Section 2:
Sizes, Masses and Formation histoires of the Milky Way and Andromeda

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Dynamical Masses of Local Group Galaxies
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Dynamical properties of ancient stars in the inner Milky Way with PIGS

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Abstract. We present recent results from the Pristine Inner Galaxy Survey (PIGS), which used metallicity-sensitive narrow-band CaHK photometry to identify and follow up spectroscopically thousands of ancient metal-poor candidates in the bulge. For the spectroscopic PIGS sample, we derive distances with StarHorse and compute orbital properties in a realistic potential including a bar. We find that a significant fraction of metal-poor stars is confined to the inner Galaxy (apocentre < 4 kpc), with an estimated confined fraction of 80%/50% at $[Fe/H] = -1.0/-2.0$. We also find that the very metal-poor population has a net prograde rotation, with a $v_\phi \sim 40$ km s^{-1}. It is still under discussion what the origin is of the population of very metal-poor inner Galaxy stars – it is likely a combination of *in-situ* and accreted stars. In future, spectroscopic observations from 4MOST will be crucial to complete our picture.

Keywords. Galaxy: bulge – Galaxy: halo – Galaxy: kinematics and dynamics – stars: Population II

1. Introduction

Old, metal-poor stars tell a unique story about the early history of the Milky Way. Their chemistry and kinematics are remnants from a time long gone, and teach us about early chemical evolution and the build-up of our Galaxy. The most metal-poor component of the Milky Way is the halo, and metal-poor stars have typically been searched for by and found in surveys looking up or down out of the Galactic disc – for good reasons, disc and bulge stars are metal-rich and dominate samples closer to the Galactic plane or the Galactic centre. For example the bulge red clump survey ARGOS contained only $\sim 0.1\%$ (16 out of 14 150 stars) very metal-poor (VMP) stars with $[Fe/H] < -2.0$ (Ness et al. 2013). This means the metal-poor inner Galaxy has remained largely unexplored, until very recently.

There are many good reasons to study the metal-poor inner Galaxy. The *oldest* metal-poor stars are expected to be very centrally concentrated (see e.g. the simulations by Tumlinson 2010; Starkenburg et al. 2017a; El-Badry et al. 2018), because the inner Galaxy is the part of the Milky Way that formed first. More observations are needed to address the nature of the metal-poor inner Galaxy, and answer open questions such as: What kind of building blocks contributed to the metal-poor inner Galaxy? Were they different from the rest of the halo? How much of the metal-poor inner Galaxy formed *in-situ*, and are there any very metal-poor stars part of the bar/bulge? Furthermore, we can gain new insights about the First Stars and galaxies from very metal-poor stars in different Galactic environments.

Recent years have seen a strong increase in interest and number of results regarding the metal-poor inner Galaxy, often using clever pre-selection methods (EMBLA/SkyMapper photometry: Howes et al. 2014, 2015, 2016, Best & Brightest IR photometry: Schlaufman & Casey 2014; Casey & Schlaufman 2015; Reggiani et al. 2020, BRAVA/RR Lyrae selection: Kunder et al. 2016, 2020; Savino et al. 2020, CaK photometry: Koch et al. 2016, 2019, COMBS/SkyMapper photometry: Lucey et al. 2019, 2021, 2022, PIGS/Pristine photometry: Arentsen et al. 2020a,b, 2021; Sestito et al. 2020, Gaia XP spectra: Rix et al. 2022). This contribution will focus on results from the Pristine survey, specifically the kinematics of (very) metal-poor stars in the inner Galaxy and what they can teach us about the ancient central Milky Way.

2. The PIGS sample with distances and orbits

The largest spectroscopic metal-poor central Milky Way survey to date is the Pristine Inner Galaxy Survey (PIGS Arentsen et al. 2020b). It uses the same technique as the main Pristine survey (Starkenburg et al. 2017b) to identify the most metal-poor stars: employing narrow-band, metallicity-sensitive *CaHK* photometry centred on the calcium H&K lines. By combining the *CaHK* photometry with broad-band photometry, one can produce a colour-colour space in which metal-poor stars separate extremely well from metal-rich stars. Candidate metal-poor stars were selected from the photometry and followed up with low/medium resolution spectroscopy with AAOmega+2dF on the AAT, 12 000 stars in total (details can be found in Arentsen et al. 2020b). Of those, 90% are metal-poor ([Fe/H] < -1.0) and the sample contains $\sim$ 1900 VMP stars ([Fe/H] < -2.0).

In order to derive orbits for the stars in PIGS, distances are needed. Distances are challenging to determine in the inner Galaxy due to the relatively large distance (Gaia parallaxes are not good enough by themselves) and high/irregular extinction. We combine the spectroscopic stellar parameters from PIGS, photometry from *Gaia*EDR3 (Gaia Collaboration et al. 2021) and PanSTARRS (Chambers et al. 2016) and parallaxes from *Gaia*EDR3 to derive the best possible distances using the StarHorse code (as in Queiroz et al. 2023, applied to other spectroscopic surveys). We find that 90% of the stars in PIGS are within 4 kpc of the Galactic centre, see the left-hand panel of Figure 1. The distances have typical uncertainties of $\sim$ 15%.

We proceed to derive orbital properties of the stars in PIGS, adopting the StarHorse distances, the PIGS radial velocities and the *Gaia* proper motions. The orbits are integrated in a Milky Way potential with a realistic bar (Portail et al. 2017; Sormani et al. 2022). For each star we draw 50 samples from the parameters and their uncertainties for which we derive the orbits, allowing us to build a probability distribution for the orbital parameters of each star.

3. Kinematics results for the metal-poor PIGS stars

3.1. *Confined stars*

The distances show that many of the PIGS metal-poor stars are *currently* in the inner Galaxy, but do they *stay* there for most of their lives? In the right-hand panel of Figure 1 we show the fraction of stars currently within 4 kpc of the Galactic Centre that is confined to the inner Galaxy, as function of metallicity. For this analysis we have classified a star

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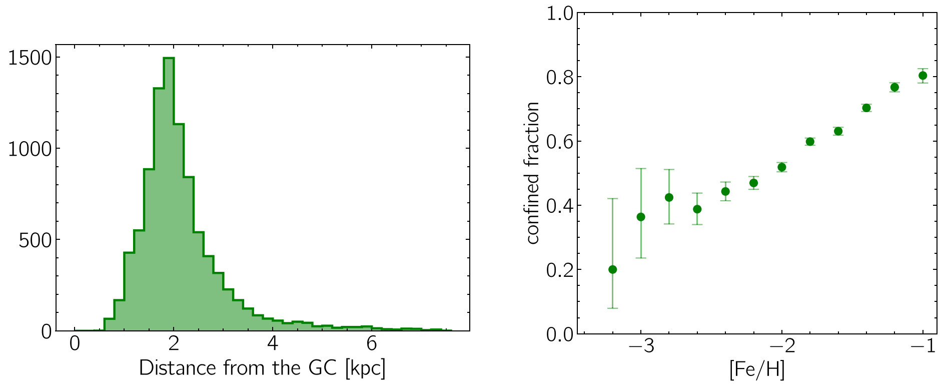

Figure 1. Left: Distribution of distances to the Galactic Centre for stars in PIGS with $[Fe/H] < -1.0$. **Right:** fraction of stars that is confined to within 4 kpc of the Galactic centre as function of metallicity.

as confined if at least 75% of the orbital samples for a star have apocentres less than 4 kpc. It can be noticed immediately that there is a strong trend with metallicity: more than 80% of the stars at $[Fe/H] = -1.0$ are confined, which steadily decreases to about 40% at $[Fe/H] = -2.5$. Below that metallicity the error bars grow, but still indicate that $20 - 40\%$ of stars are confined. The rest are halo stars just passing through the inner Galaxy. The trend of increasing number of "halo interlopers" with metallicity has been noted before (Lucey et al. 2021), based on a much smaller sample of stars, especially at the lowest metallicities. For the first time we can see that even in the very metal-poor regime there is a significant fraction of stars that is confined to the inner Galaxy (50% at $[Fe/H] = -2.0$). There appears to be a centrally concentrated metal-poor population in the inner Galaxy that has evaded previous study because typical halo surveys would not have picked up stars so close to the Galactic centre and typical bulge surveys would not have picked up enough metal-poor stars. Evidence for this was also seen by Rix et al. (2022), who used the XP spectra from *Gaia*DR3 to derive metallicities and found an over-density of metal-poor stars in the inner Milky Way.

3.2. *Rotation around the Galactic Centre*

But how does this central metal-poor population move around the Galactic centre, does it have coherent motion or is it mostly on random orbits? For stars with apocentres < 4 kpc, we projected the radial velocities to study the rotation curve as function of Galactic longitude in Figure 2. This figure is analogous to the previous PIGS rotation curves in Arentsen et al. (2020a), except that it includes 50% more data and that halo interlopers are removed. There is clearly a decrease in the rotational velocity with decreasing metallicity, but there is still some coherent rotation even for stars with $[Fe/H] < -2.0$, particularly visible at positive longitude.

We now have the full orbital properties available for the stars in PIGS instead of only the radial velocities as in Arentsen et al. (2020a). We split the sample of stars with $[Fe/H] < -1.0$ in bins of 0.25 dex and fit Gaussian distributions to the three velocity components (in spherical Galactic coordinates, v_r, v_θ, v_ϕ) using an extreme deconvolution method to take into account the effect of the uncertainties. We do this for each of the 50 orbit realisations, and only for stars with a median apocentre less than 4 kpc. For this work we only fitted one component, in the future we will test whether multiple components provide a better fit. The result is shown in Figure 3. The left-hand side presents a similar picture as Figure 2 but distilled into a mean velocity. We find that for

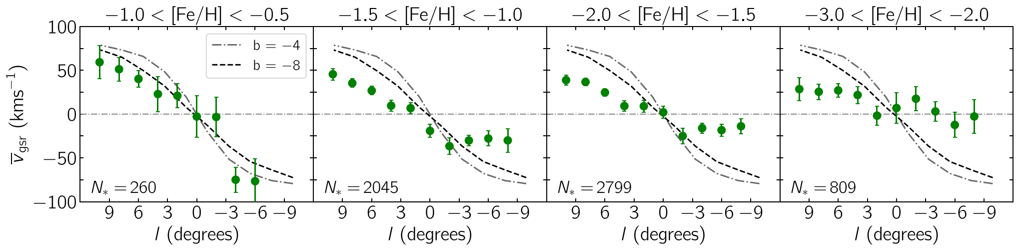

Figure 2. PIGS rotation curve as function of metallicity (only including stars with apocentres less than 4 kpc), with the number of stars included in each panel shown in the bottom left. The lines are fits to metal-rich bulge stars by Shen et al. (2010) and are the same in each panel.

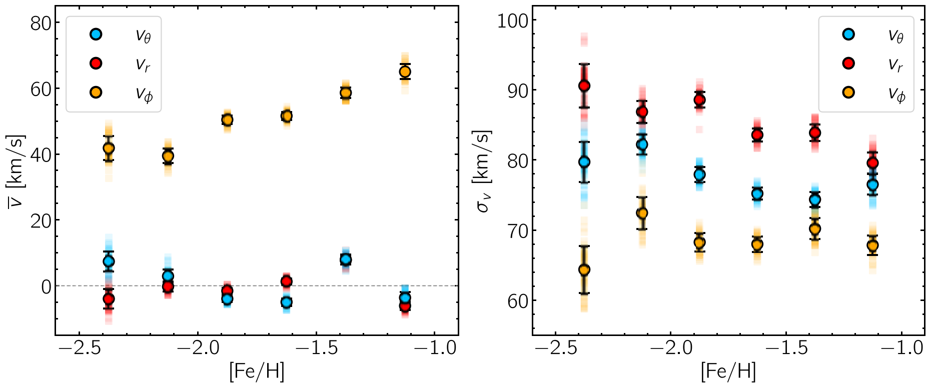

Figure 3. Mean (left) and dispersion (right) for each of the three velocity components in PIGS as a function of metallicity. The transparent squares indicate the fit for each of the 50 realisations of the PIGS orbits, the black circles and error bars the mean and standard deviation.

VMP stars, there still is an average rotational velocity of ~ 40 km s^{-1}. The right-hand panel shows the velocity dispersion. It is slightly lower for v_ϕ than for the other two velocity components, but still high (of the order of 70 km s^{-1}).

4. Discussion and conclusions

The fraction of confined stars decreases with decreasing metallicity, as well as the rotational velocity around the Galactic Centre. We do find that a large fraction of VMP stars currently in the inner Galaxy is confined to the inner Galaxy, and that this population still shows average prograde rotation. What could be the origin of this population?

Some have previously argued that there is a large *in-situ* metal-poor population in the inner Galaxy. Kunder et al. (2016, 2020) found evidence for what they called a “classical bulge”, based on the lack of net rotation of a population of RR Lyrae stars in the inner Galaxy and the confined orbits of a sub-sample of RR Lyrae. Rix et al. (2022) interpreted the spatial distribution and orbital properties of their large sample of metal-poor stars from *Gaia*XP spectra as being a remnant of the “proto-Galaxy” – the early chaotic pre-disc phase of Milky Way formation. A similar ancient pre-disc population was suggested by Belokurov & Kravtsov (2022, naming it “Aurora”), who used APOGEE spectra at slightly higher metallicity to identify *in-situ* stars based on their chemistry, which is expected to extend down to the very low-metallicity regime.

There is also evidence for accreted stars in the inner Galaxy. Kruijssen et al. (2020) and Horta et al. (2021a) suggested that there is debris from a large accreted dwarf galaxy buried in the inner Galaxy, based on the properties of globular clusters in the Milky Way or the orbital properties and chemistry of metal-poor APOGEE stars, respectively. It is unclear how many stars there would be at *very* low metallicity from such an event. From the detailed chemistry of VMP stars, there is also evidence for stars accreted from smaller dwarf galaxies (e.g. Lucey et al. 2022; Sestito et al. 2023), and there are expectations from simulations as well (e.g. Orkney et al. 2023). There are also many signs that there is a large population of disrupted globular cluster stars in the inner Galaxy based on their chemistry (Schiavon et al. 2017; Horta et al. 2021b; Lucey et al. 2019, 2022; Sestito et al. 2023), which could have come from external galaxies and/or have been born *in-situ*.

The question remains in all of these scenarios where the prograde rotation comes from for the VMP stars. It could come from the original early Milky Way build-up phase, where there was likely some net rotation after the various large building blocks coming together (e.g. suggested in the scenario of Belokurov & Kravtsov 2022). It is also possible that an originally non-rotating population gains angular momentum later on, due to the influence of the Galactic bar (e.g. Pérez-Villegas et al. 2017; Dillamore et al. 2023).

The chemical abundances of stars hold unique clues to their birth environments, and what is needed to further study the origin of metal-poor stars in the inner Galaxy, is large samples of metal-poor stars with homogeneous chemical abundances. For this we are looking forward to the upcoming multi-object spectroscopic survey 4MOST (de Jong et al. 2019), which will have dedicated metal-poor sub-surveys targeting the inner Galaxy (Chiappini et al. 2019; Bensby et al. 2019). We will provide metal-poor targets from PIGS photometry (Arentsen et al. 2020b) for the low-resolution survey, which will result in the largest sample of VMP inner Galaxy stars with multiple chemical abundances available.

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Discussion

François Hammer: I really appreciate your finding that low metallicity stars show small rotational velocities. Why do you expect no rotation at all for these stars, since almost all elliptical galaxies show even small rotation (they are generally classified as fast and slow rotators)?

Anke Arentsen: Our expectations might not have been realistic, maybe it should not be surprising that there is some net rotation indeed. But if the halo is the result of many random accretions, there should not be a large net rotation. Also the rest of the Galactic halo (at larger distances) does not appear to show a clear net rotation.

Ana Bonaca: Could there be a connection between the rotational signature of VMP stars in the inner Galaxy and the recently discovered "discy" VMP stars?

Anke Arentsen: There could be a connection indeed. In the scenario where the halo was spun up due to the Galactic bar, this could also result the local population of very metal-poor stars having net prograde rotation, looking like discy stars (see e.g. the work from Dillamore et al. 2023). There are other scenarios for the discy VMP stars discussed in e.g. Sestito et al. (2019) that can also be connected to the inner Galaxy.