Early Disk-Galaxy Formation from JWST to the Milky Way
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The Pristine Inner Galaxy Survey (PIGS) V: a chemo-dynamical investigation of the early assembly of the Milky Way with the most metal-poor stars in the bulge

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Abstract. The investigation of the metal-poor tail in the Galactic bulge provides unique information on the early Milky Way assembly and evolution. A chemo-dynamical analysis of 17 very metal-poor stars (VMP, [Fe/H]< -2.0) selected from the Pristine Inner Galaxy Survey was carried out based on Gemini/GRACES spectra. The chemistry suggests that the majority of our stars are very similar to metal-poor stars in the Galactic halo. Orbits calculated from *Gaia* EDR3 imply these stars are brought into the bulge during the earliest Galactic assembly. Most of our stars have large [Na,Ca/Mg] abundances, and thus show little evidence of enrichment by pair-instability supernovae. Two of our stars (P171457, P184700) have chemical abundances compatible with second-generation globular cluster stars, suggestive of the presence of ancient and now dissolved globular clusters in the inner Galaxy. One of them (P171457) is extremely metal-poor ([Fe/H]< -3.0) and well below the metallicity floor of globular clusters, which supports the growing evidence for the existence of lower-metallicity globular clusters in the early Universe. A third star (P180956, [Fe/H]~ -2) has low [Na,Ca/Mg] and very low [Ba/Fe] for its metallicity, which are consistent with formation in a system polluted by only one or a few low-mass supernovae. Interestingly, its orbit is confined to the Galactic plane, like other very metal-poor stars found in the literature, which have been associated with the earliest building blocks of the Milky Way.

Keywords. Galaxy: formation - Galaxy: evolution - Galaxy: bulge - Galaxy: abundances - stars: kinematics and dynamics - stars: Population II

1. Introduction

The oldest and most chemically pristine stars in the Galaxy are expected to have been enriched by only one or a few individual supernovae or hypernovae events. This means that studies of their chemical abundance patterns and orbital dynamics are invaluable for learning about the lives and deaths of the first stars, and the assembly history of the Galaxy (Freeman & Bland-Hawthorn 2002; Tumlinson 2010; Wise et al. 2012; Karlssson et al. 2013). Successive generations of stars enriched the interstellar medium, while gas inflows dilute it, contributing to a complex star formation history that depends on location within the Milky Way Galaxy. In cosmological simulations, low-metallicity stars ([Fe/H]†≤ -2.5) form in the first 2–3 *Gyr* after the Big Bang, and mostly in low-mass systems, the so-called "building blocks", (Starkenburg et al. 2017a; El-Badry et al. 2018; Sestito et al. 2021). These building blocks gradually merged to form the proto-Milky Way. These stars are expected to occupy the deepest parts of the gravitational potential, [i.e.]near the bulge, while late accretion of dwarf satellites are expected to deposit metal-poor stars primarily in the halo (Bullock & Johnston 2005; Johnston et al. 2008; Tissera et al. 2012), or even in the disc for planar accretions (e.g. Abadi et al. 2003; Sestito et al. 2021; Santistevan et al. 2021).

While the metal-poor stars in the Galactic bulge are important tracers of the earliest stages in the formation of the Milky Way, they are extremely difficult to find (e.g Schlaufman & Casey 2014). Firstly, the region of the bulge is dominated by a metal-rich population of both young and old stars, disrupted globular clusters, and ongoing star formation (Ness et al. 2013a, 2014; Bensby et al. 2013, 2017; Schiavon et al. 2017; Schultheis et al. 2019). Secondly, the heavy and variable interstellar extinction, extreme stellar crowding, and presence of complex foreground disc stellar populations have made photometric surveys of metal-poor stars extremely challenging. The ARGOS spectroscopic survey found that fewer than 1% (84) of the stars in their sample have [Fe/H] < -1.5 (Ness et al. 2013a). The Extremely Metal-poor BuLge stars with AAOmega (EMBLA; Howes et al. 2014, 2015, 2016) survey selected VMP targets with a metallicity-sensitive photometric filter from the SkyMapper Southern Survey (Bessell et al. 2011; Wolf et al. 2018). for low-resolution spectroscopy with the Anglo-Australian Telescope. EMBLA analysed with high-resolution spectroscopy 63 stars with [Fe/H] < -2.0, where the majority resemble chemically metal-poor stars in the Galactic halo. The only noticeable differences were a lack of carbon-rich stars, and possibly a larger scatter in [α/Fe] abundances. A detailed kinematics analysis of their sample also raised questions about what it means to be a "bulge star", [i.e.]a star that formed in the bulge versus one passing through the bulge on a radial orbit. Reducing their sample to stars with apocentric distances $\leq$5 kpc (36 stars), however, did not alter their conclusions (Howes et al. 2016).

The Pristine Inner Galaxy Survey (PIGS; Arentsen et al. 2020a,b) is similar to the EMBLA survey in that metal-poor targets have been selected from the narrow-band photomery, in this case the Pristine survey (Starkenburg et al. 2017b). The Pristine survey is a narrow-band imaging survey carried out at the Canada-France-Hawaii Telescope (CFHT), where the Ca[II]HK filter, in combination with broad band photometry, has been shown to find low-metallicity stars ([Fe/H]< -2.5) with $\sim$56% efficiency in the Galactic halo (Youakim et al. 2017; Aguado et al. 2019; Venn et al. 2020). The power of the Pristine survey has been demonstrated by the discovery of two new ultra metal-poor stars ("UMP", [Fe/H] < -4.0; Starkenburg et al. 2019; Lardo et al. 2021), or $\sim$5 percent of the total known UMP stars so far (see the compilation in Sestito et al. 2019). The Pristine-selected metal-poor targets in the bulge were examined with low-/medium-resolution spectroscopic observations obtained with the the AAOmega spectrograph on the Anglo Australian Telescope (AAT), from which stellar parameters, metallicities, and carbon abundances were derived for $\sim$12,000 stars. Arentsen et al. (2020b)) report an efficiency of $\sim$80% in finding very metal-poor stars ("VMP", [Fe/H] < -2.0) in the bulge avoiding the most highly extincted regions. Arentsen et al. (2020b)) used the PIGS/AAT observations to study the kinematics of metal-poor stars in the inner Galaxy, finding that the rotation around the Galactic centre decreases with decreasing metallicity, [i.e.]lower metallicity stars are more dispersion-dominated as the Galactic halo.

To chemically examine the low-metallicity tail of the Galactic bulge also requires consideration of the contributions from disrupted globular clusters and later accretions of dwarf galaxies. Some studies have suggested that up to $\sim$25 percent of the stellar mass

† [Fe/H]= $\log(N_{Fe}/N_H)_\star - \log(N_{Fe}/N_H)_\odot$, in which N_X is the number density of element X.

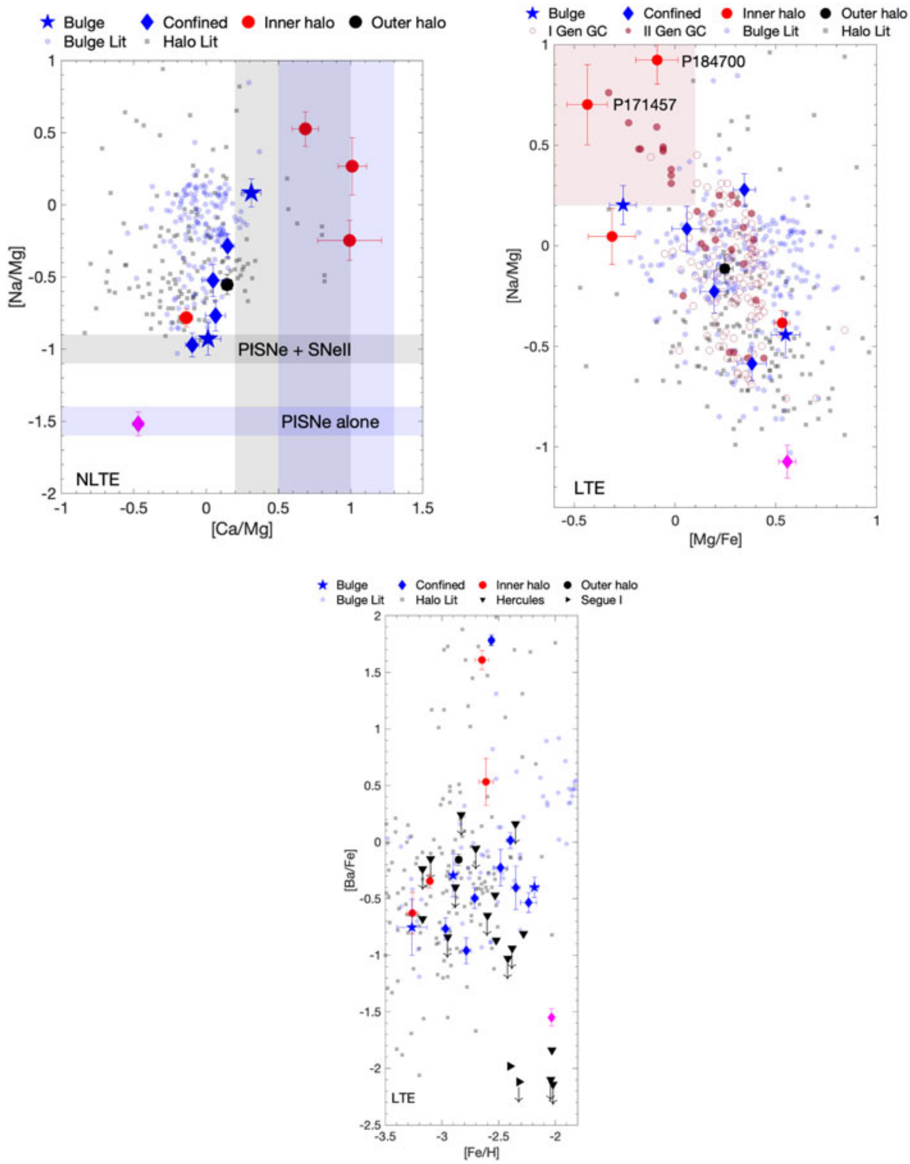

Figure 1. Top left panel: Pair-Instability Supernovae yields space. The chemical abundances ratios are corrected for NLTE effects. Stars in the overlapping region between the two blue bands would possess the signature of the PISNe yields alone scenario as shown in Takahashi et al. (2018). While the overlapping region of the grey bands is the locus in which the stars would have been polluted by a PISNe and a SN II as in Salvadori et al. (2019). For the latter case, we show the yields relative to a PISNe to SN II ratio between 0.5 and 0.9, following Figure 6 from Salvadori et al. (2019). Top right panel: Second-generation globular cluster stars space. A compilation for GC (open red circles for second-generation stars and solid red circles for first generation stars from GCs; Pancino et al. 2017) is displayed. Chemical ratios are LTE since the GC comparison stars from Pancino et al. (2017) are in LTE. Bottom panel: [Ba/Fe] vs. [Fe/H]. Not corrected by NLTE effect. Hercules stars are from Koch et al. (2008, 2013), Fran¸cois et al. (2016)m while Segue 1 stars are from Frebel et al. (2014). Upper limits on the [Ba/Fe] ratios for Hercules and Segue 1 stars are denoted with an arrow. The low-Ba star (magenta diamond marker) is likely accreted from a dwarf galaxy and its chemistry is very similar to some stars in Hercules and Segue 1. All the panels: The bulge literature sample (blue circles) is composed of stars from Howes et al. (2014, 2015, 2016), Koch et al. (2016), Reggiani et al. (2020), Lucey et al. (2022). Halo literature compilation (grey squares) is from Aoki et al. (2013), Yong et al. (2013), Kielty et al. (2021).

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of the inner region of the Milky Way is made of dissolved ancient globular clusters (e.g., Shapiro et al. 2010; Kruijssen 2015; Schiavon et al. 2017). One study (Schiavon et al. 2017) based this claim on the large number of nitrogen-rich stars that resemble the chemistry of second-generation stars in globular clusters (Gratton et al. 2004; Bastian & Lardo 2018). More recently, a few bulge stars with chemistry similar to second-generation globular cluster stars were found in the Chemical Origins of Metal-poor Bulge Stars (COMBS) survey (Lucey et al. 2019, 2021, 2022). The COMBS survey is based on VLT/UVES+GIRAFFE+FLAMES spectra of red giants in the bulge, and also reported that the number of halo stars passing through the bulge ("interlopers") increases with decreasing metallicity.

Here, we report on a chemo-dynamical investigation of 17 VMP candidates selected from the PIGS survey and observed with the high-resolution GRACES spectrograph at Gemini North.

2. Chemo-dynamical properties of the inner Galaxy

The chemistry suggests that the majority of these stars are very similar to metal-poor stars in the Galactic halo (see Figures). Orbits calculated from Gaia DR3 imply these stars are brought into the bulge during the earliest Galactic assembly. Most of our stars have large [Na,Ca/Mg] abundances, and thus show no evidence of enrichment by pair-instability supernovae (see Figure 1). Two stars (P171457, P184700) have chemical abundances compatible with second-generation globular cluster stars (see Figure 1), suggestive of the presence of ancient and now dissolved globular clusters in the inner Galaxy. One of them (P171457) is extremely metal-poor ($[Fe/H] < -3.0$) and well below the metallicity floor of globular clusters, which supports the growing evidence for the existence of lower-metallicity globular clusters in the early Universe. A third star (P180956, $[Fe/H] \sim -2.0$) has a chemical signature that suggests it was formed in a system polluted by only one or a few low-mass supernovae (see Figure 1). Interestingly, its orbit is confined to the Galactic plane, like other very metal-poor stars found in the literature (Sestito et al. 2019, 2020, 2021; Cordoni et al. 2021; Santistevan et al. 2021) which have been associated with the earliest building blocks of the Milky Way.

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