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How many thick disk subsystems are there in the Milky Way Galaxy?

V.A. Marsakov*, M.L. Gozha, V.V. Koval'

Southern Federal University, Rostov-on-Don, Russia

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It was shown that stellar populations of the Galaxy with the thick disk kinematics, namely globular clusters, field RR Lyrae variables (lyrids), and nearby field F–G stars, have different chemical compositions. Based on the analysis of the nature of the dependencies of [α/Fe] on [Fe/H] for these objects, it was concluded that the thick disk subsystem in the Galaxy is composite, and at least three components independently exist inside it. The oldest subsystem consists of the metal-rich globular clusters, which were formed from a single protogalactic cloud shortly after onset of the explosions of type Ia supernovae in it. Then a subsystem of the field thick disk stars was formed as a result of the "heating" of the stars of the primary thin disk already formed in the Galaxy by a rather massive dwarf satellite galaxy which fell onto the Galaxy. And, finally, the subsystem of field stars (including the lyrids) with the kinematics of not only the thick, but even the thin disk that fell onto the Galaxy from this captured satellite galaxy.

Keywords: Galaxy: abundances, disk – (Galaxy:) globular clusters: general – stars: variables: RR Lyraes

1 Introduction

Traditionally, the populations of the globular star clusters and the field RR Lyrae variable stars represent the components of two subsystems of the Galaxy – spherical subsystem (the halo) and the thick disk. The objects of the thick disk are usually separated by the criterion of [Fe/H] > -1.0, because the metallicity function in the vicinity of this point shows "a gap" for the clusters and "a knee" for the field lyrids (see, e. g. [1, 2]). Such separation was considered possible due to the fact that metallicity is a statistical indicator of age. Indeed, we can consider, in a first approximation, our Galaxy as a closed star–gas system, and the total abundance of heavy elements in it increases with time, and the thick disk is younger than spherical subsystem. It is clear that a single and sufficient criterion for stratification does not exist. For the reliable assignment of an object to one subsystem or another, many characteristic

*Email: marsakov@sfedu.ru

parameters of each subsystem should be taken into account, in particular, position, kinematics, metallicity, abundances of various chemical elements, as well as ages. The use of kinematic parameters is considered the most reliable method of stratification of objects by subsystems. Nearby field stars are divided to the subsystems of the Galaxy in precisely this way. In particular, the procedure described in [3], in which the probabilities of nearby field stars belonging to the subsystems of a thin disk, a thick disk, and a halo are calculated using the residual velocity components, is widely used.

In previous papers [4–6], we have shown, in particular, that the kinematic and chemical criteria are poorly combined with each other for globular clusters and field RR Lyrae variables; and for them, objects of the thick disk and the halo are really more convenient to separate by metallicity. At the same time, attention was drawn to the anomalous relative abundances of α-elements in metal-rich field lyrids and clusters. In this paper, we continue to study the chemical and spatial-kinematic properties of these objects.

2 Initial data

To analyze the behavior of α-elements in globular clusters, we used metallicities from the computer version of the compiled catalog of [7], and spectroscopic determinations of the abundances of iron and the relative abundances of two α-elements – titanium and calcium – from our compiled catalog [5]. The components of spatial velocities for stratification of 115 clusters by galactic subsystems, determined by the authors of [8] according to modern catalogs, are given in [6]. Similar data for 100 field RR Lyrae variables are taken from our catalog, available at http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/AZh/95/54 and described in [4].

For comparison, we used the catalog from [9], which lists metallicities, relative abundances of α-elements, and spatial velocity components for 781 stationary stars of the galactic field in the entire metallicity range which is of interest to us. We consider the behavior of the relative abundances of only two α-elements – calcium and titanium – as the most informative in terms of diagnosing the evolution of the early Galaxy. These two chemical elements have many lines in the visible range of the spectrum, and their abundances are quite reliably determined. The errors of the averaged relative abundances of two α-elements used in this work are approximately the same for clusters and field lyrids: $\langle\varepsilon[Ca,Ti/Fe]\rangle \approx 0.11$; and the errors of spatial velocity components are $\sim$17 km s^{-1} (for more about the justification for the choice of elements and an analysis of errors, see [4, 6, 10]).

3 Dependence of relative abundances of α-elements on metallicity

3.1 Globular star clusters

The results of papers [5, 6] show that the kinematic method of stratification is hardly suitable for the globular clusters of our Galaxy, since clusters of different subsystems

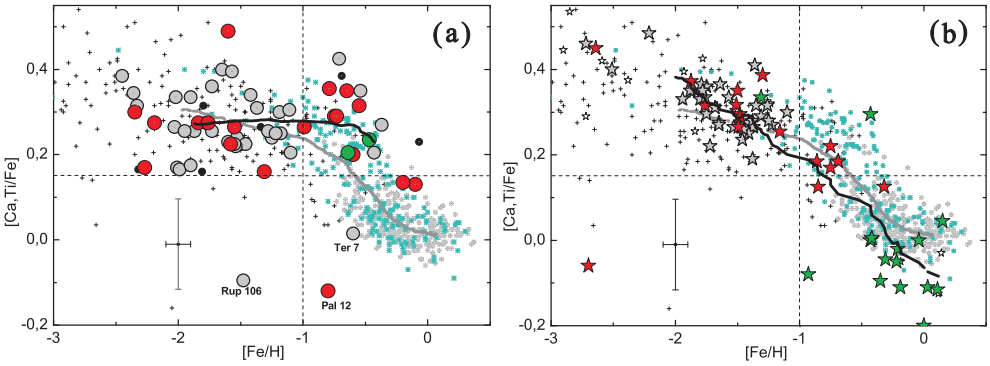


Figure 1 Dependence of the relative abundances averaged over two α-elements (Ca and Ti) on the metallicity for globular clusters from [6] (a), field stars of the RR Lyrae type from [4] (b), and field stars from ([9]). Field stars are indicated by: light gray snowflakes – a thin disk, green snowflakes – a thick disk, dark crosses – a halo. Large circles are clusters belonging, according to kinematic characteristics, to a thin disk – green, to a thick disk – red, and to a halo – gray (a). Small dark circles are non-stratified clusters (a). Lyrids are indicated by asterisks of the corresponding color (b). The names of three clusters lost by dwarf satellite galaxies are written (a). Broken curves are smoothed trends with a moving average; dark – for globular clusters (a) and field lyrids (b), light – for field stars. The average error bars of individual definitions are plotted. The vertical dashed line at [Fe/H] $= -1.0$ divides the clusters into two groups, metal-poor and metal-rich.The horizontal line at [Ca, Ti/Fe] $= 0.15$ is approximately drawn along the lower boundary of metal-poor globular clusters, field lyrids and field stars.

distinguished by kinematics demonstrate chemical properties that are radically different from the properties of field stars of the same galactic subsystems. In particular, all metal-rich ([Fe/H] > -1.0) clusters belonging to different subsystems according to the kinematic criterion turn out to be enclosed within rather narrow limits with respect to the center and the plane of the Galaxy. But in the lower metallicity range, there are clusters with large distances from the galactic plane among clusters with kinematics of the thick disk, not to mention the clusters with kinematics of the halo. At the same time, there are a large number of clusters, which lie far beyond the limits of the solar circle, among metal-poor clusters belonging by kinematics not only to the halo, but also to the thick disk. As a result, it turns out that the traditionally used procedure for separating globular clusters of the thick disk from those of the halo by metallicity seems to be more acceptable (see justification in [5, 6]).

Figure 1a shows "metallicity–abundances of α-elements" diagram for field stars and globular clusters. Belonging to different galactic subsystems according to kinematic criteria are indicated by different icons for both types of objects. It can be clearly seen from the diagram that clusters with the kinematics of the thick disk have not only a metallicity range different from the range of field stars, but also, with the same metallicity, significantly increased relative abundances of α-elements in the range [Fe/H] > -1.0. In addition, only 9 % of the field stars of the thick disk are metal-poor ([Fe/H] < -1.0), whereas among the clusters, half the number are metal-poor.

It seems that the difference in chemical composition of globular clusters and field stars selected by the kinematic criterion to the thick disk subsystem indicates the absence of a connection between the same-name subsystems for these objects. Perhaps the reasons for the formation of similar subsystems for field stars and globular clusters are different. Indeed, the high relative abundances of α-elements in metal-rich clusters indicate that they formed within about a billion years after the onset of star formation (the pre-supernova SNeIa lifetime). But in field stars, starting from [Fe/H] ≈ -1.0, these relations begin to decrease due to the onset of the era of mass outbursts of type Ia supernovae. This suggests that metal-rich field stars are younger than globular clusters of the same metallicity.

3.2 Field RR Lyrae variable stars

A contradiction, although not so expressed, between the criteria of belonging to the disk subsystems and the halo by chemical and kinematic properties is also observed between two types of field stars, F-G dwarfs and giants, on the one hand, and RR Lyrae variables on the other hand (see details in [4]). As can be seen in Figure 1b, the percentage of metal-poor objects with kinematics of the thick disk for the field lyrids is even higher than for the globular clusters. But the relative abundances of α-elements in metal-rich lyrids, unlike the clusters, systematically decrease with increasing [Fe/H]; although it is somewhat different than in other field stars.

Figure 1b demonstrates some nuances of the behavior of the [α/Fe] ratios in lyrids, which can be associated with the difference in the nature of some field stars. In particular, the relative abundances of α-elements and velocities of several tens of thousands of stars within 15 kpc from the Sun in the sample compiled by cross-identification between the SDSS-APOGEE DR14 and Gaia DR2 catalogs were analyzed in a recent paper [11]. Authors found that the [α/Fe] ratios in the part of metal-rich stars are lower than in the bulk of the field stars. It was concluded that in the early stages of evolution, our Galaxy captured a massive ($\sim 10^9 M_\odot$) satellite galaxy. As a result of this, part of the field stars born in this satellite galaxy fell into our Galaxy; and part of the stars of the primary thin disk that had already formed, at the same time "has heated", formed the subsystem of the thick disk. The authors of [12] came to the same conclusion. According to the APOGEE and Gaia DR2 surveys, as well as numerical simulations, they showed that in the inner halo, fragments of a dwarf galaxy more massive than the Small Magellanic Cloud, which they called Gaia-Enceladus, predominate. They demonstrated that among the stellar objects they studied, hundreds of lyrids and more than a dozen globular clusters formed in this galaxy. In their opinion, the merger with Gaia-Enceladus have led to the dynamic "heating" of the precursor of the thick disk of the Galaxy and, therefore, have contributed to the formation of this component about 10 Gyr ago. Most recently, the authors of [13] according to Gaia DR2 and DECaPS found evidence of not one, but two captures of massive galaxies about 9–11 Gyr ago.

Unfortunately, due to the lack of statistics, it is not possible to define the position of "the knee" point for our field lyrids with spectroscopic determinations of the abundances of chemical elements. However, from the behavior of smoothed trends on the dependence of [Ca, Ti/Fe] on [Fe/H] (Fig. 1b), it can be seen that, starting from [Fe/H] ≈ -1.3, the sequence of lyrids is lower than that of field stars. Moreover,

this value coincides with the metallicity of "the knee" noted in [11] for accreted stars of the Galaxy according to APOGEE. This fact, as well as markedly lower relative abundances of α-elements (especially titanium, see Fig. 2 in [4]) in most metal-rich lyrids with kinematics of the thick and the thin disks in comparison with nearby field stars in Figure 1b may testify in favor of the extragalactic origin of some lyrids, in particular metal-rich ones. The unusual chemical composition of the metal-rich lyrids is emphasized by the lower (beyond the errors limits) the relative abundances of scandium, yttrium and europium compared to stationary field stars. In [10] the relative abundances of these elements in metal-rich lyrids are studied; and the possible causes of the appearance of such peculiarities are analyzed.

4 Conclusions

Thus, the differences in the abundances of some chemical elements in two representatives of the old stellar populations of the Galaxy, globular clusters and field RR Lyrae variables, from similar abundances in dwarfs and giants of galactic field, which kinematically belong to the thick galactic disk, most likely indicate their formation from interstellar matter that has experienced various histories of chemical evolution. As a result, we can assume that in fact the subsystem of the thick disk in the Galaxy is composite; and at least three components exist independently within it. The oldest component is metal-rich globular clusters, which were formed from a single protogalactic cloud even before the mass outbursts of type Ia supernovae in it. Then a subsystem of the field thick disk stars was formed as a result of the "heating" of the stars of the primary thin disk that had already formed in the Galaxy by rather massive dwarf satellite galaxy that fell on it. And, finally, the subsystem of field stars (including the lyrids) with the kinematics of not only the thick, but even the thin disk that fell onto the Galaxy from this captured satellite galaxy. In this work, we consider metal-rich field RR Lyrae variable stars as representatives of the latter subsystem. For more details on the statistical analysis and justification of various chemical histories in metal-rich globular clusters, field RR Lyrae stars and stationary field stars, see [14].

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