Not That Simple: The Metallicity Dependence of the Wide Binary Fraction Changes with Separation and Stellar Mass

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Abstract

The metallicity dependence of the wide binary fraction (WBF) is critical for studying the formation of wide binaries. While controversial results have been found in recent years, here we combine the wide binary catalog recognized from Gaia EDR3 and stellar parameters from LAMOST to investigate this topic. Taking the bias of the stellar temperature at given separations into account, we find that the relationship between the WBF and metallicity depends on the temperature for the thin disk at \( s > 200 \) au. It changes from negative to positive as the temperature increases from 4000 to 7500 K. This temperature/mass dependence is not seen for the thick disk. Besides, the general tendency between the WBF and metallicity varies with the separation, consistent with previous results. It shows anticorrelation at small separations, \( s < 200 \) au for the thin disk and \( s < 600 \) au for the thick disk. Then it becomes an “arcuate” shape at larger separations (hundreds to thousands of astronomical units), peaking at \([\text{Fe/H}] \approx 0.1\) for the thin disk and \([\text{Fe/H}] \approx −0.5\) for the thick disk. Finally it becomes roughly flat for the thin disk at \( 1000 < s < 10,000 \) au. Our work provides new observational evidence for theoretical studies on binary formation and evolution.

Unified Astronomy Thesaurus concepts: Wide binary stars (1801); Stellar abundances (1577); Stellar physics (1621)

1. Introduction

Binary systems are ubiquitous in our universe. According to their separations, they are empirically classified into two groups: close binaries and wide binaries. In most cases, wide binaries refer to spatially resolved and comoving pairs, whose separations depend on their distances to us, ranging from 10 to \( 10^7 \) au. The two components of a wide binary are thought to be born at the same time and place (Goodman & Hut 1993; Fisher 2004; Kouwenhoven et al. 2010). Therefore, they are believed to have the same age and metallicity in principle. Their evolution could be treated as isolated single stars due to the large physical separation, which makes them ideal laboratories for testing stellar models and calibrating gyrochronology relations (Chanamé & Ramírez 2012). As the binding energy of wide binaries is relatively small, they are sensitive to the gravitational perturbations in the Milky Way, making them good indicators for the study of Galactic dynamics (Heggie 1975; Yoo et al. 2004; Jiang & Tremaine 2010; Kaib & Raymond 2014).

Identifications of wide binaries are challenging. Previous samples of wide binaries are small and mostly limited to the solar neighborhood \( (d < 100 \) pc\) with separations less than \( 10^7 \) au (e.g., Lépine & Bongiorno 2007; Raghavan et al. 2010; Tokovinin 2014). Thanks to the whole sky survey Gaia (Gaia Collaboration et al. 2016), a large number of wide binaries can be identified through the common proper motion technique (e.g., Hartman & Lépine 2020; Price-Whelan et al. 2017; Jiménez-Esteban et al. 2019). Using data from Gaia EDR3 (Gaia Collaboration et al. 2021a), El-Badry et al. (2021) constructed the largest catalog of spatially resolved binary stars within 1 kpc of the Sun. These much larger samples enable studies of binary properties in great detail, such as the distributions of binary separation (Andrews et al. 2017; El-Badry & Rix 2018; Tian et al. 2020), the mass ratio (El-Badry et al. 2019), and eccentricity (Hwang et al. 2022a).

The detailed metallicity dependence of the binary fraction plays a fundamental role in constraining binary formation mechanisms. Unlike the well-established anticorrelation between the (close) binary fraction and metallicity (e.g., Raghavan et al. 2010; Yuan et al. 2015a; Gao et al. 2017; Badenes et al. 2018; Tian et al. 2018; Moe et al. 2019; Niu et al. 2021), some recent works have shown that the metallicity dependence of the wide binary fraction (WBF) may be different. Using comoving pairs within 200 pc from Gaia DR2 (El-Badry & Rix 2018) and metallicities from five spectroscopic surveys (LAMOST, RAVE, APOGEE, GALAH, and Hypatia), El-Badry & Rix (2019) found that even though the WBF displays an anticorrelated behavior with \([\text{Fe/H}]\) at small separations \( (s < 200)\), which is similar to the close binary fraction, it generally becomes constant with \([\text{Fe/H}]\) at larger separations. Hwang et al. (2021a) revisited the metallicity dependence of field-wide binaries \( (s = 10^2–10^4 \) au\) using LAMOST and Gaia DR2 data sets. They limited the sample to 5000–7000 K and extended the sample out to 500 pc. They also grouped the sample into the thin disk, the thick disk, and the halo stars according to the kinematic definition. An entirely different conclusion was drawn: as metallicity increases, the WBF increases first but then decreases at the high-metallicity end. They demonstrated that the tendency steepens more in the thin disk than in the thick disk, and the WBF of the thin-disk peaks around the solar abundance while the WBF of the thick disk peaks around −0.5. Taking the kinematics of stars as a proxy for age, they also showed that younger stars tend to have a higher WBF around solar abundance.

It is reasonable to speculate that deficiencies in the previous works caused the discrepancies. It could be better to take stellar...
metallicities from one spectroscopic survey thinking of possible offsets of stellar parameters among different surveys (Nandakumar et al. 2017; Anguiano et al. 2018). Both El-Badry & Rix (2018) and Hwang et al. (2021a) used “control samples” to calculate the WBF in their methods. El-Badry & Rix (2018) constructed a distance-dependence control sample to avoid selection bias caused by unresolved close binaries. Hwang et al. (2021a) used the whole LAMOST stars as their control sample, ignoring the influences from the distance-dependent unresolved close binaries. What’s more, the trend that the total binary fraction increases with the stellar mass has been widely confirmed (Duchêne & Kraus 2013 and references therein). The same trend is also found for wide binaries (Moe & Di Stefano 2017; Gaia Collaboration et al. 2021b). Unfortunately, the bias of the stellar temperature at given binary separations is ignored by them. Besides, neither of them considered systematic errors of the spectroscopic metallicities.

In this paper, we combine the wide binary catalog recognized from Gaia EDR3 and stellar parameters from LAMOST to investigate the metallicity dependence of the WBF. Section 2 describes data selection and processing. Here we use revised metallicities. Section 3 demonstrates the method and results. “Control samples” are carefully constructed to identify the WBF tendency with metallicity. Section 4 discusses caveats in this work and compares it with previous works. Section 5 summarizes the paper.

### 2. Data

The wide binary catalog published by El-Badry et al. (2021) contains over 1 million binaries within 1 kpc and with projected separations from a few astronomical units to 1 pc. We started with main sequence/main-sequence pairs and required their rate of chance alignments $\mathcal{R} < 0.1$ to select high-confidence ones. The selected wide binaries are then cross-matched with the value-added catalog of LAMOST DR5 of Xiang et al. (2019) to obtain their chemical abundances. We further require a signal-to-noise ratio of spectra larger than 20.

Xiang et al. (2019) used a data-driven Payne approach (DD-Payne) to deliver stellar parameters as well as abundances for 16 elements of 6 million stars, training models from high-resolution surveys like GALAH and APOGEE. The precision of $T_{\text{eff}}$ and [Fe/H] are about 50 K and 0.06, respectively. [α/Fe] is defined as a weighted mean of [Mg/Fe], [Si/Fe], [Ca/Fe], and [Ti/Fe] with precision of about 0.03.

We have performed a diagnosis of chemical abundances of several spectroscopic surveys in Z. Niu et al. (2022, in preparation) using wide binaries. According to the formation theories of wide binaries (e.g., Fisher 2004), components of a wide binary are formed at the same time and place, and have the same initial surface abundances. For F/G/K-type stars, the influence of atomic diffusion during the main-sequence stage on the surface abundances (e.g., [Fe/H]) is only about 0.05 dex on average (Dotter et al. 2017; Campilho et al. 2022). This effect is much smaller than the possible systematic errors in spectroscopic surveys. Therefore, wide binaries in which both components are targeted can be used to examine the chemical abundances of spectroscopic surveys. We selected main-sequence binaries of F/G/K type with a spectral signal-to-noise ratio larger than 20. Here we briefly demonstrate the results of Xiang et al. (2019)’s catalog. Taking [Fe/H] as an example, we obtained empirical formulas of revised [Fe/H] by minimizing the loss function $[\text{Fe/H}]_{\text{rev, est}} - [\text{Fe/H}]_{\text{rev, sec}}$. Regularization was applied during the fitting to avoid over-corrections. The correction at 5770 K was set to be zero. We have validated our corrections using open clusters, whose member stars share the same surface abundances.

Coefficients for [Fe/H] and [α/Fe] are listed in Table 1 and plotted in Figure 1. We found that the [Fe/H] and [α/Fe] values are strongly affected by systematic errors. The errors are mostly temperature dependent and partly depend on chemical abundances. There are significant underestimations of [Fe/H] and over-estimations of [α/Fe] for stars colder than 5000 K, reaching $-0.4$ dex for [Fe/H] and $+0.08$ dex for [α/Fe] at 4200 K. Significant over-estimations of [α/Fe] are also for stars hotter than 7000 K. The bias of [Fe/H] can be hardly seen for stars hotter than 5000 K. We can imagine that this calibration is vital for stars colder than 5000 K. This is confirmed in Section 4.2. Corrections should be used with cautions for stars outside the ranges in Figure 1. All [Fe/H] and [α/Fe] values mentioned hereafter are revised values.

| Coeff. | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a_9$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| [Fe/H] | 17.30 | -1.302 | -3.654 | 1.219 | -1.451e-1 | 6.011e-3 | ... | -4.138e-4 | -2.729e-3 | 1.227e-3 |
| [α/Fe] | -3.060 | 1.550 | -2.300e-1 | -4.000e-3 | 3.500e-3 | -1.900e-4 | -3.326e-6 | ... | ... | ... |

Note. $\gamma_{\text{rev}} = y + f(x, y) = y + a_0 x^4 + a_2 x^2 + a_4 x^4 + a_6 x^2 + a_8 x^4 + a_{10} x + a_0 + a_2 x + y + a_8 x y + a_{10} x y^2$, where $x$ is $T_{\text{eff}}/1000$ and $y$ is [Fe/H] or [α/Fe] from the DD-Payne catalog.

### Table 1

| Coeff. | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ | $a_7$ | $a_8$ | $a_9$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| [Fe/H] | 17.30 | -1.302 | -3.654 | 1.219 | -1.451e-1 | 6.011e-3 | ... | -4.138e-4 | -2.729e-3 | 1.227e-3 |
| [α/Fe] | -3.060 | 1.550 | -2.300e-1 | -4.000e-3 | 3.500e-3 | -1.900e-4 | -3.326e-6 | ... | ... | ... |

Figure 1. Variations of $[\text{Fe/H}]_{\text{rev, est}} - [\text{Fe/H}]$ against temperature. Cases for published [Fe/H] equal to 0.5 and −1 are respectively plotted by solid and dotted lines. The horizontal red line at zero is plotted for reference.
Improvements of revised chemical abundances are demonstrated in Figure 2. We select stars from the DD-Payne catalog with high quality and plot their density distributions in the [Fe/H]–[α/Fe] plane. Before the revision, the high-density area splits into two branches. Distributions of stars with 4500–5000 K are marked by cyan squares, whose [Fe/H] values are underestimated and [α/Fe] values are overestimated. Therefore, they locate above stars with 6500–7000 K, shown by green crosses, which are less affected. When plotting with the revised abundances, the two branches merge into one, as expected.

For multiply observed Gaia objects, we combine their epoch values using inverse variance weighting. The mean parallax of two components is adopted as the parallax of the system. For most binary systems, only one component is spectroscopically matched. According to the target selection process of LAMOST (Yuan et al. 2015b), they are probably the primary star of the systems. We have verified it using Gaia colors. For systems where both components are spectroscopically matched, mean values of [Fe/H] are adopted, and hotter stars are assigned to be the primary ones. We chemically divide the samples into thin-disk and thick-disk populations according to their locations in the [Fe/H]–[α/Fe] plane. The following scheme is applied.

**Thick disk:**

\[ \frac{\alpha}{Fe} > -0.05 \times \frac{Fe}{H} + 0.16. \]

**Thin disk:**

\[ \frac{\alpha}{Fe} < -0.05 \times \frac{Fe}{H} + 0.13. \]

Verification of the disk populations is provided in the Appendix. Finally, we get the thin-disk sample containing 63,655 wide binaries, 2489 of them having both spectroscopically matched components. As for the thick-disk sample, numbers decrease to 3347 and 86.

3. Method and Result

El-Badry & Rix (2019) suggested that the relationship between WBF and [Fe/H] changes with the binary separation. As shown in Figure 3, the distribution of the temperature of the primary also changes with the binary separation, especially for separations of hundreds of astronomical units. There are more cold binaries in the samples with small separations than in samples with large separations, mainly due to the angular resolution of Gaia. Therefore, we divide our samples into various subsamples according to the separations (0–200 au, 200–600 au, 400–800 au, 600–1000 au, and 1000–10,000 au) as well as temperatures (4000–5000 K, 4500–5500 K, 5000–6000 K, 5500–6500 K, 6000–7000 K, and 6500–7500 K).

In order to investigate the tendency of WBF on [Fe/H] of different subsamples, we compare the distribution functions of [Fe/H] of wide binaries to those of control samples, as described by El-Badry & Rix (2019). We divide each subsample into 10 bins with an equal interval of [Fe/H] ranging from −1.0 to +0.5. Control samples are constructed by selecting common stars of Gaia EDR3 and LAMOST DR5. They passed the same cuts that applied to the wide binary samples (El-Badry et al. 2021). For each subsample of the wide binaries, its control sample is generated following the same distance and temperature distributions to avoid selection bias caused by unresolved binaries and physically different WBF of different stellar types. Then we calculate the probability densities of [Fe/H] for the binary subsample and the control sample, \( P_{\text{wide}} \) and \( P_{\text{control}} \). The ratio of \( P_{\text{wide}} \) and \( P_{\text{control}} \) indicates the tendency of the WBF. For example, \( P_{\text{wide}}/P_{\text{control}} = 1 \) means that the wide binaries and control samples have the same percentage at the \( i \)th bin in [Fe/H], \( P_{\text{wide}}/P_{\text{control}} > 1 \) means the percentage of the wide binaries
Figure 4. The WBF dependencies on [Fe/H] of the thin-disk sample with various temperatures of the primary and separations of the binary. $P_{\text{wide}}/P_{\text{control}}$ are the probability density functions of the wide binaries/control samples. Each control sample is randomly selected 2,000 times following the same distributions of distance and temperature as the wide binary. Five panels correspond to five separation ranges, from 0–200 au to 1000–10,000 au. Colors indicate temperatures of the primary. The general result of full temperature ranges is plotted in black. Vertical error bars include Poisson uncertainties and random errors obtained from the random sampling of the control samples. Only [Fe/H] bins with more than five wide binaries are calculated.

The general result of full temperature ranges is plotted in black. Vertical error bars include Poisson uncertainties and random errors obtained from the random sampling of control samples. Each control sample is randomly selected 2,000 times following the same distributions of distance and temperature as the wide binary. Five panels correspond to five separation ranges, from 0–200 au to 1000–10,000 au. Colors indicate temperatures of the primary. The general result of full temperature ranges is plotted in black. Vertical error bars include Poisson uncertainties and random errors obtained from the random sampling of the control samples. Only [Fe/H] bins with more than five wide binaries are calculated.

increases but the percentage of the control samples decreases, i.e., a larger WBF. To evaluate formal errors of $P_{\text{control}}$, the bootstrap sample method is taken with 2000 times of random sampling of control samples. Uncertainties of the $P_{\text{wide}}/P_{\text{control}}$ also include Poisson uncertainties of the $P_{\text{wide}}$ and $P_{\text{control}}$. Notice that $P_{\text{wide}}/P_{\text{control}}$ represents the tendency of WBF instead of the absolute value.

Figures 4 and 5 show the [Fe/H] dependence of the WBF for the thin and thick disks, respectively. Panels are ordered by binary separations. In each panel, colors represent the temperatures of primary. General results of 4000–7500 K are plotted in black. [Fe/H] bins having less than five wide binaries are excluded.

Most binaries in the first panel of Figure 4 are spectroscopically unresolved by LAMOST, considering its fiber size (3''3). They are similar to the sample used in Niu et al. (2021) in terms of separations. Although not in a linear way, the WBF decreases with the increasing [Fe/H], which agrees with previous works (e.g., Raghavan et al. 2010; Niu et al. 2021). Simultaneously, the impacts of the stellar temperatures gradually appear. The [Fe/H] dependence of the WBF keeps anticorrelated for the cold subsamples. With the increasing temperature, the WBF becomes an “arcuate” shape with [Fe/H] for intermediate temperatures and then positively correlated with [Fe/H] for the hot subsamples. This temperature-dependent gradient is particularly strong at [Fe/H] > 0. It is reasonable to transform temperatures into stellar masses since the impacts of the surface abundance and gravity are negligible compared to those of the temperature. We stress that our results focus on the tendency of the WBF, not the absolute value. The general tendency of WBF with 4000–7000 K is also plotted in black, varying with the increasing separation. But it is quite dependent on the proportions of different temperatures of the sample. In the thin disk, we prefer to mass-assign results.

As for the thick disk, the sample size is much smaller, particularly for wide binaries hotter than 6500 K and having separations less than 200 au. Unlike the dependence of the thin-disk samples, no impact of the temperature is found. The WBF is roughly negative with [Fe/H] in the two top panels of Figure 5. In the two bottom panels with larger separations, the WBF first increases and then decreases at [Fe/H] ≈ −0.5, which agrees with Hwang et al. (2021a). The general tendency including the full temperature range is also plotted in black.

4. Discussion

4.1. Effect of the Incompleteness

The wide binary sample of this work comes from El-Badry et al. (2021). They set relative parallax uncertainties less than 20% and absolute parallax uncertainties less than 2 mas to guarantee the quality of astrometry. We also require the spectral signal-to-noise ratios larger than 20. Some faint and distant objects are not selected, which barely affects control samples but wide binaries. For primaries having the same apparent magnitude, distant binaries with small mass ratios ($q$) are more likely to be missed compared to nearby binaries. The distance distributions may be different at different [Fe/H] bins, considering the vertical and radial metallicity gradient of the disk stars.

We use twin binaries to show that the mass dependence of our results is not caused by this selection bias. For a resolved twin binary, its secondary of equal brightness should be
observed once its primary is observed. The mass-ratio distribution is fixed at given ranges of mass and separation (Moe & Di Stefano 2017; El-Badry et al. 2019). Therefore, for each subsample in this work, we can roughly estimate the missing fraction of distant wide binaries using the observed proportion of twin binaries (with a $G$ magnitude difference smaller than 0.4 mag) within 200 pc. Notice that for wide binaries having separations less than 200 au, most of them are within 200 pc and barely affected. The missing fractions of various temperatures and separations as a function of distance are shown in Figure 6. In each panel, different temperature subsamples show a consistent trend. Therefore, this incompleteness hardly affects the results in this paper. The reason for a higher missing fraction in the top left panel is due to the target selection process of LAMOST (Yuan et al. 2015b). For a given target star of $m$ magnitude, it is required to have no neighbor within a 5″ radius that is brighter than ($m+1$) mag. This probably makes the resolved binaries with small separations biased to a small mass ratio. But it is independent of the stellar mass.

**4.2. Comparison with Previous Work**

El-Badry & Rix (2018) and Hwang et al. (2021a) published their results about the metallicity dependence of the WBF based on Gaia DR2. Although their samples and methods shared similarities to some extent, they came to different conclusions. Hwang et al. (2021a) attributed the discrepancies to their larger sample at larger distances and contributions of stellar ages. Our work shows that the disagreement is mostly caused by the different separation ranges. As shown in Figure 4, the general tendency varies with separation. Binaries of small separations ($s < 200$ au) contributed an important part of El-Badry & Rix (2018), while Hwang et al. (2021a) focused on binaries of $10^3 < s < 10^4$ au.

Besides, we have found underestimations of [Fe/H] for low-temperature stars of the spectroscopic catalogs (LAMOST-LASP, APOGEE DR16, and GALAH DR3) used by El-Badry & Rix (2018), particularly for stars of $T_{\text{eff}} < 4500$ K. They used samples within 200 pc, which owned a higher percentage of low-temperature binaries compared with the samples used in this work. We perform measurements of the WBF before [Fe/H] corrections for the thin-disk sample. In the left column of 4000–5000 K, the underestimation of [Fe/H] shifts the result toward the low-metallicity direction. The impacts are very small in the middle and right columns, as expected.

Hwang et al. (2021a) used metallicities from a single catalog and set temperatures between 5000 to 7000 K, in which the systematic errors are relatively small. We repeat their works and find that although Hwang et al. (2021a) did not specifically generate control samples following the same distance distribution of the wide binary samples, their distance distributions were quite similar by coincidence. We compare our results with

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**Figure 5.** Same plots as Figure 4 but for the thick-disk samples. Notice that wide binaries hotter than 6500 K as well as having separations less than 200 au are not contained in the thick-disk samples due to the small number.
we complement the study by considering the impacts of temperature/mass. Compared with Hwang et al. (2021a), we find consistent results, after applying the same temperature range. Compared with Hwang et al. (2021a), we find that the result of 6000–7000 K is close to ours. Hwang et al. (2021a) and Hwang et al. (2022b) also studied the WBF inside different stellar populations and found the trends with metallicity are quite similar between the thin and thick disks. After considering the effects of temperature, we can account for the differences between theirs and ours.

The mass dependence of the metallicity dependence of the binary fraction has been hinted at before. Using a binary sample with orbital periods <5 yr, Grether & Lineweaver (2007) found metal-poor stars own a higher binary fraction and further pointed out that this tendency is limited to relatively red stars \((B - V > 0.75)\). Raghavan et al. (2010) reported that no relationship between metallicity and the possibility to have stellar companions exists for stars of \(B - V < 0.625\). Yuan et al. (2015a) estimated the unresolved binary fraction within various ranges of stellar color and \([Fe/H]\). The redder subset shows a stronger anticorrelation between the binary fraction and metallicity than the bluer subset. Our result shows that the metallicity dependence of the WBF changes with the temperature. In particular, it varies from anticorrelation to positive correlation as the temperature increases from 4000 to 7500 K. Together with the above works, our result suggests that there are some physical processes behind the mass dependence of the metallicity dependence of the binary fraction.

We agree with the possible explanations of the WBF tendency on metallicity suggested by Hwang et al. (2021a). We also remind that more factors should be involved when considering mass dependence. For instance, high-mass stars are younger on average. The mass dependence may be related to stellar ages. The mass dependence is not found in the thick-disk stars. We suspect that it is likely related to the different formation histories of the thin and thick disks.

5. Summary

Recently, there have been disagreements about the metallicity dependence of the WBF. By combining the Gaia EDR3 wide binaries from (El-Badry et al. 2021) and LAMOST stellar parameters from Xiang et al. (2019), we present an independent study to investigate the metallicity dependence of the WBF. We find that in addition to the metallicity and separation dependence of the WBF, mass dependence exists in the thin disk, as demonstrated in Figure 4. For binaries with \(s > 200\) au, as the temperature rises from 4000 to 7500 K, the relationship between the WBF and metallicity gradually changes from negative to positive. The general tendency agrees well with previous studies (Raghavan et al. 2010; Hwang et al. 2021a; Niu et al. 2021; Moe et al. 2019). It shows anticorrelation at small separations, \(s < 200\) au for the thin disk and \(s < 600\) au for the thick disk. Then it becomes an “arcuate” shape at larger separations (hundreds to thousands of astronomical units), peaking at \([Fe/H] \approx 0.1\) for the thin disk and \([Fe/H] \approx -0.5\) for the thick disk. Finally it becomes roughly flat for the thin disk at \(1000 < s < 10000\) au. We notice the different results between the thin and thick disks, which may be related to their different formation histories.

The mass dependence of the WBF barely gets noticeable until this work because previous sample sizes were not large enough to study the WBF in detail under such high dimensions, such as \([Fe/H]\), separation, and mass. The physical explanations still need further investigations. This work provides new clues for theoretical works on the binary studies.
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We have used orbital rotational velocities \( V_\phi \) to verify the efficacy of the criteria of disk populations. Distributions of the \( V_\phi \) in the \([\text{Fe}/\text{H}]-[\alpha/\text{Fe}]\) plane are shown in Figure A1. Color bars donate the velocities, the darker the color, the higher the velocity. We find that the thick-disk stars have \( V_\phi \) values ranging from 140 km s\(^{-1}\) to 200 km s\(^{-1}\), whereas those of the thin-disk stars are generally higher with a smaller dispersion and range from 220 to 240 km s\(^{-1}\). The results are consistent with previous works (e.g., Chiba & Beers 2000; Lee et al. 2011; Jing et al. 2016; Anguiano et al. 2020).

**Figure 8.** The \([\text{Fe}/\text{H}]\) dependence of the WBF for stars between 5000 and 7000 K. The colors keep the same meaning as in Figure 4. Red points are combinations of 5000–6000 K and 6000–7000 K according to the temperature distributions of Hwang et al. (2021a). In the thick disk, wide binaries hotter than 6500 K are rare. The black points are the normalized measurements from Hwang et al. (2021a), where wide binaries from Gaia DR2 and metallicities from LAMOST DR5 are applied.

**Appendix**

**Verification of the Disk Populations**

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

This research made use of ASTROPY, a community-developed core PYTHON package for astronomy (Astropy Collaboration et al. 2013).
**Figure A1.** Distribution of the rotational velocity $V_f$ in the $[\text{Fe/H}]$-$[\alpha/\text{Fe}]$ plane. The left panel is the control sample, the right panel is the binary sample. The color indicates the $V_f$. The upper and lower colored areas are chemically defined thin and thick disks, respectively. Criteria of the thin and thick disks are listed in the main text.

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