GALAH SURVEY: CHEMICALLY TAGGING THE THICK DISK

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Abstract. The GALAH survey targets one million stars in the southern hemisphere down to a limiting magnitude of $V = 14$ at the Anglo-Australian Telescope. The project aims to measure up to 30 elemental abundances and radial velocities ($\approx 1$ km s$^{-1}$ accuracy) for each star at a resolution of $R = 28,000$. These elements fall into 8 independent groups (e.g. $\alpha$, Fe peak, $r$-process). For all stars, Gaia will provide distances to 1\% and transverse velocities to 1 km s$^{-1}$ or better, giving us a 14D set of parameters for each star, i.e. 6D phase space and 8D abundance space. There are many scientific applications but here we focus on the prospect of chemically tagging the thick disk and making a direct measurement of how stellar migration evolves with cosmic time.

1 Introduction

The GALAH survey (2014-2019; see Fig.1) is the latest major undertaking at the Anglo-Australian Telescope [De Silva et al. 2015]. It uses the $12M$ HERMES instrument fed by 400 fibres that can be positioned robotically at the prime focus [Sheinis et al. 2014]. The main science goal of the project is to chemically ‘trace’ different Galactic components aided by the stellar kinematics with a particular emphasis on old stars, i.e. stars that were born (half of the stellar mass) before $z \sim 1$. In each of these components, we propose to explore chemical tagging, introduced as a tool for reconstructing information that has been lost over billions of years as the Galaxy evolves [Freeman & Bland-Hawthorn 2002]. The central idea is that essentially all stars have been born in homogeneous gas clouds that have long since dispersed [Bland-Hawthorn et al. 2010a]. Only a small fraction remain bound today in the form of star clusters (e.g. open clusters). Thus, in certain instances, a star’s siblings may be identified by a unique chemical signature in a

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Fig. 1. Potential GALAH survey fields (4300 in total) across the southern sky are shown as open grey circles; the magenta circles indicate the fields observed up to November 2014. The full survey will target about three quarters of the potential fields.

high dimensional chemical space ($C-$space). In principle, we can hope to reconstruct where some stellar families were born, and how they have become dispersed throughout the Galaxy.

Arguably, the most interesting target is the thick disk believed to be more than 10 Gyr old. Of all components, we predict that the thick disk will carry the strongest signature of chemical tagging. The thick disk has a very well defined enhancement in $\alpha$/$\text{Fe}$ at all metallicities \cite{Bensby2014}. This is important because it means the stars were likely born in high pressure, bursty star-forming regions \cite{Aalto1995}. Massive star clusters have been observed in high-pressure turbulent disks at high redshift although their association with the thick disk is uncertain \cite{Lehnert2014}. Direct evidence of enhanced $\alpha$/$\text{Fe}$ ratios under starburst conditions comes from the small fraction of metals detected in x-ray winds from these environs \cite{Martin2002}.

This has two consequences for chemical tagging: the initial cluster mass function (ICMF) is flatter in starburst environs meaning that there are fewer low mass clusters, and the extreme clusters tend to be more massive than found in more quiescent environments. Both of these conspire to make the tagging signal stronger in the thick disk, at least in our models. The quiescent outer regions of the thin disk are characterised by in situ formation of smaller star clusters \cite{Larsen2009}.

We now investigate the expected number and size of clusters in the abundance space $C$ for different Galactic components in an observational survey like GALAH. Specifically, we investigate as to how the ICMF slope $\gamma$ and the maximum cluster mass $m_{\text{max}}$ affects our ability to detect clusters in abundance space.
2 Method

The Galaxy is modelled as consisting of the thin disk $^{[2]}(2.15 \times 10^{10} \, M_\odot)$, the thick disk $(3.91 \times 10^9 \, M_\odot)$, the stellar halo $(7.6 \times 10^8 \, M_\odot)$ and the bulge. Depending upon the geometry and the magnitude limits of the survey, different surveys will sample different fractions of the galaxy. Let $f_{\text{sample}}$ be the fraction of stars of a Galactic population that is randomly sampled by the survey. Let $M_{\text{pop}}$ be the actual stellar mass of the population, $m_\ast$ is the mean mass of stars for a given IMF (here assumed to be 0.42) and $f_{\text{mix}}$ is the fraction of mass of the population that can contribute stars to the survey volume. Then

$$f_{\text{sample}} = \frac{N_{\text{pop}}}{f_{\text{mix}}M_{\text{pop}}/m_\ast}$$ (2.1)

The factor $f_{\text{mix}}$ is the fraction of mass of the population that can contribute stars to the survey volume. If stars are uniformly mixed over the whole galaxy then $f_{\text{mix}} = 1$. More realistically, we assume stars born in an annulus of width $\Delta R$ around the Sun such that

$$f_{\text{mix}} = \frac{\int_{R_0-\Delta R/2}^{R_0+\Delta R/2} \Sigma(R)2\pi RdR}{M_{\text{pop}}}.$$ (2.2)

In practice, $\Delta R$ is never zero because orbit families develop radial excursions during their lifetime. To accommodate radial excursions, we assume $f_{\text{mix}}$ lies in the range 0.25 to 1. For GALAH we have $N_{\text{survey}} = 10^6$ stars. We simulate the selection function using the Galaxia code[Sharma et al. 2011] and find that 24% are thick disk stars and 75% are from the thin disk; 16% of stars are within 500 pc, half are within 1 kpc and 85% within 2.5 kpc.

3 The initial cluster mass function

The stars are assumed to be born in clusters and their ICMF is modeled as a power law[Elmegreen & Efremov 1997] The cumulative distribution is given by

$$\xi(>x|\gamma,x_{\text{min}},x_{\text{max}}) = \left(\frac{x_{\text{max}}^{1+\gamma} - x_{\text{min}}^{1+\gamma}}{x_{\text{max}}^{1+\gamma} - x_{\text{min}}^{1+\gamma}}\right)\left(\frac{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}}{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}}\right)$$ (3.1)

with $-2.5 < \gamma < -1$, and size $x$ is in the range $x_{\text{min}}$ to $x_{\text{max}}$. The mean cluster size is then

$$\bar{x} = \int_{x_{\text{min}}}^{x_{\text{max}}} x\xi(x)dx = \left(\frac{1 + \gamma}{2 + \gamma}\right)\left(\frac{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}}{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}}\right)$$ (3.2)

The low disk estimate is from the Besançon model which we use for consistency here; our new models presented elsewhere have updated most of the Besançon parameters.
The full cumulative distribution of the number of clusters above a certain size $x$ is given by

$$N(> x | \gamma, x_{\text{min}}, x_{\text{max}}) = \frac{M_{\text{mix}}/m_*}{\bar{x}(\gamma, x_{\text{min}}, m)_{\text{max}}} \left( \frac{x_{\text{max}}^{1+\gamma} - x_{\text{min}}^{1+\gamma}}{x_{\text{max}} - x_{\text{min}}} \right) M_{\text{mix}}/m_* \left( \frac{2 + \gamma}{1 + \gamma} \right) \left( \frac{x_{\text{max}}^{1+\gamma} - x_{\text{min}}^{1+\gamma}}{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}} \right)$$

$$= \left( \frac{x_{\text{max}}^{1+\gamma} - x_{\text{min}}^{1+\gamma}}{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}} \right) (2 + \gamma) \left( \frac{x_{\text{max}}^{1+\gamma} - x_{\text{min}}^{1+\gamma}}{x_{\text{max}}^{2+\gamma} - x_{\text{min}}^{2+\gamma}} \right) M_{\text{mix}}/m_* \left( \frac{2 + \gamma}{1 + \gamma} \right)$$

4 Predictions for cluster size distribution

Given $M_{\text{pop}}, f_{\text{mix}}, \gamma, x_{\text{min}}, x_{\text{max}}$ and $N_{\text{survey}}$, the number of clusters as function of size $n$ in survey is given by $N(> n/f_{\text{sample}} | \gamma, x_{\text{min}}, x_{\text{max}})$. As a concrete example, we predict the number of groups in thick disk that can be seen by GALAH. Here $N_{\text{survey}}^{\text{pop}} = 2.3 \times 10^5$ stars, $M_{\text{pop}} = 3.9 \times 10^9 M_{\odot}$.

In Fig. 2, we show the cumulative distribution of clusters as a function of their size in the survey. Each panel shows results for four different values of $\gamma$. The panels differ in the values of $f_{\text{mix}}, N_{\text{survey}}$ and $x_{\text{max}}$. It can be seen that if $f_{\text{mix}}$ is large we get fewer big clusters (top two panels). If $x_{\text{max}}$ is small, we expect fewer big clusters. If $\gamma$ is small we expect to see a larger number of big clusters.

The bottom right panel shows that if the number of survey stars is decreased by a factor of 10, this dramatically reduces the chances of detecting groups with size greater than $\leq 10$.

In Fig. 3, we show the case for all stars. Here $N_{\text{survey}}^{\text{pop}} = 10^6$ stars, $M_{\text{pop}} = 2.55 \times 10^{10} M_{\odot}$. The total number of clusters increase but the maximum size of clusters is smaller. This is because as compared to the thick disk case the ratio $N_{\text{survey}}^{\text{pop}}/M_{\text{pop}}$ is smaller.

5 Survey simulations

The primary motivation for the GALAH survey is the chemical tagging experiment described in §4. Our goal is to identify debris of disrupted clusters and dwarf galaxies. We assume here that all of the disrupted objects whose orbits pass through a $\pm 1$ kpc-wide annulus around the Galaxy at the solar circle are represented within the observable horizon. Simulations show that a random sample of a million stars with $V < 14$ will allow detection of about 20 thick disk dwarfs from each of about 3000 star formation sites, and about 10 thin disk dwarfs from each of about 30,000 star formation sites ([Bland-Hawthorn & Freeman 2004]).

Even a few rare outliers will be enormously valuable for tracking stellar migration over cosmic time. The specific example of the Solar Family is discussed elsewhere ([Bland-Hawthorn et al. 2010a]) and the first searches have already started ([Liu et al. 2015]).

The simulated numbers above depend on the details of the initial cluster mass function of the disrupted objects and its mass range. Let us assume the ICMF to be a power law specified by minimum mass $x_{\text{min}}$, maximum mass $x_{\text{max}}$ and power
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Fig. 2. Cumulative distribution of number of clusters as a function of cluster size for a simulated thick disk.

Fig. 3. Cumulative distribution of number of clusters as a function of cluster size for all stars, i.e. both thin and thick disk stars.
law index $\gamma$. Our expectation is that the thin disc has a steep ICMF (large $\gamma$) and low $x_{\text{max}}$ typical of a quiescent star formation history; the thick disk will have a shallower ICMF (small $\gamma$) and large $x_{\text{max}}$ representative of the turbulent high-pressure discs seen at high redshift. The size of the GALAH survey is selected to probe the slope $\gamma$ and $x_{\text{max}}$ of the ICMF.

We simulate the GALAH survey based on the Galaxia code (Sharma et al. 2011) and then applied a simple analytical prescription for generating stellar clusters. Fig. 4 shows the number of unique clusters identified in this simulated survey as a function of initial cluster mass. Setting the minimum requirement of ten member stars for a reliable identification of a cluster, we calculate the threshold cluster mass (i.e. the lowest-mass cluster we expect to recover ten stars from) as $M_{\text{thresh}} = 10 \times (M_{\text{pop}} \times f_{\text{mix}})/(f_{\text{pop}} \times N)$, where $M_{\text{pop}}$ is the total mass of the Galactic population (thin or thick disc), $N$ is the number of stars in the survey and $f_{\text{pop}}$ is the fraction of stars in the survey that belong to the population. The $f_{\text{mix}}$ is the fraction of star forming mass of the population that lies within the survey volume. If there is no mixing $f_{\text{mix}} = M'_{\text{pop}}/M_{\text{pop}}$, with $M'_{\text{pop}}$ being the physical mass of the population enclosed within the survey volume. If mixing is maximal, i.e., stars born anywhere within the Galaxy can lie in the survey volume, then $f_{\text{mix}} = 1$. For the thick disc, $M_{\text{pop}} = 3.9 \times 10^9 M_\odot$ and $f_{\text{pop}} = 0.236$, which means that $M_{\text{thresh}} = 4.2 \times 10^4 M_\odot$ for $N = 10^6$ and we assume $f_{\text{mix}} = 0.25$. Clusters with initial masses below $4.2 \times 10^4$ are outside the detection limits of the survey as noted by the green shaded region. Less efficient radial mixing brings stars from a smaller number of clusters into our survey volume, moving all of these thresholds toward lower mass and making cluster identification easier.

In Fig. 4 the red dots show the cluster masses from which we would expect to recover 20 stars (points on the left) and 40 stars (points on the right) in a million-star survey, and the number of such clusters we would expect to find if $x_{\text{max}}$ is $2 \times 10^5$ (blue curve) or $1 \times 10^6$ (green curve). The red error bars show $2\sigma$ Poisson uncertainty on the number and on the size of the recovered groups. We see that a smaller survey size would mean fewer stars per formation site, from a similar number of formation sites, and severely limit the range of cluster masses over which we can explore the ICMF.

The above calculations assume that clustering exists in chemical abundance space and that the clusters are well separated and observational errors are small enough ($<0.1$ dex) such that they can be detected by clustering algorithms. In reality, the detectability of clusters in C-space depends upon the dimensionality of this space, the intercluster separation and the observational uncertainties on abundance measurements. These questions can only be answered with a large enough data set that has been homogeneously analysed, such as the GALAH survey data.

6 Discussion

The argument for a million star survey can be understood most simply as follows. Let us assume $x_{\text{max}}$ be the maximum mass of a cluster of some galactic population
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Fig. 4. The number of clusters recovered from a simulated GALAH survey as a function of initial cluster mass. The green, dark blue and light blue shaded regions are the ranges of initial cluster mass accessible to surveys with $10^6$, $5 \times 10^5$ and $2.5 \times 10^5$ stars, respectively. The red dots show the cluster masses from which we expect to recover 20 stars (points on left) and 40 stars (points on right) in a million-star survey, and the number of such clusters we would expect to find if $x_{\text{max}}$ is $2 \times 10^5$ (blue curve) or $1 \times 10^6$ (green curve). The red error bars show the $\pm 2\sigma$ uncertainty on the number and size of the recovered groups. The top curves are for a starburst; the bottom curves are for quiescent star formation.

The size of this cluster in the GALAH survey will then be

$$ n = x_{\text{max}} \frac{f_{\text{pop}} N_{\text{survey}}}{f_{\text{mix}} M_{\text{pop}}} $$

(6.1)

For $f_{\text{mix}} = 0.1$, $f_{\text{pop}} = 1.0$ and $M_{\text{pop}} = 2.5 \times 10^{10} M_\odot$, i.e., considering the whole galaxy, we have

$$ n = 4 \frac{x_{\text{max}}}{10^4 M_\odot} \frac{N_{\text{survey}}}{10^6} $$

(6.2)

So we need $N_{\text{survey}}$ to be large so as to observe at least groups of size 10 or more.

Finally, two factors make it easier to detect groups in thick disc. First, the $\gamma$ is probably higher for the thick disc (-1.5) compared to the thin thin disc ($\leq -2$). Secondly, the maximum intrinsic size of groups $x_{\text{max}}$ is probably also higher for
thick disc. Both these effects imply that we will have more large groups for thick disc. Additionally, the ratio \( f_{\text{pop}} N_{\text{survey}} / M_{\text{pop}} \) is also higher for thick disc which also helps. This ratio is purely determined by the selection function and geometry of the survey.

The question remains as to how well we can effectively isolate thick disk stars in the GALAH survey. We will attempt a selection based on \( \alpha/\text{Fe} \) but also explore kinematic selection, and their combination. A differential comparison of the \( C \)-spaces for the thick and thin disk datasets may be the most direct route to confirming that higher levels of clumping exist in the thick disk [Bland-Hawthorn et al. 2010b]

Our model is somewhat independent of how the disk formed in that we do not need to specify whether the star formation was external or internal to the Galaxy\(^2\). In principle, some part of the thick disk may have formed through in situ turbulent processes [Lehnert et al. 2014]. If the thick disk was formed through accretion, it may be possible to detect a flattened dark-matter component, although this would be difficult to separate from the baryonic component and the dark halo. The process of accretion may indeed have flung open (and globular) clusters into the halo and the bulge [Kruisjes et al. 2012] a signature we can look for in the next few years using both Gaia kinematics and chemical tagging. These will be chemically distinct from star clusters formed in low-mass dwarf galaxies since most dwarfs have mean metallicities well below \([\text{Fe/H}]=-1\).

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\(^2\)For future reference, ‘exogenous’ and ‘endogenous’ may be useful adjectives for describing a process, e.g. star formation, that is external or internal to a system.