FORMATION OF GALACTIC SYSTEMS IN LIGHT OF THE MAGNESIUM ABUNDANCE IN FIELD STARS: THE THIN DISK

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Abstract

Data from our compiled catalog of spectroscopically determined magnesium abundances in stars with accurate parallaxes are used to select thin-disk dwarfs and subgiants according to kinematic criteria. We analyze the relations between the relative magnesium abundances in stars, [Mg/Fe], and their metallicities, Galactic orbital elements, and ages. The [Mg/Fe] ratios in the thin disk at any metallicity in the range \((-1.0 < [Fe/H] < -0.4 \, \text{dex})\) are shown to be smaller than those in the thick disk implying that the thin-disk stars are on average younger than the thick-disk stars. The relative magnesium abundances in such metal-poor thin-disk stars have been found to systematically decrease with increasing stellar orbital radii in such a way that magnesium overabundances ([Mg/Fe] > 0.2 dex) are essentially observed only in the stars whose orbits lie almost entirely within the solar circle. At the same time, the range of metallicities in magnesium-poor stars is displaced from \((-0.5 < [Fe/H] < +0.3 \, \text{dex})\) to \((-0.7 < [Fe/H] < +0.2 \, \text{dex})\) as their orbital radii increase. This behavior suggests that, first, the star formation rate decreases with increasing Galactocentric distance and, second, there was no star formation for some time outside the solar circle while this process was continuous within the solar circle. The decrease in the star formation rate with increasing Galactocentric distance is responsible for the existence of a negative radial metallicity gradient \((\text{grad}_R[Fe/H]=(-0.05 \pm 0.01) \, \text{kpc}^{-1})\) in the disk, which shows a tendency to increase with decreasing age. At the same time the relative magnesium abundance exhibits no radial gradient. We have confirmed the existence of a steep negative vertical metallicity gradient \((\text{grad}_Z[Fe/H]=(-0.29 \pm 0.06) \, \text{kpc}^{-1})\) and detected a significant positive vertical gradient in relative magnesium abundance \((\text{grad}_Z[Mg/Fe]=(0.13 \pm 0.02) \, \text{kpc}^{-1})\); both gradients increase appreciably in absolute value with decreasing age. We have found that there is not only an age–metallicity relation, but also an age–magnesium abundance relation in the thin disk. We surmise that the thin disk has a multicomponent structure but the existence of a negative trend in the star formation rate along the Galactocentric radius does not allow the stars of its various components to be identified in the immediate solar neighborhood.

Keywords: Galaxy (Milky Way), stellar chemical composition, thin disk, Galactic evolution.
Introduction

This paper is a continuation of our systematic description of chemical and spatial–kinematic properties of the stars that are currently in the solar neighborhood, but belong to different Galactic subsystems, based on data from our compiled catalog of spectroscopically determined elemental abundances in stars with accurate parallaxes (Borkova and Marsakov 2005). Previously (Marsakov and Borkova 2005), we analyzed the properties of thick-disk stars.

The relative atmospheric elemental abundances of low-mass main-sequence stars can be used to estimate the parameters of the initial mass function and the star formation rate and as the time scale of a chemically evolving system. Thus, for example, the $\alpha$-elements (O, Mg, Si, S, Ca and Ti) together with a small number of iron atoms are currently believed to be synthesized in the high-mass ($M > 10M_{\odot}$) asymptotic-giant-branch (AGB) progenitors of type II supernovae (Arnett 1978), while the bulk of the iron-group elements are produced during type Ia supernova explosions through mass accretion onto a carbon–oxygen white dwarf in a close binary system (Thielemann et al. 1986). The theoretically predicted yield of $\alpha$-elements in SNeII increases with presupernova mass (Woosley and Weaver 1995); therefore, the larger the shift of the initial mass function toward the higher masses, the larger the observed $[\alpha/Fe]$ ratio in the atmospheres of the metal-poorest stars. Beginning from the paper by Tinsley (1979), the negative trend in the $[\alpha/Fe]$ ratio as a function of metallicity observed in the Galaxy has been assumed to be due to a difference in the evolution times of these stars. Indeed, the evolution time scale for type II presupernovae is only $\approx 30$ Myr while massive SNe Ia explosions begin only in $\approx (0.5 \div 1.5)$ Gyr (Matteucci and Greggio 1986; Yoshii et al. 1996). The higher the star formation rate in the system, the larger the metallicity at which the knee attributable to the onset of SNe Ia explosions which result in an enrichment of the interstellar medium with iron-group elements, will be observed in the $\alpha$–Fe relation. The lower the star formation rate, the steeper the further decrease in the $[\alpha/Fe]$ ratio with increasing total metallicity. If star formation in the system is halted altogether then the source of $\alpha$-elements (i.e., SNeII) will vanish and only SNe Ia will enrich the interstellar medium with iron-group elements; therefore the $[\alpha/Fe]$ ratio will decrease suddenly (Wyse and Gilmore 1991).

Since more than 90% of the stars in the immediate solar neighborhood belong to the youngest (in the Galaxy) thin-disk subsystem (Buser et al. 1999), the chemical composition of this subsystem has been studied in greatest detail. However the sizes of the original samples in all works were very limited; this is probably the reason why the results and conclusions are occasionally in conflict with one another. The work of Edvardsson et al. (1993) is a classical analysis of a sample of nearby stars containing $\approx 200$ F–G dwarfs with metallicities $[Fe/H] > -1.0$. In particular this work revealed a decrease in the $[\alpha/Fe]$ ratio with increasing mean Galactocentric distance $R_m$ for stars in the range $0.8 < [Fe/H] < 0.4$ which was explained by a decrease in the star formation rate from the center to the periphery of the Galactic disk. Nissen (2004) disputes this explanation and argues that this trend is attributable solely to the fundamental difference between the relative abundances of $\alpha$-elements in the thin-disk and thick-disk stars. Indeed, Edvardsson et al. (1993) did not separate their stars into the two subsystems, while Fuhrmann et al. (1995), Fuhrmann (1998), Nissen and Shuster (1997), and Gratton et al. (2000) showed that the relative abundances of $\alpha$-elements decrease abruptly during the transition from the thick-disk to thin-disk stars. This indicates that star formation is delayed, i.e. the transition between the disk subsystems is discrete. Other studies show that there are stars
in the thick disk with the same low relative abundances of \( \alpha \)-elements as those in the thin disk; conversely there are stars in the thin disk with the same high relative abundances as those in the thick disk. Some of the authors (see, e.g. Feldzing et al. 2003; Bensby et al. 2004) argue that the \( \alpha/\text{Fe} \) ratio in the thin disk at the same metallicity (up to its solar value) is systematically lower and the slope of the \( \alpha/\text{Fe} - [\text{Fe/H}] \) relation in it is flatter than those in the thick disk. This is because the star formation rates in the subsystems differ.

Since the published results disagree, analyzing the relations between the relative abundances of \( \alpha \)-elements and metallicity and other parameters of thin-disk stars based on a much larger statistical material seems very topical. In this paper we analyze the chemical properties of thin-disk stars using data from our compiled catalog of spectroscopically determined magnesium abundances (Borkova and Marsakov 2005). Magnesium is one of the best studied \( \alpha \)-elements, because it has lines of various intensities and degrees of excitation in the visible spectral range in main-sequence F–G stars. Almost all of the published magnesium abundances in dwarfs and subgiants in the solar neighborhood determined by synthetic modeling of high-dispersion spectra as of December 2003 were gathered in the catalog. This catalog is several times larger than any homogeneous sample that has been used until now to analyze the chemical evolution of the Galaxy.

The relative magnesium abundances in the catalog were derived from 1412 spectroscopic determinations in 31 publications for 867 stars using a three-pass iterative averaging procedure with a weight assigned to each primary source and each individual determination. The internal accuracy of the catalogued relative magnesium abundances for metal-rich ([\text{Fe/H}] > −1.0 dex) stars is \( \varepsilon[\text{Mg/Fe}] = ±0.05 \) dex. The metallicities for the stars were obtained to averaging \( \approx 2000 \) [\text{Fe/H}] determinations from 80 publications; the accuracy was estimated to be \( \varepsilon[\text{Fe/H}] = ±0.07 \) dex. The distances to the stars and their space velocities were calculated based on data from currently available high-precision catalogs. We used trigonometric parallaxes with errors smaller than 25% and, if these were lacking, photometric distances calculated from uvbyH\( \beta \) photometry. Based on a multicomponent model of the Galaxy containing a disk, a bulge, and an extended massive halo from Allen and Santillan (1991), we calculated the Galactic orbital elements by simulating 30 revolutions of the star around the Galactic center. The Galactocentric distance of the Sun was assumed to be 8.5 kpc, the rotational velocity of the Galaxy at the solar Galactocentric distance was 220 km s\(^{-1}\) and the velocity of the Sun with respect to the local standard of rest was (\( U_\odot, V_\odot, W_\odot \)) = (−11, 14, 7.5) km s\(^{-1}\) (Ratnatunga et al. 1989). For 545 catalogued stars, we used the ages determined from theoretical isochrones, trigonometric parallaxes, and photometric metallicities from Nordström et al. (2004). For more details on stellar parameters, see Borkova and Marsakov (2005) and Marsakov and Borkova (2005).

**IDENTIFICATION OF THIN-DISK STARS.**

Since our main goal is to analyze the relations between the chemical composition and other parameters of thin-disk stars, we identified the latter solely according to kinematic criteria. The thin-disk stars are known to have low residual velocities with respect to the local standard of rest and nearly circular orbits with all of their points lying not high above the Galactic plane. Therefore, for reliability we identified this subsystem simultaneously by two kinematic conditions. For nearby stars, a convenient criterion is \( V_{\text{res}} = \sqrt{U^2 + V^2 + W^2} < 85 \) km s\(^{-1}\), where \( U, V, W \), and \( V_{\text{res}} \) are the space velocity components of the star and its residual velocity with respect to the local standard of rest, respectively. The other criterion does not depend on the location of the star in the Galactic orbit and is based on the
following formula suggested by Chiappini et al. (1997): \( \sqrt{Z_{\text{max}}^2 + 4 \cdot e^2} < 1.05 \) where \( Z_{\text{max}} \) is the maximum distance of the orbital points from the Galactic plane and \( e \) is the orbital eccentricity of the star. Higher-velocity stars were included in the thick disk. We chose the criteria to minimize the number of stars with high and low relative magnesium abundances in the thin and thick disks, respectively (for more details on the segregation of thick-disk and thin-disk stars, see Marsakov and Borkova (2005)). Figure 1a shows the distribution of stars in the \( V_{\text{res}} - \sqrt{Z_{\text{max}}^2 + 4 \cdot e^2} \) diagram, where the thin-disk and thick-disk stars are denoted by different symbols. We additionally identified the stars for which the probabilities of belonging to the thin disk is a factor of 10 higher than the probability of belonging to the thick disk. The stars with the same high probabilities of belonging to the thick disk were selected and identified in the figure in a similar way. The technique for calculating the corresponding probabilities based on the dispersions of the space velocity components and the mean rotational velocity of the subsystem stars at the solar Galactocentric distance was taken from Bensby et al. (2003). We see that the probability criterion is more stringent and roughly corresponds to the criterion \( \sqrt{Z_{\text{max}}^2 + 4 \cdot e^2} < 0.6 \) for the thin disk. In this case, the first condition \( V_{\text{res}} \leq 85 \text{ km s}^{-1} \) is also satisfied automatically. When more stringent criteria are used, a significant number of stars from the original catalog turn out to be unidentified. To preserve the size of the sample used, below we will analyze the thin-disk properties using the stars identified according to our criteria, but we will always test the reliability of the results using the stars selected according to this more stringent probability criterion.

Note that we cannot get rid of the overlap between the ranges of elemental abundances in the stars of the two disk subsystems by any combination of any kinematic parameters. To illustrate this conclusion regarding the magnesium abundance, Fig. 1b shows the \( V_{\text{res}} - [\text{Mg/Fe}] \) diagram for the stars selected according to our criteria and Fig. 1c shows the same diagram for the stars selected according to the stringent probability criterion. The stars in which the magnesium abundances were taken from several sources and simultaneously with a total weight larger than unity were additionally identified in both diagrams. (Recall that the largest weight equal to unity in our catalog was assigned to the source (Edvardsson et al. 1993), for whose stars the deviations of the derived magnesium abundances from their precalculated mean values were smallest.) We see from the diagrams that an appreciable percentage (\( \approx 8 \%) \) of the stars with high relative magnesium abundances remain in the thin disk even for the most stringent candidate selection and reliable \([\text{Mg/Fe}]\) determination. After applying the stringent kinematic criterion \( \approx 9 \%) \) of the stars with low magnesium abundances also remain in the thick disk but the \([\text{Mg/Fe}]\) ratios were reliably determined in our catalog from several sources only for two of these stars. The overlap between the metallicity ranges of the subsystems is discussed in the next section.

THE METALLICITY – MAGNESIUM ABUNDANCE RELATION.

Figure 2 shows the \([\text{Fe/H}] - [\text{Mg/Fe}]\) diagrams where the thin-disk and thick-disk stars are denoted by different symbols. (The stars of the so-called metal-poor tail of the thick disk i.e., those with \([\text{Fe/H}] < -1.25\) are not plotted in this figure.) A careful examination of the diagrams leads us to the following obvious conclusions. First, although the bulk of the thin-disk stars actually have \([\text{Mg/Fe}] < 0.20\) and lie mostly in the range \(-0.75 < [\text{Fe/H}] < +0.35\) a sizeable fraction of them (52 of the 569 stars, i.e. \( \approx 9 \%) \) have higher magnesium abundances at metallicities \(-1.0 < [\text{Fe/H}] < -0.30. \) (Two stars (HD 83769
and BD 30° 18140) with thin-disk kinematics and with metallicities $[Fe/H] < -2.0$ are disregarded in the subsequent analysis of the thin-disk properties. In contrast, the bulk of the thick-disk stars lie in the metallicity range $-1.25 < [Fe/H] < -0.3$ at $[Mg/Fe] > 0.2$ but there are also stars with lower magnesium abundances in it (see also Marsakov and Borkova 2005); i.e. not only the magnesium abundance ranges, but also the metallicity ranges overlap. Hence the position of the dip observed in the metallicity distributions of Galactic stars near $[Fe/H] \approx -0.5$ may be used as a criterion for separating the stars into the Galactic subsystems only in the absence of space velocities for them (see, e.g. Marsakov and Suchkov 1977). Another important result is that the metallicity–relative magnesium abundance relation in the thin disk differs in behavior from that in the thick disk although both subsystems exhibit a decrease in the relative magnesium abundance with increasing metallicity. The median sequences for the thin and thick disks are plotted in Figs. 2b and 2c, respectively. Since these cannot be constructed mathematically rigorously we drew them by eye halfway between the corresponding upper and lower envelopes in the diagrams. The circles mark the stars selected according to stringent probability criteria for their belonging to a particular subsystem and with weights of the final magnesium abundance larger than unity. In Fig. 2a, both sequences are plotted simultaneously. We see that the sequence for the thin disk in the metallicity range ($-1.0 < [Fe/H] < -0.4$) lies systematically lower than that for the thick disk thereby confirming the result of Bensby et al. (2003).

Let us now verify the result of Edvardsson et al. (1993) using our larger sample of thin-disk stars selected according to kinematic criteria, i.e. ascertain whether the positions of the thin-disk stars in $[Mg/Fe]$ the $[Fe/H]$-$[Mg/Fe]$ diagram depend on their mean orbital radii? Figure 3 shows these diagrams for the thin-disk stars divided into four approximately equal (in number) $R_m$ ranges by the following values: 8, 8.5, and 9.1 kpc. Our median sequence is plotted in all diagrams. The circles denote the stars with accurately determined magnesium abundances (more than two determinations) and selected according to the probability criterion. We see from the figure that the behavior of the relation under study changes appreciably with increasing mean Galactocentric stellar orbital radius. Indeed, only the stars with the smallest mean orbital radii in Fig. 3a closely follow our median curve at $[Fe/H] < -0.4$ dex. However in the next diagram (Fig. 3b), the overwhelming majority of such metal-poor stars lie in the range $[Mg/Fe] < 0.2$, with the number of points below the curve in the metallicity range ($-0.7 \div -0.4$) dex being considerably larger than their number above the curve. At the largest distances, the $[Mg/Fe]$–$[Fe/H]$ relation is almost linear (see the dashed line in Fig. 3d). In this case, only a small number of stars with sharply enhanced magnesium abundances are observed above the curve. At the same time, it can be noticed that the metallicity range for the bulk of the stars with $[Mg/Fe] < 0.2$ is displaced from $(0.5 < [Fe/H] < 0.3)$ for the nearest stars to $(-0.7 < [Fe/H] < +0.2)$ for the farthest stars. This change in the behavior of the $[Mg/Fe]$–$[Fe/H]$ relation and the displacement of the metallicity range for stars with low relative magnesium abundances as their mean orbital radii increase confirm the assumption by Edvardsson et al. (1993) that the star formation rate in the thin disk decreases with Galactocentric distance.

Additional information can be obtained from the histograms in Fig. 4 which shows how some of the stellar population parameters change with Galactocentric distance. The distributions in the first three upper histograms and the second upper histogram of the second column are described by the sums of two Gaussians, while the curves in the remaining histograms are eighth degree polynomials. First, note that the distributions of all parameters for the stars with the smallest mean orbital radii drop out of the general trends for all of the remaining distances. Thus for example, in the first column the distribution of the nearest
stars in relative magnesium abundance in Fig. 4a clearly shows a bimodal structure with the maxima near $[\text{Mg/Fe}] \approx 0.07$ and $0.27$ dex (the latter relative magnesium abundance is typical of the thick-disk stars). The histogram in the figure is well described by the sum of two Gaussians whose parameters were determined by the maximum likelihood method. In this case, the probability of erroneously rejecting the hypothesis about the description of the distribution by one Gaussian against its alternative representation by the sum of two Gaussians is $P_N \approx 1\%$ (see Marsakov et al. (1984) for more details on determining the statistical significance of fitting the distribution by the sum of Gaussians and Martin (1971) for a justification of the method). Edvardsson et al. (1993) also pointed out that the magnesium abundance distribution may be bimodal for the stars with mean orbital radii smaller than the solar Galactocentric distance. At larger distances, the overwhelming majority of stars lie at $[\text{Mg/Fe}] < 0.2$ (see the first column in Fig. 4). All of them have unimodal distributions, but there is a clear tendency for the positions of the distribution maxima to be displaced toward the higher relative magnesium abundances with increasing mean stellar orbital radii.

The metallicity distributions of stars in the second column behave even more expressively. Here, the stars closest to the center in Fig. 4b also exhibit a bimodal distribution ($P_N \approx 4\%$). The primary (large) maximum lies near $[\text{Fe/H}] \approx -0.30$ dex, while the secondary maximum is near $\approx +0.05$ dex. For the farther stars in Fig. 4f ($P_N < 1\%$), the primary maximum is suddenly displaced to the right flank of the diagram into the region of positive metallicities. In other words, stars with solar heavy-element abundances dominate among the stars close to the Sun with such an orbital characteristic. As the mean orbital radii increase further the distributions show a systematic increase in the relative number of stars in the metal-poor group. Although the last two distributions cannot be described by the sums of two Gaussians, the polynomial clearly shows that the primary (and already unique) maximum for the farthest stars (Fig. 4n) is again near $[\text{Fe/H}] \approx -0.30$ while the percentage of stars with solar metallicity becomes low. This behavior manifests itself in the existence of a negative radial metallicity gradient that results (in the opinion of Edvardsson et al. (1993)) from a decrease in the star formation rate with increasing Galactocentric distance.

Clearly these distributions of elemental abundances (differing sharply from others) in the stars whose orbits lie almost entirely within the solar circle are attributable to their higher (on average) eccentricities. The distributions of the latter are given in the third column. We see that not only low eccentricity stars are absent in the histogram of the nearest stars (Fig. 4c), but also it is bimodal. (Although the maximum likelihood method here yields a high probability of erroneously rejecting the hypothesis about the description of the distribution by one Gaussian against its alternative representation by the sum of two Gaussians ($P_N > 5\%$), a clearly distinguishable dip is observed in the histogram.) Since the lower-eccentricity stars from inner Galactic regions do not reach the solar orbital radius, the left hump in the histogram is truncated. However, the dip in the distribution is distinguished quite clearly; i.e., the sample of stars with small $R_m$ seems to be kinematically inhomogeneous – it most likely contains stars of two different thin-disk populations. While remaining unimodal, the histograms of stars with orbital radii larger than the solar one show a gradual change in the position of the distribution maximum with increasing $R_m$ toward the higher eccentricities; i.e., a transition from the dominance of one population to that of the other is observed. (The position of the maximum at $e < 0.1$ here is explained by the absence of selection by eccentricity at fairly large $R_m$.) The age distributions are also consistent with the assumption that the thin disk has a multicomponent structure:
although all of them are unimodal, the dispersion for the stars closest to the Galactic center in Fig. 4d is largest. In this case, as we see from the histograms in the fourth column the position of the distribution maximum is displaced appreciably toward the older ages with increasing $R_m$ beginning from the solar orbital radius.

Let us examine whether the situation will change if the apogalactic orbital radii of the stars are considered as their presumed birthplaces. Note that the mean orbital radii are preferably used in this capacity only because they are less subject to the distorting effects of external gravitational perturbations (i.e. relaxation). However under the assumption that the orbits of the stars do not undergo significant changes since their birth in the overwhelming majority of cases, it would be more appropriate to use their maximum Galactocentric orbital radii (for an insignificant role of relaxation in the thin disk, see Marsakov and Shevelev (1994)). Figure 5 shows the $[\text{Fe/H}] - [\text{Mg/Fe}]$ diagrams for the stars divided into four approximately equal (in number) groups in $R_a$ by the values of 8.8, 9.4, and 10.3 kpc. These diagrams also show a gradual decrease in the relative number of lower metallicity ($[\text{Fe/H}] < 0.4$) stars above the median curve and a displacement of the metallicity range for magnesium-poor stars with increasing orbital radius. The changes here are not so sharp as those for the mean orbital radii, but, as a result, the overwhelming majority of stars with the largest apogalactic orbital radii also lie along the straight line that starts from $[\text{Fe/H}] \approx -0.7$ and passes below the median curve up to $[\text{Fe/H}] \approx -0.3$ (see the dashed line in Fig. 5d). Thus assuming the maximum Galactocentric distances of the stars to be their birthplaces, we also conclude that the increase in the star formation rate with decreasing Galactocentric distance is responsible for the existence of a negative radial metallicity gradient.

The distribution of stars with the smallest apogalactic orbital radii in relative magnesium abundance in Fig. 6a cannot be described by the sum of two Gaussians, as in Fig. 4a, but most of the stars with $[\text{Mg/Fe}] > 0.2$ fell precisely into this group and they formed a clearly distinguishable structure in the histogram. As in the case of the division into $R_m$ ranges, the remaining histograms in the first column also exhibit a small systematic displacement of the positions of the distribution maxima toward the higher relative magnesium abundances in the disk stars with increasing apogalactic orbital radius. However this displacement is too small to be able to give rise a significant radial gradient in relative magnesium abundance. The $[\text{Fe/H}]$ distribution of stars close to the Galactic center in Fig. 6b is described by the sum of two Gaussians at a high significance level ($P_N < 1\%$); the positions of the maxima of these Gaussians coincide, within the error limits, with those found in Fig. 4a. We see from the figure that the numbers of stars under the two Gaussians initially become equal as the apogalactic orbital radii increase further (Fig. 6f) and, subsequently as $R_a$ increases, the relative number of stars in the metal-poor group becomes so large that the metal-rich hump in the histogram disappears, showing only a small excess in the distribution (Fig. 6n). (The last two distributions as well as those in Figs. 4a and 4n cannot be described by the sum of two Gaussians at a statistically significant level, but polynomials allow the displacement of the positions of the distribution maxima with increasing stellar orbital radii to be traced.) This behavior of the metallicity distributions for stars born at different Galactocentric distances, first, gives rise to a radial metallicity gradient and second, points to the possible existence of two stellar populations in the disk. A distinct bimodal eccentricity distribution of stars with the smallest orbital radii (the significance of its description by the sum of two Gaussians is $P_N \ll 1\%$) and a systematic displacement of the positions of the eccentricity distribution maxima with increasing orbital radii can be seen from this figure even more clearly than from Fig. 4.
(However this displacement can be entirely explained by the analytical dependence of the eccentricities on orbital radii.) The age histograms for the stars of the samples in \( R_a \) also exhibit a displacement of the distribution maxima toward the older ages with increasing Galactocentric distance, but this is not so clear as that in Fig. 4.

**RELATION BETWEEN THE CHEMICAL COMPOSITION AND OTHER PARAMETERS OF STARS**

The thin disk was formed over a considerably longer period than all of the older subsystems. Therefore it would be natural to expect a correlation of the chemical composition of stars in this subsystem with their ages and orbital elements. The existence of vertical and radial metallicity gradients in the Galactic thin disk is believed to have been firmly established; nevertheless, let us refine these gradients using the data of our sample and simultaneously determine the same gradients in relative magnesium abundances. The diagrams of interest are shown in Fig. 7. The circles mark the stars selected according to the probability criterion and with accurately determined magnesium abundances. The straight lines in the diagrams were drawn by the least-squares method and their slopes define the corresponding gradients. All three metallicity gradients coincided within the error limits, with the typically derived gradients for mixed-age Galactic disk stars (see, e.g. Shevelev and Marsakov (1995) and references therein): \( \text{grad}_Z[\text{Fe/H}] = -0.29 \pm 0.06 \, \text{kpc}^{-1} \), \( \text{grad}_R[\text{Fe/H}] = -0.05 \pm 0.01 \, \text{kpc}^{-1} \) and \( \text{grad}_{R_0}[\text{Fe/H}] = -0.04 \pm 0.01 \, \text{kpc}^{-1} \) with the correlation coefficients \( r = 0.21 \pm 0.05, 0.25 \pm 0.04 \) and \( 0.15 \pm 0.04 \) respectively. The large size of the original sample of thin-disk stars ensured a high reliability of the results obtained; in addition our test showed that all of the gradients calculated from the strictly selected stars (open circles) coincided with the above ones, within the error limits. The diagrams to determine the gradients in relative magnesium abundance are shown in the right column of the figure. The vertical gradient was found to be nonzero far beyond the error limits: \( \text{grad}_Z[\text{Mg/Fe}] = (0.13 \pm 0.02) \, \text{kpc}^{-1} \) at \( r = 0.28 \pm 0.04 \) (Fig. 7b). The result is stable and the gradient derived from the strictly selected stars is found to be almost the same \( (0.15 \pm 0.05 \, \text{kpc} \) at \( r = 0.28) \). (Note that the farthest points in the diagrams that often determine the correlation are automatically discarded in this case. This is further evidence that the result is reliable.) In contrast, the radial gradient in magnesium abundance turned out to be zero outside the error limits under both assumptions about the birthplaces of the stars (see Figs. 7d and 7f).

Twarog (1980) was the first to derive the age–metallicity relation in the Galactic disk from F2–G2 and argued that it was unambiguous. However it was subsequently proven that the relation was by no means unambiguous and there was a significant spread in metallicity among the stars of any ages (see Marsakov et al. 1990; Feldzing et al. 2001), which gave reason to suggest that there was no age–metallicity relation in the disk. The \( t-\text{[Fe/H]} \) diagram for the stars of our sample is shown in Fig. 8a. Note that the absolute errors in the ages we use, which were determined by Nordström et al. (2004), are less than 2 Gyr for \( \sim 55\% \) of the stars and are larger for the remaining stars, reaching \( \approx 7 \, \text{Gyr} \) for some of the stars. As our test showed, they are large mostly for old stars; therefore, we analyze here the behavior of only stars with \( t < 10 \, \text{Gyr} \).

The correlation coefficient calculated only from the stars selected according to stringent criteria at \( t < 10 \, \text{Gyr} \) (Fig. 8a) is larger than zero outside \( 3\sigma: r = 0.30 \pm 0.07 \). The probability that the determinations of the gradient from the same number of two uncorrelated quantities will yield no lower correlation coefficient is \( P_N \approx 1\% \). We see from the
figure that the correlation is attributable mainly to the absence of young metal-poor stars in the thin disk: the lower left corner in the diagram is empty (the dashed inclined line in Fig. 8a). Such an effect is revealed by absolutely all previous studies and is not the result of selection (for more detail, see Shevelev and Marsakov 1993). An event that led to a continuous increase in the mean heavy-element abundances and to a decrease in the metallicity spread in the younger generations of stars probably occurred \( \sim 4 \) Gyr ago. If the sample of thin-disk stars is limited to an age \( t > 4 \) Gyr then the age–metallicity correlation will actually disappear completely. The \( t-[\text{Mg/Fe}] \) diagram in Fig. 8b shows the same large correlation coefficient: \( r = 0.27 \pm 0.08 \) at \( P_N \approx 1\% \). As a result, it turns out that the relative magnesium abundance in the thin-disk stars slightly increases with age. The correlation here is attributable not only to the sudden increase in the \([\text{Mg/Fe}]\) spread after \( \approx 9 \) Gyr since, if the sample is limited to this age, then both the slope and the correlation coefficient will be almost constant. Here, when the sample is limited solely to old stars the correlation does not disappear completely although not only the correlation coefficient, but also the slope of the regression line decrease sharply remaining nonzero outside the error limits. The significance of the existence of both correlations is confirmed by the behavior of the strictly selected thin-disk stars with accurately determined magnesium abundances (open circles in the diagrams), according to which the values found remain constant.

The bimodal distributions of thin-disk stars in iron and magnesium abundances and in Galactic orbital eccentricity (see Figs. 4 and 6) and the existence of an abrupt change in metallicity with age (Fig. 8) most likely suggest that the population in the subsystem is inhomogeneous. Let us check whether the gradients in chemical composition in the disk populations of different ages also differ. To this end, we divide all of the thin-disk stars into two groups by \( t = 4 \) Gyr. As we see from the upper two diagrams in Fig. 9 the vertical metallicity gradient for the young group is considerably steeper than that for the old group: \( \text{grad}_Z[\text{Fe/H}] = -0.58 \pm 0.13 \) kpc\(^{-1}\) and \( -0.16 \pm 0.07 \) kpc\(^{-1}\) with the correlation coefficients \( r = 0.36 \pm 0.04 \) and \( 0.13 \pm 0.05 \) and the probabilities of random occurrence of the correlations \( \ll 1\% \) and \( \approx 2\% \) for the young and old groups, respectively. The derived gradients change only slightly if the sample is limited to the stars selected according to stringent criteria and if the five farthest points are eliminated from each diagram. That the gradient in the young group proved to be steeper closely agrees with the result obtained by Shevelev and Marsakov (1995) from a considerably larger sample, but with photometric metallicities and distances. A decrease in the vertical metallicity gradient with increasing stellar age can be observed in the case of a continuous increase in the stellar residual velocity dispersion with time, i.e., relaxation. Indeed, the distortion of the stellar orbits with time must cause the gradient to be blurred. However Fig. 9b clearly shows that the shallow gradient in the old group is attributable not to an increase in the maximum distance from the Galactic plane for all old stars of any metallicity but, on the contrary to the avoidance of large \( Z_{\text{max}} \) by the metal-poor stars (the empty lower right corner in the diagram). As a result, the lower envelope of the diagram even shows a tendency for the mean metallicity to increase with age. Therefore, we are inclined to believe that relaxation in the thin disk plays no crucial role. (Marsakov and Shevelev (1994) reached the same conclusion by analyzing the age dependences of the parameters of the velocity ellipsoids for thin-disk F stars.)

As we see from the lower diagrams in Figs. 9c and 9d, the vertical gradient in relative magnesium abundance for the young group was also found to be slightly steeper than that for the old group: \( \text{grad}_Z[\text{Mg/Fe}] = 0.12 \pm 0.04 \) kpc\(^{-1}\) and \( 0.07 \pm 0.02 \) kpc\(^{-1}\) at \( r = 0.23 \pm 0.08 \) and \( 0.18 \pm 0.06 \) for the young and old group, respectively. In both cases, despite the small correlation coefficients, the vertical gradients in relative magnesium abundance were found
to be nonzero outside $3\sigma$ for the probabilities of their random occurrence $P_N < 1\%$. Remarkably Fig. 9d reveals a paradox in the older group similar to that in Fig. 9b: the upper right corner in the diagram unexpectedly proved to be empty; i.e., while the mean relative abundance shows a general tendency to increase with $Z_{max}$, a deficit of magnesium-rich ($[\text{Mg/Fe}] > 0.25$ dex) stars far from the Galactic plane ($Z_{max} > 0.3$ kpc) is observed in the thin disk. Note also that most of the stars in the young group have metallicities $[\text{Fe/H}] > 0.4$ dex and magnesium abundances $[\text{Mg/Fe}] < 0.15$ dex and lie above the Galactic plane mainly at $Z < 400$ pc while a significant fraction of the stars in the old group exceed considerably these limits in all three parameters.

As we see from the diagrams in Fig. 10, all of the radial metallicity gradients are nonzero far beyond the error limits with $P_N \ll 1\%$ (see the inscriptions in the corresponding panels). Neither the removal of far points in the diagrams nor the use of solely strictly selected stars change the results. As a result, we see that the radial metallicity gradients show an indistinct tendency for the absolute value to decrease with increasing age (the differences in gradients lie outside $2\sigma$ in $R_m$ and do not exceed the errors in these regression coefficients in $R_\alpha$). The same small rise in the radial metallicity gradient in the thin disk with age was also found by Shevelev and Marsakov (1995).

There are no radial gradients in relative magnesium abundance in both age groups, as in the case of the complete original sample of mixed-age stars (see Fig. 7).

**THE FORMATION OF THE THIN DISK**

Analysis of the relations between the relative magnesium abundance and other parameters of the stellar populations makes it possible to better understand the formation history of the Galactic subsystems. Indeed, even the difference in the mean relative magnesium abundances between the thick-disk and thin-disk stars suggests that the bulk of the thick-disk stars formed long before the onset of massive star formation in the thin disk. However the overlap between the ranges in both metallicity and magnesium abundance for these subsystems is also observed. Hence, the star formation process most likely did not cease completely in the entire Galaxy. The [Mg/Fe] ratio begins to decrease with increasing metallicity in the thin disk immediately after the formation of the first stars in it, i.e., from $[\text{Fe/H}] \approx -1.0$ dex. This is considerably farther to the left in the diagram than in the thick disk where the point of a sharp decrease is observed at $[\text{Fe/H}] \approx 0.5$ dex. Hence, in the metal-poor interstellar matter from which the first thin-disk stars subsequently began to form, the enrichment with SNeII ejecta was less intense before this. It is quite probable that such metal-poor matter with a high relative magnesium abundance came into the thin disk as a result of accretion from regions with a different history of chemical evolution. The fast decrease in the relative magnesium abundance in the thin disk as the metallicity increases from $\approx -1.0$ dex to $\approx -0.7$ dex suggests that the star formation rate in it was initially low but it then suddenly increased, which subsequently led to a thinning of the $[\text{Fe/H}]-[\text{Mg/Fe}]$ relation. This event occurred $\sim 9$ Gyr ago, which is also evidenced by the sharp increase in the number of thin-disk stars younger than this age. Subsequently when passing to stars with metallicities higher than the solar value, the slope of the $[\text{Mg/Fe}]-[\text{Fe/H}]$ relation virtually vanishes, which is indicative of a new increase in the star formation rate $\sim 4$ Gyr ago and stabilization of the ratio of the contributions from supernovae (SNII/SNII) to the enrichment of the interstellar medium in the thin disk since then. In contrast, in the thick disk star formation virtually ceased altogether (for some time?) after the onset of massive SNII explosions, as suggested by the observed
steep decrease in [Mg/Fe] near [Fe/H] ≈ −0.5 dex.

The change in the behavior of the [Mg/Fe]–[Fe/H] relation with stellar orbital radius shows that the star formation rate closer to the Galactic center is higher than that on the periphery. Moreover it seems that star formation within the solar circle of the Galaxy has never been interrupted, but only slowed down before the massive formation of thin-disk stars. In contrast, the first thin-disk stars at great Galactocentric distances appeared only after the long phase of star formation delay. This follows from the presence of a distinct jump in the [Mg/Fe] ratio at metallicities [Fe/H] < −0.4 dex for stars with large orbital radii. The larger [Mg/Fe] ratios at high metallicities in the stars within the solar circle suggest that the star formation rate remains there higher even at present. The clear deficit of stars with metallicities higher than the solar value there is also indicative of a lower star formation rate at great Galactocentric distances. Such differing histories of chemical evolution along the radius led to the formation of a radial metallicity gradient in the Galactic disk. However the corresponding gradient in relative magnesium abundance cannot be found, most likely because it is insignificant compared to the spread in [Mg/Fe] in the subsystem. The existence of nonzero vertical gradients in both metallicity and relative magnesium abundance far beyond the error limits in the thin disk probably suggests that the fall of a metal-poor gas to the disk, the star formation, and the contraction of the interstellar medium in the forming subsystem are simultaneous processes.

The time-varying star formation rate in the thin disk could not but give rise to the age–metallicity and age–magnesium abundance relations. Since the chemical and spatial–kinematic properties of stars of different ages turned out to be different, the thin-disk structure is probably not homogeneous. This is also suggested by the bimodality of the metallicity function in it and by the difference in the kinematic parameters of the groups of stars with different metallicities (see Marsakov and Suchkov 1980). However reliable segregation of stars into populations inside it does not seem possible. This is because the stars that are currently in the solar neighborhood arrive here from regions with different (as we now see) star formation histories and the stars of different ages born far from one another may prove to have the same chemical composition.

Despite the long history of studying this question an adequate model for the formation of the Galactic thin disk and its evolution cannot be constructed so far. A thorough analysis of the detailed chemical composition of a large number of the nearest stars can help obtain additional information about these processes.

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Fig.1. - Relation between the residual velocities with respect to the local standard of rest and $\sqrt{Z_{\text{max}}} + 4 \cdot c^2$ (a), the $\text{[Mg/Fe]}$ ratios for all of the sample stars separated according to our criteria into the two disk subsystems (b) and only for the stars selected in the corresponding subsystems according to stringent probability criteria (c): the pluses and triangles indicate the thin-disk and thick-disk stars, respectively; the circles mark the stars selected according to stringent criteria (a) and with accurately determined relative magnesium abundances (b,c).

Fig.2. - Relation between metallicity and relative magnesium abundance (a) for the stars of both disk subsystems (b) for the thin-disk stars, and (c) for the thick-disk stars: the crosses and triangles indicate the thin-disk and thick-disk stars, respectively. The circles mark the stars selected according to the probability criterion and with accurately determined magnesium abundances. The broken curves represent the median lines of the relations for the thin (a) and thick (b) disks drawn by eye halfway between the upper and lower envelopes. The error bars are shown.

Fig.3. - Relation between metallicity and relative magnesium abundance for the thin-disk stars separated into four ranges in mean orbital radii by $R_m = 8, 8.5$ and $9.1$ kpc. The circles mark the stars selected according to the probability criterion and with accurately determined magnesium abundances. The broken curves in all panels represent the median line for the thin disk. The error bars are shown.

Fig.4. - Distributions for thin-disk stars separated into four ranges in $R_m$ (first column) of relative magnesium abundance, (second column) of metallicity, (third column) of galactic orbit eccentricities, and (fourth column) of ages. Distributions on the first three panels on the first line and on the second panel of the second line approximated by the sums of two Gauss functions and by the eight power polynomials on the rest panels.

Fig.5. - Same as Fig. 3 for the thin-disk stars divided into four ranges in apogalactic orbital radii by $R_a = 8.8, 9.4$ and $10.3$ kpc.

Fig.6. - Same as Fig. 4 for the thin-disk stars divided into four ranges in $R_a$.

Fig.7. - Relations of metallicity and relative magnesium abundance in the thin-disk stars to the maximum distance of their orbital points from the Galactic plane (a,b), apogalactic distance (c,d), and mean orbital radius (e,f). The circles mark the stars with accurate $\text{[Mg/Fe]}$ ratios selected in the thin disk according to a strict probability criterion. The solid lines represent the regression lines. The error bars along with the gradients and the correlation coefficients are indicated.

Fig.8. - Relations between the age of thin-disk stars and metallicity (a) and relative magnesium abundance (b). The notation is the same as that in Fig. 7.

Fig.9. - Relations between the maximum distance of thin-disk stars from the Galactic plane and their metallicity (a,b) and relative magnesium abundance (c,d): for the stars younger and older than 4 Gyr on the left and on the right, respectively.

Fig.10. - Relations between metallicity and mean stellar orbital radius (a,b) and apogalactic radius (c,d): for the stars younger and older than 4 Gyr on the left and on the right respectively. The notation is the same as that in Fig. 7.
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