Chemo-kinematics of the Milky Way from the SDSS-III MARVELS survey

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ABSTRACT
Combining stellar atmospheric parameters, such as effective temperature, surface gravity, and metallicity, with barycentric radial velocity data provides insight into the chemo-dynamics of the Milky Way and our local Galactic environment. We analyse 3075 stars with spectroscopic data from the Sloan Digital Sky Survey III MARVELS radial velocity survey and present atmospheric parameters for 2343 dwarf stars using the spectral indices method, a modified version of the equivalent width method. We present barycentric radial velocities for a sample of 2610 stars with a median uncertainty of 0.3 km s\(^{-1}\). We determine stellar ages using two independent methods and calculate ages for 2335 stars with a maximum-likelihood isochronal age-dating method and for 2194 stars with a Bayesian age-dating method. Using previously published parallax data, we compute Galactic orbits and space velocities for 2504 stars to explore stellar populations based on kinematic and age parameters. This study combines good ages and exquisite velocities to explore local chemo-kinematics of the Milky Way, which complements many of the recent studies of giant stars with the APOGEE survey, and we find our results to be in agreement with current chemo-dynamical models of the Milky Way. Particularly, we find from our metallicity distributions and velocity–age relations of a kinematically defined thin disc that the metal-rich end has stars of all ages, even after we clean the sample of highly eccentric stars, suggesting that radial migration plays a key role in the metallicity scatter of the thin disc. All stellar parameters and kinematic data derived in this work are catalogued and published online in machine-readable form.

Key words: techniques: radial velocities – techniques: spectroscopic – surveys – stars: fundamental parameters – stars: kinematics and dynamics – Galaxy: kinematics and dynamics.

1 INTRODUCTION
Studying the positions, kinematics, and chemical compositions of Galactic stars allows insight into the formation and evolution of the Milky Way (e.g. Majewski 1993; Freeman & Bland-Hawthorn 2002; Nordström et al. 2004; Rix & Bovy 2013). Specifically, obtaining precise stellar atmospheric parameters and absolute (barycentric) radial velocities for stars in the local solar neighbourhood is critical in understanding our Galactic environment. Solar-type stars are ideal for investigating the chemical evolution of the solar neighbourhood and the overall Galaxy as their atmospheric compositions remain relatively unchanged during their long lifetimes, allowing investigation into a substantial fraction of the Milky Way history. Combining these data with stellar radial velocities generates information on the chemo-dynamics of stars and ongoing processes in the Galaxy. In addition, obtaining kinematic and atmospheric information of the host stars of extrasolar planets is crucial to understanding the varying conditions in which planets can form and survive.

Recently, large surveys using multifibre spectrographs have helped to illuminate the history of the Milky Way and characterize large populations of stars. Specifically, the Sloan Digital Sky Survey (SDSS; York et al. 2000) and its legacy surveys have produced
several large-scale spectroscopic studies designed to precisely characterize large populations of stars and the Milky Way structure and evolution. The Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009) and its continuation SEGUE-2 investigated the Milky Way structure by observing over 358,000 stars covering 2500 deg² of sky with a spectral resolution of \( R = \lambda / \Delta \lambda \approx 1800 \). In order to gain insight into the Galaxy dynamical structure and chemical history, the Apache Point Observatory Galactic Evolution Experiment (APOGEE; Majewski et al. 2017) observed over 100,000 evolved late-type stars spanning the Galactic disc, bulge, and halo with a spectral resolution of \( R \approx 22,000 \) in the infrared (1.51–1.70 \( \mu \)m).

Here, we study stellar kinematics and characteristics using spectra from the Sloan Digital Sky Survey III (SDSS-III; Eisenstein et al. 2011) Multi-object APO Radial Velocity Exoplanet Large-area Survey (MARVELS; Ge et al. 2008) taken with the SDSS 2.5-m telescope at the Apache Point Observatory (Gunn et al. 2006). MARVELS used a fibre-fed dispersed fixed delay interferometer (DFDI) combined with a medium resolution (\( R \sim 11,000 \); Ge et al. 2009) spectrograph to observe \( \sim 5500 \) stars with a goal of characterizing short-to-intermediate period giant planets in a large and homogenous sample of stars. The MARVELS survey complements APOGEE in that it focused on observing FGK dwarf stars in the optical (5000–5700 Å) rather than red giants in the infrared. Grievès et al. (2017) compare the latest MARVELS radial velocity set from the University of Florida Two Dimensional (UF2D; Thomas 2015) data processing pipeline to previous MARVELS pipeline results, while Alam et al. (2015) present an overview of previous MARVELS data reductions.

We present a new radial velocity data set from the MARVELS survey using an independent spectral wavelength solution pipeline (Thomas 2015). The wavelength solutions from this new MARVELS pipeline allow determination of absolute radial velocities. These measurements can produce accurate Galactic space velocities when parallax and proper motion measurements are available, especially in view of the recent second Gaia data release (Gaia DR2; Gaia Collaboration 2018). We present space velocities when these data are available. We also derive stellar atmospheric parameters (\( \log g, T_{\text{eff}}, \) and \( [\text{Fe/H}] \)) as well as mass and radius values for the dwarf stars in our sample using spectral indices (specific spectral regions combining multiple absorption lines into broad and blended features). Ghezzi et al. (2014) used the spectral indices method to obtain accurate atmospheric parameters for 30 stars using MARVELS spectra. We extend this work using the spectral indices method to determine atmospheric parameters of all MARVELS dwarf stars with robust spectra in the latest University of Florida One Dimensional (UF1D) pipeline (Thomas et al. 2016).

In Section 2, we describe the spectral indices method and its application to the MARVELS spectra. In Section 3, we present our atmospheric parameters for MARVELS dwarf stars, compare these results to previous surveys, and provide our dwarf and giant star classifications. We describe our method to obtain absolute radial velocities, and compare these values to previous surveys in Section 4. In Section 5, we determine Galactic space velocities and Galactic orbital parameters for our absolute radial velocity stars that have external parallax and proper motion values. In Section 6, we determine ages for a sample of our stars. In Section 7, we present the distances for our sample. In Section 8, we discuss our results and investigate the Galactic chemo-kinematics of these stars and distributions of their metallicities, ages, and other characteristics. In Section 9, we summarize our conclusions.

2 THE SPECTRAL INDICES METHOD

As is the case for many recent large-scale spectroscopic surveys such as SEGUE, APOGEE, the RAdial Velocity Experiment (RAVE; Steinmetz et al. 2006), or the LAMOST Experiment for Galactic Understanding and Exploration (LEGUE; Zhao et al. 2012), MARVELS operates at a moderate spectral resolution to obtain a larger sample than would be possible with higher resolution instruments. However, accurate stellar characterization and atmospheric parameters are difficult to obtain with moderate resolution spectra because spectral features are subject to a high degree of blending. This severe blending of atomic lines and spectral features renders it unfeasible to perform classical spectroscopic methods, e.g. Sousa (2014), which depend on measurements of the equivalent widths (EWs) of individual lines. Therefore, many surveys with low to moderate resolution have employed the spectral synthesis technique to obtain atmospheric parameters such as SEGUE (Lee et al. 2008; Smolinski et al. 2011), APOGEE (García Pérez et al. 2016), RAVE (Kunder et al. 2017), and LAMOST (Wu et al. 2011, 2014). However, as detailed in Ghezzi et al. (2014) the spectral synthesis method has a number of drawbacks, including a dependency on the completeness and accuracy of atomic line data bases, the need to accurately determine broadening parameters (instrument profile, macroturbulence, and rotational velocities), and parameters are often more correlated than results obtained from classical model atmosphere analysis.

Ghezzi et al. (2014) developed the spectral indices method as an alternative approach to the spectral synthesis technique to obtain accurate atmospheric parameters for low to moderate resolution spectra. Spectral indices are specific spectral regions that have multiple absorption lines formed by similar chemical species blended into broad features. Ghezzi et al. (2014) specifically selected indices that are dominated by either neutral iron-peak species or ionized species, which have properties that allow the determination of \( T_{\text{eff}}, [\text{Fe/H}], \) and \( \log g \). Ghezzi et al. (2014) selected 96 potential indices (80 dominated by neutral iron-peak species and 16 dominated by ionized species) through detailed inspection of FEROS Gaia spectra (Ribas et al. 2010) over the wavelength range 5100–5590 Å at both the original resolution (\( R \sim 48,000 \)) and sampling and spectra downgraded to mimic the MARVELS resolution (\( R \sim 11,000 \)) and sampling.

After initial spectral indices were identified, Ghezzi et al. (2014) calibrated and validated the spectral indices method while simultaneously creating a pipeline for MARVELS spectra, which involved four steps: continuum normalization, EW measurement, calibration construction, and atmospheric parameter determination. The normalization process was automated for MARVELS spectra and uses reduced, defringed, 1D Doppler-corrected spectra as input and fits a number of 1D Legendre polynomials to the continuum points of each spectra.

Normalized spectra are input for the next step, which measures the EWs for specified indices by direct integration of their profiles. Ghezzi et al. (2014) created a set of calibrations that allow characterization of atmospheric parameters based solely on spectral indices through a multivariate analysis of both measured EWs of the spectral indices and precise atmospheric parameters (\( T_{\text{eff}}, [\text{Fe/H}], \) and \( \log g \)) derived from detailed and homogeneous high-resolution spectra for a set of calibration stars; four spectral indices were removed during this calibration determination due to poor fitting of these features.

The final code in the pipeline determines atmospheric parameters and their associated uncertainties using the measured EWs and the previously determined calibrations. Atmospheric parameters
are measured based on the minimization of the reduced chi-square between measured EWs and theoretical EWs that were calculated for each point of a 3D grid of atmospheric parameters in the following intervals: 4700 K \leq T_{\text{eff}} \leq 6600 K, with 10 K steps; \(-0.90 \leq \log g \leq 2.70\), with 0.02 dex steps; and 3.50 \leq \log g \leq 4.70, with 0.05 dex steps. For details on the spectral indices pipeline and method, see section 4 of Ghezzi et al. (2014).

Finally, Ghezzi et al. (2014) tested the method specifically for MARVELS with a validation sample of 30 MARVELS stars that had high resolution spectra obtained from other instruments and subsequent high-resolution analysis of atmospheric parameters. Each MARVELS star has two sets of spectra due to the interferometer which creates two ‘beams’. Each set of spectra is analysed separately and two sets of parameters for each star are combined using a simple average and uncertainties are obtained through an error propagation. During the MARVELS validation process, Ghezzi et al. (2014) found that only 64 of the 92 indices produced accurate atmospheric parameters. The final average offsets and 1σ Gaussian dispersions (standard deviations) obtained by Ghezzi et al. (2014) using these 64 indices for atmospheric parameters of 30 stars obtained from the spectral indices method with MARVELS spectra compared to high-resolution analysis are \(-28 \pm 81\) K for \(\Delta T_{\text{eff}}\), 0.02 \pm 0.05 for \(\Delta \log g\), and \(-0.07 \pm 0.15\) for \(\Delta \log g\).

3 ATMOSPHERIC PARAMETERS

This work uses input spectra that were pre-processed by the newest UF1D pipeline (Thomas 2015; Thomas et al. 2016), while Ghezzi et al. (2014) used input spectra that were pre-processed with the older CCF+DFDI MARVELS pipeline released in the SDSS DR11 (Alam et al. 2015). This new process was previously described in Grieves et al. (2017), who obtained stellar parameters for 10 brown dwarf host stars. Here, we obtain similar results as Grieves et al. (2017) when analysing the Ghezzi et al. (2014) 30 MARVELS validation stars with the newest UF1D input spectra; the results are displayed in Fig. 1: \(-28 \pm 84\) K for \(\Delta T_{\text{eff}}\), 0.00 \pm 0.06 for \(\Delta \log g\), and \(-0.02 \pm 0.16\) for \(\Delta \log g\). We note a possible systematic trend in \(\log g\) when compared to high-resolution results in Fig. 1, which may affect parameters derived using this data such as stellar ages and distances. We discuss possible affects further in Section 6.

We determine the mass \((M_\star)\) and radius \((R_\star)\) of each star from \(T_{\text{eff}}, [\text{Fe/H}],\) and \(\log g\) using the empirical polynomial relations of Torres, Andersen & Giménez (2010), which were derived from a sample of eclipsing binaries with precisely measured masses and radii. We estimate the uncertainties in \(M_\star\) and \(R_\star\) by propagating the uncertainties in \(T_{\text{eff}}, [\text{Fe/H}],\) and \(\log g\) using the covariance matrices of the Torres et al. (2010) relations (kindly provided by G. Torres). Approximate spectral classifications were determined from a star’s \(T_{\text{eff}}\) and its associated spectral type in table 5 of Pecaut & Mamajek (2013).

3.1 MARVELS target selection

A detailed knowledge of survey target selection and biases is required to investigate Galactic chemo-kinematics with survey data. We do not account for the selection function in this work, but here we give an overview of the MARVELS target selection, which mainly consists of FGK dwarf stars ideal for radial velocity planet surveys with ~24 per cent giant stars observed as well.

The MARVELS target selection process is described by Paegert et al. (2015). Each MARVELS field consists of a circular field of view of 7 deg² with 60 stars selected for observation. The MARVELS survey observed 92 fields for a total of 1565 observations between 2008 October and 2012 July. Optical fibres for the instrument were changed in 2011 January and thus observations for MARVELS are divided into two different phases before and after this time, the ‘initial’ (Years 1–2) and ‘final’ (Years 3–4) phases, respectively. Due to ineffective giant star removal with the initial target selection process, the two phases consist of different target selection methods. MARVELS observed 44 fields in the initial phase and 48 fields in the final phase, with three fields overlapping both phases.

Of the 92 plates in the overall MARVELS survey, only 56 plates were robustly observed 10 or more times, consisting of 3360 stars (60 stars per plate). We did not run 278 of these 3360 stars through...
the spectral indices pipeline due to various observational problems with these stars causing poor or missing observations for the majority or all observations. These issues include dead fibres, misplugged fibres, spectra suggesting the star is a spectroscopic binary, or unreasonable photon errors. This culling leaves 3082 stars (including seven duplicates) that were run through the spectral indices pipeline. For the duplicated stars, we use the average of the values from both plates to create one set of atmospheric parameters, creating a sample of 3075 unique stars.

For the 56 fields used in this study, 43 are from the initial phase and 13 are from the final phase with three initial phase fields observed in years 3–4 as well. The target selection methods for both phases were designed to observe FGK dwarfs with $7.6 \leq V \leq 13.0$, $3500 < T_{\text{eff}} \leq 6250$ K, and $\log g > 3.5$, and six (10 per cent) giant stars were selected for each field.

Both MARVELS phases used the GSC 2.3 and 2MASS catalogues to select the 1000 brightest $V$ magnitude stars for each target field that were optimal for the survey. This included only stars in the MARVELS magnitude limits ($7.6 \leq V \leq 13.0$), stars that were not clearly too hot ($J - K_s \geq 0.29$), stars that were projected to be in the field for at least 2 yr, selecting brighter stars when stars were close together, and allowing $>5$ arcsec of separation from $V < 9$ stars (Paegert et al. 2015). The final 100 stars for each target field (60 plugged and 40 in reserve in case of collision with guide stars) were then selected by removing all but the six brightest giant stars, excluding hot stars ($T_{\text{eff}} > 6250$), and limiting F stars (3500 $\leq T_{\text{eff}} \leq 6250$ K) to 40 per cent of all targets in the field (Paegert et al. 2015). Close binaries and known variable stars were also removed. Many MARVELS fields contain radial velocity reference stars (with known planets or RV stable stars), which were exempt from the target selection algorithms.

The initial and final phase selection methods differ in the selection of the final 100 stars for each target field. The initial phase used a spectroscopic snapshot taken by the SDSS double spectrograph, mainly used for SEGUE, to derive $T_{\text{eff}}$, $\log g$, and [Fe/H] using a modified version of the SEGUE Stellar Parameter Pipeline (SSPP). These stellar parameters were used to perform the final cuts of removing giant and hot stars and limiting F stars; however, the SSPP pipeline misidentified cool giants as dwarfs causing a giant contamination rate of $\sim$21 per cent (Paegert et al. 2015). The final phase replaced the SSPP parameters method with a giant cut based on reduced proper motion, detailed in Section 3.3, and estimates of the effective temperatures using the infrared flux method (IRFM; Casagrande et al. 2010). Paegert et al. (2015) estimated the giant contamination rate for the final phase to only be 4 per cent, and including the 10 per cent of stars designated to be giants Paegert et al. (2015) estimated that 31 per cent of the stars in the initial phase are giants, while 14 per cent are giants in the final phase. MARVELS does not exclude subgiants ($3.5 \leq \log g \leq 4.1$) and they are included in the ‘dwarf’ sample.

The initial and final phases of the MARVELS survey also differed in target field selection. Target field selection for the initial phase was designed to find fields with radial velocity reference stars, fields without reference stars were chosen to provide large target densities of stars with $7.5 < V < 13$, and 11 fields were chosen such that they were centred on one of the 21 Kepler photometry fields. However, the final phase was required to share target fields with APOGEE, which placed the fields outside of the Galactic plane and required excluding stars if they were too close to APOGEE targets. This requirement caused the final phase stars to be dimmer on average, with a shift in the peak $V$ magnitude distribution from around 11.25 mag for the initial phase to 11.55 mag for the final phase (Paegert et al. 2015). Fig. 7 of Paegert et al. (2015) shows the distribution of the MARVELS target fields on the sky in Galactic coordinates. The 3075 stars considered in this study consist of 2367 stars in the initial phase (175 of which were also observed in the final phase with plates HD4203, HD46375, and HIP14810) and 708 stars in the final phase.

### 3.2 MARVELS main-sequence stellar sample

As stated in section 2.1 of Ghezzi et al. (2014), the spectral indices pipeline was optimized for dwarf stars. Giant stars have considerably different spectra from those of dwarfs and subgiants, and thus a proper analysis would require a different distinct set of spectral indices. Therefore, the parameters obtained for giant stars with this pipeline should not be considered reliable. The spectral indices pipeline was also optimized for a certain range of temperatures and metallicities. Specifically, the pipeline automatically flags any star with parameters that lie outside the range of 3.5 to 4.7 for $\log g$, 4700 to 6000 K for $T_{\text{eff}}$, or $-0.9$ to 0.5 for [Fe/H]. In our sample of 3075 stars, 535 were flagged including 510 outside the $\log g$ range and 35 outside the $T_{\text{eff}}$ range, leaving a total of 2540 stars. To further avoid unreliable stellar parameters we only present measurements for dwarf stars according to the definition from Ciardi et al. (2011), where a star is considered to be a dwarf if the surface gravity is greater than the value specified in the following algorithm:

$$\log g \geq \begin{cases} 3.5 & \text{if } T_{\text{eff}} \geq 6000 \text{ K} \\ 4.0 & \text{if } T_{\text{eff}} \leq 4250 \text{ K} \\ 5.2 - 2.8 \times 10^{-4} T_{\text{eff}} & \text{if } 4250 < T_{\text{eff}} < 6000 \text{ K}. \end{cases}$$

Of the 2540 stars with no flags, this algorithm designates 2343 stars as dwarfs. We set these 2343 stars as our final MARVELS main-sequence or dwarf stellar sample. Fig. 2 displays the distributions of $T_{\text{eff}}$, $\log g$, and [Fe/H] for this sample, which has median values of 5780 K for $T_{\text{eff}}$, 4.38 for $\log g$, and $-0.03$ for [Fe/H].

### 3.3 Comparison to RPM $J$ cut designations

Previous MARVELS studies (e.g. Paegert et al. 2015; Grieves et al. 2017) have used a $J$-band reduced proper motion (RPM$_J$) constraint to assign giant or dwarf/subgiant designations for stars in the MARVELS sample. RPM$_J$ values are computed as follows:

$$\mu = \sqrt{(\cos d \times \mu_r)^2 + \mu_c^2}$$

(1)

$$\text{RPM}_J = J + 5 \log(\mu),$$

(2)

where $J$ is the star’s 2MASS Survey (Skrutskie et al. 2006) $J$-band magnitude and $\mu_r$, $\mu_c$, and $d$ are Guide Star Catalog 2.3 (GSC 2.3; Lasker et al. 2008) proper motions in right ascension and declination (in arcseconds per year) and declination, respectively. An empirical RPM$_J$ cut described in Collier Cameron et al. (2007) is applied:

$$y = -58 + 313.42(J - H) - 583.6(J - H)^2,$$

$$+ 473.18(J - H)^3 - 141.25(J - H)^4,$$

(3)

where $H$ is the star’s 2MASS Survey $H$-band magnitude. Stars with RPM$_J \leq y$ are regarded as RPM$_J$-dwarfs and stars with RPM$_J > y$ as RPM$_J$-giants. Paegert et al. (2015) found this method to have a giant contamination rate of $\sim 4$ per cent and that subgiants are mixed with the ‘dwarf’ sample at a level of 20 per cent–40 per cent.
We compare the RPM$_J$ cut method to our designation based on the Ciardi et al. (2011) definition using both $T_{\text{eff}}$ and $\log g$ values. In our initial sample of 3075 stars, 2230 were classified as RPM$_J$ dwarf/subgiants and 845 as RPM$_J$ giants. Using the new Ciardi et al. (2011) definition, we designate 2358 stars as dwarfs and 717 as giants; including 692 giants in the 845 RPM$_J$ dwarf/subgiants and 2205 dwarfs in the 2231 RPM$_J$ dwarf/subgiant sample. The RPM$_J$ cut method is more likely to designate stars as giants, as 153 of the RPM$_J$ giant stars were designated as dwarfs, and only 25 RPM$_J$ dwarf/subgiant stars were designated as giants, which gives the RPM$_J$ cut method a $\sim 1$ per cent giant contamination rate. Fig. 3 shows the RPM$_J$ cut for our sample with Ciardi et al. (2011) designations in blue and red.

3.4 Comparison to other surveys

Of our sample of 2343 dwarf stars with atmospheric parameters, 206 are in the LAMOST DR2 data set, where the stellar parameters are estimated by the LAMOST pipeline (Wu et al. 2011, 2014). Fig. 4 compares results of these two surveys. Our results agree to the LAMOST results within the errors of both surveys. The offsets (MARVELS $-$ LAMOST) for the atmospheric parameters are $\Delta T_{\text{eff}} = 35 \pm 136$ K, $\Delta [\text{Fe/H}] = 0.00 \pm 0.09$, and $\Delta \log g = 0.09 \pm 0.24$.

We also compare our measurements to the latest Kepler stellar properties (DR25; Mathur et al. 2017). For the $T_{\text{eff}}$ and $[\text{Fe/H}]$ parameters, we compare our results to stars that have been spectroscopically analysed and given the highest priority by Mathur et al. (2017), with errors of $\sim 0.15$ dex for both $T_{\text{eff}}$ and $[\text{Fe/H}]$. A total of 112 stars are in common; the $T_{\text{eff}}$ and $[\text{Fe/H}]$ parameters in the Kepler data release are displayed in Fig. 5. The differences of these parameters are within expected errors of both surveys with offsets (MARVELS $-$ Kepler) of $\Delta T_{\text{eff}} = -47 \pm 115$ K and $\Delta [\text{Fe/H}] = -0.02 \pm 0.10$.

When comparing surface gravities to Kepler parameters we use stars that were derived from asteroseismology, which are the highest priority values for Mathur et al. (2017) with errors of $\sim 0.03$ dex for $\log g$. There are 91 overlapping stars in our sample with the Kepler asteroseismology surface gravities. Our results have a systematic offset of $\Delta \log g = -0.18 \pm 0.17$; however, this level of offset is often found between surface gravity results derived from spectroscopic means and asteroseismology (e.g. Mészáros et al. 2013; Mortier et al. 2014). We address this offset and present a correction in Section 3.4.1.

3.4.1 Asteroseismology surface gravity correction

Previous studies (e.g. Torres et al. 2012; Huber et al. 2013; Mészáros et al. 2013; Mortier et al. 2013, 2014; Heiter et al. 2015; Valentini et al. 2017) have demonstrated that surface gravity measurements derived from spectroscopic methods do not typically match higher quality measurements obtained from other non-spectroscopic meth-
Comparison between atmospheric parameters obtained from LAMOST and the MARVELS spectral indices method for the 206 stars in both samples. Mean errors on the plots show the mean of the errors for each survey for this specific sample of stars. Red dashed lines in the residuals show ±200 K for $T_{\text{eff}}$ and ±0.2 dex for [Fe/H] and log g. Offsets and standard deviations are $\Delta T_{\text{eff}} = 35 \pm 136$ K, $\Delta [\text{Fe/H}] = 0.00 \pm 0.09$, $\Delta \log g = 0.09 \pm 0.24$.

The correction may be applied if desired using equation (4) and the MARVELS log g and $T_{\text{eff}}$ values presented in this work.

### 3.5 Solar twins

Solar twins are special targets for investigating how our Sun and similar stars formed and evolved, and often solar twin samples allow for more precise determination of chemical abundances and fundamental parameters (e.g. Ramírez et al. 2014; Nissen 2015). As previously demonstrated, these stars can create a high-quality data set ideal for testing planet formation, stellar composition, and galaxy formation theory. Our MARVELS stars include a sample of ‘solar twins’ defined as those that have $T_{\text{eff,log g,}}$ and [Fe/H] inside the intervals ±100 K, ±0.1 [cgs], and 0.1 dex, re-
4.1 Wavelength solution

We derive absolute radial velocities (RVs) using the 1D wavelength-calibrated MARVELS spectra. We adopt a separate wavelength calibration technique that used to derive the UF1D relative RVs. The spectral processing and RV determination for the UF1D relative RVs are detailed in Thomas et al. (2016); wavelength solutions for each beam are based on single observations of ThAr spectra and manual calibrations using Image Reduction and Analysis Facility (IRAF; Tody 1993) software, which does not account for changes over time. Here, we use a completely autonomous wavelength calibration technique to derive wavelength solutions for individual observations. An overview of this technique is provided below, with full details described in Thomas (2015).

The moderate resolution ($R \sim 11000$) of the MARVELS instrument causes almost all visible spectral features to be blended. This blending precludes the determination of a wavelength solution by matching individual features to a known line list as might be possible at higher resolution. Individual stellar observation wavelength solutions are based on matching spectral features in MARVELS spectra to a high-resolution template spectrum convolved down to MARVELS resolution. The master template spectrum is based on a solar atlas obtained from the National Solar Observatory data archive convolved to the approximate resolution of MARVELS. We expect some errors in using a solar template to calibrate the range of stellar types and metallicities in this survey; however, this issue is manageable as all survey stars are FGK types and there is no source for actual high-resolution wavelength-calibrated spectra for each of the $\sim 3000$ stars in the survey.

Individual templates for each beam are created by cropping the master template to a beam’s approximate wavelength coverage determined from the ThAr calibrations. Significant spectral features that can be matched to the template are identified in each MARVELS spectra. Each feature’s centroid is determined resulting in $\sim 200$–300 unique features with pixel locations for each stellar spectrum; MARVELS spectra have $\sim 0.15$ Å pixel$^{-1}$. Several processing steps are used to roughly align the template spectrum to each observation and match features based on pattern recognition. Mismatched features are identified and discarded, and poor performing features not present in several observations or yielding varying results are rejected. These steps allow each feature and its corresponding pixel location to be assigned a precise rest wavelength from its matching template feature. Wavelengths are also corrected for Earth’s known barycentric velocity. These results are then interpolated to integer pixel locations across the CCD to yield the wavelength solution for each individual spectrum.

Tungsten Iodine (TIO) spectra are wavelength calibrated via the same technique using a high-resolution ($R = 200000$) TIO spectrum of the MARVELS iodine cell obtained at the Coudé fed spectrograph at Kitt Peak as a master template. Comparing the TIO calibration wavelength solution and the observed stellar solution yields the Doppler shift in wavelength, allowing absolute RV determination.

4.2 Radial velocities

RVs can be directly determined from the TIO and stellar wavelength solution via equation 5:

$$ RV = \frac{c (\lambda_{\text{TIO}} - \lambda_{\text{STAR}})}{\lambda_{\text{TIO}}} ,$$

where $c$ is the speed of light and $\lambda$ is wavelength. The mean value of equation (5) across all pixels is a single observation’s RV. A final absolute RV for each star is obtained by averaging the RVs of all observations from both beams. We obtain error estimates by calculating the rms of the mean-subtracted RVs for these observations. Previous studies (e.g. Holtzman et al. 2015) often consider stars exhibiting RV scatter on the level of $\sim 500$ m s$^{-1}$ to be RV variable. We remove likely RV variable stars from our sample as these RVs are likely unreliable. Considering our relatively large absolute RV error values for stable stars ($\sim 300$ m s$^{-1}$), we set an RV variability cut based on both absolute RV errors and RV rms values from our latest and more accurate (for relative velocities) UF2D pipeline, detailed in Thomas (2015) and Grieves et al. (2017). Stars exhibiting RV rms values greater than $500$ m s$^{-1}$ in both the UF2D RVs and absolute RVs are not presented. We plan to publish binary stars in an upcoming MARVELS binary paper. This $500$ m s$^{-1}$ cut removes 465 of the 3075 stars in our sample, leaving a final sample of 2610 stars with absolute RVs from MARVELS.

4.3 Zero-point offset

As detailed in previous studies, e.g. Nidever et al. (2002), barycentric RVs have several technical challenges that are not associated with obtaining relative RVs needed to identify planets and substellar companions. Barycentric RVs experience a gravitational redshift when leaving the stellar photosphere introducing spurious velocities. Barycentric RVs must also account for a transverse Doppler effect (time dilation), subphotospheric convection (granulation), macroturbulence, stellar rotation, pressure shifts, oscillations, and activity cycles, with granulation (convective blueshift) having the greatest effect on RV measurements (Nidever et al. 2002). As in previous studies, e.g. Nidever et al. (2002), Chubak et al. (2012), we correct for gravitational redshift and convective blueshift to first order by using the known RV of the Sun to set the zero-point for the stellar RV measurements. MARVELS obtained solar spectra by observing the sky during mid-day using the same fibre path from the
which is in agreement with the mean MARVELS error of these stars in Fig. 8. We also compare our RV results for stars overlapping to share the zero-point of Nidever et al. (2002). Table 1 presents Chubak et al. (2012) constructed a catalogue of absolute velocities. shows the final sample of MARVELS RVs along with their rms errors. 

The overall mean offset is 573 m s$^{-1}$ throughout the survey, which have a mean photon limit of 12.3 m s$^{-1}$ for all beams. The mean difference between solar RVs and the barycentric velocity are calculated given the time and location of each observation and we take a mean of all offsets for all beams. The overall mean offset is 573 m s$^{-1}$, which we set as our zero-point and subtract this value from all stellar RVs. Fig. 7 shows the final sample of MARVELS RVs along with their rms errors.

4.4 Comparison to previous surveys

Chubak et al. (2012) constructed a catalogue of absolute velocities to share the zero-point of Nidever et al. (2002). Table 1 presents 18 stars in our absolute RV MARVELS sample that overlap in the catalogue created by Chubak et al. (2012) using observations from the Keck and Lick observatories (only considering stars with more than one observation and errors presented in Chubak et al. 2012). These 18 stars have a mean offset of 0.044 ± 0.210 km s$^{-1}$, which is in agreement with the mean MARVELS error of these stars (0.416 km s$^{-1}$) and the mean error Chubak et al. (2012) assigned for these stars (0.124 km s$^{-1}$). The RVs of these 18 stars are displayed in Fig. 8. We also compare our RV results for stars overlapping in the RAVE DR5 catalogue and the LAMOST DR2 catalogue. A total of 36 stars in our sample overlap with the RAVE DR5 sample; the mean offset is 0.081 ± 2.141 km s$^{-1}$. The mean error of the 36 MARVELS RVs for these stars is 0.220 km s$^{-1}$ while the RAVE RVs have a mean error of 1.306 km s$^{-1}$. There are 195 stars in our RV sample that overlap with the LAMOST DR2 sample, which yield a mean offset of 3.5 ± 4.4 km s$^{-1}$; the MARVELS errors for this sample (mean error = 0.363 km s$^{-1}$) are significantly lower than the errors LAMOST assigns to their RV values for these stars (mean error = 17.054 km s$^{-1}$). The RVs of these overlapping RAVE and LAMOST stars are presented in Fig. 8.

5 KINEMATICS

5.1 Galactic space velocities

To understand the kinematic nature of a star, its Galactic space velocity components $U$ (radially inwards towards the Galactic Centre), $V$ (along the direction of Galactic rotation), and $W$ (vertically upwards toward the North Galactic Pole) can be calculated given a star’s proper motion, radial velocity, and parallax, e.g. Johnson & Soderblom (1987). Using parallax and proper motion values from the second Gaia data release (Gaia DR2; Gaia Collaboration 2018) and the Hipparcos mission (van Leeuwen 2007), we were able to obtain space velocity components for 2504 stars in our sample of
2610 stars with absolute radial velocities. The calculated space velocities \( (U_{LSR}, V_{LSR}, W_{LSR}) \) are related to the local standard of rest (LSR; the velocity of a fictional particle that moves around the plane of the Milky Way on the closed orbit in the plane that passes through the present location of the Sun) by adding Sun’s velocity components relative to the LSR \( (U_\odot, V_\odot, W_\odot) = (11.10, 12.24, 7.25) \) km s\(^{-1}\) from Schönrich, Binney & Dehnen (2010). We present the Galactocentric Cartesian coordinates \( x, y, z \) and Galactocentric radii \( R_{Gal} \) for stars with distance values using the Galactocentric PYTHON code developed by ASTROPY (The Astropy Collaboration 2018) assuming \( R_0 = 8.2 \) kpc for Sun’s distance from the Galactic Centre. Distances are determined from the available parallax data. We also computed Galactocentric velocities in a cylindrical reference frame. In this case, the velocities components are \( V_R \) (radial), \( V_\phi \) (rotational), and \( V_Z \) (vertical) defined as positive with increasing \( R \), \( \phi \), and \( Z \), with \( Z \) pointing towards the North Galactic Pole and \( V_Z = W_{LSR} \cdot V_R \) and \( V_\phi \) are computed as follows:

\[
V_R = \frac{(x \cdot U_{LSR} + y \cdot (V_{LSR} + v_{circ}^{\odot}))}{R_{Gal}} \quad (6)
\]

\[
V_\phi = -\frac{[x \cdot (V_{LSR} + v_{circ}^{\odot}) - y \cdot U_{LSR}]}{R_{Gal}}, \quad (7)
\]

where \( x \) and \( y \) are Galactocentric Cartesian coordinates, \( R_{Gal} \) is the Galactocentric radius \( R_{Gal} = \sqrt{x^2 + y^2} \), \( U_{LSR} \) and \( V_{LSR} \) are the associated space-velocity components in the Galactic cardinal directions relative to the LSR as described above, and \( v_{circ}^{\odot} = 238 \) km s\(^{-1}\) is the circular rotation velocity at Sun’s position, which is in line with recent estimates (e.g. Bland-Hawthorn & Gerhard 2016). We also compute the guiding-centre radius of a stellar orbit, which we computed using the approximation \( R_{guide} = \frac{V_\phi}{v_{circ}} \) similar to Anders et al. (2017a).

5.2 Galactic orbits

We determine Galactic orbits for each star using its full phase-space information: right ascension, declination, distance, proper motion, and radial velocity. We calculate orbits using the PYTHON module GALPY (Bovy 2015) assuming a standard Milky Way type potential consisting of an NFW-type dark matter halo (Navarro, Frenk & White 1997), a Miyamoto–Nagai disc (Miyamoto & Nagai 1975), and a Hernquist stellar bulge (Hernquist 1990), which achieves a flat rotation curve for the model Galaxy. We again assume \( R_0 = 8.2 \) kpc for Sun’s distance from the Galactic Centre and \( v_{circ}^{\odot} = 238 \) km s\(^{-1}\) for the circular rotation velocity at Sun’s position. We adopt the Schönrich et al. (2010) values for the solar motion with respect to the LSR \( (U_\odot, V_\odot, W_\odot) = (11.10, 12.24, 7.25) \) km s\(^{-1}\). The stellar motions are integrated with SCIPY routine odeint over 10 Gyr in 10 000 steps. From the integrated Galactic orbits, we are able to characterize the median orbital eccentricity \( e \), the median Galactocentric radius \( R_{med} \), and the maximum vertical amplitude \( z_{max} \). Galactocentric coordinates and orbit parameters along with Galactic space velocities are presented in the online catalogue.

6 STELLAR AGES

We derive stellar ages for a subset of our stars using both the isochrone method (e.g. Lachante et al. 1999), or the ‘maximum-likelihood isochronal age-dating method’, and the spectro-photometric distance code StarHorse (Queiroz et al. 2018), which is a ‘Bayesian age-dating method’. The maximum-likelihood isochronal age-dating method is inspired by the statistical approach used in Takeda et al. (2007). In order to ensure smooth age probability distributions, we adopted a fine grid of evolutionary tracks from Yonsei–Yale Stellar Evolution Code (Yi, Kim & Demarque 2003) with constant steps of 0.01 M/M_⊙ \( \leq 2.00 \), 0.05 dex (from \(-2.00 \) to \(+1.00 \) dex), 0.05 dex (from \(+0.00 \) to \(+0.40 \) dex) of mass, [Fe/H], and [α/Fe], respectively. In the framework of the Bayesian probability theory, the set of available input parameters (X) of each star is compared to its theoretical prediction given by the evolutionary tracks: \( \Theta \equiv (t, M/M_\odot, [Fe/H], [\alpha/Fe]) \). We arbitrate solar [α/Fe] for all sample stars with the exception of metal-poor stars ([Fe/H] ≤ \(-0.5\)) in which [α/Fe] = +0.3 is
assigned. The complete probability functions \( P(\Theta|X) \) along all possible evolutionary steps is defined by

\[ P(\Theta|X) \propto P(X|\Theta)P(\Theta). \] (8)

\( P(X|\Theta) \) is our likelihood function which is a combination of \( N \) Gaussian probability distributions of each input atmospheric parameter (\( v^\text{input} \)) together with its respective uncertainty (\( \sigma_j \)). In the cases where the trigonometric parallaxes are available we build a set of \( N = 4 \) input parameters given by \( X \equiv (T_{\text{eff}} \pm \sigma_{T_{\text{eff}}}, \log g \pm \sigma_{\log g}, \text{[Fe/H]} \pm \sigma_{\text{[Fe/H]}}, \log(L/L_\odot) \pm \sigma_{\log L/L_\odot}). \) The stellar luminosities are calculated with equations 2 and 7 of Andrae et al. (2018) using published Gaia DR2 G magnitudes, extinctions, and bolometric corrections. The luminosity errors are computed through \( 10^4 \) Monte Carlo simulations assuming Gaussian error distributions of parallax, photometry, and MARVELS \( T_{\text{eff}}. \) Alternatively, we restrict our approach to consider only \( T_{\text{eff}}, \log g, \) and \( \text{[Fe/H]} \) as input atmospheric parameters (\( N = 3 \)) for stars without distance information:

\[
P(X|\Theta) = \prod_{j=1}^{N} \frac{1}{\sqrt{2\pi} \sigma_j} \exp \left( -\frac{1}{2} \frac{x^2}{\sigma_j^2} \right), \]

where

\[
x^2 = \sum_{j=1}^{N} \left( \frac{v^\text{input}_j - v^\text{theoretical}_j}{\sigma_j} \right)^2.
\] (10)

\( P(X|\Theta) \) is the posterior probability function which is composed of a likelihood function and the combination of collapsed prior probability functions of mass, metallicity, and age (\( P(\Phi \equiv P(t) P(M/M_\odot) P(\text{[Fe/H]})) \)). The Salpeter-like IMF prior is \( P(\text{mass}) \propto \text{mass}^{-2.35} \) (Takeda et al. 2007) and the metallicity prior is the same used by Casagrande et al. (2011), also independent on the stellar age; see their appendix A). Conservatively, we choose to adopt uniform prior distribution for the stellar ages from 0 to 14 Gyr. We stress that the mass and metallicity priors used in this approach are independent of any further age assumptions. So, we consider that our results are suitable for Galactic chemo-kinematic analysis presented in the following sections of this paper. For each star, the posterior probability function is evaluated along every possible configuration in theoretical parameter space and integrated over all dimensions of \( \Theta \) but age:

\[
P(t) \propto \int_{\Theta} P(\Theta|X) \, d(M/M_\odot) \, d[\text{Fe/H}].
\] (11)

To save computational time, models older than 14 Gyr and outside \( \pm 4\sigma \) domain defined by the observational uncertainties are ruled out from our calculations. Other relevant probability distributions of stellar properties can be also estimated in parallel to the age derivation such as mass, radius, radius and gravity at zero/terminal age main sequence, and chance of the star being placed in the main-sequence or subgiant branch according to core H-exhaustion. We compute the mean age and the 5%, 16%, 50%, 84% and 95% percentiles from the age probability distribution. We use the mean value of the probability distribution as our final age value for the maximum-likelihood isochronal age-dating method and determine stellar ages for 2335 stars. We show the age error distribution for the isochrone method in Fig. 9.

We derive a second set of independent stellar ages as well as interstellar extinctions and distances using a Bayesian age-dating method with the StarHorse code. StarHorse uses a Bayesian approach that uses spectroscopic, photometric, and astrometric information as input to calculate the posterior probability distribution over a grid of stellar evolutionary models. The code has been extensively tested and validated for simulations and external samples, for a full description see Santiago et al. (2016) and Queiroz et al. (2018). This approach works similar to the maximum-likelihood isochronal age-dating method with the model parameters independent; the likelihood can also be written as in equation (9). The prior function used by StarHorse for MARVELS includes only spatial priors, as defined in Queiroz et al. (2018), as well as a Chabrier initial mass function (Chabrier 2003), and no metallicity prior on age. For MARVELS stars we use \( T_{\text{eff}}, \log g, \) and \( \text{[Fe/H]} \) parameters derived in this work as well as previously published \( BVIJKH \) magnitudes, Gaia DR2 G-band magnitudes and extinctions, and parallax values as the set of measured parameters to obtain estimates of mass, age, distance, and V-band extinction (\( A_v \)) using PARSEC 1.2S stellar models (Bressan et al. 2012; Tang et al. 2014; Chen et al. 2015). The PARSEC 1.2S stellar models employed in the calculation ranged in \([\text{M/H]}\) (from \(-2.2\) to 0.6 in steps of 0.02 dex) and in logarithmic age (from 7.5 to 10.13 in steps of 0.01 dex) delivering a broad range in the estimated ages.

We use the mean value of the outputted probability distribution from the StarHorse code as our final age values and determine ages using StarHorse for 2194 stars with atmospheric parameters, photometry, and parallax data. We also present the 5%, 16%, 50%, 84% and 95% percentiles of the age probability distribution for the StarHorse ages in the online catalogue. Fig. 9 shows the age error distribution for these stars. Effects of systematic offsets between observed quantities (such as atmospheric parameters) and age, distance, and extinction results are discussed thoroughly in Santiago et al. (2016) and Queiroz et al. (2018). Queiroz et al. (2018) found in general systematic errors affect estimated parameters typically less than \( \pm 10\% \) per cent. Notably our data may have a systematic offset in \( \log g \) values, which could have a significant effect on the StarHorse distance estimates (presented in Section 7), as \( \log g \) is the best parameter to discriminate between low-luminosity dwarfs and more luminous giants. Thus, an overestimate in \( \log g \) leads to an underestimate in the distances, and an underestimate in \( \log g \) leads to overestimating the distance. (Santiago et al. 2016; Queiroz et al. 2018).

We compare the age results from these two methods in Fig. 10 and find relatively good agreement between the two methods, which rely on different isochrones, with a mean offset (StarHorse-
Isochrone) of 0.52 Gyr (or 6.0%) and a dispersion 1.72 Gyr (or 32.4%) for the 2186 stars with ages from both methods, where the percentages correspond to the mean offset of 0.52 ± 1.72 Gyr. Coloured symbols show stars used for our analysis and results, where both methods agree within 2 Gyr and at least one method has an error estimate below 2 Gyr.

7 DISTANCES

Here, we briefly present the distances determined for our sample of MARVELS stars. We obtain distances for 2957 stars using parallax values from the Gaia and Hipparcos missions. We also computed distances using the StarHorse code described in Section 6, which account for interstellar extinction. However, as StarHorse is a statistical method, negative extinctions can arise when the photometry and the spectroscopic or astrometric parallax are slightly inconsistent. For these cases, the interstellar extinction cannot be constrained well. Using the StarHorse code on 2194 stars to compute distances and extinctions, 353 were found to have negative extinction. We do not present the distances or extinctions for these stars in Fig. 11, giving a sample of 1841 stars with StarHorse distances and interstellar extinctions. Fig. 11 displays interstellar extinction values obtained from the StarHorse code as well as distances from the StarHorse code and distances using only parallax values. Fig. 11 also displays the error distributions outputted from the StarHorse code and errors for parallax distances using propagation of error. For our results and analysis, we use the distances derived from parallax values.

8 RESULTS

In this section, we analyse the results of the various parameters derived in this study, which are summarized in Table 2. Previous studies revealed evidence that a sizable fraction of the geometrically defined thick disc is chemically different from the thin disc (e.g. Fuhrmann 2011; Navarro et al. 2011; Adibekyan et al. 2013; Bensby, Feltzing & Oey 2014), and most of the thick disc population is kinematically hotter than the thin disc, suggesting that the thin and thick disc have a different physical origin. Analyses of kinematic data also suggest that there are substantial kinematical substructures in the solar neighbourhood associated with various stellar streams and moving groups (e.g. Nordström et al. 2004; Bensby et al. 2014; Kushniruk, Schirmer & Bensby 2017), but whether these structures are of Galactic or extragalactic origin remains uncertain.

Kinematical substructures may be due to evaporated open clusters (e.g. Eggen 1996), dynamical resonances within the Milky Way (e.g. Dehnen 1998), or possibly from remnants of accreted satellite galaxies (e.g. Navarro, Helmi & Freeman 2004). Specifically, one moving group or dynamical stream creation mechanism may be the resonant interaction between stars and the bar or spiral arms of the Milky Way. For example, the Hercules stream could be caused by the Sun being located just outside the bar’s outer Lindblad resonance (Dehnen 2000). Nevertheless, kinematic groups retain information of various processes of the Milky Way past and allow insight into the formation of the Galaxy. We investigate the metallicity distributions and other properties of the kinematically defined thin and thick discs as well as the two kinematical substructures identified in our study, the Hercules stream and the Arcturus moving group.

8.1 Defining Populations

8.1.1 Kinematically defined populations

To assign stars to a population in the Galaxy (e.g. thin disc, thick disc, or halo), we first adopt a purely kinematic approach by following the method outlined by Bensby, Feltzing & Lundström (2003), Bensby et al. (2005), Bensby et al. 2014 and assume the stellar populations in the thin disc, the thick disc, and the halo (as well as other stars that may not be kinematically associated with the thin
where the factor \( V \) velocity dispersions and \( \sigma \) normalizes the expression.

The final probability is then determined by dividing a given population with their population designation based on their relative population distribution, and portrays a star’s total velocity, \( \nu_{\text{tot}} = (U^2_{\text{LSR}} + V^2_{\text{LSR}} + W^2_{\text{LSR}})^{1/2} \). Using total velocities allows rough approximations for population assignments where low-velocity stars (\( \nu_{\text{tot}} < 50 \text{ km s}^{-1} \)) are typically thin disc stars, stars with 70 km s\(^{-1} \) are likely thick disc stars, and stars with \( \nu_{\text{tot}} > 180 \text{ km s}^{-1} \) are likely halo stars (Nissen 2004; Bensby et al. 2014). Fig. 13 shows a Toomre diagram for our sample of 2504 stars with Galactic space velocities, with their population designation based on their relative population distribution. Of the 2504 stars in our sample, 1701 dwarfs and 543 giants are in the thin disc, 92 dwarfs and 25 giants are in between the thin and thick disc cut-offs, and 98 dwarfs and 45 giants are in the thick disc.

Our sample contains 1878 dwarfs with Galactic space velocities and measured atmospheric parameters. Fig. 14 shows the thick-to-thin disc probability ratios versus metallicities ([Fe/H]), and Fig. 15 displays the metallicity distributions for stars designated to the thick, thin/thick, or thin disc. The metallicity distributions in these three samples overlap, but a clear distinction in metallicity distribution is visible between the thick and thin disc stars.

### 8.1.2 Age-defined populations

We explore age-defined thin and thick disc populations using a 8 Gyr cut as prescribed by Haywood et al. (2013). We assign age-defined populations using the age probability distribution percentiles from 1125 stars with age errors less than 2 Gyr and where both methods agree within 2 Gyr. We define thin disc stars as having their 95th percentiles (age95) \(< 8 \text{ Gyr}, \) thick disc stars as having their 5th percentiles (age05) \( > 8 \text{ Gyr}, \) and thin/thick stars are those in between these two regimes. Fig. 16 displays the metallicity distri-
8.2 Kinematics and metallicities

Table 3 displays the median and quartile values of the kinematically defined thin and thick disc, which exhibit a clear separation in metallicity between these kinematically defined populations. The large metallicity dispersion in the thin disc can be explained by inward radial mixing of metal-poor and outward migration of metal-rich stars according to migration-based scenarios (Sellwood & Binney 2002; Roškar et al. 2008; Schönrich & Binney 2009; Minchev & Famaey 2010; Brunetti, Chiappini & Pfenniger 2011) as well as 'blurring' (i.e. wandering high-eccentricity stars passing in the local volume, but with \( R_{\text{guide}} \) outside the local snapshot of stars at the present time; Schönrich & Binney 2009; Minchev, Chiappini & Martig 2013). In Section 8.4.2, we examine the metallicity distribution for a blurring cleaned thin disc.

We also analysed the metallicity distributions of the other two kinematically identified population groups, which are displayed in Table 3. We find a large dispersion in the Arcturus stars; a metallicity homogeneity would suggest an origin from remnants of open clusters, but the lack of a clear chemical signature of the Arcturus stars indicates origins from dynamical perturbations within the Galaxy (e.g. Williams et al. 2009; Ramya, Reddy & Lambert 2012). All 19 of our Arcturus moving group candidate stars are designated to the thick disc. Arifyanto & Fuchs (2006) determined that the Arcturus group resided in the thick disc, and Bensby et al. (2014) found the general appearance (\( \alpha \)-abundance, age, and kinematics) to be similar to thick disc stars.

The large spread in metallicity of the Hercules stream is consistent with some previous studies (e.g. Raboud et al. 1998; Antoja et al. 2008) that reported large metallicity dispersions for this group. However, Arifyanto & Fuchs (2006) and Kushniruk et al. (2017) reported that the Hercules stream primarily resided in the thin disc. Bensby et al. (2014) measured the abundance trend of the Hercules stars to be similar to the inner disc (\( R_{\text{Gal}} = 4 \) to 7 kpc, \( R_{\text{Gal}} \equiv \) Galactocentric radius), but the stars lay between the inner and...
outer ($R_{\text{Gal}} = 9$ to $12$ kpc) disc. The net velocity component of
the Hercules stars is directed radially outwards from the Galactic
centre, suggesting origins at slightly smaller Galactocentric radii
(Bensby et al. 2014), which is consistent with previous speculations
that the Hercules stream stars originated in the inner parts
of the Galaxy where they were kinematically heated by the central
bar (e.g. Dehnen 2000). Our Hercules stream stars have seven
in the thin disc, two in the thin/thick disc, and eight in the thick
disc.

Using GALAH survey (De Silva et al. 2015) data of nearby stars,
Quillen et al. (2018) found that the Hercules stream is most strongly
seen in higher metallicity stars [Fe/H] $> 0.2$, and disagree with
previous studies that found no significant metallicity preference for
Hercules stream stars in the solar neighbourhood. However, we use
the (U,V,W) definitions for the population from Bensby et al. (2014).
As thoroughly discussed by Ramya et al. (2016), this definition
places the stream deeper among the thick disc stars, explaining the
large contribution from the thick disc and lower metallicity in our
proposed Hercules stream members.

The top of Fig. 17 displays total space velocities, $v_{\text{tot}}$, versus
metallicity to examine any possible trends. This figure reveals a
possible small correlation between the two properties, with higher
velocity stars likely having lower metallicity, as would be expected if
these stars are kinematically different than the sun. The blue squares
display the median values with first and third quartiles as error bars
for the data binned at 0.2 dex. Overall the metallicity and total space
velocity relationship appears relatively flat up to $\sim 50$ km s$^{-1}$
with a negative trend in metallicity from 50 to 200 km s$^{-1}$.

The bottom of Fig. 17 displays total space velocity dispersion versus
metallicity binned at 0.2 dex. We found the dispersion for each
bin by taking the standard deviation of the total space velocities
and required at least four stars for each bin. Errors for dispersion
were estimated by taking 1000 bootstrap realizations with replacement
for each [Fe/H] bin and taking the overall standard deviation of all the
standard deviations of each bootstrap as the error. We find that
the total space velocity dispersion decreases with higher metallicity
for thick disc stars, while the velocity dispersion for thin disc stars
is relatively flat, which is expected as our thin disc stars are selected
to be kinematically cooler.

Fig. 18 displays velocity dispersions for $V_Z$, $V_\phi$, and $V_R$ in 0.2 dex
bins of [Fe/H]. Using the Gaia-ESO Survey, Recio-Blanco et al.
(2014) examined velocity dispersions of FGK-type stars for their
chemically separated thin and thick populations and found velocity
dispersions are higher for the thick disc than the thin disc. Recio-
Blanco et al. (2014) found no significant dependence on either $\sigma_{V_Z}$
or $\sigma_{V_\phi}$ with metallicity, but that for the thick disc $\sigma_{V_\phi}$ may increase
with distance to the Galactic plane that is not visible for $\sigma_{V_Z}$. We
find that both the kinematically defined thin disc and all stars exhibit
a negative trend in $\sigma_{V_Z}$, $\sigma_{V_\phi}$, and $\sigma_{V_R}$ with increasing metallicity.
The kinematically defined thick disc displays a negative trend with
metallicity for $\sigma_{V_\phi}$ as well. Differences between our results and
those of Recio-Blanco et al. (2014) may arise from our sample
being in a very local volume, whereas Recio-Blanco et al. (2014)
is taking a larger volume where more stars from other radii are
included. Thus, the dispersion and [Fe/H] relations are likely very
dependent on sample selection. We also note that differences in our
results may arise from our kinematic population definitions, which

| Kin. Pop. | $N^*$ | Mean | $\sigma$ | $Pk$ | $Sk$ | $Md$ | $Q_1$ | $Q_3$ |
|-----------|-------|------|---------|------|------|------|-------|-------|
| Thin      | 1690  | $-0.01$ | 0.20 | 0.0  | $-0.25$ | $-0.01$ | $-0.14$ | 0.12 |
| Thin/thick| 91    | $-0.11$ | 0.23 | 0.0  | 0.16 | $-0.01$ | $-0.30$ | 0.05 |
| Thick     | 97    | $-0.31$ | 0.27 | $-0.5$ | 0.22 | $-0.34$ | $-0.51$ | $-0.10$ |
| Hercules  | 14    | $-0.26$ | 0.31 | $-0.1$ | $-0.32$ | $-0.10$ | $-0.49$ | $-0.05$ |
| Arcturus  | 13    | $-0.50$ | 0.19 | $-0.7$ | $-0.47$ | $-0.49$ | $-0.64$ | $-0.41$ |

| Age. Pop. | $N^*$ | Mean | $\sigma$ | $Pk$ | $Sk$ | $Md$ | $Q_1$ | $Q_3$ |
|-----------|-------|------|---------|------|------|------|-------|-------|
| Thin      | 851   | 0.01 | 0.20    | $-0.1$ | $-0.28$ | 0.01 | $-0.12$ | 0.14 |
| Thin/thick| 217   | $-0.04$ | 0.25 | $-0.1$ | $-0.20$ | $-0.03$ | $-0.25$ | 0.16 |
| Thick     | 57    | $-0.26$ | 0.27 | $-0.5$ | 0.05 | $-0.26$ | $-0.45$ | $-0.05$ |

Figure 17. Top: metallicity versus total space velocity, $v_{\text{tot}} = (U_{\text{LSR}}^2 + V_{\text{LSR}}^2 + W_{\text{LSR}}^2)^{1/2}$, for our sample of 1878 stars with kinematic and atmospheric parameters. Blue squares show the median values with first and third quartiles as error bars for the data binned at 0.2 dex. Bottom: metallicity versus total space velocity dispersion binned at 0.2 dex. Black symbols represent all stars, while red and blue symbols represent stars in the kinematically defined thin and thick disc, respectively. Errors were estimated using 1000 bootstrap realizations.
Figure 18. Metallicity versus velocity dispersion binned at 0.2 dex for velocity dispersions of $V_Z$, $V_\phi$, and $V_R$ (from top to bottom). Black symbols represent all stars, while red and blue symbols represent stars in the kinematically defined thin and thick disc, respectively. Errors were estimated using 1000 bootstrap realizations.

are not the same as the chemical definitions used in other analyses such as Recio-Blanco et al. (2014). By construction, the thick disc stars shown here are kinematically hot and the thin disc stars are kinematically cool, which is not necessarily the case for a thin and thick disc constructed chemically.

Fig. 19 displays median eccentricity as a function of [Fe/H] for kinematically defined thick disc stars binned at 0.2 dex. Hayden et al. (2018) used 3000 stars selected from the fourth internal data release of the Gaia-ESO Survey and studied median eccentricity as function of [Fe/H] for their chemically defined thick disc. As previously suggested by Recio-Blanco et al. (2014), Hayden et al. (2018) found the eccentricity distribution to have a strong dependence on metallicity for the chemically defined thick disc. For our kinematically defined thick disc, we do not find a trend of decreasing median eccentricity with [Fe/H], unlike Recio-Blanco et al. (2014) and Hayden et al. (2018). However, this result is not surprising given our kinematic population selection instead of a chemical selection as done by the previously mentioned studies, which demonstrates a possible drawback of selecting populations kinematically. Differences may also arise due to different volume sizes of the two samples, as previously mentioned.

8.3 Ages and metallicities

Stellar ages may likely be the best discriminator between the thin and thick disc (e.g. Fuhrmann 2011; Haywood et al. 2013; Bensby et al. 2014); however, obtaining accurate stellar ages for a wide range of stars is notoriously difficult (e.g. Soderblom 2010). Previous investigations find a clear age difference between the thin and thick disc and possible differences in the age–metallicity relations. Haywood et al. (2013) suggest that thin disc stars tend to be less than 8 Gyr old, but metal-poor thin disc objects may have ages up to $\sim$10 Gyr. Haywood et al. (2013) find the thick disc formed over a period of 4–5 Gyr and the younger thick disc stars are 9–10 Gyr old. Haywood et al. (2013) find a correlation between age and metallicity for stars in the thick disc sequence and that the iron enrichment rate in the thick disc was about five times higher than the thin disc phase. However, Holmberg, Nordström & Andersen (2007) find little or no variation in mean metallicity with age in the thin disc with a large and real scatter in [Fe/H] at all ages as well as no evidence for a significant age–metallicity relation in the thick disc.

Kubryk, Prantzos & Athanassoula (2015) found that assuming the thick disc is composed of stars $>9$ Gyr leads to results consistent with most of the observed chemical and morphological properties of the thick disc. Kilic et al. (2017) used nearly (<40 pc) white dwarfs and derived ages of 6.8–7.0 Gyr for the thin disc and 8.7 ± 0.1 Gyr for the thick disc, and when using a deep proper motion catalogue they derived ages of 7.4–8.2 Gyr for the thin disc and 9.5–9.9 Gyr for the thick disc. Notably, by combining results from the local and deep samples, Kilic et al. (2017) find an age difference between the thin disc and thick disc to be 1.6 ± 0.4 Gyr.

As previously described, we create a final sample of ages for analysis consisting of 1125 stars that have our most confident age estimates, where both methods agree to within 2 Gyr and error estimates are below 2 Gyr. We use these ages to examine the age properties of the kinematically defined populations. Fig. 20 and Table 4 display the kinematically defined population age distributions. The thin and thick disc exhibit significant differences in age distributions, as two clearly separated age peaks can be seen between the thin and thick disc populations in Fig. 20. We also show a
‘Fuhrmann-like’ thick disc (e.g. Fuhrmann 1998, 2004) where only low-metallicity stars ([Fe/H] > −0.2 dex) are included in the sample. We find that the Fuhrmann-like thick disc is generally older than the kinematically defined thick disc that includes all metallicities.

Previous studies found that stars associated with the Hercules stream have a mixture of ages as seen in the thin and thick disc, but the Arcturus moving group have few stars younger than 10 Gyr and ages are generally similar to the thick disc (Bensby et al. 2014). In our limited sample and given our specific kinematic definitions, which as discussed above may inherently include more thick disc stars, we find both kinematic groups to be similar in age to the thick disc, with age distribution parameters displayed in Table 4.

The top of Fig. 21 displays the relationship between metallicity and age for the overall sample and is colour-coded by $R_{\text{med}}$. We find that outer disc stars ($R_{\text{med}} > 9$ kpc) generally have lower metallicity across all ages, as expected from inside-out chemical evolution models (e.g. Chiappini, Matteucci & Romano 2001; Chiappini et al. 2009) combined with radial migration (e.g. fig 4 of Minchev et al. 2013). The bottom of Fig. 21 shows the kinematically defined populations binned at 1 Gyr, which exhibits an enrichment in metallicity from ∼11 to 8 Gyr. As previously discussed, the large metallicity dispersion in the thin disc at fixed age can be explained by a combination of inward and outward radial migration and blurring. In Section 8.4.2, we show a blurring cleaned age–metallicity relationship for the thin disc.

Fig. 22 displays velocity dispersions for $V_{\phi}$, $V_{\rho}$, and $V_{z}$ binned at 2 Gyr. Using the Geneva–Copenhagen survey Casagrande et al. (2011) found a prominent rise in velocity dispersion with age. Using 494 main-sequence turnoff and subgiant stars from the AMBRE:HRPS survey with accurate astrometric information from Gaia DR1, Hayden et al. (2017) analysed vertical velocity dispersion as a function of age. Hayden et al. (2017) found that both low- and high-[Mg/Fe] star sequences have vertical velocity dispersion that generally increases with age. In fig. 6 of Minchev et al. (2013), they display expected age–velocity relations for their chemo-dynamical model for the radial and vertical velocity dispersions. Examining the total population, Minchev et al. (2013) find that for ages older than ∼3 Gyr $\sigma_{V_{\phi}}$ flattens significantly and rises again after 8 Gyr, and they find similar behaviour for $\sigma_{V_{\rho}}$, which is consistent with a violent origin for the hottest stellar population in the solar neighbourhood.

Fig. 22 shows that in general the kinematically defined thin disc stars have low velocity dispersion, as expected from how we defined the thin disc. The black curve (all stars) in Fig. 22 gives a better comparison to the Minchev et al. (2013) results, which do not have thick disc stars. We find that all stars have velocity dispersions that increase with age, which is generally expected from the Minchev et al. (2013) model, but we do not find a steep increase in $\sigma_{V_{\phi}}$ and $\sigma_{V_{z}}$ at 8 Gyr for the sample of all stars (black curve). However, these plots are affected by selection effects, i.e. the proportions of thick and thin disc stars in the sample.

Fig. 23 displays median $V_{\rho}$ as a function of age for metal-rich ([Fe/H] > 0.2 dex) stars. Hayden et al. (2018) found clear differences with $V_{\rho}$ at different metallicities and [Mg/Fe] abundances, which has been previously observed (e.g. Lee et al. 2011b; Recio-Blanco et al. 2014; Guiglion et al. 2015). Fig. 6 of Minchev et al. (2013) also displays their model expectations for $V_{\rho}$ and age. For our sample, we find a very similar relation to the Minchev et al. (2013) results for $V_{\rho}$ and age, even for only metal-rich stars. Notably this shows that we have a mix of populations in the metal-rich end, similar to the mixing seen for thin disc stars.

Table 4. Age distribution parameters of kinematic populations.

| Kin. Pop. | $N^*$ | Mean (Gyr) | $\sigma$ (Gyr) | $M_d$ (Gyr) | $Q_1$ (Gyr) | $Q_3$ (Gyr) |
|-----------|-------|------------|----------------|-------------|-------------|-------------|
| Thin      | 842   | 4.6        | 2.4            | 4.0         | 3.1         | 5.5         |
| Thin/thick| 31    | 6.7        | 2.8            | 5.9         | 4.2         | 9.4         |
| Thick     | 36    | 7.9        | 3.3            | 9.1         | 4.9         | 10.6        |
| Hercules  | 6     | 8.9        | 3.8            | 10.5        | 4.6         | 12.4        |
| Arcturus  | 9     | 7.9        | 3.5            | 9.2         | 4.9         | 10.8        |

Figure 20. Stellar age distributions for the kinematically defined thin, thin/thick, and thick disc stars, as well as a Fuhrmann-like thick disc where the thick disc does not include stars with [Fe/H] > −0.2 dex.

Figure 21. Top: metallicity and stellar ages for the 1125 stars with confident ages used for our analysis. Symbols are coloured based on $R_{\text{med}}$. Bottom: median metallicity for stellar age distributions of the kinematically defined thin, thin/thick, and thick disc binned at 1 Gyr. Error bars display the first and third quartiles of the metallicity for each age bin. A bin must contain four stars to be displayed.

Figure 22 shows that in general the kinematically defined thin disc stars have low velocity dispersion, as expected from how we defined the thin disc. The black curve (all stars) in Fig. 22 gives a better comparison to the Minchev et al. (2013) results, which do not have thick disc stars. We find that all stars have velocity dispersions that increase with age, which is generally expected from the Minchev et al. (2013) model, but we do not find a steep increase in $\sigma_{V_{\phi}}$ and $\sigma_{V_{z}}$ at 8 Gyr for the sample of all stars (black curve). However, these plots are affected by selection effects, i.e. the proportions of thick and thin disc stars in the sample.

Fig. 23 displays median $V_{\rho}$ as a function of age for metal-rich ([Fe/H] > 0.2 dex) stars. Hayden et al. (2018) found clear differences with $V_{\rho}$ at different metallicities and [Mg/Fe] abundances, which has been previously observed (e.g. Lee et al. 2011b; Recio-Blanco et al. 2014; Guiglion et al. 2015). Fig. 6 of Minchev et al. (2013) also displays their model expectations for $V_{\rho}$ and age. For our sample, we find a very similar relation to the Minchev et al. (2013) results for $V_{\rho}$ and age, even for only metal-rich stars. Notably this shows that we have a mix of populations in the metal-rich end, similar to the mixing seen for thin disc stars.
8.4 Galactic orbit analysis

8.4.1 Age and metallicity distributions

Here, we analyse Galactic orbital parameters of our stars and how they compare with age and [Fe/H]. Fig. 24 shows Galactic orbital parameters $\sigma_{\text{med}}$, $\epsilon$, and $z_{\text{max}}$ for the MARVELS stars with derived Galactic orbits and compares each individually as a function of [Fe/H] and age. The distributions display that [Fe/H] decreases with larger $z_{\text{max}}$ and higher $\epsilon$. The [Fe/H] and $R_{\text{med}}$ distribution displays a slightly lower metallicity distribution for smaller $R_{\text{med}}$; we analyse $R_{\text{med}}$ and [Fe/H] in further detail by including scale height below. The age of MARVELS stars displays little dependence with $R_{\text{med}}$, but increases with both larger $z_{\text{max}}$ and higher $\epsilon$ values. These increases of age with $z_{\text{max}}$ and $\epsilon$ are expected as the age–$\epsilon$ and age–$z_{\text{max}}$ distributions are similar to the age–velocity dispersion relation and are directly related to the heating rate of stellar orbits in the disc.

In Fig. 25, we display Galactocentric orbital radii using both $R_{\text{Gal}}$ and [Fe/H] for stars with various ages in a geometrically thin disc defined as $z < 0.3$ kpc as in Anders et al. (2017b). The MARVELS data show a clear increase in metallicity range to more negative [Fe/H] values with larger age. We overlay the 418 stars from the Anders et al. (2017b) study and find the MARVELS stars to agree with the general trends of the giant stars from APOGEE, which display a negative slope in [Fe/H]/$R_{\text{Gal}}$ for ages < 4 Gyr and a flat distribution for older ages. Anders et al. (2017b) find their results with [Fe/H]–$R_{\text{Gal}}$ are compatible with the N-body chemodynamical Milky Way model by Minchev et al. (2013) and Minchev, Chiappini & Martig 2014.

We also show these distributions using $R_{\text{med}}$ and $z_{\text{max}}$ in Fig. 25, which allows us to look at a larger radial range with this local sample. Using $R_{\text{med}}$ and $z_{\text{max}}$ also allows the abundance gradient to be cleaned from the effect of ‘blurring’ (stars passing by the solar vicinity with high eccentricity) as opposed to ‘churning’ or genuine radial migration. If the initial [Fe/H] gradient of the interstellar medium is smooth, then scatter across the gradient through age is due to observational uncertainties, blurring (radial heating), and churning (radial migration). As expected we see slightly less scatter in the [Fe/H] gradient per age bin when observing $R_{\text{med}}$ as we remove the effect of blurring.

When analysing the metallicity distribution function (MDF) across the disc of the Galaxy, Hayden et al. (2015) found more metal rich populations in the inner Galaxy and that the shape and skewness of the MDF in the mid-plane of the Galaxy are dependent on location, where the inner disc has a large negative skewness, the solar neighbourhood MDF is roughly Gaussian, and the outer disc has a positive skewness. Fig. 26 shows the MARVELS MDFs for stars with maximum Galactic scale heights above and below 0.5 kpc. Here, we again use $R_{\text{med}}$ and $z_{\text{max}}$, which cleans the MDFs from the blurring of stellar orbits compared to the MDFs of Hayden et al. (2015). Similarly to Anders et al. (2014), who also looked at the MDFs over $R_{\text{med}}$ ranges, we find that the MDF is broader in the inner regions when compared to the outer ones, which is in agreement with pure chemical-evolution models for the thin disc (e.g. Chiappini et al. 2001) and predictions of the chemo-dynamical model of Minchev et al. (2013, 2014). We note that analysing stars based on $R_{\text{med}}$ may only represent stars that are blurred to the solar neighbourhood, which is likely biased towards older stellar populations relative to the in situ populations at those $R_{\text{med}}$.

In Fig. 27, we analyse the mean and skewness of the [Fe/H] distribution through Galactic orbital radii in bins of 1 kpc from...
Figure 24. Galactic orbital parameter distributions for $R_{\text{med}}$, $r$, and $z_{\text{max}}$ and their distributions with [Fe/H] and age. Blue symbols show median values with the first and third quartiles as errors for the data binned at 0.1 dex for [Fe/H] plots and 1 Gyr for age plots.

Figure 25. Top: Galactic orbital radius ($R_{\text{Gal}}$) and [Fe/H] for MARVELS stars with various ages in the thin disc geometrically defined as $z < 0.3$ kpc. APOGEE giant stars from Anders et al. (2017b) are shown with blue triangles. Bottom: same as above now using the orbital parameters $R_{\text{med}}$ and $z_{\text{max}}$ instead of $R_{\text{Gal}}$ and $z$ for MARVELS stars. For APOGEE stars we now display $R_{\text{guide}}$ values.
those with $z > 5$. For stars closer to the Galactic disc (the inner disc stars are more metal rich; however, stars farther from a strong correlation between mean $[\text{Fe/H}]$ and Galactic radii where $6.5 \, \text{kpc} < R_{\text{gal}} < 11.5 \, \text{kpc}$ for MARVELS stars in bins of 1 kpc from 6.5 kpc to 11.5 kpc. These values are presented in Table 5. For stars closer to the Galactic disc ($z_{\text{max}} > 0.5$ kpc), we also find a strong correlation between mean $[\text{Fe/H}]$ and Galactic radii where the inner disc stars are more metal rich; however, stars farther from the Galactic disc ($z_{\text{max}} > 0.5$ kpc) do not display as clear of trend with the most metal poor population residing around $R_{\text{gal}} \sim 7$ kpc. We also see a variance in skewness across Galactic radii where the outer disc stars show a more positive $[\text{Fe/H}]$ skewness than inner disc stars. As suggested by Hayden et al. (2015), the positively skewed MDFs of the outer disc could be due to radial migration with the high-metallicity tail caused by stars that were born in the inner Galaxy. We note again that analysing stars based on $R_{\text{gal}}$ may only represent stars that are blurred to the solar neighbourhood, and the thick disc is likely the dominant population that is blurred to the solar location from the inner Galaxy. This may not be representative of the in situ populations in the inner disc.

8.4.2 Blurring clean thin disc

Metallicity dispersion with age can be caused by blurring, or high eccentricity stars passing in the local volume. Galactic radial position ($R_{\text{gal}}$) gives a snapshot of stars at the present time, which covers a limited range in distance; however, guiding radii ($R_{\text{guide}}$) probe larger distances and are more suitable for studying the metallicity gradient of the thin disc. We present a ‘blurring clean sample’ for our thin disc stars where we only consider stars with $R_{\text{gal}} = 8.2 \pm 1$ kpc, to observe ‘local’ stars. This cut reduces the kinematically defined thin disc population with ages and metallicities from 1690 to 1381 stars.

Fig. 28 shows the age–metallicity relationship for the blurring cleaned kinematically defined thin disc population. As expected, we still observe scatter across the age–metallicity relationship, but this shows the scatter is mainly due to radial migration as the blurring has been taken out. Fig. 28 also displays metallicity distributions of the thin disc in different age bins. Slicing the MDF into different age bins Casagrande et al. (2011) found that young stars have a considerably narrower distribution than old stars, though the peak always remains around the solar value. Previous studies have found that the most metal rich thin disc stars are not the youngest ones and therefore are not a product of the chemical enrichment of the local snapshot, but include migrated stars (e.g. Casagrande et al. 2011; Trevisan et al. 2011). Our MDF shows again, in agreement with the velocity–age relation for metal-rich stars, that the metal-rich end has stars of all ages. Fig. 28 displays that most of the youngest stars are more metal rich, but we find that there is an important contribution of old and intermediate age stars around $[\text{Fe/H}] = 0.2$.

Table 5. Metallicity distribution functions for MARVELS stars across Galactocentric radii $R_{\text{gal}}$ of the Milky Way.

| $R_{\text{gal}}$ range (kpc) | $N$ stars | $[\text{Fe/H}]$ median | $\sigma_{[\text{Fe/H}]}$ | Skewness |
|-----------------------------|-----------|------------------------|------------------------|----------|
| $6.5–7.5$                   | 259       | $0.01$                 | $0.24$                 | $-0.53 \pm 0.15$ |
| $7.5–8.5$                   | 837       | $0.01$                 | $0.20$                 | $-0.37 \pm 0.08$ |
| $8.5–9.5$                   | 369       | $-0.04$                | $0.17$                 | $-0.15 \pm 0.13$ |
| $9.5–10.5$                  | 76        | $-0.12$                | $0.20$                 | $-0.28 \pm 0.28$ |
| $10.5–11.5$                 | 8         | $-0.28$                | $0.13$                 | $0.45 \pm 0.87$ |

| $R_{\text{gal}}$ range (kpc) | $N$ stars | $[\text{Fe/H}]$ median | $\sigma_{[\text{Fe/H}]}$ | Skewness |
|-----------------------------|-----------|------------------------|------------------------|----------|
| $6.5–7.5$                   | 65        | $-0.23$                | $0.28$                 | $-0.01 \pm 0.30$ |
| $7.5–8.5$                   | 111       | $-0.09$                | $0.23$                 | $-0.17 \pm 0.23$ |
| $8.5–9.5$                   | 96        | $-0.13$                | $0.22$                 | $-0.10 \pm 0.25$ |
| $9.5–10.5$                  | 39        | $-0.15$                | $0.21$                 | $-0.01 \pm 0.39$ |
| $10.5–11.5$                 | 5         | $-0.22$                | $0.28$                 | $0.39 \pm 1.10$ |

Figure 26. Top: metallicity ($[\text{Fe/H}]$) distribution functions for various Galactic orbital radii ($R_{\text{gal}}$) for stars with $z_{\text{max}} < 0.5$ kpc. Bottom: same distributions for stars with $z_{\text{max}} > 0.5$ kpc.

Figure 27. Top: Galactic orbital radius ($R_{\text{gal}}$) with skewness of $[\text{Fe/H}]$ for MARVELS stars in bins of 1 kpc from 6.5 kpc to $R_{\text{gal}} < 11.5$ kpc. Bottom: Galactic orbital radius ($R_{\text{gal}}$) with mean of the $[\text{Fe/H}]$ distribution for MARVELS stars in bins of 1 kpc from 6.5 kpc to $R_{\text{gal}} < 11.5$ kpc.

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parameters found from high-resolution data and analysis to within 84 K for $T_{\text{eff}}$, 0.16 dex for log g, and 0.06 dex for [Fe/H]. Our sample of atmospheric parameters have median values of 5780 K for $T_{\text{eff}}$, 4.38 dex for log g, and $-0.03$ dex for [Fe/H]. Using a surface gravity and effective temperature relationship, we analysed all 3075 stars and designated 2358 as dwarfs and 717 as giants.

With our sample of absolute RVs, we determined Galactic space velocities for 2504 stars using external sources for parallax and proper motion values. By assigning Gaussian distributions to populations within the Galaxy, we identified likely kinematic population assignments for each of these stars. We designated 2244 thin disc stars, 117 thin/thick disc stars, and 143 thick disc stars. Of these stars three likely reside in the halo, 17 may be part of the Hercules stream, and 19 may be associated with the Arcturus moving group. Of the 2504 stars in our sample, 1701 dwarfs and 543 giants are thin disc stars, 92 dwarfs and 25 giants are thin/thick disc stars, and 98 dwarfs and 45 giants are thick disc stars. We also assigned age-defined thick and thin disc populations using an 8 Gyr cut and age probability distributions to assign 851 stars to the thin disc and 57 stars to the thick disc, which displayed a clear separation in metallicity distributions.

By analysing the 1878 stars with both space velocities and atmospheric parameters, we determined median metallicities ([Fe/H]) of $-0.01$ dex for the kinematically defined thin disc and $-0.31$ dex for the thick disc. We determined stellar ages using both the spectro-photometric distance code StarHorse and the isochronal age-dating method and obtained median ages of 4.0 and 9.1 Gyr for the kinematically defined thin and thick disc, respectively. These results agree with previous findings that the thick disc is likely populated with older and more metal poor stars. Our kinematically identified Arcturus moving group consists of thick disc stars with a median metallicity of $-0.49$ dex, while the Hercules stream had a mixture of thin and thick disc stars with a median metallicity of $-0.10$ dex. We found large dispersions in metallicity for both of these populations, which suggests they originated from dynamical perturbations rather than coming from the remnants of open clusters. With our limited sample, we find age distributions similar to the thick disc for both of these populations with median ages of 10.5 and 9.2 Gyr for the Hercules stream and Arcturus moving group, respectively.

We find a likely negative trend in metallicity with total space velocity ($v_{\text{tot}}$) for stars with $v_{\text{tot}} > 50$ km s$^{-1}$. Analysing the total velocity dispersion and metallicity, we found total velocity dispersion to decrease with higher metallicity for thick disc stars, while the total velocity dispersion for thin disc stars is relatively flat. Our kinematically defined thin disc and all stars exhibit a negative trend in $\sigma_{\varphi}$, $\sigma_{\varphi}$, and $\sigma_{\varphi}$ with increasing metallicity, while the kinematically defined thick disc displays a negative trend with metallicity for $\sigma_{\varphi}$ as well. Unlike previous findings, our thick disc stars do not exhibit a trend of decreasing median eccentricity with [Fe/H]; however, this is likely due to biases of our kinematic population selection. We find that our total sample is compatible with the predictions of Minchev et al. (2013). When analysing velocity dispersion and age, we find that all stars have velocity dispersion that generally increases with age and that the kinematically defined thick disc is larger in velocity dispersion across all ages. We observe $V_{\varphi}$ to decrease with age for metal-rich stars for both our age estimation methods, showing that we have a mix of populations in the metal-rich end of our sample.

Analysing the Galactic orbital parameters of the MARVELS stars, we find distributions between age, [Fe/H], and Galactocentric radius for stars with Galactic scale heights of less than 0.3 kpc to agree with the trends of Anders et al. (2017b), which are com-

8.5 Previous MARVELS Companions

Of the 19 previously published MARVELS low-mass stellar and substellar companions (Lee et al. 2011a; Fleming et al. 2012; Wisniewski et al. 2012; De Lee et al. 2013; Jiang et al. 2013; Ma et al. 2013, 2016; Grieves et al. 2017), we obtained Galactic space velocities for seven stars: HD 87646 (Ma et al. 2016), TYC 4955-00369-1, TYC 3469-00492-1, GSC 03467-00030, TYC 3547-01007-1, TYC 3556-03602-1, and TYC 3148-02071-1 (Grieves et al. 2017). All seven stars likely reside in the thin disc and have total space velocities $v_{\text{tot}} > 247$ km s$^{-1}$. Although this sample size is extremely limited, the lack of brown dwarf hosting thick disc stars is interesting as Adibekyan et al. (2012a,b) reported the frequency of planet hosting stars to be higher in the chemically assigned thick disc than in the thin disc, with 8 of 65 stars hosting planets in the thick disc but only 3 of 136 stars hosting planets in the thin disc. Our age analysis sample includes 10 of the 19 MARVELS companions. These stars range in age from 2.4 to 7.5 Gyr with a mean age of 3.9 Gyr. We do not find any trends with brown dwarf companion mass and host star age.

9 CONCLUSIONS

We analysed 3075 stars in the MARVELS radial velocity survey and obtained absolute radial velocities for 2610 stars and atmospheric parameters, radii, and masses for 2343 dwarf stars, of which 1971 have both absolute RV and atmospheric parameters. Our absolute RV values agree with previous high-resolution results to within 0.210 km s$^{-1}$. Our atmospheric parameter results agree to previous
patible with the chemo-dynamical Milky Way model by Minchev et al. (2013, 2014). We observe stars closer to the Galactic disc ($R_{\text{max}} < 0.5$ kpc) to be more metal rich for smaller $R_{\text{med}}$ and have a more positive skewness in [Fe/H] for larger $R_{\text{med}}$. Stars farther from the Galactic disc ($R_{\text{max}} > 0.5$ kpc) do not display as clear of trend in mean metallicity across $R_{\text{med}}$, but still exhibit a high [Fe/H] skewness for larger $R_{\text{med}}$. The positive [Fe/H] skewness of the outer disc may be caused by stars migrating from the inner to the outer disc over time. We find that outer disc stars ($R_{\text{med}} > 9$ kpc) generally have lower metallicity across all ages, as expected from inside-out chemical evolution models (e.g. Chiappini et al. 2001, 2009) combined with radial migration (e.g. fig 4 of Minchev et al. 2013). Our blurring clean thin disc displays that stars of all ages are in the metal-rich end, which agrees with our velocity–age relation for metal-rich stars, suggesting radial migration dominates metallicity scatter in the thin disc.

This work corresponds to a large and homogenous sample of stars with precise radial velocities. The parameters from this work are critical for future analysis of substellar companions orbiting these stars and ideal for a homogenous study of substellar companions. These results may be used for future analysis of brown dwarf and planet completeness around solar-type stars.

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