Ages of Main-sequence Turnoff Stars from the GALAH Survey

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Abstract

Main-sequence turnoff (MSTO) stars are good tracers of Galactic populations since their ages can be reliably estimated from atmospheric parameters. Based on the GALAH survey, we use the Yale rotation evolution code to determine the ages of 2926 MSTO stars with a mean age uncertainty of ~10% considering the variation of C and O abundances. The ages of CO-poor stars are systematically affected by ~10% due to the C and O abundances, globally shifting to ~0.5 Gyr older compared to the results using solar metal mixture. Of the stars with [Fe/H] ~ 0.3–0.5 or [O/Fe] ≤ −0.25, many have fractional age differences of ≥20%, and even reach up to 36%. The age–metallicity relation appears to possibly indicate the existence of two distinct sequences: a young sequence of stars with ages mostly <7 Gyr, and a relatively older sequence of stars with ages mostly >7 Gyr, overlapping at 5 Gyr ≤ age ≤ 7 Gyr. Moreover, the trends of abundances-to-age ratios show two corresponding sequences, especially in the [O/Fe]–age plane. We also find that [Y/Mg] is a good chemical clock in disk populations. The young sequence and the old sequence cannot be separated based on chemistry or kinematics; therefore, stellar age is an important parameter to distinguish these two sequences in our sample.

Unified Astronomy Thesaurus concepts: Chemical abundances (224); Milky Way disk (1050); Fundamental parameters of stars (555)

Supporting material: machine-readable tables

1. Introduction

The Galactic evolution history is imprinted in the positions, velocities, and chemical abundances of its stars. Since Gilmore & Reid (1983) first divide the Galactic disk into a thin disk and a thick disk with different scale heights, many works study different populations in the Galactic disk based on chemistry or kinematics (e.g., Adibekyan et al. 2012; Silva Aguirre et al. 2018). However, there have also been doubts about whether the thick disk exists (Bovy et al. 2012). There is still an active discussion on how the thin and thick disk components should be defined, and a thorough understanding of the formation and evolution of the Galactic disk requires precise chemical abundances, kinematics, and stellar ages.

The original spatial distribution of stars is changed by the kinematic evolution of the galaxy; therefore, many works suggest that the stellar age rather than kinematics is a better parameter to study different disk populations (e.g., Haywood et al. 2013; Bensby et al. 2014; Delgado Mena et al. 2019). The relations between abundances and stellar age, which can contribute to future models of the Galactic chemical evolution, are widely studied (Buder et al. 2019; Delgado Mena et al. 2019; Hayden et al. 2020; Sharma et al. 2022). The age structure of different disk populations are shown, providing clues for the formation history of the Galactic disk (Haywood et al. 2013). Some abnormal populations such as young α-rich stars (Chiappini et al. 2015; Martig et al. 2015) and old metal-rich stars (Chen et al. 2003, 2008) are found, indicating the complex evolution history of the Galactic disk. It is of high importance to describe existing populations in the Galactic disk in combination with reliable age measurements of stars. In recent years, a great effort has been made to derive reliable stellar ages (e.g., Nissen et al. 2017; Silva Aguirre et al. 2018; Delgado Mena et al. 2019). The advent of asteroseismology provides a great advance in obtaining stellar ages (e.g., Silva Aguirre et al. 2018), but the sample is limited to specific stars such as red giants. Using a grid-based stellar evolution model to determine stellar ages is a common and reliable way.

In a stellar evolution model, the metal-mixture pattern is a crucial part that can affect the opacity. The solar metal-mixture pattern (hereafter, solar-mixture; Grevesse & Sauval 1998) and the α-enhanced metal-mixture pattern (hereafter, α-mixture) are widely used in stellar evolution models, e.g., Yongse–Yale (YY) isochrones (Yi et al. 2001, 2003; Kim et al. 2002; Demarque et al. 2004) and the Dartmouth Stellar Evolution Database (Dotter et al. 2008). In the past decades, many observations show that the O abundance shows different behavior from other α-elements (Bensby et al. 2005; Reddy et al. 2006; Nissen et al. 2014; Bertran de Lis et al. 2015; Amarsi et al. 2019; Delgado Mena et al. 2019; Pavlenko et al. 2019; Franchini et al. 2021), and C enhancement also exists (Bensby et al. 2005; Reddy et al. 2006; Nissen et al. 2014). To study stars with C and O enhancements,
the CO extreme metal-mixture pattern (hereafter, CO-mixture), in which the enhancement factors of C and O are added individually and other abundances are consistent with solar-mixtures or $\alpha$-mixtures, is proposed (Ge et al. 2016). Ge et al. (2016) use a CO-mixture to study a sample of halo stars and find that C and O could influence the age determination of stars with C and O enhancements. Based on a sample of disk stars, Chen et al. (2020) find that ages of stars with $[O/\alpha] \geq 0.2$ are obviously younger by $\sim 1$ Gyr than those determined by the $\alpha$-mixture, and the age difference can affect the $[\alpha/Fe]$-age relation. Furthermore, there are many stars with C and O abundance deficiency, and their age determination should also be affected by C and O abundances. However, due to the lack of high-resolution spectra with precise C and O abundances, the previous samples of Ge et al. (2016) and Chen et al. (2020) are limited in size and mainly comprise stars with C and O enhancements that were compiled from various sources.

The GALAH DR3 catalog (Buder et al. 2021) provides atmospheric parameters and element abundances, including precise and homogeneous C and O abundances for 588,571 unique stars that are mainly nearby, enabling us to study a large and self-consistent sample with respect to age, abundance, and kinematics. Furthermore, we can complement our previous studies aiming to understand the influence of C and O enhancements on the stellar age determination by including stars with C and O abundance deficiency.

MSTO stars are good tracers of Galactic populations and star clusters (Mackey et al. 2008; Goudrooj et al. 2009; Yang et al. 2013; Wu et al. 2017). The $T_{\text{eff}}$ of MSTO stars are sensitive to their ages at fixed [Fe/H]; therefore, their ages can be reliably obtained based on accurate atmospheric parameters. Moreover, the surface chemical abundances of MSTO stars are nearly primordial, essentially without contamination from nuclear reactions in the stellar interior (Nissen 2013). Thus, we select 2926 MSTO stars from GALAH DR3 as sample stars and determine their ages considering the variation of C and O abundances. We show the impact of C and O elements on stellar evolution tracks and age determination. We study abundance-to-age ratios and the chemical clocks in the Galactic disk. With the Gaia EDR3 database, we determine and analyze the kinematic properties of sample stars. In Section 2, we show the target selection. In Section 3, we present the stellar evolution model. In Section 4, we describe the results, including chemical and kinematic analysis. In Section 5, we summarize our findings.

2. Target Selection

2.1. Main-sequence Turnoff Stars

We select our targets from the GALAH DR3 catalog (Buder et al. 2021). This catalog provides $T_{\text{eff}}$, $\log g$, [Fe/H], and up to 30 element abundances for 588,571 unique stars. Along with the other elements, the C and O abundances are derived through non-LTE computation. First, we only keep stars without bad flags in flag_sp, flag_fe_h, flag_alpha_fe, flag_c_e, flag_o_fe, flag_mg_fe, flag_s_i_fe, flag_ca_fe, flag_ti_fe. For precision, we then prune our sample by demanding the formal uncertainties of [Fe/H], [C/Fe], and [O/Fe] to be less than 0.05, 0.1, and 0.1, respectively. According to Bonaca et al. (2020), we apply their criteria of $3.8 \leq \log g \leq 4.3$ to select MSTO stars. Finally, similarly to Buder et al. (2019), we remove hot stars with $T_{\text{eff}} \geq 6900$ K and evolved stars with $\log g \leq 3.8$, $T_{\text{eff}} \leq 5600$ K, leaving us with 3025 targets. Figure 1 shows the distribution of the selected MSTO stars in the Kiel diagram. Table 1 shows the atmospheric parameters, [C/H], [O/H], typical errors for temperature, $\log g$, and [Fe/H] of the sample stars.

2.2. Stars with Extreme [C/Fe] and [O/Fe]

Our sample contains 18 high-O stars, defined as $[O/\alpha] \geq 0.2$ and $[\alpha/Fe] \geq 0.05$, according to Chen et al. (2020). Our sample also incorporates stars with negative values of [C/Fe] and [O/Fe], which are hereafter referred to as CO-poor stars. We use the following criteria to define the CO-poor stars:

1. $[C/Fe] \leq -0.05$ and $[O/Fe] \leq -0.05$
2. $[O/\alpha] \leq -0.1$
3. $-0.05 \leq [\alpha/Fe] \leq 0.05$

These criteria ensure that the CO-poor stars have truly negative values of [C/Fe] and [O/Fe], and their [O/Fe] differs with $[\alpha/Fe]$. We keep their $[\alpha/Fe]$~0, consistent with the solar-mixture that will be used as a reference for comparison in the following section. With the above criteria, we select 439 CO-poor stars. This sample of 18 high-O stars and 439 CO-poor stars are regarded as stars with extreme [C/Fe] and [O/Fe], enabling our age study to give an insight into the impact of the variation of C and O abundances on the age determination of stars.

Figure 2 shows relations of [C/Fe], [O/Fe], and $[\alpha/Fe]$ versus [Fe/H]. The trends of the [X/Fe] versus [Fe/H] relations can be interpreted as the result of a chemical enrichment regulated by the timescales of the polluters. Elements such as C, N, and Fe are mainly produced by long-living stars (AGB and Type Ia supernovae (SNe)), while others, such as $\alpha$-elements (O, Mg, Si, Ca) are produced by short-living stars (through winds and core-collapse supernovae (CCSNe)). In particular, Fe is mainly produced by

![Figure 1. Kiel diagram of the stars from the GALAH DR3 data (gray dots) and the targets used in our work (blue circles). The main-sequence turnoff is delimited by black dotted lines (3.8 $\leq \log g \leq 4.3$, 5600 K $\leq T_{\text{eff}} \leq 6900$ K). Red dashed lines show 1.0 $M_\odot$ evolutionary tracks and black solid lines show 1.2 $M_\odot$ evolutionary tracks. At a given mass, metallicities range from $\sim$0.6 through to 0.3 in steps of 0.3 (from left to right).](image)
Figure 2. [C/Fe], [O/Fe], and [$\alpha$/Fe] as functions of [Fe/H] for the same stars shown in blue in Figure 1. Red squares: high-O stars. Blue points: sample stars. Black circles: CO-poor stars.

Table 1
The Observational Atmospheric Parameters, [C/H], [O/H], Typical Errors for Temperature, log $g$, and [Fe/H] of the Sample Stars

| Star ID       | $T_{\text{eff}}$ (K) | log $g$ (dex) | [Fe/H] (dex) | [C/H] | [O/H] | [$\alpha$/Fe] (dex) |
|---------------|----------------------|---------------|--------------|-------|-------|--------------------|
| 11285775-0440070 | 6176 ± 72           | 4.16 ± 0.06   | −0.15 ± 0.05 | −0.24 | −0.24 | 0.02               |
| 17215393+0618245 | 6000 ± 72           | 4.29 ± 0.07   | 0.21 ± 0.05  | −0.06 | 0.13  | 0.02               |
| ...           | ...                 | ...           | ...          | ...   | ...   | ...                |

(This table is available in its entirety in machine-readable form.)

Table 2
Metal Mixtures for the GS98 Solar-mixture, the $\alpha$-enhanced Mixture ([C/Fe] = 0.2), and the CO-mixture ([C/Fe] = −0.1, [O/Fe] = −0.2, and [$\alpha$/Fe] = 0 in the CO-poor Case, and [C/Fe] = 0.2, [O/Fe] = 0.4, and [$\alpha$/Fe] = 0.2 in the CO-rich Case, Respectively)

| Element | log $N_C$ | log $N_O$ | log $N_{C\text{O}}$ (CO-poor) | log $N_{C\text{O}}$ (CO-rich) |
|---------|-----------|-----------|-------------------------------|-------------------------------|
| C       | 8.52      | 8.52      | 8.52+0.1                       | 8.52+0.2                      |
| N       | 7.92      | 7.92      | 7.92                          | 7.92                          |
| O       | 8.83      | 8.83+0.2 | 8.83+0.2                       | 8.83+0.4                      |
| F       | 4.56      | 4.56      | 4.56                          | 4.56                          |
| Ne      | 8.08      | 8.08+0.2 | 8.08+0.2                       | 8.08+0.2                      |
| Na      | 6.33      | 6.33      | 6.33                          | 6.33                          |
| Mg      | 7.58      | 7.58+0.2 | 7.58+0.2                       | 7.58+0.2                      |
| Al      | 6.47      | 6.47      | 6.47                          | 6.47                          |
| Si      | 7.55      | 7.55+0.2 | 7.55+0.2                       | 7.55+0.2                      |
| P       | 5.45      | 5.45      | 5.45                          | 5.45                          |
| S       | 7.33      | 7.33+0.2 | 7.33+0.2                       | 7.33+0.2                      |
| Cl      | 5.50      | 5.50      | 5.50                          | 5.50                          |
| Ar      | 6.40      | 6.40      | 6.40                          | 6.40                          |
| K       | 5.12      | 5.12      | 5.12                          | 5.12                          |
| Ca      | 6.36      | 6.36+0.2 | 6.36+0.2                       | 6.36+0.2                      |
| Sc      | 3.17      | 3.17      | 3.17                          | 3.17                          |
| Ti      | 5.02      | 5.02+0.2 | 5.02+0.2                       | 5.02+0.2                      |
| V       | 4.00      | 4.00      | 4.00                          | 4.00                          |
| Cr      | 5.67      | 5.67      | 5.67                          | 5.67                          |
| Mn      | 5.39      | 5.39      | 5.39                          | 5.39                          |
| Fe      | 7.50      | 7.50      | 7.50                          | 7.50                          |
| Co      | 4.92      | 4.92      | 4.92                          | 4.92                          |
| Ni      | 6.25      | 6.25      | 6.25                          | 6.25                          |

Note. The $\alpha$-elements are O, Ne, Mg, Si, S, Ca, and Ti, excluding Ar.

The positive values of the [$\alpha$/Fe] ratios at low [Fe/H] are then due to the CCSNe, which restore the $\alpha$-elements on short timescales. When Type Ia SNe, originating from CO white dwarfs, start restoring the bulk of Fe, then the [$\alpha$/Fe] ratios start decreasing. Observations can therefore set strong constraints on the origin of the different elements, and many works have chemically selected high-$\alpha$ and low-$\alpha$ populations in the [$\alpha$/Fe]–[Fe/H] plane (e.g., Adibekyan et al. 2012; Silva Aguirre et al. 2018). In our sample, the [Fe/H] of sample stars ranges from −0.6 to 0.6, and shows a continuous distribution, indicating no clear separation based on chemistry. Most high-O stars have [C/Fe] ≃ 0 to 0.4 and [O/Fe] ≃ 0.2 to 0.4, while CO-poor stars have [C/Fe] ≃ −0.3 to −0.1 and [O/Fe] ≃ −0.4 to −0.1. Almost all the CO-poor stars have [Fe/H] ≳ 0. Having a negative value of [O/Fe] at [Fe/H] ⩾ 0 is typically interpreted as being due to the occurrence of Type Ia SNe that enrich the Fe.

3. Stellar Models
3.1. Input Physics

We use the Yale rotation evolution code (Guenther et al. 1992) in its nonrotation configuration to compute a grid of stellar evolutionary tracks. The helium abundance is calibrated against standard solar models, and thus Y = 0.248 + 1.33242Z (Spiegel et al. 2007). The mixing-length parameter $\alpha_l$ is fixed to 1.75. Our stellar models are based on the 2005 update of the OPAL equation of state tables (Rogers & Nayfonov 2002), the OPAL opacity tables (Iglesias & Rogers 1996) with GS98 mixture (Grevesse & Sauval 1998) at high temperature, and the Ferguson opacity tables (Ferguson et al. 2005) at low temperature. We use a solar-mixture to determine the ages of Type Ia SNe and only a small fraction is ejected by CCSNe. Type Ia SNe explode on longer timescales than CCSNe and therefore ratios such as [$\alpha$/Fe] can be used as cosmic clocks.
Figure 3. Solar metallicity evolutionary tracks of $M = 1.2 M_\odot$ with multiple $[\text{C/Fe}]$ and $[\text{O/Fe}]$ combinations at four $Z$ values as indicated. The black point on each track represents the model at the end of the main sequence ($X = 0.01$).

Table 3

| Metal Mixture | $[\text{C/Fe}]$ (dex) | $[\text{O/Fe}]$ (dex) | $[\alpha/\text{Fe}]$ (dex) | Mass Range ($M_\odot$) | $Z$ Range | Heavy Element Abundance |
|---------------|------------------------|------------------------|---------------------------|------------------------|-----------|--------------------------|
| CO-mixture    | −0.1                   | −0.1                   | 0                         | $0.86 \sim 1.54$       | 0.0110 − 0.0460 | $0.0110 \sim 0.0340$ |
|               | −0.1                   | −0.2                   | 0                         | $0.86 \sim 1.44$ (1.46 − 1.54) | 0.0110 − 0.0420 | $0.0110 \sim 0.0340$ |
|               | −0.1                   | −0.3                   | 0                         | $0.86 \sim 1.44$       | 0.0110 − 0.0430 | $0.0120 \sim 0.0420$ |
|               | −0.2                   | −0.2                   | 0                         | $0.86 \sim 1.54$       | 0.0120 − 0.0450 | $0.0180 \sim 0.0380$ |
|               | −0.2                   | −0.3                   | 0                         | $0.86 \sim 1.44$ (1.46 − 1.54) | 0.0120 − 0.0450 | $0.0180 \sim 0.0380$ |
|               | 0                      | 0.3                    | 0.1                       | $0.86 \sim 1.34$       | 0.0060 − 0.0310 | $0.0060 \sim 0.0310$ |
|               | 0.2                    | 0.4                    | 0.2                       | $0.96 \sim 1.34$       | 0.0060 − 0.0310 | $0.0060 \sim 0.0310$ |
| solar-mixture | 0                      | 0                      | 0                         | $0.86 \sim 1.54$       | 0.0060 − 0.0500 | $0.0060 \sim 0.0500$ |
| $\alpha$-mixture | 0                      | 0.1                    | 0.1                       | $0.86 \sim 1.54$       | 0.0100 − 0.0360 | $0.0180 \sim 0.0210$ |
|               | 0                      | 0.2                    | 0.2                       | $0.76 \sim 1.44$ (1.46 − 1.54) | 0.0060 − 0.0250 | $0.0180 \sim 0.0210$ |

Note. The mass step is 0.02 $M_\odot$ and the $Z$ step is 0.0010.
Note. Z represents the heavy element abundance.

stars without α enhancements, and a α-mixture to determine the ages of α-enhanced stars.

For the high-O and CO-poor stars, we construct a CO-mixture to redetermine their ages. Assuming [Fe/H] = 0, for GS98 scaled-solar metal mixture, the metallicity Z (in mass fraction) is 0.0166, and the elements have the same proportion as solar metal elements:

\[ \frac{[M/Fe]}{[Fe/Fe]} = \frac{[M/Fe]}{[Fe/Fe]} = 0 \] (1)

where \( M \) corresponds to the metal element, and the enhancement of a single element could be considered as

\[ [M/Fe] = \log \left( \frac{N_M}{N_{Fe}} \right)_{\text{star}} - \log \left( \frac{N_M}{N_{Fe}} \right)_{\odot} \] (2)

where \( N \) stands for the number of the particles in a unit volume (e.g., the abundance by number), and \( \log N_M = 12 \). From this relation, we consider \([M/Fe]\) as the enhancement of a metal element to the solar-mixture, and the value of \([M/Fe]\) can be calculated from the observed element abundances:

\[ [M/Fe] = [M/H] - [Fe/H]. \] (3)

We construct the CO-mixture by adding enhancement factors to the solar log \( N_i \) values with stable log \( N_{Fe} \) (\( N_i \) represents the volume density of the element \( i \); in our case they are C, O, and α-elements) in the same way as Ge et al. (2015). For example, Table 2 lists metal mixtures for the GS98 solar-mixture, the α-enhanced mixture ([α/Fe] = 0.2) and the CO-mixture ([C/Fe] = -0.1, [O/Fe] = -0.2, and [α/Fe] = 0 in the CO-poor case, and [C/Fe] = 0.2, [O/Fe] = 0.4, and [α/Fe] = 0.2 in the CO-rich case, respectively). The OPAL high-temperature opacity tables are constructed online9 with 3.75 \( \leq \log T \leq 8.7 \). The low-temperature opacity tables are reconstructed with 2.7 \( \leq \log T \leq 4.5 \) according to the CO-mixture in a similar way to Ferguson et al. (2005). The metal-mixture patterns used in this work and the detailed parameters of the grid computation are listed in Table 3.

### 3.2. Effects of the Variation of C and O Abundances on Evolutionary Tracks

Figure 3 shows evolutionary tracks with four combinations of [C/Fe] and [O/Fe] for a given Z in each panel. We find that the tracks with lower [C/Fe] and [O/Fe] globally shift to lower \( T_{\text{eff}} \) at a given Z. For each track, we choose one model at the end of the main sequence (X ≲ 0.01; black dots in Figure 3). Table 4 lists the parameters of these models (1 ~ 16). From models 1 to 4, the luminosities decrease with decreasing [C/Fe] and [O/Fe] and the ages increase with decreasing [C/Fe] and [O/Fe]. At fixed Z, the variation of [C/Fe] and [O/Fe] would influence opacity, which could influence the energy transfer efficiency and the thermal structure. Therefore, the lifetime of the main-sequence phase is changed.

Figure 4 shows tracks of different [C/Fe] and [O/Fe] at a given [Fe/H] in each panel. We find that tracks of [C/Fe] = 0 and [O/Fe] = 0 globally have the lowest temperatures at [Fe/H] = -1, and gradually become irregular at [Fe/H] = 0.3. We also select models at the end of the main sequence (black dots in Figure 4) to analyze. Table 5 lists the parameters of these models (17 ~ 32). From models 17 to 20, the Z decreases with decreasing [C/Fe] and [O/Fe] for a given [Fe/H], but the lifetime of the main sequence is not always longer with decreasing [C/Fe] and [O/Fe]. At fixed [Fe/H], the variation of C and O abundances would change the heavy metal abundance Z, resulting in changes to the hydrogen abundance X and the helium abundance Y.

### 3.3. Fundamental Parameter Estimation

In order to obtain fundamental parameters including stellar age, we use a Bayesian scheme that is similar to Kallinger et al. (2010) and Basu et al. (2010), to find the most probable stellar models from evolutionary tracks. Based on a set of observed constraints \( \phi \) (in our case, they are \( T_{\text{eff}}, \log g, \) and [Fe/H]), we

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| Model | Mass \((M_\odot)\) | Z | \([\text{Fe/H}]\) (dex) | \([\text{C/Fe}]\) (dex) | \([\text{O/Fe}]\) (dex) | \(T_{\text{eff}}\) (K) | \(\log(L/L_\odot)\) | Age (Gyr) |
|-------|-----------------|---|----------------|----------------|----------------|---------------|----------------|----------|
| 1     | 1.2             | 0.050 | 0.53         | 0                | 0                | 5641          | 0.32             | 5.65     |
| 2     | 1.2             | 0.050 | 0.63         | -0.1             | -0.2             | 5522          | 0.25             | 6.73     |
| 3     | 1.2             | 0.050 | 0.66         | -0.2             | -0.3             | 5483          | 0.23             | 7.09     |
| 4     | 1.2             | 0.050 | 0.68         | -0.2             | -0.3             | 5463          | 0.22             | 7.30     |
| 5     | 1.2             | 0.010 | -0.23        | 0                | 0                | 6481          | 0.61             | 3.34     |
| 6     | 1.2             | 0.010 | -0.13        | -0.1             | -0.2             | 6396          | 0.53             | 3.46     |
| 7     | 1.2             | 0.010 | -0.09        | -0.1             | -0.3             | 6363          | 0.52             | 3.63     |
| 8     | 1.2             | 0.010 | -0.08        | -0.2             | -0.3             | 6346          | 0.51             | 3.73     |
| 9     | 1.2             | 0.005 | -0.54        | 0                | 0                | 7083          | 0.68             | 2.64     |
| 10    | 1.2             | 0.005 | -0.44        | -0.1             | -0.2             | 6873          | 0.66             | 2.88     |
| 11    | 1.2             | 0.005 | -0.40        | -0.1             | -0.3             | 6825          | 0.65             | 2.97     |
| 12    | 1.2             | 0.005 | -0.39        | -0.2             | -0.3             | 6799          | 0.65             | 3.03     |
| 13    | 1.2             | 0.001 | -1.24        | 0                | 0                | 8542          | 0.86             | 2.33     |
| 14    | 1.2             | 0.001 | -1.14        | -0.1             | -0.2             | 8461          | 0.86             | 2.41     |
| 15    | 1.2             | 0.001 | -1.11        | -0.1             | -0.3             | 8434          | 0.86             | 2.44     |
| 16    | 1.2             | 0.001 | -1.09        | -0.2             | -0.3             | 8419          | 0.86             | 2.46     |

9 http://opalopacity.llnl.gov/new.html
define the likelihood that matches the observed constraints as

\[ L = \frac{1}{\sqrt{2\pi \sigma}} \exp \left( -\frac{\chi^2}{2} \right), \]  

(4)

where

\[ \chi^2 = \left( \frac{\varphi_{\text{obs}} - \varphi_{\text{mode}}}{\sigma} \right)^2. \]  

(5)

Here \( \sigma \) is the error of the observation \( \varphi_{\text{obs}} \). According to Bayes’ theorem, the posterior probability of model \( M_i \) given data \( D \) is computed via

\[ p(M_i | D, I) = \frac{p(D | M_i, I) p(M_i | I)}{p(D | I)}. \]  

(6)

We assume a uniform prior \( p(M_i | I) = \frac{1}{N_m} \), where \( N_m \) is the total number of computed models. Our likelihood function is defined as

\[ p(D | M_i, I) = L(T_{\text{eff}}, \log g, [\text{Fe}/\text{H}]) = L_{\text{Teff}} L_{\log g} L_{[\text{Fe}/\text{H}]} \]  

(7)

Since \( p(D | I) \) is just a normalization factor and \( p(M_i | I) \) is constant, we have

\[ p(M_i | D, I) \propto p(D | M_i, I). \]  

(8)

Thus, maximizing the likelihood function yields the most probable model. We estimate the optimal parameters \( (T_{\text{eff}}, \log g, [\text{Fe}/\text{H}], \text{age}, \text{etc.}) \) and their errors by calculating the 16th, 50th, and 84th percentiles of individual marginal posterior distributions.

4. Result

4.1. Stellar Ages

We obtain the ages of 2926 MSTO stars with a mean age uncertainty of \( \sim 10\% \), including 18 high-O stars and 384 CO-poor stars. Stars with age uncertainty of \( \geq 20\% \) have been removed. The fundamental parameters of our sample stars are listed in Table 6. Figure 5 shows the distribution of \([\text{Fe}/\text{H}], \text{mass}, \text{age} \) of the total sample stars. Our sample stars mainly belong to F- and G-type stars, having a mean \([\text{Fe}/\text{H}] \) of \( \sim 0 \). The age distribution is well fitted by two Gaussian profiles, indicating two different groups in our sample: a young group with a mean age of \( \sim 4.5 \text{ Gyr} \), and a relatively old group with a mean age of \( \sim 8 \text{ Gyr} \).
Figure 6 shows a comparison between ages determined with the CO-mixture and the solar-mixture or $\alpha$-mixture of high-O and CO-poor stars. Ages calculated with the CO-mixture are systematically older than ages with the solar-mixture or $\alpha$-mixture by $\sim 0.5$ Gyr ($\text{Age}_{CO} > \text{Age}$). Of the 18 high-O stars, 13 are younger after considering the CO-mixture, which is consistent with Chen et al. (2020). Therefore, the C and O abundances can systematically influence the age determination of both CO-poor stars and high-O stars.

Table 5  
Parameters of 16 Models at the End of the Main Sequence at Fixed [Fe/H]

| Model | Mass ($M_\odot$) | Z   | [Fe/H] (dex) | [C/Fe] (dex) | [O/Fe] (dex) | $T_{\text{eff}}$ (K) | log($L/L_\odot$) | Age (Gyr) |
|-------|------------------|-----|-------------|--------------|--------------|---------------------|-----------------|-----------|
| 17    | 1.2              | 0.0315 | 0.3  | 0  | 0  | 5857 | 0.39 | 5.22     |
| 18    | 1.2              | 0.0255 | 0.3  | −0.1  | −0.2  | 5883 | 0.37 | 5.49     |
| 19    | 1.2              | 0.0237 | 0.3  | −0.1  | −0.3  | 5938 | 0.32 | 5.02     |
| 20    | 1.2              | 0.0229 | 0.3  | −0.2  | −0.3  | 5887 | 0.32 | 5.15     |
| 21    | 1.2              | 0.0166 | 0  | 0  | 0  | 6202 | 0.52 | 4.17     |
| 22    | 1.2              | 0.0133 | 0  | −0.1  | −0.2  | 6250 | 0.46 | 3.85     |
| 23    | 1.2              | 0.0123 | 0  | −0.1  | −0.3  | 6258 | 0.47 | 3.93     |
| 24    | 1.2              | 0.0119 | 0  | −0.2  | −0.3  | 6255 | 0.47 | 4.00     |
| 25    | 1.2              | 0.0054 | −0.5  | 0  | 0  | 6968 | 0.67 | 2.66     |
| 26    | 1.2              | 0.0043 | −0.5  | −0.1  | −0.2  | 7036 | 0.69 | 2.79     |
| 27    | 1.2              | 0.0040 | −0.5  | −0.1  | −0.3  | 7096 | 0.69 | 2.84     |
| 28    | 1.2              | 0.0039 | −0.5  | −0.2  | −0.3  | 7090 | 0.70 | 2.89     |
| 29    | 1.2              | 0.0017 | −1.0  | 0  | 0  | 8121 | 0.11 | 2.35     |
| 30    | 1.2              | 0.0014 | −1.0  | −0.1  | −0.2  | 8175 | 0.11 | 2.44     |
| 31    | 1.2              | 0.0013 | −1.0  | −0.1  | −0.3  | 8208 | 0.11 | 2.47     |
| 32    | 1.2              | 0.0012 | −1.0  | −0.2  | −0.3  | 8262 | 0.11 | 2.48     |

Note. Z represents the heavy element abundance.

Figure 7 shows how the fractional differences of age vary with [Fe/H], [O/Fe], and log g for CO-poor stars. We perform local nonparametric regression fitting (LOESS model) for our sample in each panel (black solid lines, the same below). The mean fractional age difference is $\sim 10\%$. Figures 7(a) and (b) show the fractional difference increases with increasing [Fe/H] and decreases with increasing [O/Fe], respectively. Of the stars with [Fe/H] $\sim 0.3$–0.5 or [O/Fe] $\leq -0.25$, many have fractional age differences of $\geq 20\%$, and even reach up to 36%.

Table 6  
Fundamental and Kinematic Parameters for the Whole Sample Determined in This Work

| Star ID     | Mass ($M_\odot$) | AgeCO (Gyr) | Age (Gyr) | $U_{\text{LSR}}$ (km/s) | $V_{\text{LSR}}$ (km/s) | $W_{\text{LSR}}$ (km/s) |
|-------------|------------------|-------------|-----------|----------------------|------------------------|------------------------|
| 11285775-0440070 | 1.18$^{+0.04}_{-0.02}$ | 4.24$^{+0.56}_{-0.50}$ | 3.83$^{+0.65}_{-0.36}$ | −34.3 | −50.0 | 11.5 |
| 17215393+0618245 | 1.20$^{+0.02}_{-0.02}$ | 3.21$^{+0.55}_{-0.66}$ | 2.99$^{+0.50}_{-0.65}$ | −9.41 | −52.8 | −5.39 |

(This table is available in its entirety in machine-readable form.)
Figure 7(c) shows that the fractional age difference increases with \( \log g \). Therefore, the impact of C and O abundances on stellar evolution (age) is related to \( \frac{[\text{Fe}]}{[\text{H}]} \), \( \frac{[\text{O}]}{[\text{Fe}]} \), and \( g \log \).

4.2. Chemical Abundance Trends with Age

Different elements are released to the interstellar medium by stars with different masses and therefore on different timescales. Thus, abundances-to-age ratios could provide information about the past history of star formation and gas accretion for the Milky Way. Here we present abundances-to-age ratios in the disk population with ages calculated considering the variation of C and O abundances. Figure 8 shows the \( [\text{Fe}]/[\text{H}] \)–age diagram. We find a predominantly flat trend at ages \( \leq 7 \text{ Gyr} \), and a decreasing trend at ages \( \geq 7 \text{ Gyr} \), indicating the possible existence of two different sequences in our sample, which is consistent with the results of Figure 5(c). Nissen et al. (2020; their Figure 3) also found two sequences in the \( [\text{Fe}]/[\text{H}] \)–age plane for solar-type stars.

Based on the different trends, we divide our sample stars into a young sequence of stars with ages mostly \( < 7 \text{ Gyr} \) (blue circles), and a relatively older sequence of stars with ages mostly \( > 7 \text{ Gyr} \) (red asterisks), overlapping at \( 5 \text{ Gyr} \leq \text{age} \leq 7 \text{ Gyr} \) (dark-blue triangles).

Figure 9 shows the relations between various chemical abundance ratios and age in the disk population. The trends of abundances-to-age ratios also show two sequences corresponding to the young sequence and the old sequence. The ratios of \([\text{C}]/[\text{Fe}]\) and \([\text{O}]/[\text{Fe}]\) slightly decrease with large scatter in the young sequence, and then start to increase with age in the old sequence. The tight correlation between \([\text{C}]/[\text{Fe}]\) or \([\text{O}]/[\text{Fe}]\) and age with small dispersion in the old sequence suggests that the ratios could be good age proxies for old stars. Recalling that the root cause(s) of the chemical evolution of C in the galaxy is unclear (e.g., Type II SNe, stellar winds from massive stars such as Wolf–Rayet stars, intermediate-mass and low-mass stars in the planetary nebula phase, and stars at the end of the giant phase as mentioned in Nissen 2013), the origin of O is exclusively by CCSNe (Franchini et al. 2021), the similarity of the two relations ([C/Fe]–age and [O/Fe]–age) could imply that C and O might be from similar sources. The Na, Al, K, and Cu are mainly produced by exploding massive stars, but they show different trends in the \([\text{X}/[\text{Fe}]\)–age plane. This is due to the fact that they are odd Z elements that are strongly related to the metallicity of progenitors (Kobayashi et al. 2020). For \( \alpha \)-elements (Mg, Si, Ca, and Ti), they are even Z elements, mainly produced by exploding massive stars. The \([\text{Mg}]/[\text{Fe}]\) shows increasing trends with small dispersion, indicating that \([\text{Mg}]/[\text{Fe}]\) is a good age proxy for the disk population.
[Si/Fe], [Ca/Fe], and [Ti/Fe] show flat trends in the young sequence, and increasing trends in the old sequence. For Cr and Zn, they are mainly produced by Type Ia SNe, and they show the scattered distribution at all ages. The Mn and Ni are iron-peak elements, which are mainly produced by exploding massive stars and exploding white dwarfs. They show increasing trends in the young sequence and decreasing trends in the old sequence. The [Y/Fe] shows a decline at all ages, indicative of a strong dependence on age. This is due to the delayed production from successive captures of neutrons by iron-peak elements in low-mass AGB stars with respect to the early contribution of SNe Ia and SNe II that produce iron (Casali et al. 2020).

The chemical clocks are empirical relations that can derive stellar ages from chemical abundances. Based on 1111 dwarfs stars from the HARPS GTO program, Delgado Mena et al. (2019) propose that any ratio of [Y or Sr] over α-elements (plus Zn and Al) is a good candidate to be a chemical clock. Similarly to Delgado Mena et al. (2019), we use the Spearman correlation coefficient (ρ) to study the correlation of the chemical species with age. Table 7 shows the values of ρ between different chemical species and age. Generally, a higher |ρ| corresponds to a better linear correlation. For [Si/Fe], [Ca/Fe], and [Ti/Fe], their |ρ| are extremely low, indicating that they are not chemical clocks. The [Y/Mg] has the highest |ρ|, corresponding to the strongest anticorrelation with age. Therefore, [Y/Mg] can be a good chemical clock for disk populations. Figure 10 shows the relation of [Y/Mg] versus age. We present the polynomial fit on sample stars and the formula is as follows:

\[
[Y/\text{Mg}] = -0.053(\pm 0.001) \ast \text{Age}_{\text{CO}} + 0.244(\pm 0.006).
\]

The C and O can influence the age determination and therefore, it is significant to study the effect of C an O on chemical clocks. We illustrate the age bins for CO-poor stars. The CO-poor stars are sorted by their age and then divided into 19 bins with each bin containing 20 stars (the last bin contains 24 stars). Figure 11 shows the relation of [Y/Mg] versus age for CO-poor stars. We perform the polynomial fit for all age bins and the specific formulas are as follows:

\[
[Y/\text{Mg}] = -0.054(\pm 0.006) \ast \text{Age} + 0.202(\pm 0.028)
\]

\[
[Y/\text{Mg}] = -0.050(\pm 0.005) \ast \text{Age}_{\text{CO}} + 0.205(\pm 0.025).
\]

The age bins by the CO-mixture are systematically older than those by the solar-mixture, causing changes of slope and intercept in the [Y/Mg]-age relation for CO-poor stars. The fractional age difference between two models can be simply given by

\[
\frac{\text{Age}_{\text{CO}} - \text{Age}}{\text{Age}} = \frac{3}{37} + \frac{0.057}{-18.5[Y/\text{Mg}] + 3.74}.
\]

For CO-poor stars, the C and O can influence the age determination based on chemical clocks globally by >8%.

4.3 Kinematic Analysis: Spatial Velocity versus Age

We determine the kinematic properties of spatial velocity of our sample stars with the Gaia EDR3 database (Gaia Collaboration et al. 2021). For our sample stars, the distances are derived from Bailer-Jones et al. (2021). The proper motions are obtained from the Gaia EDR3 database; the radial velocity is given by GALAH DR3 (Buder et al. 2021). The space velocity components, $U_{\text{LSR}}, V_{\text{LSR}},$ and $W_{\text{LSR}}$ are calculated with respect to the local standard of rest, adopting the standard solar motion $(U, V, W) = (-8.5, 13.38, 6.49) \text{ km s}^{-1}$ (Coskunoglu et al. 2011). All the kinematic properties of our sample are listed in Table 5.

The Toomre diagram is widely used to divide thin-disk and thick-disk populations in kinematic space (e.g., Adibekyan et al. 2012; Buder et al. 2019). Figure 12 shows the Toomre diagram for our sample stars. Most stars show solar-disk-like motion because their $U$, $V$, and $W$ are similar to the local standard of rest. Stars of the young sequence and the old sequence show similar behavior, indicating no clues for separating these two sequences based on kinematics. This should be due to the kinematic evolution of the galaxy, which altered the original spatial and kinematic distributions of stars (Nissen 2013). As we mentioned in Section 2.1, the young sequence and the old sequence cannot be separated based on chemistry either; therefore, stellar age is an important parameter to distinguish these two sequences in our sample.

Figure 13 shows relations between $V_{\text{LSR}}$, the scatter of $V_{\text{LSR}}$, and age. Panel (a) of Figure 13 shows that the $V_{\text{LSR}}$ becomes clearly more scattered in the old sequence compared to that in the young sequence. We also illustrate the age bins for our sample stars. The stars are sorted by their age and then divided into 15 bins with each bin containing 200 stars (the last bin contains 126 stars). For each bin, we calculate the standard deviation of the $V_{\text{LSR}}$ ($\sigma_{V_{\text{LSR}}}$). Panel (b) of Figure 13 shows the relation of the scatter of $V_{\text{LSR}}$ versus age. The $\sigma_{V_{\text{LSR}}}$ increases with age in the disk population, which is also found in many previous works (e.g., Almeida-Fernandes & Rocha-Pinto 2018).

5 Conclusion

MSTO stars are good tracers of Galactic populations because their ages can be reliably obtained. Based on the GALAH survey, we select a sample of 2926 MSTO stars and determine their ages with a mean age uncertainty of ~10%. The age distribution of our sample stars shows two different groups: a
young group with a mean age of $\sim 4.5$ Gyr and an old group with a mean age of $\sim 8$ Gyr.

We estimate the ages of 384 CO-poor stars and 18 high-O stars considering the variation of C and O abundances. Compared to the results by the $\alpha$-mixture or solar-mixture, the ages of most of the high-O stars calculated by the CO-mixture are younger. The ages of CO-poor stars are systematically affected by $\sim 10\%$, globally shifting to $\sim 0.5$ Gyr older compared to the results using the solar metal mixture. The age difference increases with [Fe/H] or the absolute value of [O/Fe]. Of the stars with [Fe/H] $\sim 0.3$–0.5 or [O/Fe] $\leq -0.25$, many have age differences $\geq 20\%$, and even reach up to 36%.

The [Fe/H]–age relation shows three different trends, indicating the possible existence of two distinct sequences. Based on the different trends, we divide our sample stars into a young sequence of stars with ages mostly $< 7$ Gyr, and a relatively older sequence of stars with ages mostly $> 7$ Gyr, overlapping at 5 Gyr $\leq$ age $\leq 7$ Gyr. These two sequences also show different trends in [X/Fe]–age planes, especially in the [O/Fe]–age plane. The [C/Fe] and [O/Fe] show similar behavior, indicating that they might be from

**Figure 9.** Relations between various chemical abundance ratios (indicated in each panel) and ages for our sample stars. The symbols are the same as those defined in Figure 8. The black solid line represents the best local nonparametric regression.
similar sources. The [O/Fe] correlates with age in the old sequence, indicative of a good age proxy for old stars.

We use the Spearman correlation coefficient to study the correlation of the chemical species with age. The [Y/Mg] has the strongest correlation with age, indicating that [Y/Mg] is a good chemical clock for the disk population. We calculate the empirical relation between [Y/Mg] and stellar age in our sample, and the specific formula is 

\[ \frac{[Y/Mg]}{\text{Age}_{\text{CO}}} = -0.053 \left(\pm 0.001\right) \times \text{Age}_{\text{CO}} + 0.244 \left(\pm 0.006\right) \]

For CO-poor stars, stellar ages based on chemical clocks can be affected by \( \geq 8\% \) due to C and O abundances.

Based on the Gaia EDR3 database, we calculate the space velocity components, \( U_{\text{LSR}}, V_{\text{LSR}}, \) and \( W_{\text{LSR}} \), with respect to the local standard of rest for our sample stars. Most stars show solar-like motion. The young sequence and the old sequence cannot be separated based on chemistry or kinematics, and stellar age is an
Table 7
Spearman Correlation Coefficients, ρ, of [X/Fe] or [Y/X] Abundance Ratios versus the Stellar Age

| Element  | ρ   |
|----------|-----|
| [Mg/Fe]  | 0.455 |
| [Al/Fe]  | 0.523 |
| [Si/Fe]  | 0.125 |
| [Ca/Fe]  | −0.219 |
| [Ti/Fe]  | 0.012 |
| [Y/Fe]   | −0.656 |
| [Y/Mg]   | −0.701 |
| [Y/Al]   | −0.694 |
| [Y/Si]   | −0.639 |
| [Y/Ca]   | −0.517 |
| [Y/Ti]   | −0.606 |

important parameter to distinguish these two sequences. In the $V_LSR$–age plane, the old sequence clearly shows a more scattered trend compared to that of the young sequence. The scatter of $V_LSR$ increases with age in the disk population.

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References

Adibekyan, V. Z., Sousa, S. G., Santos, N. C., et al. 2012, A&A, 545, A32  
Almeida-Fernandes, F., & Rocha-Pinto, H. J. 2018, MNRAS, 476, 184  
Amarsi, A. M., Nissen, P. E., & Skuladóttir, A. 2019, A&A, 630, A104  
Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., et al. 2021, AJ, 161, 147  
Basu, S., Chaplin, W. J., & Elsworth, Y. 2010, ApJ, 710, 1596  
Bensby, T., Feltzing, S., Lundström, I., et al. 2005, A&A, 433, 185  
Bensby, T., Feltzing, S., & Oey, M. S. 2014, A&A, 562, A71  
Bertran de Lis, S., Delgado Mena, E., Adibekyan, V. Z., et al. 2015, A&A, 576, A89  
Bonaca, A., Conroy, C., Cargile, P. A., et al. 2020, ApJL, 897, L18  
Bovy, J., Rix, H.-W., & Hogg, D. W. 2012, ApJ, 751, 131  
Buder, S., Lind, K., Ness, M. K., et al. 2019, A&A, 624, A19  
Buder, S., Sharma, S., & Kos, J., et al. 2021, MNRAS, 506, 150  
Casali, G., Spina, L., Magrini, L., et al. 2020, A&A, 639, A127  
Chen, X., Ge, Z., Chen, Y., et al. 2020, ApJ, 889, 157  
Chen, Y. Q., Zhao, G., Izumiura, H., et al. 2008, AJ, 135, 618  
Chen, Y. Q., Zhao, G., Nissen, P. E., et al. 2003, ApJ, 591, 925  
Chiappini, C., Anders, F., Rodrigues, T. S., et al. 2015, A&A, 576, L12  
Coskunoglu, B., Ak, S., Bilir, S., et al. 2011, MNRAS, 412, 1237  
Delgado Mena, E., Moya, A., Adibekyan, V., et al. 2019, A&A, 624, A78  
Demarque, P., Woo, J.-H., Kim, Y.-C., et al. 2004, ApJS, 155, 667  
 Dotter, A., Chaboyer, B., Jevremovic, D., et al. 2008, ApJS, 178, 89  
Ferguson, J. W., Alexander, D. R., Allard, F., et al. 2005, ApJ, 623, 585  
Franchini, M., Morossi, C., Di Marcoantonio, P., et al. 2021, AJ, 161, 9  
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1  
Ge, Z. S., Bi, S. L., Chen, Y. Q., et al. 2016, ApJ, 833, 161  
Ge, Z. S., Bi, S. L., Li, T. D., et al. 2015, MNRAS, 447, 680  
Gilmoure, G., & Reid, N. 1983, MNRAS, 202, 1025  
Gouldfroot, P., Puzia, T. H., Kozhurina-Platais, V., et al. 2009, AJ, 137, 4988  
Grevesse, N., & Sauval, A. J. 1998, SSRv, 85, 161  
Guenther, D. B., Demarque, P., Kim, Y.-C., et al. 1992, ApJ, 387, 372  
Hayden, M. R., Sharma, S., Bland-Hawthorn, J., et al. 2020, arXiv:2011.13745  
Haywood, M., Di Matteo, P., Lehnert, M. D., et al. 2013, A&A, 560, A109  
Iglesias, C. A., & Rogers, F. J. 1996, ApJ, 464, 943  
Kallinger, T., Mosser, B., Hekker, S., et al. 2010, A&A, 522, A1  
Kim, Y.-C., Demarque, P., Yi, S. K., et al. 2003, ApJS, 144, 259  
Kobayashi, C., Karakas, A. I., & Lugaro, M. 2020, ApJ, 900, 179  
Mackey, A. D., Broby Nielsen, P., Ferguson, A. M. N., et al. 2008, ApJL, 681, L17  
Martig, M., Rix, H.-W., Silva Aguirre, V., et al. 2015, MNRAS, 451, 2230  
Nissen, P. E. 2013, Planets, Stars and Stellar Systems, Galactic Structure and Stellar Populations, Vol. 5 (Dordrecht: Springer Science & Business Media), 21  
Nissen, P. E., Cheng, X., Carigi, L., et al. 2014, A&A, 568, A25  
Nissen, P. E., Christensen-Dalsgaard, J., Mosumgaard, J. R., et al. 2020, A&A, 640, A81  
Nissen, P. E., Silva Aguirre, V., Christensen-Dalsgaard, J., et al. 2017, A&A, 608, A112  
Pavlenko, Y. V., Kaminsky, B. M., Jenkins, J. S., et al. 2019, A&A, 621, A112  
Reddy, B. E., Lambert, D. L., & Allende Prieto, C. 2006, MNRAS, 367, 1329  
Rogers, F. J., & Nayfonov, A. 2002, ApJ, 576, 1064  
Sharma, S., Hayden, M. R., Bland-Hawthorn, J., et al. 2022, MNRAS, 510, 734  
Silva Aguirre, V., Bojso-Hansen, M., Slumanstrup, D., et al. 2018, MNRAS, 475, 5487  
Spergel, D. N., Bean, R., Doré, O., et al. 2007, ApJS, 170, 377  
Wu, Y.-Q., Xiang, M.-S., Zhang, X.-F., et al. 2017, RAA, 17, 7  
Yang, W., Bi, S., Meng, X., et al. 2013, ApJ, 776, 112  
Yi, S., Demarque, P., Kim, Y.-C., et al. 2001, ApJS, 136, 417  
Yi, S. K., Kim, Y.-C., & Demarque, P. 2003, ApJ, 144, 259