Estimation of Ages and Masses via Carbon and Nitrogen Abundances for 556,007 Giants from LAMOST

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Abstract Estimating ages for a large number of giants is of great importance for studying the Galactic evolution. In this work, we determine stellar ages and masses for 556,007 giants from LAMOST DR5 with empirical relations estimated from chemical [C/N] abundance ratios. Our sample reveals the two well-known sequences in the age-[\(\alpha/M\)] relation. The high-\(\alpha\) sequence is composed of stars older than 8 Gyr and low-\(\alpha\) sequence is composed of stars with age ranging from 0 Gyr to 13.8 Gyr. Our sample also shows a flat age-[M/H] relation up until 12 Gyr. We compare these distributions with Galactic Chemical Evolution models for reference. When looking at the spatial distribution of stars in 2 Gyr age bins, we find that young stars are concentrated towards the Galactic plane and older stars extend to higher height above and below the disc. We find a smooth transition of median Galactic height for different age bins, which suggests a strong age-dependence of Galactic scale height.

Key words: stars: fundamental parameters — Galaxy: structure — Galaxy: evolution — Galaxy: abundances

1 INTRODUCTION

Obtaining accurate and precise ages for large numbers of stars is important for understanding the Milky Way evolution. Stellar age, together with mass and metallicity, is one of key parameters to determine the evolutionary state of a star. However, it cannot be measured directly from observations and is always model-dependent (e.g. Soderblom 2010).

A practical way to measure ages for large samples of stars is to determine their position on the Herzprung-Russell Diagram (HRD). This method yields precise ages for stars at the main-sequence turn-off and on the subgiant branch in regions of the HRD. However, the method is less precise for determining ages for giants, as isochrones of giants of different ages are close in temperature and color space. Due to their high luminosity, giants are crucial probes of the structure of the Milky Way, especially for the distant halo. Thus age estimates for giants are of enormous importance. Modern large scale surveys, such as the Large sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Zhao et al. 2006, 2012; Cui et al. 2012) survey, the Apache Point Observatory Galactic Evolution Experiment
(APOGEE; Majewski et al. 2017) and Galactic Archaeology with HERMES (GALAH; De Silva et al. 2015), have obtained high-quality spectra for a large number of giants, which allow the derivation of detailed stellar chemical compositions. To unlock the chemical/chemodynamical evolution of the Milky Way, it is also vital to estimate stellar ages.

Masseron et al. (2015) and Martig et al. (2016) have shown that the photospheric ratio of [C/N] changes depending on stellar mass during the post-main-sequence evolution as a result of dredge-up. Based on measurements from APOGEE, Martig et al. (2016) have shown that masses of red giants can be predicted from photospheric carbon and nitrogen abundances as well as spectroscopic stellar labels $T_{\text{eff}}$, $\log g$ and [M/H]. They also established an empirical relation between these quantities with seismic mass and subsequently also age estimates by 1475 red giants from the Kepler mission (Borucki et al. 2010). With this empirical model, they estimated masses and ages for $\sim$52,000 stars in APOGEE DR12 (Majewski et al. 2017). Ho et al. (2017b) excellently applied the empirical relation established by Martig et al. (2016) to LAMOST DR2 and estimated ages for a large sample of 230,000 giants. Using the APOKASC (Pinsonneault et al. 2014) sample as a training set, Ness et al. (2016) accurately estimated ages and masses for $\sim$70,000 APOGEE red giants with The Cannon. Wu et al. (2018) deduced ages and masses from LAMOST spectra with a machine learning method named Kernel Principal Component Analysis (KPCA), which means we can directly estimate age and mass from spectra, taking red giant branch (RGB) stars from Kepler as training dataset, and they also explored the feasibility of estimating ages and masses based on spectroscopically measured carbon and nitrogen abundances and established an empirical relation to derive mass and age by carbon and nitrogen abundances. Sharma et al. (2020) greatly explored the dependence of elemental abundances on stellar age and metallicity among Galactic disc stars with data from the third data release of GALAH (Buder et al. 2020). Zhang et al. (2019) have determined stellar parameters and $\alpha$, C, N elemental abundances for 938,720 giants from LAMOST DR5 with deep learning for 938,720 giants, as part of LAMOST DR5, for which the empirical formulae can be applied to estimate ages and masses for this even larger sample of giants.

The paper is arranged as follows. In Section 2, we introduce the LAMOST survey and its stellar parameters. We select a subsample from this data, which is suitable for the empirical formula by Wu et al. (2018). In Section 3, we estimate ages and masses for 556,007 giants based on C and N abundances with said empirical relation and compare our results with masses and ages from the literature. In Section 4, we explore age-$[\alpha/M]$ and age-$[M/H]$ relations with this large sample, and detect spatial distribution of these stars in different age bins. Finally, we discuss the results in Section 5.

2 DATA

2.1 The LAMOST Survey

The Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST) survey is a low-resolution ($R \sim 1800$) optical (3700-9000 Å) spectroscopic survey (Zhao et al. 2006, 2012; Cui et al. 2012). It can collect 4000 fiber spectra in a wide field ($5^\circ$) simultaneously. LAMOST has collected 9,026,365 spectra totally in DR5 (see http://dr5.lamost.org/).

2.2 Stellar Parameters

There are several different ways to estimate stellar parameters from LAMOST spectra. The LASP (Luo et al. 2015; Wu et al. 2011) used the Correlation Function Initial method to guess the initial values of the parameters and then used UlySS method (Koleva et al. 2009; Wu et al. 2011) to generate the final parameters. Ho et al. (2017a) used the data-driven method The Cannon to derive stellar parameters through training based on APOGEE labels. Zhang et al. (2019) have determined stellar atmospheric parameters and $\alpha$, C, N elemental abundances for 938,720 giants from LAMOST DR5 with a deep learning method named StarNet (Fabbro et al. 2018; O’briain et al. 2020). In this work, we will use stellar parameters from Zhang et al. (2019) to derive reliable stellar age and mass.
Fig. 1 Comparison of stellar parameters from Zhang et al. (2019) with those from Xiang et al. (2018). $T_{\text{eff}}$, log $g$, [M/H], [$\alpha$/M], [C/H] and [N/H] are compared. And we also compare [C/N] which is used to derive age and mass in the panel g). [C/N] is calculated with [C/N]=[C/H]−[N/H]. Bias and scatter for each parameter are marked in the corresponding panel. Colors represent number density. Bias represents median or mean value of residuals and scatter represents standard deviation of residuals. We have shifted the data with the median biases shown in each panel.
Before using stellar parameters from Zhang et al. (2019), we firstly compare the data with those from Xiang et al. (2017b) which was used in Wu et al. (2018) to confirm that the data is on the same scale, and this applicable for the empirical relation by Wu et al. (2018). In Figure 1, we show the comparison between the data by Zhang et al. (2019), applying StarNet, and Xiang et al. (2017b), applying KPCA. There are 433,523 stars for comparison, where bias represents the median value of residuals and scatter represents the standard deviation of residuals. The bias is $-55$ K for $T_{\text{eff}}$, 0.02 dex for log $g$, 0.00 dex for [M/H], 0.025 dex for [C/H] and $-0.115$ dex for [N/H]. The scatter is 152 K for $T_{\text{eff}}$, 0.24 dex for log $g$, 0.16 dex for [M/H], 0.05 dex for [C/M], 0.16 dex for [C/H] and 0.17 dex for [N/H], respectively. In the [C/M] comparison map, there are few stars with [C/M] $< 0.0$ dex in Zhang et al. (2019). Distribution of training set is inhomogeneous in Zhang et al. (2019). There are absolutely relatively few stars below [C/M] $< 0.0$ dex in the training set. In the panel g), [C/N] which is used to derive mass and age, is also compared, showing a bias of 0.14 dex and a scatter of 0.14 dex. While the bias is significant, it is constant. Therefore, we simply apply a bias correction so that our data is now on the same scale.

### 2.3 Quality cuts

Zhang et al. (2019) have determined stellar atmospheric parameters and α, C, N elemental abundances for 938,720 giants from LAMOST DR5. The relation by Wu et al. (2018), is however only applicable for a subset of these stars, that is stellar disk giants. Following the selection by Ho et al. (2017b), we apply quality cuts to our data, as listed below. It leaves 556,007 objects which are suitable for the empirical formula in Wu et al. (2018). We derive [(C + N)/M] with [(C + N)/M] = [(C + N)/H] where

$$
\frac{[C+N]}{[M]} = \log 10\left\{ \frac{[C]}{[H]} \times \frac{[N]}{[H]} + 1 \right\} = \log 10\left\{ \frac{[N]}{[H]} + \frac{[C]}{[H]} + 1 \right\} = \log 10\left\{ \frac{[N]}{[H]} \times 10^{-3.61} + 10^{[C]/[H]} \times 10^{-4.21} \right\}.
$$

Quality Cuts

- $-0.8$ dex $< [M/H] < 0.25$ dex
- $4000$ K $< T_{\text{eff}} < 5000$ K
- $1.8$ dex $< \log g < 3.3$ dex
- $-0.25$ dex $< [C/M] < 0.15$ dex
- $-0.1$ dex $< [N/M] < 0.45$ dex
- $-0.05$ dex $< [\alpha/M] < 0.3$ dex
- $-0.1$ dex $< [(C + N)/M] < 0.15$ dex
- $-0.6$ dex $< [C/N] < 0.2$ dex

### 3 ANALYSIS

#### 3.1 Estimating age and mass from C and N abundances

Wu et al. (2018) estimate age and mass based on the [C/H] and [N/H] abundance with a polynomial regression method. They assumed a quadratic function between the age or mass and the stellar parameters: age or mass = $f(T_{\text{eff}}, \log g, [M/H], [C/N], [C/M])$. Coefficients of the fits are listed in table 2b and table 3b in Wu et al. (2018). We apply the same relation to our data selected as described in Section 2.

From Figure 1, we can see small systematic deviation (bias) between measurements from Zhang et al. (2019) and those used by Wu et al. (2018), that is from Xiang et al. (2017b). These biases are mainly only offsets. Therefore, we apply these median biases as annotated in Figure 1 onto our data when pluggin them into the empirical formula to make it consistent with the KPCA ones.

#### 3.2 Age and Mass distribution of the sample

Figure 2 shows histograms of the derived age and mass estimates for these stars. Panel a) shows that the sample covers the whole range of possible ages of stars from zero on the young end to the age of
universe (~13.8 Gyr). There are also a small number of stars with unphysical ages, i.e. younger than 0 Gyr and older than 13.8 Gyr. This is mostly caused by parameters errors in either stellar parameters or C, N abundances, which can lead to unphysical ages in an empirical quadratic relations. The peak of age distribution is at ~3 Gyr. The 5th, 50th and 95th percentiles are at −0.08 Gyr, 3.79 Gyr, and 8.59 Gyr, respectively. In panel b), we can see most of stars have mass between 0.8 M⊙ - 2.6 M⊙. The peak is at 1.4 M⊙. The 5th, 50th and 95th percentiles are at 1.09 M⊙, 1.45 M⊙, and 2 M⊙, respectively.

3.3 Comparison with age and mass from the literature

Wu et al. (2018) also estimated ages and masses from LAMOST spectra with the KPCA method. The latter is a non-linear method that extracts principal components from high-dimensional data and was applied to a different set of stellar parameters estimated for the LAMOST stars. There are 151,908...
objects in common between our estimates and KPCA estimates, and we compare them in Figure 3. We find a generally good agreement between both methods, with a median bias of 1.1 Gyr for age and $-0.06 \, M_\odot$ for mass. This corresponds to median biases of 15.9% in age and 5.2% in mass. The scatter within the estimates is 2.4 Gyr and 0.3 M_\odot, that is 33.1% and 19.0% relatively. While this comparison shows that the absolute age values are contentious, it confirms that our ages are agreeing very well on a relative scale. Wu et al. (2019) also estimates ages for stars from LAMOST with C and N abundances. We compare our ages with those from Wu et al. (2019). Ages of 135,151 stars are compared. The median bias is 0.38 Gyr, mean bias is 0.42 Gyr and scatter is 2.38 Gyr. These values are very reasonable.

![Fig. 4](image.png)

**Fig. 4** Panel a): comparison of our age estimates with ones from Martig et al. (2016) and Ness et al. (2016). The black dots represent comparison between our estimates and ones from Martig et al. (2016) and the red dots represent comparison between our estimates and ones from Ness et al. (2016). The blue line shows a linear fit for the black dots with $\text{Age}_{\text{Martig}} = 2.6 + 0.4 \times \text{Age}_{[C/N]}$. Panel b): same as panel a), but for mass comparison.

Martig et al. (2016) estimate age and mass for 52,286 stars from APOGEE DR12 and Ness et al. (2016) estimate age and mass for 73,180 stars from APOGEE DR12. So we compare our values of age and mass with ones from Martig et al. (2016) and Ness et al. (2016). Figure 4 shows the comparison results. When we compare our values with ones from Martig et al. (2016), 11,067 common stars are used for comparison. For age, bias is 1.00 Gyr and scatter is 2.77 Gyr. For mass, bias is 0.015 M_\odot and scatter is 0.19 M_\odot. When we compare our values with ones from Ness et al. (2016), 118 common stars are used for comparison. Bias is 1.45 Gyr and scatter is 3.00 Gyr for age, and bias is 0.06 M_\odot and scatter is 0.19 M_\odot for mass. Again, we see that the absolute values of ages disagree, even more significantly here than in the comparison with Wu et al. (2018). However, the difference between both estimates can be well described by a small linear bias, confirming that our ages follow the same relative trend.

### 3.4 Spatial information

We can get photogeometric distances from Bailer-Jones et al. (2020), proper motions from Gaia EDR3 (Gaia Collaboration 2020a) and radial velocity from LAMOST DR5 v1 version catalog for 419,038 stars in our sample. Combining all these parameters, we calculate 3D Galactic coordinates (X, Y, Z)
and galactocentric distance (R) of these stars with orbit function from galpy (Bovy 2015). Equatorial input such as R.A., Decl., distance, proper motion in R.A. direction, proper motion in Decl. direction and radial velocity are fed into the function. We define the distance of the Sun from the Galactic centre as 8.178 kpc (Gravity Collaboration 2018) and the distance of the Sun from the Galactic plane as 25 pc (Bland-Hawthorn et al. 2016). We use the solar (U, V, W)⊙ = (11.1, 12.24, 7.25) km s\(^{-1}\) from Schoenrich et al. (2010). Based on the apparent motion of Sgr A* (6.379 mas yr\(^{-1}\)) with respect to the Sun, estimated by Reid et al. (2004), we then estimate the circular velocity to be 235.1 km s\(^{-1}\). An example of ten stars in our sample are listed in Table 1 and the whole table is available online.

4 RESULTS

4.1 Correlations among age, metallicity and abundances

We explore possible correlations among age, metallicity, and [\(\alpha/\text{M}\)] abundances. In Figure 5, we plot the distributions of stars in the age-[\(\alpha/\text{M}\)] and age-[M/H] planes. In the age-[\(\alpha/\text{M}\)] plane, the majority of stars with solar [\(\alpha/\text{M}\)] are located from 0 Gyr to 8 Gyr and stars older than 10 Gyr have typically enhanced \(\alpha\)-abundance. Stars in the low-\(\alpha\) part exhibit an extensive age distribution from 0 Gyr to 13.8 Gyr, but with a steep drop above 10 Gyr. The high-\(\alpha\) part is mainly composed of stars older than 8 Gyr and ages of stars increase with the increase of [\(\alpha/\text{M}\)]. This distribution is similar to that found by Wu et al. (2018), while the [\(\alpha/\text{M}\)] come from different methods. We note that our sample also includes some young stars (< 8 Gyr) with high [\(\alpha/\text{M}\)] values (> 0.15 dex) which are called young [\(\alpha/\text{M}\)]-rich stars. The shade area is where the young [\(\alpha/\text{M}\)]-rich stars locate, which is same as Chiappini et al. (2015). There are 18,420 (4.3%) young [\(\alpha/\text{M}\)]-rich stars in our sample. The relative number of young [\(\alpha/\text{M}\)]-rich stars reported by Chiappini et al. (2015) amounts is 4.5% in their sample. Possible explanations of their origin are they were formed near the ends of the Galactic bar (Chiappini et al. 2015) or they are merger products.

In the age-[M/H] panel of Figure 5, we see a large dispersion of ages across the metallicity range of our sample (−0.75 dex < [M/H] < 0.25 dex) and no clear correlation. There is a flat age-[M/H] relation up until 12 Gyr which is consistent with previous work using solar neighbourhood stars (Nordstrom et
al. 2004; Bergemann et al. 2014). It is probably caused by radial migration (Sellwood et al. 2002) that mixes stars born at various positions with different [M/H], the complex star formation and chemical enrichment history of the Galactic disc.

Figure 6 shows the number density distribution in the [M/H]-[α/M] plane for stars in different age bins. In panel a), we show all stars from 0 Gyr - 13.8 Gyr in the [M/H]-[α/M] panel. The plot shows two prominent sequences of chemical composition. This double sequence feature is consistent with the thin and thick disc sequence (Fuhrmann 1998; Bensby et al. 2003; Lee et al. 2011; Haywood et al. 2013; Hayden et al. 2015; Xiang et al. 2017b). Stars in the thick disc have high [α/M] and low [M/H] values, while stars in the thin disc have low [α/M] and high [M/H] values. It has therefore been proposed (see e.g. Bland-Hawthorn et al. 2019) to rename the populations to low-α and high-α disk or sequences. As the age increases from 0 Gyr - 2 Gyr to 12 Gyr - 13.8 Gyr, the number density of thin disc is decreasing but the number density of thick disc is increasing. In the first 0 Gyr - 2 Gyr panel, a clear sequence is at [M/H] \sim 0.0 dex and [α/M] \sim 0.0 dex. Then, in the 2 Gyr - 4 Gyr panel, the distribution widens towards lower [M/H] and higher [α/M] and reaches the upper limit of [M/H] = 0.25 dex for our data on the metal-rich end. As stars get older, more and more stars appear at [M/H] \sim −0.5 dex and [α/M] \sim 0.2 dex until 10 Gyr - 12 Gyr. We can clearly see one sequence of high-α up to [α/M] \sim 0.2 dex in the 10 Gyr - 12 Gyr panel. Stars of the high-α sequence overlap with those from the low-α sequence in solar and super-solar metallicity regime. However, we confirm the finding by Buder et al. (2019), who found that one can tell apart the sequences down to the age uncertainty, when using chemistry and age. In the 12 Gyr - 13.8 Gyr panel, only the sequence at [M/H] \sim −0.5 dex and [α/M] \sim 0.2 dex can be seen. In our sample, we found a typical scatter of 2.4 Gyr from the literature comparison, suggesting that a separation into low-α and high-α sequence via age and chemistry with our sample is only uncertain for the 8 Gyr - 10 Gyr bin.
Fig. 6  Number density distribution of stars in the [M/H]-[$\alpha$/M] plane in different age bins. Colors indicate number density. Black lines represent revised two-infall model from Spotti et al. (2019) for reference. In panel a), all stars from 0 Gyr to 13.8 Gyr are plotted. Two sequences of stars can be seen clearly. The low-$\alpha$ sequence is at [M/H] $\sim$ 0.0 dex and [$\alpha$/M] $\sim$ 0.0 dex and the high-$\alpha$ sequence is at [M/H] $\sim$ −0.5 dex and [$\alpha$/M] $\sim$ 0.2 dex. There are more stars in the low-$\alpha$ sequence than in the high-$\alpha$ sequence. In panel b), stars mainly distribute at [M/H] $\sim$ 0.0 dex and [$\alpha$/M] $\sim$ 0.0 dex. In panel c), some stars with [M/H] $\sim$ −0.5 dex and [$\alpha$/M] $\sim$ 0.2 dex appear. In panel d), distribution of stars is similar with distribution in panel b), but more stars appear at [$\alpha$/M] $\sim$ 0.20 dex. In panel e), distribution of stars is similar with distribution in panel c), but more stars appear at [$\alpha$/M] $\sim$ 0.20 dex. In panel f), the number of stars at [M/H] $\sim$ −0.5 dex and [$\alpha$/M] $\sim$ 0.2 dex is similar with the number of stars at [M/H] $\sim$ −0.5 dex and [$\alpha$/M] $\sim$ 0.2 dex. Stars almost evenly distribute throughout the region. In panel g), few stars are distribute at [M/H] $\sim$ 0.0 dex and [$\alpha$/M] $\sim$ 0.0 dex. Most of stars distribute at [M/H] $\sim$ −0.5 dex and [$\alpha$/M] $\sim$ 0.2 dex. In panel h), stars still mainly distribute at [M/H] $\sim$ −0.5 dex and [$\alpha$/M] $\sim$ 0.2 dex region. But the number of stars is less than the number of stars in panel f).
4.2 Spatial distribution of stars with different ages

Fig. 7 Number density distribution of stars in the R-Z plane in different age bins. Colors represent number density. In panel a), all stars from 0 Gyr to 13.8 Gyr are plotted. It shows dense region of stars extend from $R \sim 8.0$ kpc to $R \sim 16.0$ kpc. Most of stars distribute in the range of $-3.0$ kpc $< Z < 3.0$ kpc. In panel b), most of young stars whose age is 0 Gyr - 2 Gyr distribute in the range of $-1.0$ kpc $< Z < 1.0$ kpc. In panel c), most of stars distribute in the range of $-1.0$ kpc $< Z < 1.0$ kpc. But some stars appear in the $|Z| > 2.0$ kpc region. In panel d), distribution of stars is similar with distribution in panel b), but more stars appear in the $|Z| > 2.0$ kpc region. In panel e), distribution of stars is similar with distribution in panel c), but distribution of stars extend to $|Z| \sim 3.0$ kpc region. In panel f), dense region of stars extend to $R \sim 14.0$ kpc. Most of stars distribute in the range of $-3.0$ kpc $< Z < 3.0$ kpc. In panel g), stars are almost evenly distributed through the region. In panel h), stars are evenly distributed through the region.
Figure 7 shows the number density distribution in the R-Z plane for stars in the different age bins. Here R is the projected Galactocentric distance, and Z is the height above the disk midplane. The panel a) shows the number density distribution of all stars in the R-Z plane. We can see lots of stars distribute in the range of $-3 \text{kpc} < Z < 3 \text{kpc}$, $8 \text{kpc} < R < 16 \text{kpc}$. Number of stars becomes less higher than $3.0 \text{kpc}$ in the Z direction and number of stars also becomes less further than $16 \text{kpc}$ in the R direction. In the $0 \text{Gyr} - 2 \text{Gyr}$ panel, these early stars are concentrated on the midplane in the range of $-1.5 \text{kpc} < Z < 1.5 \text{kpc}$. And a small number of young stars are distributed higher than $|Z| > 2.5 \text{kpc}$. This means most of young stars are born at the midplane. There is no obvious number density change in the R direction from 8 kpc to 13 kpc and the number density becomes smaller from 13 kpc to 17 kpc. In the $2 \text{Gyr} - 4 \text{Gyr}$ panel, an obvious difference from the $0 \text{Gyr} - 2 \text{Gyr}$ panel is that there are more stars in the range of $|Z| > 2.5 \text{kpc}$ (refer to Figure 11). As age increases until $12 \text{Gyr} - 13.8 \text{Gyr}$, there are more and more stars in the range of $|Z| > 2.5 \text{kpc}$. But stars in the range of $-2.5 \text{kpc} < Z < 2.5 \text{kpc}$ become relatively fewer from $10 \text{Gyr} - 12 \text{Gyr}$. We can see an almost uniform distribution for old stars in the $12 \text{Gyr} - 13.8 \text{Gyr}$ panel. This distribution is same as findings by Hayden et al. (2015) for the thick disk.

![Fig. 8 Changes of the peaks in $|Z|$ as a function of R for different ages. Different colors represent stars in different age bins.](image)

In Figure 8, we can see the peaks in $|Z|$ change as a function of R for different ages quantitatively. For stars with age $0 \text{Gyr} - 2 \text{Gyr}$, distribution of $|Z|$ decreases gradually from $|Z| \sim 0.8 \text{kpc}$ to $|Z| \sim 0.1 \text{kpc}$ with R from 5 kpc to 9 kpc. And the distribution is almost flat at $|Z| \sim 0.2 \text{kpc}$ with R from 9 kpc to 15 kpc. For stars with age $12 \text{Gyr} - 13.8 \text{Gyr}$, distribution of $|Z|$ decreases gradually from $|Z| \sim 1.2 \text{kpc}$ to $|Z| \sim 0.5 \text{kpc}$ with R from 5 kpc to 9 kpc. But the distribution increases from $|Z| \sim 0.5 \text{kpc}$ to $|Z| \sim 2.2 \text{kpc}$ with R from 9 kpc to 15 kpc. For stars in other age bins, distributions of $|Z|$ also show downward trends with R from 5 kpc to 9 kpc and increasing trends with R from 9 kpc to 15 kpc. The distributions of stars are more dispers for larger R in the range of $9 \text{kpc} < R < 15 \text{kpc}$. We also can see that older stars are distributed in higher regions, and younger stars are distributed in lower regions.
Fig. 9 Distribution of stars in the (l, b) map colored by $[\alpha/M]$ with 2 Gyr age steps. Colors represent $[\alpha/M]$. In panel a), most of young stars whose age is 0 Gyr - 2 Gyr distribute in the range of $-30^\circ < \text{Latitude} < 30^\circ$. $[\alpha/M]$ of these stars is close to 0.00 dex. In panel b), most of stars with $[\alpha/M] \sim 0.00$ dex distribute in the range of $-30^\circ < \text{Latitude} < 30^\circ$. But some stars with $[\alpha/M] \sim 0.10$ dex appear in the $|\text{Latitude}| > 30^\circ$ region. In panel c), distribution of stars is similar with distribution in panel b), but some stars with $[\alpha/M] \sim 0.20$ dex distribute in the $|\text{Latitude}| > 30^\circ$ region. In panel d), distribution of stars is similar with distribution in panel c), but more stars with $[\alpha/M] \sim 0.10$ dex distribute in the $|\text{Latitude}| > 30^\circ$ region. In panel e), stars with $[\alpha/M] \sim 0.05$ dex distribute in the $-30^\circ < \text{Latitude} < 30^\circ$ region. Stars with $[\alpha/M] \sim 0.20$ dex distribute in the $|\text{Latitude}| > 30^\circ$ region. In panel f), a small number of stars with $[\alpha/M] \sim 0.05$ dex distribute in the $-30^\circ < \text{Latitude} < 30^\circ$ region. Most of stars with $[\alpha/M] \sim 0.20$ dex distribute in the $|\text{Latitude}| > 30^\circ$ region. In panel g), almost all stars with $[\alpha/M] \sim 0.20$ dex distribute in all region. In the panel h), all stars from 0 Gyr to 13.8 Gyr are plotted. It shows stars with $[\alpha/M] \sim 0.02$ dex distribute in the $-30^\circ < \text{Latitude} < 30^\circ$ region and stars with $[\alpha/M] \sim 0.20$ dex distribute in the $|\text{Latitude}| > 30^\circ$ region.
Table 1 Stellar parameters of the first ten stars in the catalog

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Notes: This table is available online. A portion is shown here for guidance regarding its form and content.

Figure 9 shows the distribution of stars in Galactic coordinates (l, b) colored by $[\alpha/\text{M}]$ for different age bins. As we have found from Figure 6, for young stars from 0 Gyr - 2 Gyr, most of them have low-$\alpha$ abundance and few stars have high-$\alpha$ abundance. From the panel a) (0 Gyr - 2 Gyr) of Figure 9, we can see these low-$\alpha$ stars distribute in the low latitude region ($-30^\circ < \text{Latitude} < 30^\circ$) and few stars which have high-$\alpha$ abundance distribute in the high latitude region. As the age increases, more and more $\alpha$-rich stars come out in the high latitude. Until 12 Gyr - 13.8 Gyr, i.e. old stars, most of these old stars are high-$\alpha$ stars. We find these high-$\alpha$ stars distribute everywhere. In panel h), it shows distribution of all stars in the Galactic axis. We can see low-$\alpha$ stars are concentrated on the mid-plane and high-$\alpha$ stars distribute on the high-latitude region.

Similar to Figure 9, we plot the distribution of stars in (l, b) map in Figure 10 but here in bins of $[\alpha/\text{M}]$ and colored by age. From all these plots, we can clearly see age of stars increases with the increase of $[\alpha/\text{M}]$ abundance. Stars are evenly distributed in the (l, b) map in each plot. In panel f), we plot all stars in the (l, b) map colored with age. Young stars distribute in the low-latitude region and old stars distribute in the high-latitude region. This distribution is same as that Ho et al. (2017b) found before.

5 DISCUSSION

5.1 Our data in the view of Galactic Chemical Evolution models

The relation of age with $[\alpha/\text{M}]$ and metallicity is broadly consistent with established expections based on detailed studies of the solar neighbourhood (Hayden et al. 2015; Xiang et al. 2017a). We show the theoretical evolution model named revised two infall model from Spitoni et al. (2019) in Figure 5 to make a comparison with observed data.

While the general trend of higher ages with higher $[\alpha/\text{M}]$ are recovered by the model, we see a significant disagreement in quantities. The youngest stars exhibit $[\alpha/\text{M}]$ of 0.00 dex in our data, whereas the model suggests a slightly subsolar $[\alpha/\text{M}]$ of $-0.05$ dex. This is likely caused by the incomplete low-$\alpha$ training data in the sample used in our study. Data and model agree around ages of 4 Gyr - 8 Gyr, but whereas our data suggests a strict increase of $[\alpha/\text{M}]$ beyond 8 Gyr, the model suggests a drop (corresponding to the time of major infall). Above 10 Gyr, our data agrees again.

When looking at the age-metallicity relation, we see good agreement between 0 Gyr and 8 Gyr, but our data does not hint to an increase in $[\text{M/H}]$ around 8 Gyr - 10 Gyr, as suggested by the revised two-infall model. Beyond this range, we can not compare data and model due to the metallicity limit of our sample ($[\text{M/H}] > -0.75$ dex).

In the $[\text{M/H}]-[\alpha/\text{M}]$ panels, for the oldest stars (10 Gyr - 13.8 Gyr), our data overlaps extremely well with the Spitoni models above 10 Gyr. For 6 Gyr - 8 Gyr, we see stars in a similar $[\text{M/H}]$ regime as the revised two-infall model, but our $[\alpha/\text{M}]$ is typically 0.05 dex higher than the model. Below 8 Gyr,
Fig. 10 Distribution of stars in the (l, b) map colored by age with 0.05 dex [α/M] steps. Colors indicate ages. In panel a), age of stars is in the range of 0 Gyr - 7 Gyr. Young stars whose age is ∼ 2 Gyr distribute in the range of −30° < Latitude < 30°. Stars with age ∼ 6 Gyr distribute in the [(Latitud] > 30° region. In panel b), age of stars is in the range of 4 Gyr - 10 Gyr. Young stars whose age is ∼ 4 Gyr distribute in the range of −30° < Latitude < 30°. Stars with age ∼ 8 Gyr distribute in the [(Latitud] > 30° region. In panel c), age of stars is in the range of 6 Gyr - 11 Gyr. Stars distribute in all regions. In panel d), age of stars is in the range of 9 Gyr - 12 Gyr. Stars distribute in all regions. In panel e), age of stars is in the range of 10 Gyr - 13.8 Gyr. Stars distribute in all regions. In panel f), all stars from 0.0 dex to 0.3 dex are plotted. Young stars distribute in the range of −30° < Latitude < 30° while old stars distribute in the range of [Latitude] > 30° region.
the location of the loop of $[\alpha/M]$ for the lowest [M/H] predicted by the revised two-infall model agrees well with our data.

5.2 Galactic vertical scale height as a function of age

![Histogram of $|Z|$ for stars in different age bins.](image)

**Fig. 11** Panel a): Histogram of $|Z|$ for stars in different age bins. Different colors correspond to stars in different age bins. Panel b): median values of $|Z|$ and peak values of $|Z|$ in different age bins. The blue dots represent median values and the red crosses represent peak values. Grey color represents the estimates of the thick and thin disk vertical scale length from Bland-Hawthorn et al. (2016).

We assume the distribution of stars in the Galaxy is symmetrical to the Z axis, so we explore histograms of $|Z|$ for stars in different age bins in panel a) of Figure 11. For stars in the range of 0 Gyr - 2 Gyr, 2 Gyr - 4 Gyr and 4 Gyr - 6 Gyr, the peaks of $|Z|$ are close to 0 kpc. But for stars in the range of 6 Gyr - 8 Gyr, 8 Gyr - 10 Gyr, 10 Gyr -12 Gyr, the peaks are nearly at 0.5 kpc. For stars in the range of 12 Gyr - 13.8 Gyr, the peak is close to 1.0 kpc. Although we also report the median of the distribution, we rely on the peak position, as the distributions are highly skewed.

In the panel b) of Figure 11, we also overplot the thin and thick disk vertical scale-heights, $z^t = 300 \pm 50$ pc and $z^T = 900 \pm 180$ pc, as review by Bland-Hawthorn et al. (2016). While we see that this scale-height agrees between the thin disk scale-height for stars with the stars of 2 Gyr - 6 Gyr, and the thick disk scale-height for stars above 12 Gyr, we see that our data disagrees for the intermediate age (6 Gyr - 12 Gyr) and the youngest stars (with our data suggesting a smaller vertical scale length). This has important implications, as it suggests that the scale-length is not only population-dependent (that is thin/thick or low-/high-$\alpha$ population), but also strongly age-dependent.
5.3 Age-abundance gradients with Galactic height

In Figure 12, we show the metallicity gradient and α-enhancement gradient for stars in different age bins. With the increase of |Z| from 0 kpc to 3 kpc, metallicity presents a decreasing trend for stars in every age bin. Metallicity decreases from ~−0.1 dex to ~−0.5 dex, which means there is a metallicity gradient from Galactic plane to higher region. With the increase of |Z| from 0 kpc to 3 kpc, [α/M] presents an increasing trend for stars in every age bin. For 0 Gyr to 2 Gyr stars, [α/M] increases from ~0.02 dex to ~0.05 dex. For 2 Gyr to 4 Gyr stars, [α/M] increases from ~0.03 dex to ~0.12 dex. For 4 Gyr to 6 Gyr stars, [α/M] increases from ~0.03 dex to ~0.15 dex. For 6 Gyr to 8 Gyr stars, [α/M] increases from ~0.03 dex to ~0.15 dex. For 8 Gyr to 10 Gyr stars, [α/M] increases from ~0.06 dex to ~0.16 dex. For 10 Gyr to 12 Gyr stars, [α/M] increases from ~0.09 dex to ~0.18 dex. For 12 Gyr to 13.8 Gyr stars, [α/M] increases from ~0.13 dex to ~0.22 dex. The increasing trend means there is an α-enhancement gradient from Galactic plane to higher region. So we think that young stars are close to the Galactic plane and stars which are old are on dynamically hot orbits.

6 CONCLUSIONS

In this study, we estimate stellar ages and masses for giant stars observed by LAMOST and use them to further the understanding of Galactic spatial and abundance gradients and their dependence on stellar age. We have got 938,720 giants which have stellar parameters and α, C, N estimates from LAMOST DR5 v1 version (Zhang et al. 2019). These stellar parameters are compared with those from Xiang et al. (2018). Taking the bias offsets into account, we are utilizing the empirical formula estimated from the data by Xiang et al. (2018). 556,007 stars with the empirical formula applied are selected. We estimate ages and masses for these stars based on the [C/N] abundance ratio and main stellar parameters. The age distribution of these stars ranges from 0 Gyr to 13.8 Gyr and mass distribution ranges from 0.8 M☉ to 2.4 M☉. Compared with ages and massed derived from KPCA method (Wu et al. 2018), it yields uncertain of 2.4 Gyr and bias of 1.1 Gyr in age, uncertain of 0.3 M☉ and bias of 0.06 M☉ in mass. Our age and mass estimates are also consistent with values from Martig et al. (2016) and Ness et al. (2016). Combining photogeometric distances (Bailer-Jones et al. 2020; Gaia Collaboration 2020a) and proper motion from Gaia EDR3 (Gaia Collaboration 2020a) and radial velocity from LAMOST DR5 (Luo et al. 2020a), we finally get the uncertainty of age and mass for LAMOST giants.
al. 2015; Wu et al. 2011), we get 3D coordinates (X, Y, Z) and galactocentric distance (R) for 419,038 stars.

With this large sample, we further investigated possible correlations among age, [α/M] and [M/H]. The age-[α/M] relation exhibits two separate sequence. The high-α sequence is dominated by stars older than 8 Gyr and the low-α sequence is composed of stars with a wide range of ages, from younger as 0 Gyr to older than 11 Gyr. There is a weak correlation between age and [M/H] within the stellar disk populations. Two prominent sequences of chemical composition which is consistent with the thin and thick disc sequence are shown in the [M/H] - [α/M] panel with all stars from 0 Gyr - 13.8 Gyr.

We detect spatial distribution of stars with 2 Gyr bins. The distributions of stars are more dispers in |Z| for larger R in the range of 9 kpc < R < 15 kpc. The much more extensive area coverage of the LAMOST data on the sky than previous spectroscopic survey is immediately apparent. Young stars distribute in the low-latitude region while the old stars distribute in the high-latitude region.

Our observed data agree well with Galactic Chemical Evolution model (Spitoni et al. 2019) from 4 Gyr to 8 Gyr and above 10 Gyr in the age-[α/M] relation, from 0 Gyr to 8 Gyr in the age-[M/H] relation, and from 10 Gyr to 13.8 Gyr in the [M/H]-[α/M] relation. There are most stars in the range of 4 Gyr - 6 Gyr. With our age estimates and their uncertainties, we find a smooth transition of median Galactic height |Z| for different age bins, with the median |Z| of the youngest stars agreeing well with the canonical thin disk scale height, and the median |Z| of the oldest stars agreeing well with the canonical thick disk, suggesting a strong age-dependence of Galactic scale height. We can detect the metallicity gradient and [α/M]-enhancement gradient in the |Z| direction for stars in each age bin. So we confirm the conclusion that young stars are close to the Galactic plane and stars which are old are on dynamically hot orbits.

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