Inconsistency of Chemical Properties of Stellar Populations in the Thick Disk Subsystem of Our Galaxy

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Abstract

Using modern published data on velocities and spectroscopic definitions of chemical elements in stellar objects of the Galaxy, we investigated the relationship of chemical composition with the kinematics of different populations. The paper shows that the old stellar populations of the Galaxy, belonging (by the kinematic criterion) to the thick disk subsystem—globular clusters, field variables of the type RR Lyrae (lyrids), as well as close F-G dwarfs and field giants, have different chemical composition. In particular, the dwarfs and giants of the field are on average more metallic than the globular clusters and lyrids of the field. Moreover, the relative abundances of α-elements in the range \([\text{Fe/H}] > -1.0\) are the highest for globular clusters, and are the lowest for field variables of the RR Lyrae type. Based on the analysis of the nature of the dependences of \([\alpha/\text{Fe}]\) on \([\text{Fe/H}]\) for these objects it was suggested that the thick disk subsystem in the Galaxy is composite and at least three components exist independently within it. The oldest one includes metal-rich globular clusters that formed from a single proto-galactic cloud shortly after the start of type Ia supernovae outbursts. Then the subsystem of field stars of a thick disk was formed as a result of “heating” of stars of already formed thin disk of the Galaxy by a rather massive dwarf satellite galaxy that fell on it. And finally, subsystems of field stars with the kinematics of not only a thick, but even a thin disk that fell on the Galaxy from this captured satellite galaxy.

Key words: Galaxy: structure–globular clusters: general–stars: variables: RR Lyrae.

1 Introduction

As far back as the fifties of the last century, it was noticed that metal-rich globular clusters occupy a relatively small volume near the center of the Galaxy, while metal-poor clusters are found in a much larger space of the galactic halo (see, for example, Kinman 1959; Morgan 1959). The discussion continued for several decades: are metal-rich clusters representatives of the disk subsystem of the Galaxy, or is there simply a negative radial gradient of metallicity in the spherical galactic halo? It should be said that in those years both the distances and the metallicities of the clusters were determined with great uncertainties. The existence of yet another subsystem intermediate between the disk and spherical components was first discussed after the appearance of the catalog of globular star clusters (Kukarkin 1974) containing the characteristics of 129 objects reduced to a single system. An analysis of the catalog revealed a dip of the metallicity function of clusters in the vicinity of the value \([\text{Fe/H}] \approx -1.0\), dividing all clusters into two discrete groups (Marsakov and Suchkov 1976). Moreover, the metal-poor group turned out to be a spherically symmetric, slowly rotating halo subsystem, and the metal-rich group was a rather flat fast-rotating subsystem of the thick disk (Zinn 1985). Since then, metal-rich clusters continue to be considered as a separate subsystem, which was called the “thick disk”.

It turned out that the distribution of metals in field stars is also discrete, and among them it is also possible to distinguish an intermediate subsystem by dips on the metallicity function (Marsakov
and Suchkov 1977). As a result, metallicity has become a criterion for attribution of stellar objects to the Galaxy subsystems, since it is a statistical indicator of age. Indeed, in a closed star-gas system, which in the first approximation can be considered our Galaxy, the total abundance of heavy elements increases with time. According to observations, the oldest stellar objects in the Galaxy have the lowest metallicity, while stars of solar age—the greatest. Therefore, despite contemporary ideas about the formation of giant spiral galaxies, like our own, from the merging of several less massive ones in the early stages of evolution of the Universe (see standard cosmological model ΛCDM), the model of the monolithic collapse of a protogalactical cloud described in the classical model (Eggen et al. 1962) has not lost its relevance. It is clear that there is no single and sufficient criterion for stratification. To reliably assign an object to a particular subsystem, one should take into account many parameters characteristic of each subsystem, in particular, the position in the Galaxy, kinematics, metallicity, the abundance of various chemical elements, and age. There are no clear boundaries for the subsystems; therefore, their sizes can be estimated only approximately. Geometric boundaries imply certain values and dispersions of velocities of objects belonging to this subsystem. The use of kinematic parameters is considered the most reliable method of stratification of objects by subsystems. It is in this way that close field stars are divided into subsystems of the Galaxy. In particular, the technique described in Bensby et al. (2003) is widely used, when the probabilities of belonging of nearby field stars to subsystems of a thin and thick disks, or halo are calculated from the components of residual velocities. It is understood that the components of the spatial velocities of stars in each subsystem obey normal distributions. The average values of the velocity components, their dispersion, and the relative proportions of stars in each subsystem are set according to independent studies. The subsystems differ mainly in the velocity of motion around the galactic center: for a thick disk, it turns out to be intermediate between the corresponding velocities of a thin disk (approximately solar) and a halo (almost zero). For objects distant from the Sun, the velocity components must be in a cylindrical coordinate system, since in the rectangular coordinate system, the velocity components will be multidirectional with respect to the center and direction of rotation of the Galaxy, the values of which mainly determine their subsystems.

The mechanism of formation of the thick disk subsystem has long been a subject of discussion. The modeling of the structures of our Galaxy is based on the results of counting the field stars of both disk subsystems and studying their chemical composition. All the proposed scenarios for the formation of a thick disk can be divided into several categories, but all are in some way unsatisfactory. So, if a thick disk is formed during the collapse of a protogalactic cloud, then it will inevitably have a change in the relative abundance of \( \alpha \)-elements with an increase in the abundance of heavy elements (Prochaska et al. 2000). The difficulty of this representation is that the time of complete collapse of the proto-galactic cloud is much less than the characteristic time of evolution of pre-supernova SNe Ia. This discrepancy is easily avoided in another class of models, where the thick disk subsystem is formed as a result of the heating of the primary stellar thin disk due to the interaction of the Galaxy with a very close satellite galaxy (see Kroupa 2002). The problem with this model is to explain the existence of metal-rich globular clusters in the thick disk. They cannot heat as stars by the satellite galaxy and can arise only as a result of star formation accompanying this interaction (Gratton et al. 2000). Another mechanism for the formation of the subsystem involves the capture of small dwarf satellite galaxies and getting their stars in the thick disk (Abadi et al. 2003). The formation of a stellar thick disk inside our Galaxy is possible as a result of the so-called ”wet merging” with a satellite, with a large amount of interstellar matter and the accretion of its gas (Brook et al. 2004). Finally, a thick disk could be produced from field stars simply because of the radial migration of thin disk stars (see Schönrich and Binney 2009). Unfortunately, as noted above, people try to explain the origin of the thick disk, taking into account the detailed chemical composition, only for stationary stars of the galactic field, whereas for globular clusters and field variable stars of the type RR Lyrae, such models do not take into account the features of the abundances of chemical elements in them.

This paper is a continuation of the study of chemical and spatial-kinematic properties of globular clusters and the field variables of the RR Lyrae type, started in Marsakov et al. (2018, 2019b,c). In
them, we, in particular, showed that the kinematics of both types of objects do not combine well with metallicity, therefore, to separate thick-disk objects from halo, we should be guided for clusters by a dip, and for field lyrids—by a knee of their metallicity functions in a neighborhood of \( [\text{Fe}/\text{H}] \sim -1.0 \). Here we will compare the chemical composition of globular clusters and two types of field stars (close F and G dwarfs and giants and stars of the type RR Lyrae), identified as a thick disk subsystem by the kinematic criterion.

2 BASIC DATA

To analyze the behavior of certain chemical elements in globular clusters, we took metallicity from the computer version of the compilation catalog (Harris 2010), spectroscopic determination of the abundance of iron and the relative abundances of two \( \alpha \)-elements — titanium and calcium — from our compilation catalog (Marsakov et al. 2019c). The components of spatial velocities for stratification by galactic subsystems of 115 clusters, defined by Chemel et al. (2018) according to modern catalogs, are given in Marsakov et al. (2019b). Analogous data, as well as the relative abundances of one element of slow neutron capture (yttrium), for 100 field variable stars of the type RR Lyrae are taken from our catalog described in Marsakov et al. (2018). For comparison, we used the catalog from Venn et al. (2004), which shows metallicity, relative abundances of \( \alpha \)-elements, s-elements and components of spatial velocities for 785 stars of the galactic field in the entire range of metallicity of interest to us, as well as the catalog in Bensby et al. (2014), which abundances similar data for 714 F–G dwarfs and giants of the field, belonging mainly to the disk subsystems of the Galaxy, that is, to the sample of very few metal-poor stars. The errors of the averaged relative abundances of two \( \alpha \)-elements used in this paper are approximately the same for clusters and lyrids of the field: \( \langle \varepsilon[\text{Ca}, \text{Ti}/\text{Fe}] \rangle \approx 0.11 \), and the errors of the spatial velocity components are approximately 17 km s\(^{-1}\) (for details, see Marsakov et al. 2018, 2019b).

Fig. 1a,b shows the metallicity functions of globular clusters and field variables of the type RR Lyrae and, for comparison,— two samples of nearby field stars (1c,d). Within each distribution, the histograms of the same objects that kinematically fall into the thick disk subsystem are highlighted in darker color. For more information on the separation of our field lyrids and globular clusters to the subsystems of the Galaxy, see Marsakov et al. (2018, 2019b). Despite the fact that the method of stratification of all objects is the same (that is, the components of the residual velocities of all objects fall into the same ranges, the values of which are set in advance), there is a difference in the metallicity distributions between different objects caught in a thick disk. The difference between field stars and older objects — globular clusters and field stars of the type RR Lyrae is mainly noteworthy. From Fig. 1 it is seen that all field stars (except the lyrids) are on average more metallic. So, if the field stars of the thick disk have average metallicities \( [\text{Fe}/\text{H}] = -0.58 \pm 0.04 \) and \( -0.44 \pm 0.03 \) according to Venn et al. (2004) and Bensby et al. (2014) respectively, for clusters and field lyrids they are an order of magnitude smaller — \( \langle [\text{Fe}/\text{H}] \rangle = -1.16 \pm 0.11 \) and \( -1.39 \pm 0.04 \) respectively. Moreover, whereas in globular clusters, the objects with the kinematics of the thick disk fairly uniformly fill the entire range of metallicity, the field lyrids show a confident maximum in the region of \( [\text{Fe}/\text{H}] \sim -1.3 \). In close field stars, this maximum is observed at a much higher metallicity — \( [\text{Fe}/\text{H}] \approx -0.4 \). Let’s consider the difference in the chemical composition of different objects in more detail.

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1 Actually, the dip in globular clusters is located at a slightly higher metallicity (see Borkova and Marsakov (2000)), but its more convenient to accept this round number used commonly.

2 http://vizier.u-strasbg.fr/viz-bin/VizieR? -source=J/AZh/95/54

3 Note that the maxima of distributions in field stars of the thick disk have slightly higher metallicity than the average values due to long low-metal “tails”.
The results of Marsakov et al. (2019b,c) show that the kinematic method of stratification is hardly suitable for globular clusters of our Galaxy, since the clusters of different subsystems selected by kinematics radically differ in chemical properties from the field stars of the same galactic subsystems. In particular, all metal-rich ([Fe/H] > −1.0) clusters that belong, according to the kinematic criterion from Bensby et al. (2003), to different subsystems, are within rather restricted limits with respect to the center and plane of the Galaxy. But in the range of less metallicity among clusters with kinematics of the thick disk there are also objects quite distant from the galactic plane, not to mention clusters with kinematics of the halo. At the same time, among the metal-poor clusters that belong, by kinematics, not only to the halo, but also to the thick disk, there is a large number of them lying far beyond the solar circle. This is reflected in the well-known negative radial and vertical metallicity gradients in the general population of globular clusters of the Galaxy. As a result, it turns out that the traditionally used procedure for separating globular clusters of the thick disk from halo clusters by metallicity is more acceptable (see the justification in Marsakov et al. 2019b,c).

Let us consider in more detail the chemical composition of globular clusters, kinematically related to different subsystems, based on the study of the relative abundances in globular clusters of only two α-elements — calcium and titanium, as the most informative for the diagnosis of the evolution of the early Galaxy. In the visible range of the spectrum, these two chemical elements have many lines, and their abundances are fairly reliably determined. The choice of these elements is due to the fact that the average relative abundances of the two primary α-elements — oxygen and magnesium — in the course of the evolution of a globular cluster are reduced in comparison with their abundances in the parent proto-clouds. And the abundances of another α-element — silicon — are defined for a smaller number of clusters and are not defined at all for the field stars from Venn et al. (2004), which we use for comparison. Although titanium, strictly speaking, is not exclusively an α-element and partially belongs to the iron peak elements produced in SNe Ia as well, its relative abundances well follow the behavior of “pure” α-elements – O, Mg, Si, and Ca (see, in particular, Bensby et al. 2014). The same authors note that, unlike other α-elements, the uncertainty in [Ti/Fe] is low and unchanged for almost all parameters. Therefore, they (and other authors) most often use the results on titanium as a more informative element to study the properties of galactic subsystems. Fig. 2 shows the diagram “metallicity – relative abundances of α-elements” for field stars and globular clusters. For both types of objects, different icons indicate the belonging to different galactic subsystems by kinematic criteria. The darkest, most prominent icons indicate objects with kinematics of the thick disk. It can be clearly seen from the figure that the clusters of this subsystem have not only a metallicity range different from the range of field stars, but also relative abundances of α-elements significantly increased with the same metallicity in the [Fe/H] > −1.0. Moreover, in 7 out of 9 clusters, the relationship is [Ca, Ti/Fe] > 0.2, and in two (NGC 6528 and NGC 6553) only slightly less. The three signed clusters at the bottom of the diagram in the past belonged to destroyed dwarf galaxies (Marsakov et al. 2019c). In addition, only 9% of field stars of the thick disk are metal-poor ([Fe/H] < −1.0), whereas among the clusters there are half of such ones. Let us pay attention to one more feature of clusters. White small circles inside large circles in the figure indicate clusters that we considered genetically related to a single protogalactic cloud. These are clusters with a direct revolution around the galactic center, which, according to the positions and elements of the galactic orbits, no one has associated with the destroyed dwarf satellite galaxies, and all of them are located or have maximum points of their orbits less than 15 kpc. There are 60% of such clusters in the sample. Among them were clusters with the kinematics of all three galactic subsystems identified by us, as well as all metal-rich clusters (except for two with halo kinematics and retrograde orbits).

It is not unlikely that the difference in the chemical composition of globular clusters and field stars, assigned to the subsystem of the thick disk by the kinematic criterion, indicates the absence of a connection between these subsystems of the same name. Perhaps the reasons for the formation of similar subsystems in field stars and globular clusters are different. Indeed, as can be clearly seen
From Fig. 3 one can see a steady monotonous decrease in the ages of a complete sample of clusters.

Oldest clusters of least metallicities, which indicates that the age of clusters is not sufficiently reliable.

Weiss (2002), all metal-rich clusters are older than this age and appeared simultaneously with the related clusters are older (except NGC 6362). However, according to the definitions from Salaris and the left of the dip in the histogram, i.e. in the metal-poor range), while all less metallic, genetically related clusters are highlighted in white circles. We see that all metal-rich clusters are younger than 11.5 Gyr (47 Tuc is only slightly older, and the old cluster NGC 6362, as seen in Fig. 1a, is slightly to the left of the dip in the histogram, i.e. in the metal-poor range), while all less metallic, genetically related clusters are older (except NGC 362).

Indeed, since metallicity increases over time in our Galaxy from the halo to the disk, it is therefore a statistical indicator of age. This is clearly seen from the smoothed trends plotted for globular clusters and field stars in Fig. 2. Recall that according to modern concepts, α-elements and a small amount of iron are thrown into the interstellar medium by type II supernovae, whose lifetime is less than 100 Myr. The main amount of iron peak elements is produced during bursts of type Ia supernovae, which begin to explode in mass approximately 1 Gyr after the start of star formation (Matteucci 2003). Therefore, after the onset of mass bursts of SNe Ia in the star-gas system, the so-called “kink” on the dependence “[Fe/H] – [α/Fe]” is observed. As you can see from the smoothed trend for field stars in Fig. 2 from Venn et al. (2004), in our Galaxy a “kink” is observed in the vicinity of [Fe/H] ≈ −1.0. Hence, the high relative abundances of α-elements in metal-rich clusters indicate that they formed within about a billion years after the start of star formation. This means that metal-rich stars are younger than globular clusters of the same metallicity.

The clusters identified by us as genetically related are by definition located closer than 15 kpc from the galactic center. In addition, as seen in Fig. 2 and 3, they are the absolute majority in the metal-rich group, which, on the metallicity distribution (see Fig. 1a), is separated near the point [Fe/H] ≈ −1.0 by a dip from less metallic clusters. Such properties of metal-rich clusters can probably be explained by the existence of an active phase in the Galaxy’s evolution (see Marsakov and Suchkov 1976, 1977, for more information). The active phase period occurs after massive supernova bursts in the halo, heating interstellar matter, resulting in a delay in star formation. During this delay, the interstellar matter of the Galaxy, already contaminated with heavy elements, is mixed, cools, and collapses to a smaller size, after which star formation begins again and disk subsystems are formed. However, this scenario of the formation of subsystems in globular clusters contradicts, as can be seen from Fig. 2, high relative abundances of α-elements in them: [α/Fe] > 0.2. As noted above, the high [α/Fe] ratios of almost all clusters indicate that they all formed before the beginning of SNe Ia bursts, that is, during the first billion years after the beginning of star formation in the proto-galactic cloud.

The same figure shows that within the metallic range, clusters can also show a decrease in the relative abundances of α-elements with an increase in metallicity, but on average, the ratio [α/Fe] for any metallicity in this range remains higher than for field stars of the thick disk. As a result, in the range [Fe/H] > −1.0, the dependence of [α/Fe] on [Fe/H] for them is higher and parallel to the same dependence for stars. And among them there are clusters of all the subsystems allocated by kinematics. A significant proportion of such metal-rich clusters have the kinematics characteristic of halo objects, that is, they are on very elongated orbits (eccentricities up to e = 0.9), although the orbits themselves are completely located inside the solar circle (see Fig. 2 and 3). This could well have happened during the formation of these clusters during the renewed collapse of the proto-galactic cloud, already enriched with heavy elements, after the active phase.

If the appearance of metal-rich clusters that are genetically linked to a single proto-galactic cloud owes its origin to the active phase, then all of them must be younger than less metallic clusters. Indeed, since metallicity increases over time in our Galaxy from the halo to the disk, it is therefore a statistical indicator of age. This is clearly seen in Fig. 3, where the relationship of metallicity to age is given for globular clusters from VandenBerg et al. (2013). In the figure, genetically related clusters are highlighted in white circles. We see that all metal-rich clusters are younger than 11.5 Gyr (47 Tuc is only slightly older, and the old cluster NGC 6362, as seen in Fig. 1a, is slightly to the left of the dip in the histogram, i.e. in the metal-poor range), while all less metallic, genetically related clusters are older (except NGC 362). However, according to the definitions from Salaris and Weiss (2002), all metal-rich clusters are older than this age and appeared simultaneously with the oldest clusters of least metallicities, which indicates that the age of clusters is not sufficiently reliable. From Fig. 3 one can see a steady monotonous decrease in the ages of a complete sample of clusters...
with an increase in metallicity. In this case, two separate parallel dependences for clusters of varying metallicities are clearly distinguished, with age ranges for these dependences being the same, while their \([\text{Fe/H]}\) ranges are, respectively: from \(-2.4\) to \(-1.2\) dex and from \(-1.3\) to \(-0.3\) dex. We see that the more metallic sequence consists entirely of genetically related clusters (except NGC 6652). About half of the genetically related clusters turned out to be in a less metallic group. Note that the authors of VandenBerg et al. (2013) themselves did not find an unambiguous explanation of the nature of the two sequences, but attributed their occurrence to the difference in the clusters’ loss of gas ejected by their giants of the asymptotic branch — it is from this gas that the second generation of cluster stars with the changed chemical composition is born afterwards. From Fig. 3 it is also seen that clusters of only one sequence fall into the range \([\text{Fe/H}] > -1.0\). Recall that we included all close clusters \((R_G < 15 \text{ kpc})\) in the genetically related ones, not all of which have computed orbital elements, so there may be distant ones (i.e., with \(R_{\text{max}} > 15 \text{ kpc}\)), but formally such clusters cannot be assigned to this group. Note that the dip we have discussed in the metallicity function in the vicinity \([\text{Fe/H}] \approx -1.0\) can hardly be considered a consequence or cause of the existence of two sequences of clusters with different ages and metallicities in Fig. 3, because, although it cuts off the metal-poor sequence, it divides the metal-rich one almost in half. Note that in Fig. 3 there is only one equally young, but metal-poor, genetically connected cluster, whose orbit also lies completely inside the solar circle — NGC 362.

It turns out that the most metal-rich, genetically related clusters were born later. In the lower right quadrant of Fig. 3 in the metallic range you can see a statistically insignificant, weak tendency to decrease age with increasing metallicity. At least two of the youngest metal-rich clusters belong to a thin disk by kinematics. By determination from Salaris and Weiss (2002), this dependence is also very uncertain. Apparently, for a final clarification of the question of the behavior of the ages of clusters in the range \([\text{Fe/H}] > -1.0\), their new determinations are needed with modern photometric and astrometric data. Only two (NGC 6652 and NGC 6637) of the metal-rich clusters in Fig. 3 have the halo kinematics. Moreover, the second cluster has an orbit completely inside the solar circle. According to the ages we used from VandenBerg et al. (2013), the supernovae SNe Ia still manage to enrich the interstellar medium with metals, from which subsequently clusters of the metal-rich group were born. In this case, the chemical and kinematic properties of metal-rich clusters do not contradict the hypothesis of active phases in the evolution of the Galaxy. Moreover, the higher relative abundances of \(\alpha\)-elements in all metal-rich clusters can be explained by the fact that they were formed from high-density interstellar matter enriched with heavy elements after a delay in star formation, which led to an increase in the upper limit of the masses of the formed stars, and consequently, of supernovae of the second type, ejecting a greater number of \(\alpha\)-elements. Then metal-poor, genetically related clusters, whose orbits also lie almost entirely within the solar circle, should have been born before the onset of the active phase. Indeed, as seen in Fig. 3, the ages of less metallic genetically related clusters are systematically greater. It is possible that by the time they were born, the rate of collapse of the proto-galactic cloud slowed significantly, which led to the appearance of clusters among them with a “younger” kinematics of the thick disk.

Thus, using the hypothesis of active phases in the evolution of the Galaxy, we can try to give a consistent explanation of the reason for the abrupt change in the volume of the Galaxy occupied by clusters when passing through \([\text{Fe/H}] \approx -1.0\). Nevertheless, the existence of old metal-poor clusters with the kinematics of the thick disk and with orbits also enclosed within the solar circle leaves open the question of the reason for the divergence of stratification results on the metallicity and kinematics of clusters and field stars. It turns out that what we call the thick disk of field stars and clusters are different subsystems.

Otherwise, if subsequently it turns out that there is no dependence between metallicity and age for globular clusters, a consistent explanation cannot be found why, when passing through \([\text{Fe/H}] \approx -1.0\), clusters abruptly change the occupied volume in the Galaxy. But in any case, the high relative abundances of \(\alpha\)-elements in metal-rich clusters indicate their greater age than the age of field stars of the thick-disk, in which these abundances are much smaller due to the massive pollution of their
parent interstellar medium by emissions of relatively long-lived SNe Ia.

4 FIELD VARIABLE STARS of TYPE RR Lyrae

The contradiction, although not so pronounced, between the criteria of belonging to disk subsystems and to halo in terms of chemical and kinematic properties is also observed between two types of field stars: F–G dwarfs and giants on the one hand, and variables of the type RR Lyrae, on the other (for more information, see Marsakov et al. 2018). Such variable stars are typical representatives of globular clusters, so the similarity of their metallicity functions is not surprising. From Fig. 1 it can be seen that the percentage of metal-poor objects with thick disk kinematics in the field lyrids is even higher than in globular clusters. But, unlike clusters, the relative abundances of α-elements in metal-rich lyrids systematically decrease with the growth of [Fe/H], as in other stars of the field. This is clearly seen in Fig. 4, where the diagram “metallicity – relative abundances of α-elements” for field stars and field variables of type RR Lyrae is shown. The abundances of the same two α-elements — calcium and titanium — are taken from the authors compilation catalog described in Marsakov et al. (2018). In this paper, we also proposed a possible explanation for these differences by the fact that, being older stars than the main part of dwarfs, lyrids track the chemical composition of the interstellar medium at the initial stages of the formation of the thick disk subsystem. Unfortunately, the ages of these variables cannot be determined, as in the case of globular clusters. A knee in the dependences of [α/Fe] and [Fe/H] in the lyrids indicates the fact that the era of type Ia supernovae outbursts has begun in the star-gas system in which they were formed, that is, about 1 Gyr have passed since the start of star formation. The large duration of the evolution of the thick disk subsystem is also clearly observed in Fig. 1c,d and Fig. 3c,d from Marsakov et al. (2018) systematic trends within this subsystem of both metallicity and relative abundances of α-elements with changes in kinematic indicators.

Pay attention to the peculiarities of the chemical composition of the lyrids observed in Fig. 4, which can be associated with the difference in the nature of some field stars. In particular, the recent work Mackereth et al. (2019) analyzed the relative abundances of α-elements and velocities of several tens of thousands of stars within 15 kpc from the Sun. The sample was compiled by cross-identification between the SDSS–APOGEE DR 14 and Gaia DR2 catalogs. As a result, it was concluded that, in the early stages of evolution, our Galaxy captured a massive (about $10^9 M_\odot$) satellite galaxy, as a result of which part of the field stars born in this satellite galaxy fell into our Galaxy, and part of the stars of the already formed thin disk thus “heated”, forming a subsystem of the thick disk. We emphasize that Mackereth et al. (2019) notes that the nature of such low-velocity stars is not completely clear, and the authors only assume that the thick disk subsystem was formed as a result of simultaneous processes — star formation in a single protogalactic cloud and accretion processes. This assumption is also supported by the conclusions of Belokurov et al. (2018), the authors of which investigated the change in the relationship between the Oosterhof classes of field stars of the type RR Lyr with distance from the galactic center according to GAIA data. They found confirmation of the fact that some of these stars entered our Galaxy from a decaying dwarf satellite galaxy of large mass. The same conclusion was reached by Helmi et al. (2018), who, basing on APOGEE and Gaia DR2, as well as numerical simulations, showed that remnants of a dwarf galaxy (they called it Gaia-Enceladus) more massive than the Small Magellanic Cloud prevail in the inner halo. They demonstrated that among the stellar objects they studied, hundreds of lyrids and more than a dozen globular clusters formed in this galaxy. Moreover, in their opinion, the merging with Gaia-Enceladus, led to a dynamic “heating” of the predecessor of the thick disk of the Galaxy and, consequently, contributed to the formation of this component about 10 Gyr ago.

This means that not all of the field lyrids are genetically related to our Galaxy. Indeed, by now, some of these “captured” field stars may well have become variables of the type RR Lyrae. Unfortunately, due to the lack of observational data, it is not possible to trace the existence of a “knee” in our field lyrids with a known abundance of chemical elements. However, from the form of
smoothed trends on the dependence of \([\text{Ca,Ti/Fe}]\) on \([\text{Fe/H}]\) (Fig. 4a) it can be seen that starting from \([\text{Fe/H}] \approx -1.3\) the sequence of lyrids is lower than that of the field stars, and this value coincides with the metallicity of the “knee” noted in Mackereth et al. (2019) for accreted Galaxy stars according to APOGEE data. This fact, as well as the relatively lower relative abundances of \(\alpha\)-elements, especially titanium (see Fig. 2 in Marsakov et al. 2018), in most metal-rich lyrids, with the kinematics of thick and thin disks in Fig. 4 compared with nearby stars, may testify in favor of the extragalactic origin of some, in particular metal-rich lyrids. As the calculation showed, in the range ([Fe/H] > -0.5), all lyrids on average have ratios \(\langle [\text{Ca, Ti/Fe}]_{\text{RLyr}} \rangle = -0.02 \pm 0.03\), which is far beyond errors and lower than in field stars of equally metallicity: \(\langle [\text{Ca, Ti/Fe}]_{\text{field stars}} \rangle = +0.042 \pm 0.003\). In Fig. 4a it can be seen that almost all these lyrids lie in the lower part of the strip occupied by the field stars.

It is known that, along with \(\alpha\)-elements, supernovae of the type SNe II also eject atoms of elements of \(r\)-processes, in particular, europium. Therefore, the relative abundances of this element, which is well defined in stars, change depending on the metallicity like \(\alpha\)-elements, which allows increasing the reliability of determining the course of the dependence “[\text{el/Fe}] – [\text{Fe/H}]” from a single chemical element. But, unfortunately, neither europium nor other \(r\)-elements were found for any field lyrids with \(r m [\text{Fc/Fe}] > -1.0\). Although for other metal-rich variable stars — Cepheids — the abundances of europium are well defined and the relations [Eu/Fe] are the same as for field dwarfs and giants (Marsakov et al. 2013).

However, not only the \([\text{Ca,Ti/Fe}]\) ratios, but also the relative abundances of the light \(s\)-element — yttrium — demonstrate very low values in metal-rich lyrids. This is clearly visible in Fig. 4b, where the change in the \([\text{Y/Fe}]\) ratio with the change in metallicity for the field lyrids and comparison stars is shown. Note that heavy \(s\)-elements in metal-rich lyrids give almost solar [el/Fe] ratios. Moreover, according to modern concepts, the overwhelming number of atoms of all \(s\)-elements is produced in the interior of the giants of the asymptotic branch with masses greater than 4\(M_\odot\) (the main component of the \(s\)-process) and, by dumping the shell, enters interstellar space. Recall that some stars of the asymptotic branch of the giants turn out to be close binaries that explode later as type Ia supernovae. That is, the time of ejection of these elements and iron are approximately the same. Nevertheless, in the metallic range in Fig. 4b, together with a sharp jump-like decrease in the \([\text{Y/Fe}]\) ratios for lyrids, one can see a slight tendency to increase them with increasing \([\text{Fe/H}]\), as for stationary field stars. It turns out that metal-rich lyrids are formed from a substance depleted in this element. We emphasize that the low \([\text{Y/Fe}]\) ratios in the field lyrids were previously noticed and people tried to explain them by the unusual state of the atmospheres of these variable stars. In particular, Clementini et al. (1995) suggests that the abnormal abundance of yttrium is caused by superionization caused by strong emission lines Ly\(\alpha\), which are induced by shock waves in a pulsating atmosphere. However, Liu et al. (2013) denied this possibility due to the lack of a similar effect in metal-poor lyrids and proposed to consider this an effect caused by the difference in surface gravity between evolved stars of the type RR Lyrae and non-evolved dwarfs. However, numerous definitions of gravity accelerations on the surface of metallic lyrids from high-resolution spectra showed that they are in the range: \(\lg g = (2.5 – 3.0)\), that is, they are approximately the same as in our comparison giants (see, for example, Marsakov et al. 2019a). And in other metal-rich stars — Cepheids — gravitational accelerations are even less than that of lyrids, and the \([\text{Y/Fe}]\) ratios are slightly larger than that of dwarfs and giants of the field (see Andrievsky et al. 2013). Since the influence of atmospheric features cannot explain the abnormal yttrium abundance in metal-rich lyrids, it can be assumed that it is caused by an external cause. Perhaps in the interstellar medium, from which metal-rich stars were formed, which have now become lyrids, in addition to an excess of helium, there were also a deficit of \(\alpha\)-elements and the light \(s\)-element — yttrium? The fact is that in Marsakov et al. (2019a) we hypothesized that relatively young metal-rich field lyrids have increased helium abundances leading to faster evolution of stars, and in the vicinity of the Sun they are carried out by radial migration from the central regions of

\[4\text{Features of the change in each of the four } \alpha\text{-elements can be seen in Fig. 2a-d in Marsakov et al. (2018), which show that the lowest relative contents are observed for titanium, although for other elements they are usually lower than the average for field stars.}\]
the Galaxy, where such stars are already detected. If we now assume that part of the field lyrids has an extragalactic origin, it becomes necessary to explain how such metal-rich stars could have been formed in the early stages of evolution, now in a dwarf galaxy, and in our Galaxy to acquire the kinematics of field stars of the thick and thin disk. Of course, this assumption is very superficial and requires a comprehensive justification.

5 CONCLUSIONS

Thus, the differences in the abundances of certain chemical elements in two representatives of the old stellar populations of the Galaxy — globular clusters and field variables of the type RR Lyrae, from similar abundances in field dwarfs and giants, which by kinematic parameters belong to the thick galactic disk, may indicate their formation from matter that has passed through different paths of chemical evolution. As a result, we can assume that the thick disk subsystem in the Galaxy turns out to be composite, and at least three components exist independently within it. The oldest one is metal-rich globular clusters, which were formed from a single protogalactic cloud shortly after the onset of bursts of type Ia supernovae in it. Then a subsystem of field stars of the thick disk was formed as a result of the “heating” of the stars of the thin disk already formed in the Galaxy by a rather massive dwarf satellite galaxy that fell on it. And, finally, a subsystem of field stars with the kinematics of not only a thick, but even a thin disk that fell on the Galaxy from this captured satellite galaxy. In this work, by the representatives of the last subsystem, we consider metal-rich field variable stars of the type RR Lyrae. At present, we are preparing an article for publication in which we will demonstrate on basis of more voluminous observational material, the differences in abundances of chemical elements, other than those considered, in variable stars of type RR Lyrae and stationary field stars, and also will analyze the possible causes of their occurrence.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Figure 1: Metallicity distributions of globular clusters (a), field lyrids (b), field stars from Venn et al. (2004) (c), and F–G–field stars from Bensby et al. (2014) (d). Distributions of objects with the thick disk kinematics are highlighted in dark color. The metallicities for clusters are taken from Harris (2010), for lyrids from Dambis et al. (2013), and the spectroscopic values [Fe/H] for field stars – from the above articles. Vertical dashed lines on all panels at [Fe/H] = −1.0 roughly correspond to a dip or bend in the histograms for all objects. The panels show the average metallicity of objects of the thick disk.
Figure 2: Changes in the relative contents averaged over two $\alpha$-elements (Ca and Ti) with a change in the metallicity of field stars from Venn et al. (2004) and globular clusters from Marsakov et al. (2019b). The field stars are indicated as follows: light gray snowflakes are for the thin disk, dark snowflakes are for the thick disk, dark crosses are for halo. Large circles of the clusters, which, according to kinematic features, belong to a thin disk are light, to a thick disk–dark, halo–gray. Small dark circles denote non-stratified clusters. White circles inside large circles denote genetically related clusters. Three clusters lost by dwarf satellite galaxies are signed. The dark and gray broken curves are smoothed trends with a moving average for globular clusters and field stars, respectively. The average error bars of individual definitions are plotted. The vertical dashed line $[\text{Fe/H}] = -1.0$ divides the clusters into two groups metal-poor and metal-rich, and the horizontal line $[\text{Ca,Ti/Fe}] = 0.15$ is approximately drawn along the lower boundary between metal-poor globular clusters and field stars.
Figure 3: Metallic – diagram for all globular clusters. Metallicities are taken from Harris (2010), and ages from VandenBerg et al. 2013). Designations, as in Fig. 2 The clusters that are mentioned in the text are signed. The vertical dashed line approximately corresponds to a dip in the metallicity function, and the horizontal dashed line corresponds to an age value of 11.5 Gyr.
Figure 4: Changes in the relative abundances averaged over two α-elements (Ca and Ti) (a) and the relative of yttrium (b) with a change in metallicity for field stars from Venn et al. (2004) and field stars of the RR Lyrae type from Marsakov et al. (2018). Notations are identical to those of Fig. 2, but the lyrids are marked with asterisks of the corresponding color. The dark and gray broken curves are the smoothed trends for lyrids and field stars, respectively (a). On both panels, the vertical dashed lines are as in Fig. 2, and the horizontal ones approximately correspond to the lower values of the corresponding [el/Fe] ratios for metal-poor lyrids.