihalas, D., & Binney, J. 1981, *Galactic astronomy: Structure and kinematics*, 2nd edn. (San Francisco)
- Minniti, D., Olszewski, E. W., Liebert, J., White, S. D. M., Hill, J. M., & Irwin, M. J. 1995, *Monthly Notices of the Royal Astronomical Society*, 277, 1293
- Minniti, D., et al. 2010, *New Astronomy*, 15, 433
- Mitschang, A. W., De Silva, G., Zucker, D. B., Anguiano, B., Bensby, T., & Feltzing, S. 2014, *Monthly Notices of the Royal Astronomical Society*, 438, 2753
- Murphy, S., Keller, S., Schmidt, B., Tisserand, P., Bessell, M., Francis, P., & Costa, G. D. 2009, *The Eighth Pacific Rim Conference on Stellar Astrophysics: A Tribute to Kam-Ching Leung ASP Conference Series*, 404, 356
- Nakamura, F., & Umemura, M. 2001, *The Astrophysical Journal*, 548, 19
- Nataf, D. M., et al. 2013, *The Astrophysical Journal*, 769, 88

- . 2015, *Monthly Notices of the Royal Astronomical Society*, 447, 1535
- Ness, M., Debattista, V. P., Bensby, T., Feltzing, S., Roskar, R., Cole, D. R., Johnson, J. A., & Freeman, K. 2014, *The Astrophysical Journal Letters*, 787, L19
- Ness, M., et al. 2013a, *Monthly Notices of the Royal Astronomical Society*, 430, 836
- . 2013b, *Monthly Notices of the Royal Astronomical Society*, 432, 2092
- Nishiyama, S., Nagata, T., Tamura, M., Kandori, R., Hatano, H., Sato, S., & Sugitani, K. 2008, *The Astrophysical Journal*, 680, 1174
- Nissen, P. E., & Schuster, W. J. 2010, *Astronomy & Astrophysics*, 511, L10
- Nomoto, K., Maeda, K., Umeda, H., Ohkubo, T., Deng, J., & Mazzali, P. 2003, *Progress of Theoretical Physics Supplement*, 151, 44
- Norris, J. E., Christlieb, N., Korn, A. J., Eriksson, K., Bessell, M. S., Beers, T. C., Wisotzki, L., & Reimers, D. 2007, *The Astrophysical Journal*, 670, 774
- Norris, J. E., et al. 2013a, *The Astrophysical Journal*, 762, 25
- . 2013b, *The Astrophysical Journal*, 762, 28
- O'Shea, B. W., & Norman, M. L. 2007, *The Astrophysical Journal*, 654, 66
- Pasquini, L., et al. 2002, *The Messenger*, 110, 1
- Perryman, M. A. C., et al. 2001, *Astronomy & Astrophysics*, 369, 339
- Pirzkal, N., et al. 2015, *The Astrophysical Journal*, 804, 11
- Placco, V. M., Frebel, A., Beers, T. C., & Stancliffe, R. J. 2014, *The Astrophysical Journal*, 797, 21
- Planck Collaboration, P., et al. 2014, *Astronomy & Astrophysics*, 571, A16
- Poleski, R., et al. 2013, *The Astrophysical Journal*, 776, 76
- Ramirez, S. V., Stephens, A., Frogel, J. A., & DePoy, D. L. 2000, *The Astronomical Journal*, 120, 833
- Randich, S., et al. 2013, *The Messenger*, 154, 47
- Rich, R. M. 1988, *The Astronomical Journal*, 95, 828
- Robin, A. C., Marshall, D. J., Schultheis, M., & Reyl  , C. 2012, *Astronomy & Astrophysics*, 538, A106
- Robin, A. C., Reyl  , C., Derri  re, S., & Picaud, S. 2003, *Astronomy & Astrophysics*, 409, 523
- Roederer, I. U. 2009, *The Astronomical Journal*, 137, 272

- Roederer, I. U., Cowan, J. J., Karakas, A. I., Kratz, K.-L., Lugaro, M., Simmerer, J., Farouqi, K., & Sneden, C. 2010, *The Astrophysical Journal*, 724, 975
- Roederer, I. U., Preston, G. W., Thompson, I. B., Shectman, S. A., Sneden, C., Burley, G. S., & Kelson, D. D. 2014, *The Astronomical Journal*, 147, 136
- Roeser, S., Demleitner, M., & Schilbach, E. 2010, *The Astronomical Journal*, 139, 2440
- Rojas-Arriagada, A., et al. 2014, *Astronomy & Astrophysics*, 569, A103
- Ryan, S. G., & Norris, J. E. 1991a, *The Astronomical Journal*, 101, 1835
- . 1991b, *The Astronomical Journal*, 101, 1865
- Ryde, N., et al. 2010, *Astronomy & Astrophysics*, 509, A20
- Sacco, G. G., et al. 2014, *Astronomy & Astrophysics*, 565, 113
- Sadler, E. M., Rich, R. M., & Terndrup, D. M. 1996, *The Astronomical Journal*, 112, 171
- Salvadori, S., Ferrara, A., Schneider, R., Scannapieco, E., & Kawata, D. 2010, *Monthly Notices of the Royal Astronomical Society*, 401, L5
- Saunders, W., et al. 2004, in *Ground-based Instrumentation for Astronomy. Proceedings of the SPIE, Anglo-Australian Observatory, (Australia) (International Society for Optics and Photonics)*, 389–400
- Sbordone, L., et al. 2010, *Astronomy & Astrophysics*, 522, A26
- Scannapieco, E., Kawata, D., Brook, C. B., Schneider, R., Ferrara, A., & Gibson, B. K. 2006, *The Astrophysical Journal*, 653, 285
- Schlafly, E. F., & Finkbeiner, D. P. 2011, *The Astrophysical Journal*, 737, 103
- Schlaufman, K. C., & Casey, A. R. 2014, *The Astrophysical Journal*, 797, 13
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *The Astrophysical Journal*, 500, 525
- Schneider, R., Omukai, K., Limongi, M., Ferrara, A., Salvaterra, R., Chieffi, A., & Bianchi, S. 2012, *Monthly Notices of the Royal Astronomical Society*, 423, L60
- Schönrich, R., Asplund, M., & Casagrande, L. 2011, *Monthly Notices of the Royal Astronomical Society*, 415, 3807
- . 2014, *The Astrophysical Journal*, 786, 7
- Schörck, T., et al. 2009, *Astronomy & Astrophysics*, 507, 817
- Searle, L., & Zinn, R. 1978, *Astrophysical Journal*, 225, 357
- Serenelli, A. M., Bergemann, M., Ruchti, G., & Casagrande, L. 2013, *Monthly Notices of the Royal Astronomical Society*, 429, 3645

- Sharp, R., et al. 2006, *Astronomical Telescopes and Instrumentation*. Proceedings of the SPIE, 6269
- Sheinis, A., et al. 2014, in *Proceedings of the SPIE, Australian Astronomical Observatory (Australia)* (International Society for Optics and Photonics)
- Shen, J., Rich, R. M., Kormendy, J., Howard, C. D., de Propriis, R., & Kunder, A. 2010, *The Astrophysical Journal Letters*, 720, L72
- Skrutskie, M. F., et al. 2006, *The Astronomical Journal*, 131, 1163
- Smiljanic, R., et al. 2014, *Astronomy & Astrophysics*, 570, A122
- Snedden, C., Bean, J., Ivans, I., Lucatello, S., & Sobek, J. 2012, *Astrophysics Source Code Library*, 02009
- Snedden, C., Cowan, J. J., & Gallino, R. 2008, *Annual Review of Astronomy & Astrophysics*, 46, 241
- Soderblom, D. R., Stauffer, J. R., MacGregor, K. B., & Jones, B. F. 1993, *The Astrophysical Journal*, 409, 624
- Spite, F., & Spite, M. 1982, *Astronomy & Astrophysics*, 115, 357
- Spite, M., Spite, F., Bonifacio, P., Caffau, E., Francois, P., & Sbordone, L. 2014, *Astronomy & Astrophysics*, 571, A40
- Stacy, A., Greif, T. H., Klessen, R. S., Bromm, V., & Loeb, A. 2013, *Monthly Notices of the Royal Astronomical Society*, 431, 1470
- Starkenburg, E., et al. 2013, *Astronomy & Astrophysics*, 549, 88
- Sumi, T., et al. 2004, *Monthly Notices of the Royal Astronomical Society*, 348, 1439
- Szymański, M. K. 2005, *Acta Astronomica*, 55, 43
- Tafelmeyer, M., et al. 2010, *Astronomy & Astrophysics*, 524, 58
- Takeda, Y., Zhao, G., Chen, Y.-Q., Qiu, H.-M., & Takada-Hidai, M. 2002, *Publications of the Astronomical Society of Japan*, 54, 275
- Tody, D. 1986, in *Instrumentation in Astronomy VI; Proceedings of the Meeting*, ed. D. L. Crawford (International Society for Optics and Photonics), 733–748
- Tody, D. 1993, *Astronomical Data Analysis Software and Systems II*, 52, 173
- Travaglio, C., Gallino, R., Arnone, E., & Cowan, J. 2004, *The Astrophysical Journal*, 601, 864
- Tumlinson, J. 2007, *The Astrophysical Journal*, 664, L63
- . 2010, *The Astrophysical Journal*, 708, 1398

- Udalski, A., Szymański, M. K., & Szymański, G. 2015, *Acta Astronomica*, 65, 1
- Umeda, H., & Nomoto, K. 2002, *The Astrophysical Journal*, 565, 385
- . 2005, *The Astrophysical Journal*, 619, 427
- Valenti, J. A., & Piskunov, N. 1996, *Astronomy and Astrophysics Supplement*, 118, 595
- Wegg, C., & Gerhard, O. 2013, *Monthly Notices of the Royal Astronomical Society*, 435, 1874
- Wenger, M., et al. 2000, *Astronomy and Astrophysics Supplement*, 143, 9
- White, S. D. M., & Springel, V. 2000, in *The First Stars* (Berlin/Heidelberg: Springer-Verlag), 327–335
- Wisotzki, L., Christlieb, N., Bade, N., Beckmann, V., Köhler, T., Vanelle, C., & Reimers, D. 2000, *Astronomy & Astrophysics*, 358, 77
- Wyse, R. F. G., & Gilmore, G. 1992, *The Astronomical Journal*, 104, 144
- Yanny, B., et al. 2009, *The Astronomical Journal*, 137, 4377
- Yong, D., et al. 2013a, *The Astrophysical Journal*, 762, 26
- . 2013b, *The Astrophysical Journal*, 762, 27
- York, D. G., et al. 2000, *The Astronomical Journal*, 120, 1579
- Zacharias, N., Finch, C. T., Girard, T. M., Henden, A., Bartlett, J. L., Monet, D. G., & Zacharias, M. I. 2013, *The Astronomical Journal*, 145, 44
- Zoccali, M., Hill, V., Lecureur, A., Barbuy, B., Renzini, A., Minniti, D., Gomez, A., & Ortolani, S. 2008, *Astronomy & Astrophysics*, 486, 177
- Zoccali, M., et al. 2006, *Astronomy & Astrophysics*, 457, L1

APPENDIX A

Online Data Tables

A.1. Tables from Chapter 4

Table A.1 Full list of the lines measured including atomic data.

Ion	λ (nm)	χ (eV)	$\log gf$	Ion	λ (nm)	χ (eV)	$\log gf$
Li I	670.776	0.000	0.174	Si I	390.552	1.910	-1.090
O I	630.030	0.000	-9.715	Si I	410.294	1.910	-3.140
O I	636.378	0.000	-10.190	Si I	566.555	4.900	-1.730
Na I	588.995	0.000	0.108	Si I	570.110	4.930	-1.953
Na I	589.592	0.000	-0.194	Si I	570.840	4.954	-1.370
Na I	818.326	2.102	0.237	Si I	577.215	5.060	-1.740
Na I	819.482	2.104	0.492	Si I	615.513	5.619	-0.754
Mg I	382.936	2.710	-0.227	K I	769.897	0.000	-0.177
Mg I	383.230	2.710	0.125	Ca I	422.673	0.000	0.244
Mg I	383.829	2.720	0.397	Ca I	442.544	1.879	-0.358
Mg I	470.299	4.345	-0.440	Ca I	443.570	1.886	-0.519
Mg I	517.268	2.712	-0.450	Ca I	526.170	2.521	-0.579
Mg I	518.360	2.717	-0.239	Ca I	534.947	2.709	-0.310
Mg I	552.841	4.346	-0.620	Ca I	558.197	2.523	-0.555
Mg I	571.109	4.346	-1.724	Ca I	558.875	2.526	0.358
Mg I	880.676	4.346	-0.130	Ca I	559.011	2.521	-0.571
Al I	396.152	0.014	-0.340	Ca I	559.446	2.523	0.097

Table A.1 Full list of the lines measured including atomic data. (continued)

Ion	λ (nm)	χ (eV)	$\log gf$	Ion	λ (nm)	χ (eV)	$\log gf$
Ca I	560.128	2.526	-0.523	Ti I	521.039	0.048	-0.820
Ca I	585.745	2.933	0.240	Ti II	375.930	0.610	0.270
Ca I	610.272	1.879	-0.793	Ti II	376.132	0.570	0.170
Ca I	612.222	1.886	-0.316	Ti II	439.585	1.240	-1.970
Ca I	616.217	1.899	-0.090	Ti II	444.379	1.080	-0.700
Ca I	616.904	2.523	-0.797	Ti II	446.851	1.130	-0.600
Ca I	616.956	2.526	-0.478	Ti II	449.352	1.080	-2.830
Ca I	643.908	2.526	0.390	Ti II	450.127	1.120	-0.760
Ca I	644.981	2.521	-0.502	Ti II	470.866	1.237	-2.370
Ca I	647.166	2.526	-0.686	Ti II	477.999	2.048	-1.248
Ca I	649.965	2.523	-0.818	Ti II	479.852	1.080	-2.670
Ca I	671.768	2.709	-0.524	Ti II	486.561	1.116	-2.970
Ca II	393.366	0.000	0.135	Ti II	491.120	3.124	-0.640
Ca II	849.802	1.692	-1.469	Ti II	500.516	1.566	-2.730
Ca II	854.209	1.700	-0.514	Ti II	501.368	1.582	-2.190
Ca II	866.214	1.692	-0.770	Ti II	518.590	1.893	-1.490
Sc II	523.981	1.455	-0.765	Ti II	533.677	1.582	-1.630
Sc II	552.679	1.768	0.024	Ti II	538.102	1.566	-1.970
Sc II	564.100	1.500	-1.131	Ti II	541.875	1.582	-2.110
Sc II	565.790	1.507	-0.603	Cr I	425.433	0.000	-0.090
Sc II	566.715	1.500	-1.309	Cr I	461.612	0.983	-1.190
Sc II	566.904	1.500	-1.200	Cr I	462.617	0.968	-1.330
Sc II	568.420	1.507	-1.074	Cr I	464.615	1.030	-0.740
Sc II	624.564	1.507	-1.022	Cr I	465.128	0.983	-1.460
Ti I	399.860	0.048	0.020	Cr I	465.215	1.004	-1.040
Ti I	451.270	0.836	-0.400	Cr I	520.604	0.941	0.020
Ti I	451.802	0.826	-0.250	Cr I	524.757	0.961	-1.590
Ti I	453.324	0.850	0.540	Cr I	529.669	0.983	-1.360
Ti I	453.478	0.840	0.350	Cr I	529.827	0.983	-1.140
Ti I	498.173	0.848	0.570	Cr I	534.580	1.004	-0.950
Ti I	499.950	0.826	0.320	Cr I	534.832	1.004	-1.210
Ti I	503.996	0.021	-1.080	Cr I	540.978	1.030	-0.670
Ti I	506.465	0.048	-0.940	Cr II	484.824	3.864	-1.180
Ti I	517.374	0.000	-1.060	Cr II	487.640	3.854	-1.481
Ti I	519.297	0.021	-0.950	Mn I	403.075	0.000	-0.480

Table A.1 Full list of the lines measured including atomic data. (continued)

Ion	λ (nm)	χ (eV)	$\log gf$	Ion	λ (nm)	χ (eV)	$\log gf$
Mn I	403.306	0.000	-0.620	Fe I	536.747	4.415	0.444
Mn I	403.448	0.000	-0.810	Fe I	536.996	4.371	0.536
Mn I	482.347	2.319	0.136	Fe I	538.337	4.312	0.632
Fe I	487.214	2.882	-0.567	Fe I	539.317	3.241	-0.715
Fe I	489.149	2.851	-0.111	Fe I	540.578	0.990	-1.858
Fe I	492.050	2.832	0.072	Fe I	541.520	4.386	0.643
Fe I	492.477	2.279	-2.178	Fe I	542.407	4.320	0.520
Fe I	493.881	2.875	-1.077	Fe I	543.452	1.011	-2.119
Fe I	493.969	0.859	-3.302	Fe I	550.147	0.958	-3.046
Fe I	494.639	3.368	-1.170	Fe I	550.678	0.990	-2.793
Fe I	499.413	0.915	-3.002	Fe I	556.962	3.417	-0.486
Fe I	502.813	3.573	-1.122	Fe I	557.284	3.396	-0.275
Fe I	504.982	2.279	-1.349	Fe I	557.609	3.430	-0.900
Fe I	506.008	0.000	-5.431	Fe I	558.676	3.368	-0.120
Fe I	506.877	2.940	-1.041	Fe I	561.564	3.332	0.050
Fe I	508.334	0.958	-2.871	Fe I	606.548	2.608	-1.470
Fe I	512.736	0.915	-3.278	Fe I	613.662	2.453	-1.405
Fe I	514.174	2.424	-2.101	Fe I	617.333	2.223	-2.880
Fe I	515.191	1.011	-3.322	Fe I	619.156	2.433	-1.416
Fe I	516.227	4.178	0.020	Fe I	621.343	2.223	-2.481
Fe I	517.160	1.485	-1.721	Fe I	621.928	2.198	-2.434
Fe I	519.494	1.557	-2.021	Fe I	624.632	3.602	-0.805
Fe I	519.871	2.223	-2.113	Fe I	625.256	2.404	-1.727
Fe I	521.627	1.608	-2.082	Fe I	633.533	2.198	-2.177
Fe I	521.739	3.211	-1.116	Fe I	635.870	0.859	-4.468
Fe I	522.553	0.110	-4.755	Fe I	639.360	2.433	-1.504
Fe I	523.294	2.940	-0.076	Fe I	641.165	3.654	-0.656
Fe I	524.705	0.087	-4.975	Fe I	643.085	2.176	-1.976
Fe I	525.021	0.121	-4.918	Fe I	649.498	2.404	-1.256
Fe I	526.954	0.859	-1.327	Fe I	654.624	2.758	-1.536
Fe I	528.179	3.038	-0.833	Fe I	659.291	2.727	-1.473
Fe I	530.230	3.283	-0.720	Fe I	659.387	2.433	-2.394
Fe I	530.736	1.608	-2.912	Fe I	868.862	2.176	-1.204
Fe I	532.418	3.211	-0.103	Fe I	882.422	2.198	-1.540
Fe I	533.993	3.266	-0.684	Fe II	412.875	2.583	-3.630

Table A.1 Full list of the lines measured including atomic data. (continued)

Ion	λ (nm)	χ (eV)	$\log gf$	Ion	λ (nm)	χ (eV)	$\log gf$
Fe II	417.886	2.582	-2.510	Ni I	619.117	1.676	-2.939
Fe II	441.683	2.779	-2.650	Ni I	664.363	1.676	-2.300
Fe II	449.141	2.856	-2.710	Ni I	676.777	1.826	-2.170
Fe II	450.829	2.856	-2.440	Cu I	510.554	1.389	-1.516
Fe II	452.022	2.807	-2.650	Cu I	578.213	1.642	-1.781
Fe II	457.634	2.844	-2.950	Zn I	472.216	4.030	-0.380
Fe II	466.676	2.828	-3.280	Zn I	481.053	4.078	-0.160
Fe II	473.145	2.891	-3.100	Sr II	407.771	0.000	0.148
Fe II	492.393	2.891	-1.260	Sr II	421.552	0.000	-0.173
Fe II	499.336	2.807	-3.684	Y II	374.755	0.100	-0.910
Fe II	501.844	2.891	-1.100	Y II	377.433	0.130	0.210
Fe II	519.758	3.230	-2.220	Y II	378.869	0.100	-0.070
Fe II	523.463	3.221	-2.180	Y II	395.035	0.100	-0.490
Fe II	526.481	3.230	-3.130	Y II	439.802	0.130	-1.000
Fe II	528.411	2.891	-3.195	Y II	488.368	1.084	0.070
Fe II	531.662	3.153	-1.870	Y II	490.012	1.033	-0.101
Fe II	532.555	3.221	-3.160	Y II	508.742	1.084	-0.170
Fe II	542.526	3.199	-3.220	Y II	520.041	0.992	-0.570
Fe II	553.485	3.245	-2.865	Zr II	375.159	0.972	0.000
Fe II	624.756	3.892	-2.435	Zr II	399.110	0.758	-0.310
Fe II	643.268	2.891	-3.570	Zr II	416.120	0.713	-0.590
Fe II	645.638	3.903	-2.185	Zr II	420.898	0.713	-0.510
Fe II	651.608	2.891	-3.310	Zr II	421.180	0.527	-1.040
Co I	384.205	0.920	-0.770	Ba II	455.403	0.000	0.140
Co I	384.547	0.920	0.010	Ba II	585.367	0.604	-0.907
Co I	389.408	1.050	0.090	Ba II	649.690	0.604	-0.407
Co I	412.132	0.920	-0.300	La II	408.671	0.000	-0.070
Ni I	380.714	0.420	-1.180	Eu II	381.960	0.000	0.510
Ni I	385.829	0.420	-0.970	Eu II	412.972	0.000	0.220
Ni I	490.441	3.542	-0.016	Eu II	420.500	0.000	0.210
Ni I	503.536	3.635	0.290				
Ni I	508.111	3.847	0.462				
Ni I	508.409	3.679	-0.084				
Ni I	513.707	1.676	-1.990				
Ni I	547.690	1.826	-0.890				

Table A.2 Chemical abundances for all 14 stars.

Name (SMSS)	[C/Fe]	[O/Fe]	[Na/Fe]	[Mg/Fe]	[Al/Fe]	[Si/Fe]	[K/Fe]	[Ca/Fe]	[Sc/Fe]
J182637.10-342924.2	0.68 ± 0.20	-	-0.36 ± 0.14	0.50 ± 0.16	-0.93 ± 0.20	0.26 ± 0.10	0.76 ± 0.16	0.26 ± 0.09	0.05 ± 0.07
J182600.09-332531.0	-0.41 ± 0.22	-	-0.10 ± 0.18	0.16 ± 0.10	-0.3 ± 0.19	0.60 ± 0.12	0.48 ± 0.14	0.15 ± 0.08	0.16 ± 0.07
J182601.24-332358.3	0.32 ± 0.20	-	0.27 ± 0.18	0.78 ± 0.10	-0.45 ± 0.16	0.56 ± 0.19	0.69 ± 0.12	0.30 ± 0.10	-
J182753.81-334607.7	-0.41 ± 0.25	-	-0.40 ± 0.14	0.29 ± 0.12	-1.42 ± 0.18	0.34 ± 0.17	0.55 ± 0.14	0.21 ± 0.09	0.16 ± 0.08
J183000.36-333919.3	0.04 ± 0.24	-	-0.51 ± 0.17	0.34 ± 0.12	-1.02 ± 0.18	0.48 ± 0.15	-	0.35 ± 0.08	0.19 ± 0.09
J182922.48-335559.4	0.00 ± 0.23	-	-0.05 ± 0.23	0.71 ± 0.12	-0.99 ± 0.15	0.12 ± 0.19	-	0.44 ± 0.08	0.34 ± 0.12
J182930.47-335958.3	-0.12 ± 0.19	0.79 ± 0.11	-0.25 ± 0.18	0.37 ± 0.11	-0.11 ± 0.19	0.71 ± 0.12	0.76 ± 0.14	0.29 ± 0.09	0.14 ± 0.08
J183225.29-334938.4	-0.22 ± 0.21	-	-0.14 ± 0.15	0.42 ± 0.13	-1.12 ± 0.20	0.05 ± 0.16	-	0.26 ± 0.12	0.25 ± 0.13
J183128.71-341018.4	0.01 ± 0.20	0.73 ± 0.13	-0.63 ± 0.14	0.22 ± 0.12	-0.91 ± 0.20	0.48 ± 0.19	0.61 ± 0.15	0.02 ± 0.09	0.31 ± 0.08
J182948.48-341053.9	0.68 ± 0.22	-	-0.46 ± 0.15	0.57 ± 0.10	-0.70 ± 0.17	0.69 ± 0.10	-	0.37 ± 0.08	-
J182153.85-341018.8	-	-	-0.18 ± 0.19	0.47 ± 0.13	-	0.34 ± 0.08	-	0.26 ± 0.08	0.05 ± 0.07
J183617.33-270005.3	-	-	-	0.12 ± 0.18	-	-	-	0.23 ± 0.09	0.17 ± 0.10
J175510.50-412812.1	-	-	-	0.03 ± 0.15	-	-	-	0.20 ± 0.15	-
J175652.43-413612.8	-	-	-0.28 ± 0.20	-0.14 ± 0.17	-	-	-	0.14 ± 0.11	0.48 ± 0.12

Table A.2 Chemical abundances for all 14 stars. (continued)

Name (SMSS)	[Ti/Fe]	[Cr/Fe]	[Mn/Fe]	[Co/Fe]	[Ni/Fe]	[Zn/Fe]	[Sr/Fe]	[Y/Fe]	[Zr/Fe]
J182637.10-342924.2	0.27 ±0.09	-0.17 ±0.13	-0.13 ±0.19	0.23 ±0.20	-0.07 ±0.11	0.16 ±0.08	0.14 ±0.14	-0.11 ±0.09	0.28 ±0.10
J182600.09-332531.0	0.28 ±0.06	-0.21 ±0.15	-0.56 ±0.17	0.01 ±0.19	0.12 ±0.16	0.50 ±0.10	-0.17 ±0.16	-0.30 ±0.12	0.16 ±0.11
J182601.24-332358.3	0.12 ±0.09	-0.35 ±0.13	-0.74 ±0.14	0.31 ±0.16	0.04 ±0.17	-	0.34 ±0.21	0.41 ±0.11	-
J182753.81-334607.7	0.32 ±0.07	-0.20 ±0.15	-0.96 ±0.22	0.08 ±0.20	0.24 ±0.15	0.01 ±0.11	-0.12 ±0.19	-0.19 ±0.10	-
J183000.36-333919.3	0.24 ±0.08	-0.40 ±0.16	-0.58 ±0.24	0.51 ±0.20	0.20 ±0.15	0.36 ±0.11	-0.50 ±0.19	-0.35 ±0.09	0.38 ±0.11
J182922.48-335559.4	0.42 ±0.10	-0.03 ±0.12	-0.61 ±0.14	0.46 ±0.14	0.17 ±0.14	-	0.15 ±0.21	-0.02 ±0.10	0.35 ±0.13
J182930.47-335958.3	0.21 ±0.10	-0.20 ±0.15	-0.37 ±0.22	0.05 ±0.21	0.27 ±0.17	0.11 ±0.09	-0.13 ±0.13	-0.31 ±0.11	0.04 ±0.10
J183225.29-334938.4	0.39 ±0.11	-0.26 ±0.14	-0.15 ±0.23	-0.11 ±0.20	-0.07 ±0.12	0.21 ±0.21	0.26 ±0.15	-0.16 ±0.10	0.19 ±0.10
J183128.71-341018.4	0.30 ±0.12	-0.40 ±0.15	-0.32 ±0.19	-0.28 ±0.22	0.11 ±0.14	-0.08 ±0.11	0.09 ±0.14	0.01 ±0.09	0.92 ±0.22
J182948.48-341053.9	-0.01 ±0.12	-0.28 ±0.14	-0.73 ±0.21	-0.07 ±0.17	-0.01 ±0.15	0.26 ±0.11	-0.27 ±0.18	-	-
J182153.85-341018.8	0.27 ±0.07	-0.18 ±0.13	-0.45 ±0.15	-	0.06 ±0.11	0.53 ±0.11	-	-0.48 ±0.09	-
J183617.33-270005.3	0.38 ±0.08	-0.24 ±0.15	-	-	0.22 ±0.11	-	-	0.31 ±0.10	-
J175510.50-412812.1	0.22 ±0.15	-	-	-	-0.01 ±0.14	-	-	-	-
J175652.43-413612.8	0.86 ±0.13	-0.39 ±0.14	-0.49 ±0.13	-	0.43 ±0.19	-	-	-	-

Table A.2 Chemical abundances for all 14 stars. (continued)

Name (SMSS)	[Ba/Fe]	[La/Fe]	[Eu/Fe]
J182637.10-342924.2	0.92 ±0.21	0.49 ±0.14	0.39 ±0.13
J182600.09-332531.0	-0.23 ±0.12	-	-
J182601.24-332358.3	-0.05 ±0.15	-	0.70 ±0.13
J182753.81-334607.7	-0.15 ±0.13	-0.12 ±0.13	0.58 ±0.13
J183000.36-333919.3	-0.12 ±0.14	-	0.30 ±0.11
J182922.48-335559.4	-0.23 ±0.14	-	-
J182930.47-335958.3	0.02 ±0.15	-	0.29 ±0.11
J183225.29-334938.4	0.50 ±0.18	0.37 ±0.14	1.08 ±0.21
J183128.71-341018.4	0.53 ±0.20	0.48 ±0.14	1.25 ±0.21
J182948.48-341053.9	-0.27 ±0.13	-	-
J182153.85-341018.8	-0.53 ±0.13	-	-
J183617.33-270005.3	0.32 ±0.15	-	-
J175510.50-412812.1	-0.34 ±0.19	-	-
J175652.43-413612.8	0.04 ±0.15	-	-

A.2. Tables from Chapter 5

Table A.3 Coordinates and 2MASS photometry of the 23 stars observed. RA, right ascension; Dec., declination; l and b , Galactic longitude and latitude, respectively.

Name (SMSS)	RA (°)	Dec (°)	l (°)	b (°)	J (mag)	H (mag)	K_S (mag)
J173823.38-145701.1	264.597	-14.950	11.1	8.7	10.85	10.22	10.03
J182048.26-273329.2	275.201	-27.558	5.0	-6.1	12.94	12.42	12.25
J183744.90-280831.1	279.437	-28.142	6.2	-9.7	12.29	11.69	11.53
J183647.89-274333.1	279.200	-27.726	6.5	-9.3	10.68	10.03	9.77
J183812.72-270746.3	279.553	-27.130	7.1	-9.3	13.38	12.79	12.61
J183719.09-262725.0	279.330	-26.457	7.7	-8.9	12.79	12.19	12.03
J184201.19-302159.6	280.505	-30.367	4.5	-11.5	14.52	14.08	14.00
J184656.07-292351.5	281.734	-29.398	5.9	-12.0	13.12	12.61	12.51
J181406.68-313106.1	273.528	-31.518	0.8	-6.6	12.12	11.56	11.35
J181317.69-343801.9	273.324	-34.634	357.9	-7.9	13.09	12.55	12.50
J181219.68-343726.4	273.082	-34.624	357.9	-7.7	12.80	12.28	12.15
J181609.62-333218.7	274.040	-33.539	359.2	-7.9	13.39	12.84	12.71
J181634.60-340342.5	274.144	-34.062	358.8	-8.3	12.56	11.99	11.90
J175544.54-392700.9	268.936	-39.450	352.0	-7.1	13.71	13.19	13.09
J175455.52-380339.3	268.731	-38.061	353.1	-6.3	11.98	11.39	11.26
J175746.58-384750.0	269.444	-38.797	352.8	-7.2	13.09	12.60	12.51
J181736.59-391303.3	274.402	-39.218	354.2	-10.8	12.06	11.54	11.37
J181505.16-385514.9	273.772	-38.921	354.2	-10.2	13.63	13.15	13.09
J181921.64-381429.0	274.840	-38.241	355.2	-10.6	13.64	13.13	13.03
J175722.68-411731.8	269.345	-41.292	350.5	-8.3	13.85	13.25	13.21
J175021.86-414627.1	267.591	-41.774	349.4	-7.4	11.74	11.23	11.17
J175636.59-403545.9	269.152	-40.596	351.1	-7.9	12.86	12.29	12.19
J175433.19-411048.9	268.638	-41.180	350.4	-7.8	11.94	11.43	11.33

Table A.4 Stellar parameters of the 23 stars observed. V_{helio} , heliocentric velocity; $d_{\odot}$, distance from the Sun to the star; T_{eff} , effective temperature; $\log g$, stellar surface gravity; ξ_t , microturbulence; $[\alpha/Fe] = ([Mg/Fe] + [Ca/Fe] + [Ti/Fe])/3$. Average uncertainties: velocity, 1.0 km s^{-1} ; distance, 3.0 kpc ; temperature, 160 K ; microturbulence, 0.2 dex ; $\log g$, 0.14 dex ; $[Fe/H]$, 0.09 dex ; $[\alpha/Fe]$, 0.13 dex .

Name (SMSS)	V_{helio} (km s^{-1})	$d_{\odot}$ (kpc)	T_{eff} (K)	$\log g$ (cgs)	[Fe/H] (dex)	ξ_t (km s^{-1})	$[\alpha/Fe]$ (dex)
J173823.38-145701.1	46.1	8.5	4599	0.99	-3.36	2.30	0.12
J182048.26-273329.2	51.5	6.0	4949	2.22	-3.48	1.90	0.37
J183744.90-280831.1	-132.6	17.6	4597	0.98	-2.92	2.05	0.33
J183647.89-274333.1	-381.4	6.6	4649	1.17	-2.48	2.50	0.30
J183812.72-270746.3	155.3	12.3	4873	1.74	-3.22	1.81	-0.01
J183719.09-262725.0	-244.7	10.0	4791	1.64	-3.18	1.81	0.32
J184201.19-302159.6	171.8	9.6	5136	2.55	-2.84	1.96	0.30
J184656.07-292351.5	91.0	9.5	4857	1.93	-2.76	1.83	0.34
J181406.68-313106.1	4.9	9.3	4821	1.48	-2.82	1.96	0.22
J181317.69-343801.9	139.3	6.5	5015	2.25	-2.28	1.48	0.41
J181219.68-343726.4	-386.2	8.0	4873	1.94	-2.50	1.93	0.32
J181609.62-333218.7	27.4	10.4	4809	1.93	-3.94	1.60	0.14
J181634.60-340342.5	-170.3	10.5	4821	1.61	-2.46	1.79	0.06
J175544.54-392700.9	-279.6	13.5	4857	1.83	-2.65	1.60	0.32
J175455.52-380339.3	23.5	13.5	4714	1.10	-3.36	1.80	0.08
J175746.58-384750.0	-59.4	9.1	5064	1.96	-2.81	2.36	0.29
J181736.59-391303.3	-177.9	15.7	4612	1.05	-2.59	2.09	0.32
J181505.16-385514.9	202.1	5.0	4962	2.73	-3.29	2.10	0.35
J181921.64-381429.0	-97.7	11.2	4917	2.02	-2.72	1.94	0.30
J175722.68-411731.8	63.8	12.4	4894	1.97	-2.88	2.02	0.19
J175021.86-414627.1	181.4	4.1	5015	2.12	-2.60	1.55	0.30
J175636.59-403545.9	-28.8	9.8	4934	1.79	-3.21	1.96	0.20
J175433.19-411048.9	-229.3	5.6	4912	1.91	-3.26	1.94	0.35

Table A.5 Chemical abundances measured for each star (Li to Ca). A(Li) is the logarithmic abundance of lithium. All abundances are derived using LTE, except for Li, Na, Mg, and Ca, where non-LTE corrections have been applied. Average uncertainties: Li, 0.20; C, 0.25; Na, 0.20; Mg, 0.16; Al, 0.22; Si, 0.21; K, 0.17; Ca, 0.12.

Name (SMSS)	A(Li)	[C/Fe]	[Na/Fe]	[Mg/Fe]	[Al/Fe]	[Si/Fe]	[K/Fe]	[Ca/Fe]
J173823.38-145701.1	-	0.49	0.04	0.17	-0.78	0.27	-	0.12
J182048.26-273329.2	-	0.98	-0.28	0.54	-0.63	0.96	-	0.30
J183744.90-280831.1	0.16	-0.20	-0.28	0.44	-0.52	0.58	0.36	0.25
J183647.89-274333.1	-	-0.47	-0.24	0.33	-0.66	0.51	-	0.18
J183812.72-270746.3	0.93	0.22	-0.39	0.05	-1.23	0.14	-	0.03
J183719.09-262725.0	-	0.40	-0.19	0.47	-0.77	0.36	0.41	0.25
J184201.19-302159.6	-	0.34	-0.38	0.26	-0.89	0.38	0.53	0.37
J184656.07-292351.5	1.04	0.08	-0.30	0.41	-0.95	0.36	0.58	0.28
J181406.68-313106.1	-	-0.51	0.18	0.23	-0.94	0.32	-	0.16
J181317.69-343801.9	1.05	0.17	-0.33	0.53	-0.82	0.33	0.63	0.34
J181219.68-343726.4	1.01	0.19	-0.22	0.30	-0.86	0.25	-	0.31
J181609.62-333218.7	-	<0.06	-0.01<0.91 ^a	0.20	-1.08	0.54	-	0.00
J181634.60-340342.5	-	-0.10	-0.53	0.05	-1.08	0.11	0.21	0.03

^a-0.01 is the lower limit, and 0.91 is the upper limit; see Section 5.3.2 for details.

Table A.5 Chemical abundances measured for each star (Li to Ca). $A(\text{Li})$ is the logarithmic abundance of lithium. All abundances are derived using LTE, except for Li, Na, Mg, and Ca, where non-LTE corrections have been applied. Average uncertainties: Li, 0.20; C, 0.25; Na, 0.20; Mg, 0.16; Al, 0.22; Si, 0.21; K, 0.17; Ca, 0.12. (continued)

Name (SMSS)	$A(\text{Li})$	[C/Fe]	[Na/Fe]	[Mg/Fe]	[Al/Fe]	[Si/Fe]	[K/Fe]	[Ca/Fe]
J175544.54-392700.9	0.87	0.12	-0.32	0.29	-0.88	0.34	0.36	0.29
J175455.52-380339.3	-	-0.64	-	0.06	-0.88	0.30	-	0.03
J175746.58-384750.0	-	-0.04	-	0.37	-1.10	0.44	-	0.24
J181736.59-391303.3	-	-0.28	-0.11	0.38	-0.69	0.53	0.53	0.26
J181505.16-385514.9	-	0.23	-0.23	0.21	-0.96	0.15	-	0.36
J181921.64-381429.0	1.04	0.32	-0.24	0.28	-0.82	0.54	0.44	0.26
J175722.68-411731.8	-	0.42	-0.42	0.21	-0.70	0.48	0.14	0.13
J175021.86-414627.1	0.98	0.23	-0.37	0.30	-0.82	0.42	-	0.28
J175636.59-403545.9	0.93	0.65	-	0.30	-0.76	0.45	-	0.11
J175433.19-411048.9	0.92	0.24	-0.03	0.40	-0.74	0.43	0.44	0.32

Table A.6 Chemical abundances measured for each star (Sc to Cu). All abundances are derived using LTE. Average uncertainties: Sc, 0.10; Ti, 0.10; Cr, 0.21; Mn, 0.25; Co, 0.23; Ni, 0.19; Cu, 0.25.

Name (SMSS)	[Sc/Fe]	[Ti/Fe]	[Cr/Fe]	[Mn/Fe]	[Co/Fe]	[Ni/Fe]	[Cu/Fe]
J173823.38-145701.1	-	-0.09	-0.22	-0.80	0.17	-0.21	<0.96
J182048.26-273329.2	-	0.16	-0.51	-0.97	0.24	-0.33	<1.33
J183744.90-280831.1	0.04	0.20	-0.23	-0.38	0.36	0.14	<0.29
J183647.89-274333.1	0.14	0.34	-0.27	-0.35	0.01	0.02	-0.43
J183812.72-270746.3	-	-0.20	-0.51	-0.32	0.22	-0.08	<1.06
J183719.09-262725.0	0.18	0.14	-0.33	-0.34	0.23	0.23	<1.10
J184201.19-302159.6	-0.03	0.20	-0.24	-0.57	0.35	-0.02	<0.72
J184656.07-292351.5	0.11	0.28	-0.19	-0.31	0.11	0.07	<0.45
J181406.68-313106.1	0.08	0.19	-0.30	-0.60	0.22	0.09	<0.50
J181317.69-343801.9	0.11	0.34	-0.19	-0.08	0.12	0.10	<0.13
J181219.68-343726.4	0.18	0.31	-0.15	-0.14	0.22	0.22	<0.17
J181609.62-333218.7	-	0.13	-0.65	-1.28	0.13	-0.11	<1.57
J181634.60-340342.5	-0.26	0.04	-0.24	-0.35	-0.20	-0.03	<-0.05

Table A.6 Chemical abundances measured for each star (Sc to Cu). All abundances are derived using LTE. Average uncertainties: Sc, 0.10; Ti, 0.10; Cr, 0.21; Mn, 0.25; Co, 0.23; Ni, 0.19; Cu, 0.25. (continued)

Name (SMSS)	[Sc/Fe]	[Ti/Fe]	[Cr/Fe]	[Mn/Fe]	[Co/Fe]	[Ni/Fe]	[Cu/Fe]
J175544.54-392700.9	-0.05	0.32	-0.22	-0.18	0.24	-0.05	<0.32
J175455.52-380339.3	-	0.02	-0.47	-1.05	0.07	-0.12	<0.85
J175746.58-384750.0	0.12	0.19	-0.44	-0.59	0.09	-0.01	<0.79
J181736.59-391303.3	0.15	0.24	-0.31	-0.34	0.00	0.08	<0.10
J181505.16-385514.9	0.40	0.38	-0.54	-0.81	0.17	-0.11	<1.02
J181921.64-381429.0	0.01	0.32	-0.17	-0.44	0.33	0.25	<0.50
J175722.68-411731.8	-0.22	0.15	-0.31	-0.48	-0.04	0.04	<0.82
J175021.86-414627.1	-0.23	0.26	-0.27	-0.31	0.16	0.16	<0.27
J175636.59-403545.9	-0.28	0.06	-0.29	-0.72	0.17	-0.26	<0.95
J175433.19-411048.9	-	0.22	-0.52	-0.91	0.29	0.02	<1.08

Table A.7 Chemical abundances measured for each star (Zn to Eu). All abundances are derived using LTE. Average uncertainties: Zn, 0.10; Sr, 0.20; Y, 0.12; Zr, 0.12; Ba, 0.17; La, 0.15; Eu: 0.16.

Name (SMSS)	[Zn/Fe]	[Sr/Fe]	[Y/Fe]	[Zr/Fe]	[Ba/Fe]	[La/Fe]	[Eu/Fe]
J173823.38-145701.1	0.66	0.03	0.02	0.23	-0.04	-0.10	-
J182048.26-273329.2	<1.01	-0.47	-	-	0.03	<1.33	-
J183744.90-280831.1	0.27	-0.29	-0.32	0.03	-0.31	<0.12	-
J183647.89-274333.1	0.23	0.18	-0.20	0.45	0.13	0.17	0.82
J183812.72-270746.3	<0.79	-1.03	-	-	-0.70	<0.77	-
J183719.09-262725.0	0.48	0.04	0.53	-	-0.51	<1.03	-
J184201.19-302159.6	<1.15	-0.20	0.04	0.70	0.16	<0.94	-
J184656.07-292351.5	0.48	-0.26	-0.51	0.14	-0.32	<0.36	-
J181406.68-313106.1	0.42	-1.61	-	-	-0.72	<0.32	-
J181317.69-343801.9	0.17	0.17	-0.11	0.34	0.22	-0.09	0.15-
J181219.68-343726.4	0.33	-0.06	-0.11	0.09	0.13	<0.90	0.48
J181609.62-333218.7	<1.40	-0.85	0.23	-	<-0.66	<1.09	0.91
J181634.60-340342.5	0.21	-0.25	-0.65	-0.21	-0.32	-0.14	-0.11

Table A.7 Chemical abundances measured for each star (Zn to Eu). All abundances are derived using LTE. Average uncertainties: Zn, 0.10; Sr, 0.20; Y, 0.12; Zr, 0.12; Ba, 0.17; La, 0.15; Eu: 0.16. (continued)

Name (SMSS)	[Zn/Fe]	[Sr/Fe]	[Y/Fe]	[Zr/Fe]	[Ba/Fe]	[La/Fe]	[Eu/Fe]
J175544.54-392700.9	0.36	-0.10	-0.2	0.38	-0.11	-0.15	0.21
J175455.52-380339.3	0.63	0.47	0.01	0.14	-0.57	<0.66	-
J175746.58-384750.0	-	-0.21	0.04	0.91	0.23	<1.26	0.65
J181736.59-391303.3	0.23	-0.14	-0.47	0.14	-0.28	<1.19	0.21
J181505.16-385514.9	<0.95	-0.19	0.14	0.71	0.04	<0.54	0.96
J181921.64-381429.0	0.42	-0.21	-0.14	0.51	-0.01	0.48	0.59
J175722.68-411731.8	<0.95	-0.30	-0.30	0.24	-0.19	<0.63	0.52
J175021.86-414627.1	0.41	-0.14	-0.40	0.25	-0.08	<0.60	0.23
J175636.59-403545.9	0.86	0.55	0.24	0.71	-0.95	<1.21	-
J175433.19-411048.9	0.50	-0.81	-0.29	-	-0.42	<0.91	-

Table A.8 Orbital Parameters. $\mu_\alpha \cos \delta$ and μ_δ are the proper motions in equatorial coordinates. r_{peri} and r_{ap} are the pericentric and apocentric radii of the orbit, respectively. Z_{max} is the maximum distance the orbit reaches above/below the Galactic plane, and E_{tot} is the total energy of the orbit. All values given here are the mean values from the Monte Carlo simulation of 1,000 orbits.

Name (SMSS)	$\mu_\alpha \cos \delta$ (mas yr ⁻¹)	μ_δ (mas yr ⁻¹)	Mean r_{peri} (kpc)	Mean r_{ap} (kpc)	Mean Eccentricity	Mean Z_{max} (kpc)	E_{tot} (10 ⁴ km ² s ⁻²)
J182048.26-273329.2	-4.10 ± 0.52	-6.38 ± 0.51	0.5 ^{+0.9} _{-0.2}	2.9 ^{+1.7} _{-1.1}	0.70 ^{+0.11} _{-0.23}	0.9 ^{+0.2} _{-0.5}	-11.3 ^{+2.2} _{-1.4}
J184201.19-302159.6	-0.38 ± 0.90	-0.82 ± 0.90	1.2 ^{+1.1} _{-0.7}	6.6 ^{+4.3} _{-1.6}	0.72 ^{+0.13} _{-0.20}	4.3 ^{+1.7} _{-1.8}	-7.1 ^{+2.1} _{-1.2}
J184656.07-292351.5	1.17 ± 0.89	-2.32 ± 0.89	1.2 ^{+1.5} _{-0.8}	4.8 ^{+2.7} _{-1.4}	0.65 ^{+0.19} _{-0.41}	3.2 ^{+1.2} _{-1.4}	-8.3 ^{+1.9} _{-1.2}
J181406.68-313106.1	2.28 ± 0.52	-8.25 ± 0.52	1.1 ^{+2.3} _{-0.8}	3.5 ^{+9.1} _{-1.3}	0.63 ^{+0.18} _{-0.16}	2.7 ^{+8.6} _{-0.8}	-9.5 ^{+5.4} _{-1.8}
J181219.68-343726.4	-2.42 ± 1.14	-1.29 ± 1.14	0.7 ^{+0.8} _{-0.4}	17.3 ^{+11.3} _{-4.9}	0.92 ^{+0.05} _{-0.03}	7.2 ^{+3.2} _{-1.8}	-3.4 ^{+1.9} _{-1.4}
J181609.62-333218.7	-4.14 ± 0.64	-3.74 ± 0.64	1.0 ^{+3.5} _{-0.8}	3.4 ^{+3.3} _{-1.8}	0.53 ^{+0.23} _{-0.28}	1.9 ^{+2.6} _{-0.9}	-9.9 ^{+4.0} _{-2.6}
J181634.60-340342.5	1.92 ± 0.62	-0.31 ± 0.62	1.9 ^{+2.0} _{-1.3}	7.9 ^{+8.3} _{-2.4}	0.65 ^{+0.15} _{-0.10}	3.9 ^{+4.2} _{-1.7}	-6.3 ^{+3.0} _{-2.0}
J175544.54-392700.9	0.03 ± 1.49	-0.35 ± 1.46	1.7 ^{+2.3} _{-1.2}	29.3 ^{+67.4} _{-16.5}	0.92 ^{+0.05} _{-0.04}	10.8 ^{+29.6} _{-6.0}	-1.4 ^{+3.7} _{-3.2}
J175455.52-380339.3	1.98 ± 1.14	4.76 ± 1.14	5.5 ^{+4.8} _{-3.9}	811.5 ^{+1216.1} _{-796.2}	0.98 ^{+0.01} _{-0.16}	81.0 ^{+259.4} _{-76.6}	6.9 ^{+12.2} _{-10.7}
J175746.58-384750.0	1.86 ± 1.25	0.17 ± 1.25	1.8 ^{+1.9} _{-1.2}	5.9 ^{+5.0} _{-1.9}	0.59 ^{+0.24} _{-0.28}	2.3 ^{+2.8} _{-1.1}	-7.5 ^{+2.9} _{-1.8}