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UNCOVERING THE VERY METAL-POOR TAIL OF THE THIN DISC

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Abstract. In this talk we present the results of the recent published study by Fernández-Alvar et al. (2021), consisted on the exploration of the rotational velocity distribution as a function of the metallicity of stars located towards the Galactic anticenter. The analyzed sample was observed as part of the Pristine survey, a photometric program devised to find the most metal-poor stellar populations in the Galaxy in order to understand the first Galactic formation processes. When combining metallicities obtained from the Pristine photometry with rotational velocities derived from proper motions several stellar structures emerge. The most intriguing one is the metal-poor tail of stars moving like the thin disc extended down to very low metallicities, [Fe/H] ~ -2. Fast rotators are also observed at even lower metallicities, $-3.5 <$ [Fe/H] < -2, but in a scarcer number. These recently discovered very and extremely metal-poor disc-like stars merit a dedicated spectroscopic follow-up to provide a complete chemical characterization to better constrain their origin. The clarification of their formation scenario will undoubtly shed light on the understanding of the first formation episodes of the Milky-Way.

Keywords: Galaxy: disc – Galaxy: kinematics and dynamics – Galaxy: abundances

1 Introduction

Chemo-dynamics of metal-poor stars encode key information to understand how our Galaxy formed. For this reason, several programs have been devised through the last decades in order to find and characterize these kind of objects. This is the case of the Pristine survey (Starkenburg et al. 2017). Pristine is a photometric survey whose strategy to observe metal-poor objects relies on the use of a filter centered in the CaII doublet H&K, at 3933 and 3968 Å, which is a spectral feature very sensitive to the stellar metallicity. The survey is carried out with the 3.6-meter optical/infrared Canadian-French-Hawaiian Telescop on the Mauna Kea Hawaiian Observatory. It already mapped around 12 millions of targets over 5000 square degrees on the sky. Its efficiency to detect extremely metal-poor stars has been largely probed (Youakim et al. 2017, Aguado et al. 2019). It aims to provide a comprehensive view of the metallicity distribution of the metal-poor Galaxy and an insight on the Galaxy build-up and structure. The metallicity sensitivity of Pristine photometry is used to derive a metallicity estimation for each target. The CaHK magnitude is combined with broad-band colours in a colour-colour space that separates out the temperature and metallicity effects. Then, metallicity estimates from a subsample of stars with an spectroscopic counterpart are used to derive a global metallicity calibration, as explained in detail in Starkenburg et al. (2017).

We aim to combine Pristine metallicities with the unprecedently accurate Gaia early third data release (EDR3 – Gaia Collaboration et al. 2021) astrometry. Our goal is to perform a chemo-kinematical analysis over the metal-poor Milky Way stellar populations observed with Pristine. All Pristine targets have Gaia proper motions measurements, but a very low fraction count with radial velocity measurements ($\sim$0.5%), preventing the full velocity characterization. However, in the direction towards the anticenter the rotational velocity, V_ϕ, is perpendicular to the line-of-sight. Consequently, V_ϕ does not depend on the radial velocity and only the proper motion measured along the galactic longitude direction, μ_ℓ, is required. Taking advantage of this fact, we are able to explore the V_ϕ and [Fe/H] distributions of stars observed by the Pristine survey towards the anticenter direction.

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2 The rotational velocity and metallicity distribution towards the anticenter: statistical evidence of a very metal-poor thin disc.

We choose stars located at $(170 < \ell < 190, 20 < b < 40)^\circ$, the Pristine footprint region where the uncertainty of V_ϕ determined with the proper motion approximation is lower than 5 $\mathrm{km\,s^{-1}}$on average, as probed by evaluating a Gaia EDR3 mock catalogue (see Fernández-Alvar et al. 2021 for the detailed explanation). Figure 1 shows the resulting V_ℓ, derived from the Gaia EDR3 proper motions, as a function of the [Fe/H], estimated from Pristine photometry combined with Sloan Digital Sky Survey magnitudes (Starkenburg et al. 2017). Just a rough inspection of the distribution of stars on the V_ℓ vs. [Fe/H] plane reveals the presence of several structures. First, our stellar sample is mostly comprised by thin disc stars with metallicities close to solar and moving with velocities typical of the Local Standard of Rest (LSR), i.e., -238 $\mathrm{km\,s^{-1}}$[*] (Schönrich 2012). We see, however, that fast rotating stars are not restricted to the highest metallicity range but that there is a continuous extension down to the lowest metallicity values. This feature is surprising, since the thin disc distribution is expected to be metal-rich, with a negligible number of stars with metallicities lower than ~ -0.7 (e.g. Bensby et al. 2014).

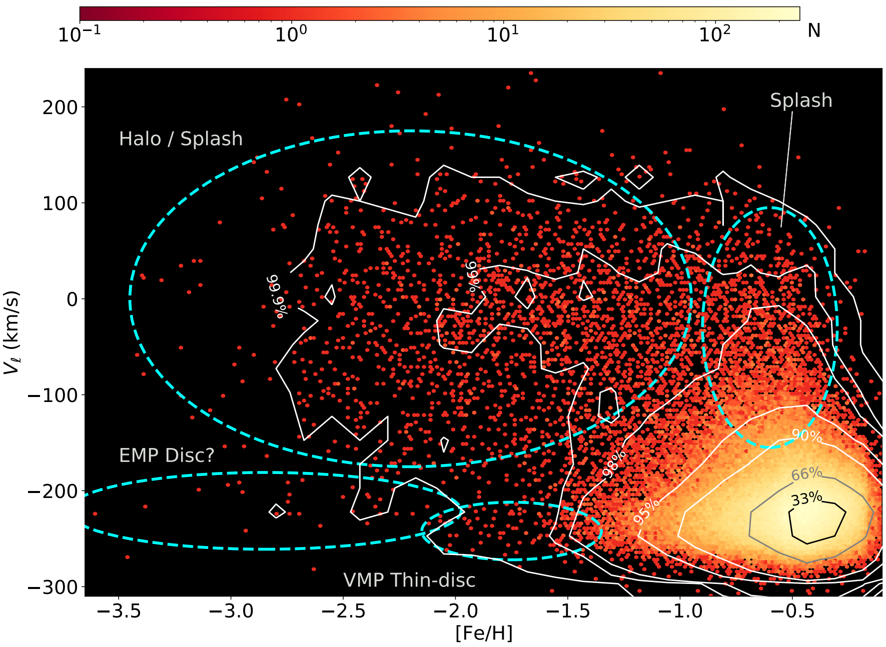

Fig. 1. V_ℓ as a function of [Fe/H], colour coded by density (the color code lower limit is set to 0.1 due to color contrast purposes). The density is measured in bins of 10 $\mathrm{km\,s^{-1}}$and 0.1 dex and contour lines show the 33, 66, 98, 99 and 99.9% of the cumulative distribution. The most evident stellar substructures are pointed out with annotated cyan ellipses: a presumed extremely metal-poor disc (EMP disc), the very metal-poor thin disc (VMP thin disc), the Splash, and the halo. Stars on prograde motion are those with $V_\ell < 0$, while stars on retrograde motion have $V_\ell > 0$.

Figure 1 also reveals that high metallicity stars show a velocity distribution which extends towards non-rotating velocities and even retrograde motions. This velocity tail is similar to the heated disc stellar population recently discovered (Fernández-Alvar et al. 2019, Di Matteo et al. 2019,Belokurov et al. 2020), the so-called *Splash*. Finally, stars with [Fe/H] < -1.5 are dominated by a stellar sample that resembles the classical kinematical stellar halo, with a velocity distribution centered around 0 $\mathrm{km\,s^{-1}}$with a large dispersion (Fermani & Schönrich 2013).

In order to distinguish more quantitatively the subyacent stellar populations based on their chemo-kinematical characteristics we fit the data with Gaussian Mixture Models[†]. This technique consists on a clustering algorithm that searches for the best number of gaussian components that reproduces a data set. We split our sample in

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[*] In our reference system negative velocity values correspond to a prograde motion.

[†] We make use of the python module sklearn.mixture (Pedregosa et al. 2011)

metallicity bins and fit the V_ℓ data with Gaussian Mixture Models. We evaluate models comprised by one up to six gaussians.

For the metallicity range typically dominated by thin and thick disc stars, $-0.8 < [\mathrm{Fe/H}] < -0.2$ [‡], we obtained that a five-gaussian model is the one that best fit the data. Two of these gaussians are centered at values close to the typical rotational velocity of the LSR in the solar neighbourhood, $V_\phi \sim -238~\mathrm{km\,s^{-1}}$. Other two gaussian components peak at velocities around those of thick disc stars, lagging prograde rotation respect to the thin disc (Recio-Blanco et al. 2014). These four gaussians are, thus, comprised by thin and thick disc stars. The fact that we need more than two gaussians to reproduce the two disc components is not completely surprising, since we already know that their velocity distributions are not perfect gaussians (e.g., Sharma & Bland-Hawthorn 2013, and references therein). Besides, it is also known that there is a velocity correlation with the metallicity, negative for the thin disc and positive for the thick disc as the metallicity increases (e.g. Kordopatis et al. 2017). Interestingly, there is need of an additional gaussian component to take into account for the non-rotating and retrograde stars, i.e., the *Splash*. As the metallicity decreases, the gaussian components shift toward higher velocity values, with those comprising velocities typical of the thick disc and the one counting for the *Splash* increasing in relative weight.

Noticible, at $-1.5 < [\mathrm{Fe/H}] < -0.8$ there is still a large contribution of stars moving with velocities typical of the thin disc. We verified whether such fast rotating stars at a metallicity range where the contribution of the thin disc should be very low could be an artifact, consequence of a problem in the metallicity calibration. Indeed, the comparison of photometric metallicities with those derived spectroscopically for the targets with a spectroscopic follow-up reveals large differences at metallicities between -1.5 and -0.8 approximately. In order to quantify the possible contamination of metal-rich stars at lower photometric metallicity bins we model a thin disc metallicity distribution function and how it is modified due to the error function of our metallicity calibration. This exercise shows that around 45% of our stars with photometric metallicities between $-1.5 < [\mathrm{Fe/H}] < -0.8$ are likely more metal-rich thin disc stars.

At lower metallicities, $-2 < [\mathrm{Fe/H}] < -1.5$, the best Gaussian Mixture Model fit is a two-gaussian model: one centered around $-233~\mathrm{km\,s^{-1}}$(a velocity value closer to the LSR rotational velocity rather than the typical velocities of the thick-disc or the halo) and the other around $-38~\mathrm{km\,s^{-1}}$. Interestingly, the estimated contamination in this metallicity bin is very low ($< 1\%$) and cannot take into account all the stars moving with thin-disc-like velocities. We also verified that errors in velocities are not the responsible for this feature. We performed a Monte Carlo simulation by calculating 1000 times the velocity taking into account the measurement errors in parallax and proper motions considering they follow a gaussian distribution. The best Gaussian Mixture Model fit for more than 90% of the simulations is the two-gaussian model. These verifications reinforce the statistical significance of this feature. At metallicities $-3.5 < [\mathrm{Fe/H}] < -2$ there is no significant evidence of a distinct kinematically thin disc stellar population, although there is still the presence of fast rotating stars.

3 Hypothetical formation scenarios.

This is not the first time that fast rotating stars with extremely low metallicities have been detected. The first one was the work by Sestito et al. (2019), who discovered that 26% of all known ultra metal-poor stars with radial velocities were confined to $z_{max} < 3$ kpc to the plane, and 5% moving in prograde circular orbits. Since then subsequent works confirmed these results and found evidence of extremely and ultra metal-poor stars moving with thick-disc-like velocities (Sestito et al. 2020, Di Matteo et al. 2019, Di Matteo et al. 2020; Venn et al. 2020; Carter et al. 2021; Cordoni et al. 2021). In particular, Di Matteo et al. (2020) compared the chemo-dynamical properties of stars from the ESO's Large Program "First Stars" with other stellar samples covering a metallicity range between $[\mathrm{Fe/H}] < -4$ up to $[\mathrm{Fe/H}] \sim 0$. This work showed that there is evidence of a kinematical disc and halo populations coexisting at every metallicity range.

Our work shows from an homogeneous data set that there is indeed statistical evidence of a kinematical disc and halo populations coexisting down to, at least, $[\mathrm{Fe/H}] \sim -2$. Interestingly, our kinematical disc rotates more like the thin disc than a thick disc. Our sample is mostly confined at low z, what could be the reason why we are able to probe this fast rotating stellar population better than previous works.

The existence of fast rotators at such low metallicities is puzzling. From the theoretical point of view, stars with $[\mathrm{Fe/H}] < -2$ are expected to form during the first couple of Gyr after the Big Bang (El-Badry et al. 2018), the epoch at which the Galaxy was assembling through the hierarchical merger of smaller systems.

[‡] -0.2 is the upper limit up to which the Pristine metallicity calibration is reliable

Consequently, stars were expected to be pressure supported or heated into halo-like kinematics due to the impact of the mergers, preventing a disc configuration. However, some recent cosmological simulations predict that thin disc stars formed first, later evolving to a thicker configuration as a result of heating (Park et al. 2020). The existence of metal-poor stars moving like the thin disc could be explained as a fraction of stars formed in the early disc that succeded in maintaining their original motion without being heated. These stars would be characterized by high [α/Fe] ratios. Further investigation with cosmological simulations is needed to explore this scenario.

On the other hand, there are recent results of a two-infall chemical evolution model based on an inside-out formation scenario able to predict the formation of thin disc stars with metallicities down to [Fe/H] ~ -2 after the dilution of the second infall of gas (Spitoni et al. 2021). These stars should have lower [α/Fe] ratios compared with the scenario where they would have formed in the first stages of Galaxy formation. However, the two-infall model cannot explain the presence of kinematical disc stars with lower metallicities, [Fe/H] < -2. Further analysis of the chemical abundances of these stars is needed to clarify whether stars with metallicities higher and lower than [Fe/H] ~ -2 are belong to one or two different stellar populations.

4 Conclusions

In this talk we have presented the main results of the rotational velocity and metallicity distributions analysis of stars observed by the Pristine survey recently published in Fernández-Alvar et al. (2021). In this work we discovered statistical evidence of the existence of a very metal-poor ([Fe/H] > -2) stellar population moving with rotational velocities resembling the thin disc motion. This is not the first time metal-poor stars, even at lower metallicities ([Fe/H] < -4), moving in disc-like orbits had been detected, although without such fast rotating velocities. This is an exciting discovery with important implications regarding the first stages of star formation of the Milky Way. For this reason, it merits a detailed follow-up, in particular with spectroscopic stellar surveys that could allow a deeper chemo-dynamical characterization in order to clarify their formation scenario.

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