Radial Migration from the Metallicity Gradient of Open Clusters and Outliers

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Abstract

Radial migration is an important process in the evolution of the Galactic disk. The metallicity gradient of open clusters and its outliers provide an effective way to examine this process. In this work, we compile metallicity, age, and kinematic parameters for 225 open clusters and carry out a quantitative analysis of radial migration via the calculated migration distances. Based on clusters with age $<0.5$ Gyr, we obtain a present-day metallicity gradient of $-0.074 \pm 0.007$ dex kpc$^{-1}$. Three sequences are distributed along this gradient, and clusters in the upper, middle, and lower groups are found to be old outward migrators, in situ clusters, and inward migrators, respectively. The migration distance increases with age, but the time when it is most effective is probably less than 3 Gyr. The metallicity gradient breaks at guiding center radius $R_g \sim 11.5$ kpc, which is caused by the lack of young open clusters in the outer disk and the presence of old outward migrators in the upper sequence. This shows that this boundary is related to the different effects of radial migration between the inner and outer disks. We also found many special open clusters in and near the outer disk with $R > 11$ kpc and a steeper metallicity gradient from the inner disk of $R_g < 7$ kpc, which tells of a complicated evolution history of the Galactic disk caused by different effects of stellar radial migration.

Unified Astronomy Thesaurus concepts: Galaxy disks (589); Galaxy evolution (594); Galaxy abundances (574); Solar neighborhood (1509); Open star clusters (1160); Stellar kinematics (1608)

1. Introduction

In recent years, with the progress of large-scale surveys in astrometry, e.g., Gaia (Gaia Collaboration 2018), and spectroscopy, e.g., APOGEE (Majewski et al. 2017), GALAH (De Silva et al. 2015), Gaia-ESO (Gilmore et al. 2012), and LAMOST (Cui et al. 2012; Deng et al. 2012; Zhao et al. 2012), a large number of stars’ positions, velocities, ages, and chemical abundances can be obtained, providing the most reliable and detailed observational constraints on the theory of the formation and evolution of the Milky Way. In the Galactic halo, the low-$\alpha$ abundance pattern of stellar streams provides evidence of the merging history of the Milky Way with dwarf galaxies in the context of the $\Lambda$ cold dark matter model (e.g., Helmi et al. 2018; Nissen & Gustafsson 2018; Zhao & Chen 2021). In the Galactic disk, the lack of an age–metallicity relation indicates the important process of stellar radial migration, which is a recent hot topic in astrophysics (e.g., Bergemann et al. 2014; Minchev et al. 2018).

According to Sellwood & Binney (2002), the interaction between a star and a transient spiral arm will cause the angular momentum to change, and the star’s guiding center will also change accordingly. Minchev & Famaey (2010) and Minchev et al. (2011) proposed a new mechanism for radial migration, which is caused by the nonlinear resonance overlap between the central bar and spiral arms of the galaxy. In addition, the disturbance caused by minor mergers can also give rise to radial migration (e.g., Quillen et al. 2009; Bird et al. 2012). Minor mergers usually play a role in the outer disk, but they strengthen the structure of the spiral arms and bars, thereby indirectly affecting the entire disk (e.g., Gómez et al. 2012; Minchev et al. 2013).

For a long time, open clusters have been widely used to trace the evolution of the Galactic disk. Since the ages and chemical compositions of open clusters can be determined with higher accuracy than those of field stars, they are better tracers of the variation with time of the Galactic properties, and they can be useful to study the effect of radial migration over time. However, we should recall that open clusters are more massive than single stars, and thus the effect of the interactions with spiral arms, bars, etc., might be different and less pronounced. In this respect, Anders et al. (2017) first suggested that open clusters experience significant radial migration. Minchev et al. (2018) and Quillen et al. (2018) proposed that radial migration is expected to flatten the radial metallicity gradient on a long enough timescale. Using the catalog of Netopil et al. (2016), Chen & Zhao (2020) calculated the migration distances for 146 open clusters and found that 56% of them had migrated. They measured the migration rate of $1.5 \pm 0.5$ kpc Gyr$^{-1}$ from intermediate-age open clusters in the outer disk, and found a fraction of clusters tend to migrate inward.

In this work, we aim to increase the number of open clusters by combining multiple spectroscopic survey data into the catalog of Netopil et al. (2016), and investigate how radial migration introduces scatter in the metallicity gradient and what outlier clusters in the metallicity gradient tell us about different mechanisms of radial migration. Moreover, since Netopil et al. (2016) included mainly nearby clusters, the inclusion of more spectroscopic data in this work will enlarge the sky coverage, and thus provide sufficient data for studying the radial migration of the Galactic disk, especially the outer disk.

2. Data and Methods

Metallicity and age are two important parameters for estimating the birth sites of stars, which are required in studying the radial migration of the Galactic disk. Based on color–magnitude diagrams from high-precision photometry, the ages of most open clusters are available in the literature. However, only a small percentage of open clusters have reliable metallicities in
the literature due to the lack of spectroscopic data for many clusters. Netopil et al. (2016) provided a homogenous sample of nearby open clusters with metallicities compiled from previous works. They used high-resolution spectroscopic, low-resolution spectroscopic, and photometric data to derive the metallicity of 172 open clusters. We integrate this sample and only use high-resolution spectroscopic data to ensure the reliability of metallicities. For these clusters, Soubiran et al. (2018) provided radial velocities based on Gaia DR2. This sample is the same as that of Chen & Zhao (2020), but we perform a stricter check on metallicity by comparing their values to other works.

With the recent release of high-resolution spectroscopic surveys, including APOGEE, GALAH, and Gaia-ESO, more open clusters have reliable metallicities and can be included in the study of radial migration of the disk. Casali et al. (2019) determined the metallicity and radial velocity of 17 open clusters from Gaia-ESO data. Donor et al. (2020) released the metallicity and radial velocity of 128 open clusters in Open Cluster Chemical Abundances and Mapping (OCCAM) survey IV, which are based on APOGEE DR16. Spina et al. (2021) obtained chemical abundances of 134 open clusters and kinematic properties of 226 open clusters from GALAH+ and APOGEE DR16 data. In addition, the Stellar Population Astrophysics (SPA) survey can also provide chemical and kinematic information from high-resolution spectra of six open clusters (see Frasca et al. 2019; Casali et al. 2020; D’Orazi et al. 2020). For clusters in common in different samples, we prefer the idea that using more member stars to determine the metallicity will enhance the reliability of the data. Finally, the LAMOST DR7 data can provide a large number of member stars’ spectroscopic data, including metallicity and radial velocity. We cross-match the LAMOST DR7 data with the list of member stars of open clusters from Cantat-Gaudin et al. (2020), and all stars with a membership probability not less than 0.7. The method is the same as in Zhong et al. (2020), who obtained a catalog of 295 open clusters based on the LAMOST DR5, but we have stricter selections. If the number of cluster members is greater than three, we calculate the average values (and standard deviations) of the metallicity and radial velocity. We use this sample as a supplement when open clusters were not included in high-resolution spectroscopic data. We cross-match all samples with the cluster catalog of Cantat-Gaudin et al. (2020) to obtain distance, proper motion, and age information.

In order to ensure the accuracy of the following calculation, we require the uncertainty of the clusters’ metallicities and radial velocities to be less than 0.15 dex and 10 km s\(^{-1}\). As we are interested primarily in the thin disk, we only use the sample with \(|Z| < 0.5\) kpc in the following analysis to ensure that the metallicity gradient can be used to estimate their birth sites. Because most of the metallicities of clusters come from Spina et al. (2021), we compare the metallicities from Netopil et al. (2016), Casali et al. (2019), Donor et al. (2020), and LAMOST DR7 with those from Spina et al. (2021), and derive the metallicity calibrations based on clusters in common by linear fits to the data, as shown by the red solid lines in Figure 1. We do not calibrate the metallicities from the SPA survey because this sample is too small. With these calibrations, we obtain a total sample of 231 open clusters with metallicities on the same scale.

3. Analysis

3.1. Three Sequences in the Radial Metallicity Gradient

Quantitative analysis of the effect of radial migration requires kinematic and orbital parameters to calculate birth sites and migration distances. We thus use galpy (Bovy 2015) to calculate the orbital parameters of the clusters. The gravitational potential in galpy used in our work is MWPotential2014, rescaled such that \(R_\circ = 8.178\) kpc (Abuter et al. 2018), \(Z_\circ = 25\) pc (Bennett & Bovy 2019), and the circular velocity is \(229\) km s\(^{-1}\) (Eilers et al. 2019). We adopt the solar motion relative to the local standard of rest of \((11.1, 12.24, 7.25)\) km s\(^{-1}\) \((U_\odot, V_\odot, W_\odot)\) Schönrich et al. (2010). We calculate several orbital parameters of the clusters, \(R_g\) (guiding center radius), and pericenter/apocenter distances. We use the observational uncertainties of each cluster to calculate the errors of \(R_g\) through 1000 Monte Carlo runs, and the median is 0.04 kpc.

The star’s guiding center is a good proxy for the current orbital distance (Chen & Zhao 2020), which is not altered by blurring, and churning leads to a change in the star’s guiding center (Sellwood & Binney 2002), so we will use \(R_g\) rather than \(R\) to analyze the radial metallicity gradient of open clusters. Figure 2 shows the radial metallicity gradient for the whole sample with an \(X\)-axis of \(R_g\). There are six clusters that deviate far from the general trend, and they are marked by their names in the three dashed boxes. Among these clusters, King 12, NGC 6383, NGC 2311, and Berkeley 18 have only one member star in Donor et al. (2020) and Spina et al. (2021), so these values could be uncertain. Note that the metallicity of Koppov 63 is \(-0.58\) dex in Spina et al. (2021) based on only one member star, while Zhong et al. (2020) gave \([\text{Fe}/\text{H}] = -0.08\) dex (determined from three members). If we adopt the latter, it does not deviate from the general trend anymore. The metallicity of Berkeley 32 is reliable based on 11 member stars in Netopil et al. (2016) and is close to the value of \(-0.29\) dex obtained by Dias et al. (2002). Thus, Berkeley 32 is a special cluster and will be discussed in Section 4.

Excluding these clusters in the three dashed boxes, we obtain a total sample of 225 open clusters, and we perform a running average metallicity for the remaining clusters, using a similar approach to Genovali et al. (2014) and Netopil et al. (2016), by grouping the sample into a constant number of 15 clusters or a maximum distance range of 1.5 kpc, whichever criterion is met first. The result of the running average is shown by the red solid curve in Figure 2. The clusters in the dashed boxes deviate from the running average by at least 3\(\sigma\), which also confirms their specialty. For comparison, we perform a linear fit to the clusters with \(R_g < 10\) kpc, and get a gradient of \(-0.071\) dex kpc\(^{-1}\). In general, the two sets of data are consistent until \(R_g = 11.5\) kpc, beyond which the radial metallicity gradient begins to flatten out, and there is a significant discrepancy at \(R_g \sim 13\) kpc. The reason for this discrepancy has been a hot topic for decades and remains an unsolved question today. We also find that the radial metallicity gradient is steeper at \(R_g < 7\) kpc, which will be discussed in Section 3.4. Usually, the linear fitting gradient is significantly affected by clusters on both sides in different samples, and thus the running average may represent a more reasonable relation between \([\text{Fe}/\text{H}]\) and \(R_g\).

In this work, we avoid investigating how the metallicity gradient flattens out in the outer disk, since we have only six
open clusters at $R_g > 13$ kpc, and they have a metallicity range of $[\text{Fe/H}]$ from $-0.35$ to $-0.1$ dex. Instead, we would like to analyze the scatter in metallicity at a given $R_g$ in more detail. Generally, the scatter in metallicity is quite similar for all $R_g$, of the order of 0.08 dex but with a wide range of 0.4 dex, which is larger than the uncertainty in metallicity of 0.05 dex in high-resolution spectroscopic samples (the main part of our data). It is suggested that radial migration makes a significant contribution to the scatter in the $[\text{Fe/H}]$ versus $R_g$ diagram. According to Donor et al. (2020), the metallicity at a given Galactocentric distance fits well with the model prediction of Chiappini (2009) (without taking into account radial migration) for young clusters (age $< 0.8$ Gyr), but it deviates significantly from this model prediction for older clusters. This deviation becomes more significant for the oldest clusters (age $> 2.0$ Gyr) and is thought to be evidence for radial migration.

Interestingly, we notice that open clusters below the dashed line seem to form a (lower) sequence parallel to the red dashed line, as shown by the green dashed line, which indicates that clusters with lower metallicity at the same $R_g$ also have the same gradient as the total sample. Accordingly, we suggest that open clusters above the red dashed line may represent another (upper) sequence, as shown by another green dashed line. Note that the upper sequence is also found to be a separated one consisting of old clusters with age $> 2$ Gyr in Donor et al. (2020, Figure 13) based on high-quality data on 71 open clusters. But they do not have clusters in the lower sequence. We check our data in the lower sequence, and they have

Figure 1. The metallicity calibrations between Spina et al. (2021) and Donor et al. (2020), Netopil et al. (2016), Casali et al. (2019), and LAMOST DR7 based on common clusters. Red solid lines are linear fits to the data and red dashed lines show the one-to-one relations.
consistent metallicities in the literature. Moreover, they do not show much greater uncertainties in metallicity than the upper sequence. Thus, we suggest that the lower sequence may be real, rather than a false feature from unreliable data. In the chemodynamical simulation of Minchev et al. (2013, 2014), data below the theoretical prediction of Chiappini (2009) exist (as well as data above) as a result of radial migration, which supports the reality of the lower sequence in our work.

3.2. The Age Distributions of the Three Sequences

The age–metallicity relation for the total sample is shown in Figure 3. The [Fe/H] range of clusters is −0.4 to 0.3 dex, the $R_g$ range 6–15 kpc, and the age range 0–8 Gyr. As expected, there is no age–metallicity relation, as already shown by many previous works (e.g., Carraro & Chiosi 1994; Friel et al. 2010; Yong et al. 2012). In particular, for the youngest clusters of age <0.5 Gyr, there is an [Fe/H] range from −0.3 to 0.3 dex, almost as large as for the whole sample. This is also the case for clusters with age ∼4 Gyr. In different $R$ bins ($R \leq 9$, $9 < R \leq 12$, $R > 12$ kpc), there is also no obvious age–metallicity relation, just that the mean metallicity decreases from the inner to the outer disk (see Figure 3). The age–metallicity relation of open clusters with age <4 Gyr is similar to that of the theoretical models. For example, in the input chemical model of Minchev et al. (2013), the difference in [Fe/H] between the present epoch and 4 Gyr ago is 0.17 dex in the solar neighborhood, which is smaller than the scatter. However, for several clusters with age >5 Gyr, their metallicities are significantly higher than the theoretical values, which suggests that they may be related to radial migration.

Since radial migration requires time to take effect, young clusters are preferred for establishing the radial metallicity gradient. In view of this, we select the clusters with age <0.5 Gyr and try to estimate the present-day metallicity gradient based on high-resolution spectroscopic data to ensure the reliability of metallicities, and we require at least three member stars for each cluster. A linear fit to the data gives $−0.074 \pm 0.007$ dex kpc$^{-1}$ (see Figure 4), which is consistent with that of Donor et al. (2020) ($−0.068$ dex kpc$^{-1}$ for $R_{gc} < 13.9$ kpc, $R_{gc}$ is the Galactocentric distance). The linear fit depends significantly on the points on each side. Meanwhile, even for clusters with age <0.5 Gyr, several open clusters belonging to the upper and lower sequences persist, which indicates that radial migration has a very short timescale. Therefore, it is not wise to limit the clusters’ age to get a reliable present-day metallicity gradient. Instead, we attempt to include more clusters that do not suffer from significant radial migration in their lives. This is actually the advantage of using the running average method, which avoids the dependence of a few points on each side and reflects the mean metallicity of locally born clusters (assuming that the majority of clusters were born locally). Note that our derived value of $−0.074$ dex kpc$^{-1}$ is close to the linear fit of $−0.071$ dex kpc$^{-1}$ in Figure 2, and both are consistent with the running average in the range of $R_g = 7–11.5$ kpc.

With the help of the derived present-day metallicity gradient, we select a middle sequence from a shift of 0.05 dex (corresponding to the error in metallicity) upward and downward, and then the upper and lower clusters are the remaining clusters in

![Figure 2](image-url). The radial gradient of metallicity for open clusters; different symbols indicate different sources of metallicities. The clusters within the dashed boxes deviate from the radial gradient and are eliminated in the following work. The red solid curve is the running average of the samples outside the dashed boxes, and the red dashed line is the linear fit to the $R_g < 10$ kpc samples, as discussed in the text. The green dashed lines are obtained by shifting the red dashed line up and down by 0.1 dex.
the upper and lower sequences as shown in Figure 5. The upper sequence is consistent with Donor et al. (2020), who suggest that the clusters with high metallicity originated in the inner Galaxy and then migrated radially outward to their present locations. In contrast, the lower sequence indicates that they are inward migrated clusters from the outer disk, which will be confirmed in terms of migration distance later. The cumulative curves for the three sequences in Figure 5 indicate that the upper sequence is obviously older than the middle sequence. As in the middle sequence, more than half of the clusters in the lower sequence are younger than 0.5 Gyr. The difference is that there are also many clusters older than 2 Gyr in the lower sequence. Different ages in the outward and inward clusters may indicate different timescales or different mechanisms of radial migration.

Figure 6 shows the distributions of clusters in the three sequences in the Galactic plane. It shows that the upper sequence has the widest distribution and can be distributed outside the Outer Arm. The middle sequence corresponds to the clump of in situ clusters at the solar location near the Local Arm \((X = 8.2 \text{ kpc}, Y = 0 \text{ kpc})\), and there is no cluster near the Outer Arm. The distribution of the lower sequence is similar to that of the middle sequence. Again, these distributions indicate that the effect of radial migration is related to age. The upper sequence includes more old clusters and thus they have enough time to migrate away from their birth site and distribute more widely in the Galactic plane.

### 3.3. Migration Distance as a Function of Age

We use the variation in ISM metallicity with time at the solar radius and the variation in ISM metallicity gradient with time from Minchev et al. (2018) to calculate the birth radius \(R_b\) of clusters. Minchev et al. (2018) adopt a semiempirical and largely model-independent method, which is based on an assumption for the ISM metallicity distribution in the disk and AMBRE-HARPS and HARPS-GTO high-quality data sets to deduce the evolution of the ISM metallicity gradient with time. This is a good alternative approach in the absence of ISM-related data, because the method of Minchev et al. (2018) is also based on observation data. It should be noted that an important assumption of Minchev et al. (2018) is that the ISM is well mixed at a given radius. The results of Nieva & Przybilla (2012) using early B-type stars are consistent with this assumption. Using the data on H II regions in 88 galaxies, Zinchenko et al. (2016) proposed that there is no significant global azimuthal asymmetry of [O/H] for their sample, and it is usually lower than 0.05 dex, although some other works analyzing in the Milky Way (Balser et al. 2015) or individual external galaxies (Sánchez et al. 2015) indicate otherwise. Sánchez et al. (2015) used NGC 6754 to conclude that the variation in oxygen abundance with azimuth is more obvious in external galactic regions, and the maximum scatter of [O/H] at a given radius is about 0.2 dex. Considering that this effect is symmetric around the mean, and most of the open clusters in our sample are in the solar neighborhood rather than in the...
outer regions of the Milky Way, we think the assumption of Minchev et al. (2018) is reasonable. However, this profile obtained by Minchev et al. (2018) using field stars may be systematically different from the samples of the open clusters. As shown in Figure 4, for the youngest open clusters with ages of 0–0.5 Gyr, according to the linear fit, [Fe/H] of the open clusters at solar radius is $-0.04$ dex, while it is 0.1 dex in Figure 5 of Minchev et al. (2018). We thus shift the ISM...
metallicity at the solar radius downward by 0.14 dex in subsequent analysis. This will cause a shift of birth site toward the inner Galaxy for the upper sequence, and a smaller number of clusters in the lower sequence suffer from inward radial migration. The median error of clusters in the lower sequence is about 0.5 kpc based on 1000 Monte Carlo runs, using the uncertainties in age and metallicity for each cluster.

In this work, we define 

\[
R_g - R_b = \begin{cases} 
\text{MD} & \text{if MD is a migrator,} \\
0 & \text{if MD is an in situ cluster,}
\end{cases}
\]

as the migration distance (MD) due to churning, and the deviation of the present location \(R\) from \(R_g\) due to blurring. Figure 7 shows the migration distance MD and \(R - R_g\) as functions of age. It is obvious that churning is more significant than blurring: about half of the clusters have \(|R_g - R_b| > 1\) kpc, but only 14 clusters lie above \(|R - R_g| = 1\) kpc. Blurring has an even distribution around the median \(R - R_g\) of 0.06 kpc, close to zero. However, there is an increasing average of \(|R - R_g|\) with age. For clusters with \(t < 0.5\), \(0.5 < t \leq 1.0\), \(1.0 < t \leq 2.5\), and \(t > 2.5\) Gyr, the mean \(|R - R_g|\) are 0.30, 0.38, 0.49, and 0.71 kpc, respectively. This means that blurring does not cause significant displacement in the radial distance, but it does become more effective for old clusters.

In this work, we define a cluster with \(|MD| > 1\) kpc as a migrator, and one with \(|MD| \leq 1\) kpc as an in situ cluster, based on the median error in MD of 0.5 kpc and over 90% of clusters having errors less than 1 kpc. With this definition, 46% of the open clusters are migrators, and 33% of the youngest clusters with age \(\leq 0.5\) Gyr have migrated, either inward or outward. In order to further analyze the change in the migration distance with age, we performed a running average using the same method as in Section 3.1. We adopt a maximum age range of 1 Gyr in the second criterion. The running average curve is shown as a black solid curve in the left panel of Figure 7. The average migration distance increases with age at age \(\leq 3.2\) Gyr from 0 kpc to 2.9 kpc, leading to a migration rate of approximately 1 kpc Gyr\(^{-1}\), which is similar to that estimated by Quillen et al. (2018) (1 kpc Gyr\(^{-1}\)) based on the Gaussian bar model in Comparetta & Quillen (2012), and slightly smaller than that of Chen & Zhao (2020) (1.5 kpc Gyr\(^{-1}\)). The migration rate decreases at age \(\geq 3.2\) Gyr. We do not have enough old clusters in this analysis, and thus this black line stops at 4 Gyr. It seems that the time when radial migration is most effective is in the initial 3 Gyr, with a migration rate of 1 kpc Gyr\(^{-1}\). If the results of our analysis are confirmed, this period may be related to the timescale of radial migration caused by the interaction between the bar and spiral arms in Minchev et al. (2013). Further work is desirable to confirm this suggestion. In the left panel of Figure 7, there are three clusters that deviate from the others. We have marked their names in the figure and will discuss them in Section 4 as special clusters.

We also show the MD distributions for different age bins in Figure 8. For clusters with \(t \leq 0.5\), \(0.5 < t \leq 1.0\), \(1.0 < t \leq 2.5\), and \(t > 2.5\) Gyr, the mean MDs are 0.28, 0.88, 1.66, and 2.00 kpc, respectively. Again, we see the increase in the migration distance with age. Although quite a large fraction of young clusters migrate inward, which reduces the mean value of MD in the first two age bins, the general trend of increasing MD with age is valid and this is expected for radial migration, which requires time to move from one place to another.
3.4. Migration Distance as a Function of $R_g$

An obvious feature in Figure 7 is that clusters with $R > 12$ kpc are located in the upper envelope of the plot of MD versus age, which may be related to the discrepancy of the metallicity gradient in Figure 2. Here we adopt $R_g = 11.5$ kpc as a division between the inner disk and the outer disk since it corresponds to the discrepancy of the metallicity gradient between the linear fit and the running average in Figure 2. As shown in the left panel of Figure 9, migration distances of clusters in the inner disk and the outer disk show different trends with $R_g$. The distribution of migration distance is not related to $R_g$ in the inner disk, where half of the clusters are in situ, and the majority of the remaining clusters migrate outward with only 12 clusters (with young ages of $t \leq 0.5$ Gyr) showing inward migration. In the outer disk, the migration distance increases with $R_g$, and only four clusters are born locally. The right panel of Figure 9 shows $R_b$ as a function of $R_g$. It can be seen that the birth sites of clusters in the inner and outer disks are different: the inner disk clusters mainly have $R_b$ in the range 3–12 kpc, and those in the outer disk mainly have $R_b$ in the range 8–12 kpc. There are no clusters born outside 12.1 kpc in this sample, and most of the clusters in the outer disk have migrated outward to their current locations. For clusters with $R_g < 11.5$ kpc, $R_b$ increases with $R_g$; this trend breaks when $R_g \sim 11.5$ kpc, where $R_b$ no longer increases with $R_g$ but flattens. This flattening trend in the outer disk mainly occurs in clusters with age $>1$ Gyr. In addition, all outer disk clusters are born outside 7.4 kpc, and only Berkeley 36 was born within the solar radius. Only two old clusters (Berkeley 17 and Berkeley 36) are born within the solar radius and have a migration distance greater than 4 kpc. They have $R_g$ of 10.9 and 11.8 kpc respectively and they are both old open clusters (7.2 and 6.8 Gyr). The above results indicate that the break in metallicity gradient is caused by the existence of old open clusters ($>1$ Gyr) in the outer disk beyond 11.5 kpc, which are born in the inner side and migrate to their current location. But clusters born within the solar radius may need a longer time to have a chance to migrate to the outer disk.

As can be seen in Figure 9, more than half of the clusters in the inner disk of $R_g < 7$ kpc migrated outward to their current positions, which is more than for those near the solar radius. $R_b$ and $R_g$ of these outward migrating clusters are 3–5 kpc and 6–7 kpc respectively. Since the clusters with $R_g < 7$ kpc are closer to the central bar, they will be more strongly affected by the coupling of the spiral arm and bar, and thus the effect of radial migration will be more obvious. According to Bovy et al. (2019) and Queiroz et al. (2020), the highest metallicity is not located in the Galactic center, but roughly at $R = 3$–5 kpc. According to Minchev et al. (2013), the corotation radius is 4.7 kpc, where radial migration is the most intense and produces inward migration as well as outward migration. Therefore, many metal-rich clusters migrated to $R_g > 5$ kpc, which also led to the steepening of the metallicity gradient of the clusters with $R_g < 7$ kpc in Figure 2.

3.5. MDF for Migrants and in situ Clusters

It is interesting to investigate the metallicity distribution function (MDF) between migrants and in situ clusters for different Galactic distances. Figure 10 shows the MDF of the total sample (upper left), and samples with $R \leq 9$ kpc (upper right), $9 < R \leq 12$ kpc (lower left), and $R > 12$ kpc (lower right). As can be seen from the upper left panel, the metallicity range of the total sample is $-0.45 < [\text{Fe/H}] < 0.3$ dex, which is similar to the range of migrants and in situ clusters. But clusters with supersolar metallicity are mainly migrants, which form at the inner disk and migrate outward to their current locations. Due to the high star formation rate (SFR) and high metallicity of the ISM in the inner disk, we would expect the difference between migrants and in situ clusters to be more significant at the metal-rich end, which is also shown in the upper left panel of Figure 10.

The MDF of in situ clusters is peaked at $-0.05$ dex, and has a long tail toward lower metallicities, indicating an obvious skewness. The MDF peak of the total sample is also at $-0.05$ dex, but the skewness is not obvious. The MDF of migrants has multiple peaks and tends to extend significantly toward supersolar metallicity. The skewnesses of the total sample,
migrators, and in situ clusters are 0.1, 0.3, and −1.2, respectively. The skewness of the MDF of the total sample toward low metallicities disappears due to the contribution of the less skewed migrators, and the peak is determined by in situ clusters.

We further divide the sample into three groups according to Galactic radial distance $R$: $R \leq 9$ kpc, $9 < R \leq 12$ kpc, and $R > 12$ kpc. For the largest group of $R \leq 9$ kpc, the MDF peak of the total sample is still determined by in situ clusters, and the peak is determined by in situ clusters. The inward migrators are evenly distributed at −0.1 to 0.2 dex. The outward migrators at −0.05 to 0.3 dex, and there are few in situ clusters where $[\text{Fe/H}] > 0.05$ dex. For clusters with $9 < R \leq 12$ kpc, the characteristics of the MDF are basically the same as for those with $R \leq 9$ kpc: the peak value of the overall sample is determined by in situ clusters, and the high-metallicity tail is determined by migrators. The difference is that the number of inward migrating clusters is very small, which has little effect on the MDF. Almost all clusters with $R > 12$ kpc are outward migrators.

Loebman et al. (2016) used a high-resolution N-body + smoothed particle hydrodynamics simulation and APOGEE DR12 data to study the effect of radial migration on the MDF of field stars. They proposed that the radial migration caused the MDF to be negatively skewed at small $R$ and positively skewed at large $R$. Due to the small number of open clusters in our sample, we cannot analyze the skewness of MDF in each $R$ bin to compare it with the MDF of field stars. But the same result is that their peaks are all determined by in situ clusters, and the high-metallicity tail is almost all contributed by migrators (see their Figure 4).

### 3.6. Migration Distance for the Three Sequences

It is found that the metallicity of intermediate-age open clusters is higher than that of young open clusters at a given Galactocentric distance (e.g., Jacobson et al. 2016; Netopil et al. 2016; Spina et al. 2017), which corresponds to the upper sequence in Figure 5. This sequence is composed of clusters that migrate outward as shown in Figure 11, and has an extensive $R_g$ range from the inner disk (5.5 kpc) to the outer disk (up to 14.5 kpc), i.e., the whole Galactic disk. The lower sequence is mainly composed of inwardly migrated clusters, and the $R_g$ distribution has a cutoff at 12.5 kpc, which causes the radial
migrated clusters in the outer disk metallicity gradient to break. That is, there is a lack of inwardly migrated clusters from the more metal-rich inner disk which can reach farther, increasing the mean metallicity of the outer disk and thus the radial metallicity gradient flattens out. In addition, radial migration leads to dispersion in the radial metallicity distribution of open clusters, as suggested by Anders et al. (2017). As more clusters are migrating outward than inward, the number of clusters in the inner disk decreases. They also proposed that non- and inward migrating clusters are disrupted faster, which can explain the present-day radial metallicity distribution. According to the inside-out formation mechanism, the number density of stars in the inner disk is higher, and open clusters are more easily disrupted by collisions. As can be seen in Figure 2, there are few open clusters with \( R_\gamma < 6 \) kpc in our samples.

The above analysis shows the different effects of radial migration between the inner disk and outer disk with a division around \( \sim 11.5 \) kpc. According to Minchev et al. (2013), the coupled interaction between the Galactic bar and spiral arms could invoke very effective radial migration. This mechanism plays an important role in the inner disk, since the Galactic bar is located in the inner Galaxy at \( R < 5 \) kpc (e.g., Bovy et al. 2019). For the outer disk far away from the bar, the bar–spiral-arm mechanism may still work, but the impact is less than in the inner disk. Meanwhile, there may be other mechanisms at work in the outer disk, such as minor mergers (Quillen et al. 2009), which will cause many special clusters to appear in the outer disk. But our sample is limited to \( |Z| < 0.5 \) kpc, so these special clusters are basically excluded.

4. Special Open Clusters throughout the Galactic Disk

As discussed in Section 3.1, Berkeley 32 is a special cluster with underabundant metallicity for its location. Specifically, Berkeley 32 has a metallicity of \(-0.34\) dex, and its age is 4.9 Gyr. It is located at \( R = 11.0 \) kpc, close to the boundary between the inner and outer disks. Its birth radius is 9.6 kpc and its guiding center radius is \( R_\gamma = 8.8 \) kpc, and thus it is an in situ cluster. However, its radial oscillation is 4.9 kpc, which is very large. Based on these data, it is blurring, rather than churning, that affects Berkeley 32.

We also found three special clusters in the left panel of Figure 7: King 2, Trumpler 5, and IC 166. Like Berkeley 32, Trumpler 5 and King 2 are both in situ clusters older than 4 Gyr with \( R_\gamma - R_\delta \) of 0.8 and –0.1 kpc, respectively. Therefore, there are still a few clusters that have not left their birth location after 4 Gyr. King 2 has a similar situation to Berkeley 32: it has \([\text{Fe}/H] = -0.36, \) age = 4.1 Gyr, \( R = 11.4 \) kpc, \( R_\gamma = 10.3 \) kpc, and \( R_\delta = 10.4 \) kpc. It also has a large radial oscillation of 3.8 kpc, so the effect of blurring is larger than that of churning for King 2. Trumpler 5 has a different situation: neither churning nor blurring has much effect on it. It has typical thin-disk kinematics, \( e = 0.08, \) and \( Z_{\text{max}} = 0.1 \) kpc, which leads to radial oscillation of only 1.9 kpc. Donati et al. (2015) analyzed the abundances of several elements of Trumpler 5 using high-resolution UVES spectra, and compared them with the abundance ratios of field stars with the same metallicity, and concluded that Trumpler 5 has a typical thin-disk abundance ratio (see their Figure 10). Trumpler 5 has an age of 4.3 Gyr and is located at \( R = 11.3 \) kpc. Buck (2020) proposed that the merger brought fresh metal-poor gas to dilute the ISM’s metallicity in the Galactic outskirts starting from about 7 Gyr ago, resulting in the formation of a large number of low-\( \alpha \) metal-poor stars. According to the simulation of Buck (2020), the age, location, \([\text{Fe}/H], \) and \([\alpha/\text{Fe}]\) of Trumpler 5 indicate that it may have been born after the merger of metal-poor gas.

IC 166 is currently in the outer disk with \( R = 12.3 \) kpc and \( R_\gamma = 14.1 \) kpc, but its metallicity of \(-0.1\) dex is relatively high. Hence it becomes the most metal-rich cluster in the outer disk in the sample. With an age of 1.3 Gyr and \( R_\gamma = 8.5 \) kpc, it has a high migration rate of 4.3 kpc Gyr\(^{-1}\). Also, it shows a large radial oscillation (4.6 kpc) due to blurring. In short, this is a metal-rich cluster in the outer disk with strong effects from both churning and blurring due to an unknown mechanism. Using APOGEE data, Schiappacasse-Ulloa et al. (2018) calculated the chemical abundances of eight species (Mg, Ca, Ti, Si, Al, K, Fe, and Mn) for IC 166, and suggested that the cluster lies in the low-\( \alpha \) sequence of the canonical thin disk.

In summary, blurring also plays an important role for some old (age >1 Gyr) open clusters located at \( R > 11 \) kpc, such as Berkeley 32, King 2, and IC 166. In addition, there are clusters on which neither churning nor blurring has much effect, such as Trumpler 5, which may have been born after the merger of metal-poor gas in the Galactic outskirts. These special clusters reveal the complicated history of the evolution of the outer Galactic disk.

5. Conclusions

Metallicity, age, and kinematics for a sample of 225 open clusters are compiled from the literature to study the radial migration of the thin disk of the Galaxy. The metallicity and
radial velocity data come from the catalog of open clusters of Netopil et al. (2016) (only metallicity, based on a variety of high-resolution spectroscopic data), Soubiran et al. (2018) (only radial velocity, based on Gaia DR2), Casali et al. (2019) (based on Gaia-ESO), Donor et al. (2020) (based on APOGEE DR16), Spina et al. (2021) (based on GALAH+ and APOGEE DR16), and the SPA survey, supplemented by the LAMOST DR7 data. The age data and the rest of the kinematic parameters are from Cantat-Gaudin et al. (2020) based on Gaia DR2.

Based on the high-resolution spectroscopic data of clusters with age <0.5 Gyr, we calculate the present-day metallicity gradient by a linear fit to open clusters in the solar neighborhood, and it is $-0.074 \pm 0.007$ dex kpc$^{-1}$. The systematic difference between the radial metallicity profile of the ISM in Minchev et al. (2018) and our sample is modified by the present-day metallicity gradient, and the birth radius is calculated as well as the migration distance $R_g - R_b$. According to the criterion of $|R_g - R_b| > 1$ kpc, 46% of open clusters have migrated. We divide clusters into three sequences in the diagram of [Fe/H] versus $R_g$ according to their distribution along the present-day metallicity gradient: upper (above the fitting line), middle (near the fitting line), and lower (below the fitting line). These three sequences of clusters are mainly outward migrants, in situ clusters, and inward migrants, respectively. This indicates that the scatter in metallicity in the radial metallicity distribution of open clusters is mainly caused by radial migration, not only by the uncertainty in metallicity, $R_g - R_b$ and $|R - R_g|$ of clusters both increase with age, but the time when radial migration is most effective is when the age is less than 3 Gyr. At age >3 Gyr, the migration rate becomes lower. Therefore, the radial migration of open clusters is closely related to age, and old clusters generally migrate outward.

The radial migration takes effect in an extensive range of the Galactic disk. There are many more clusters migrating outward than inward, and their distribution range is 5.5–14.5 kpc, which is almost the same as the distribution range of the overall sample, while the inwardly migrating clusters are distributed at 5.5–12.5 kpc. This explains why the radial metallicity distribution of open clusters has obvious scatter throughout the disk. Besides, the flattening of the metallicity gradient of the open clusters outside 11.5 kpc can be explained by the absence of clusters from the lower sequence.

The determination of the boundary between the inner and outer disks of the Milky Way is complicated, and different works give different results (e.g., 10 kpc in Haywood et al. 2013, 2016). In our work, the break in the radial metallicity gradient of open clusters is found to be at 11.5 kpc, where the linear function starts to deviate from the running average curve, and the gradient flattens out. We thus suggested that 11.5 kpc is the boundary between the inner and outer disks based on the churning of open clusters. We propose that the main mechanism of radial migration by the coupling of the bar and spiral arms (Minchev et al. 2013) works in both the inner and outer disks, but this mechanism is more effective within 11.5 kpc. There are both inwardly and outwardly migrating clusters in the inner disk, but the clusters in the outer disk almost all migrate from the inner disk, and there are almost no young clusters. Some complex extra mechanisms join the main mechanism in the inner disk and the outer boundary, which will cause some special clusters to appear, such as Berkeley 32, King 2, IC 166, and Trumpler 5.

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This page contains references related to the study of radial migration and metallicity gradients in open clusters. It includes a description of the method used to calculate the present-day metallicity gradient and the migration distance of clusters. The study also discusses the migration rate, which becomes lower as the age increases, and the scatter in metallicity in the radial metallicity distribution of open clusters. The work concludes with a discussion of the boundary between the inner and outer disks of the Milky Way, which is complicated by different works giving different results. The study is supported by the National Natural Science Foundation of China and acknowledges funding from the Gaia Data Processing and Analysis Consortium (DPAC).
