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Information from the Kinematics of F and G Stars in the Solar Neighborhood

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Abstract We have calculated the orbital parameters for 90 stars in Chen et al. and updated the kinematic data for stars in Edvardsson et al. by using the accurate Hipparcos parallaxes and proper motions, and recalculated the α-element abundances in Edvardsson et al. in a way consistent with Chen et al. The two sets of data are combined in a study of stellar populations and characteristics of F & G stars in the solar neighborhood. We confirm the result of Chen et al. that a distinguishable group of stars may belong to the thick disk rather than the thin disk. The ages for the stars are determined using the theoretical isochrones of VandenBerg et al. The age-metallicity relation is investigated for different subgroups according to distance from the sun and galactic orbital parameters. It is found that a mixing of stars with different orbital parameters significantly affect the age-metallicity relation for the disk. Stars with orbits confined to the solar circle all have metallicities [Fe/H] > -0.3 irrespective of their distances from the sun or from the Galactic plane.

Key words: stars: kinematics – Galaxy: evolution – Galaxy: solar neighborhood

1 INTRODUCTION

Stellar kinematic data are useful for studying the evolution of the Galaxy. On one hand, they provide much direct information on the dynamical history of the Galaxy; on the other hand, they help to interpret stellar abundances, which, more than anything else, tell us about the chemical history of the Galaxy. The combined information of stellar abundances and kinematics are often used to distinguish stellar populations and to summarize the main properties of a given population. For example, Nissen & Schuster (1997) detected some low-α stars in the Galactic halo population, and this is a challenge to the classical homogeneous model of chemical evolution of our Galaxy.

An inhomogeneous evolution of the Galactic disk or a mixing of stars from different populations are evident in Edvardsson et al. (1993a, hereafter EAGLNT), who found an abundance

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gradient for [α/Fe] in disk stars at a metallicity around –0.5 to –0.8, and in Chen et al. (2000, hereafter Chen00), who suggested that stars in the metallicity range $-1.0 <$ [Fe/H] < -0.6 with $V_{\rm LSR} < -50$ km s^{-1}probably belong to the thick disk. More accurate kinematical data including orbital parameters for the two star samples are desirable for clarifying the stellar populations and for probing the chemical evolution of the Galaxy.

With this aim, we updated the kinematics and abundance data of the stars in EAGLNT and calculated the orbital parameters for the stars in Chen00. The kinematical data used by EAGLNT are based on photometric parallaxes and ground-based proper motions, which should be improved with the more accurate Hipparcos data. Moreover, more precise abundances can be obtained for the stars in EAGLNT by using new temperatures from the infrared flux calibration of Alonso et al. (1996) and values of $\log g$ derived from the Hipparcos parallaxes, which were found to be 0.1 dex lower than the photometric values. Given that the differences in [α/Fe] in EAGLNT is generally less than 0.2 dex, it is desirable to revise both the kinematical and abundance data before deriving the all-important [α/Fe] gradient. In Chen00 in which the UVW data were given, an interesting grouping effect in the [Fe/H] vs. $V_{\rm LSR}$ diagram was noted. Here we calculate the orbital parameters, which could help clarify this effect.

The second goal of this work is to investigate the age-metallicity relation (AMR), in which both EAGLNT and Chen00 found a substantial scatter. The revised age determinations for the EAGLNT sample based on new data have been provided by Ng et al. (1998) and they gave a better AMR. Rocha-Pinto et al. (2000) found a more clearly defined AMR and claimed that the substantial scatter in the AMR in EAGLNT is due to selection effect. With the revised stellar ages based on new stellar parameters and the VandenBerg isochrones for the EAGLNT sample, we hope to clarify the AMR by taking advantage of the data of stellar kinematics calculated in the present work.

2 RECALCULATION OF KINEMATICS AND ABUNDANCES

We recalculate the kinematics for the sample stars in EAGLNT based on Hipparcos parallaxes and proper motions. The radial velocities are updated, if available in the recent literatures, but the differences are quite small and do not introduce significant errors into the kinematical data. The deviation between Hipparcos parallax (adopted in the present work) and photometrically-derived parallax (used in EAGLNT) for most stars is within 20 mas and the differences in proper motions are at a level of ± 15 mas yr^{-1} but for some (especially distant) stars the deviation could be very large, and these are the ones that cause most of the errors in the spatial velocities UVW (U in the anticentric direction, V in the direction of the Galactic rotation and W perpendicular to the Galactic plane). The differences in the distance and UVW between the two sets of data as functions of the metallicity are shown in Fig. 1. Although no clear trends can be seen, the size of the difference for some stars are quite large, so it is useful to re-investigate the EAGLNT result based on the new data. In the following sections, the space velocities (U, V, W) are relative to the Local Standard of Rest (LSR), assumed to be at (-10.0, $+5.2$, $+7.2$), as derived from the Hipparcos data by Dehnen & Binney (1998). the orbital parameters were calculated for Chen00 and the updated EAGLNT sample stars based on the method provided by Allen et al. (1991). The Galactic potential consists of three parts: a massive spherical halo, a Miyamoto-Nagai disk and a central sphere. The orbital parameters include the maximum and minimum Galactocentric distances ($R_{\rm max}$ and $R_{\rm min}$) and the maximum distance to the Galactic plane ($Z_{\rm max}$).

In order to make our study consistent with that of Chen00, we followed their procedure and recalculated the α-element abundances for the EAGLNT stars using updated values of both $T_{\rm eff}$ and $\log g$: $T_{\rm eff}$ based on Alonso's (1996) calibration, and $\log g$ from the updated $T_{\rm eff}$, the Hipparcos parallax, the mass derived from the evolutionary tracks of VandenBerg et al. (2000). We found that the temperatures in this paper are lower by 54 ± 53 K than in EAGLNT and the difference in $\log g$ is -0.06 ± 0.12. The equivalent widths and $\log gf$ values are taken from EAGLNT. The abundances are relative to the Sun, the solar values were also derived from the data given in EAGLNT. The differences between our abundances and EAGLNT are presented in Table 1. In general, our result is in agreement with that of EAGLNT considering the different parameters and models used.

Table 1 Mean Abundance Differences (This Paper−EAGLNT) and Standard Deviations (N is the number of stars)

	$<\Delta>$	σ	N
[FeI/H]	0.070	0.043	187
[FeII/H]	0.047	0.055	187
[O/Fe]	0.010	0.057	83
[Mg/Fe]	−0.044	0.035	175
[Si/Fe]	−0.018	0.027	183
[Ca/Fe]	−0.009	0.020	185
[Ti/Fe]	−0.067	0.031	174

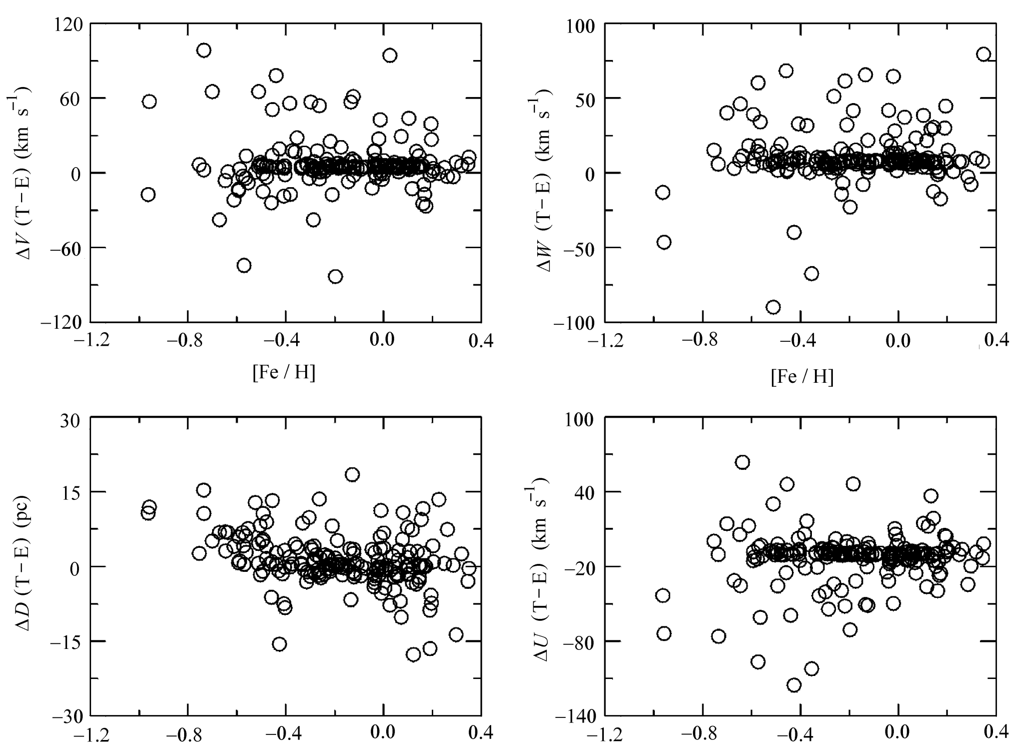

Fig. 1 Differences in distance, and U, V, W velocities between this work (T) and EAGLNT (E) as functions of metallicity

3 RESULTS AND DISCUSSION

3.1 Stellar Populations

Following Chen00, we study the relation between $V_{\rm LSR}$ and [Fe/H] for the two sample stars in Fig. 2. Obviously, the same three groups of stars as in Chen00 (see their fig. 7) are found here: stars with $[{\rm Fe/H}] < -0.5$ fall into two kinematical groups, $V_{\rm LSR} > -10\,{\rm km\,s^{-1}}$ (group A) and $V_{\rm LSR} < -50\,{\rm km\,s^{-1}}$ (group C), while stars with $[{\rm Fe/H}] > -0.5$ fall into a third group $V_{\rm LSR} \sim -10\,{\rm km\,s^{-1}}$ (group B). That the same structure is shown by two independent studies indicates that the grouping in this diagram is real for the F & G stars in the solar neighborhood.

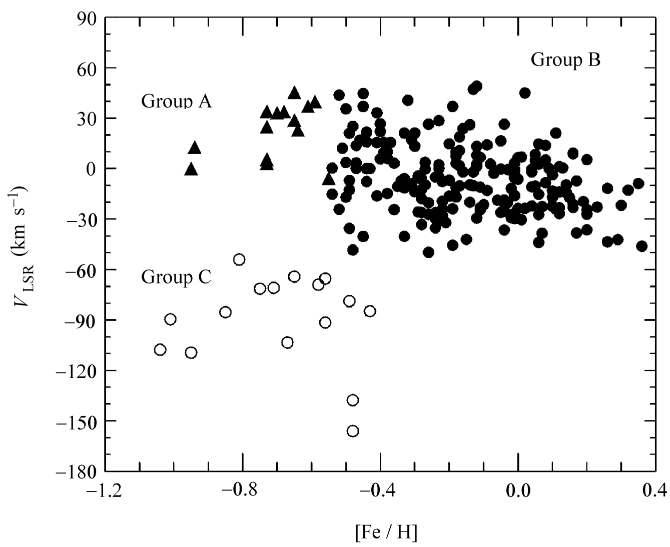

Fig. 2 Plot of $V_{\rm LSR}$ versus [Fe/H] shows stars in the solar neighborhood fall into three groups: group A for stars with $[{\rm Fe/H}] < -0.5$ and $V_{\rm LSR} > -10\,{\rm km\,s^{-1}}$ (filled triangles); group B for stars with $[{\rm Fe/H}] > -0.5$ and $V_{\rm LSR} \sim -10\,{\rm km\,s^{-1}}$ (filled circles) and group C for stars with $[{\rm Fe/H}] < -0.5$ and $V_{\rm LSR} < -50\,{\rm km\,s^{-1}}$ (open circles).

Chen00 suggested that stars from group C may belong to the thick disk. In Fig. 3 it is clear that stars in group C are not coeval with the stars in group A and B; they are systematically older and their ages are consistent with the thick disk population. We show the α element abundances for the different groups in Fig. 4. There is a hint that stars in group C show slightly higher $[\alpha/{\rm Fe}]$ than in the other groups. Although the difference is only within 0.1 dex, the number of stars is large enough for the result to be considered statistically significant. Moreover, the $W_{\rm LSR}$ dispersion is $\sim 40\,{\rm km\,s^{-1}}$ (close to that of the thick disk, $45\,{\rm km\,s^{-1}}$) while stars in group A and B have $\sigma(W_{\rm LSR}) \sim 20\,{\rm km\,s^{-1}}$ (typical for the thin disk). The higher mean $[\alpha/{\rm Fe}]$ and higher $W_{\rm LSR}$ dispersion for group C stars indicate their originating in the thick disk.

We investigated other pieces of kinematical information of these stars for their dependence on $V_{\rm LSR}$. we found stars with $V_{\rm LSR} < -50\,{\rm km\,s^{-1}}$ have eccentricities larger than 0.4, and most of them have $Z_{\rm max}$ larger than 0.5 kpc. These confirmed the suggestion that stars in Group C are physically different from the other stars, as claimed in Chen00. Since the thick disk has a typical height of 1.5 kpc, we suspect that these stars probably populated the lower parts of the thick disk. They have a higher probability of passing through the solar neighborhood as compared with stars in the higher parts (> 1.5 kpc). Stars in groups A and B are indistinguishable in eccentricity and $Z_{\rm max}$, as a result of their belonging to the same population.

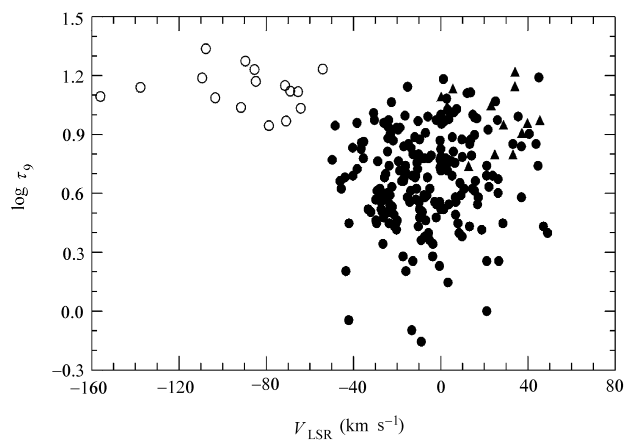

Fig. 3 Relation between $V_{\rm LSR}$ and age. The symbols are the same as in Fig. 2.

3.2 Relation between $V_{\rm LSR}$ and R_m

There is a correlation between $V_{\rm LSR}$ and R_m ($= \frac{R_{\rm max}+R_{\rm min}}{2}$), which was first suggested by Edvardsson et al. (1993b) for disk stars. As a by-product of our present study, we investigate this correlation based on our new data. Figure 5 shows that such a correlation can only be confirmed at a level of ± 2 kpc at a given $V_{\rm LSR}$. From our point of view, the definition of R_m, as an indicator of the star's origin, seems to be objectionable, even though it may be better than using either $R_{\rm max}$ or $R_{\rm min}$ alone. It is significantly affected by the constraints of the initial input parameter in the orbit calculation. As Fig. 5 shows, stars with $V_{\rm LSR} > 20\,{\rm km\,s^{-1}}$ show a constant $R_{\rm min}$ ($\sim$ 8.5 kpc) and quite a few stars with $V_{\rm LSR} < -50\,{\rm km\,s^{-1}}$ have $R_{\rm max}$ around 8.5 kpc. This is understandable because these stars are presently located in the solar neighborhood, which the model places at radius 8.5 kpc. Thus, the $R_{\rm min}$ could not be any larger and the $R_{\rm max}$ should not be less than 8.5 kpc for all the sample stars. Instead, we find that $V_{\rm LSR}$ is a better tracer for stellar population, with positive $V_{\rm LSR}$ values replacing $R_{\rm max}$ and large negative values ($< -50\,{\rm km\,s^{-1}}$) replacing $R_{\rm min}$, while intermediate values replacing neither. We especially note that for $V_{\rm LSR} < -160\,{\rm km\,s^{-1}}$, there is no correlation between R_m and $V_{\rm LSR}$, therefore it makes no sense to use R_m as indicator of the origin of metal-poor stars. On the other hand, $V_{\rm LSR}$, or equivalently V_{rot}, still correctly predicts $R_{\rm min}$.

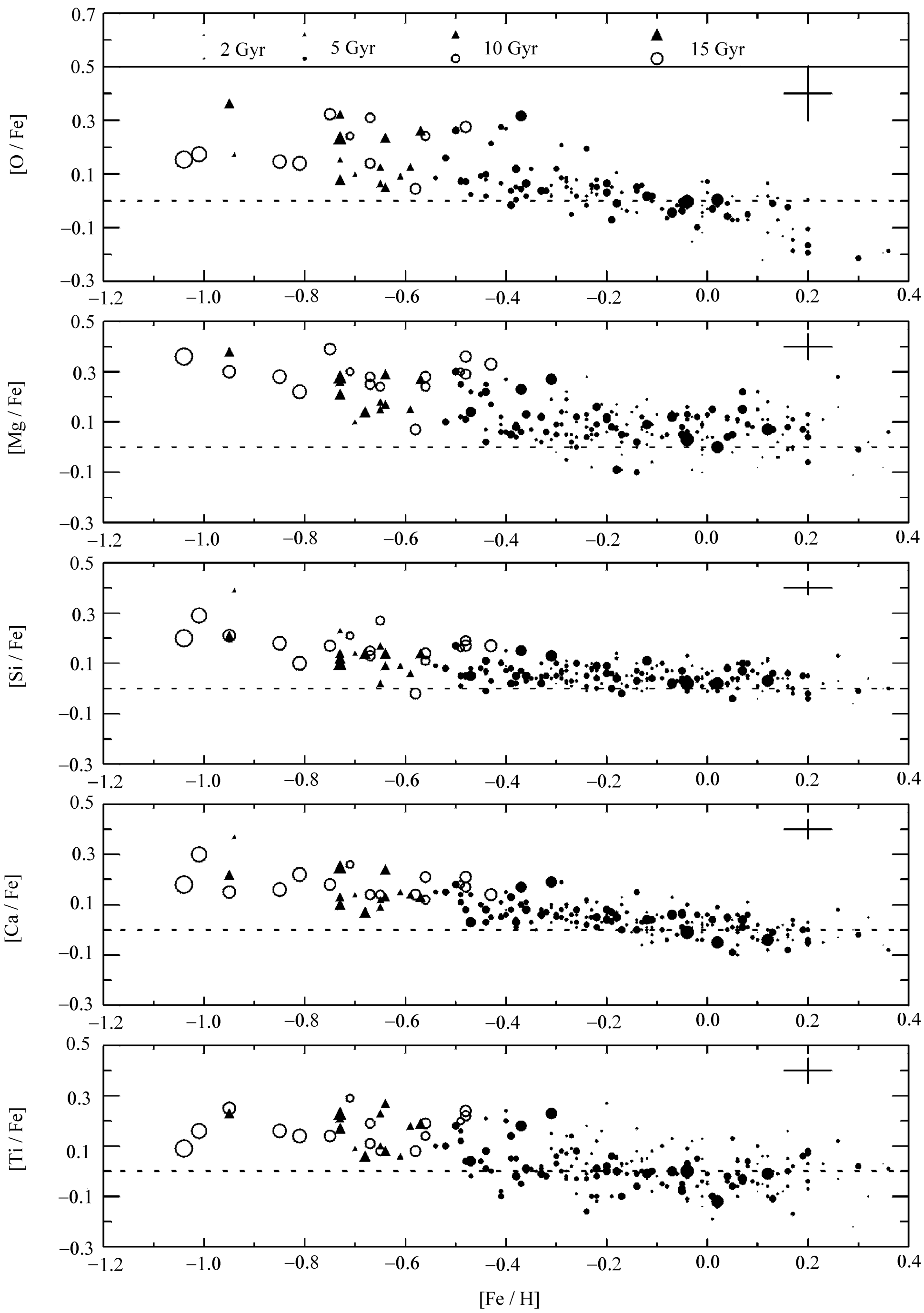

Fig. 4 [α/Fe] vs. [Fe/H] relation. The symbols are the same as in Fig. 2 and their size is proportional to the star's age.

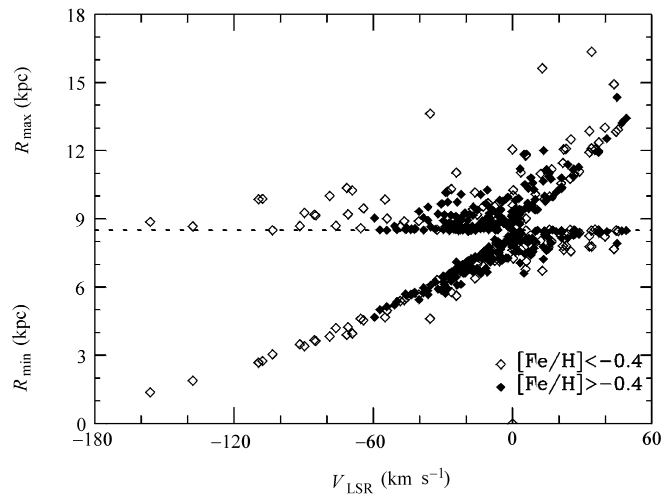

Fig. 5 Relation of V_{LSR} versus R_{max} and R_{min}.

3.3 The Age-metallicity Relation

Figure 6 shows the age-metallicity plot for all stars in the sample. The main feature is the lack of metal-poor young stars in the left-bottom corner, which supports the existence of a age-metallicity relation. However, there exist some old metal-rich stars in the right-upper corner, which leads to the substantial scatter in the plot. It is difficult to conclude from this plot whether or not an age-metallicity relation exists. On one hand, stars in Group C should be excluded if we only consider the age-metallicity relation for the thin disk. On the other hand, old metal-rich stars may come from the inner part of the disk, which may have a faster evolution than at the solar distance.

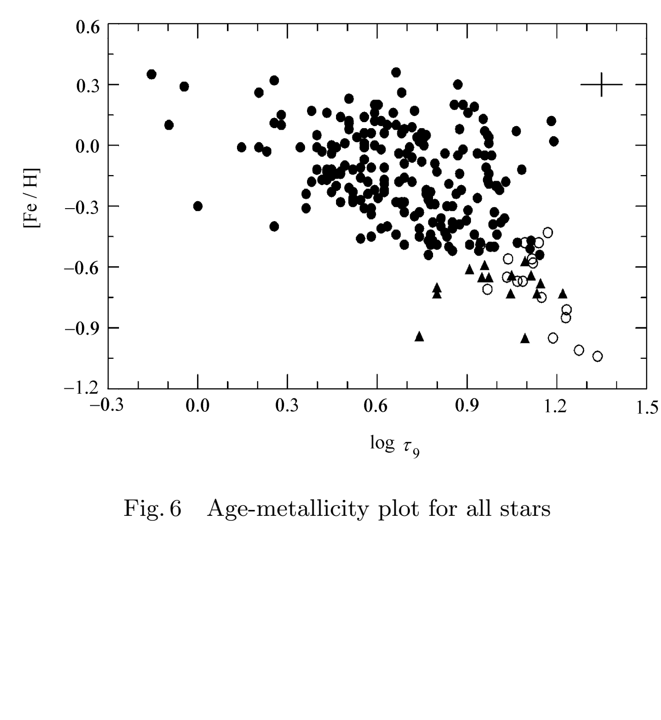

Fig. 6 Age-metallicity plot for all stars

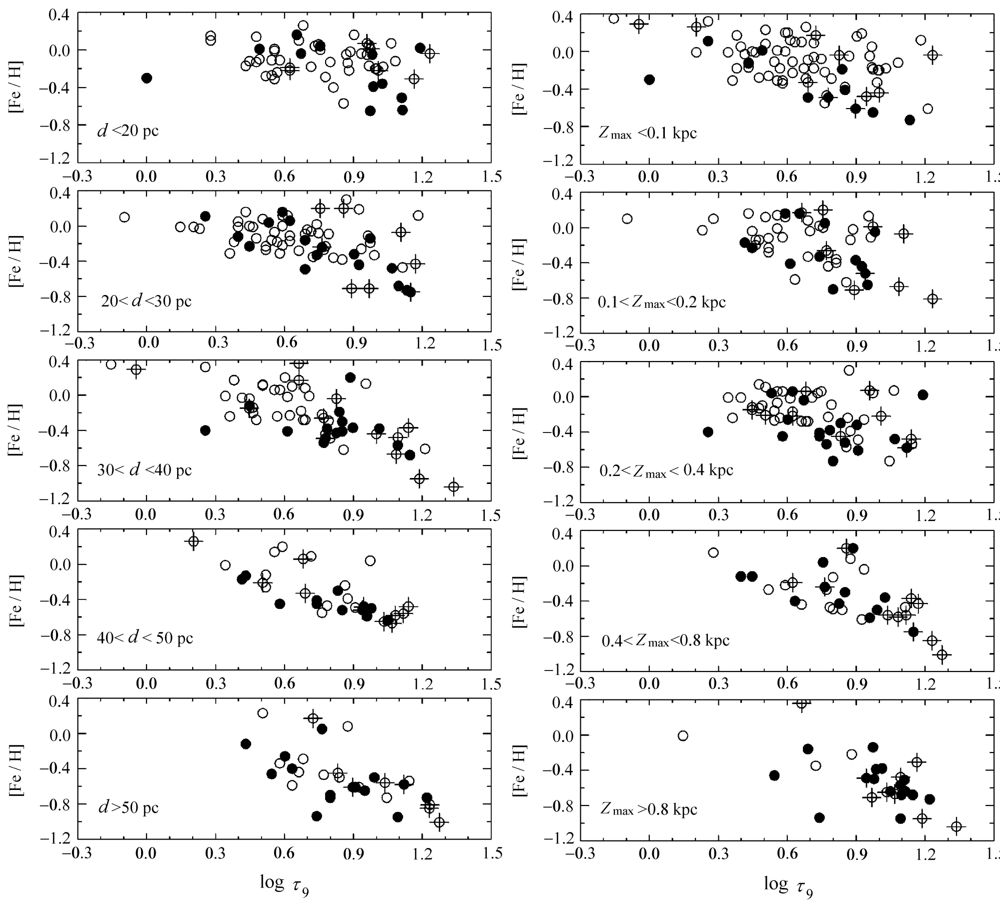

Fig. 7 Age-metallicity plot for different distance intervals (left) and for different $Z_{\rm max}$ intervals (right). Plus-circles for $R_{\rm min} < 6$ kpc, filled circles for $R_{\rm max} > 10$ kpc, open circles for the rest.

While the kinematical data are useful for probing the age-metallicity relation, we should keep in mind the selection effects when interpreting the resulting plot. For example, Garnett & Kobulnicky (2000) suggested that a selection bias toward metal-poor stars sets in when the sample stars have distances larger than 30 pc. For the large sample of stars in the solar neighbourhood, we show the age-metallicity plot separately for stars with different distance ranges (See the left panel of Fig. 7). It is clear that the age range is similar for $d < 30$ pc and $30 < d < 50$ pc, but the metallicity range is different: [Fe/H] ~ -0.7 to 0.3 for $d < 30$ pc and [Fe/H] ~ -1.1 to 0.3 for $30 < d < 50$ pc. Stars with $d > 50$ pc are systematically older (> 7 Gyr) and generally have [Fe/H] $= -0.5$ to -0.9. This confirms the result given in Garnett & Kobulnicky (2000) that there are more metal-poor stars among the more distant stars. However, we would ascribe this finding to a real feature of the Galaxy, rather than a selection bias as did Garnett & Kobulnicky (2000).

Strictly speaking, distance may not provide a good explanation for the scatter in metallicity within the solar neighbourhood because stars with larger distances from the Sun could come from both inside and outside of the solar circle. For stars coming from deep inside the solar circle, they would have large distances but their metallicities may be higher (instead of lower) than stars in the solar circle. Moreover, different stellar populations have different scale heights. As we include stars with larger distances from the Sun, the possibility of mixing stars from different populations increases. In view of these two factors, we now consider whether there are any correlations between the orbital parameters and the metallicity for stars in the solar neighbourhood.

In Fig. 7, different symbols are used for stars with $R_{\rm min} < 6\,{\rm kpc}$, stars with $R_{\rm max} > 10\,{\rm kpc}$, and the rest. This division is useful for it separates the chemical evolution from the dynamical effect of the Galaxy by greatly reducing the effect of the radial metallicity gradient in the disk. It is clear that the metallicity range for the local sample stars becomes even narrower if those stars are excluded. Also, the maximum vertical distance from the Galactic plane, $Z_{\rm max}$, may be a useful parameter for extracting stars from different populations, so in the right panel of Fig. 7, we show the age-metallicity plot for different $Z_{\rm max}$ ranges. As $Z_{\rm max}$ increases, more metal-poor stars are included and at the same time the mean age increases. Especially, stars with $Z_{\rm max} > 0.8$ kpc are all more metal-poor than -0.4 and older than 7 Gyr. This is reasonable because this value of $Z_{\rm max}$ marks the end of the thin disk and the beginning of the thick disk. It seems that stars with $Z_{\rm max}$ restricted to the Galactic plane have their metallicities restricted in a narrow range around the solar value.

4 IMPLICATIONS AND CONCLUSIONS

Based on a consistently reduced body of data of chemical abundance, age and kinematics for the stars in Chen00 and EAGLNT, we confirm the result that some stars presently in the solar neighbourhood may come from the thick disk. The age-metallicity relation of stars in the solar neighbourhood varies not only with the distance from the sun but also with the galactic orbital parameters. It was found that stars with larger distances from the sun tend to be more metal-poor and older. We suspect that this effect is caused by the mixing of stars with $Z_{\rm max}$ larger than 0.4 kpc because the AMR depends on the $Z_{\rm max}$ range. This effect becomes more pronounced as $Z_{\rm max}$ gets larger than 0.8 kpc because the lower part of the thick disk population with scale heights 0.7–1.5 kpc starts to enter significantly into the sample.

When the stars of group C and some stars from outside the solar circle are excluded, the metallicity range becomes narrow with $[{\rm Fe/H}] = -0.2 \pm 0.2$ dex. These results indicate that the metallicity of the stars located around the solar circle is quite homogeneous and that the products from supernovae are well-mixed into the stellar medium in the Galactic disk. In the meantime, dynamical evolution or stellar orbit diffusion can mix stars from different populations into the solar neighborhood, and this could confuse our understanding of the evolution of the Galactic disk.

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