Reliability and limitations of inferring birth radii in the Milky Way disk

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ABSTRACT

Recovering the birth radii of observed stars in the Milky Way is one of the ultimate goals of Galactic Archaeology. One method to infer the birth radius and the evolution of the ISM metallicity assumes a linear relation between the ISM metallicity with radius at any given look-back time. Here we test the reliability of this assumption by using 4 zoom-in cosmological hydrodynamic simulations from the NIHAO-UHD project. We find that one can infer precise birth radii only when the stellar disk starts to form, which for our modeled galaxies happens $\sim$ 10 Gyr ago, in agreement with recent estimates for the Milky Way. At later times the linear correlation between the ISM metallicity and radius increases, as stellar motions become more ordered and the azimuthal variations of the ISM metallicity start to drop. The formation of a central bar and perturbations from mergers can increase this uncertainty in the inner and outer disk, respectively.

Key words: Galaxy: evolution – Galaxy: abundances

1 INTRODUCTION

It is widely accepted that stars move away from their birth locations over time in the process commonly referred to as radial migration. Radial migration was first suggested by Grenon (1972, 1989), in which they found old metal-rich stars in the solar neighborhood that exhibited kinematic and abundance properties consistent with those of the inner disk. Stars can move away from their birth radii either because they have high eccentricities or due to a permanent change in their angular momentum. The latter process is also referred to as radial migration or mixing. Stars oscillating around their guiding radii can blur the intrinsic relations, however, this process can be accounted for by estimating the stellar guiding radius. On the other hand, migrating stars are largely indistinguishable in their kinematics from stars born locally (e.g. Sellwood & Binney 2002; Roškar et al. 2008; Minchev & Famaey 2010). Moreover, they can flatten the intrinsic abundance gradient in the disk significantly over time (e.g. see Figure 5 from Minchev et al. 2013).

As a result, to truly understand the enrichment history of the Milky Way (MW), we need to connect the present-day observables to the birth properties of stars. Without such knowledge, reconstructing birth properties of stars with sensible assumptions, one of which included the method shows promising results by inferring $R_{\text{birth}}$ (Adibekyan et al. 2012). The method relied on the following assumptions: (1) the gas is well mixed azimuthally, (2) stars are born from a narrow metallicity range at a certain radius at any given time, (3) the ISM [Fe/H](t, R) evolved smoothly with both radius and time, and (4) the MW disk formed inside-out. Feltzing et al. (2020) concluded the method shows promising results by inferring $R_{\text{birth}}$ with APOGEE DR14 data and comparing the resulted $R_{\text{birth}}$ distributions to those in a hydrodynamic simulation from Agertz et al. (2021). Other derivations of the radial migration strength can be found in the works by, e.g., Frankel et al. (2019, 2020); Lian et al. (2022).

Although the method described in Minchev et al. (2018) has shown to be successful, the information about birth radius in the MW is lost, and therefore, the inferred $R_{\text{birth}}$ from data cannot be truly validated.
Moreover, inferring a star’s birth radius with its metallicity and age requires a correlation between the ISM [Fe/H] and R at the time when the star was born (look-back time = age of the star). In this letter, we will show that precise $R_{\text{birth}}$ can only be inferred when a rotationally supported stellar disk is starting to form. We use MW-like cosmological zoom-in simulations from NIHAO-UHD (Buck 2020; Buck et al. 2020), in which we have access to the enrichment history and $R_{\text{birth}}$ of stars. We will do this by linking the evolution of ISM metallicity, the orderliness of the gas-particle orbits, mergers, and the existence of a stellar bar with the intrinsic uncertainty on inferring $R_{\text{birth}}$.

In section 3.1, we investigate at what time does the correlation between the ISM metallicity and R is strong enough to infer reliable $R_{\text{birth}}$. Once the correlation is established, the dispersion around the metallicity – R linear relation can still lead to intrinsic uncertainty in inferring $R_{\text{birth}}$. This scatter can be created from the azimuthal variation of ISM metallicity caused by satellite infall, the spiral arms, the bar, or possibly other perturbations (e.g. Bellardini et al. 2021; Spitoni et al. 2019; Sánchez-Menguiano et al. 2020). We examine the connection between the ISM metallicity gradient, azimuthal ISM metallicity variation, the orderliness of the gas-particle orbits, and the uncertainty of inferring $R_{\text{birth}}$, assuming a linear relation between the ISM metallicity and R at all times in section 3.2. Finally, we discuss the implication for inferring $R_{\text{birth}}$ in the MW in section 4.

2 DATA & METHODS

2.1 Simulated Data

The simulated galaxies used in this work were first presented by (Buck et al. 2018). They are taken from a suite of high-resolution cosmological hydrodynamical simulations of MW-mass galaxies from the NIHAO-UHD project (Buck et al. 2020). A modified version of the smoothed particle hydrodynamics (SPH) solver GASOLINE2 (Wadsley et al. 2017) was used to calculate the simulations from cosmological initial conditions. Star formation and feedback (both energetic and chemical elements) are modeled following the prescriptions in (Stinson et al. 2006, 2013). The simulations used in this work trace oxygen and iron separately (see Buck et al. 2021, for a recent update to the chemical enrichment) and adopted a metal diffusion algorithm between particles as described in Wadsley et al. (2008). The parameters for simulations used in this letter are taken from Buck et al. (2020). The numbers in the naming represent the total Dark Matter (DM) halo mass in units of solar mass. The time separation between every two consecutive output snapshots is ~ 200 Myr, and all of the galaxies have been integrated until redshift 0. For more information on the simulation details and galaxy properties, we refer the readers to Buck et al. (2020).

3 RESULTS

To infer the birth radius for a star from its [Fe/H] and stellar age alone, a correlation between the ISM metallicity and R at a look-back time equal to the stellar age of the star is required. However, as shown in simulations (e.g. Gurvich et al. 2022; Bird et al. 2013; Bellardini et al. 2022), observations of high-redshift galaxies (e.g. Ciucă et al. 2021; Wisnioski et al. 2015; Übler et al. 2019; Elmegreen et al. 2007) and observations of the MW (e.g. Belokurov & Kravtsov 2022; Conroy et al. 2022), hot, turbulent gas is likely to be common in early galaxy formation. This means a correlation between the ISM metallicity and R at early times may not exist. Similarly, as pointed out in Minchev et al. (2018), if the MW started with a flat gradient, their method would fail for stars ≥ 10 Gyr.

3.1 When can we infer reliable $R_{\text{birth}}$ from stellar [Fe/H] and age?

Figure 1 summarizes the formation histories of the 4 simulated galaxies of interest. The metallicity evolution of the stars is shown in the background, colored by $R_{\text{birth}}$. The blue and red histograms show the instantaneous mass increase ($\Delta M/M$) within 2$R_{\text{half}}$ of the galaxies for star and gas particles, respectively, where $R_{\text{half}}$ is the half-light radius of the galaxies at each look-back time, calculated by (13.8 Gyr - cosmic time). $\Delta M/M$ is calculated by $\Delta M/M = (M_{n+1} - M_n)/M_n$, where $n$ is the snapshot number and $n = 0$ represents the snapshot at a look-back time of 13.8 Gyr. The increase in stellar mass is a combination of in-situ star formation and ex-situ gas accretion. Similarly, the gas mass increase results from in-situ supernova and ex-situ gas accretion. The red dashed line shows the time when the stellar disk is starting to form, which is defined here as most stars are on circular orbits (see Figure 10 of Buck et al. 2020, or Figure 3 left plot). The black dashed line in the bottom figure shows the formation of the bar taken from Buck et al. (2018) Figure 10. The vertical grey/orange lines are the times when there is a satellite > 1%/10% total mass ratio in the main galaxy’s viral radius, indicating on-going merger events. The red dashed lines, black dashed lines, and the grey/orange lines are used throughout the figures in this letter. The green line shows the absolute value of the Pearson correlation coefficient (PCC) between the metallicity and R of the gas particles at each look-back time when the snapshot is available. PCC is a statistical quantity that identifies the linear correlation between two variables, in which -1 and 1 represent a perfectly negative or positive linear correlation, respectively. Two strongly correlated variables typically have a |PCC| > 0.7, meaning ~ 50% of the variation has been accounted for in the data by fitting a line. We have indicated the line of |PCC| = 0.7 in the Figures (cyan dashed line).

It is clear that all 4 galaxies formed bottom-up, meaning they originated from a series of galaxy mergers and gas accretion events, as the increase in star and gas mass are > 100% early on (see blue/red histograms). Most stars are born in the inner galaxy early on, while later on the birth radius distribution broadens, indicating inside-out formation. During this early time, when $\Delta M/M$ is large, the |PCC| is starting to form and when a significant amount of stars are formed in the outer disk (> ~ 5 kpc; indicated by the red dashed line) for most galaxies. However, once the frequent mergers/accretions have subsided and a well ordered stellar disk begins to form, the |PCC| stays above 0.7 for all galaxies. This implies that inferring birth radii with [Fe/H] and age is most precise and accurate after the turbulent phase of galaxy formation has ended, which for the MW has been suspected to be ~ 10 Gyr ago based on comparing simulations with observations (Belokurov & Kravtsov 2022)\(^2\).

\(^1\) Due to the frequent merger history at low redshift, galaxy g6.96e11 has a lower |PCC| compared to the other galaxies after its stellar disk has begun to form.

\(^2\) Conroy et al. (2022) also pointed out the thick disk formed ~ 13 Gyr ago defined by star formation efficiency. However, for the purpose of this study, we find the definition of disk formation from Belokurov & Kravtsov (2022) fits best with this study.
How well does a straight line fit the metallicity gradient at all times, and what uncertainty will that bring in inferring $R_{\text{birth}}$? The answer lies within Figure 2. The top plot shows the metallicity gradient evolution over time, and the solid lines display the smoothed version of the points, using a 1D Gaussian filter after the disk has started to form for each galaxy. The slopes are calculated by fitting a line between the gas particles' metallicity and $R$ within 25 kpc of the galaxy. The red dashed line shows a natural log function to guide the eye. Minchev et al. (2018) derived a natural-log functional form for the metallicity gradient evolution, and it fits well with most of the galaxies soon after their disks have begun to form. As pointed out earlier, the g6.96e11 galaxy has frequent mergers/infalls at low redshift, causing a more chaotic ISM evolution. The metallicity dispersion ($\frac{\Delta \text{[Fe/H]}}{\text{disp}}$) around the linear relation between the ISM metallicity and $R$ at each snapshot is shown in the middle plot. Similar to the conclusion from section 3.1, the ISM is more turbulent at earlier times and thus, the $\text{PCC}$ between ISM $\text{[Fe/H]}$ and $R$ is low, and $\frac{\Delta \text{[Fe/H]}}{\text{disp}}$ is high. However, as the stellar disk started to form, $\text{[Fe/H]}_{\text{disp}}$ settled to $<0.1$ dex.

We can also estimate the intrinsic uncertainty in inferring $R_{\text{birth}}$, $\sigma_{R_{\text{birth}}}$, assuming 1) we know the linear fits of the ISM metallicity at a given look-back time, and that 2) there is no error on the observables ($\frac{\text{[Fe/H]}}{R}$ and age; see the bottom plot of Figure 2). The intrinsic uncertainty is estimated using $\sigma_{R_{\text{birth}}} = \frac{\text{[Fe/H]}}{\text{disp}} / d[\text{Fe/H}]_{\text{ISM}} / dR$.

The intrinsic dispersion of $\frac{\text{[Fe/H]}}{R}$ is smaller than the measurement uncertainty of $0.14$ dex, implying the actual dispersion can be smaller. We also note that the metallicity gradient in the Galaxy is still not well constrained (e.g. Spina et al. 2022; Eilers et al. 2022).

We can also connect the ISM evolution and $\sigma_{R_{\text{birth}}}$ with the “orderliness” of the stars orbit (a proxy for circularity of the star’s orbits), $\left< v_\phi \right> / \sigma_{v_\phi}$, for the ISM, where $\left< v_\phi \right>$ is the average azimuthal velocity, and $\sigma_{v_\phi}$ is the azimuthal velocity dispersion. Figure 3 left column plots show the time evolution of $\left< v_\phi \right> / \sigma_{v_\phi}$ for the 4 simulated galaxies. We look at $\left< v_\phi \right> / \sigma_{v_\phi}$ in 6 different radial bins between 0-18 kpc. The solid lines are the smoothed version of the points, using a 1D Gaussian filter after the stellar disk begins to form. The black dashed line in the bottom figure shows the formation of the bar taken from Buck et al. (2018) Figure 10. Darker vertical lines mean more satellites exist in the viral radius at that time. Figure 3 right plot shows the same as the left but with the ISM metallicity variation in a small radial bin ($\sigma_{\text{Fe/H}}$) at 6 different radius between 0-18 kpc. The metallicity variation increases towards the outer disk, and can also be affected by the bar, agreeing with findings from other simulations and chemical evolution models (e.g. Bellardini et al. 2021; Spitoni et al. 2019).

Figure 3 suggest when the stellar disk begins to form, the orbits transition rapidly into a more ordered configuration and the ISM metallicity azimuthal variation also started to decrease. The rapid increase in $\left< v_\phi \right> / \sigma_{v_\phi}$ and the decrease of ISM metallicity azimuthal variation shows a fast transition from the turbulent gas phase to the quiescent disk phase (see also Gurvich et al. 2022). This rapid phase transition also leads to a well-established metallicity gradient with a high correlation (PCC) $> 0.7$. This means, after the rapid increase in the orderliness of the gas-particle orbits, a star formed from the ISM has a well-constraint metallicity at a certain radius, meaning we can infer birth radii with smaller $\sigma_{R_{\text{birth}}}$ (Figure 2). However, late mergers can induce turbulence in gas, and therefore, increase $\sigma_{\text{Fe/H}}$ and $\sigma_{R_{\text{birth}}}$ in mostly the outer galaxy, c.f. dispersion in $\left< v_\phi \right> / \sigma_{v_\phi}$. The bar can also induce variation in metallicity in the inner galaxy. As a result, the uncertainty in inferred $R_{\text{birth}}$ for the inner Galaxy after the formation of the bar, and the outer Galaxy during a time of merger could be higher.
Figure 2. Metallicity gradient evolution (top), metallicity dispersion around the linear fit, [Fe/H]_{disp} (middle), and uncertainty in inferring R_{birth} (σ_{Rbirth}) assuming the metallicity gradient evolution is known and that there is no error on [Fe/H] and age measurements. The uncertainty, σ_{Rbirth}, calculated by [Fe/H]_{disp}/(d[Fe/H]_{ISM}/dR). The solid lines are the smoothed version of the points, using a 1D Gaussian filter, after the stellar disk begins to form. The red line in the top plot shows a natural log function to guide the eye.

4 CONCLUSIONS AND DISCUSSION OF THE IMPLICATIONS FOR THE MW

By using MW-like simulations from the NIHAO-UHD project, we are able to connect the phases of galaxy formation with the possibility of inferring birth radii of stars. In particular, this letter shows:

- Precise birth radii can be inferred from stellar ages, guiding center radii, and metallicities only once the stellar disk starts to form at ~ 10 Gyr ago for the MW (Belokurov & Kravtsov 2022).
- At later times the linear correlation between the ISM metallicity and R increases, as stellar motions become more ordered and the azimuthal variations of the ISM metallicity decrease by an order of magnitude (see Figure 1 and Figure 3).
- A central bar and perturbations from mergers can increase the intrinsic uncertainty of inferred R_{birth} in the inner and outer disk by up to 50%, respectively (see Figure 3).
- Considering the observed present-day ISM metallicity gradient, derived from Cepheids, of ~0.05 dex/kpc with a scatter of 0.1 dex (Luck 2018), the minimum intrinsic uncertainty on inferring R_{birth} in the MW is ~ 2 kpc. However, as pointed out in Luck (2018), this scatter is smaller than the measurement uncertainty (0.14 dex), and therefore, the true scatter and the intrinsic uncertainty is likely to be smaller than 2 kpc.

However, in this study, we only investigated a linear relation between the ISM metallicity and R. Future work should investigate the possibility that other functional forms exist, that better describe this correlation. We also only used the ISM gradient derived from Cepheids and other studies have found slightly different gradients ranging from around ~0.05 to ~0.07 dex/kpc (e.g. Anders et al. 2017; Maciel & Andrievsky 2019). Studies derive local metallicity gradient using neutral gas and HII regions have found a slightly shallower gradient of ~ ~0.04 dex/kpc (e.g. De Cia et al. 2021; Esteban et al. 2022). Most of the studies either do not report the metallicity intrinsic dispersion around the relations or have a scatter that is on the order of the measurement uncertainty. As a result, the intrinsic uncertainty on R_{birth} for the MW is not constrained. We also want to point out that the evolution of the simulated galaxies may not match exactly with that of the MW. One discrepancy is that the disk seems to form earlier for the MW compared to simulations (see also Belokurov & Kravtsov 2022), which could indicate missing/incorrect physics in the simulations. Future work is needed to further investigate this discrepancy.

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DATA AVAILABILITY

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

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Figure 3. Time evolution of $\langle v_\phi \rangle / \sigma_{v_\phi}$ (left) and the azimuthal ISM metallicity variation, $\sigma_{[Fe/H]}$, (right) for the four simulated galaxies, in which $\langle v_\phi \rangle$ is the average azimuthal velocity, and $\sigma_{v_\phi}$ is the azimuthal velocity dispersion. $\langle v_\phi \rangle / \sigma_{v_\phi}$ can be taken as the “orderliness” of the gas-particle orbits, or a proxy for the circularity of the star’s orbits. We look at $\langle v_\phi \rangle / \sigma_{v_\phi}$ in 6 different radial bins and $\sigma_{[Fe/H]}$ in 6 narrow radial bins ranging from 0-18 kpc. The solid lines are the smoothed version of the points, using a 1D Gaussian filter after the stellar disk begins to form.