Early Disk-Galaxy Formation from JWST to the Milky Way
Proceedings IAU Symposium No. 377, 2024
F. Tabatabaei, B. Barbuy & Y.-S. Ting, eds.
doi:10.1017/S1743921323001436

Using Metal-Poor Stars in the Inner Galaxy to Uncover the Ancient Milky Way

Madeline Lucey

Department of Astronomy, The University of Texas at Austin, 2515 Speedway Boulevard, Austin, TX 78712, USA. email: m_lucey@utexas.edu

Abstract. The chemo-dynamics of the stellar populations in the Galactic Bulge inform and constrain the Milky Way's formation and evolution. The metal-poor population is particularly important in light of cosmological simulations, which predict that some of the oldest stars in the Galaxy now reside in its center. The metal-poor bulge appears to consist of multiple stellar populations that require chemo-dynamical analyses to disentangle. In this paper, I describe the detailed chemo-dynamical study of the metal-poor stars in the inner Galaxy, named The COMBS Survey which uses VLT/FLAMES spectra of 350 metal-poor stars. I discuss the results and the implications for early Milky Way formation and chemical evolution. In addition, I preview results from an ongoing survey of carbon-enhanced metal-poor stars, which are thought to be solely enriched by the first generation of stars.

Keywords. Galaxy: bulge, Galaxy: evolution, stars: Population II, stars: abundances

1. Introduction

ΛCDM cosmology makes specific predictions for the structure, dynamics and chemistry of the Milky Way's stellar population. Therefore, observations of the Milky Way are crucial tests of ΛCDM. The oldest stars in the Milky Way are especially informative for testing ΛCDM predictions of the early universe.

Cosmological simulations predict that the oldest stars are found in the inner Galaxy (El-Badry *et al.* 2018). Furthermore, stars of a given metallicity are more likely to be older if found closer to the center of the Galaxy (Tumlinson 2010). However, searches for the oldest stars historically have been focused on the Galactic halo rather than the inner Galaxy (e.g., Frebel 2015). This is because it is difficult to observe metal-poor stars in the inner Galaxy given there is high dust extinction and an abundance of metal-rich stars. With the advent of metallicity-sensitive photometric surveys (e.g., SkyMapper; Casagrande *et al.* 2019), it is now possible to target large numbers of metal-poor stars in the inner Galaxy and measure their chemical abundances.

The chemical abundances of the oldest stars are of great interest because they constrain the properties of the first generation of stars through their nucleosynthetic yields. The first stars would form in a metal-free environment and are therefore thought to be different than stars formed today. Specifically, simulations of metal-free star formation predict that initial mass function (IMF) would be top-heavy with more massive stars than the present-day IMF (Hirano *et al.* 2014). Furthermore, it is thought that these massive metal-free stars may have different nucleosynthetic yields than the typical core-collapse supernova. For example, stars with $140\ M_\odot \leq M_* \leq 260\ M_\odot$ are predicted to explode in a pair-instability supernova (PISN) which would produce an overabundance of explosive α-elements, Ca and Si (Heger *et al.* 2003; Takahashi *et al.* 2018). Additionally, it has

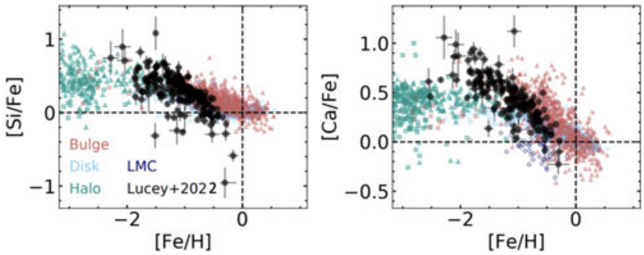

Figure 1. The Ca and Si abundances of metal-poor inner Galaxy stars from the COMBS survey (black circles) compared to other Milky Way samples from the literature. Specifically, we show other Milky Way bulge samples in red, including results from the HERBS survey (red open triangles; Duong *et al.* 2019) and results from the EMBLA survey (red open squares Howes *et al.* 2016). Also shown are abundances for the halo (green), the Large Magellanic Cloud (LMC; dark blue), and the disk (light blue). The halo abundances are from Roederer *et al.* (2014, green open triangles) and Yong *et al.* (2013, green open squares). The LMC abundances are from Van der Swaelman *et al.* (2013, dark blue open diamonds). The disk abundances are from Bensby *et al.* (2014, light blue open squares), Adibekyan *et al.* (2012, light blue open circles), and Battistini *et al.* (2015, light blue open diamonds).

been suggested that the first stars may be rapid rotators (i.e., spinstars) which would create an overabundance of C, N and O (Meynet *et al.* 2010).

In this paper, I test these predictions for nucleosynthetic yields of the first stars by investigating the chemistry of metal-poor stars in the inner Galaxy. Furthermore, I investigate the role of hierarchical evolution in the formation of the inner Galaxy as predicted by ΛCDM cosmology. This work comprises the Chemo-dynamical Origins of Metal-poor Bulge Stars (COMBS) survey (Lucey *et al.* 2019, 2021, 2022) whose results I summarize in Section 2. I also address the dearth of carbon-enhanced metal-poor (CEMP) stars observed in the inner Galaxy in Section 3. Finally, in Section 4, I summarize the conclusions of this work.

2. The COMBS survey

Targeting with SkyMapper photometry, spectra of metal-poor inner Galaxy stars were obtained using the VLT/FLAMES instrument. With the spectra, I performed chemical abundance analysis. Furthermore, I constrained the Galactic orbits of the target stars in order to determine whether the stars stay confined to the inner Galaxy.

The Galactic component that the metal-poor inner Galaxy stars are associated with has long been debated. Specifically, it has been suggested that the metal-poor inner Galaxy stars comprise a classical bulge component (Zoccali *et al.* 2014; Arentsen *et al.* 2020). However, it has also been proposed that these stars may simply be Galactic halo stars that are just passing through the inner Galaxy, but spend the majority of their orbits at large distances from the Galactic center (Debattista *et al.* 2017). It is crucial to distinguish between these scenarios in order to better constrain the Milky Way's formation history.

By calculating the orbits of the COMBS targets, I am able to distinguish between the halo interlopers and those that stay confined to the inner Galaxy. I find that only ≈50% of the metal-poor stars in the inner Galaxy will stay confined while the other half are halo interlopers with apocenters >3.5 kpc. When the halo interlopers are removed the sample, we find that the line-of-sight velocity dispersion decreases. Specifically, I find that the line-of-sight velocity dispersion as a function of the Galactic latitude and longitude matches expectations for a boxy/peanut-shape (B/P) bulge and there is no evidence for a classical bulge component. In Figure 1, I show the Ca and Si abundances of our target

https://doi.org/10.1017/S1743921323001436 Published online by Cambridge University Press

stars (black circles) compared to literature abundances of Milky Way samples. Literature halo sample are shown in green while literature inner Galaxy samples are shown in red, disk samples in light blue and the LMC in dark blue. Our abundances for stars with [Fe/H]>-1 are generally consistent with the previous inner Galaxy samples. However, there are few literature abundances for the inner Galaxy at [Fe/H]<-1 to which we can compare.

At [Fe/H]<-1, the results include the clear overabundance of the explosive α-elements, Ca and Si. Specifically, the most metal-poor stars in our sample have [Ca/Fe]≈1 while similar metallicity stars in the Galactic halo have [Ca/Fe]≈0.5. As these metal-poor stars in the inner Galaxy are expected to be very old, they are likely to have only been enriched by the explosion of massive stars rather than Type Ia supernovae or AGB stars. In core-collapse (Type II) supernovae, the yields of Ca and Si are mass-dependent in that more massive stars will enrich the interstellar medium to higher [Ca+Si/Fe]. Therefore, the high Ca and Si abundances indicate that these stars were enriched by a population with a more top-heavy initial mass function. Additionally, the overabundance of Ca and Si general, the chemical results are consistent with predictions for the nulceosynthetic yields of the first generation of stars.

3. CEMP Stars from Gaia XP Spectra

One of the biggest remaining questions about the metal-poor inner Galaxy stars is the occurrence rate of carbon-enhanced metal-poor (CEMP) stars. CEMP stars make up ≈30% of stars with [Fe/H]<–2 in the local Galactic halo, but are rarely observed in surveys of metal-poor inner Galaxy stars (Howes *et al.* 2015; Lucey *et al.* 2022). Recent work estimates the CEMP occurrence rate as <10% for stars with [Fe/H]<–2 in the inner Galaxy (Arentsen *et al.* 2021). However, it is important to note that all of these surveys have used metallicity-sensitive photometry to target metal-poor stars which has been shown to be biased against detecting CEMP stars (Da Costa *et al.* 2019). Therefore, the unbiased occurrence rate is yet to be measured. As these stars are thought to be enriched by the first supernovae (Meynet *et al.* 2010; Nomoto *et al.* 2013), it is crucial to determine their origins and whether they exist in the inner Galaxy where we expect the oldest stars reside.

In the most recent data release (DR3), the *Gaia* mission released ≈220 million low-resolution (R≈70) XP spectra with wavelength coverage from 400-900 nm. These spectra cover the entire sky with limited selection biases. Using synthetic data, I demonstrate that these spectra can be used to distinguish CEMP stars from carbon-normal stars for stars with $T_{\rm eff}$ <6000 K.

Using the gradient-boosted decision tree algorithm, `XGBoost`, I classify 182,815,672 spectra with $0.8 < G_{BP} - G_{RP} < 2.75$ and $G + 5\log_{10}(\varpi) + 5 < 7.0$. From this data, I find 58,872 CEMP candidates with a contamination rate of ≈12%. This sample spans from the inner to outer Milky Way with distances as low as $r \approx 0.8$ kpc from the Galactic center, and as far as $r > 30$ kpc. We find that the parallax distribution of our candidate CEMP sample closes resembles that of metal-poor carbon-normal stars which differs significantly from metal-rich carbon-normal stars. Higher resolution spectroscopic follow-up of these CEMP candidate will be obtained to confirm their carbon abundance and better constrain the occurrence rate of CEMP stars in the inner Galaxy.

4. Conclusions

The major conclusions of this work can be summarized as follows:

• The most metal-poor inner Galaxy stars have Ca and Si abundances that are consistent with enrichment by a population with a more top-heavy IMF than what is

https://doi.org/10.1017/S1743921323001436 Published online by Cambridge University Press

observed in the typical halo or disk Milky Way stellar population. This is consistent with predictions that the first generation metal-free stars would be massive.

- Approximately 50% of metal-poor stars in the inner Galaxy are halo interlopers that spend the majority of their orbits at distances > 3.5 kpc from the Galactic center. When these halo interlopers are removed, the kinematics of metal-poor inner Galaxy stars no longer show evidence for a classical bulge and are consistent with predictions for a (B/P) bulge.
- Using *Gaia* XP spectra, I detected 58,872 CEMP candidates with a success rate of $\approx$88%. The parallax distribution of these stars closely follow that of metal-poor carbon-normal stars, including peaking at a parallax consistent with that of the Galactic center.

Higher resolution follow-up is required to confirm the CEMP candidates in the inner Galaxy and measure their occurrence rate. Furthermore, the upcoming SDSS-V Milky Way Mapper survey will observe millions of stars in the inner Galaxy, including thousands of metal-poor stars. Future chemodynamical analysis of this data will shed further light on the origins of metal-poor stars in the inner Galaxy and the hunt for the nulceosynthetic yields of the first generation of stars.

References

Adibekyan, V. Z., Sousa, S. G., Santos, N. C., *et al.* 2012, *A&A*, 545, A32
Arentsen, A., *et al.* 2020, *MNRAS*, 491, L11
Arentsen, A., *et al.* 2021, *MNRAS*, 505, 1239
Battistini, C., Bensby, T., 2015, *A&A*, 577, A9
Bensby, T., Feltzing, S., Oey, M. S. 2014, *A&A*, 562, A71
Casagrande, L., Wolf, C., Mackey., A. D., *et al.* 2019, *MNRAS*, 482, 2770
Da Costa, G. S., *et al.* 2019, *MNRAS*, 489, 5900
Debattista, V. P., Ness, M., Gonzalez, O. A., *et al.* 2017, *MNRAS*, 469, 1587
Duong, L., Asplund, M., Nataf, D. M., *et al.* 2019, *MNRAS*, 486, 3586
El-Badry, K., Bland-Hawthorn, J., Wetzel, A., *et al.* 2018, *MNRAS*, 480, 652
Frebel, A., Norris, J. E. 2015, *ARA&A*, 53, 631
Heger. A., Fryer, C. L., Woosley, S. E., *et al.* 2003, *ApJ*, 591, 288
Hirano, S., Hosokawa, T., Yoshida, N., *et al.* 2014, *ApJ*, 781, 60
Howes, L. M., *et al.* 2015, *Nature*, 527, 484
Howes, L. M., *et al.* 2016, *MNRAS*, 460, 884
Lucey, M., *et al.* 2019, *MNRAS*, 488, 2283
Lucey, M., *et al.* 2021, *MNRAS*, 501, 5981
Lucey, M., *et al.* 2022, *MNRAS*, 509, 122
Meynet, G., Hirschim R., Ekstrom, S., *et al.* 2010, *A&A*, 521, A30
Nomoto, K., Kobayashim C., Tominaga, N. 2013, *ARA&A*, 51, 457
Roederer, I. U., Preston, G. W., Thompson, I. B., *et al.* 2014, *AJ*, 147, 136
Takahashi, K., Yoshida, T., Umeda, H. 2018, *ApJ*, 857, 111
Tumlinson, J. 2010, *ApJ*, 708, 1398
Van der Swaelmen, M., Hill, V., Primas, F., *et al.* 2013, *A&A*, 560, A44
Yong D., *et al.* 2013, *ApJ*, 762, 26
Zoccali, M., *et al.* 2014, *A&A*, 562, A66