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The influence of radial stellar migration on the chemical evolution of the Milky Way

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Abstract. The existence of stellar migration in Galactic disk has been demonstrated by several works in recent years. Here we use an analytical method to model radial stellar migration in the Galactic disk, then add it to detailed Galactic chemical evolution model to study its influence on the chemical evolution of the Milky Way, especially for the abundance gradients. We found that the radial stellar migration in the Galactic disk can scatter the age-metallicity relation, but cannot change essentially the abundance distributions along the Galactic radius. However, it can flatten the radial gradients of the mean chemical abundance of stars, and older stars possess flatter abundance gradients than younger stars. Besides, the migration can also scatter the abundance of stars at a place from a relatively concentrated value to a range.

Key words. Galaxy: abundances – Galaxy: evolution – Galaxy: disk – Galaxy: kinematics and dynamics

1. Introduction

The existence of stellar migration in the Galactic disk has been demonstrated by several works in recent years. Observationally, the age-metallicity relation of stars in the solar neighborhood is shown to be flat together with large scatter (Edvardsson et al. 1993; Nordström et al. 2004), and the scatter increases with age increasing (Haywood 2008; Casagrande et al. 2011). Besides, the metallicity distribution function (MDF) in the solar neighborhood obtained by Casagrande et al. (2011) shows that old stars have a considerably broader distribution than young stars while the peak always remains around the solar value. All these phenomena suggest that stars in the solar neighbour could have been born at various Galactocentric radii with different metallicities and migrated to the current position over different timescales. Theoretically, Schönrich & Binney (2009) has distinguished two drivers of radial migration: by scattering at an orbital resonance or by non-resonant scattering by a molecular cloud. Minchev & Famaey (2010) identified another radial migration mechanism in barred galaxies that the resonance overlap of the bar and spiral structure can induce a nonlinear response leading to a strong redistribution of angular momentum in the disk. As a consequence, the radial stellar migration is an important component that should be considered in the Galactic chemical evolution model.

Abundance gradients are very important constraints for the Galactic chemical evolution model. As suggested by Sellwood & Binney (2002) and Schönrich & Binney (2009), since the migration of stars makes it possible to transport materials to any place along the disk no matter where they originally located, the mixture of chemical elements over large range of radius would reduce the differences of abundances between different regions along the disk and flatten the abundance gradients. Here, we study the influence of radial stellar migration in the disk on the chemical evolution of the Milky Way, especially for the abundance gradients.

2. Galactic chemical evolution model and radial stellar migration

The model adopted here is based on the model of Portinari & Chiosi (2000), in which the disk forms gradually by accretion of protogalactic gas and radial gas flow exists. We consider an inside-out disk formation scenario in which the disk formation time scale increases with Galactic radius. The main parameters of models are listed in Table 1.

We describe the radial stellar migration with normal and Gama distribution functions respectively, modeling the probability that stars, born at a given radius, appear at different radii after migrating for a period of time. For the normal distribution,

$$f_{SM} = f_N(r) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{r-\mu}{\sigma}\right)^2\right] \quad (1)$$

We make its center at the birth radii of stars and σ increase with the stellar age exponentially so that stars would stay around their birth radii with the highest probability and migrate further with time elapsing. The normal distributions at all radii are adopted to be same.

Following the hint of Figure 13 of Sellwood & Binney (2002), we also use Gama distribution $\Gamma(\alpha,\beta)$ which is an asymmetrical distribution. The basic form of $\Gamma(\alpha,\beta)$ is

$$f_{SM} = f_G(r) = \frac{1}{\beta^\alpha\,\Gamma(\alpha)}\, r^{\alpha-1} \exp\left(-\frac{r}{\beta}\right),\ r > 0 \quad (2)$$

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-t} dt \quad (3)$$

We make α radius-dependent indicating stars born at different radii have different migration tendencies or preferences, and β increases with stellar age exponentially. The peaks of the Gama distributions are also made to correspond to the birth radii of stars.

For both the normal and Gama distributions, we adopt two scenarios for the variation of their profiles with stellar age: standard condition and extreme condition. In the extreme condition, stars migrate much faster than in the standard condition, to test what the effects would be if stars migrate under an extreme scenario.

3. Results and conclusions

In the top panel of Figure 1 we show the distributions of birth radii of stars that are at present in the solar neighbourhood. While most stars come from the local area, a large proportion come from inner disk, as a consequence of the higher stellar density there, which is more obvious for the models adopting Gama-distribution stellar migration. For our best model GCM2G, we show this distribution for stars in different ages in the bottom panel. With the age increasing, the birth radii of stars cover larger range of the disk, and more stars come from inner disk, which is consistent with the stellar migration theory.

The stellar age-metallicity relation (AMR) in the solar neighbourhood is an important factor when consider stellar migration. As a consequence of radial stellar migration, the solar neighbourhood consists of stars of different ages and metallicities coming from different radii, and they scatter the classic AMR to an age-metallicity distribution (AMD), as roughly shown in Figure 2, while a slope is preserved in the AMD and stars from the same birth radius still follow a classic local AMR. This phenomenon is also found by Minchev et al. (2012).

Figure 3 shows the comparison among the abundance distributions from models and observation. It can be seen that our models can

Table 1. Main parameters of the models. '(e)' represents the model adopting extreme condition for stellar migration, eg. GCM2Ne. τ_D is the disk formation time scale, $v_{gf}(r)$ is the velocity of radial gas flow.

Models	Stellar migration	τ_D (Gyr)	$v_{gf}(r)$ ($km\ s^{-1}$)
GCM2	No	$0.88r - 0.9$	$-0.16r + 0.6, r < 10\ kpc$
GCM2N(e)	Normal	$0.88r - 0.9$	$-0.2r + 1.0, 10\ kpc \leq r < 15\ kpc$
GCM2G(e)	Gama	$0.88r - 0.9$	$-1/3r + 3.0, r \geq 15\ kpc$

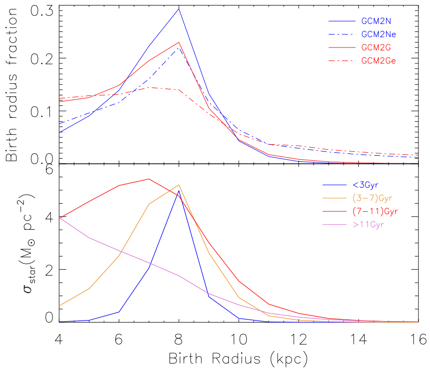

Fig. 1. Top panel shows the distributions of birth radii of the stars that are at present in the solar neighbourhood. Bottom panel shows the same distribution by model GCM2G but for stars in different ages.

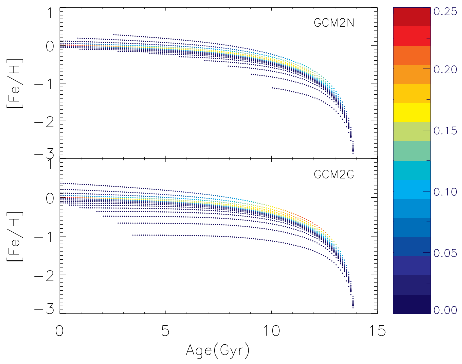

Fig. 2. Age-metallicity distribution in the solar neighbourhood. In each panel the lines from top to bottom represent the stars migrated to the solar neighbourhood from their birth radii of $r = 4\ kpc$ to $18\ kpc$, respectively, and the relative proportion are shown by the colors increasing from blue to red.

reproduce the observational [Fe/H] (top panel) and oxygen abundance (bottom panel) distributions on the whole. In each panel, different lines representing the distributions produced by different models coincide with each other. Being inconsistent with previous predictions, looking from the whole radius range, the radial distributions of chemical element abundances have not flattened after radial stellar migration, even in the extreme condition the abundance gradients also have not changed much. So we may infer that the radial stellar migration cannot lead to significant flattening of radial chemical abundance gradients. It can be understood as the important chemical contributors are massive stars which only have short lifetime and contribute mostly around their birth regions, so few stars can migrate far to a region and contribute to change significantly the chemical composition there. However, as the migration is a motion of stars, it can flatten the radial gradient of the mean chemical abundance of stars. Since older stars have migrated for more time, their chemical abundances are higher with flatter abundance gradients compared with young stars, which is consistent with the findings of Minchev et al. (2012). Besides, the abundance of stars at a place can be scattered by the radial migration from a relatively concentrated value to a range, which can already been inferred from the age-metallicity distribution.

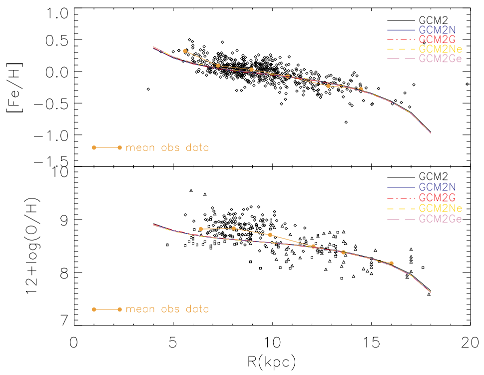

Fig. 3. [Fe/H] (top) and oxygen abundance (bottom) along the disk obtained from models and observation. The black rhombuses, triangles and squares represent the observational abundances of Cepheids, HII regions and OB stars, respectively. The iron abundance are from: Andrievsky et al. (2002c,a,b, 2004), Luck et al. (2003, 2006), Luck & Lambert (2011), and Lemasle et al. (2007, 2008). The oxygen abundance are from: Andrievsky et al. (2002c,a,b, 2004), Lemasle et al. (2007), Luck et al. (2003, 2006), Shaver et al. (1983), Esteban et al. (2005), Vilchez & Esteban (1996), Rudolph et al. (1997), and Rudolph et al. (2006), Smartt & Rolleston (1997), Gummersbach et al. (1998), and Daflon & Cunha (2004). The yellow line with filled circles shows the mean value of the observational data.

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