Relationship between the Elemental Abundances and the Kinematics of Galactic-Field RR Lyrae Stars

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Abstract

Abstract—Data of our compiled catalog containing the positions, velocities, and metallicities of 415 RR Lyrae variable stars and the relative abundances $[{\text{el}}/{\text{Fe}}]$ of 12 elements for 101 RR Lyrae stars, including four $\alpha$ elements (Mg, Ca, Si, and Ti), are used to study the relationships between the chemical and spatial–kinematic properties of these stars. In general, the dependences of the relative abundances of $\alpha$ elements on metallicity and velocity for the RR Lyrae stars are approximately the same as those for field dwarfs. Despite the usual claim that these stars are old, among them are representatives of the thin disk, which is the youngest subsystem of the Galaxy. Attention is called to the problem of low-metallicity RR Lyrae stars. Most RR Lyrae stars that have the kinematic properties of thick disk stars have metallicities $[{\text{Fe}}/{\text{H}}] < -1.0$ and high ratios $[{\alpha}/{\text{Fe}}] \approx 0.4$, whereas only about 10% of field dwarfs belonging to the so-called “low-metallicity tail” have this chemical composition. At the same time, there is a sharp change in $[{\alpha}/{\text{Fe}}]$ in RR Lyrae stars belonging just to the thick disk, providing evidence for a long period of formation of this subsystem. The chemical compositions of SDSS J1707+58, V455 Oph, MACHO 176.18833.411, V456 Ser, and BPS CS 30339–046 do not correspond to their kinematics. While the first three of these stars belong to the halo, according to their kinematics, the last two belong to the thick disk. It is proposed that they are all most likely extragalactic, but the possible appearance of some of them in the solar neighborhood as a result of the gravitational action of the bar on field stars cannot be ruled out.

Key words: RR Lyrae stars, chemical composition, kinematics, Galaxy (Milky Way).

1 Introduction

RR Lyrae variables populate the horizontal branch of the Hertzsprung–Russell diagram. They are considered to be typical Population II objects according to the classification of Baade, and are among the oldest stars of the Galaxy. These high-luminosity stars are easily identified due to their short-period brightness variability, they are visible to large distances, and their absolute magnitudes can be fairly reliably calculated using their metallicities. For this reason, field RR Lyraes are often used in studies of the structure and evolution of the young Galaxy. The heliocentric distances of field RR Lyrae stars and the tangential components of their velocities are continuously being refined. For example, Damibis et al. [1] recently used proper motions, visual magnitudes, and two infrared magnitudes from the UCAC4 together with the statistical-parallax method to refine the zero points of the dependences of the absolute magnitudes on metallicity and the variability period, and provided corresponding calibration relations. The distances and velocities of four hundred Galactic RR Lyrae stars obtained from the data of [1] are currently the most accurate and homogeneous.

It is not possible to estimate ages of individual RR Lyrae stars using theoretical evolutionary tracks, since their positions in the Hertzsprung–Russell diagram are essentially independent of age. Studies of their chemical compositions can help to some extent in putting order on the chronology
of the formation of these stars. Various elements are synthesized in thermonuclear fusion reactions in stars with different masses which evolve on different timescales and eject these elements into the interstellar medium at different epochs. In particular, α elements, rapid neutron capture elements, and a small number of iron-peak elements are ejected by massive Type II supernovae a few tens of millions of years after the formation of their progenitors. On the other hand, most iron-group elements are formed in Type Ia supernovae, which occur approximately a billion years after the formation of their progenitors (see, for example, [2]). Therefore, in a closed stellar system, the ratios [α/Fe] and [r/Fe] for stars formed from interstellar material enriched in SN II products will begin to decrease steadily in time approximately a billion years after a burst of star formation. Thus, the relative abundances of these elements will become statistical indicators of the ages of these stars. Despite the complex processes taking place in the interiors of RR Lyrae stars, the chemical compositions of their atmospheres usually reflect the chemical composition of the environment in which they were formed (see, for instance, [3] and references therein).

Traditionally, the population of field RR Lyrae stars is represented as components of two subsystems of the Galaxy – the halo and thick disk (see, for example, [1]). However, even a glance at the chemical and kinematic parameters of individual RR Lyrae stars finds among them both stars with essentially solar chemical compositions and velocities and those with retrograde orbits, low metallicities and relative elemental abundances significantly different from the solar values. Therefore, the aim of this study was to compile a catalog of spectroscopic determinations of the metallicities, the relative elemental abundances, particular of α elements, and the spatial velocity components for as much RR Lyrae stars in the Galactic field as possible, with the aim of using the data of this catalog to identify regular relationships between these parameters for RR Lyrae stars belonging to different Galactic subsystems.

2 INPUT DATA

For our multi-faceted study, we took the catalog [1] as the main source of spatial and kinematic data. This catalog contains the variability periods, metallicities calculated using the Preston index, proper motions, and radial velocities of 392 RR Lyrae stars. The distances to the stars were calculated by applying one of three equivalent period-metallicity–luminosity calibration relations presented in the catalog, based on the infrared magnitude $K_s$. We then used these distances to calculate the Cartesian coordinates $(x, y, z)$, and spatial velocity components $(V_R, V_\Theta, V_Z)$ in cylindrical coordinates, corrected for the solar motion relative to the Local Standard of Rest (local centroid, LSR). The components of the solar motion relative to the LSR were taken to be $(U, V, W)_\odot = (11.1, 12.24, 7.25)$ km/s [4], the solar Galactocentric distance to be 8.0 kpc, and the rotation velocity of the local centroid to be 220 km/s. The differences between the distances calculated using the three calibration relations given in [1], based on different magnitudes, are no greater than 10%. Given this uncertainty and the uncertainties in the radial velocities and proper motions for each RR Lyrae star in the catalog, the mean uncertainty in the spatial velocity is 16 km/s. We found information for calculating the Cartesian coordinates and velocities of 15 RR Lyrae stars with known chemical compositions that were not included in [1] from several sources in the literature. References to the sources of the distances, proper motions, and radial velocities are listed in our compiled catalog (see below).

Atmospheric elemental abundances provide information on the chemical evolution of the interstellar matter from which they were formed, and thus make it possible to trace the chemical evolution of the Galaxy. Unfortunately, the exposures required for obtaining high-quality spectra with high signal-to-noise ratios for distant RR Lyrae stars are limited by their short pulsation periods and the high amplitudes of their radial-velocity variations in their envelopes. Nevertheless, a large number of elemental abundances for field RR Lyrae stars determined from high-quality spectra obtained on fairly large telescopes have been published recently. These data have shown that the strongest and most symmetric spectral lines are obtained close to the minimum brightness (maximum radius) of the variable star, when the atmosphere is stationary (see, for example [5, 6]). The temperature, gravity
and microturbulence velocities in the stellar atmosphere vary synchronously with phase, while the derived elemental abundances (apart from those for silicon and barium) are essentially insensitive to the phase \[ \mathbb{I} \] [8]. Therefore, in most cases, the spectra used to determine the abundances were obtained during quiescent phases close to 0.35.

We collected spectroscopic determinations of the relative abundances of 13 elements in 101 field RR Lyrae stars from the literature (25 papers published in 1995–2017); references are provided in the catalog. We selected data on the abundances of \( \alpha \) elements (O, Mg, Si, Ca, Ti), iron-peak elements (Fe), neutron-capture elements (Y, Ba, La, Zr, Eu), and elements with an odd number of protons (Na, Al). The elemental abundances were determined using high-resolution spectra. The analysis of most of the spectra was carried out in the approximation of local thermodynamic equilibrium (LTE), but non-LTE effects were taken into account in a number of studies. In the vast majority of cases, Kurucz model atmospheres [9] were used. About a hundred RR Lyrae stars had two values of \([\text{Fe/H}]\). One of the metallicities in [10] was calculated based on the Preston index and calibrated using the Zinn–West scale, while the other was an average over spectroscopic determinations of iron abundances collected from the literature. Examination of these data showed that the metallicity scales do not display systematic differences, and the metallicities for almost all the RR Lyrae stars are the same within the uncertainties.

The data from various studies for which the solar abundances used were indicated were reduced to the solar composition recommended in [10]. In our case, only such a correction was possible. In a small number of studies, the adopted scale for the solar composition was not indicated. In these cases, the relative abundances were not corrected. For 59 RR Lyrae stars, abundances were determined in a single study only. For 42 RR Lyrae stars, the abundance of a given element was determined more than once (up to eight times); in such cases, we computed the weighted mean values with coefficients inversely proportional to the uncertainties claimed in those studies. The quoted uncertainties in several studies exceeded 0.3 dex. Unfortunately, in two cases, these were the only determinations available. If the relative uncertainties were not specified, we assumed them to be 0.2 for studies published before 2000 and 0.1 for later papers. The mean uncertainties for each element proved to be in the range \( \varepsilon[\text{el}/\text{Fe}] = (0.11 - 0.18) \), and the mean value for all elements was \( \langle \varepsilon[\text{el}/\text{Fe}] \rangle = 0.14 \).

To verify the external convergence of the determinations of the abundance of each element, we constructed distributions of the deviations of the relative abundances derived in a given study for a specified star from the weighted mean values. All these histograms are described well by normal laws, consistent with the uncertainties being random. The dispersions of the distributions for the different elements are in the range \( \sigma[\text{el}/\text{Fe}] = (0.06 - 0.17) \), while the mean value for all the elements is \( \langle \sigma[\text{el}/\text{Fe}] \rangle = 0.11 \). This means that the external convergence of the relative abundance determinations is even slightly lower than the uncertainties claimed in the initial studies. Analysis of the external convergence demonstrated an absence of systematic offsets. Although the number of overlapping determinations for most of the elements is not very large, we believe that our compilation of abundances of elements produced in various nuclear fusion processes in field RR Lyrae stars can be used to study the chronology of their formation and the evolution of the Galaxy.

As a result, we compiled a catalog of the kinematic and chemical parameters of 415 field RR Lyrae variables. For 407, we provide distances and coordinates, for 401 velocity components, and for 101 relative elemental abundances. A fragment of the catalog is shown in the Table 1. The columns of the Table present (1) the name of the star, (2)–(3) the Galactic coordinates \((l, b)\), (4) the fundamental pulsation period (for RRc stars, this was calculated using the formula \( \log \log P_F = \log P + 0.127 [11] \)), (5) the heliocentric distance \(d\), (6)–(8) coordinates \((x, y, z)\) in a right-handed orthogonal system, (9) the Galactocentric distance \(R_G\) in kpc, (10)–(12) the calculated spatial velocity components relative to the LSR \((U, V, W)_{\text{LSR}}\), (13)–(15) the velocity components in cylindrical coordinates \((V_R, V_\theta, V_Z)\), where \(V_R\) is directed toward the Galactic anticenter, \(V_\theta\) in the direction of the Galactic rotation, and \(V_Z\) toward the North Galactic pole, (16) references for the distance, proper motion, and velocity, (17) the values of \([\text{Fe/H}]_D\) from [1], (18)–(30) the relative abundances of iron \([\text{Fe/H}]\) and twelve other

\[ \text{The Table is available in full only in electronic form.} \]
elements ([el/Fe]) we have found, and (31) references to the sources of the abundances. A key for the references for the kinematic data, [Fe/H], and [el/Fe] is given in the electronic catalog. The stars are listed alphabetically in the catalog in order of the constellation names or the names given in the original sources of data.

We used the data of Bensby et al. [12], which contains metallicities, relative abundances of α elements, and spatial-velocity components for 714 F–G field dwarfs, for comparison.

3 SEPARATION OF RR LYRAE STARS OVER THE GALACTIC SUBSYSTEMS

There is no single necessary and sufficient criterion that can be used to assign each star to a particular subsystem of the Galaxy with absolute confidence. Old objects of the Galaxy, such as globular clusters, subdwarfs and RR Lyrae stars, are usually grouped into two subsystems—the thick disk and the halo. In this case, it is convenient to distinguish the subsystems according to metallicity, since this is an indicator of age albeit somewhat rough. The metallicity distributions of these objects show a dip close to [Fe/H] ≈ −1.0, like globular clusters (see, for example, [13, Fig. 1]) or a break of the metallicity function, like field RR Lyrae stars (see, for example, [14] and Fig. 1 in that paper). Such a feature in the metallicity distributions of globular clusters and subdwarfs, as well as red dwarfs and giants with [Fe/H] < −0.5, which were earlier considered to be typical representatives of the spherical subsystem of the Galaxy, was first noted in [15, 16]. Since the purpose of our current study is to investigate the chemical compositions of RR Lyrae stars in different subsystems, we distinguished the subsystems based on the kinematic parameters. For this, we used the methodology suggested in [17], where the probabilities for field stars to belong to the thin disk, thick disk, and halo are computed using their spatial-velocity components relative to the local centroid and the dispersions of these components in each subsystem. This method assumes that the spatial-velocity components of the stars in each subsystem obey normal distributions.

Application of this technique showed that, out of the 401 stars in our catalog with known velocities, 56 most likely belong the thin disk subsystem, 122 to the thick disk, and 223 to the halo. According to our current understanding, the halo consists of two unrelated subsystemsthe intrinsic halo and an accreted halo (see, for example, [13, 14, 18]). The objects in the intrinsic halo are genetically related to objects in the younger subsystems of the Galaxy— the thin and thick disks formed of matter from the same protogalactic cloud. Some globular clusters and individual stars making up the accreted halo were captured by the Galaxy from dwarf satellite galaxies that were disrupted by Galactic tidal forces, and are formed of matter that went through a different chemical evolution history. For simplicity, we distinguished such stars here only via their retrograde motion around the Galactic center, since we believe that this is the most characteristic signature of an extragalactic origin. More than half of the halo RR Lyrae stars in our catalog (139 objects) have $V_\Theta < 0$ km/s. Since the subsystems do not have sharp boundaries and are embedded in one another, the velocity dispersions and other kinematic parameters characterizing the properties of the Galactic subsystems, which are included in formulas defining the separation of stars over the subsystems, are determined only approximately. To minimize ambiguity in assigning a particular star to a particular subsystem, it is recommended to consider a star to belong to a given subsystem if the probability that it belongs to another subsystem is at least a factor of two lower (for reliability, sometimes even a factor of ten) [17]. According to this criterion, we cannot assign a number of stars in the sample to a subsystem, even when kinematic data are available. Such stars are usually referred to as intermediate stars. Since we are interested in statistical regularities in the subsystems, which can be identified only using sufficiently large samples of objects, we assigned all of the stars to subsystems, taking a greater probability of belonging to one particular subsystem to be sufficient.

Figure 1a shows the distributions of F–G dwarfs from [12] and of field RR Lyrae stars of the selected subsystems in the Toomre diagram, that is, $V_{LSR} - (U_{LSR}^2 + W_{LSR}^2)^{0.5}$. Generally, the distributions of both types of objects are approximately the same. However, in the transition to
older subsystems, the fraction of RR Lyrae stars becomes appreciably larger than the fraction of typically younger main-sequence stars. It is noteworthy that, according to their kinematic parameters, RR Lyrae stars, which have traditionally been regarded as typical representatives of the very old subsystems of the Galaxy, are present in the fairly young thin-disk subsystem. (Note that, in [8], using a probabilistic kinematic criterion similar to ours, but with other kinematic data, 10 out of 23 high metallicity field RR Lyrae stars with spectroscopic elemental abundances, as in our study, were defined to be thin-disk objects). At the same time, a significant fraction of RR Lyrae stars are even overtaking the local centroid in its rotation around the Galactic center. In our samples, such stars comprise more than 40% of thin disk field RR Lyrae stars, while they constitute only one-third of field dwarfs. To examination the reliability of assigning the RR Lyrae stars to the thin disk, we applied a recurrent procedure and set the parameters in the formulas used to calculate the probabilities equal to the values we obtained for the RR Lyrae stars in the different subsystems. In this case, all the velocity dispersions in the subsystems increased slightly, but the fraction of stars in the thin-disk subsystem drastically decreased. The recalculation only redistributed the allocations of a few RR Lyrae stars, whose kinematics indicate they are in the transition zone between the thin and thick disks. In particular, among RR Lyrae stars with spectroscopic elemental abundances, only PH Peg and BPS CS 30339–046 changed subsystems.

Figure 1b shows the distribution of RR Lyrae stars in a plot of metallicity versus the distance from the Galactic plane (z). The RR Lyrae stars of the thick disk are located mainly at large distances from the Galactic plane and, unlike the thin-disk RR Lyrae stars, do not show an increased concentration toward this plane. As a result, the scale height of the subsystem formally defined by these stars, $Z_0 = 1.1 \pm 0.1$ kpc, is larger than the scale height defined by field dwarfs (see, for example, [19], where $Z_0 = 0.6 \pm 0.1$ kpc). This is due to observational selection effects caused by the increase in absorption with approach toward the Galactic plane. As a result, the relative number of distant RR Lyrae stars with small $z$ values is underestimated. Let us now see how justified assignment to the thick-disk subsystem based on metallicity is for field RR Lyrae stars.

The histograms in Fig. 1d, where the metallicity functions of field RR Lyrae stars and field dwarfs of the thick disk are compared, clearly show that there is a significant difference between them. Unexpectedly, the overwhelming majority of the thick-disk RR Lyrae stars (83%) have metallicities $[\text{Fe}/\text{H}] < -1.0$. The thick-disk dwarfs also include some low-metallicity stars, the so-called “low-metallicity tail”. However, according to many studies, the fraction of such stars barely exceeds 10% (see, for example, [20]). The metallicity functions in Fig. 1d show that the lowest metallicity objects of both types reach approximately the same metallicity, $[\text{Fe}/\text{H}] \approx -2.0$. However, among the more metal-rich stars, the metallicity function of the RR Lyrae stars reaches only half the corresponding distribution for the field dwarfs, and ends at approximately $[\text{Fe}/\text{H}] \approx -0.5$: there are no more metal-rich field RR Lyrae stars with thick-disk kinematics, whereas the nature of field dwarfs with essentially solar metallicities and thick-disk kinematics has been very actively discussed (see, for instance, [12]). A similar shift is observed for the metallicity function of the thin-disk RR Lyrae stars. In the halo, the ranges of the metallicity distributions of the two types of objects are similar, but their maxima are also separated, though only slightly (the histograms are not present in order to economize space).

Figure 1e presents the metallicity as a function of the azimuthal velocity ($V_\phi$) for the same objects. Small symbols show RR Lyrae stars with metallicities from [1] determined using Prestonfs index, and large symbols show objects with spectroscopic metallicities. The two slanted almost parallel dashed lines show an approximate separation of the stars into Galactic subsystems by eye, without computing the probability that they belong to a particular subsystem. The separation corresponding to these lines satisfactorily correlates with the separation according to our probability criterion, and the lines themselves pass through the regions occupied by stars with uncertain membership. Since, as we noted above, there is no unambiguous criterion for separating the stars into subsystems, it is impossible to unconditionally reject any of the approaches. Moreover, the velocities of some of the stars could well be distorted by radial migration. The diagram also shows that several RR Lyrae stars with thick-disk
kinematics turned out to be less metal-rich than the F–G dwarfs with the lowest metallicities in the same subsystems. Most of them got fell into the zone of uncertain separation, and may actually belong to the thick disk. (Liu et al. [8] found velocity components of DH Peg — one of the lowest metallicity objects among the RR Lyrae stars they classified (or indeed among those classified by us)—assigned to the thin disk in another source, according to their kinematics; it was subsequently reclassified even not as a thick-disk, but as a halo star). Figure 1e shows that neither in the thin disk, nor in the halo are there obvious dependences between the azimuthal velocities of the stars and their metallicities. However, a progressive decrease in the upper limit of the metallicity with decreasing azimuthal velocity ($V_\Theta$) is observed in the thick-disk stars. Note that the two lowest-metallicity RR Lyrae stars with spectroscopic determinations of [Fe/H] (V456 Ser and BPS CS 30339–046), which we placed in the thick disk with a high probability, are missing from the catalog [1] with homogeneous spatial and kinematic parameters, and their distances and velocities were taken from other sources. In particular, these data for the latter star were taken from [21], which is devoted exclusively to this star. The iron abundance in these RR Lyrae stars is much lower than those in the other thick disk stars. One of these stars has a rotational velocity around the Galactic center exceeding the solar value. They are also far from the other stars in the other diagrams (see below).

It is very possible that these RR Lyrae stars, which have velocities typical for thick-disk objects, actually entered the Galaxy from disrupted satellite galaxies, like the stars of the Arcturus moving group (see [19], [22]). According to its spatial-velocity components, one of these RR Lyrae stars (V456 Ser) may even belong to this stellar stream.

Figure 1e also shows that almost all RR Lyrae stars with retrograde rotations have metallicities [Fe/H] < −1.0, and these RR Lyrae stars constitute a majority in the halo subgroup. A similar ratio of the numbers of genuine Galactic objects and accreted objects is obtained for the field stars [23]. However, RR Lyrae stars with the kinematics of the accreted halo also include some very metal-rich objects. For example, V455 Oph has a spectroscopic metal abundance exceeding the solar value. However, with the metallicity determined using the Preston index [Fe/H] = −1.42, which is consistent with the distance [11], it falls into the center of the distribution of halo RR Lyrae stars in a “$V_\Theta$ – [Fe/H]” diagram. (This is one of the three RR Lyrae stars of our sample for which the difference between the metallicities determined using the two methods exceeds than 0.5 dex). Note, if we recalculate its heliocentric distance taking the value of [Fe/H]_Sp = 0.19 used by us, the azimuthal velocity remains zero within the uncertainties, although it formally becomes positive. In other words, its orbit remains essentially perpendicular to the Galactic plane. One of the RR Lyrae stars from our catalog that is most remote and has among the lowest metallicities—SDSS J170733.93+585059.7 (henceforth, SDSS J1707+58)—also has a retrograde orbit.

The full residual velocity of the star relative to the local centroid is sometimes used to separate stars into subsystems. Figure 1f shows the distributions of stars in a plot of [Fe/H] vs. $V_{\text{res}}$. Unlike the azimuthal velocity, the residual velocity has all spatial components. The dependence of the metallicity on the velocity in the thick disk stands out more clearly in this diagram. At the same time, it is clear that this kinematic parameter can also be used as a statistical indicator of membership of a star to one or another subsystem. The two vertical dashed lines in this diagram approximately separate stars of the thick and thin disks ($V_{\text{res}} \approx 80$ km/s) and those of the thick disk and halo ($V_{\text{res}} \approx 200$ km/s). Note that if the latter value of the residual velocity is exceeded, many objects with retrograde orbits appear, as is clearly seen in the diagram. This diagram also shows that the two low-metallicity RR Lyrae stars noted above have residual velocities almost in the middle of the range, typical for the thick disk. By the way, the prototype of the population, RR Lyrae, is also in the thick disk; it is located almost in the Galactic plane, and its vertical velocity component is zero within the uncertainties. Although its azimuthal velocity is quite typical for this subsystem, $V_\Theta = 112$ km/s, its residual velocity is very high, $V_{\text{res}} = 257$ km/s. More than half a century ago, based on its kinematic and photometric parameters, RR Lyrae was included in the moving group of fast halo stars Groombridge 1830 [24]. The last two diagrams also show that the line [Fe/H] = −1.0 collects into the group of metal-rich field dwarfs nearly all stars of both disk subsystems, whereas it collects
a large fraction of the field RR Lyrae stars with the thin disk kinematics, and only a small fraction with the thick-disk kinematics. It turns out that the chemical and kinematic criteria for separating the subsystems of RR Lyrae stars are not unambiguous.

4 RELATIONSHIPS BETWEEN THE RELATIVE ABUNDANCES OF $\alpha$ ELEMENTS AND OTHER PARAMETERS

Figure 2 shows the dependences of the relative abundances of magnesium, silicon, calcium and titanium on $[\text{Fe/H}]$ for F–G field dwarfs and field RR Lyrae stars. For both types of object, the sequences of relative abundances of magnesium and calcium are fairly narrow, and practically coincide when $[\text{Fe/H}] > -1.0$, while RR Lyrae stars have slightly higher $[\text{Mg/Fe}]$ and $[\text{Ca/Fe}]$ values than the field dwarfs at lower metallicities. In the lower-metallicity range, most of the relative elemental abundances were taken from [25, 26]. Similar excesses at low metallicities are show by two other $\alpha$ elements — silicon and titanium. However, there is a very large scatter in the relative abundance of silicon, and all the RR Lyrae stars have high metallicity, but significantly lower $[\text{Ti/Fe}]$, than the field dwarfs. The relative abundances $[\text{Fe/H}] > -1.0$ were main determined in [8]; however, they are consistent with the results of other studies for this range. We emphasize that the noted deviations of the relative abundances of the listed $\alpha$ elements are not a consequence of differences in the methods used to determine them in the dwarfs and RR Lyrae stars, since these deviations were also noted in the original studies, and their nature remained unexplained, although it was emphasized there that they cannot be interpreted in terms of the chemical evolution of the Galaxy [8, 25]. Thus, the systematic deviations of the sequences of $\alpha$ elements for the RR Lyrae stars from the analogous sequences for the field dwarfs could well be due to distortions associated with the influence of the continually changing physical conditions in the atmospheres of variable stars. Further, to minimize any artificially created patterns, we will consider the behavior of the dependences of the relative abundances of $\alpha$ elements on the metallicity and velocity averaged only over the two $\alpha$ elements magnesium and calcium, for which the systematic deviations are within the uncertainties in the abundances.

Figure 3a shows the dependences of $[\text{Mg, Ca/Fe}]$ ratios averaged in this way on the metallicity for field dwarfs and RR Lyrae stars. The two types of objects show fairly close sequences. For comparison, Fig. 3b presents the same dependences averaged over all four $\alpha$ elements which show good agreement with Fig. 3a. Unfortunately, all four $\alpha$ elements were simultaneously determined for a smaller number of RR Lyrae stars. At the same time, the sequences became narrower than in Fig. 3a for both types of objects, and a gap between the thin and thick disks near $[\alpha/\text{Fe}] \approx 0.16$ became distinctly visible for the dwarfs. While the systematic differences from the dwarfs could be due to distortions associated with the influence of the continually changing physical conditions in the atmospheres of variable stars. Further, to minimize any artificially created patterns, we will consider the behavior of the dependences of the relative abundances of $\alpha$ elements on the metallicity and velocity averaged only over the two $\alpha$ elements magnesium and calcium, for which the systematic deviations are within the uncertainties in the abundances.

It follows from Fig. 3a that the dependence of the $[\text{Mg, Ca/Fe}]$ ratios on $[\text{Fe/H}]$ in thin-disk RR Lyrae stars is in good agreement with its behavior for the field dwarfs. An exception is the RR Lyrae star DH Peg, which has a lower metallicity than the lowest metallicity field dwarfs in this subsystem. In addition, the relative abundance of $\alpha$ elements in this star are somewhat higher compared to the remaining thin-disk RR Lyrae stars. Note that DH Peg is classified as a halo object in [8] based on its velocity components, and its chemical composition is then consistent with those of either halo stars or thick-disk stars. TV Lib, in the metallicity range characteristic of most thin-disk stars, also have high $[\alpha/\text{Fe}]$ values. In fact, the abundances of this star were determined in the only study, and it proved impossible to reduce the data to a single solar composition. According to their positions in Figs. 3a, b, DH Peg and TV Lib are more naturally classified as thick-disk stars. The RR Lyrae star KP Cyg, which has the lowest relative abundance in our sample, $[\text{Mg, Ca/Fe}] = -0.18$, also belongs to the thin disk, according ot its kinematics. As can be seen from Figs. 2b and 2d, the abundances of two other $\alpha$ elements (Si and Ti) in this star are, on the contrary, enhanced. The study [27] is devoted to an analysis of the chemical composition of this star, which has a very high metal abundance and
abnormally high abundances of carbon and nitrogen in its atmosphere. It is proposed in [27] this star, as well as UY CrB, are in reality not long-period RR Lyrae stars, but instead short-period CWB-type cepheids. In other words, their presence in a list of RR Lyrae stars is questionable. The unusual nature of these stars is also confirmed by their anomalous positions in some of our diagrams (the abundances of α elements were not determined for UY CrB, but it has a large distance from the Galactic plane in Fig. 1b).

The largest systematic differences between the field RR Lyrae stars and dwarfs are observed for the stars with thick-disk kinematics. One of the differences has already been noted: instead of a sparsely populated low-metallicity tail, as is present for the thick-disk dwarfs, low-metallicity stars dominate among the thick-disk RR Lyrae stars. Figure 3a also shows that the thick-disk dwarfs show a distinct break in the [Fe/H] – [α/Fe] diagram near [Fe/H] ≈ −0.5 (see also [28]). However, the break in Figs. 3,a,b for the RR Lyrae stars is located near [Fe/H] ≈ −1.0. The presence of a small break at this location for thick-disk field dwarfs was also noted earlier in [9]. However, this conclusion has been questioned in some other studies [29]. A reduction in the relative abundance of α elements in field RR Lyrae stars, starting from [Fe/H] ≈ −1.0, was also noted in [8]. However, we note that the conclusion that a break is present at this metallicity for the RR Lyrae stars is not statistically significant, due to the small number of objects. We can also see that one of the two thick disk RR Lyrae stars with uncharacteristically low metallicities for this subsystem—BPS CS 30339–046—has a very low relative abundance of α elements, compared to the average value for stars of the same metallicity. This difference is appreciably higher than the uncertainties stated in the studies where the abundances were calculated. However, the RR Lyrae star V456 Ser, which satisfies the kinematic criterion for membership in the Arcturus stream, falls in the middle of the general sequence for the low-metallicity stars in Fig. 3a, just like the detected field stars in this stream [12, 19]. This provides further evidence for its membership in the Arcturus stream. However, it is positioned somewhat lower in Fig. 3b, where the sequence for the averaged values of all four investigated α elements is shown, due to the fairly low silicon abundance of this star. Although the kinematics of another RR Lyrae star, TY Gru, correspond to the thick disk, it has an abnormally low abundance of heavy elements for this subsystem, and is located very far from the Galactic plane (z = −4.2 kpc).

RR Lyrae stars and dwarfs exhibiting halo kinematics behave approximately the same. We expect an appreciable spread in the investigated relations among the field stars with retrograde orbits, since the atmospheric chemical compositions of stars that were presumably formed in various satellite galaxies may be different from the composition of genetically related Galactic objects with similar metallicities. Indeed, in one of the lowest metallicity stars of the sample, SDSS J1707+58, the abundance of α elements turned out to be abnormally high compared to all the field stars. Note that the abundances of α elements in SDSS J1707+58 were averaged over the results of two studies, and the values of [el/Fe] for the corresponding elements were very close.

The RR Lyrae star V455 Oph, which has retrograde rotation and is located in the strip of thin-disk stars, also occupies an anomalous position in Figs. 3,a,b. Figures 3,c,d show relations between the averaged relative abundances of two α elements and the kinematic parameters of the investigated stars. Since the velocities, like the metallicities, are statistical indicators of age, it is not surprising that the dependences of [α/Fe] on these parameters are somewhat similar. However, there are also peculiarities. For example, two halo stars (MACHO 176.18833.411 and AO Peg) with metallicities and relative abundances of α elements that are consistent with both the thick disk and halo (see Fig. 3a) have velocities around the Galactic disk that are much higher than the solar value (Fig. 3c). AO Peg has a total residual velocity of 409 km/s, and MACHO 176.18833.411 a total velocity of 485 km/s (Fig. 3d). In [30], which is devoted to the latter object, taking into account its position near the Galactic center and the shape of its orbit, it is concluded that the star was most likely thrown out of the Galactic center and has its origin in the low-metallicity tail of the Galactic bulge.

The RR Lyrae star that is the most metal-poor and simultaneously has the highest [α/Fe] value and exhibits the kinematics of the accreted halo, SDSS J1707+58, also has an exceptionally high negative azimuthal velocity (see Fig. 1e and Fig. 3c). The accreted halo RR Lyrae star V455 Oph has
5 DISCUSSION

Thus, our analysis of the chemical and kinematic properties of field RR Lyrae variable stars has shown that such stars are present in all four subsystems of the Galaxy we have distinguished: the thin and thick disks, and the intrinsic and accreted Galactic halos. Thus, contrary to traditional ideas, our sample of field RR Lyrae stars includes objects with kinematics and chemical compositions typical of stars of the thin disk. Modern estimates of the age of the thin disk are $< 9$ Gyr (see, for instance, [12]). Hence, contrary to traditional picture (e.g., [31]), RR Lyrae stars include both old ($> 10$ Gyr) objects and younger stars. On the other hand, the thin-disk RR Lyrae stars include objects with lower metallicities and with higher relative abundances of $\alpha$ elements than those for field dwarfs in this subsystem. For the absolute majority of thin-disk RR Lyrae stars, the $[\alpha/\text{Fe}]$ ratios are close to solar, as is also true for F–G dwarfs of this subsystem.

Strictly speaking, RR Lyrae stars with metallicities characteristic of the thin disk should not exist, since the horizontal branch for such stars is located in the region of the red-giant clump, alongside the instability strip, and these stars should not be variable. However, according to our results, the kinematics and chemical compositions of these stars with high probability indicate that they belong precisely to the thin disk. This means that the reason for this discrepancy should be sought in their classification as variable stars. This list should include at least two more high-metallicity RR Lyrae stars from other subsystems — AA Aql and V455 Oph. We already noted above that the RR Lyrae star from our list with the highest metallicity and the longest period, KP Cyg, is probably a classical Cepheid with a very short period [27]. It may be that the metal-rich stars we are discussing do not pulsate in the fundamental mode, but in an overtone, in which case all of them could actually be Cepheids. Examples of Cepheids with periods less than a day include V1334 Cyg, V1726 Cyg, and V1154 Cyg from the catalog [32]. It is unlikely that they are $\delta$ Sct variables, which are Population I stars, since the variability periods of $\delta$ Sct stars are shorter than those of RR Lyrae stars. In any case, their verification requires a thorough investigation of every such a variable.

Most of the RR Lyrae stars with thick-disk kinematics turned out to have [Fe/H] values that would usually be considered to be in the low-metallicity tail of thick-disk field stars. This can be explained by the fact that, being older than most dwarfs, they trace the chemical composition of the interstellar medium in the initial stages of the formation of this subsystem. The break in the dependence of $[\alpha/\text{Fe}]$ on [Fe/H] indicates that the epoch of Type Ia supernova had begun in the star-gas system; i.e., about 1 Gyr had passed since the onset of star formation. Apparently, the first SNe Ia began to explode when the metallicity of the interstellar medium in the Galaxy reached [Fe/H] $\approx -1.0$, and only when higher metallicities were reached did SNe Ia begin to explode en masse. The long duration of the evolution of the thick-disk subsystem is testified to by the systematic trends in both the metallicity and the relative abundance of elements with changes in the kinematic parameters within a given subsystem, which is clearly visible in Figs. 1e,f and Figs. 3c,d. These dependences support the hypothesis of a prolonged formation for the thick disk in the process of the collapse of the protogalactic cloud.

The two lowest metallicity RR Lyrae stars of this subsystem (BPS CS 30339–046 and V456 Ser) demonstrate chemical compositions that differ from those of the other RR Lyrae stars of the subsystem, beyond the uncertainties. This suggests that they have an extragalactic origin, similarly to the stars of the well-known Arcturus stream. The spatial velocity of the RR Lyrae star V456 Ser suggests that it may well also belong to this stream. The very low value of [Mg/Ca] = −0.3 and the high relative abundance of the fast-neutron-capture element [Eu/Fe] = 1.0 for V456 Ser [25] also supports an extragalactic origin for this star. These are the most extreme values for the RR Lyrae
stars of our sample (see our catalog). Both these quantities indicate a low mass of the Type II supernovae that enriched the interstellar material from which this star was formed. According to our current understanding, the yield of primary $\alpha$ elements (such as magnesium) compared to secondary $\alpha$ elements (such as calcium) decreases with the pre-supernova mass, while virtually all europium is formed in the r-process, which occurs during the least massive SNe II explosions, with masses of $(8-10)M_\odot$ (see, e.g., [33]). Low-mass supernovae explode with higher probability in dwarf low-mass galaxies [34]. Note, however, that some authors prefer the hypothesis that the Arcturus stream, to which this RR Lyrae star probably belongs, formed as a result of the gravitational perturbation of field stars by the Galactic bar (see [12] and references therein).

In contrast to V456 Ser, BPS CS 30339–046 shows a very low relative abundance of $\alpha$ elements and a very low metallicity. This could arise if this star formed in a dwarf galaxy, where the rate of star formation was so low that SNe Ia began to explode when the interstellar medium was still not very enriched in iron from SNe II. However, these possibilities require additional research.

Virtually all the RR Lyrae stars with halo kinematics have relative abundances of $\alpha$ elements that correspond to their metallicity. This applies fully to the RR Lyrae stars of the intrinsic Galactic halo, that is, to stars that are genetically related to the protogalactic cloud. The RR Lyrae stars of the accreted halo, to which we have attributed all stars with retrograde orbits, have a somewhat larger spread of the relative abundances of some $\alpha$ elements for the given metallicity. This circumstance requires a more careful determination of the atmospheric chemical compositions of these stars, which have often been determined in one study only. Like another low-metallicity RR Lyrae star of the thick disk, TY Gru, SDSS J1707+58 is considered to be a low-metallicity star with an enhanced abundance of carbon and $s$ elements. It has been suggested that this RR Lyrae star is a binary and that its companion is losing mass, being in the asymptotic branch giant stage (see [21] and references therein). At the same time, there are doubts as to how such a star could complete its evolution in the red giant branch without experiencing the consequences of Roche lobe overflow. However, it turns out that it also has an enhanced relative abundance of $\alpha$ elements. The very high ratio $[\alpha/Fe]$ in SDSS J1707+58 may be more easily understood if its protostellar cloud was enriched by the ejecta of a very massive SN II, whose explosion provoked star formation in this cloud, also accelerating it.

We also consider the chemical composition of V455 Oph to be unique. While this star is located in the general sequence of thin-disk stars in the $[Fe/H]$–$[\alpha/Fe]$ diagram and has almost solar elemental abundances, it has a retrograde orbit that is nearly perpendicular to the Galactic plane. This high abundance of metals in combination with such a high orbit could hardly arise in a low-mass dwarf satellite galaxy. According to the numerical model for the hierarchical formation of the Galactic halo [35], only a low-mass satellite galaxy could be destroyed by the tidal forces of the Galaxy while still distant from the Galactic plane, that is, in a perpendicular orbit. It is also possible that this star, like MACHO 176.18833.411, was ejected away from the Galactic bulge. Its current distance from the center of the Galaxy is very large, $R_G \approx 6.8$ kpc, but it has a high velocity in the direction toward the center, 163 km/s. Clarifying this situation requires investigating the trajectory of its orbit. We emphasize again that additional research is required to verify all our conclusions concerning individual stars.

We plan to investigate the behavior of the relative abundances of other elements in field RR Lyrae stars from our catalog and the relationship between the chemical compositions and the parameters of the Galactic orbits of these stars in a future paper.

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Figure 1: (a) Toomre diagram, (b) dependence of metallicity on distance from the Galactic plane, metallicity distributions for (c) all stars of the sample and (d) thick disk stars only, and dependence of metallicity on (e) the rotational velocity about the Galactic center and (f) the total residual velocity for 714 F-G dwarfs and 401 field RR Lyrae stars. Thin disk field dwarfs are shown by light gray asterisks, thick disk field dwarfs by gray pluses, and halo field dwarfs by black asterisks. Field RR Lyrae stars with metallicities from [1] are shown by small triangles, and those with spectroscopic metallicities by large circles. Dark circles show RR Lyrae stars in the thin disk, thick disk, and halo are shown by filled circles, gray circles, and hollow circles, respectively; a dark dot inside a large circle indicates a star displaying retrograde rotation. The slanted (e) and vertical (f) dashed lines show the conventional separation of stars into different subsystems in the diagram. The dashed horizontal lines are drawn at $[\text{Fe/H}] = -1.0$ (b, e, f). The vertical dashed lines are drawn through the values $V_\Theta = 0$ and $220 \text{ km/s}$ (e). RR Lyrae stars with spectroscopic metallicities or velocities that strongly deviate from the mean velocities for the corresponding subsystems are named (d, e). In the metallicity distributions, RR Lyrae stars are plotted in gray, and dwarfs are shown by slanted shading. The numbers indicate the average metallicities and their dispersions (c, d).
Figure 2: Dependence of relative abundances of (a) magnesium, (b) silicon, (c) calcium, and (d) titanium on the metallicity for field dwarfs and RR Lyrae stars. The notation is the same as in Fig. 1.
Figure 3: Dependence of the relative abundances on the metallicity. Panel (a) shows the abundances averaged over two $\alpha$ elements (Mg and Ca), and Panel (b) the abundances averaged over four $\alpha$ elements (Mg, Ca, Si, and Ti). Panels (c) and (d) show the dependence of $\text{[Mg, Ca/Fe]}$ on the rotational velocity around the Galactic center and the total residual velocity for field dwarfs and RR Lyrae stars. The notation is the same as in Fig. 1.
Table 1: Kinematic parameters and relative elemental abundances in the field RR Lyrae stars (a fragment of the catalog)

| Name      | $l,^\circ$ | $b,^\circ$ | $P_F$, day | $d$, kpc | $x$, kpc | $y$, kpc | $z$, kpc | $R_G$, kpc | $U_{LSR}$, km/s | $V_{LSR}$, km/s |
|-----------|------------|------------|------------|----------|----------|----------|----------|------------|----------------|----------------|
| SW And    | 115.7250   | -33.0825   | 0.4423     | 0.495    | -0.180   | 0.374    | -0.270   | 8.193      | 50.7           | -15.2          |
| CI And    | 134.9313   | -17.6169   | 0.4848     | 1.597    | -1.075   | 1.078    | -0.483   | 9.152      | 9.2            | 19.1           |
| DR And    | 126.1660   | -28.5670   | 0.5328     | 2.072    | -1.074   | 1.469    | -0.991   | 9.245      | -160.2         | -228.3         |
| BS Aps    | 317.8839   | -15.1835   | 0.5826     | 1.738    | 1.244    | -1.125   | -0.455   | 6.864      | -146.0         | -1.9           |
| KP Cyg    | 77.2592    | 5.0360     | 0.8360     | 2.147    | 0.472    | 2.086    | 0.188    | 7.814      | 27.1           | 25.2           |

| Name      | $W_{LSR}$, km/s | $V_R$, km/s | $V_\theta$, km/s | $V_Z$, km/s | $d$, pmRA | pmDE | RV | [Fe/H] | [Fe/H] | [O/Fe] | [Na/Fe] | [Mg/Fe] |
|-----------|-----------------|-------------|-------------------|-------------|------------|------|----|--------|--------|--------|---------|---------|
| SW And    | -18.6           | -41.3       | 206.9             | -18.6       | 7          | -0.38| -0.22| 0.09   | 0.08   |
| CI And    | -11.8           | 37.3        | 236.3             | -11.8       | 7          | -0.83| -0.43| -       | 0.01   | 0.15   |
| DR And    | 5.7             | 156.8       | -33.8             | 5.7         | 7          | -1.48| -1.37| -       | -      | 0.37   |
| BS Aps    | 22.2            | 108.2       | 239.1             | 22.2        | 7          | -1.33| -1.48| -       | 0.15   | 0.45   |
| KP Cyg    | 17.3            | 39.4        | 243.6             | 17.3        | 13, 18     | 0.15 | 0.06 | 0.31   | -0.22  |

| Name      | [Al/Fe] | [Si/Fe] | [Ca/Fe] | [Ti/Fe] | [Y/Fe] | [Zr/Fe] | [Ba/Fe] | [La/Fe] | [Eu/Fe] | [el/Fe] |
|-----------|---------|---------|---------|---------|--------|---------|---------|---------|---------|---------|
| SW And    | -0.07   | 0.01    | 0.06    | -0.16   | -0.53  | -       | -0.26   | -       | -       | 5,10,21,22,30,31 |
| CI And    | -       | 0.12    | 0.05    | -0.05   | -      | -       | -0.21   | -       | -       | 22      |
| DR And    | -       | 0.71    | 0.26    | 0.27    | -      | -       | -       | -       | -       | 23      |
| BS Aps    | 0.59    | 0.56    | 0.29    | 0.30    | 0.04   | 0.57    | 0.04    | -0.03   | 0.14    | 4, 12   |
| KP Cyg    | 0.25    | 0.07    | -0.13   | 0.22    | -0.02  | -       | -0.35   | -       | -       | 2, 30   |