The non-monotonic, strong metallicity dependence of the wide-binary fraction
Hsiang-Chih Hwang,1 Yuan-Sen Ting,2,3,4,5,* Kevin C. Schlaufman,1 Nadia L. Zakamska,1 and Rosemary F.G. Wyse1

1Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
2Institute for Advanced Study, Princeton, NJ 08540, USA
3Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA
4Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA
5Research School of Astronomy & Astrophysics, Australian National University, Cotter Rd., Weston, ACT 2611, Australia

ABSTRACT
The metallicity dependence of the wide-binary fraction in stellar populations plays a critical role in resolving the open question of wide binary formation. In this paper, we investigate the metallicity ([Fe/H]) and age dependence of the wide-binary fraction (binary separations between 10^3 and 10^4 AU) for field F and G dwarfs within 500 pc by combining their metallicity and radial velocity measurements from LAMOST DR5 with the astrometric information from Gaia DR2. We show that the wide-binary fraction strongly depends on the metallicity: as metallicity increases, the wide-binary fraction first increases, peaks at [Fe/H] ≃ 0, and then decreases at the high metallicity end. The wide-binary fraction at [Fe/H] = 0 is about two times larger than that at [Fe/H] = −1 and [Fe/H] ≃ +0.5. This metallicity dependence is dominated by the thin-disk stars. Using stellar kinematics as a proxy of stellar age, we show that younger stars have a higher wide-binary fraction. We propose that multiple formation channels are responsible for the metallicity and age dependence. In particular, the positive metallicity correlation at [Fe/H] < 0 and the age dependence may be due to the denser formation environments and higher-mass clusters at earlier times. The negative metallicity correlation at [Fe/H] > 0 can be inherited from the similar metallicity dependence of close binaries, although we cannot rule out the possibility that radial migration may play a role in enhancing the wide-binary fraction around the solar metallicity.

Keywords: binaries: general — stars: kinematics and dynamics — stars: abundances — stars: formation

1. INTRODUCTION
Wide binaries are weakly bound, as such they are sensitive to the gravitational perturbations in the Milky Way and have been used to investigate the visible and invisible Galactic structures (Heggie 1975; Bahcall & Soneira 1981; Bahcall et al. 1985; Weinberg et al. 1987; Chaname & Gould 2004; Yoo et al. 2004; Quinn et al. 2009; Jiang & Tremaine 2010). Wide binaries may also be able to probe the dark matter substructure in dwarf galaxies (Peñarrubia et al. 2016). Furthermore, a significant fraction of stars are in binaries and multiple systems (Abt & Levy 1976; Duquennoy & Mayor 1991; Fischer & Marcy 1992; Duchêne & Kraus 2013), and about half of wide binaries (separations a > 1000 AU) are the outer binaries of high-order hierarchical systems (Raghavan et al. 2010; Tokovinin 2014a,b; Moe & Di Stefano 2017), so understanding the formation of wide binaries is crucial for the formation of hierarchical systems and the implications for both large-scale and small-scale Galactic structures.

The formation of wide binaries is still not well understood. They are unlikely to form by capture of random field stars, due to the low stellar density in the field (e.g. Goodman & Hut 1993). This is further supported by the similarity of the chemical compositions of the wide binary components with separations ≤ 1 pc ∼ 2 × 10^5 AU (Andrews et al. 2018, 2019; Hawkins et al. 2020), indicating that the components of wide binaries are born together, and several mechanisms have been proposed for their formation. For example, turbulent core fragmentation can form binaries with separations from ∼ 100 AU to ∼ 1000 AU (Padoan & Nordlund 2002; Fisher 2004; Offner et al. 2010). Binaries

* Hubble Fellow
with separations of $10^3 - 10^5$ AU can be formed through the dynamical unfolding of compact triples (Reipurth & Mikkola 2012), the dissolution of star clusters (Kouwenhoven et al. 2010; Moekel & Clarke 2011), or by the random pairing of adjacent pre-stellar cores (Tokovinin 2017). Many observational efforts have been directed at constraining the formation of wide binaries. Several young (< a few Myr) wide binaries have been found (e.g. Kraus et al. 2011; Pineda et al. 2015; Tobin et al. 2016b; Lee et al. 2017), supporting the proposal that wide binaries can be formed during the pre-main sequence phase, through turbulent core fragmentation and/or the pairing of pre-stellar cores. However, it is known that the wide-binary fraction is higher in pre-main sequence stars compared to that of field stars (Ghez et al. 1993; Köhler et al. 2000). Furthermore, the separation distribution of binaries in low-density star-forming regions (Simon 1997; Kraus & Hillenbrand 2009; Tobin et al. 2016a; Joncour et al. 2017) is found to be flatter than that of main-sequence field binaries (Tokovinin & Lépine 2012; El-Badry & Rix 2018). It has been argued that these differences may arise from the different formation environments and/or ages in the current young star-forming regions compared to those of the field stars (Kroupa 1995; Kraus & Hillenbrand 2009). Therefore, it remains challenging to directly infer the formation of field wide binaries from the multiplicity in young star-forming regions alone.

Theory has suggested that wide binaries can form from the dissolution of clusters (Kouwenhoven et al. 2010; Moekel & Clarke 2011), which similar to the turbulent core fragmentation and the random pairing of pre-stellar cores, is also environment-dependent. In this scenario, wide binaries are formed by the pairing of initially unbound stars when the cluster rapidly expands after gas expulsion. The formation timescale of wide binaries in this case correlates with how fast the gas is dispersed, which is of the order of ~10 Myr (Lada & Lada 2003; Bastian et al. 2005; Fall et al. 2005; Mengel et al. 2005). Kouwenhoven et al. (2010) show that the dissolution of lower-mass clusters results in a higher wide-binary fraction because the lower velocity dispersion increases the pairing probability in the phase space. Observational studies find a lower wide-binary fraction in open clusters than that of the low-density star-forming regions and the field (Bouvier et al. 1997; Deacon & Kraus 2020). Since the surviving open clusters are usually at the massive end of the cluster mass function, these results are most likely due to that the high-density environments reduce the wide binary formation within the clusters. Therefore, the wide-binary fraction resulting directly from the cluster dissolution remains not well constrained.

Besides forming from the dissolution of clusters, wide binaries can also form through the dynamical unfolding of compact triples. Three stars are initially formed in a compact, unstable configuration, and the subsequent dynamical evolution can bring one component closer and push the other component further away, and if it is not ejected entirely, the object appears as a wide binary (Reipurth & Mikkola 2012). This scenario is supported by that these wide systems are frequently members of higher-order multiples (Law et al. 2010; Allen et al. 2012; Elliott & Bayo 2016), and that main-sequence contact binaries have a factor of 3 higher wide companion fraction at separations > 1000 AU than that of the field stars (Hwang et al. 2020). However, the importance of the dynamical unfolding to form wide binaries is still debated. In particular, this scenario should lead to outer companions with eccentric orbits, but Tokovinin (2020) shows that the eccentricity distribution of wide binaries is close to thermal, inconsistent with the dynamical unfolding explanation.

With the multiple interconnected formation channels, the exact explanation remains elusive despite decades of research. This situation is drastically changing with the advent of recent large spectroscopic surveys. In particular, metallicity dependence of binary fraction measured from these surveys is proving useful in disentangling binary formation. In terms of close binaries, recent studies have shown that the close-binary fraction is anti-correlated with metallicity (Grether & Lineweaver 2007; Raghavan et al. 2010; Yuan et al. 2015; Badenes et al. 2018; Moe et al. 2019; El-Badry & Rix 2019; Mazzola et al. 2020). This finding supports the scenario that close binaries are formed via disk fragmentation and the lower-metallicity disks are more prone to fragmentation (Kratter & Matzner 2006; Tanaka & Omukai 2014; Moe et al. 2019; Tokovinin & Moe 2020). Alternatively, radiation hydrodynamical simulations from Bate (2019) suggest that the anti-correlation between close-binary fraction and metallicity could also be explained by the fact that lower metallicities facilitate all kinds of small-scale fragmentation (disk, filament, and core fragmentation), not just disk fragmentation. Regardless of their exact physical explanations, it has been proposed that such metallicity dependence of the close-binary fraction may ultimately be passed on to their final products – blue stragglers (Wyse et al. 2020).

While the studies of close binaries have reached more consensus, the metallicity dependence of the wide-binary fraction is less conclusive, with competing conclusions from various studies (Zapatero Osorio & Mar-
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Wu et al. 2011a,b) and the data-driven Payne pipeline from the LAMOST Stellar Parameter pipeline (LASP; providing a rich dataset for Galactic archaeology.

In a recent study, El-Badry & Rix (2019) investigate the binary fraction as a function of separation and metallicity. They use Gaia DR2 to establish the comoving pair sample within 200 pc (El-Badry & Rix 2018), and combine it with wide-field spectroscopic surveys, including LAMOST, RAVE, APOGEE, GALAH, and Hypatia. They find an emergence of an anti-correlation between the binary fraction and metallicity at separations $a < 200$ AU, while the binary fraction at $a \geq 200$ AU remains relatively constant with respect to metallicity. The authors conclude that a significant fraction of binaries with $a < 200$ AU are formed by disk fragmentation while binaries with $a \geq 200$ AU may be formed from turbulent core fragmentation which may be formed from turbulent core fragmentation which has a weaker dependence on metallicity.

In this paper, we revisit the metallicity dependence of field wide binaries ($a = 10^3 - 10^4$ AU) using the LAMOST and Gaia DR2 datasets. Our sample consists of stars out to 500 pc, important for inclusion of sufficient numbers of the thick and halo stars. By doubling the sample size compared to El-Badry & Rix (2019) and, more importantly, dissecting the kinematics of these stars as age proxy which is left unexamined in El-Badry & Rix (2019), we are able to investigate metallicity and age effects and better constrain both the formation and evolution scenarios for wide binaries.

Through out the paper, we refer to wide binaries as those with separations between $10^3$ to $10^4$ AU. While we adopt the notation ‘binary’ for our multiple systems, we caution that some of them might be actually unresolved higher-order multiples. The paper is organized as follows. Section 2 describes the LAMOST and Gaia datasets and the method of searching for comoving companions. Section 3 presents our main result that the wide-binary fraction is strongly dependent on the metallicity. We discuss the implications for the wide binary formation in Section 4 and conclude in Section 5.

2. SAMPLE SELECTION AND METHOD

2.1. LAMOST and metallicity measurements

Our sample is selected from The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Deng et al. 2012; Zhao et al. 2012). In its final data release of the LAMOST Phase I (2011–2017) survey, LAMOST DR5 has released optical (3700–9000 Å) low-resolution spectra ($R \sim 1800$) for about 10 million stars, providing a rich dataset for Galactic archaeology.

The metallicity ([Fe/H]) used in this work is derived from the LAMOST Stellar Parameter pipeline (LASP; Wu et al. 2011a,b) and the data-driven Payne pipeline (DD-Payne; Xiang et al. 2019). LASP fits the observed spectrum using a full spectrum fitting package ULySS (Université de Lyon Spectroscopic analysis Software; Koleva et al. 2009). Specifically, each observed spectrum is fit to a grid of model spectra based on the ELODIE library (Prugniel & Soubran 2001; Prugniel et al. 2007) to derive $T_{\text{eff}}$, log $g$, and [Fe/H].

The Payne is designed to measure multiple elemental abundances where the model spectra are emulated with neutral networks (Ting et al. 2019). When combined with data-driven models with theoretical prior, the Payne can be applied to low-resolution spectra ($R \sim 1000$) to derive reliable elemental abundances, a method that has been dubbed the name Data-Driven Payne, or DD-Payne (Ting et al. 2017a,b, see also Ness et al. 2015; O’Briain et al. 2020). Based on this, Xiang et al. (2019) train the spectral model using the LAMOST stars where the stellar labels have been derived from other high-resolution surveys like GALAH (De Silva et al. 2015) and APOGEE (Majewski et al. 2017). DD-Payne provides a final product with stellar parameters ($T_{\text{eff}}$, log $g$, $V_{\text{mic}}$) and 16 elemental abundances.

By comparing the metallicity measured by LASP and DD-Payne, we find that LASP metallicities are systematically higher than DD-Payne metallicities by 0.07 dex, with a standard deviation of 0.07 dex. The 0.07 dex offset between LASP and DD-Payne does not strongly correlate with metallicity. Since LASP metallicities are calibrated to the ELODIE spectral library and DD-Payne ties the metallicity to APOGEE, this systematic offset might be due to the different abundance scale used by ELODIE and APOGEE (M. Xiang, private communication). Otherwise, the small scatter of 0.07 dex shows that the metallicities of LASP and DD-Payne are in good agreement. Since we focus on the relative trend of the wide-binary fraction with respect to metallicity, the accuracy of the absolute values of metallicities is not the main concern.

2.2. Gaia and the comoving companion search

We use Gaia Data Release 2 (DR2) to search for the comoving companions around the LAMOST stars. Gaia DR2 provides broad-filter G-band magnitudes, blue-band BP magnitudes, red-band RP magnitudes, sky positions, parallaxes, and proper motions for 1.33 billion objects and radial velocities for 7 million stars (Gaia Collaboration et al. 2016, 2018a), resulting in an unprecedented dataset for the phase-space information of the Milky Way.

We cross-match the LAMOST catalog with Gaia DR2 using a matching radius of 2 arcsec. When an object has multiple visits by LAMOST, we only keep the one...
with the highest signal-to-noise ratio (SNR) in SDSS $g$-band. For LAMOST stars where multiple Gaia sources are matched, we keep the one with the smallest separation. If one Gaia source\_id is matched to multiple LAMOST designations, which most of the time is due to the repeated LAMOST designation naming, we keep the one with the highest SNR in SDSS $g$-band.

The comoving companion searching method is detailed in Hwang et al. (2020). Briefly, for each target star, we select a nearby star sample where the stars have similar parallaxes (either parallax difference $< 0.2$ mas, Gaia DR2’s typical parallax errors, or the line-of-sight distance difference $< 20$ pc) as the target star. Then between the target star and each nearby star, we compute the two-dimensional relative velocity (proper motion difference divided by the mean parallax of the two stars) on the sky and the projected separation. We do not consider the component along the line of sight because that involves the parallax difference of two stars, which is dominated by the parallax measurement errors. The physical projected distance remains accurate because it does not involve the parallax difference of the two stars. In the remaining paper, the relative velocity and separation refer to the projected quantities (except for the total velocity $v_{\text{tot}}$ explained in Sec. 2.5 that uses the radial velocity component). The comoving companions are well separated from the chance projection stars in the relative velocity-separation space, and we use an empirical demarcation line introduced in Hwang et al. (2020) to select comoving companions.

To exclude contamination from open clusters or comoving groups, we exclude stars that belong to aggregates with more than 50 stars within separation $10^5 - 10^6$ AU and relative velocity $< 10$ km s$^{-1}$. This only excludes 0.4% of the targets and does not have a strong impact on our result. For the ease of interpretation and counting, we further exclude targets that have more than one comoving companion, which affects only 0.1% of the sample.

Hwang et al. (2020) test the contamination of this searching method by flipping (and thus randomizing) the sign Galactic latitude and proper motion (after removal of solar motion and Galactic differential rotation). The test shows that the contamination from chance alignments is $< 1\%$. Furthermore, most of the LAMOST stars are located in lines-of-sight towards the outer disc (Zhao et al. 2012), and so the expected contamination is even lower than in Hwang et al. (2020) (which is purely based on Gaia) because of the lower stellar density. In short, the level of contamination from chance alignments is low and does not affect our results significantly.

2.3. Selection criteria for the main sample

To ensure that the LAMOST pipeline metallicity (LASP) are reliable for our targets, we require that their spectral SNR per pixel be $> 50$ in the SDSS $g$-band. For DD-Payne metallicity, we require that their spectral SNR per pixel $> 50$ in the SDSS $g$-band and the fitting quality flag ${\text{QFLAG,CH12}} = {\text{good}}$. We limit our sample to the effective temperature between 5000 and 7000 K and surface gravity $g > 3.7$. For DD-Payne, we require that ${\text{TEFF,FLAG}} = {\text{good}}$ and ${\text{LOGG,FLAG}} = {\text{good}}$. Based on the spectral type classified by LASP, $\sim 94\%$ of the selected sample are F and G dwarfs.

After cross-matching with Gaia DR2, we limit our sample to parallaxes $> 2$ mas (distances within 500 pc). We further exclude unreliable photometric and astrometric measurements following the criteria in the Appendix B in Gaia Collaboration et al. (2018b), except that we relax the criteria on BP and RP fluxes. These criteria require that the S/N of Gaia G band larger than 50, the parallax over error $> 10$, the visibility periods $> 8$, and an astrometric quality criteria introduced in the Appendix C of Lindegren et al. (2018). We do not apply any criteria for BP and RP fluxes because BP and RP photometry has a worse spatial resolution than G band (Evans et al. 2018), and also BP and RP have inferior sensitivity than G-band, which may affect the detection of faint companions. We use the same criteria for the nearby star sample where the comoving companion is searched.

With these selections and the removal of sources in comoving groups, we end up with $\sim 260,000$ F and G dwarfs with LASP metallicity, and $\sim 250,000$ with DD-Payne metallicity.

2.4. Computing the wide-binary fraction

In this study, we adopt a conservative angular resolution of 2 arcsec, corresponding to 1000 AU at 500 pc, i.e., we consider only wide binaries with separations of two stars to be at least 1000 AU. This choice is motivated by several factors. Gaia G-band uses PSF-fitting photometry, and its spatial resolution is $\sim 0.5$ arcsec in DR2 (Arenou et al. 2018). Furthermore, we find that the number of comoving pairs decreases at angular separations $\lesssim 1.5$ arcsec, which may be due to the worse quality of astrometric measurements in the presence of a nearby source. Also, the diameter of LAMOST fibers is 3.3 arcsec (Zhao et al. 2012). Therefore, two stars with an angular separations $\lesssim 3.3/2$ arcsec would be located in a single fiber, which may affect metallicity measurements.

We define the wide-binary fraction (WBF) to be

$$WBF = \frac{N_{\text{companion}}}{N_{\text{LAMOST}}},$$

(1)
where $N_{\text{LAMOST}}$ is the number of LAMOST stars, and $N_{\text{companion}}$ is the number of LAMOST stars that have one comoving companion in Gaia at $10^3$ to $10^4$ AU.

In most cases, LAMOST does not observe both stars due to its random subsampling. The random subsampling does not affect our definition of wide binaries since we only require one of two stars to have LAMOST observations (and both stars have Gaia phase space information). Nonetheless, the metallicity of the two stars, individually, might not be accessible. Here we assume that both stars have the same metallicity and adopt the metallicity from the stellar component with LAMOST measurements. We argue that this assumption is justified because previous studies have shown that wide binaries with separations $\lesssim 10^4$ AU have nearly identical elemental abundances (Andrews et al. 2018, 2019; Hawkins et al. 2020), and simulations have suggested that most pairs with separations $\lesssim 10^4$ AU and small relative velocities ($\lesssim 2 \text{ km/s}$) are conatal (Kamdar et al. 2020). Due to turbulent mixing, conatal stars from the same gas cloud are expected to be homogeneous in metallicity (Feng & Krumholz 2014).

One possible bias is the higher detection rate of fainter companions for less distant targets. Therefore, when computing $N_{\text{companion}}$, we only consider companions that have absolute G-band magnitudes $< 10$, where our companion search is complete across the entire distance range of the sample. This criterion removes most of white dwarf companions, which may induce an age dependence of $N_{\text{companion}}$ if young, bright white dwarfs are detected but old, faint white dwarfs are not. This is not a strong effect because white dwarf-main sequence pairs are more than ten times less frequent than main sequence-main sequence pairs (El-Badry & Rix 2018). The absolute magnitude criterion also excludes faint M dwarf companions, but because the lifetime of M dwarfs is longer than the age of Universe, this does not induce age dependence.

We select a sub-sample within 100 pc to test the completeness. In this sub-sample, without the absolute magnitude constraint for the companions, the wide-binary fraction is $7.0 \pm 0.7\%$. This is consistent with Raghavan et al. (2010) where they measure that $7 \pm 1\%$ of solar-like stars within 25 pc have companions at separations between $10^3$ to $10^4$ AU. With an additional cut on absolute G-band magnitudes $< 10$ mag, the wide-binary fraction of our 100-pc sample is reduced to $3.8 \pm 0.5\%$, where 84% of the excluded companions are faint M dwarfs and 16% are white dwarfs. The wide-binary fraction (with the absolute magnitude cut on the companions) of our full 500-pc sample is consistent with the 100-pc sample, illustrating that the companions with absolute G-band magnitudes $< 10$ mag are indeed well detected within 500 pc.

Values of $N_{\text{LAMOST}}$ and $N_{\text{companion}}$ may weakly depend on the distance because of the spatial resolution. For example, in the case of triple stars, the counting of $N_{\text{LAMOST}}$ and $N_{\text{companion}}$ depends on whether the inner binary of a hierarchical triple is resolved or not. Specifically, if the inner binary is unresolved, then this triple system would be considered as a binary during the counting; if the inner binary is resolved, the system would be considered as one having multiple comoving companions and hence are excluded in our counting. Nonetheless, the contribution of marginally resolved hierarchical triples (those only resolved at small distances) is expected to be small and should not affect our conclusions.

With the absolute magnitude criterion for the companions, we end up with $\sim 7,700$ comoving pairs with separations of $10^3$-$10^4$ AU. Among them, there are $\sim 300$ pairs (600 LAMOST stars) where both stars in the pair were observed by LAMOST. Some of these pairs have been studied to show that the components of wide binaries have similar metallicity and elemental abundances (Andrews et al. 2018, 2019). These pairs are counted twice in $N_{\text{LAMOST}}$ and $N_{\text{companion}}$ because every such pair has two LAMOST stars. Because of rarity, their counting (e.g. whether we should count them twice) plays a minor role in our results. LAMOST targeting does not depend on the binarity of stars (Carlin et al. 2012), so no direct systematics is inherited from the targeting.

### 2.5. Distinguishing thin disk, thick disk, and halo stars

We consider two methods to distinguish the thin disk, thick disk, and halo stars: (1) the maximum Galactic height of the Galactic orbits (maximum vertical excursion, $z_{\text{max}}$); and (2) total 3-dimensional velocity ($v_{\text{tot}}$), computed from the projected velocity from Gaia and the radial velocity from LAMOST LASP, with respect to the local standard of rest (Schönrich et al. 2010). We use galpy (Bovy 2015) to derive the $z_{\text{max}}$ of the Galactic orbits. Specifically, we use the fast estimation of orbit parameters via the Stäckel approximation, and the estimation for $z_{\text{max}}$ is precise to a level better than $\sim 1\%$ (Mackereth & Bovy 2018). We use the Milky Way potential MWPotential2014 from Bovy (2015) and a solar motion with respect to the local standard of rest from Schönrich et al. (2010).

We use the Gaia DR2 mock catalogue (Rybizki et al. 2018) to test our selection for thin-disk, thick-disk, and halo stars. The Gaia DR2 mock catalogue is generated using Galaxia (Sharma et al. 2011) that samples
stars from the Besançon Galactic model (Robin et al. 2003). To match the properties of our LAMOST F- and G dwarfs, we select main-sequence mock stars with $0.6 < BP-RP < 1.1$ and parallax $> 2$ mas. Following Hwang & Zakamska (2020), we assign weights to the mock stars so that they have a similar sky distribution as our LAMOST sample. Then we use galpy to derive the $z_{\text{max}}$ for the mock stars.

Using Gaia DR2 mock catalogue, we find that 91% of $v_{\text{tot}} < 120$ km/s stars belong to the thin disk, 87% of $120 < v_{\text{tot}} < 250$ km/s stars belong to the thick disk, and 88% of $v_{\text{tot}} > 250$ km/s stars belong to the halo. For the $z_{\text{max}}$ selection, 92% of $z_{\text{max}} < 1$ kpc stars are thin disk, 80% of $1 < z_{\text{max}} < 5$ kpc are thick disk, and 35% of $z_{\text{max}} > 5$ kpc are halo stars. Therefore, we consider $v_{\text{tot}}$ as a better selection for the halo sample than $z_{\text{max}}$. Their metallicity distributions are shown in Fig. 1. The low-metallicity tail at $[\text{Fe/H}] < -1$ in the thin-disk stars may be partially contributed by the contamination from the thick-disk stars. By using the $v_{\text{tot}} (z_{\text{max}})$ selection, we have 7650 (7380), 66 (336), and 2 (2) wide binaries in the thin disk, thick disk, and halo respectively. We caution readers for the results for the halo in this study due to its small sample, and one of the $z_{\text{max}}$-selected halo wide binaries has $[\text{Fe/H}] = -0.46$ and is likely a thick disk contaminant.

3. THE METALLICITY AND AGE DEPENDENCE OF THE WIDE-BINARY FRACTION

Fig. 2 shows the wide-binary fraction as a function of stellar metallicity. The black points use the LASP metallicity, and the blue points use the metallicity derived by DD-Payne. The metallicity bins span from $[\text{Fe/H}] = -2$ to $+0.5$, with the markers located at the center of each metallicity bin. The black and the blue points are slightly offset horizontally for clarity. Error bars of the wide-binary fractions are Poisson uncertainties.

The overall metallicity dependence is similar for LASP metallicity and DD-Payne metallicity: the wide-binary fraction first increases with increasing metallicity, peaks at $[\text{Fe/H}] \approx 0$, and then decreases at the high metallicity end. The metallicity where the wide-binary fraction peaks is slightly different between LASP and DD-Payne, which is likely due to the systematic metallicity offset of 0.07 dex between LASP and DD-Payne (Sec. 2.1). Otherwise, our result is robust over different metallicity pipelines. We focus on the results using LASP metallicity for the rest of the figures, and we do not find significant difference from those using DD-Payne metallicity.

We perform the Kolmogorov-Smirnov test to quantify the significance of the difference in the metallicity distributions between the stars with wide companions and the entire main sample (with criteria described in Sec. 2.3). The $p$-value, the probability that two metallicity distributions are sampled from the same parent distribution, is $2 \times 10^{-10}$. Therefore, the difference is statistically significant, suggesting that wide binaries show robust metallicity dependence and are not a randomly drawn subsample of the parent distribution.

Since different populations may dominate at different metallicities, we further divide the sample into thin-disk, thick-disk, and halo stars using the total velocity (left panel) and the $z_{\text{max}}$ (right panel) in Fig. 3. For comparison, the black points are the LASP points from Fig. 2. For the thin-disk samples, we adopt the same metallicity bins as for the full sample (black points), and we use larger metallicity bins for the thick-disk and halo samples to reduce the Poisson uncertainties. Overall, the velocity-selected samples are in agreement with the $z_{\text{max}}$-selected samples. The thin-disk sample shows

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**Figure 1.** The LASP metallicity distribution for the thin-disk, thick-disk, and halo stars, selected using total velocity (top) and the maximum Galactic height (bottom).
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Figure 2. The metallicity dependence of the wide-binary fraction (10³-10⁴ AU). The black points use the [Fe/H] derived from LAMOST Stellar Parameter pipeline (LASP), and the blue points use the LAMOST [Fe/H] measured by DD-Payne. The black and the blue points are slightly offset along the horizontal axis for clarity. Both results show that, as [Fe/H] increases, the wide-binary fraction first increases at low [Fe/H], peaks at [Fe/H] ≃ 0, and then decreases at high [Fe/H].

Figure 3. The metallicity dependence of the wide-binary fraction in the thin disk, thick disk, and halo. The LASP metallicity is adopted here, and results from DD-Payne are similar. For comparison, the black points show the same result from Fig. 2. The left panel uses the total velocity to select different populations, and the right panel uses the maximum Galactic height of the orbits. The results of these two selections are in good agreement with each other. The metallicity dependence of wide binaries is dominated by the thin-disk stars. The wide-binary fraction of the thick disk follows a similar trend as the thin disk at low [Fe/H], and then become flat with increasing metallicity at [Fe/H] ≳ −0.5.

a similar trend as in Fig. 2, meaning that the global metallicity dependence is dominated by the thin disk stars, which constitutes a large fraction of the LAMOST sample. The thick-disk sample follows the metallicity relation of the thin-disk stars at [Fe/H] < −0.4. At [Fe/H] > −0.4, the wide-binary fraction of the thick-disk sample is much lower than that of the thin disk. The halo sample has a wide-binary fraction of ≲ 1.5% in the metallicity bin of −2 < [Fe/H] < −1. While it is consistent with the wide-binary fractions in the thin-disk and thick-disk stars at the same metallicity, the wide-binary fraction in the halo is not well constrained given that there are only two wide binaries in the halo sample.

Directly age-dating main-sequence stars is difficult, and in most cases, impossible. However, kinematics of main-sequence stars nonetheless gives a statis-
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Figure 4. The wide-binary fraction as a function of metallicity for the thin-disk stars in bins of total velocity. Points are slightly offset horizontally for clarity. For comparison, the black points show the result from all stars in Fig. 2. The velocity is a proxy of the stellar age, where older stars typically exhibit larger velocities. The wide-binary fraction of the low-velocity (young) stars has a stronger metallicity dependence.

Figure 5. The relation between the wide-binary fraction and the total velocity, where the total velocity is a proxy of stellar age. Here we only consider [Fe/H] between −0.2 and +0.5. The wide-binary fraction shows a prominent decrement with increasing velocity (and hence increasing stellar age) at \( v_{\text{tot}} < 50 \text{ km s}^{-1} \). This age dependence is also present in the wide binaries with smaller separations of \( 10^{2.5} \text{ AU} \).

atical estimate of the ages, especially for the thin-disk stars because their dynamical evolution is mostly secular (Dehnen & Binney 1998; Nordström et al. 2004; Reid et al. 2009; Sharma et al. 2014; Ting & Rix 2019). Hence, in Fig. 4, we use total velocities to investigate the stellar age dependence of the wide-binary fraction in the thin disk as a function of metallicity. Here we select thin-disk stars by \( z_{\text{max}} < 1 \text{ kpc} \) and bin the sample into the low-velocity \( (v_{\text{tot}} < 30 \text{ km s}^{-1}) \), the middle-velocity \( (30 < v_{\text{tot}} < 60 \text{ km s}^{-1}) \), and the high-velocity \( (60 < v_{\text{tot}} < 120 \text{ km s}^{-1}) \) sample.

Fig. 4 shows that wide-binary fractions of all velocity sub-samples have a similar metallicity trend, but such metallicity dependence is strongest in the low-velocity, young sample. In the metal-poor regime \( ([\text{Fe/H}] \lesssim -0.5) \), the wide-binary fractions of stars are about the same, irrespective of their velocity. In contrast, the lowest-velocity sample has a higher wide-binary fraction at \( [\text{Fe/H}] \sim 0 \) than that of the higher-velocity samples. This result also means that the metallicity dependence of the wide-binary fraction in the thin disk is not due to the varying levels of contamination from the thick-disk stars with respect to metallicity, in which case we would expect a weaker metallicity dependence in the low-velocity thin-disk sample where the contamination is the lowest.

Fig. 4 demonstrates that younger stars have a higher wide-binary fraction, especially at \( [\text{Fe/H}] \sim 0 \). However, we caution that Fig. 4 does not necessarily mean that there is a metallicity-dependent age evolution for wide binaries, because each metallicity bin may have different age distributions. It is possible that the lack of age evolution in the metal-poor regime \( ([\text{Fe/H}] \lesssim -0.5) \) is simply because these metallicity bins lack young stars (e.g. Casagrande et al. 2011; Lin et al. 2020).

To explore the stellar age dependence further, in Fig. 5 we investigate the wide-binary fraction as a function of total velocity. We also present the wide-binary fraction for separations between \( 10^{2.5} \) and \( 10^{3} \text{ AU} \), where we apply a parallax cut > 6.3 mas for the sample so that \( 10^{2.5} \text{ AU} \) corresponds to the angular resolution of 2 arcsec. Furthermore, we adopt an absolute G-band magnitude criterion of 12.5 mag for the \( 10^{2.5}-10^{3} \text{ AU} \) case. The result is similar but noisier if we use the original criterion of 10 mag. Here we only consider metallicity between −0.2 and 0.5 because they cover a wider age distribution compared to the metal-poor stars.

Fig. 5 shows that stars having \( v_{\text{tot}} < 50 \text{ km s}^{-1} \) have a higher wide-binary fraction with separations down to \( 10^{2.5} \text{ AU} \). Based on the Gaia DR2 mock catalogue (Rybicki et al. 2018) which sample mock stars from the Besançon Galactic model (Robin et al. 2003), the total velocity of \( \sim 50 \text{ km s}^{-1} \) corresponds to a mean stellar age of \( \sim 5 \text{ Gyr} \). Therefore, the wide-binary fraction seems to be higher in younger stars with ages \( \lesssim \) a few Gyr.

4. DISCUSSION
We have found that in the thin disk, the wide-binary fraction increases with metallicity at $[\text{Fe/H}] < 0$, and then decreases with metallicity in the super-solar regime. Furthermore, based on the kinematics, the enhanced wide-binary fraction at $[\text{Fe/H}] \approx 0$ is age dependent, with a higher wide-binary fraction in younger stars. In the following sections, we compare these results to those from past studies, and seek an interpretation that would simultaneously explain the metallicity and age dependence of the wide-binary fraction.

4.1. Comparison with previous work

In the pre-Gaia era, some studies concluded that the wide-binary fraction was relatively independent of metallicity (Zapatero Osorio & Martin 2004; Zinnecker et al. 2004), while some found a lower wide-binary fraction for metal-poor stars (Rastegaev et al. 2008; Jao et al. 2009; Lodieu et al. 2009; Zhang et al. 2013; Ziegler et al. 2015). Moe et al. (2019) argued that a lower wide-binary fraction of the metal-poor stars from high-resolution imaging studies may be a selection effect, because photometric selection of metal-poor stars may exclude unresolved metal-poor binaries since they are brighter than the metal-poor single stars and may be considered as metal-rich single stars. Our results do not involve any photometric estimates of metallicity and are free from such selection effect.

In the Gaia era, with proper motions and parallaxes available for billions of stars, a large sample of comoving pairs has been made possible (Oh et al. 2017; El-Badry & Rix 2018; Jiménez-Esteban et al. 2019). In particular, El-Badry & Rix (2019) study the metallicity dependence of wide binaries with separations from $\sim 50$ to $\sim 50,000$ AU by combining the comoving pair sample from Gaia DR2 and wide-field spectroscopic surveys. For binaries with separations $\gtrsim 250$ AU, they conclude that the binary fraction remains constant with respect to metallicity.

Our sample bears some similarities to the one from El-Badry & Rix (2019), but here we complement the study by expanding the sample to 500 pc. Their sample is restricted within 200 pc. Therefore, we have a larger sample at larger distances, which strongly improves the constraints on the thick-disk and halo stars at the low-metallicity end. Our sample enables us to further dissect the wide-binary fraction as a function of metallicity and age, while El-Badry & Rix (2019) do not take the kinematics and ages into account.

While our findings of the strong metallicity dependence for the wide-binary fraction seem at odds with their conclusion, El-Badry & Rix (2019) do comment that there is a slight excess of wide binaries at $[\text{Fe/H}] \approx 0$, consistent with our results. They suspect that such excess may be due to the age effect such that old wide binaries are disrupted by gravitational perturbations from other stars and molecular clouds. In the following section, we investigate this possibility in detail, and will argue that gravitational perturbations are unlikely to play a dominant role.

4.2. Wide binary disruption

When time passes, wide binaries may be disrupted by passing stars, molecular clouds, and Galactic tidal fields (Bahcall et al. 1985; Weinberg et al. 1987; Chaname & Gould 2004; Yoo et al. 2004; Quinn & Smith 2009; Jiang & Tremaine 2010). Binaries with wider separations are easier to be disrupted due to the weaker binding energy. In particular, given the stellar density in the solar neighborhood, theoretical estimates show that binaries with separations $\gtrsim 0.1$ pc ($2 \times 10^4$ AU) would be disrupted within 10 Gyr (Weinberg et al. 1987). Therefore, fewer binaries with separations $\gtrsim 10^4$ AU are expected in the old disk stars (Bahcall & Soneira 1981; Retterer & King 1982; Weinberg et al. 1987). Tian et al. (2020) may detect this effect in their ‘halo sample’ selected by the high tangential velocities ($> 85$ km s$^{-1}$), and the authors argue that their results cannot be explained by the binary disruption due to the low density in the halo. While this hints that there might be other effects beyond gravitational perturbations which shape the wide-binary fraction, we note that their results might not be conclusive, as a tangential velocity cut at $> 85$ km s$^{-1}$ likely results in predominantly old thin-disk stars and thick-disk stars, instead of halo stars.

While the disruption of binaries by the gravitational perturbations (passing stars, molecular clouds, and Galactic tidal fields) may be able to make the wide-binary fraction lower in the metal-poor stars because they are on average older, this explanation alone is at odds with some results presented in this study. First, theoretical arguments have shown that the disruption lifetime of $10^4$ AU binaries is $\sim 100$ Gyr, much longer than the age of Universe (Weinberg et al. 1987). Furthermore, if binary disruption were to play an important role, we expect wider binaries should be preferentially disrupted. However, our data do not show a significant difference in the age evolution between $10^{2.5−3.0}$ AU and $10^{3−4}$ AU binaries (Fig. 5). Also, binary disruption is not able to explain the anti-correlation between wide-binary fraction and metallicity at $[\text{Fe/H}] > 0$. Therefore, we conclude that the age and metallicity dependence of the wide-binary fraction cannot solely be explained by binary disruption.
4.3. Wide binary formation and evolution

Since wide binary disruption cannot be the whole story, here we investigate whether the metallicity and age dependence arise from wide binary formation. Wide binaries with separations of \(10^3-10^4\,\text{AU}\) can be formed through multiple channels, including the turbulent core fragmentation (Padoan & Nordlund 2002; Fisher 2004; Offner et al. 2010), dynamical unfolding of unstable compact triples (Reipurth & Mikkola 2012; Elliott & Bayo 2016), the dissolution of star clusters (Kouwenhoven et al. 2010; Moeckel & Clarke 2011), and the pairing of adjacent pre-stellar cores (Tokovinin 2017). However, not all of these channels can provide the observed metallicity and age dependence of the wide-binary fraction.

4.3.1. The negative metallicity dependence

We first tackle the decrease of the wide-binary fraction with metallicity at \([\text{Fe/H}] > 0\). The dynamical unfolding of compact triples may be able explain such metallicity dependence. In this scenario, triple stars are born in compact, unstable configurations, and then they evolve to a hierarchical architecture with one companion scattered into a wide orbit (Reipurth & Mikkola 2012). As a result, the formation of wide binaries is influenced by the occurrence of close binaries, so the metallicity dependence of the wide binaries is inherited from the formation of compact systems through disk and other small-scale fragmentation. If wide companions were preferentially formed via this scenario, then the wide-binary fraction would follow a similar metallicity dependence as close binaries. Indeed, close binaries also show a declining occurrence rate as a function of metallicity (Grether & Lineweaver 2007; Raghavan et al. 2010; Yuan et al. 2015; Badenes et al. 2018; Moe et al. 2019; El-Badry & Rix 2019; Mazzola et al. 2020), as is observed for the super-solar metallicity sample in this study. Fig. 2 shows that the wide-binary fraction decreases by a factor of \(\sim 2\) from \([\text{Fe/H}] \sim 0\) to +0.5. This is very similar to the metallicity dependence of the close-binary fraction \((a < 10\,\text{AU})\), also decreasing by a factor of \(\sim 2\) from \([\text{Fe/H}] = 0\) to +0.5 (Moe et al. 2019), suggestive of a connection between wide and close binaries.

The connection between wide companions and close binaries is supported by other observational studies. For instance, 96\% of close binaries with orbital periods < 3 days have tertiary companions (Pribulla & Rucinski 2006; Tokovinin et al. 2006). Hwang et al. (2020) find that the occurrence rate of the wide companions at \(10^3-10^4\,\text{AU}\) around main-sequence contact binaries is a factor of \(\sim 3\) higher compared to that of the field stars. Conversely, about half of wide pairs with separations of \(10^3-10^4\,\text{AU}\) are hierarchical multiples (Raghavan et al. 2010; Moe & Di Stefano 2017; Moe & Kratter 2019).

The enhanced occurrence rate of tertiary companions around close binaries possibly suggests that tertiary companions play a critical role in the orbital migration of the inner binary through the Kozai-Lidov mechanism, where the outer tertiary companion excites the high eccentricity of the inner binary (Kozai 1962; Lidov 1962; Kiseleva et al. 1998; Eggleton & Kiseleva-Eggleton 2001; Eggleton & Kiseleva-Eggleton 2006; Fabrycky & Tremaine 2007; Naoz et al. 2013; Borkovits et al. 2016). Nonetheless, noting that the Kozai-Lidov mechanism is only effective under certain inner-to-outer separation ratios and mutual inclinations, it remains unclear whether this mechanism can be responsible for the majority of those triple systems consisting of close binaries (Moe & Kratter 2018; Hwang & Zakamska 2020; Hwang et al. 2020). Alternatively, the enhanced occurrence rate of tertiary companions may be a result of compact multiple stars forming from disk fragmentation (Tokovinin & Moe 2020), then the occurrence of these wide companions would follow the similar anti-correlation with metallicity as the close binaries, in line with the scenario of dynamical unfolding of compact triples.

Another possibility is that these wide binaries may evolve from close binaries directly, not via triple interaction. This is in line with the excess of equal-mass binaries (‘twin’ binaries) at separations > 1000 AU, which also suggests that these wide binary twins are formed at close separations initially \((a < 100\,\text{AU})\) and then their orbits are widened by the dynamical interaction with the birth environments (El-Badry et al. 2019). In this case, wide binaries inherit the metallicity dependence from close binary formation and are not necessarily associated with triple systems. However, this scenario is likely not the dominant formation mechanism for wide binaries because such twin excess decreases strongly with increasing separations (El-Badry et al. 2019).

To sum up, we argue that the negative metallicity dependence of the wide-binary fraction is inherited from that of the close-binary fraction through the dynamical unfolding of triple stars. Nonetheless, the metallicity dependence of the wide-binary fraction is clearly non-monotonic. It raises a question why this anti-correlation is only present at \([\text{Fe/H}] \gtrsim 0\), while that of the close-binary fraction spans from \([\text{Fe/H}] = -3\) to +0.5. This implies that there is another limiting factor dominating the wide binary formation at the metal-poor regime, which we investigate in detail in the next section.

4.3.2. The positive metallicity dependence
During the pre-main sequence phase (ages < a few Myr), wide binaries can form through the turbulent core fragmentation and the random pairing of adjacent pre-stellar cores. While the wide-binary fractions from these two mechanisms are not explicitly dependent on metallicity, as is shown in the hydrodynamical simulations (Bate 2005, 2014, 2019), wide binaries themselves are sensitive to the formation environments. In particular, most if not all stars form in clustered environments (Lada & Lada 2003), and about 20-30% of stars originate from bound clusters (Bressert et al. 2010; Kruijssen 2012; Chandar et al. 2017). Environments with a higher stellar density have small stellar separations, making wide binaries more difficult to survive. Furthermore, the higher velocity dispersion accompanied by the higher stellar density makes the random pairing less likely. Indeed, observational studies have found that wide-binary fractions are higher in the low-density star-formation regions compared to the higher-density clustered environment (Simon 1997; Kraus & Hillenbrand 2009; Tobin et al. 2016a; Elliott & Bayo 2016; Joncour et al. 2017; Deacon & Kraus 2020). Therefore, density of the formation environment plays a critical role in the wide binary formation.

When the gas is removed after ∼ 10 Myr (Bastian et al. 2005; Fall et al. 2005; Mengel et al. 2005), the cluster expands in response to the change in the gravitational potential (Goodwin & Bastian 2006; Goodwin 2009). At this cluster dissolution phase, two unbound stars that are originally close in the phase space may pair together and become a wide binary (Kouwenhoven et al. 2010; Moeckel & Clarke 2011). Using Monte Carlo and N-body simulations, Kouwenhoven et al. (2010) further find that the wide-binary fraction decreases strongly with increasing cluster mass, where the main driving factor may be associated with the increasing velocity dispersion that makes two stars less likely to pair in the phase space.

In the earlier Universe, star formation environments tend to have a higher pressure and density than the present day, and high-mass clusters are preferentially formed in such environments (Harris & Pudritz 1994; Elmegreen & Efremov 1997; Kravtsov & Gnedin 2005; Kruijssen 2014; Ma et al. 2020). A higher-density environment reduces the wide binary formation from the turbulent core fragmentation and the random pairing of adjacent pre-stellar cores, and also fewer wide binaries can form from the dissolution of higher-mass clusters. As a result, the wide-binary fraction would be lower in the older stars, which explains the age dependence in Fig. 4 and Fig. 5. Furthermore, because metal-poor stars are on average older stars, this naturally explains the positive correlation between the wide-binary fraction and metallicity.

4.4. A holistic view and future outlook

So far we have discussed various wide binary formation channels and how they may or may not induce metallicity and age dependence in the observed wide-binary fraction. In reality, these mechanisms must all play a role in varying degrees. It is unlikely that our result can be explained by only one mechanism. In particular, no one formation mechanism can explain the non-monotonic relation between metallicity and the wide-binary fraction.

Fig. 6 summarizes the metallicity dependence of the wide binary formation channels, and we propose that the observed metallicity and age dependence are caused by the combination these formation mechanisms. Briefly, the higher stellar density in the star formation environments and the dissolution of higher-mass clusters at an earlier time result in the lower wide-binary fraction in the older stars and the positive metallicity correlation at [Fe/H] ≲ 0. The metallicity dependence of dynamical unfolding of compact triples follows the anti-correlation between metallicity and the close-binary fraction, which may explain the declining wide-binary fraction at the super-solar metallicity regime. The values and slopes of the lines in Fig. 6 are only for schematic illustration.

The reason that the wide-binary fraction does not follow a similar anti-correlation of metallicity of the close-binary fraction at [Fe/H] < 0 may be that dense environments disrupt the wide binaries or prohibit their formation in the first place. Since the cluster disruption timescale (Bastian et al. 2005; Fall et al. 2005; Mengel et al. 2005) is comparable to the dynamical unfolding timescale (Reipurth & Mikkola 2012), wide companions evolved from the dynamical unfolding continue to be disrupted within the dense environments. The reason that the positive metallicity correlation of wide-binary fraction ceases at [Fe/H] ∼ 0 may be that the mean stellar age is similar at [Fe/H] ∼ 0 and ∼ 0.5 (Casagrande et al. 2011; Bensby et al. 2014; Silva Aguirre et al. 2018). Since their formation times are similar, there is no much difference in their formation environments. As the environmental effect ceases to play a dominant role, the anti-correlation with metallicity inherited from the close-binary fraction manifests itself at the regime of super-solar metallicity.

Given that the wide-binary fraction conspicuous peaks around the solar metallicity, close to the current metallicity of the interstellar medium in the solar neighborhood, it is natural to speculate if the metallicity trend in the wide-binary fraction is due to the radial migration of stars in the Milky Way. Stars that do
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Figure 6. Schematic illustration of the metallicity dependence of various proposed wide binary formation channels in this study. The observed metallicity dependence (black points) is likely the consequence of multiple formation channels of wide binaries. The dashed lines show the metallicity trend of the proposed mechanisms, and their values and slopes are only for schematic illustration. The dynamical unfolding of compact triples (blue line) follows the metallicity anti-correlation of the close-binary fraction. The trend at [Fe/H]< 0 can be due to that the density of the formation environments and the cluster mass are higher at earlier times (pink line). The environmental effect ceases to play a role at the high metallicity because the formation time is similar at [Fe/H]> 0, and therefore the anti-correlation from the dynamical unfolding of triple stars manifests itself at high metallicities. Radial migration may also play a role in enhancing the wide-binary fraction around the solar metallicity (red line).

Finally, for the entire population (irrespective of metallicity), the wide-binary fraction of the thick-disk stars is lower than that of the thin-disk stars, and that of the halo stars is marginally lower than the thick-disk stars (Fig. 3). However, the age distribution of the thin-disk stars is different from the thick-disk and halo stars. Silva Aguirre et al. (2018) show that the age distribution of the low-α-element disk (thin disk) peaks at ∼ 2 Gyr, while the high-α-element disk (thick disk) peaks at ∼ 11 Gyr. Halo stars in the solar neighborhood are also ∼ 11 Gyr old (e.g. Jofre & Weiss 2011; Kalirai 2012). Therefore, the lower wide-binary fraction in the thick-disk and halo stars may be due to that they are older than the thin-disk stars. This suggests that their wide-binary fractions are likely driven by the same effect as the thin-disk stars, which is mostly determined by the formation environments at the different time.

In this study, we propose that multiple formation mechanisms are responsible for the metallicity and age dependence of the wide-binary fraction. Several lines of future work may be able to further constrain their individual contributions. First, different formation mechanisms predict different mass-ratio distributions. For example, the mass ratio distribution from cluster dissolution is consistent with random pairing (Kouwenhoven et al. 2010), while that of the dynamical unfolding of compact triples is not (Reipurth & Mikkola 2012). Therefore, an investigation in the mass ratios of wide binaries as a function of metallicity may shed light on the underlying formation mechanisms. Second, a statistical study of wide binary eccentricity (e.g. Tokovinin & Kiyaeva 2016) as a function of metallicity may be helpful, because dynamical unfolding of compact triples...
leads to more eccentric outer orbits. However, the interpretation may be complicated, because multiple mechanisms may be at work at the same time, and these wide companions from dynamical unfolding may interact with their formation environments, altering their eccentricity. Also, spectroscopic age estimates for giants via C/N-related features in spectra (e.g. Martig et al. 2016; Ting & Rix 2019) can further constrain the age evolution of wide binaries.

5. CONCLUSIONS

In this paper, we investigate the metallicity and age dependence of the wide-binary \((a = 10^3-10^4 \text{AU})\) fraction. Specifically, we use the metallicity and radial velocity from LAMOST DR5 combined with the astrometric information from Gaia DR2 to measure the wide-binary fraction of field F and G dwarfs. Our findings include:

1. Wide-binary fraction strongly depends on the metallicity (Fig. 2). As metallicity increases, wide-binary fraction first increases, peaks at \([\text{Fe/H}] \simeq 0\), and then decreases at the high metallicity end. The wide-binary fraction at \([\text{Fe/H}] = 0\) is about two times larger than that at \([\text{Fe/H}] = -1\) and \([\text{Fe/H}] \simeq +0.5\). Such metallicity dependence is dominated by the thin-disk stars (Fig. 3).

2. The wide-binary fraction is further dependent on the stellar age, with younger stars having a higher wide-binary fraction (Fig. 4, Fig. 5).

3. Our results suggest that multiple formation channels may be responsible for the formation of wide binaries, resulting in the metallicity and age dependence of the wide-binary fraction (Fig. 6). Binaries of \(10^3-10^4 \text{AU}\) are unlikely to be disrupted by the gravitational perturbations on the relevant timescale. The positive correlation between the wide-binary fraction and metallicity at \([\text{Fe/H}] < 0\) may be due to that the density of formation environments and the cluster masses are higher at earlier times, lowering the wide-binary fraction at the low-metallicity end. This also explains the age dependence that younger stars have a higher wide-binary fraction. The anti-correlation between metallicity and the wide-binary fraction at \([\text{Fe/H}] > 0\) can be inherited from the similar anti-correlation of the close-binary fraction through the dynamical unfolding of compact triples. If the radial migration process is inhospitable to wide binaries, it may play a role in enhancing the wide-binary fraction around the solar metallicity.

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This research makes use of Astropy, a community-developed core Python package for Astronomy (Robitaille et al. 2013; Price-Whelan et al. 2018).

6. DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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