

STAR FORMATION HISTORY IN THE GALACTIC THIN DISK

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ABSTRACT. We analyze the relations between the relative magnesium abundances in stars, $[\text{Mg}/\text{Fe}]$, and their metallicities, Galactic orbital elements, and ages. The relative magnesium abundances in metal-poor thin-disk stars have been found to systematically decrease with increasing stellar orbital radii. 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 ($\text{grad}_R[\text{Fe}/\text{H}] = (-0.05 \pm 0.01) \text{ kpc}^{-1}$) in the disk. At the same time the relative magnesium abundance exhibits no radial gradient. We discovered that in the thin disk there is not only the connection between age and metallicity, but between age and relative magnesium abundance also. It is in detail considered the influence of selective effects on the form of both age – metallicity and age – relative magnesium abundance diagrams. It is shown that the first several billion years of the formation of the thin disk interstellar medium in it was on the average sufficiently rich in heavy elements. At the same time the relative magnesium abundance exhibits no radial gradient. We discovered that in the thin disk there is not only the connection between age and metallicity, but between age and relative magnesium abundance also. It is in detail considered the influence of selective effects on the form of both age – metallicity and age – relative magnesium abundance diagrams. It is shown that the first several billion years of the formation of the thin disk interstellar medium in it was on average sufficiently rich in heavy elements ($\langle[\text{Fe}/\text{H}]\rangle \approx -0.22$), badly mixed ($\sigma_{[\text{Fe}/\text{H}]} \approx 0.21$), and the average relative magnesium abundance was comparatively high ($\langle[\text{Mg}/\text{Fe}]\rangle \approx 0.10$). Approximately 5 billion years ago average metallicity began to systematically increase, and its dispersion and the average relative magnesium abundance – to decrease. These properties may be explained by an increase in star formation rate with the simultaneous intensification of the processes of mixing the interstellar medium in the thin disk,

provoke possible by interaction the Galaxy with the completely massive galaxy-satellite.

Key words: Galaxy (Milky Way), stellar chemical composition, thin disk, Galactic evolution.

The chemical composition of low-mass main-sequence stars can be used to estimate the star formation rate and as the time scale of a chemically evolving closed system. Thus, for example, the α -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 progenitors of type II supernovae, while the bulk of the iron-group elements are produced during type Ia supernova explosions. Beginning from the paper by Tinsley (1979), the negative trend in the $[\alpha/\text{Fe}]$ 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 supernovae is only ≈ 30 Myr while low massive SNe Ia explosions begin only in $\approx (0.5 \div 1.5)$ Gyr. 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 $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$ relation. The lower the star formation rate in the system, the steeper the further decrease in the $[\alpha/\text{Fe}]$ ratio with increasing total metallicity. If star formation in the system is halted altogether then the source of α -elements (i. e., SNe II) will vanish and only SNe Ia will enrich the interstellar medium with iron-group elements; therefore the $[\alpha/\text{Fe}]$ ratio will decrease suddenly.

Since more than 90% of the stars in the immediate solar neighborhood belong to the youngest (in the Galaxy) thin-disk subsystem, 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.

Since the published results disagree, analyzing the relations between the relative abundances of α -elements and metallicity and other parameters of thin-

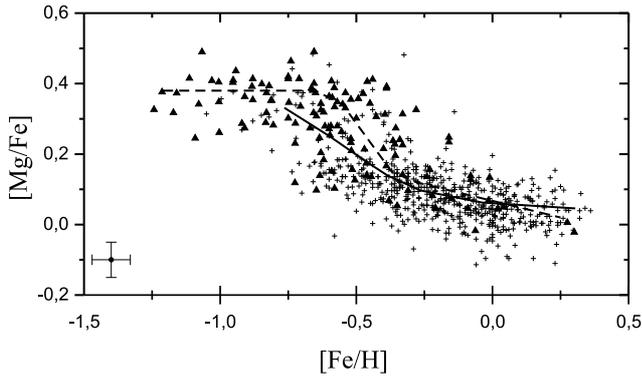


Figure 1: Relation between metallicity and relative magnesium abundance for the stars of both disk subsystems: the crosses and triangles indicate the thin-disk and thick-disk stars, respectively. The broken curves represent the median lines of the relations for the thin (solid line) and thick (dotted line) disks drawn by eye halfway between the upper and lower envelopes. The error bars are shown

disk stars based on a much larger statistical material seems very topical. At the beginning of this work we analyze the chemical properties of thin-disk stars using data from our compiled catalog of spectroscopically determined magnesium abundances (Borkova and Marsakov 2005). 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 our 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 for 867 stars using a three-pass iterative averaging procedure with a weight assigned to each primary source and each individual determination.

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 kinematical criteria. The technique for identified the stars for which the probabilities of belonging to the thin disk is higher than the probability of belonging to the thick disk based on the dispersions of the space velocity components and the mean rotational velocity of both subsystem at the solar Galactocentric distance was taken from Bensby et al. (2003).

Figure 1 shows the $[Fe/H]$ – $[Mg/Fe]$ diagram where the thin-disk and thick-disk stars are denoted by different symbols. 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. This suggests that the bulk of the thick-disk stars formed long before the onset of massive star formation in the thin disk. The $[Mg/Fe]$ ratio begins to decrease with

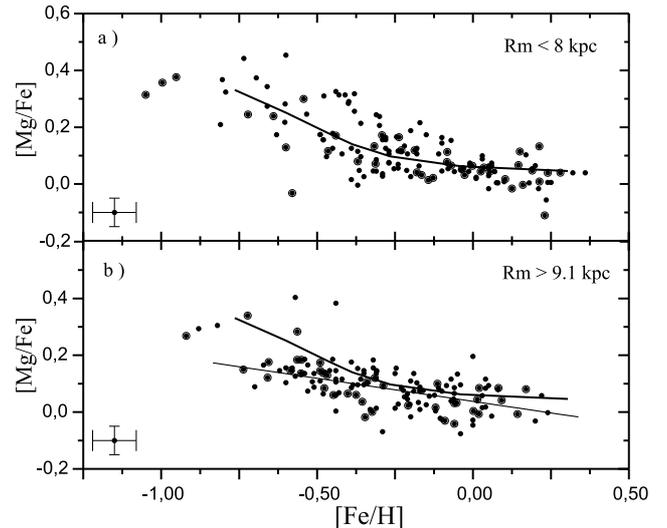


Figure 2: Relation between metallicity and relative magnesium abundance for the thin-disk stars in two ranges in mean orbital radii $R_m < 8$, and > 9.1 kpc. The broken curves in all panels represent the median curve for the thin disk. Thin line in panel (b) – straight regression for stars with $[Mg/Fe] < 0.2$. Is evident the decrease of the relative abundance of magnesium in the metal poor ($[Fe/H] < -0.4$) stars with an increase in the radii of the orbits.

increasing metallicity in the thin disk immediately after the formation of the first stars in it, i.e., from $[Fe/H] \approx -1.0$. 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 $[Fe/H] \approx 0.5$. 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 ≈ -1.0 dex to ≈ -0.7 suggests that the star formation rate in it was initially low but it then suddenly increased, which subsequently led to a attending of the $[Fe/H]$ – $[Mg/Fe]$ relation. Subsequently when passing to stars with metallicities higher than the solar value, the slope of the $[Mg/Fe]$ – $[Fe/H]$ relation virtually vanishes, which is indicative of a new increase in the star formation rate and stabilization of the ratio of the contributions from supernovae (SN II/SN Ia) to the enrichment of the interstellar medium in the thin disk since then.

Let us now verify whether the positions of the thin-disk stars in $[Mg/Fe]$ the $[Fe/H]$ – $[Mg/Fe]$ diagram depend on their mean orbital radii? Figure 2 shows two diagrams for the thin-disk stars with low ($R_m < 8$ kpc) and large ($R_m > 9.1$ kpc) orbits. Our median se-

quence is plotted in both diagrams. We see from the figure that only the stars with smallest mean orbital radii in Fig. 2a closely follow our median curve at $[Fe/H] < -0.4$ dex. However at the largest distances, the $[Mg/Fe]$ – $[Fe/H]$ relation is almost linear (see the dashed line in Fig. 2b). 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. 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.

Our interpretation was constructed on the suggestions that metallicity is good statistical age indicator in the thin disk. Indeed, lifetime of the thin disk is compared with the Galactic age, therefore the continuous process of the synthesis of chemical elements must lead during this period to a noticeable increase in the general abundance of heavy elements in the younger stars of subsystem. As a result in the thin disk the well expressed trend of metallicity from the age must be observed. However, in spite of the large history of the study of this question, in regard to this there is no unanimous opinion. Twarog (1980) was the first to derive the age–metallicity relation in the Galactic disk from F2–G2-stars 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. This gave reason to suggest that there was no age–metallicity relation in the thin disk. The purpose of this work is the thorough analysis of possible selective effects on the age–metallicity diagram with the attraction together with photometric data of the spectroscopic determinations of the iron and magnesium abundances for the main sequence stars over a wide range of spectral classes. For investigation we used Geneva-Copenhagen Surveu (Nordström et al. 2004), where on the data uvby β photometry, and Hipparcos parallaxes

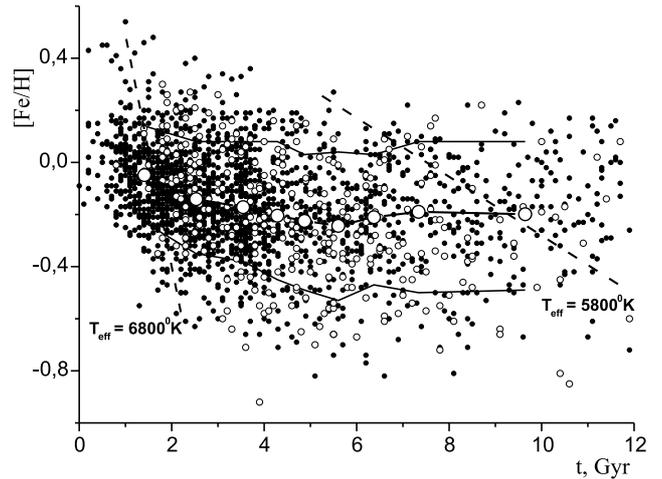


Figure 3: Age – metallicity diagram for the thin-disk stars from the catalog (Nordström et al. 2004) with $(\varepsilon t > \pm 3$ Gyr), which lie nearer than 70 pc of the Sun. Large open circles connected by linear segments are the average values of the metallicity of stars in the narrow age ranges; broken lines - upper and lower ten-percent envelopes; inclined broken lines – theoretical isotherms for $T_{\text{eff}} = 6800$ and 5800 K; the small open circles – star with the spectroscopic determinations $[Fe/H]$ from the catalog (Borkova, Marsakov, 2005).

were determined temperature, metallicity, distance, absolute magnitude, and ages for about 14000 nearest F-G-K stars. The most probable ages was calculated on the base of Padova theoretical isochrones, using the sophisticated interpolation method, and Bayesian computational techniques. After removing of the binary stars, marked in the catalog, far evolving stars ($\delta M_V > 3^m$), and stars with uncertainly determined ages ($\varepsilon t > \pm 3$ Gyr), in the sample remained 5540 supposedly single stars of thin disk. (Total average error in determination of age for the stars of the received sample comprised $(\varepsilon t) = \pm 1.0$ Gyr.) In order to get rid of the selective effects, connected with a difference in the depth of survey for the stars of different metallicity and temperature, we limited sample with the distance from the Sun equal to 70 pc, within limits of which our sample can be considered complete for temperature range $(5400 - 7200)$ K°. In finally formed thus sample remained 1890 stars of the thin disk.

Figure 3 gives age – metallicity diagram for the thin-disk stars of our sample. The large opened circles in the figure put average values of the metallicity of stars in nine narrow ranges on age. Upper and lower ten-percent envelopes are also constructed. From the figure one can see that among the old stars of Galactic disk is observed large spread in values $[Fe/H]$, whereas among the young stars the explicit scarcity of metal poor stars (empty left-hand lower corner on the diagram) is observed. (Nordström et al. 2004) explained

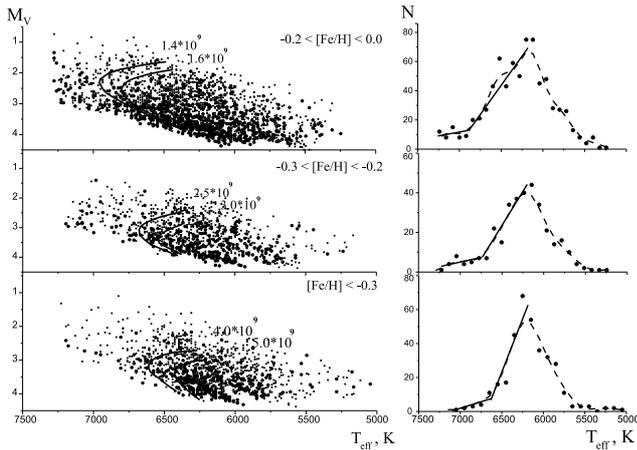


Figure 4: $T_{\text{eff}} - M_V$ diagrams for the metal-poor stars lying within 70 pc from the Sun into narrow ranges on the metallicity (to the left) and distribution the number of stars depending on temperature for the same diagrams (to the right). Broken dotted lines on the histograms - smoothed on three points trends with the sliding averages, linear segments emphasize the positions of sharp fractures on the left boundaries of distributions. On left panels are substituted theoretical isochrones from works (Demarque et al., 2004), which correspond to the positions of fractures on the histograms (for comparison the isochrone of larger age are substituted more to the right them). The ages of isochrones are indicated.

this by the effect of the limitation of their catalog from the high-temperature side on the index ($b - y$). In this case, in their opinion, the difference at the ages of the metal rich and metal poor stars of the same temperature just also provides observed inclination of lower envelope on the diagram. Let us verify this statement.

In Fig. 4 at the left the $T_{\text{eff}} - M_V$ diagrams for the stars lying within 70 pc from the Sun into three narrow ranges on the metallicity are given. On the right for the same diagrams the distributions of number of stars depending on temperature are constructed. Broken lines on the right panels represent trends, smoothed on three points, and linear segments schematically designate the behavior of the left boundaries of distributions. It is seen that all metal poor groups ($[Fe/H] < 0.0$) demonstrate the sharp inflection envelope, when more to the right "inflection points" the number of stars abruptly increases. It is interesting that the temperature value of these points for all metal poor groups are far from the left edge of the diagrams. This means that the sharp scarcity of hotter (so also younger) stars in the metal poor groups is connected not to high-temperature limitation of sample but with existence of minimum age for the majority of the stars of given metallicity in the thin disk, i. e., with existence of "turnoff points" in the metal poor stars of field. On the

left panels of figure the theoretical isochrones, passing through those isolated on the right panels "inflection points", are carried out according to the data of work (Demarque et al., 2004). For the comparison are more to the right are everywhere substituted the isochrones of larger age

The effect of the limitation of sample from the high-temperature side, which it is discussed in the work (Nordström et al. 2004), also somewhat distorts real age - metallicity diagram. In figure 3 the dash inclined line is conducted on the basis of the theoretical isochrones for $T_{\text{eff}} = 5800$ K. This line corresponds to boundary, more to the right of which stars, hotter this temperature, cannot be - they have left from the main sequence already. (Let us note that precisely the limitation of sample from the low-temperature side with approximately Solar value of temperature (see the dash inclined line in the upper right-hand corner in the diagram) led to the exception of the oldest metal rich stars from the sample (Twarog, 1980), which caused his conclusion about a monotonic increase of the metallicity with the age in the thin disk.)

However, as can be seen from the diagrams, not this line, which intercepts an entirely small quantity of very young metal poor stars, but relative numbers of stars of different metallicity with the identical age determine the variation of average metallicity on the age. Note that lower envelope in Fig. 3 in the range ($1 < t < 4$) Gyr practically coincides with left envelope of diagram. This means, that lower envelope reflects the variation of the "turnoff points" position of the stars of this metallicity on the age. As a result we see that "turnoff points" of metal poor stars are located in the middle of the temperature range, occupied by the stars of the sample, i. e., they are not connected with the action boundary selective effect.

To the distortion of the ages of stars can lead also the effect of their unresolved binary. Actually, the luminosities of the unresolved close binaries, calculated from the trigonometric parallaxes, are more than true (Suchkov, 2000). As a result the ages of stars not yet reached their turnoff point will be overestimated, whereas higher than it are located ever younger stars at an identical temperature. We isolated in our sample candidates into the dual according to the criterion, proposed in latter work. Such proved to be about 20%, but constructed for the remained single stars age - metallicity diagram demonstrated that its form practically did not change.

Despite the fact that the position of a sufficiently large quantity of stars with the solar metallicity on the Hertzsprung - Russel diagram indicates their large ages, in the work (Pont, Eyer, 2004) existence of old metallic stars undergoes doubt.

Therefore let us verify, actually whether some metal rich stars are actually old? It is possible to do on the independent statistical indicator of age - kinematics.

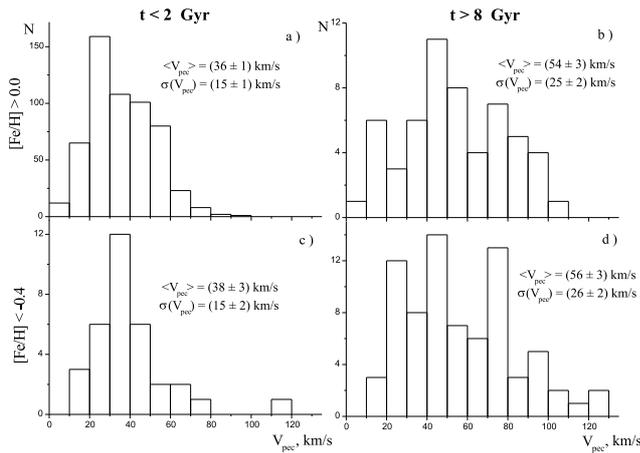


Figure 5: Distributions on peculiar velocities of metal-rich and metal-poor stars of different age. The corresponding values of average velocities and their dispersions are indicated on the panels. It is seen the coincidence of histogram of similar age.

For this let us compare peculiar velocities distributions of metal rich ($[Fe/H] > 0.0$) and metal poor ($[Fe/H] < -0.4$) thin-disk stars, preliminarily isolate among them very young ($t < 2$ Gyr) and very old ($t > 8$ Gyr) star. The indicated histograms are given in Fig. 5. Comparison shows that the distributions of the stellar velocity of identical age, but different metallicity, are very similar. In this case old stars demonstrate one and a half times higher in both the average values and dispersions of peculiar velocities than young stars (see inscription on the appropriate panels). This behavior makes it possible to assert that the some metal rich stars have actually very large age.

We assume that none of the selective effects the known to us cannot substantially distort the common form of age – metallicity diagram in Fig. 3 for the sample of F-G stars in the 70 pc of the Sun. Therefore let us trace the behavior of the dependences of average value and dispersion of metallicity from age, constructed on the basis of these data. From Fig. 6 a, where the corresponding values were calculated in 9 narrow bins from the age, can be seen that at first average metallicity noticeably decreases with an increase in the age, and after ≈ 5 Gyr it remains practically constant and equal to $\langle [Fe/H] \rangle = -0.22$. (Local minimum in the environment of 5 Gyr is most likely connected with the special features of the age determination procedure in the work (Nordström et al. 2004).) Dispersion of metallicity, as can be seen from Fig. 6 b, always monotonically increases from 0.16 to 0.21; however, after ≈ 5 Gyr this increase significantly slows down.

Photometric metallicity in some stars can be distorted by the disregarded systematic effects; therefore it is necessary to investigate age – metallicity dependence, also on the stars of our catalogue with the spec-

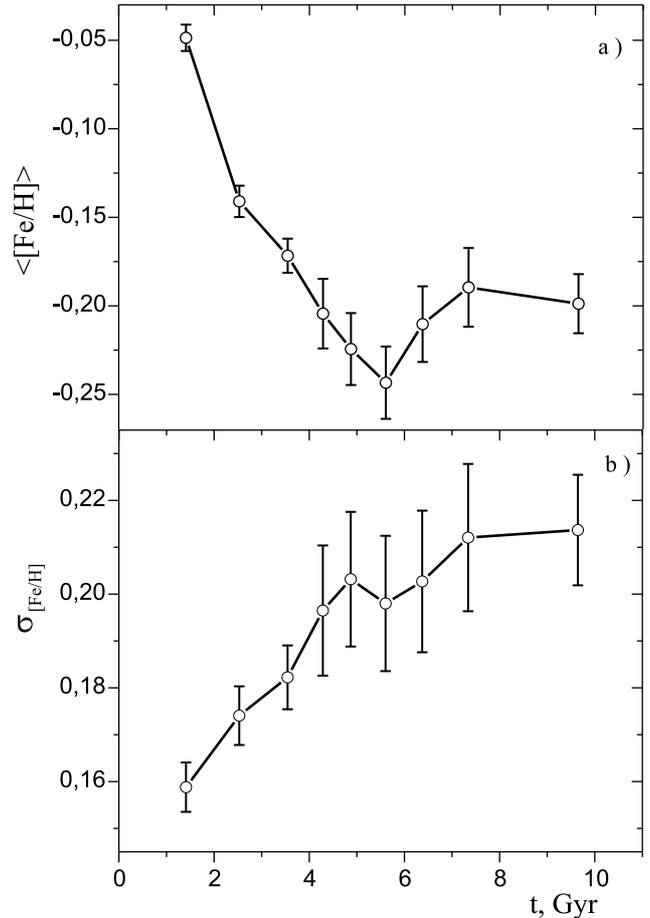


Figure 6: Dependences of average value (a) and dispersion of metallicity (b) from the age for the stars of thin disk in the 70 pc of the Sun from the catalog (Nordström et al. 2004). Bars are error in determination of the corresponding values.

troscopic determinations of $[Fe/H]$ (see the small open circles in Fig. 3). Let us note that in this sample the unresolved binaries deliberately be absent – otherwise they with the great probability would be known as spectrally binaries. Let us recall that since the number of stars here is not very great, we left all stars of thin disk in the sample. It is seen that on this diagram be absent very metal rich ($[Fe/H] > 0.3$) star – the apparently photometric “super-metallicity” of these stars actually is explained as an artifact of the deredding procedure for distant stars as this predicted in the work (Nordström et al. 2004). In other respects the form of diagram practically did not change. From Fig. 7 a we see that age – metallicity relation, constructed on the stars of catalog with the spectroscopic determinations of $[Fe/H]$, demonstrates the same behavior.

For understanding of the reason for such complex behavior of age – metallicity dependence it is important to trace the dependence of the relative content of magnesium on the age among the disk stars. Age –

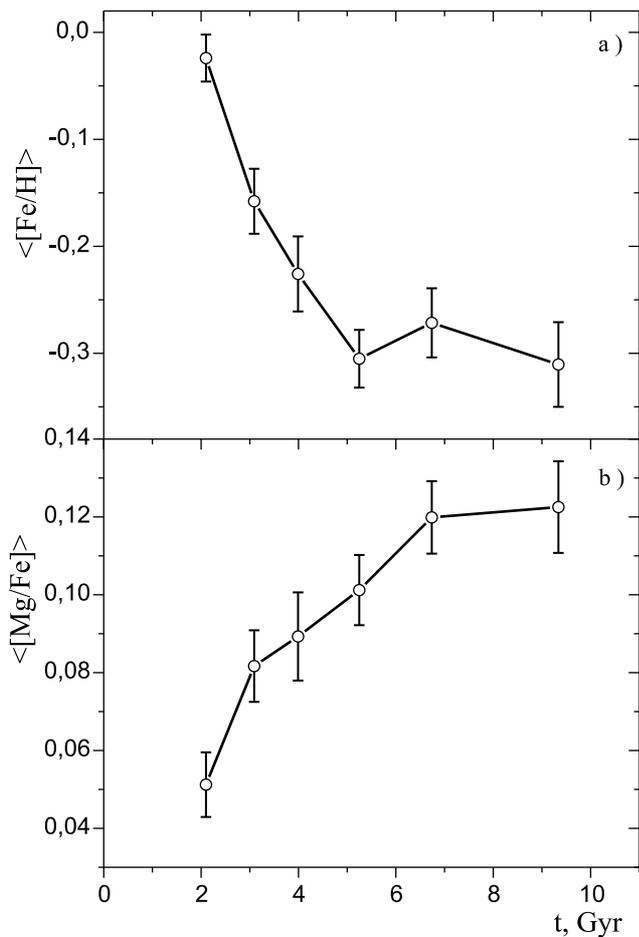


Figure 7: Dependences of average values $\langle [Fe/H] \rangle$ (a) and $\langle [Mg/Fe] \rangle$ (b) from the age for the thin-disk stars with the spectroscopically specific abundances of iron and magnesium from (Borkova, Marsakov, 2005). Bars are error in determination of the corresponding values.

magnesium abundance diagram itself according to the data of our catalog is given in Fig. ?? [b] in the work (Marsakov, Borkova, 2006), here in Fig. 7b is represented only the variation of the relation $\langle [Mg/Fe] \rangle$ from the age. From the Fig. 7b one can also see that, as in the case the connection between the age and the metallicity, bend is observed in the middle of the dependence between relative magnesium abundance and age. Bend evidences that the relative magnesium abundance in the thin-disk stars of being in the subsystem formation initial stages was sufficiently high ($\langle [Mg/Fe] \rangle \approx 0.10$). About 5 billion years ago it began to sharply decrease with the approximation to the present time. Thus, taking into account the uncertainty of the estimations of average values, we can assert that an increase in the average metallicity and the decrease of the average relative magnesium abundance in the stars of thin disk began simultaneously.

Thus components, confidently revealing on both $t - [Fe/H]$ and $t - [Mg/Fe]$ diagrams, testify that into the

first several billion years of the formation of the thin-disk subsystem interstellar medium in it was, on average, sufficiently rich in heavy elements ($\langle [Fe/H] \rangle \approx -0.20$) and is badly mixed ($\sigma_{[Fe/H]} \approx 0.21$), and the average relative abundance of magnesium was comparatively high ($\langle [Mg/Fe] \rangle \approx 0.10$). Approximately 5 billion years ago the average metallicity began to increase, and the dispersion of metallicity and the relative magnesium abundance – to decrease. This occurred as a result sharply increased rate of star formation and making more active of the processes of mixing to the interstellar medium. By the possible reason for this could be interaction of the Galaxy with the completely massive satellite galaxy.

Thus, not all stars of the thin disk, which are at present located in the Solar neighborhood, were formed from the matter, which experienced united chemical evolution. We suppose that the difference in the star formation rate at the different galactocentric distances and sporadic fall out to the disk of gas from the exteriors of the Galaxy led to the ambiguity of dependence between the age and the metallicity in the so long-life subsystem.

The complete description of the first part of this work was published in (Marsakov, Borkova, 2006), but the second part will be published latter.

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