The Age–Metallicity Relation in the Thin Disk of the Galaxy

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Abstract
HST trigonometric distances, photometric metallicities, isochronic ages from the second revised version of the Geneva–Copenhagen survey, and uniform spectroscopic $Fe$ and $Mg$ abundances from our master catalog are used to construct and analyze the age–metallicity and age–relative $Mg$ abundance relations for stars of the thin disk. The influences of selection effects are discussed in detail. It is demonstrated that the radial migration of stars does not lead to appreciable distortions in the age dependence of the metallicity. During the first several billion years of the formation of the thin disk, the interstellar material in this disk was, on average, fairly rich in heavy elements ($\langle[Fe/H]\rangle \approx -0.2$) and poorly mixed. However, the metallicity dispersion continuously decreased with age, from $\sigma_{[Fe/H]} \approx 0.22$ to $\approx 0.13$. All this time, the mean relative abundance of $Mg$ was somewhat higher than the solar value ($\langle[Mg/Fe]\rangle \approx 0.1$). Roughly four to five billion years ago, the mean metallicity began to systematically increase, while retaining the same dispersion; the mean relative $Mg$ abundance began to decrease immediately following this. The number of stars in this subsystem increased sharply at the same time. These properties suggest that the star-formation rate was low in the initial stage of formation of the thin disk, but abruptly increased about four to five billion years ago.

Keywords: age–metallicity relation, thin disk of the Galaxy

Introduction
The time for the existence of the thin-disk subsystem is comparable to the age of the Galaxy itself. Therefore, ongoing elemental-synthesis processes during this period should lead to an appreciable enhancement of the general heavy-element abundance in young stars of this subsystem. As a result, we would expect the thin disk to display a well defined age–metallicity dependence, with the highest metallicities being observed in the youngest stars. However, numerous investigations into this question have left the existence of such a dependence open.

The first systematic studies of the relationship between age and metallicity in the Galactic disk were those carried out by Twarog [1] for $\sim 1000$ field stars, based on data obtained in the mean-filter Strömgren photometric system, which made it possible to carry out a three-dimensional classification of these stars. The results were consistent with expectations, since they demonstrated that, beginning with the oldest stars of the subsystem, the metallicity increased uniformly with decreasing age. Strömgren [2] underscored another
aspect of the age–metallicity relation found by Twarog: the very small dispersion of the metallicity \( \sigma_{[Fe/H]} \) for stars of a given age, which only slightly exceeded the scatter due to observational uncertainties.

Subsequently, both of these conclusions evaporated. Based on \( uvby \) photometry for \( \sim 5500 \) F2–G2 dwarfs of the disk, Marsakov et al. [3] showed, using kinematics as a statistical indicator of the age of a stellar group, that the age–metallicity dependence is two-dimensional, with the following main properties: a large scatter in the metal contents of old stars, and a lowering of the metallicity scatter together with an increase in the mean metallicity with decreasing age.

Based on more reliable spectroscopic measurements of the \( Fe \) abundances and isochronic ages for roughly 200 stars of the disk, Edvardsson et al. [4] established that the real scatter in the metallicities for stars of a single age was appreciably higher than the observational uncertainties. Simultaneously, attention was turned to the existence of very old stars with high metallicities in the subsystem. Edvardsson et al. [4] also asserted that, if an age dependence of the mean metallicity in the disk exists, it is very weak. However, all these early studies were subject to a priori selection effects, due to the limited nature of samples of stars with temperatures below spectral type G2, leading to an obvious exclusion of possible old, metal-rich stars, whose turn-off points lie in the region of lower temperatures, according to theoretical calculations (see Fig. 2a and the sloped dashed line, corresponding to \( T_{eff} = 5800 \) K).

In recent studies based on new \( uvby \) photometry data and satellite astrometric data for several thousand disk stars (5 – 7), it has become possible to include stars to the end of spectral type G, and even later-type stars. The ages in [5] are based on theoretical evolutionary tracks constructed using an algorithm that minimized the difference between the observed and theoretical magnitudes and effective temperatures for each star. This algorithm excludes the main-sequence turn-off, where the isochrones admit the existence of stars with the same atmospheric parameters but different ages. The studies [6, 7] represent different versions of the Geneva–Copenhagen survey (the main version, and a later version corrected for systematic errors in the stellar parameters). These ages were estimated using theoretical isochrones based on Bayesian theory [8]. This method takes into account systematic effects, and enables more reliable estimation of stellar ages based on probability distribution functions. All the scales are consistent with ages obtained based on the chromospheric activity of the stars.

Numerous studies have shown the existence of very old super-metal-rich stars, and simultaneously asserted that all features on age–metallicity plots giving rise to the observed correlation are due to various selection effects. In particular, it is suggested in [6] that the observed higher mean metallicities for stars younger than three billion years have two artificial origins: first, high-temperature limits imposed on samples and, second, the presence of distant, hot, highluminosity stars in samples selected based purely on apparent magnitude, whose ”supermetallicities” are due exclusively to ”overcorrection” of the photometry data for interstellar reddening.

However, following the traditional method for determining isochronic ages, Pont and Eyer [9] showed that the non-linear division of the isochrones in the Hertzsprung–Russel diagram leads to statistical selection effects when determining isochronic stellar ages, which artificially ascribe them large ages. Analyzing various errors in atmospheric parameters and isochronic ages of stars in [4], Pont and Eyer [9] concluded that the identification of old, metal-rich stars (\( t > 5 \) billion years, \( [Fe/H] \sim 0.0 \)) and young, metal-poor stars (\( t < 5 \) billion years, \( [Fe/H] < -0.5 \)) is erroneous. They explain that there are systematic errors in
the ages of these stars as a consequence of the very simple method used to derive ages from theoretical isochrones, and assert that application of a correct statistical method corrected for this selection effect would indicate that the Geneva–Copenhagen catalog data actually indicate a monotonic growth in the metallicity in the Galactic disk with approach toward the current epoch, with dispersions $\sigma_{[Fe/H]} < 0.15$ for stars of the same age.

These conclusions are in agreement with the results of Rocha-Pinto et al. [10, 11], who used data on the chromospheric activity of several hundred nearby main-sequence dwarfs to estimate their ages, and found a significant trend for the mean metallicity with a fairly small dispersion for stars of a single age ($\sigma_{[Fe/H]} \sim 0.12$). (Note, however, that the photometric and spectroscopic metallicities in that study were very poorly correlated.) Subsequently, Rocha-Pinto et al. [12] suggested that evidence for the existence of an age–metallicity relation in the thin disk was also provided by the observed decrease in the mean metallicity with both increasing and decreasing mean orbital radius of stars that are currently located near the Sun. If the mean radius of a star’s orbit is an indicator of the Galactocentric distance of its birth [4, 13], the increase in the difference between the mean orbital radii of stars and the radius of the solar orbit with increasing stellar age observed for nearby field stars indicates that the mean metallicity falls off with age in the disk. (Note that [14] earlier explained the observed break in the dependence of the mean metallicities of stars of this subsystem on their mean radii as a consequence of a decrease in metallicity with age in the Galactic disk.)

Reid et al. [15] composed a representative sample of nearby stars based on Hipparcos data for studies of the age–metallicity relation. One characteristic feature of the sample is that it includes only stars whose main-sequence lifetimes are comparable to or exceed the age of the thin disk (i.e., stars with $M_V > +4m$). The sample is limited from below by the absolute magnitude, $M_V < +6m$, which makes it complete for F5–K0 dwarfs located within $\approx 30$ pc. They determined the metallicities of the stars using the calibration of [16], based on Strömgren photometric data; as the authors themselves note, the resulting metallicities were systematically higher than those in [4] by $\Delta[Fe/H] \approx 0.1$. It is striking that the ages they found based on the Yale isochrones [17] are fairly well correlated with the ages of [4], but appear completely uncorrelated with the ages of [6]. As a result, Reid et al. [15] concluded that the mean metallicity in the solar neighborhood increases from $[Fe/H] \approx -0.3$ for an age of ten billion years to $\approx +0.15$ at the current epoch, although the dispersion of the metallicity at any given epoch is fairly high.

Haywood’s [18, 19] analysis of the kinematics of nearby stars showed that the orbital elements of the most metal-rich and metal-poor stars currently located in the solar neighborhood suggest that most of them were born in inner and outer regions of the Galactic disk, respectively. As a result, as Haywood notes, we actually only see an absence of metal-poor stars younger than two billion years and an increase in the metallicity dispersion with age in the observed age–metallicity diagram. He concludes that thin disk stars at the solar Galactocentric distance were born within a narrow range of metallicities ($-0.2 < [Fe/H] < 0.2$), supporting the hypothesis that the chemical evolution in the Galaxy primarily preceded the formation of the disk subsystem. Simultaneously, Roskar et al. [20] numerically modeled hydrodynamical processes in the formation of the Galactic disk, showing that the virtual absence of a slope and the large scatter in observed age-metallicity diagrams and the comparatively small number of young, metal-poor stars in the solar neighborhood could be explained by a radial migration of stars.

However, Karatas et al. [21] suggest that it is not possible to draw firm conclusions about the existence of an age-metallicity dependence in the thin disk for $t > 3$ billion
years, due to the scatter in the metallicities for stars of the same age and the existence of old, metal-rich stars, supporting the conclusions of [5, 6]. They reached this conclusion based on their analysis of a sample containing more than four hundred stars, which they identified with the thin-disk subsystem using the criterion of [22], applying information about both the kinematics and metallicities of the stars. They used only dwarfs near the turn-off point and subgiants, since their isochronic ages can be determined with high accuracy.

As the existence of monotonic metallicity variations with age in the thin disk remains unproven, our goal here is to carry out a detailed analysis of all possible selection effects capable of distorting the form of the observed age–metallicity diagram, and to investigate variations in the character of this diagram based on stars born at different Galactocentric distances. To improve the reliability of the results, we consider spectroscopic $Fe$ and $Mg$ abundances together with photometric metallicities, as well as independent age estimates.

**OBSERVATIONAL DATA**

Holmberg et al. [7] recently published a revised version of the Geneva–Copenhagen survey, which includes appreciably different stellar metallicities and ages than in the previous edition [6, 23]. Therefore, we used this revised version, which contains the atmospheric parameters, ages, metallicities, and kinematics of 14 000 F–K dwarfs, as the main source of data for our study, supplementing this with our master catalog of spectroscopic $Fe$ and $Mg$ abundances in 867 stars with accurately known parallaxes [24]. The atmospheric parameters and metallicities in the former catalog were based on $uvby\beta$ photometric indices corrected for interstellar reddening. Figures 1a, b depict the stars present in both catalogs used. In each panel, we present lines corresponding to full agreement between the quantities plotted, together with linear fits to the data. For the vast majority of these stars, the photometric metallicities and effective temperatures coincide with the spectroscopic values from our master catalog within the errors. Neither of the photometric parameters display any overall systematic deviations, only small inclinations of the linear fits relative to the median lines. The metallicities of the stars that are richest in heavy elements are slightly underestimated, by $\Delta[Fe/H] \leq 0.1$, while the effective temperatures of the hottest stars are underestimated by $\Delta T_{\text{eff}} \leq 50$ K. Such small discrepancies will not lead to any appreciable increase in the uncertainties in the derived ages for the majority of the catalog stars.

The distances for approximately 75% of the stars in [7] are based on Hipparcos trigonometric parallaxes; only parallaxes with uncertainties below 13% were included. We used photometric distances for stars without parallaxes or stars whose parallaxes have larger errors. The cited accuracy for these distances is also about 13%. Analysis of the uncertainties in the trigonometric parallaxes showed that photometric distances in the catalog were adopted primarily for distant stars, whereas 98% of stars within 70 pc of the Sun have trigonometric distances.

Holmberg et al. [7] calculated the most probable ages for the stars based on the theoretical isochrones of [25, 26], taking into account the uncertainties in the effective temperature, absolute magnitudes, and metallicities. Unfortunately, the variability of the speeds with which the stars moved along the evolutionary tracks was automatically also taken into account, leading to some distortion of the ages of stars located near the turn-off point, since stars in these sections evolve comparatively rapidly, and the probability of finding them in this stage is very low. As a result, stars located near the evolutionary stage corresponding to the depletion of the last percent of hydrogen in their cores just prior to their collapse
were ascribed ages that were too young.

This age distortion affected only stars with metallicities such that neighboring isochrones in the region of the turn-off point have similar shapes and intersect. This effect can be seen in the age-absolute magnitude diagram constructed for all stars in the catalog in Fig. 1 of [27] (although this plot was constructed for data from the previous version of the catalog [23], its character remains the same). Two separate sequences can be clearly distinguished in this diagram, which close up near two billion years due to the appreciable motion away from the main-sequence of the turn-off points for younger isochrones with higher heavy-element contents, while the gap between the sequences is filled near ages of \( t > 5.5 \) billion years by older stars that have evolved beyond their turn-off points. We nevertheless considered it to be possible to use these data, since the uncertainty in assigning ages for stars near the turn-off point is less than a billion years, as can be seen in the figure cited above. Koval’ et al. [27] emphasize that their procedure for calculating the ages does not distort the general trend on the age-metallicity diagram. The analysis of the age uncertainties of [7] showed that mean uncertainties of \( t < \pm 2 \) billion years are achieved for \( \approx 85\% \) of the stars, while uncertainties of \( t < \pm 3 \) billion years are achieved for \( \approx 90\% \) of the catalog stars.

Radial velocities at different epochs were obtained in [7] as part of the CORAVEL project, while the proper motions were taken primarily from the Tycho-2 catalog. The resulting uncertainty in the stellar velocity components is \( \pm 1.5 \) km s\(^{-1}\). The orbital parameters in [7] were calculated based on the Galactic gravitational potential of [28], and assumed a solar Galactocentric distance of 8 kpc and a rotational velocity of the thin disk at the solar distance of 220 km s\(^{-1}\).

We used the method proposed in [27] to select stars for our analysis for which the probability of membership in the thin disk exceeds the membership probability for the thick disk. This method uses the dispersions of each of the three spatial velocity components obtained in [27] and the mean rotational velocity of the two subsystems at the solar Galactocentric distance. Verification based on our master catalog of spectroscopic \( Fe \) and \( Mg \) abundances for nearby stars [24] shows that this kinematic criterion is in very good agreement with chemical criteria that indicate that the majority of thin-disk stars selected in this way have low ratios \( [Mg/Fe] < 0.25 \) and high ratios \( [Fe/H] > -0.5 \) (see, in particular, [29, 30]).

After removing binary stars, very evolved stars (\( \delta M_V > 3^m \)), and stars with uncertain ages (\( \epsilon(t) > \pm 3 \) billion years), the remaining sample had 5805 presumed single thin-disk stars. (The resulting mean age uncertainty for stars in this sample was \( \epsilon(t) = 1.0 \) billion years). Figure 1c plots the effective temperature versus absolute magnitude for this sample (for comparison, the small symbols show all thin disk stars from the input catalog). It is possible to obtain trustworthy age estimates only for stars with absolute magnitudes \( M_V \leq 4.6^m \): stars with lower luminosities fall in the region where the isochrones are densely packed and the age uncertainties become very large. The stars in the resulting thin disk sample cover a fairly wide range of effective temperature, \( \approx (5400 - 7000) \) K, which obviously includes both some of the oldest and some very young stars of this subsystem.

The analysis of [27] showed that the left wing of the distribution of the distance from the Sun (\( d \)) for the sample stars can be fit well by a power law, with the index equal to two within the errors for \( d < 60 \) pc, as is expected if the distribution of stars is uniform in the studied volume. To eliminate selection effects associated with the different depths of the survey for stars of different metallicities and temperatures, it is desirable to restrict the sample to a distance from the Sun of 60 pc, within which the sample can be considered
to be complete. However, taking into account the fact that the maximum of the distance distribution is observed at a distance of \( \approx 70 \) pc and the number of nearby F–G stars suitable for our statistical analyses is limited, we decided to restrict our sample to this slightly greater distance (leading to an increase in the sample volume by about 20\%). As a result of this restriction, we simultaneously minimize the errors associated with correcting the photometric indices for interstellar reddening, since reddening is negligible out to this distance. Moreover, the trigonometric parallaxes of nearly all stars within this distance are independent of photometric measurements. The final sample contains 2255 nearby thin-disk stars.

We used data from our master catalog of reference spectroscopic Fe and Mg abundance measurements [24] to identify possible selection effects due to deriving the metallicities from photometric data, and also to study the age dependence of the relative abundances of \( \alpha \) elements. This catalog is a collection of virtually all Mg abundances for dwarfs and subgiants in the solar neighborhood derived via synthetic modeling of high-dispersion spectra published up to January 2004. The internal accuracy of the relative Mg abundances for metal-rich ([Fe/H] > −1.0) stars was \( \epsilon([\text{Mg/Fe}]) = \pm 0.05 \), while the corresponding internal accuracy for the Fe abundances was \( \epsilon([\text{Fe/H}]) = \pm 0.07 \). The distances and spatial velocities of the stars were calculated using data from large, modern, high-accuracy catalogs. We used trigonometric parallaxes with uncertainties less than 25\%, or, if these weren’t available, photometric distances based on \( uvby\beta \) photometry. The catalog initially contains some selection effects distorting the relative numbers of stars with different metallicities and temperatures [24]; the subsample that is within 40 pc of the Sun is fairly representative of F–G dwarfs of the thin disk. Nevertheless, to retain a sufficient number of stars with spectroscopic chemical compositions for our analysis, we decided to restrict the sample to a somewhat larger distance (70 pc), since it was only used as a supplementary sample in our study. After applying the probability criterion of [27] and excluding stars with large age uncertainties (\( \epsilon(t) > \pm 3 \) billion years), the sample included only 220 thin-disk stars.

**ANALYSIS OF SELECTION EFFECTS IN THE AGE–METALLICITY DIAGRAM**

Figure 2a presents the age-metallicity diagram for the stars in our thin-disk sample from [7]. The small number of stars with ages exceeding 12 billion years are not shown, since such great ages are likely to be overestimated, as was noted by Holmberg et al [7]. (Stars with spectroscopic metallicities are shown by big, hollow circles.) The large, hollow circles show the mean metallicities for stars in ten narrow age ranges, each containing 225 stars. The uncertainties in the mean values are comparable to the sizes of the big, hollow circles. The smooth curve is a third-order polynomial fit to all the stars, which traces the behavior of the mean points along the entire horizontal axis well and effectively smooths the desired age dependence of the metallicity. Upper and lower envelopes at the 5\% level are also shown.

For comparison with independent age estimates, Fig. 2b presents analogous diagrams for stars with ages from [5, 11]. Both of these studies used \( uvby\beta \) photometry to determine [Fe/H], but our analysis showed that their values differ appreciably from those derived from later spectroscopic and photometric data, and we have accordingly used the metallicities from [7]. The ages in the former study were obtained from theoretical isochrones, and in the latter study from the chromospheric activity of the stars. Since there is no kinematic data for the reliable identification of thin-disk stars within 70 pc of the Sun in these studies,
we identified stars coinciding with those in our sample based on their HD numbers. This left 1078 stars from [5], and only 206 from [11]. Comparisons show that the distribution of the stars and the general run of the age dependences of the metallicity in the lower diagram are overall consistent with the data in the upper diagram; therefore, we will further focus on the latter data.

Thus, Fig. 2a shows that the largest scatter in \([Fe/H]\) is observed for old stars of the Galactic disk, while this scatter is appreciably smaller for young stars due to the obvious deficit of metal-poor stars among them (the lower-left corner of the diagram is nearly empty). This is explained in [6] as an effect of the limitation of the input Geneva.Copenhagen survey at high temperatures due to the restriction on the temperature index \(b - y\). In the opinion of [6], the difference in the isochronic ages of metal-rich and metal-poor stars with the same temperatures can explain the observed slope of the lower envelope in the diagram. The effect of limiting the sample at high temperatures somewhat distorts the real age–metallicity diagram.

The dashed line in Fig. 2a is based on the theoretical isochrones used in [7] for \(T_{\text{eff}} = 7000\) K, which corresponds to the boundary to the right of which stars hotter than this temperature are not included in the sample. This temperature corresponds to the upper temperature limit for our sample. The region to the left of this line contains mainly cooler stars that have not moved far from their zero age main sequences, as well as small numbers of massive stars in the subgiant stage. As can be seen in the diagram, to some extent, the high-temperature limit of the sample indeed leads to a small inclination in the age dependence of the mean metallicities for ages less than \(\approx 1.5\) billion years. (We already noted above that the lower temperature limit of the sample of roughly the solar temperature [see the right dashed line] led to the exclusion of the oldest metal-rich stars from the sample [1], bringing about the conclusion of a monotonic increase in metallicity with age in the disk subsystem of the Galaxy.) However, as we can see in the diagram, the age dependence of the mean metallicity is determined by the relative numbers of stars with different metallicities but the same age, not by this nearly vertical line, to the right of which, as before, we observe a deficit of young, metal-poor stars. In particular, we can see that, with increasing temperature, the densities of stars in the diagram with \([Fe/H] < -0.1\) begin to grow sharply at greater distances from the line \(T_{\text{eff}} = 7000\) K as the metallicity decreases. This could come about due to the existence in the thin disk of main-sequence turn-off points for stars with different metallicities, assuming that metal-poor stars have been born in relatively small numbers in recent times. We will now verify this hypothesis.

**Main-Sequence Turn-off Points for Stars with Different Metallicities**

The left panels in Fig. 3 present \(T_{\text{eff}} - M_V\) plots for stars within 70 pc of the Sun in four fairly narrow metallicity ranges; the right panels show histograms of the temperature distributions for these same stars. The line segments in the histograms schematically denote the behavior of the left envelopes of these distributions. The progressive decrease in the numbers of stars in the right-hand sections of the distributions is due to the limited depth of the survey of the input catalog (magnitudes < 8.5\(^{m}\)), as well as selection effects associated with uncertainties in the age determinations [Fig. 1c].) All the metal-poor groups (\([Fe/H] < 0.0\)) display breaks in their envelopes – inflections. While the increase in the number of stars with decreasing temperature to the left of the ”inflection point” essentially corresponds to a Salpeter mass distribution, the number of stars grows with decreasing
Table 1: Kinematic parameters of four groups of nearby thin-disk stars

| Parameter | $t < 2$ billion years | $t > 5$ billion years |
|-----------|----------------------|----------------------|
| $(V_{LSR})$, km s$^{-1}$ | $[Fe/H] > 0.0$ | $[Fe/H] < -0.3$ | $[Fe/H] > 0.0$ | $[Fe/H] < -0.3$ |
|           | 26 ± 1                | 32 ± 2                | 44 ± 2                | 48 ± 2                |
| $\sigma_V$, km s$^{-1}$ | 11 ± 1                | 10 ± 2                | 19 ± 2                | 21 ± 2                |
| $N$       | 197                   | 33                    | 133                   | 159                   |

temperature in a jump-like fashion to the right of this point. Note that the temperatures of these points are far to the left of the edge of the diagram for all the metal-poor groups. This means that the sharp deficit of hotter (and therefore younger) metal-poor stars is not associated with the high-temperature limit for the sample, but instead with the existence of a minimum age for the majority of stars of a given metallicity in the thin disk; i.e., with the existence in the thin disk of main-sequence turn-off points for metal-poor field stars.

Theoretical isochrones from [17] passing through the “inflection points” in the right-hand panels are shown in the three left-hand panels of Fig. 3 (for comparison, isochrones for a higher age are also shown to the right of these curves). Isochrones for the most metal-rich group are not presented, since the “inflection point” is not clearly distinguished in this case. With growth in the metallicity, the position of the turn-off point shifts toward higher temperatures (younger ages), remaining within the studied temperature range for stars with $[Fe/H] < 0.0$. The small number of stars that are hotter than the turnoff point are probably blue stragglers or stars born in small numbers after the formation of the main mass of stars of the given metallicity in the Galactic disk.

Do Old Metal-Rich Stars Exist?

In spite of the fact that, according to theoretical isochrones, the positions of a fairly large number of stars with the solar metallicity on the Hertzsprung Russell diagram indicate old ages, the existence of old, metal-rich stars was subject to doubt in [9]. Pont and Eyer [9] arrived at this conclusion after discovering that the spectroscopic data in the sample [4] for most metal-rich stars older than five billion years display substantial discrepancies in one of the following parameters: their trigonometric distance, photometric temperature, photometric metallicity, or isochronic ages from [6]. They suggest that these discrepancies led to an artificial enhancement in the ages of stars located in the region of enhanced isochrone density, so that the apparent existence of old, metal-rich stars is an artefact.

However, Fig. 2a shows that our sample of thin disk stars with spectroscopic Fe abundances and stars of the Geneva–Copenhagen survey from [7] with revised ages likewise demonstrate a large number of such stars. Of course, a reduction in the metallicities in [7] for the richest stars observed in Fig. 1a could testify to a selective overestimation of the ages of the oldest metal-rich stars. To verify this hypothesis, the hollow circles in Fig. 1 show stars with ages exceeding five billion years. Most old stars lie below the diagonal line; i.e., their $[Fe/H]$ values are all reduced, independent of their metallicity (within the uncertainties).

This distortion leads only to a small statistical overestimation of the ages of old stars of any metallicity. Our analysis shows that taking into account the deviations between the spectroscopic and photometric metallicities and effective temperatures in Figs. 1a and 1b does not appreciably change the relative number of stars in the upper-right corner of the age–metallicity diagram. The chromospheric ages from [11] in Fig. 2b also display some
number of such stars. In other words, independent spectroscopic atmospheric parameters, Fe abundances, and ages confirm the existence of an appreciable number of old, metal-rich stars in the thin disk, near the Sun.

The effect of unresolved binarity of some stars could also lead to distortion of their ages. The luminosities of unresolved close binaries calculated from their trigonometric parallaxes are higher than their true values [31]. Therefore, the derived ages of such stars that have not yet reached their turn-off point will be overestimated, while younger stars at the same temperature will be located above this point. Our analysis showed that this effect is manifest for stars that have not yet passed their turn-off points, but induces an age distortion of no more than two billion years, which is less than the upper limit to the age uncertainties adopted here. Nevertheless, we separated out binary candidates in our sample using the criterion proposed in [32]. These comprised about 20% of our stars, but the age-metallicity diagram constructed for the remaining single stars remained virtually unchanged, and we therefore do not present this diagram here.

We can also verify whether all metal-rich stars are, in fact, young using an independent statistical age indicator – the stellar kinematics. We compare the distributions of the velocities relative to the local standard of rest for metal-rich ([Fe/H] > 0.0) and metal-poor ([Fe/H] < −0.3) thin disk stars in our sample from [7], having first separated out very young (t < 2 billion years) and very old (t > 5 billion years) stars. The Table presents the corresponding data. Comparisons show that the parameters of the velocity distributions for stars of the same age but different metallicities are very similar. At the same time, old stars display mean values and residual velocity dispersions that are a factor of 1.5–2 higher than those for young stars. This suggests that the discussed metal-rich stars do indeed have similar ages to old, metal-poor disk stars. It is therefore important to verify whether old, metal-rich stars have migrated from regions closer to the Galactic center, where the mean metallicity is higher.

**INFLUENCE OF RADIAL MIGRATION OF STARS ON THE AGE–METALLICITY RELATION**

It is shown by Roskar et al. [20] (theoretically) and Haywood [18, 19] (based on stars near the Sun) that the joint action of radial migration of stars due to relaxation effects and the negative radial metallicity gradient in the Galactic disk lead to the large metallicity dispersion observed for nearby stars, which, in turn, masks any age–metallicity relation that may intrinsically be present in these stars. According to modern concepts, a star born from the interstellar medium initially moves in a circular orbit. The eccentricity of the orbit increases with time due to interactions with the perturbations associated with the gravitational potential of the Galaxy. However, it is believed that the mean radii of the stellar orbits remain virtually unchanged, reflecting the Galactocentric distances where the stars were born [4, 32]. Therefore, explaining the comparatively high orbital eccentricities of supermetallic stars ([Fe/H] > 0.2), Grenon [32] proposed that they had migrated toward the region of the Sun from distances closer to the Galactic center. Such stars should be fairly old, to allow time for the eccentricities and apogalactic radii of their orbits to appreciably change. It is also thought that metal-poor stars currently near the Sun, on the contrary, were born at larger Galactocentric distances, where the star-formation rate is lower. Let us determine how the diagrams for stars with various mean orbital radii will appear.
Metallicity–Age Relation for Thin-Disk Stars Born at Different Galactocentric Distances

To better visualize the differences between age-metallicity sequences for stars with different $R_m$ values, Fig. 4 shows only the third-order polynomial fits for the corresponding diagrams. (The polynomials are preferable to the mean points constructed in Fig. 2 in this case, since they better trace the mean dependences when there are a small number of stars in the sample, and are not subject to random excursions; in the presence of sufficiently good statistics, the polynomial fit and set of lines joining the mean points essentially coincide.)

We first separated the stars in our sample of thin-disk stars within 70 pc of the Sun into two groups, with mean orbital radii larger and smaller than the solar value. We then separated the latter group (which contained more than twice as many stars as the former group) into two roughly equal groups in orbital radii divided by the value $R_m = 7.6$ kpc (a maximum in the $R_m$ distribution for the disk stars is observed at this value). Moreover, we distinguished another group with approximately solar orbital radii ($7.9 < R_m < 8.1$) kpc.

Figure 4 shows that the age-metallicity relations for all the groups are similar within the uncertainties. However, with increase in the mean orbital radius, their positions drift in a non-uniform way – the sequences for both groups of stars with orbital radii smaller than the solar value become higher, while remaining similar to each other, and even cross each other. This behavior can be explained if stars with increasingly higher eccentricities end up in the vicinity of the Sun as the difference between their mean orbital radius and the solar Galactocentric distance increases; these stars with higher eccentricities, in turn, include an increasingly higher fraction of stars that are older and more metal-rich. At radii $R_m < R_\odot$, two opposite effects act in the thin disk – the negative radial gradient of the metallicity and the decrease in the metallicities of stars with increasing age (at least over the past several billion years; see below for more detail). At $R_m > R_\odot$, these two effects act in the same sense. (This gives rise to a break in a plot of the mean orbital radius versus metallicity, as is discussed in [12, 14].)

Age-metallicity Diagram for Stars Born near the Solar Circle

Figure 5 presents an age-metallicity diagram for thin-disk stars located within 70 pc of the Sun and having mean orbital radii ($7.7 < R_m < 8.4$) kpc. When determining the sizes of this range, we were guided by the following considerations. First, the variation of [Fe/H] within this range due to the radial metallicity gradient should be substantially less than the uncertainty in this quantity. For the usually adopted value of the gradient $grad_{R_m}[Fe/H] \approx -0.1$ (see, for example, [33]), the difference in the metallicities at the edges of this range are smaller than the metallicity uncertainties cited in [7]. Second, to obtain as large a sample volume as possible, we tried to approach as closely as possible to the maximum in the stellar distribution for our initial sample in mean orbital radius, observed at $R_m \approx 7.60$ kpc. We continued the interval somewhat further in the direction of increasing $R_m$, to improve the balance in the numbers of stars with larger and smaller orbital radii, since the number of stars falls off monotonically on either side of the maximum. On Fig. 5, as on Fig. 2, we plot the mean metallicities in narrow age ranges and third-order polynomial fits to the data. A comparison of the figures indicates that the age dependence of the metallicity remains virtually unchanged, and the metallicity scatter for stars of the same age has not decreased. As a result, neither old, metal-rich ([Fe/H] > 0.0) nor comparatively
young, metal-poor \((Fe/H) < -0.3\) stars from the sample fully disappeared. The small, hollow circles in Fig. 5 distinguish stars from the very narrow interval \((7.9 < R_m < 8.1)\) kpc, which show that, in any section of the diagram, the number of stars decreases roughly proportional to their initial number. The behavior of the mean \([Fe/H]\) values (solid curve in Fig. 5; see also Fig. 4) is essentially independent of the width of the interval in \(R_m\). In particular, for stars older than five billion years and for the total sample of stars within 70 kpc of the Sun, the mean values and dispersions of the metallicities for the subsample of stars with \((7.9 < R_m < 8.1)\) kpc essentially coincide, although the numbers of stars in these samples differ by more than an order of magnitude. In other words, the observed metallicity scatter is beyond the uncertainties for any age of star, even for stars born at the solar Galactocentric distance; however, the mean metallicity in roughly the last five billion years all the same changes with age. The upper and lower envelopes in the diagram (dashed lines) also demonstrate an increase in the metallicity with approach toward the current epoch.

We note one important property of the age distribution of the disk stars that is clearly visible in the age–metallicity diagram: the sharp increase in the density of stars of any metallicity passing through an age of \(\approx 4.5\) billion years toward younger ages. (Note that the distortion of the ages near three to five billion years noted above could shift the observed boundary for the sharp increase in the number of stars somewhat.) The predominance of thin-disk stars with ages < 5 billion years was already noted earlier (see, for example, [7, 19, 34]).

**AGE–METALLICITY AND AGE–RELATIVE Mg ABUNDANCE RELATIONS**

Thus, we see that none of the discussed effects is able to appreciably distort the general appearance of the age–metallicity diagram in Fig. 2a for F–G stars of the thin-disk subsystem located within 70 pc of the Sun. Nevertheless, let us trace the behavior of the age dependences of the mean metallicity and the metallicity dispersion constructed for the sample stars in the range \((7.7 < R_m < 8.4)\) kpc. We can see in Fig. 6a, where these quantities were calculated in ten narrow age bins, that the mean metallicities of thin disk stars born at the solar Galactocentric distance first decreases appreciably with increasing age, but then remains constant within the uncertainties and equal to \(\langle[Fe/H]\rangle \approx -0.19\) after four to five billion years. Figure 6b shows that the metallicity dispersion is initially virtually independent of age and equal to \(\approx 0.13\), but then begins to rapidly increase after four to five billion years, reaching \(\approx 0.22\) for the oldest stars.

**Use of Spectroscopic Fe and Mg Abundances**

Since the photometric metallicities of some stars could be distorted by unaccounted or systematic effects, it is necessary to also analyze the age–metallicity dependence based on stars with spectroscopic metallicities, \([Fe/H]_{sp}\). The corresponding diagram for stars within 70 pc of the Sun is presented in Fig. 7. Recall that the ages for these stars were taken from [7], where they were determined with somewhat different spectroscopic metallicities; however, as is shown by Fig. 1a, these differences are within the cited uncertainties in both catalogs. Note that unresolved binaries are clearly absent from this sample – otherwise, they would very likely be known as spectroscopic binaries. since the number of thin-disk
stars in the catalog is modest, we did not restrict the sample in the mean orbital radii of the stars, all the more so that, as we have demonstrated, this leaves the character of the age dependence of the mean metallicity essentially unchanged.

When comparing the positions of the stars in Figs. 5 and 7a, we must allow for selection effects in the sample with spectroscopic metallicities, including the fact that the depth of the survey increases appreciably with decreasing metallicity [24]. This means that the mean metallicity for thin-disk stars of this last sample with ages \( t > 4 \) billion years is somewhat lower than the value for the representative sample of thin-disk stars from [7]. Overall, the stars of the two samples occupy the same region in the age metallicity diagram (Fig. 2a). (As we noted above, this remains valid when independently determined ages are used; Fig. 2b.) Figure 7a shows that, as for the substantially larger sample, the mean values of \( \langle [Fe/H]_{sp} \rangle \) decrease systematically with increasing age, but remain unchanged within the uncertainties at ages exceeding four to five billion years. Thus, we conclude that features reflecting the relative metallicities of stars with different ages in spectroscopic and photometric age–metallicity relations coincide within the uncertainties.

To understand the origin of the complex behavior of the age–metallicity relation, it is also important to trace the age dependence of the relative abundance of \( Mg \) (a representative of the \( \alpha \) elements) for disk stars. Recall that, according to modern concepts, \( \alpha \) elements and a small number of Fe atoms are ejected by type \( II \) supernovae, whose evolution times before their explosions are about 10 million years. On the other hand, the main source of iron-peak elements is type \( Ia \) supernova explosions, which occur after a characteristic evolution time of \( \approx 1 \) billion years after the birth of the precursor star (see, for example, [35, 36]). Therefore, following a sudden onset of accelerated star formation in a stellar–gaseous system, the relative abundance of \( \alpha \) elements in the newly born stars could initially even increase somewhat; it should then systematically decrease after about a billion years due to the onset of an era of massive type \( Ia \) supernovae.

The age–relative \( Mg \) abundance diagram for thin disk stars within 70 pc of the Sun based on data from our catalog with spectroscopic \( Mg \) abundances is presented in Fig. 7b. Indeed, an inflection is observed in the middle of this relation. (Although the probability of erroneously rejecting the hypothesis that this relation can be fit by a straight line in favour of the third-order polynomial fit is rather high due to the small number of points, the existence of this inflection testifies to an appreciable difference between the mean ratios \( \langle [Mg/Fe] \rangle \) for stars younger than two billion years \( \langle [Mg/Fe] \rangle = 0.04 \pm 0.01 \) and older than four billion years \( \langle [Mg/Fe] \rangle = 0.11 \pm 0.01 \).) As a result, the mean relative abundance of \( Mg \) in stars of the thin disk, which is fairly high in the initial stages of its formation \( \langle [Mg/Fe] \rangle \approx 0.10 \) and is independent of the age within the uncertainties, began to appreciably more rapidly decrease with approach toward the current epoch starting several billion years ago. Unfortunately, the insufficient number of stars with spectroscopic relative \( Mg \) abundances and large age uncertainties hinders our ability to trace the behavior of the age dependence of this abundance in detail, and to statistically confidently identify the epoch of the onset of the more rapid decrease in the ratio \( \langle [Mg/Fe] \rangle \). However, comparison of the age–metallicity and age–relative \( Mg \) abundance diagrams shows that the decrease in the mean relative \( Mg \) abundance in thin-disk stars appears to have begun approximately three to four billion years ago, somewhat later than the increase in the mean metallicity. The observed decrease in \( [Mg/Fe] \) right to the current epoch testifies that, following the sudden burst of star formation, the rate of this decrease slowed somewhat, but always remained higher than before this burst.

THE CHEMICAL COMPOSITION IN THE THIN DISK
SCENARIOS FOR THE EVOLUTION OF THE CHEMICAL COMPOSITION IN THE THIN DISK

Thus, if we suppose that the mean orbital radii of stars indeed reflects the Galactocentric distances of their birth places, both the age [Fe/H] and age–[Mg/Fe] diagrams testify that, during the first several billion years of formation of the thin-disk subsystem, the interstellar material was, on average, fairly rich in heavy elements (⟨[Fe/H]⟩ ≈ −0.2), while the mean relative Mg abundance was only slightly higher than the solar value (⟨[Mg/Fe]⟩ ≈ 0.1). The dispersion of the heavy-element abundances were fairly large. The reason for this constancy of the mean heavy-element abundance and its large dispersion in the newly born stars is likely a low star-formation rate, together with a continuous raining of metal-poor interstellar matter from outer parts of the Galaxy onto the disk. However, approximately four to five billion years ago, the mean metallicity began to systematically increase, while the mean relative Mg abundance began to decrease slightly later. This probably occurred due to a sudden increase in the star-formation rate in the thin disk, which is confirmed by the substantial increase in the number of stars beginning approximately from this age. As a result of continuous mixing of the interstellar medium, the high dispersion of the metallicity at the epoch of formation of the first thin-disk stars (σ[Fe/H] ≈ 0.22) systematically decreases during the first several billion years of the formation of this subsystem. However, four to five billion years ago, the onset of a burst of star formation stopped this process, and the metallicity dispersion subsequently remained constant right to the current epoch (σ[Fe/H] ≈ 0.13).

In this picture, like the high mean metallicity of stars in early stages of the formation of the thin disk subsystem, the existence of metal-rich old stars can be explained by the fact that, in a strongly inhomogeneous interstellar medium in terms of its metal content, star formation proceeds more intensively in clouds with enhanced heavy-element contents. This simultaneously testifies to the fact that the main enrichment in metals in the Galaxy occurred in previous stages in its evolution, whereas this enrichment was modest in the thin-disk stage and has been appreciable only over the last four to five billion years. This provides further support for the existence of a prolonged interval in which star formation was suppressed (an active phase in the evolution of the Galaxy), between the formation of the main mass of stars in the thick and thin Galactic disks [29, 30].

It is interesting that the epoch ≈ 4 billion years ago (redshifts of z ≈ 0.4) appears to have been special in a more general sense in the Universe. A massive "transformation" of spiral into lenticular galaxies is observed in galaxy clusters roughly at this epoch: while spiral galaxies dominate (70%) in clusters at z > 0.5, they almost disappear after z < 0.4, when the dominant population becomes lenticular galaxies [37–39]. At approximately the same time, nearly all of the most massive spheroidal and elliptical dwarf galaxies in the Local Group displayed bursts of star formation (see, for example, [40, 41]). These facts suggest that our Galaxy, which had previously been isolated, became one of the central galaxies in the Local Group about four billion years ago. The outer gaseous halo of the Galaxy probably fell into its center and disk due to tidal processes. (No fairly massive gaseous halo is currently observed in our Galaxy, although it is possible that such a halo existed before the Galaxy became a member of the Local Group.) It may be that precisely this event provoked an amplification of star formation in the thin disk of the galaxy, and also led to a cessation of the infall of metal-poor gas. This scenario is also in good agreement with theoretical modeling of the "clustering" of galaxies in groups of various mass, according to which the number of galaxy clusters with masses comparable to the
Local Group reaches saturation at $z \approx 0.4$ [42, Fig. 4].

This picture overall differs from those considered previously (see the Introduction), although all its features have been noted separated in earlier studies. Our preference for this model is due to the fact that, first, we have constructed the age–metallicity diagram here for the first time based on an essentially general collection of single F–G dwarfs located within 70 pc of the Sun; second, the number of stars belonging to the thick disk has been minimized in our sample; and, third, the results have been refined based on stars born at the solar Galactocentric distance. Unfortunately, the insufficient depth of the Geneva Copenhagen survey and limited trustworthiness of the stellar ages in the range 3.5 billion years hinder us from composing a sample large enough to trace the epochs of the onset of the sharp increase in the star formation rate at various distances from the Galactic center.

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Figure 1: (a) Comparison of photometric and spectroscopic metallicities. The hollow circles denote stars with ages exceeding five billion years. (b) Comparison of photometric and spectroscopic effective temperatures. The bold lines in (a) and (b) correspond to a perfect agreement between the compared quantities, while the thin lines show the results of linear fits. (c) Plot of effective temperature versus absolute magnitude. Small symbols show all stars from the input catalog, while hollow circles show stars with age uncertainties $\epsilon(t) < 3$ billion years.
Figure 2: Age–metallicity diagram for thin-disk stars with $\epsilon(t) < \pm 3$ billion years located within 70 pc of the Sun, from the catalogs (a) [7] and (b) [5] (crosses) and [11] (circles). The smooth curves are third-order polynomial fits of the $[Fe/H]$–age dependences for all stars in the samples of [7] (a) and [5] (b). The large hollow circles in (a) show the mean metallicities of stars within narrow age ranges; the broken dashed lines show the upper and lower 5% envelopes; the sloped dashed lines show theoretical isotherms for $T_{\text{eff}} = 7000$ and 5800 K; the small hollow circles show stars with spectroscopic $[Fe/H]$ values from [24] and ages from [7]. The small number of stars with ages greater than 12 billion years are not shown on the diagram.
Figure 3: Plot of $T_{\text{eff}}$ versus $M_V$ for stars within 70 pc of the Sun in four narrow metallicity ranges (left) and temperature distributions for the same stars (right). The line segments on the histograms underscore the positions of sharp breaks in their high-temperature intervals. Theoretical isochrones from [17] whose turn-off points correspond to the positions of the breaks in the histograms are shown in the left-hand plots (solid curves); isochrones for a higher age are shown to the right of these for comparison (dashed curves). The ages of the isochrones are indicated (in years).
Figure 4: Dependences fit to the metallicity–age relation for thin-disk stars located within 70 pc of the Sun and having mean orbital radii $R_m < 7.6$ kpc, $(7.6 < R_m < 8.0)$ kpc, $(7.9 < R_m < 8.1)$ kpc, and $R_m > 8.0$ kpc. The drift in the position of the fit dependence with increase in the mean orbital radius, while preserving the general form of the trends, is clearly visible.
Figure 5: Age–metallicity diagram for thin-disk stars located within 70 pc of the Sun and having mean orbital radii of $(7.7 < R_m < 8.4)$ kpc. The notation is the same as in Fig. 2a. The small, hollow circles show stars with mean orbital radii $(7.9 < R_m < 8.1)$ kpc.

Figure 6: Age dependences of the (a) mean value and (b) dispersion of the metallicity for thin-disk stars within 70 pc of the Sun with mean orbital radii $(7.7 < R_m < 8.4)$ kpc. The bars show the uncertainties. The curve in the left panel shows a third-order polynomial fit.
Figure 7: (a) Age–[Fe/H] and (b) age–[Mg/Fe] diagrams for thin-disk stars located within 70 pc of the Sun with spectroscopic Fe and Mg abundances from [24] and age uncertainties $\epsilon(t) < \pm 3$ billion years. The curves show third-order polynomial fits.