Stellar Populations in the Milky Way and Beyond
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The ancient central population

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Abstract. The oldest stars in the Milky Way are expected to have a high density in the inner few kpc, spatially overlapping with the Galactic bulge. I will briefly summarise how to find the most metal-poor stars in this challenging region, and what their kinematics and chemistry are like. I specifically highlight the relevance of carbon-enhanced metal-poor (CEMP) stars.

Keywords. Galaxy: formation - Galaxy: kinematics and dynamics - Galaxy: stellar content - stars: Population II - techniques: spectroscopic - stars: chemically peculiar

1. Introduction

The oldest stars in the Milky Way are expected to be centrally concentrated – overlapping with the Galactic bulge region (e.g. Starkenburg et al. 2017b, El-Badry et al. 2018). At the same metallicity, stars that were born *in-situ* are expected to be older than those that were accreted from smaller systems. The very metal-poor (VMP, [Fe/H] < -2.0) stars in the inner Milky Way are valuable tracers of the earliest phases of galaxy formation, however, most stars in the bulge are metal-rich ([Fe/H] > -1.0, e.g. Ness et al. 2013) and it is therefore challenging to find the VMP stars in this region.

2. Finding ancient stars in the inner Milky Way

The first VMP stars in the inner regions of the Galaxy were found "accidentally" in large surveys, such as in APOGEE (García Pérez et al. 2013) and ARGOS (Ness et al. 2013), but there were only a handful. Larger samples only came after dedicated photometric searches in the inner Galaxy started. It is possible to find a metallicity-sensitive combination of infrared photometry (2MASS and WISE), which has resulted in detailed observations of several metal-poor stars in the inner Milky Way (Casey and Schlaufman 2015; Reggiani et al. 2020). The advantage of this is that infrared photometry is less sensitive to dust than optical photometry, but it is only available for the brightest stars. Larger surveys were done with narrow-band photometry in the calcium H&K region ($\sim 3700 - 4000$ Å), see the left panel of Figure 1. The first was EMBLA, which used SkyMapper photometry (Howes et al. 2014). They followed up their candidates with AAT/AAOmega+2dF and picked the most exciting targets for high-resolution spectroscopic follow-up (Howes et al. 2014, 2015, 2016). The SkyMapper photometry was also used to select metal-poor candidates for the COMBS project (Lucey et al. 2019, 2021, 2022), which will be discussed in a different contribution in these proceedings. There was a smaller survey using a Ca K filter by Koch et al. (2016), finding several interesting objects.

The other large project has been the Pristine Inner Galaxy Survey (PIGS, Arentsen et al. 2020a), using the *CaHK* filter on the CFHT (Starkenburg et al. 2017a). Narrow-band filters are used in combination with broad-band photometry, as shown for a spectroscopic sample of giants in the right-hand panel of Figure 1. For PIGS, there was no calibrated model available yet and the most promising stars in each field,

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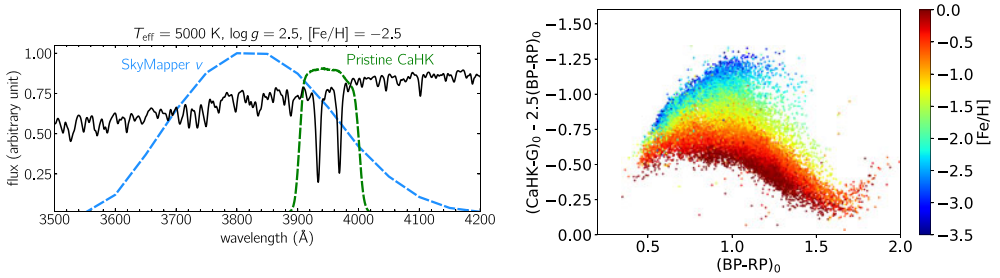


Figure 1. Left: filter curves used in the SkyMapper EMBLA and Pristine PIGS surveys, on top of a synthetic spectrum of a metal-poor giant. **Right:** metallicity-sensitive colour-colour diagram used in the Pristine survey, showing the giant stars in the Pristine spectroscopic training sample (Martin et al. 2024).

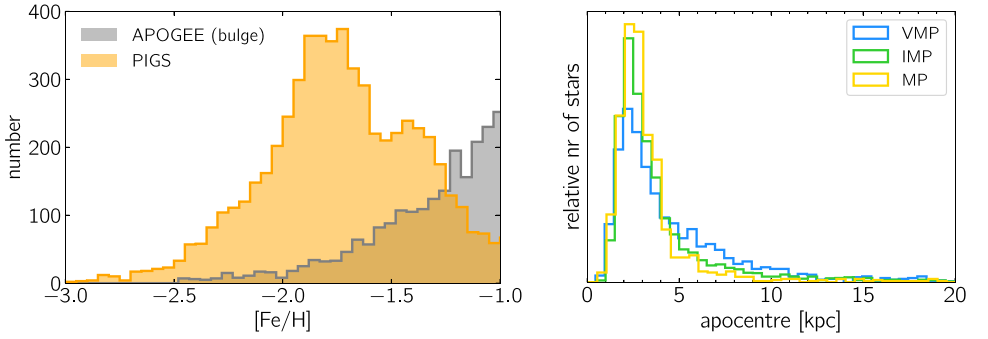


Figure 2. Left: PIGS/AAT spectroscopic metallicity distribution (orange, Ardern-Arentsen et al. 2024) compared to inner Galaxy stars in APOGEE DR17 (grey). The APOGEE distribution is the result after the following cuts: $|b| < 12°$, SNR > 20 and excluding stars in globular cluster programs. **Right:** distribution of Galactic apocentres for stars in PIGS currently within 3.5 kpc from the Galactic centre, in three different metallicity regimes (VMP: [Fe/H] < -2, IMP: $-2.0 <$ [Fe/H] < -1.5, MP: $-1.5 <$ [Fe/H] < -1.0 (Ardern-Arentsen et al. 2024).

most towards the top of this diagram, were selected for spectroscopic follow-up with AAT/AAOmega+2dF. The distribution of the spectroscopic metallicities is shown in the left-hand panel of Figure 2, compared to the tail of the APOGEE DR17 distribution for inner Galaxy stars. For stars with [Fe/H] < -1.5, PIGS is the largest spectroscopic inner Galaxy survey to date.

It is now also possible to get metallicities from the very low-resolution Gaia XP spectrophotometry, mostly using machine learning, which has been used to study the metal-poor inner Milky Way (e.g. Rix et al. 2022, Kurbatov et al. 2024). Maps of metal-poor stars from these samples show strong over-densities in the inner Galaxy. Combined with Gaia RVS radial velocities, they are a powerful sample to trace the dynamical properties. A note: PIGS goes about two magnitudes deeper than Gaia RVS and can therefore probe deeper into the inner Galaxy, and still has slightly more VMP stars.

An alternative way of studying the ancient inner Milky Way is by using RR Lyrae stars (e.g. Dékány et al. 2013; Pietrukowicz et al. 2015; Kunder et al. 2016). These are old metal-poor stars that can be found by their photometric variability, and one of their advantages is that they are standard candles. Their use will be discussed elsewhere in these proceedings.

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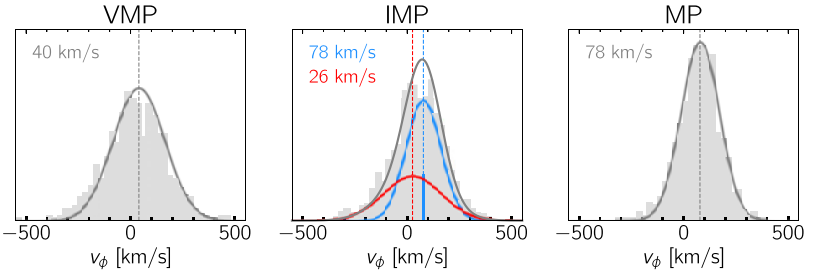


Figure 3. Distributions of azimuthal velocity in PIGS for stars with distances from the Galactic centre between 1.5 and 3.5 kpc, in three metallicity ranges (the same as in the right-hand panel of Figure 2). The optimal components of the extreme deconvolution Gaussian mixture modelling are over-plotted with their median values indicated.

3. Kinematics of the metal-poor inner Galaxy with PIGS

The first orbital properties for inner Galaxy VMP stars were derived in the pre-Gaia era by Howes et al. (2015) for ten EMBLA VMP stars. They found that more than half of their stars were on tight, confined orbits. The first kinematic analysis of a large sample of VMP stars was done by Arentsen et al. (2020b), using only the projected radial velocities. We found that stars with $-2.0 <$ [Fe/H] < -1.5 were clearly rotating around the Galactic centre but at a lower level than typical metal-rich bulge stars. For VMP stars, we did not find significant rotation, but the analysis was limited by both sample size and only using the projected radial velocities.

We extended this analysis recently using Gaia DR3 data, studying the full orbital properties of the stars in Ardern-Arentsen et al. (2024). The distribution of Galactic apocentres for our sample is shown for different metallicities in the right-hand panel of Figure 2. The distribution drops off very strongly for apocentres $> 4-5$ kpc – most stars in this metal-poor inner Galaxy population will never come near the Sun. Lucey et al. (2021) find that for their metal-poor COMBS sample, the VMP stars are not very confined at all. This discrepancy is potentially due to their sample going less deep into the inner Galaxy, as well as their limited sample size at the lowest metallicities. Our histogram is only for stars *currently* within 3.5 kpc from the Galactic centre.

A way to probe the rotational properties of a population is by studying the v_ϕ distribution – the azimuthal velocity around the Galactic centre. In Ardern-Arentsen et al. (2024), we applied a Gaussian Mixture Model to the PIGS velocities, finding that there appear to be two distinct components in the v_ϕ distribution for stars with $-2.0 <$ [Fe/H] < -1.5 – see the middle panel of Figure 3. Both of them have $v/\sigma < 1$, but one is cooler and faster and the other is slower and hotter. As seen in the other panels of Figure 3, the faster component dominates for [Fe/H] > -1.5, whereas there is likely still a mix of the two populations for VMP stars with the hotter component becoming more important (but the sample size is too small to tell). The two components have similar properties in azimuthal velocity and its dispersion compared to the two halo components found in the Solar neighbourhood using the same methodology by Zhang et al. (2024). We speculate that these two components correspond to the predominantly *in-situ* "proto-Galaxy" (faster, cooler, more metal-rich component) and stars accreted at a later time and/or from smaller systems (slower, hotter, more metal-poor component) – but for now this is simply speculation. This should leave traces in the chemistry, which we discuss next.

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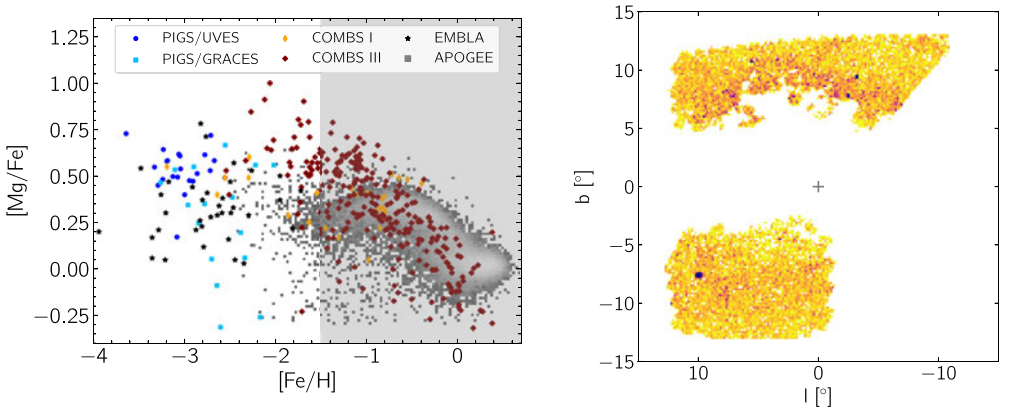


Figure 4. Left: compilation of [Mg/Fe] vs. [Fe/H] for stars from PIGS (from Sestito et al. 2023 using GRACES and Aguado et al. in prep. using UVES), COMBS (Lucey et al. 2019, 2022), EMBLA (Howes et al. 2014, 2015, 2016) and inner Galaxy stars in APOGEE DR17 (with `MG_FE_FLAG` = 0 and [Mg/Fe] and [Fe/H] uncertainties < 0.2 dex). **Right:** footprint of the 30 000 stars in the 4MOST VMP_PIGS sub-survey (within 4MIDABLE-LR, Chiappini et al. 2019). Overdensities correspond to known metal-poor globular compilation of CEMP frequencies clusters.

4. Chemistry of the metal-poor inner Galaxy

There has been a lot of work on the chemistry of metal-poor inner Galaxy stars over the past 10 years, starting with EMBLA. This is not the place to review each of them, but I will summarise the overall findings.

At intermediate-low metallicities ($-2.0 <$ [Fe/H] < -1.0), there are potentially signs in the chemistry of significant contributions from larger building blocks than in the rest of the halo and/or the presence of an *in-situ* component (e.g. Horta et al. 2021b, 2024; Queiroz et al. 2021; Belokurov and Kravtsov 2022; Lucey et al. 2022; Razera et al. 2022; Barbuy et al. 2024). Additionally, the frequency of former globular cluster stars (based on their high nitrogen abundances) appears higher than further away from the Galactic centre (e.g. Schiavon et al. 2017; Horta et al. 2021a; Belokurov and Kravtsov 2024; Kane et al. 2025).

At very low metallicities ([Fe/H] < -2), inner Galaxy stars appear reasonably "normal", in the sense that they do not stand out in their detailed chemical abundance patterns (e.g. Howes et al. 2014, 2015, 2016; Casey and Schlaufman 2015; Reggiani et al. 2020; Koch et al. 2016; Lucey et al. 2019, 2022; Sestito et al. 2023, 2024; Mashonkina et al. 2023), although there are a few outliers. One promising difference, however, is in the population of CEMP stars, which we will discuss in the next section.

A challenge with interpreting the results from the different works at low metallicity is that they all have small samples (from less than a handful to ~ 20 stars), all analysed in different ways. A compilation of the example abundance [Mg/Fe] is shown in the left panel of Figure 4. For [Fe/H] < -1.5 there is a huge scatter between different samples, as well as systematics between them. It seems impossible at this stage to draw the location of the alpha plateau and/or to determine the intrinsic scatter in the population. Large, homogeneous samples are necessary to address this issue.

One such homogeneous samples will be produced by 4MOST, a multi-object spectroscopic survey in the Southern hemisphere with a significant Galactic bulge component. Specifically, there will be a sub-survey targeting metal-poor candidates selected from PIGS within the 4MOST MIlky way Disk And BuLgE Low-Resolution Survey

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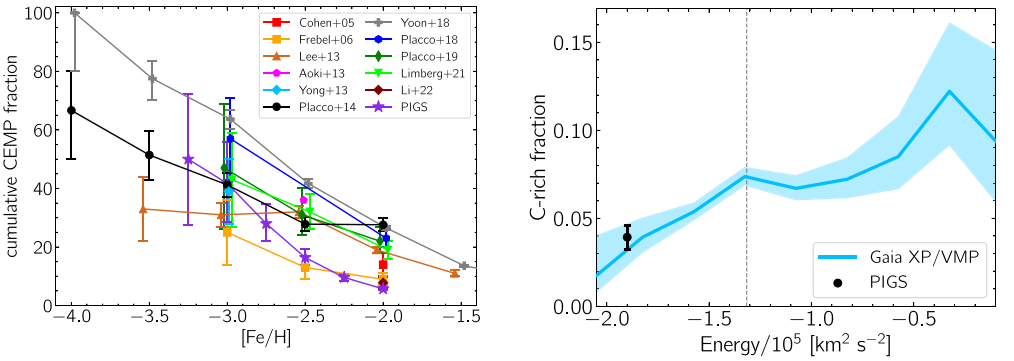


Figure 5. Left: compilation of CEMP frequencies in the literature from Arentsen et al. (2022), with the PIGS results from Arentsen et al. (2021) added. **Right:** frequency of CEMP stars as function of energy for VMP stars (between −2.5 and −2.0). The inner Galaxy is on the left, the dashed line indicates the Belokurov and Kravtsov (2022) accreted/*in-situ* boundary, and the outer Galaxy is on the right. The PIGS results in the same metallicity range are shown too. Note that the left-hand panel shows cumulative CEMP fractions whereas the right-hand panel shows differential fractions.

(4MIDABLE-LR) (Chiappini et al. 2019). I selected 30 000 stars with photometric metallicities < -1.7, of which $\sim 75\%$ will be observed. The footprint is shown in the right-hand panel of Figure 4, following the photometric PIGS footprint that is avoiding the highest extinction regions with E(B−V) > 0.7 and limited to the Northern hemisphere (missing part of the coverage at negative longitudes). We expect to be able to get metallicities and alpha, iron-peak and s-process abundances. There is a different sub-survey in high-resolution within 4MIDABLE-HR (Bensby et al. 2019), which is going less deep and will have fewer stars, but with more abundances and at higher precision.

Other relevant samples will come from for example SDSS-V, but mostly in the intermediate metal-poor regime, given it will have APOGEE-type infrared spectra that do not contain much information for more metal-poor stars.

5. Carbon-enhanced metal-poor stars in the inner Galaxy

One chemical signature that might be different for VMP stars in the inner Galaxy versus the rest of the halo, is the potential low frequency of carbon-enhanced metal-poor (CEMP) stars (Howes et al. 2016; Arentsen et al. 2021). CEMP stars are typically classified by having [C/Fe] $> +0.7$, and there are two main types. The CEMP-s stars are thought to be the result of binary mass-transfer from an AGB companion, revealed by their enhanced s-process abundances as well as their common radial velocity variations. The CEMP-no are more common for [Fe/H] < -3.0 and have their own kind of peculiar abundance patterns, but are not rich in s-process elements. They are thought to have been born carbon-rich, from gas enriched by massive metal-free stars.

A compilation of CEMP frequencies as function of metallicity is shown in the left-hand panel of Figure 5, including the one from PIGS. There are various caveats in samples and comparisons of VMP/CEMP stars, such as photometric selection effects and other biases, with the latter discussed extensively in Arentsen et al. (2022). But, if we take the results at face value, it looks like the CEMP frequency in PIGS is most discrepant for [Fe/H] > -2.5, which is the regime of the CEMP-s stars. This would imply a lower binary fraction in the inner Milky Way compared to the rest of the halo. Since high-density globular clusters can destroy binary systems and the frequency of former globular cluster stars is higher in the intermediate metallicity regime (discussed above), we suggested that there could also be a higher globular cluster contribution in the VMP regime.

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Preferably, we would like to have all-sky homogeneous carbon abundances to trace CEMP trends with Galactic environment. I attempted this using a neural network applied to the Gaia XP spectra, with a dedicated training sample with spectroscopic carbon abundances (Ardern-Arentsen et al. 2025). This worked very well, finding thousands of new C-rich candidates all across the sky. To test variations with Galactic environment, I plot the C-rich fraction as function of Galactic binding energy, shown in the right-hand panel of Figure 5. This is for stars with $-2.5 <$ [Fe/H] < -2.0, the regime of CEMP-s stars. There is a clear trend, with the frequencies being lower in the inner regions and higher towards the outer regions. For reference, the PIGS frequency in the same metallicity regime has been over-plotted at the average energy for that sample. We also tested the CEMP frequency in surviving globular clusters, finding lower values than for the field. This supports the connection between a lower CEMP-s/binary fraction and a higher frequency of disrupted globular clusters in the inner Galaxy, suggesting much of the earliest star formation in the ancient Milky Way occurred in globular cluster-like environments.

6. Summarising

In this contribution, I discussed some of the properties of the ancient central population of the Milky Way from a (biased) observational perspective. The most metal-poor stars in the inner Galaxy are unique links to the earliest star formation in the Universe.

There is a central, slowly rotating concentration of old stars in our Galaxy. It likely consists of a mix of *in-situ* and accreted stars, with a non-negligible contribution from disrupted globular clusters for all metal-poor populations. CEMP stars are an incredibly useful and interesting probe of early chemical evolution and binary populations. Much progress will be made in this field with the upcoming spectroscopic surveys, specifically 4MOST, as well as the next data release from Gaia.

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