**Planets Across Space and Time (PAST). II. Catalog and Analyses of the LAMOST–Gaia–Kepler Stellar Kinematic Properties**

Di-Chang Chen1,2 ☑, Jia-Yi Yang1,2 ☑, Ji-Wei Xie1,2 ☑, Ji-Lin Zhou1,2 ☑, Subo Dong3 ☑, Zheng Zheng4 ☑, Jing-Hui Zhang5 ☑, Yang Huang8 ☑, Ji-Lin Zhou1,2 ☑, Zheng Zheng4 ☑, and Ali Luo5 ☑

1 School of Astronomy and Space Science, Nanjing University, Nanjing 210023, People’s Republic of China; 2 Key Laboratory of Modern Astronomy and Astrophysics, Ministry of Education, Nanjing 210023, People’s Republic of China
2 Key Laboratory of Optical Astronomy, National Astronomical Observatories of China, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
3 Key Lab of Space Astronomy and Technology, National Astronomical Observatories, CAS, 100101, People’s Republic of China
4 Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
5 University of Chinese Academy of Sciences, Beijing, 100049, People’s Republic of China
6 Key Laboratory of Modern Astronomy and Astrophysics, Ministry of Education, Nanjing 210023, People’s Republic of China
7 Department of Astronomy, Beijing Normal University, Beijing 100875, People’s Republic of China
8 South-Western Institute for Astronomy Research, Yunnan University, Kunming, 650500, People’s Republic of China
9 CEPI, Observatoire de Paris, Université PSL, CNRS, Place Jules Janssen 92195, Meudon, France
10 Max-Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
11 Department of Astronomy, Beijing Normal University, Beijing 100875, People’s Republic of China

Received 2021 March 15; revised 2021 June 18; accepted 2021 June 22; published 2021 August 13

---

**Abstract**

The Kepler telescope has discovered over 4000 planets (candidates) by searching ∼200,000 stars over a wide range of distance (order of kpc) in our Galaxy. Characterizing the kinematic properties (e.g., Galactic component membership and kinematic age) of these Kepler targets (including the planet candidate hosts) is the first step toward studying Kepler planets in the Galactic context, which will reveal fresh insights into planet formation and evolution. In this paper, the second part of the Planets Across the Space and Time (PAST) series, by combining the data from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) and Gaia and then applying the revised kinematic methods from PAST I, we present a catalog of kinematic properties (i.e., Galactic positions, velocities, and the relative membership probabilities among the thin disk, thick disk, Hercules stream, and the halo) as well as other basic stellar parameters for 35,835 Kepler stars. Further analyses of the LAMOST–Gaia–Kepler catalog demonstrate that our derived kinematic age reveals the expected stellar activity-age trend. Furthermore, we find that the fraction of thin (thick) disk stars increases (decreases) with the transiting planet multiplicity \( N_p = 0, 1, 2 \) and 3+ and the kinematic age decreases with \( N_p \), which could be a consequence of the dynamical evolution of planetary architecture with age. The LAMOST–Gaia–Kepler catalog will be useful for future studies on the correlations between the exoplanet distributions and the stellar Galactic environments as well as ages.

**Unified Astronomy Thesaurus concepts:** Exoplanet catalogs (488); Stellar kinematics (1608); Exoplanets (498)

**Supporting material:** machine-readable table

---

**1. Introduction**

With the discovery of thousands of exoplanets, the scope of planetary research has been expanding from the Solar system/neighborhood to a wider range of the Milky Way. Understanding how planetary properties depend on the Galactic environment and age will provide crucial insights on planet formation and evolution. Toward a Galactic census of planets, we have started a research project; dubbed Planets Across Space and Time (PAST). In Paper I (hereafter PAST I; Chen et al. 2021) of the PAST series, we revisited the kinematic methods for classification of Galactic components and extended the applicable range of the methods from ∼100–200 pc to ∼1.5 kpc to cover most of planet candidate host stars. Additionally, we revised the age–velocity dispersion relation (AVR), which allows us to derive kinematic age with a typical uncertainty of ∼10%–20% for an ensemble of stars. Here, in the second paper of PAST (PAST II), we apply the revised kinematic methods and AVR to a large homogeneous sample of stars with the observational synergy among the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; also known as Goushoujing Telescope; spectroscopy; Wang et al. 1996; Su & Cui 2004; Cui et al. 2012; Luo et al. 2012; Zhao et al. 2012; Zong et al. 2018), Gaia (astrometry; Gaia Collaboration et al. 2018a, 2018b), and Kepler (photometry; Mathur et al. 2017).

The Kepler mission has provided an unprecedented legacy sample for stellar astrophysics and exoplanet science, thanks to the long-term baseline, high-precision observations of a large amount (∼200,000) of stars (Brown et al. 2011; Huber et al. 2014; Mathur et al. 2017), which discovered 2348 confirmed planets and 2368 candidates (data from NASA Exoplanet Archive; hereafter EA; Akeson et al. 2013), contributing to the majority of confirmed exoplanets and candidates. One of the advantages of the Kepler sample is that it is suitable for studies on planetary systems in the Galactic context because they spread over different Galactic environments in a wide region up to several kpc in our Milky way (Figure 13 of PAST I; Chen et al. 2021). In order to have a reliable Galactic census of planets, one needs accurate characterizations of the Kepler stars (not just the planet candidate hosts). For most Kepler stars, some stellar parameters can be measured in relatively high precision, e.g., 7% for mass, 4% for radius, and 112 K for effective temperature; while the uncertainty of stellar age is relatively large, e.g., 56% on average from isochrone fitting (Berger et al. 2020b). The kinematic properties (e.g., Galactic velocities and thin/thick disk memberships) of Kepler stars,
To ensure that the matched stars from radial velocity plus parallax, celestial coordinates release corresponding proper motions. Fortunately, the second Data candidate hosts 30% of all Kepler targets with no bias toward Kepler-planet-data from LAMOST, which provides radial velocities for over magnitude of Kepler stars (stars based on their astrometry and radial velocities provided by concerning stellar physical properties. Soderblom 2010; Bergemann et al. 2014) involving stellar evolutionary mode kinematic age, we only need the 3D space motions without on the kinematic characterization of the Kepler stars.

The Astronomical Journal, 162:100 (13pp), 2021 September

1.2 Kepler: Exoplanet Transit Surveys

We initialized our sample from the Kepler Data Release 25 (DR25) catalog, which contains 197,096 Kepler target stars as well as 8054 Kepler objects of interest (KOIs; Mathur et al. 2017). Here, we excluded KOIs flagged by false positive (FAP), leaving 4034 planets (candidates). We also removed potential binaries by eliminating stars with Gaia DR2 re-normalized unit-weight error > 1.2 (Rizzuto et al. 2018; Berger et al. 2020a) as additional motions caused by binary orbits could affect the results of kinematic characterization. After these cuts, we are left with 175,280 Kepler stars and 3620 planets (candidates).

2. Data Collections

This section describes how we constructed the stellar sample from Gaia, Kepler and LAMOST for kinematic characterizing.

2.1. Kepler: Exoplanet Transit Surveys

We initialized our sample from the Kepler Data Release 25 catalog, which contains 197,096 Kepler target stars as well as 8054 Kepler objects of interest (KOIs; Mathur et al. 2017). Here, we excluded KOIs flagged by false positive (FAP), leaving 4034 planets (candidates). We also removed potential binaries by eliminating stars with Gaia DR2 re-normalized unit-weight error > 1.2 (Rizzuto et al. 2018; Berger et al. 2020a) as additional motions caused by binary orbits could affect the results of kinematic characterization. After these cuts, we are left with 175,280 Kepler stars and 3620 planets (candidates).

2.2. Obtaining Five Astrometric Parameters from Gaia

To obtain the astrometric parameters for Kepler stars, we crossmatched them with Gaia DR2, which includes positions on the sky ($\alpha, \delta$), parallaxes, and proper motions ($\mu_x, \mu_y$) for more than 1.3 billion stars with a limiting magnitude of $G = 21$ and a bright limit of $G \approx 3$ (Gaia Collaboration et al. 2018a). The crossmatching was done by adopting the X-match service of the Centre de Donnees astronomiques de Strasbourg (CDS; http://cdsxmatch.u-strasbg.fr; Boch et al. 2012). After inspecting the distribution of separations, we select the separation limit of the crossmatching as where the distribution of separations displayed a minimum, $\sim1^\circ.5$. To ensure that the matched stars are of similar brightness, we also make a magnitude cut. The magnitude limit was set by inspecting the distribution of magnitude difference, which is 2 mag in Gaia $G$ mag. Multiple matches satisfied these two criteria for the same star and we kept the one with the smallest angular separation. After these selections, we obtained 163,454 stars and 3409 candidates.

2.3. Obtaining RV from LAMOST

Next, to obtain RV data, we rely on the spectroscopic data from LAMOST (Cui et al. 2012; Zhao et al. 2012). The LAMOST DR4 value-added catalog contains parameters derived from a total of 6.5 million stellar spectra for 4.4 million unique stars (Xiang et al. 2017). RVs, $T_{\mathrm{eff}}$, log $g$, and [Fe/H] have been deduced using both the official LAMOST Stellar parameter Pipeline (LASP; Wu et al. 2011) and the LAMOST Stellar Parameter Pipeline at Peking University (Xiang et al. 2015). The typical uncertainties for RVs, $T_{\mathrm{eff}}$, log $g$, and [Fe/H] are 5.0 km s$^{-1}$, 150 K, 0.25 dex, and 0.15 dex, respectively.

We crossmatched the foregoing sample with LAMOST DR4 value-added catalog by using CDS with the same procedure detailed in Section 2.2. By inspecting the distribution of separations and magnitude difference, the separation limit and magnitude cut were set as 5″ and 2.3 mag. Besides, we applied a quality cut of SNR > 10. To ensure the reliability of RV, we also crossmatched with the LAMOST DR7 catalog (http://dr7.lamost.org/) and removed the stars when the differences in RVs are larger than three times of the uncertainties. We only kept stars with a distance less than 1.54 kpc to the Sun, which is the applicable limit of the revised kinematic characteristics and AVR in PAST I (Chen et al. 2021). Finally we obtained a LAMOST–Gaia–Kepler sample of 35,835 stars and 1060 planets. In Table 1, we summarize the composition of the sample after each step mentioned above.

3. Methods: Classification of Galactic Components and Estimation of Kinematic Ages

In this section, we describe how we distinguish star into different Galactic components (Section 3.2) and estimate stellar
ages (Section 3.3) by revisiting the velocity ellipsoid and AVR from PAST I based on data from LAMOST and Gaia DR2.

### 3.1. Space Velocities and Galactic Orbits

We calculated the 3D Galactocentric cylindrical coordinates \((R, \theta, Z)\) by adopting a location of the Sun of \(R_\odot = 8.34\) kpc (Reid et al. 2014) and \(Z_\odot = 27\) pc (Chen et al. 2001). By adopting the formulae and matrix equations presented in Johnson & Soderblom (1987), we calculate the Galactic rectangular velocities relative to the Sun \((U, V, W)\) and their errors for the LAMOST–Gaia–Kepler sample. Here \(U\) is positive when pointing to the direction of the Galactic center, \(V\) is positive along the direction of the Sun orbiting around the Galactic center, and \(W\) is positive when pointing toward the North Galactic Pole. To obtain the Galactic rectangular velocities relative to the local standard of rest (LSR) \((U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}})\), we adopted the solar peculiar motion \([U_\odot, V_\odot, W_\odot] = [9.58, 10.52, 7.01]\) km s\(^{-1}\) (Tian et al. 2015). Cylindrical velocities \(V_R, V_\theta, V_Z\) are defined as positive with increasing \(R, \theta, \) and \(Z\), with the latter toward the North Galactic Pole.

### 3.2. Classification of Galactic Components

In this section, by adopting the widely-used kinematic approaches (Bensby et al. 2003, 2014), we classify stars into different Galactic components (i.e., thin disk, thick disk, halo, and Hercules stream) based on their Galactic positions and velocities. The kinematic methods assumes the Galactic velocities to the LSR \((U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}})\) have multidimensional Gaussian distributions:

\[
f(U, V, W) = k \times \exp\left\{ -\frac{(U_{\text{LSR}} - U_{\text{asym}})^2}{2\sigma_U^2} - \frac{(V_{\text{LSR}} - V_{\text{asym}})^2}{2\sigma_V^2} - \frac{W_{\text{LSR}}^2}{2\sigma_W^2} \right\},
\]

where \(\sigma_U, \sigma_V, \) and \(\sigma_W\) are the characteristic velocity dispersions, and \(V_{\text{asym}}\) and \(U_{\text{asym}}\) are the asymmetric drifts for different components (the thin disk, the thick disk, the halo, and the Hercules stream). The normalization coefficient is defined as

\[
k = \frac{1}{(2\pi)^{3/2}\sigma_U\sigma_V\sigma_W}.
\]

The relative probabilities between two different components, i.e., the thick-disk-to-thin-disk \((TD/D)\), thick-disk-to-halo \((TD/H)\), the Hercules-to-thin disk \((Herc/D)\), and the Hercules-to-thick disk \((Herc/D)\) can be calculated as

\[
\frac{TD}{D} = \frac{X_{TD}}{X_D} \cdot \frac{f_{TD}}{f_D}, \quad \frac{TD}{H} = \frac{X_{TD}}{X_H} \cdot \frac{f_{TD}}{f_H},
\]

\[
\frac{Herc}{D} = \frac{X_{Herc}}{X_D} \cdot \frac{f_{Herc}}{f_D}, \quad \frac{Herc}{TD} = \frac{X_{Herc}}{X_{TD}} \cdot \frac{f_{Herc}}{f_{TD}},
\]

where \(X\) is the fraction of stars for a given component.

Here we adopt the revised kinematic characteristics and X factor of different Galactic components in PAST I (Chen et al. 2021) and calculate the above Galactic component membership probabilities for the LAMOST–Gaia–Kepler stars. Then we classified them into different Galactic components by adopting the same criteria as in Bensby et al. (2014), which are:

1. thin disk: \(TD/D < 0.5\) and \(Herc/D < 0.5\);
2. thick disk: \(TD/D > 2\) and \(TD/H > 1\) and \(Herc/TD < 0.5\);
3. halo: \(TD/D > 2\) and \(TD/H < 1\) and \(Herc/TD < 0.5\);
4. Hercules: \(Herc/D > 1\) and \(Herc/TD > 1\).

### 3.3. Calculating Kinematic Age and Uncertainty

As described in Section 3.6 of PAST I, for a group of stars, the typical kinematic age can be derived by using the AVR, which gives

\[
\text{Age}_{\text{kin}} = t = \left(\frac{\sigma}{k \text{km s}^{-1}}\right)^{1/2} \text{Gyr},
\]

where \(\sigma\) is the velocity dispersion, which is defined as the root mean square of stellar Galactic velocity. \(k, \beta\) are the fitting coefficients of AVR. By means of error propagation, the relative uncertainty of kinematic age can be estimated as:

\[
\frac{\Delta t}{t} = \sqrt{\left(\frac{\partial \ln t}{\partial \beta} \Delta \beta\right)^2 + \left(\frac{\partial \ln t}{\partial k} \Delta k\right)^2 + \left(\frac{\partial \ln t}{\partial \sigma} \Delta \sigma\right)^2}
\]

\[
= \sqrt{\left(\ln \frac{t}{\text{Gyr}}\right)^2 \left(\frac{\Delta \beta}{\beta}\right)^2 + \left(\frac{1}{\beta^2}\left(\Delta k\right)^2 + \frac{1}{\beta^2}\left(\Delta \sigma\right)^2}\right)},
\]

where \(\Delta\) represents the absolute uncertainty. Here we adopt the two coefficients \((k, \beta)\) derived in PAST I (Chen et al. 2021), which are listed in Table 2.

### 4. A Catalog of LAMOST–Gaia–Kepler Stars with Kinematic Characterizations

Applying the methods described in Section 3 to the LAMOST–Gaia–Kepler sample (Section 2), we characterize the kinematic properties, e.g., Galactic orbit, velocities and the relative membership probabilities between different Galactic components \((TD/D, TD/H, Herc/D, \text{and Herc/TD})\) for the 35,835 LAMOST–Gaia–Kepler stars (Table 3). Among these stars, there are 764 stars hosting 1060 planets.

Based on the derived relative membership probabilities between different Galactic components \((TD/D, TD/H, Herc/D, \text{and Herc/TD in Table 3})\), following the criteria as mentioned in Section 3.2, we then classify the 35,835 stars into four Galactic components, i.e., thin disk, thick disk, Hercules stream and halo. For these stars not belonging to the above four components, we assign them into a category dubbed “in between” referring to Bensby et al. (2014).

The numbers of stars and planets in different Galactic components are summarized in Table 4. As can be seen, about
Table 3
The Catalog of the LAMOST–Gaia–Kepler Stellar Sample

| Column | Name | Format      | Units           | Description                                                                 |
|--------|------|-------------|-----------------|-----------------------------------------------------------------------------|
| 1      | Gaia_ID | Long        |                 | Unique Gaia source identifier                                                |
| 2      | LAMOST_ID | string      |                 | LAMOST unique spectral ID                                                    |
| 3      | Kepler_ID | integer     |                 | Kepler input catalog (KIC) ID                                               |
| 4      | Gaia RA | Double deg  |                 | Barycentric R.A.                                                            |
| 5      | Gaia Dec | Double deg  |                 | Barycentric decl.                                                           |
| 6      | Gaia parallax | Double mas |                 | Absolute stellar parallax                                                   |
| 7      | Gaia e_parallax | Double mas |                 | Standard error of parallax                                                  |
| 8      | Gaia pmra | Double mas yr^{-1} |                 | Proper motion in R.A. direction                                              |
| 9      | Gaia e_pmra | Double mas yr^{-1} |                 | Standard error of proper motion in R.A. direction                          |
| 10     | Gaia pmdec | Double mas yr^{-1} |                 | Proper motion in decl. direction                                             |
| 11     | Gaia e_pmdec | Double mas yr^{-1} |                 | Standard error of proper motion in decl. direction                         |
| 12     | Gaia G mag | Double mag |                 | Gaia G band apparent magnitude                                              |
| 13     | Kepler mag | Double mag |                 | Kepler apparent magnitude                                                   |
| 14     | T_{eff} | Float K     |                 | Effective temperature from LAMOST                                          |
| 15     | e_{T_{eff}} | Float K |                 | Error of effective temperature                                              |
| 16     | log g   | Float       |                 | Surface gravity from LAMOST                                                 |
| 17     | e_{log g} | Float       |                 | Error of surface gravity from LAMOST                                         |
| 18     | [Fe/H]  | Float dex   |                 | Metallicity from LAMOST                                                     |
| 19     | e_{[Fe/H]} | Float dex |                 | Error of metallicity                                                        |
| 20     | [\alpha/Fe]  | Float dex   |                 | $\alpha$ elements abundance from LAMOST                                     |
| 21     | e_{[\alpha/Fe]} | Float dex |                 | Error of $\alpha$ elements abundance                                       |
| 22     | v_t     | Double km s^{-1} |                 | Radial velocity from LAMOST                                                 |
| 23     | e_{v_t} | Double km s^{-1} |                 | Error of radial velocity                                                    |
| 24     | N_p    | integer     |                 | Planet (candidate) multiplicity                                              |

Parameters derived in this work

| 25 | R | Double kpc | Galactocentric Cylindrical radial distance |
| 26 | $\theta$ | Double deg | Galactocentric Cylindrical azimuth angle |
| 27 | Z | Double kpc | Galactocentric Cylindrical vertical height |
| 28 | V_R | Double km s^{-1} | Galactocentric Cylindrical $R$ velocities |
| 29 | V_theta | Double km s^{-1} | Galactocentric Cylindrical $\theta$ velocities |
| 30 | V_Z | Double km s^{-1} | Galactocentric Cylindrical $Z$ velocities |
| 31 | U_LSR | Double km s^{-1} | Cartesian Galactocentric $x$ velocity to the LSR |
| 32 | e_{U_LSR} | Double km s^{-1} | Error of Cartesian Galactocentric $x$ velocity to the LSR |
| 33 | V_LSR | Double km s^{-1} | Cartesian Galactocentric $y$ velocity to the LSR |
| 34 | e_{V_LSR} | Double km s^{-1} | Error of Cartesian Galactocentric $y$ velocity to the LSR |
| 35 | W_LSR | Double km s^{-1} | Cartesian Galactocentric $z$ velocity to the LSR |
| 36 | e_{W_LSR} | Double km s^{-1} | Error of Cartesian Galactocentric $z$ velocity to the LSR |
| 37 | TD/D | Double | thick disk to thin disk membership probability |
| 38 | TD/H | Double | thick disk to halo membership probability |
| 39 | Herc/D | Double | Hercules stream to thin disk membership probability |
| 40 | Herc/TD | Double | Hercules stream to thick disk membership probability |
| 41 | Component | string | Classification of Galactic components |

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

Table 4
Numbers of Stars ($N_s$) and Planets ($N_p$), and Kinematic and Chemical Properties of Different Galactic Components for the LAMOST–Gaia–Kepler Sample

| Galactic Component | $N_s$ | $N_p$ | $V_{LSR}$ (km s^{-1}) | [Fe/H] (dex) | [$\alpha$/Fe] (dex) | Age, kin (Gyr) |
|--------------------|------|------|------------------------|--------------|---------------------|-----------------|
| Thin disk          | 31,218 | 955  | 40.2$^{+3.9}_{-3.0}$  | $-0.03^{+0.13}_{-0.23}$ | $0.04^{+0.09}_{-0.07}$ | 2.49$^{+0.23}_{-0.19}$ |
| Thick disk         | 1832  | 36   | 109.3$^{+2.9}_{-2.2}$ | $-0.30^{+0.32}_{-0.30}$ | $0.16^{+0.12}_{-0.12}$ | 9.83$^{+1.16}_{-1.07}$ |
| Halo               | 59    | 0    | 291.3$^{+0.7}_{-0.7}$ | $-1.16^{+0.36}_{-0.53}$ | $0.27^{+0.21}_{-0.08}$ | NA              |
| Hercules           | 545   | 20   | 73.5$^{+0.3}_{-0.3}$  | $-0.09^{+0.24}_{-0.32}$ | $0.08^{+0.12}_{-0.09}$ | NA              |

87.1% (31,218/35,835) of the stars in our sample are in thin disk and about 5.1% (1832/35835) stars are in thick disk. The fractions of halo and Hercules stream stars are about 0.16% (59/35,835) and 1.5% (545/35,835). There are another ~6.1% (2181/35,835) stars belonging to the “in between” category.
To display the distribution of velocities, in Figure 1, we plot the Toomre diagram of the LAMOST–Gaia–Kepler stars. As can be seen, most stars with low velocities ($V_{tot} \lesssim 70$ km s$^{-1}$) are in the thin disk, while those with moderate velocities ($V_{tot} \sim 70$–$180$ km s$^{-1}$) are mainly in thick disk. The velocities of halo stars are all larger than 200 km s$^{-1}$. For the Hercules stream, most of these stars have $V_{SR}$ around $-50 \pm 9$ km s$^{-1}$ and $(U_{SR}^2 + W_{SR}^2)^{1/2}$ $\sim$ 30–90 km s$^{-1}$. This is very consistent with the results derived by previous works (e.g., Feltzing et al. 2003; Adibekyan et al. 2013; Bensby et al. 2014; Bonaca et al. 2017).

Then we compare the distributions of chemical abundances for different components in Figure 2. As expected, the thick disk stars are metal-poorer ($\sim$0.3 dex) and $\alpha$-richer ($\sim$0.1 dex) than the thin disk stars. The Hercules stream stars have velocities and chemical abundances that are between those of thin and thick disk stars. For the halo, these stars have the highest Galactic velocities, poorest [Fe/H], and richest [$\alpha$/Fe]. In Figure 3, we plot the total velocity $V_{tot}$, [Fe/H] and [$\alpha$/Fe] as a function of $TD/D$. As can be seen, with the increasing of $TD/D$, $V_{tot}$, and [$\alpha$/Fe] increase, while [Fe/H] decreases. Because there seems no clear trend between velocity dispersions and ages for stars in the halo and Hercules stream (Chen et al. 2021), here we only compare the age distributions for stars in the Galactic disk. The typical ages are $2.43^{+0.32}_{-0.19}$ Gyr and $9.83^{+1.30}_{-0.72}$ Gyr for thin and thick disk, respectively. The Numbers of stars and planets, kinematic properties, and chemical abundances of different Galactic components are summarized in Table 4.

For the sake of completeness, we also add the stellar parameters that were used during the process of our kinematic characterization (e.g., parallax, proper motion, and RV) and other basic stellar parameters (e.g., $T_{eff}$, log g, [Fe/H], and [$\alpha$/Fe]) into the catalog. In what follows, we conduct some further analyses and discussions on this catalog.

5. Further Catalog Analyses and Discussions

In this section, based on the LAMOST–Gaia–Kepler catalog, we perform some tests and comparisons to verify the reliability of the kinematic age (Section 5.1), explore the evolution of stellar magnetic activity with kinematic ages (Section 5.2), and analyze the kinematic properties of Kepler-planet-candidate host stars (Section 5.3).

5.1. Verifying the Kinematic Age

In order to verify the reliability of the kinematic age, we compare it with ages derived from other methods, such as asteroseismology, gyrochronology, and isochrone fitting in this subsection.

With seismic parameters $\Delta$ and $\nu$ derived from Kepler asteroseismic data, and spectroscopic parameters from the Apache Point Observatory Galactic Evolution Experiment project (Majewski et al. 2017), Pinsonneault et al. (2018) provided asteroseismic ages for 6676 evolved stars.

Gyrochronology can estimate the age of a main-sequence star based on its rotation period (Barnes 2010; Barnes & Kim 2010). We use rotation data for Kepler stars from McQuillan et al. (2013a, 2013b, 2014), and derive gyrochronology ages for 5851 stars by adopting the method provided by Spada & Lanzafame (2020).

Fitting isochrone grid provided by the latest MIST models ( Paxton et al. 2011, 2013, 2015, 2018; Choi et al. 2016; Dotter 2016), Berger et al. (2020b) obtained isotropic ages for 186,301 Kepler stars with a typical uncertainty of $\sim$56%. Here, we only consider stars with relatively reliable isochrone ages by applying the selection criteria as suggested by Berger et al. (2020b), i.e., stars with GOF > 0.99, having TAMS less than 20 Gyr, and metallicity measured by the spectroscopic method. We also remove stars with an isochrone age older than 14 Gyr.

In Figure 4, we compare kinematic age inferred from this work and ages derived with other methods to each other. Subplots in each column and row share the same x-axis and y-axis, respectively. We label the methods to derive age and the relevant literatures in the corresponding coordinates. In each subplot, we crossmatch the two samples shown in the x and y-axes, and print the number of stars in the matched sample in the left upper corner. We sort each sample in ascending order according to the x-axis, and divide them into 10 bins with approximately equal size. For asteroseismic, gyrochronology, and isochrone ages, the dots and error bars shown in Figure 4 are median ages and median values of relative error. For the kinematic age, we calculate the age and uncertainty with methods mentioned in Section 3.3.

Since the ages derived from asteroseismology are mainly for giant stars and gyrochronology applies only to main-sequence stars, there is no common star between these two samples and thus comparison has never been made between gyrochronology age and asteroseismic age yet. In the upper panels, the isochrone age is compared with asteroseismic age and gyrochronology age. The isochrone age exhibits systematic
Figure 2. The cumulative distributions of velocity $V_{\text{tot}}$ (a), [Fe/H] (b), and [$\alpha$/Fe] (c) for LAMOST–Gaia–Kepler stars of different Galactic components, i.e., thin disk, thick disk, halo, and Hercules stream.

Figure 3. Kinematic and chemical properties (from top to bottom: total velocity $V_{\text{tot}}$, abundances [Fe/H], and [$\alpha$/Fe]) as functions of the relative probability between thick disk to thin disk ($TD/D$) for the LAMOST–Gaia–Kepler stars. Medians and 1σ dispersions are marked in the plots. Histograms of $V_{\text{tot}}$, [Fe/H], and [$\alpha$/Fe] are shown in the right panels. Histogram of $TD/D$ is displayed in the topmost. The vertical dashed lines represent where $TD/D = 1$. 

The Astronomical Journal, 162:100 (13pp), 2021 September Chen et al.
deviation from asteroseismic age and apparent discrepancy with gyrochronology age for stars younger than 3 Gyr, though in most of the cases they are generally consistent with each other due to the large uncertainty of isochrone age. In the lower panels, we show comparisons between kinematic age and other ages. In general, kinematic age matches well with ages derived from asteroseismic, gyrochronology, and isochrone, with relative large differences only in the young end (<2 Gyr for asteroseismic age, <3 Gyr for gyrochronology, and isochrone ages). Such a discrepancy is not unexpected because the stellar velocity dispersion during the early days might be dominated by the initial condition rather than dynamical evolution and thus age derived from velocity dispersion would be overestimated.

5.2. Stellar Magnetic Activity Evolves with Kinematic Age

Stellar properties, such as rotation period and stellar activity, are indicators of stellar age. We explore the connections between them and kinematic age in this subsection.

We match our LAMOST–Gaia–Kepler sample with rotation periods from McQuillan et al. (2013a, 2013b, 2014) by KIC, obtaining 10,548 common stars. We sort the sample according to the TD/D value, divide them into 10 groups with approximately equal size, and calculate kinematic ages and uncertainties for each group using the method mentioned in Section 3.3. For each bin, we calculated the median rotation period and median value of relative error, and show them with dots and error bars in the upper panel of Figure 5. As kinematic age increases, the rotation period becomes longer, which is in agreement with the gyrochronology theory (Barnes 2010; Barnes & Kim 2010). For comparison, we show the age (4.57 Gyr) and rotation period (16.09 days) of the Sun with a yellow dot. As can be seen, the Sun is a typical star, which fits well to the kinematic age–rotation period trend.

In our LAMOST–Gaia–Kepler sample, 20,417 stars have the S-index measurements based on the LAMOST spectra (Zhang et al. 2020). We group the sample into 10 subgroups. For each bin, we calculate the median value of S index and the uncertainty is set as the median value of the relative error, which are plotted as dots and error bars in the upper panel of Figure 5. As stars age, stellar activity reduces and the median value of S index decreases as expected. For S index of the Sun, we adopt the mean value $\langle S \rangle = 0.1694$ suggested by Egeland et al. (2017), and plot it in the figure with a yellow dot. As can be seen, the Sun is exceptionally quiet as compared to stars in the LAMOST–Gaia–Kepler sample, confirming the results of previous studies (e.g., Reinhold et al. 2020).

Stellar magnetic activity can also be revealed by photometry. In Figure 6, we investigate how the photometric noise levels of stars change with kinematic age. For every target, Kepler DR 25 provides Combined Differential Photometric Precision...
than age, such as the evolve state, magnitude, and spectral type, we restrict our sample to stars with log \( g \) > 4, a Kepler magnitude (kepmag) lower than 14, and an effective temperature between 4700 and 6500 K, which contains 14,372 stars. Since CDPP is partly contributed by photon noise, following the method of Bastien et al. (2013), we subtract photon noise in quadrature from CDPP, i.e., CDPP—photon noise. Again, we group the star sample into 10 bins then calculate their corresponding kinematic ages and the median value of CDPP—photon noise. We show the CDPP—photon—Age noise relationship in Figure 6, each line with a different color presents CDPP with a different duration. For a longer duration, CDPP—photon noise decreases as stars age. The 15 hr CDPP—photon noise drops from 65 to 25 ppm as kinematic age grows from 0.3 to 12 Gyr. Gilliland et al. (2011) modeled the stellar noise level as a function of age and found that the total noise on a 6.5 hr timescale is dominated by stellar activity decreases as the stars age. Our result support their model from the aspect of observation. For a shorter duration, the declining trend between CDPP—photon noise and kinematic age is weaker. This is not unexpected because shorter timescale noises could be contributed to by granulation that generally increases with age, and thus compensating the decline trend. For main-sequence stars, the typical timescale of granulation is in the order of a few hundreds seconds (Gilliland et al. 2011; Kallinger et al. 2014). The effect of granulation will be more evident on CDPP with a shorter range, such as 1.5 hr.

5.3. Kinematic Properties of Kepler-planet Candidate Host Stars

In this section, we explore the differences between the kinematic properties of Kepler-planet-candidate host stars and those of other stars without Kepler planets, which are meaningful to study the formation and evolution environment of planetary systems. To avoid the influence of the stellar evolutionary stage and spectral type, here we only compare the distribution of Solar-type stars, which are the bulk of LAMOST–Gaia–Kepler sample. The selection criteria are taken as an effective temperature \( T_{\text{eff}} \) in the range of 4700–6500 K and a stellar surface gravity log \( g \) > 4.0. Finally, we are left with 563 Kepler-planet-candidate hosts and 20,795 stars without Kepler planets.

5.3.1. Spatial Distribution

Here we compare the distribution of spatial position in Figure 7. As can be seen, the stars without Kepler planets (solid black lines) have a wider distribution in the distance to the Sun, Galactic radius (\( R \)), azimuth angle (\( \theta \)), and height (\( Z \)) than that of Kepler-planet-candidate host stars (dashed red lines). We did Kolmogorov–Smirnov (KS) tests between the distance to the Sun, Galactic coordinates (\( R, \theta, Z \)) of the Kepler-planet-candidate host stars, and those of stars without Kepler planets. The resulting \( p \)-values are all smaller than 0.003, demonstrating that there are significant differences between their spatial positions. As shown in Figures 5 and 6, the stellar activity (and therefore noise properties) are correlated to their kinematics. This may affect the detectability of planets in multiplanet systems, e.g., by creating a bias against smaller planets around active/noisy stars (typically corresponding to younger stars) Thus in the following comparison in stellar kinematic properties, to avoid the bias caused by spatial distribution and stellar
activity/noise, we construct a control sample by adopting the NearestNeighbors function in scikit-learn (Pedregosa et al. 2011) to select the nearest neighbors for every host star from stars without Kepler planets in their spatial distribution (i.e., \( R, \theta, \) and \( Z \)), CDPP, and \( S_{\text{index}} \). Here we select the CDPP of 4.5 hr as the transit duration are 4.3 hr by taking the median values of stellar mass (1.03 \( M_\odot \)), radius (1.10 \( R_\odot \)), and planetary period (10.37 days) in our sample. In the case that a star without planets is selected as the nearest neighbors for every Kepler-planet-candidate host star from stars without Kepler planets (labeled as \( N_p = 0 \text{ (Nei)} \)). In each panel, the \( p \) denotes the \( p \)-value of the two sample KS test for the distributions of the other samples (the subscripts are the same as the labels) compared to the neighbor stars without Kepler planets (\( N_p = 0 \text{ (Nei)} \)).

In the following discussions, we divided the Kepler-planet-candidate host sample into three subsamples according to the number of transiting planets (\( N_p \)) in each system: \( N_p = 1 \) (403 stars), \( N_p = 2 \) (100 stars), and \( N_p \geq 3 \) (60 stars). The \( p \)-values of the KS test between the distribution of the distance and Galactic coordinates for the neighbor stellar sample without Kepler planets and the three subsamples (blue, yellow, red lines in Figure 7) are all larger than 0.25, which proves that their spatial distribution are statistically indistinguishable. Therefore, the selected neighbor stars form a reliable control sample to minimize the spatial and detection bias.

In Table 5, we summarized the typical value of physical properties. The uncertainties are taken as the 50 ± 34.1

![Figure 7](image-url)
and TD/D becomes greater and greater with the increase of \( N_p \). Especially for stars hosting 2 and 3+ tranets systems, the \( p \)-values are smaller than 0.05, demonstrating statistically smaller Galactic velocities and TD/D (smaller fraction of thick disk).

Next, we compare the number fractions of different Galactic components. The number fractions of different Galactic components are calculated with the following formula:

\[
F_i = \frac{N_i}{N_D + N_{TD} + N_H + N_{Herc} + N_{IB}},
\]

where \( i \) represents the different Galactic components, i.e., \( D \), TD, \( H \), Herc, and in between. To obtain the uncertainties, we assume that the observation numbers of different Galactic components obey the Poisson distribution. Then we resample the observation numbers of different Galactic components from the given distribution and calculate the number fractions for 10,000 times. The uncertainty (1σ interval) of each parameter is set as the range of 50 ± 34.1 percentages of the 10,000 calculations. The fractions of different components for the stellar sample without Kepler planets, the Kepler-planet-candidate host sample, and the three subsamples are summarized in Table 5. We find that with the increase of planet multiplicity (\( N_p \) from 0 to 3+), the number fraction of the thin disk \( F_D \) increases, while the fraction of thick disk \( F_{TD} \) generally decreases, which are illustrated in the upper and middle panels of Figure 9.

Then, we compare the kinematic ages of stars with and without Kepler planets. The kinematic ages and uncertainties are calculated from the velocity dispersions with Equations (5) and (6). As suggested in PAST I, there is no clear trend between velocity dispersions and ages for stars belonging to Hercules stream and halo. Therefore we only consider stars with Herc/\( D < 0.5 \) & Herc/\( TD < 0.5 \) & TD/\( H > 1 \) in calculating the kinematic ages. As shown in the bottom panel of Figure 9, the typical ages decrease from 4.49±0.60 Gyr, 3.82±0.50 Gyr, 2.98±0.36 Gyr to 2.84±0.34 Gyr when the number of planets \( N_p \) increases from 0 to 3+. In 10,000 sets of resampled data, the kinematic age of neighbor non-Keplerian-planet candidate host

| \( M_\star \) (\( M_\odot \)) | \( R_\star \) (\( R_\odot \)) | [Fe/H] (dex) | \( \alpha/\text{Fe} \) (dex) | \( F_D \) | \( F_{TD} \) | \( F_H \) | \( F_{Herc} \) | \( V_{\text{rot}} \) (km s\(^{-1}\)) | \( \sigma_{\text{rot}} \) (km s\(^{-1}\)) | Age_Kin (Gyr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.06±0.21 | 1.20±0.41 | -0.02±0.19 | 0.05±0.10 | 86.9±0.27 | 5.2±0.26 | 0.17±0.02 | 1.6±0.06 | 44.06±31.14 | 49.07±0.84 | 4.28±0.55 |
| 1.04±0.20 | 1.15±0.38 | -0.01±0.19 | 0.05±0.09 | 86.8±0.25 | 5.8±1.0 | 0.36±0.25 | 0.90±0.59 | 43.05±22.04 | 49.99±11.21 | 4.49±0.60 |
| 1.03±0.18 | 1.09±0.39 | -0.01±0.19 | 0.04±0.09 | 88.8±1.76 | 5.5±1.2 | 0.5% | 1.8±0.5 | 37.89±17.49 | 46.92±17.29 | 3.82±0.50 |
| 1.03±0.18 | 1.12±0.38 | -0.01±0.19 | 0.04±0.09 | 88.8±1.76 | 5.5±1.2 | 0.5% | 1.8±0.5 | 37.89±17.49 | 46.92±17.29 | 3.82±0.50 |
| 1.03±0.18 | 1.13±0.38 | -0.01±0.19 | 0.04±0.09 | 90.0±3.17 | 5.5±1.2 | 0.5% | 1.8±0.5 | 37.89±17.49 | 46.92±17.29 | 3.82±0.50 |
| 1.03±0.18 | 1.13±0.38 | -0.01±0.19 | 0.04±0.09 | 91.7±3.5 | 5.5±1.2 | 0.5% | 1.8±0.5 | 37.89±17.49 | 46.92±17.29 | 3.82±0.50 |

Table 5: Stellar Properties of Kepler-planet Candidate Host Stars and Stars Without Kepler Planets

Note. \( F \) represents the number fraction of different components: thin disk (\( D \)), thick disk (\( TD \)), halo (\( H \)), and Hercules stream (\( Herc \)).
A sample is bigger than that of $N_p = 1$, $N_p = 2$, and $N_p \geq 3$ subsamples for 8639, 9981, and 9995 times, corresponding to confidence level of 86.39%, 99.81%, and 99.95% respectively. We therefore conclude that the ages of 2 and 3 transiting planets systems are statistically smaller than stars without Kepler planets, while there is no significant difference for one transiting system within the precision of our age estimations. We summarized the median value and 1σ interval of physical and kinematic properties in Table 5.

Last but not least, we evaluate the statistical significance of the above trends as seen in Figure 9. As can be seen in Figure 9, with the increase of $N_p$, the number fraction of the thin disk $F_D$ increases, while the fraction of thick disk $F_{TD}$ and kinematic age $\text{Age}_{\text{kin}}$ generally decrease. To describe the property of the above trends mathematically, we fit the relation between $F_D$, $F_{TD}$, $\text{Age}_{\text{kin}}$ as a function of $N_p$ with two models: constant model ($y = A_0$) and linear model ($y = A \times N_p + b$). For each model, we fit the relationships with the Levenberg–Marquardt algorithm (LMA). In order to compare the fitting of different models, we calculate the Akaike information criterion (AIC; Cavanaugh 1997) for each model. The AIC differences between the constant and linear model ($\Delta \text{AIC} = \text{AIC}_{\text{con}} - \text{AIC}_{\text{lin}}$) are 14.36, 7.69, and 9.15 for the trend of $F_D$, $F_{TD}$, and $\text{Age}_{\text{kin}}$, respectively. Therefore a constant model can be confidently ruled out compared with the linear model with an AIC score difference $\Delta \text{AIC} > 6$. To obtain the confidence level, we fit the relationships with LMA for the foregoing resampled data of $F_D$, $F_{TD}$, and $\text{Age}_{\text{kin}}$. Of the 10,000 sets of resampling and fitting, the linear models are preferred with a
smaller AIC score than the constant model for 9525, 9724, and 9948 sets for the $F_D$, $F_{TD}$, and $Age_{kin}$, corresponding to a confidence level of 95.25%, 97.24%, and 99.48%, respectively.

Furthermore, as shown in Figure 4, kinematic age is overestimated as compared to asteroseismic age at the young end, i.e., <2–3 Gyr. If one adopts such an age correction, the actual age of multiplanet systems (shown in bottom panel of Figure 9) should be smaller, which will make the trend even stronger.

Based on the above tests, we conclude that the trends between $F_D$, $F_{TD}$, $Age_{kin}$, and $N_p$ as shown in Figure 9 are statistically significant. The trends cannot be explained by the spatial bias and other effects related to stellar mass, radius, temperature, and chemical abundances because, as can be seen in Table 5 and Figure 7, the Kepler-planet-candidate host subsamples and the control sample all have similar distributions in spatial positions and physical properties. Therefore, we believe that these trends may be some footprints left in the evolution of planetary dynamics.

6. Summary

The Kepler mission has detected over 4000 planets (candidates) by monitoring ~200,000 stars. Accurately characterizing the properties of these stars is essential to study planet properties and their relations to stellar hosts and environments. Previous studies have investigated some of basic stellar properties, e.g., mass, radius (Berger et al. 2018), and metallicity (Dong & Zhu 2013); however, the kinematic properties (e.g., Galactic component memberships and kinematic ages) of these stars are yet to be well characterized.

In this paper, as Paper II of the PAST series, we construct a LAMOST–Gaia–Kepler catalog of 35,835 Kepler stars and 764 Kepler-planet-candidate host stars with kinematic properties as well as other basic stellar properties (Section 4, Table 3) by combining data from Gaia DR2 and LAMOST DR4 (Section 2, Table 1). By adopting the revised kinematic methods in PAST I, we calculate the kinematics (i.e., Galactic position and velocity) and the Galactic component membership probabilities for the stars and then classify them into different Galactic components. The fractions of stars belonging to the thin disk, thick disk, Halo, and Hercules stream are 87.1% (31,218/35,835), 5.1% (1832/35,835), 0.16% (59/35,835), and 1.5% (545/35,835), respectively. We also explore the kinematics and chemical abundances of different Galactic components. As expected, from the thin disk, Hercules stream, thick disk to the halo, the Galactic velocity is getting larger, the metallicity [Fe/H] decreases, and [$\alpha$/Fe] increases (Table 4 and Figure 2).

Based on our LAMOST–Gaia–Kepler catalog, we derive the stellar kinematic ages with typical uncertainties of 10%–20% by adopting the refined AVR of PAST I (Chen et al. 2021). Compared to ages derived from other methods (Section 5.1), we find kinematic age generally matches with asteroseismic, gyrochronology, and isochrone ages (Figure 4). We have carried out some analyses to explore the connection between stellar activity and kinematic age (Section 5.2). As expected, as stars age, they spin down and become less active in terms of both the magnetic S index (Figure 5) and the photometric variability (Figure 6), which, in turn, verify the kinematic ages derived in this work.

We have also explored the differences in kinematic properties (e.g., Galactic velocities, thin/thick disk memberships, and kinematic ages) between the Kepler-planet-candidate hosts and stars without Kepler planets (Section 5.3). For the aspect of spatial position, the stars without Kepler planets have a wider distribution in the distance to the Sun, Galactic radius ($R$), azimuth angle ($\theta$), and height ($Z$) than that of Kepler-planet-candidate host stars (Figure 7), which could be an observational selection bias as planet systems closer to us are easier to be detected (e.g., McTier & Kipping 2019). Thus for a fair comparison between the kinematic properties of stars with and without Kepler planets, we construct a control sample by selecting the nearest neighbors of planet candidate hosts in the spatial distribution (Figure 7). Compared to stars in the control sample, we find that planet candidate hosts, especially those with large planet multiplicity ($N_p \geq 3$), differ significantly in distributions of the Galactic velocity $V_{\alpha \text{Gal}}$ and the relative probability between thick and thin disks $TD/D$ (Figure 8). In particular, we find a trend that the fraction of thin (thick) disk stars increases (decreases) with transiting planet multiplicity ($N_p$) and the kinematic age decreases with $N_p$ (Figure 9 and Table 5). This provides insights into the formation and evolution of planetary systems with the Galactic components and stellar age. One possible explanation for the trend is that the long-term dynamical evolution can pump up orbital eccentricity/inclination of planets (e.g., Zhou et al. 2007) or even cause planet merger/ejection (e.g., Pu & Wu 2015), which reduces the observed transiting planet multiplicity, i.e., $N_p$. Specifically, in a subsequent paper of the PAST project (J. Y. Yang et al. 2021, in preparation), we will study whether/how planetary occurrence and architecture (e.g., inclination) change with the ages and Galactic environments based on the LAMOST–Gaia–Kepler catalog of this work.

The LAMOST–Gaia–Kepler catalog provides the kinematics, Galactic component memberships, [Fe/H], [$\alpha$/Fe], and ages information for thousands of planets (candidates) down to about the Earth radius and tens of thousands of well-characterized field stars with no bias toward Kepler-planet-candidate hosts, which will be useful for more future studies of exoplanets at different positions/components of the Galaxy with different ages. The answers to these questions will deepen our understanding of planet formation and evolution.

This work has included data from Guoshoujing Telescope (LAMOST), which is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. This work presents results from the European Space Agency space mission Gaia. Gaia data are being processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular the institutions participating in the Gaia MultiLateral Agreement. The Gaia mission website is https://www.cosmos.esa.int/Gaia. The Gaia archive website is https://archives.esac.esa.int/Gaia. We acknowledge the NASA Exoplanet archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

This work is supported by the National Key R&D Program of China (No. 2019YFA0405100) and the National Natural Science Foundation of China (NSFC; grant No. 11933001, 11973028, 11803012, 11673011, 12003027). J.-W.X. also acknowledges the support from the National Youth Talent Support Program and the Distinguished Youth Foundation of...
Jiangsu, C.L. thanks National Key R&D Program of China No. 2019YFA0405500 and the NSFC with grant No. 11835057. H.F.W. is supported by the LAMOST Fellow project, National Key Basic R&D Program of China via 2019YFA0405500, and funded by China Postdoctoral Science Foundation via grant 2019M653504 and 2020T103563, Yunnan province postdoctoral Directed culture Foundation, and the Cultivation Project for LAMOST Scientific Payoff and Research Achievement of CAMS-CAS. M.X. & Y.H. acknowledge the National Natural Science Foundation of China (grant No. 11703035).

ORCID iDs

Di-Chang Chen  https://orcid.org/0000-0003-0707-3213
Jia-Yi Yang  https://orcid.org/0000-0002-6332-0453
Ji-Wei Xie  https://orcid.org/0000-0002-6472-5348
Ji-Lin Zhou  https://orcid.org/0000-0003-1680-2940
Subo Dong  https://orcid.org/0000-0002-1027-0990
Zheng Zheng  https://orcid.org/0000-0003-1887-6732
Chao Liu  https://orcid.org/0000-0002-1802-6917
Hai-Feng Wang  https://orcid.org/0000-0001-8459-1036
Mao-Sheng Xiang  https://orcid.org/0000-0002-5818-8769
Weikai Zong  https://orcid.org/0000-0002-7660-9803
Yang Huang  https://orcid.org/0000-0003-3250-2876
Ali Luo  https://orcid.org/0000-0001-7865-2648

References

Adibekyan, V. Z., Figueira, P., Santos, N. C., et al. 2013, A&A, 554, A44
Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, PASP, 125, 989
Barnes, S. A. 2010, ApJ, 722, 222
Barnes, S. A., & Kim, Y.-C. 2010, ApJ, 721, 675
Bastien, F. A., Stassun, K. G., Basri, G., & Pepper, J. 2013, Nat, 500, 427
Bensby, T., Feltzing, S., & Lundström, I. 2003, A&A, 410, 527
Bensby, T., Feltzing, S., & Oey, M. S. 2014, A&A, 562, A71
Bergemann, M., Ruchti, G. R., Serenelli, A., et al. 2014, A&A, 565, A89
Berger, T. A., Huber, D., Gaidos, E., & van Sader, J. L. 2018, ApJ, 866, 99
Berger, T. A., Huber, D., Gaidos, E., van Sader, J. L., & Weiss, L. M. 2020a, AJ, 160, 108
Berger, T. A., Huber, D., van Sader, J. L., et al. 2020b, AJ, 159, 280
Boch, T., Pineau, F., & Derrière, S. 2012, in ASP Conf. Ser. 461, Astronomical Data Analysis Software and Systems XXI, ed. P. Ballester, D. Egret, & N. P. F. Lorente (San Francisco, CA: ASP), 291
Bonaca, A., Conroy, C., Wetzel, A., Hopkins, P. F., & Kereš, D. 2017, ApJ, 845, 101
Brown, T. M., Latham, D. W., Everett, M. E., & Esqueor, G. A. 2011, AJ, 142, 112
Cavanaugh, J. E. 1997, Stat. Probab. Lett., 33, 201

C.L. thanks the National Key R&D Program of China No. 2019YFA0405500 and the NSFC with grant No. 11835057. H.F.W. is supported by the LAMOST Fellow project, National Key Basic R&D Program of China via 2019YFA0405500, and funded by China Postdoctoral Science Foundation via grant 2019M653504 and 2020T103563, Yunnan province postdoctoral Directed culture Foundation, and the Cultivation Project for LAMOST Scientific Payoff and Research Achievement of CAMS-CAS. M.X. & Y.H. acknowledge the National Natural Science Foundation of China (grant No. 11703035).