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Efficiency and success rates of the *Pristine* survey from spectroscopic follow-up

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Abstract. The *Pristine* survey uses narrow-band photometry on the region of the Ca II H & K absorption lines to find extremely metal-poor stars. With a spectroscopic follow-up sample of 205 stars in the magnitude range $14 < V < 18$, we compute the success rates for finding extremely metal-poor stars and modify the selection criteria used to select stars for follow-up. This reduces the sample to 149 stars, and from these we report success rates of 22% for recovering stars with $[\mathrm{Fe/H}] < -3.0$ and 70% for $[\mathrm{Fe/H}] < -2.5$. When compared to previous works that search for extremely metal-poor stars, the success rates of *Pristine* show an improvement in efficiency by a factor of $\sim 4-5$.

Keywords. Galaxy: halo, Galaxy: evolution, Galaxy: formation

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1. Introduction

The most metal-poor stars in the Galaxy represent a population of relics from the early stages of its formation. For this reason, these stars are of great interest in studying the chemical history and evolution of the Milky Way. Their chemical abundance patterns may contain the imprints of the supernovae events of the very first generation of stars (e.g., Keller *et al.* 2014), and their spatial distributions can encode information about the accretion history of satellite galaxies in the halo, and the *in situ* star formation history of the disk and bulge.

However, these stars are difficult to study because they are very rare and greatly outnumbered by more recently formed metal-rich stellar populations. From the Besançon model of the Galaxy (Robin *et al.* 2003), in a high Galactic latitude field towards the anti-centre direction ([l,b] = [0°, 60°]) and in the magnitude range $14 < V < 18$, it is expected that only $\sim 1/2000$ stars will be extremely metal-poor (EMP), with an $[\mathrm{Fe/H}] \leqslant -3$. Furthermore, from metallicity distribution functions of the halo produced with real data, it is estimated that only 1 in 100 EMP stars are expected to be ultra metal-poor (UMP), with an $[\mathrm{Fe/H}] \leqslant -4$ (Schörck *et al.* 2009; Allende Prieto *et al.* 2014).

A significant amount of work has been done in the last decades to try to uncover these most metal-poor stars, using Ca H & K objective-prism techniques (Beers *et al.* 1985; Christlieb *et al.* 2002), large scale, blind spectroscopic surveys (e.g., Caffau *et al.* 2013; Aoki *et al.* 2013; Allende Prieto *et al.* 2015; Aguado *et al.* 2016), and broad-band photometric colour combinations, either fully based on optical colours (Ivezić *et al.* 2008; An *et al.* 2013; Ibata *et al.* 2017), or in combination with infrared magnitudes (Schlaufman & Casey 2014, hereafter referred to as SC14).

Another technique that has been shown to quite successfully target metal-poor stars is pre-screening with narrow-band photometry on the Ca II H & K absorption lines (e.g., Anthony-Twarog *et al.* 1991). This method is based on the principle that, using a narrow-band filter, it is possible to measure the photometric flux on this specific wavelength region and use this to estimate the [Fe/H] content of a star. Two surveys which have been particularly successful with this method, are the *SkyMapper* survey (e.g., Keller *et al.* 2007) in the southern hemisphere and the *Pristine* survey (Starkenburg *et al.* 2017a) in the northern hemisphere. *SkyMapper* has uncovered the most iron-poor star currently known, with an [Fe/H] < -7.1 (Keller *et al.* 2014), as well as several other notable metal-poor stars in the halo and in the bulge (e.g., Howes *et al.* 2014), and the *Pristine* survey has shown some very promising preliminary results (Youakim *et al.* 2017).

2. The Pristine survey

The *Pristine* survey utilizes a specially designed narrow-band filter mounted on the Canada France Hawaii Telescope (CFHT) on Mauna Kea in Hawaii. The photometric CaHK magnitudes that are obtained from this filter are combined with SDSS broad-band photometric magnitudes to provide photometric metallicity information. The *Pristine* footprint as of September 2016 covered a contiguous ~ 1000 deg^2 area in the northern Galactic halo, down to a depth of $V \sim 20.5$, and data collection is ongoing with the aim of collecting a total of at least ~ 3000 deg^2. The footprint overlaps by design with the SDSS such that good quality broad-band photometry is readily available, as well as several thousand SDSS/SEGUE spectra that are distributed over the footprint and can be used for the photometric metallicity calibration. In parallel with photometric observations, there is also an ongoing spectroscopic follow-up campaign on 2-4m class telescopes at medium- and high-resolutions to improve the calibration of the survey and pre-select interesting candidates for follow-up with larger telescopes at higher resolutions. Here we focus on a sample of 205 stars observed at medium-resolution, obtained between March and September 2016 with the 2.5m Isaac Newton Telescope (INT) and the 4.2m William Herschel Telescope (WHT), both of which are located at the Roque de Los Muchachos Observatory in La Palma, Canary Islands.

3. Success rates and comparison to other works

With the analyzed spectra in hand, we re-assessed and improved the selection criteria used to select metal-poor candidates from the *Pristine* narrow-band CaHK + SDSS photometry. Applying the new selection criteria (described in detail in Youakim *et al.* 2017) reduced the sample down to 149 stars. The spectroscopic follow-up sample can therefore be divided into three sub-samples: a total sample of all 205 stars that were observed, a sample of the 149 stars that pass all of the selection criteria, and a sample of the 46 stars which were predicted by *Pristine* to be EMP, i.e. $[\mathrm{Fe/H}]_{Pristine} \leqslant -3.0$. The metallicity distributions of these samples are depicted in the left panel of Figure 1. The relation between the predicted photometric metallicity and the spectroscopic metallicity for the same three sub-samples is shown in the right panel. Most notably, when compared to the total sample, the sample with the new selection criteria applied improves the relative fraction of EMP stars from 13% to 17% and decreases the number of contaminants (stars with $[\mathrm{Fe/H}]_{spectroscopic} \geqslant -2.0$) from 20% to 7%. The most selective sample, which includes only stars with $[\mathrm{Fe/H}]_{Pristine} \leqslant -3.0$, further improves the relative fraction of EMP stars confirmed by spectroscopy to 22%. This is the number that we quote as the

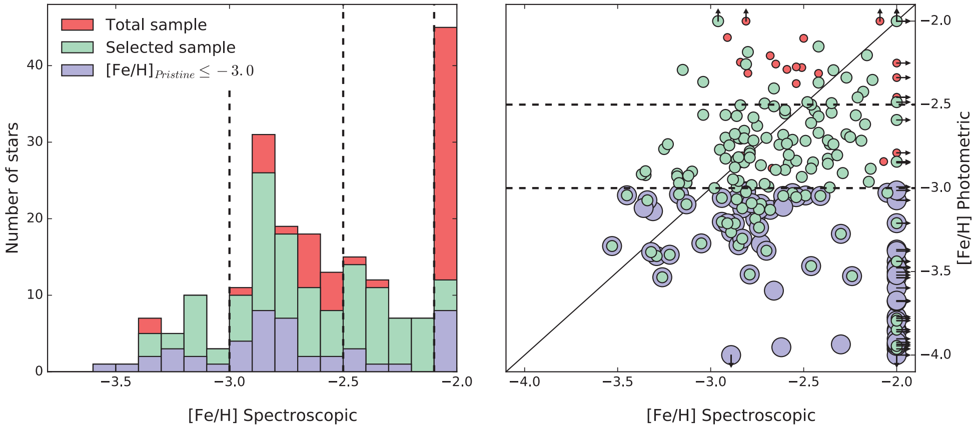

Figure 1. Left panel: metallicity distribution functions for the three follow-up samples. Right panel: photometric versus spectroscopic metallicity for the total follow-up sample of 205 stars (small points), the selected sample of 149 stars (medium circles), and the sample with [Fe/H]$_{Pristine} \leqslant -3.0$ (large circles). Note: the total sample was plotted on the bottom layer to avoid cluttering, and therefore all larger circles on this plot also have a small point behind them.

success rate, since this is the number of stars predicted photometrically to be EMP that are spectroscopically confirmed as such. The success rate for the stars predicted to have [Fe/H]$_{Pristine} \leqslant -2.5$ is 70%.

For a comparison to other works, we compare to the results of SC14 and the Hamburg ESO survey (HES, Christlieb *et al.* 2002). The reason that these particular surveys were chosen for comparison is that they have coherently quantified their success in recovering metal-poor stars, which is not the case for some of the larger surveys which have had many different groups conducting follow-ups on public data. Furthermore, these two surveys have been particularly successful at finding metal-poor stars (with other surveys reporting similar or lower success rates e.g., Allende Prieto *et al.* 2000). From their colour cuts using infrared and optical colours to select metal-poor star candidates, SC14 report a return rate of $3.8^{+1.3}_{-1.1}$% for recovering stars with [Fe/H] $\lesssim -3.0$, and $32^{+3.0}_{-2.9}$% for stars with $-3.0 \lesssim$ [Fe/H] $\lesssim -2.0$. In a follow-up sample of the HES, Schörck *et al.* (2009) report 65 out of 1 638 stars with [Fe/H] $\leqslant -3.0$, a fraction of 4%. Therefore, *Pristine* improves upon previous works by a factor of $4-5$ for recovering stars with [Fe/H] $\leqslant -3.0$ (see Youakim *et al.* 2017 for an in depth discussion about success rates).

4. Projections

Given these success rates, we project that we will find $\sim 1000-1200$ EMP stars over the ~ 1000 deg^2 *Pristine* footprint, in the magnitude range $14 < V < 18$. Although we have not found any UMP stars in this current spectroscopic sample, we project to find $\sim 10-12$ UMP stars over the ~ 1000 deg^2 *Pristine* footprint, based on the frequencies of UMP stars reported in Schörck *et al.* (2009) and Allende Prieto *et al.* (2014). Including the fainter magnitude ranges of *Pristine* candidates would further increase the projected number of EMP and UMP stars projected to be found, both because of the increased number of candidates and also because the survey would be probing deeper into the metal-poor outer halo. The addition of several thousand EMP stars to the literature would contribute significantly to improving the characterization of the metal-poor tail of the halo metallicity distribution function, and the addition of several dozen UMP stars would have a significant impact on our understanding of this rare stellar population, given that to date only two dozen stars with $[\mathrm{Fe/H}]_{Pristine} \leqslant -4.0$ are currently known in the literature. The major limitation is that following up the many thousand candidates in the fainter magnitude ranges using single-slit spectroscopy is very inefficient. Therefore, *Pristine* is an ideal complement to feed targets into upcoming large coverage, multi-object, spectrographic surveys, such as the William Herschel Telescope Enhanced Area Velocity Explorer (WEAVE, Dalton *et al.* 2012, 2014, 2016), the 4-metre Multi-Object Spectroscopic Telescope (4MOST, de Jong *et al.* 2016), the Subaru Prime Focus Spectrograph (PFS, Takada *et al.* 2014), and the Maunakea Spectroscopic Explorer (MSE, McConnachie *et al.* 2016).

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