Abstract

We use the data of our extended catalog of spectroscopic determinations of elemental abundances in the atmospheres of Galactic-field RR Lyrae type variables to show that metal-rich RR Lyraes ([Fe/H] > −1.0) have anomalous abundances of some elements. In particular, the relative abundances of scandium, titanium, and yttrium in metal-rich RR Lyrae type variables are lower than the corresponding abundances in field stars of similar metallicity beyond the errors. We discuss the errors of the determination of the abundances of the above elements and point out the fact that no europium, zirconium, and lanthanum abundance determinations are available for metal-rich RR Lyrae type variables. We also analyze various possible causes of the observed peculiarities of the chemical composition of metal-rich RR Lyrae type variables.

Key words: stars: variables: RR Lyrae.

1 Introduction

RR Lyrae type stars are radially pulsating A–F-type low-mass variables populating the instability strip of the horizontal branch. Metal abundances of Galactic-field RR Lyraes vary over a wide range. Unlike globular-cluster RR Lyraes, some of Galactic-field RR Lyraes have high metallicities and kinematic properties typical of disk subsystems. RR Lyrae type variables are stars at the late evolutionary stage. However, studies of RR Lyraes show that the abundances of most of the heavy elements in their surface layers remain unchanged (see, e.g., Clementini et al., 1995). Hence the [el/Fe] ratios can serve as indicators of the chemical composition of the matter from which these stars formed.

In our earlier papers (Marsakov et al., 2018a, b) we used our catalog containing the data about the positions, velocities, and metallicities for 415 field RR Lyrae type variables and relative abundances [el/Fe] of 12 chemical elements in one hundred RR Lyrae type variables to show that metal-rich ([Fe/H] > −1.0) RR Lyraes with low relative abundances of α-elements ([α/Fe] < 0.2) in our Galaxy have kinematics that is typical of the youngest subsystem – the thin Galactic disk. Low residual velocities of these variables indicate that such stars must be younger than the oldest stars of this subsystem, i.e., their ages should be smaller than 9 Gyr (see, e.g., Bensby et al., 2014). However, our estimates based on Dartmouth evolutionary tracks (Marsakov et al., 2019a, b) have shown that the masses of these stars are rather small (0.51 – 0.60 M⊙), and, according to current views, their initial masses should have been of about 0.7 – 0.8 M⊙ (see Taam et al., 1976, and references therein). The evolutionary time scale of such low-mass stars is longer than the age of the thin disk. We suggested in our paper (Marsakov et al., 2019a) that the presence of such young and metal-rich RR Lyraes may be due to high helium abundances of their progenitors.

In our earlier studies (Marsakov et al., 2018a, b, 2020) we investigated the dependencies of relative abundances of magnesium, silicon, calcium, and titanium (representing α-elements) on [Fe/H] in F–G-type dwarfs and field RR Lyraes. On the whole, the metallicity dependencies of the abundances
of α-elements in RR Lyraes practically reproduce the corresponding dependencies for field dwarfs. However, at \( [\text{Fe/H}] > -1.0 \) the relative titanium abundances in most of the RR Lyraes are significantly lower than in field dwarfs (note that such RR Lyrae have subsolar \([\text{Ti/Fe}]\) ratios). The authors of the original studies we cite already pointed out the anomalous abundances of some elements. In particular, Chadid et al. (2017); Clementini et al. (1995); Liu et al. (2013) also tried to explain the lower relative abundances not only of titanium, but also of scandium and yttrium in RR Lyraes with \( [\text{Fe/H}] > -1.0 \) compared to stationary stars of the same metallicity.

Thus Clementini et al. (1995) point out that the anomalously low scandium and yttrium abundances that they found in two metal-rich RR Lyrae of their sample. The above authors could not explain such results by a combination of errors of atmospheric parameters or attribute them to nucleosynthesis processes. They suggested that such low abundances of these elements could have resulted from superionization caused by photons emitted in Lyman lines, which are induced by shocks in the pulsating atmospheres of RR Lyraes because stationary stars with the atmospheric parameters like those of RR Lyrae variables exhibit no scandium or yttrium deficit. Underestimation of the effect of superionization in LTE model atmospheres may result in underestimated abundances of these elements. However, the above authors and Liu et al. (2013) considered such explanation unpersuasive because of the lack of a similar effect in RR Lyrae with \([\text{Fe/H}] < -1.0\).

In contrast to the above explanation, Liu et al. (2013) estimate the possible effect of the fact that scandium lines are subject to hyperfine splitting and found this effect to be insignificant. They argue that anomalously low relative abundances of Sc and Y in metal-rich RR Lyrae type stars cannot be explained and there fire they cannot be used for analyzing the chemical evolution of our Galaxy. The above authors suggest that given that the \([\text{Sc/Fe}]\) and \([\text{Y/Fe}]\) ratios are determined using lines of ionized atoms, which are sensitive to surface gravity, the deviations can be due to differences of \( \log g \) between RR Lyrae type variables and dwarfs. However, our analysis of numerous determinations of surface gravity in metal-rich RR Lyraes from high-resolution spectra showed that these parameters are confined within the \( \log g = 2.5 - 3.0 \) interval, i.e., they are more or less the same as in red giants (see, e.g., Gozha et al., 2019; Marsakov et al., 2019a). Moreover, the surface gravities of other metal-rich variables – Cepheids - are even lower than those of RR Lyraes (e.g., Luck, 2018), whereas the \([\text{el/Fe}]\) ratios of the elements considered (especially those of scandium and yttrium) are, on the average, somewhat higher in Cepheids than in field dwarfs and giants and than in metal-rich RR Lyraes (see below).

Chadid et al. (2017) argue that the nature of metal-rich RR Lyrae type variables is unique despite the fact that both metal-poor and metal-rich RR Lyraes are helium-core burning horizontal-branch stars. They believed that the dynamics and structure of the atmospheres of these stars differ. The differences, which are most conspicuous in RRab type variables, show up in the strength and localization of shocks. Note that in metal-rich RR Lyraes the strength of main shock is higher in photospheres, whereas in more metal-poor RR Lyraes it is higher in the upper layers of the atmospheres. The above authors believe that the differences in the mechanisms of shock propagation are due to the differences between the atmospheric parameters of these stars, because in their sample metal-rich RR Lyraes have higher effective temperatures and surface gravities than more metal-poor stars. However, although the \( T_{\text{eff}} \) and \( \log g \) values that we inferred for one hundred RR Lyraes (Marsakov et al., 2019a) are, on the average, slightly higher for metal-rich stars, they nevertheless agree within the quoted errors. Note that all metal-rich RR Lyraes are located inside broad intervals of the corresponding parameters spanned by metal-poor RR Lyraes.

Given the inconclusive nature of the hypotheses suggested by different authors to explain the peculiarities of the abundances of some chemical elements in Galactic field RR Lyrae type variables, here we critically review the proposed arguments and analyze in detail the relative abundances in metal-rich \(( [\text{Fe/H}] > -1.0 )\) field RR Lyraes of the elements that exhibit anomalies. Our careful preliminary analysis of all available determinations of elemental abundances allowed us to identify the elements that clearly exhibit anomalous relative abundances in metal-rich RR Lyraes. We found these to be scandium, titanium, yttrium, as well as europium, zirconium, and lanthanum – the latter...
three have never been found in any metal-rich RR Lyrae type variable.

2 FORMATION OF CHEMICAL ELEMENTS

According to current theoretical views, isotopes of chemical elements form in certain nuclear synthesis reactions in stars of various masses. Let is recall how and where the above chemical elements are synthesized.

Scandium is an iron-peak element with odd number of protons. It is believed to be synthesized in massive stars during explosive burning of oxygen and silicon as the radioactive progenitor of $^{45}\text{Ti}$, and also in the process of neon burning. It also synthesized in the envelopes of the same stars in the weak component of the slow neutron capture processes (the s-process) during the helium and carbon envelope burning (Ernandes et al., 2018; Limongi and Chieffi, 2003; Woosley and Weaver, 1995).

Titanium is classified as an α-element, but in some cases it is referred to as an iron-group element (e.g., Sneden et al., 2016). This element is synthesized during explosive burning of silicon and oxygen mostly by massive ($M > 10M_\odot$) type II supernovas and, in small amounts, by SN Ia (Thielemann et al., 2002; Tsujimoto et al., 1995; Woosley and Weaver, 1995). It has long been observed that relative titanium abundances depend on metallicity similarly to the relative abundances of other α-elements.

Unfortunately, current theoretical models are incapable to reproduce the observed trends for $[\text{Sc/Fe}]$ and $[\text{Ti/Fe}]$, and therefore the nucleosynthesis problem for scandium and titanium remains unsolved (see Mishenina et al., 2017).

Yttrium is synthesized in slow neutron capture processes. S-process elements form in low- and intermediate-mass stars (1.5 – $8M_\odot$) during the double-shell burning stage (the main component of the s-process) as a result of thermal pulsations in the envelopes of asymptotic-branch giants (AGB stars), and during the ejection of the envelope they are released to the interstellar space (Gallino et al., 1998). A certain fraction of these elements are synthesized in the cores of massive ($M \geq 8M_\odot$) stars during the hydrostatic stage of the helium core burning (the weak component of the s-process). The number of neutrons required for s-processes is synthesized in AGB star in the process of the reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$ (Bisterzo et al., 2011; Gallino et al., 1998), or, in the interiors of massive stars these elements are synthesized in reactions $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ (Pignatari et al., 2010; Woosley et al., 1994). The main component provides about 70 – 90% of the yttrium abundance in the Sun (e.g., Arlandini et al., 1999; Travaglio et al., 2004). Yttrium can also be synthesized in the r-process.

Zirconium and lanthanum owe their origin to the s-process.

Europium is a typical rapid neutron capture element (the r-process). Ninety-four percent of the europium abundance in the Sun is provided by the r-process (Bisterzo et al., 2017). It is believed that the synthesis of the bulk amount of the atoms of rapid neutron capture elements occurs during explosions of type-II supernovas with masses 8 – $10M_\odot$ (Marsakov et al., 2019a). Although particular mechanisms of the production of r-process elements have not yet been entirely understood, they in any case are associated with the final stages of the evolution of short-lived massive stars (Thielemann et al., 2011).

3 INITIAL DATA

For our analysis of the behavior of the above chemical elements in Galactic-field RR Lyrae type stars we used the spectroscopic determinations of metallicity and relative abundances of titanium, yttrium, zirconium, lanthanum, and europium for one hundred field RR Lyraes from our compiled catalog described in Marsakov et al. (2018a). The catalog is available at [http://vizier.ustrasbg.fr/viz-bin/VizieR?-source=J/AZh/95/54](http://vizier.ustrasbg.fr/viz-bin/VizieR?-source=J/AZh/95/54). The $[\text{Fe/H}]$ and $[\text{el/Fe}]$ relative abundances in this catalog are compiled from 25 publications, and the case of two or more determinations by different authors the weighted averages are computed and reduced to the common solar abundance (see Gozha et al., 2018).

We added to these data relative scandium abundances $[\text{Sc/Fe}]$ for 77 RR Lyraes adopted from 15 papers published from 1995 through 2017. The original studies used high-resolution spectra,
which were analyzed in terms of LTE approximation. The scandium abundances for 31 stars were determined in several (two to four) papers. In those cases, we computed the weighted averages with the coefficients inversely proportional to the errors quoted by the authors. The authors of several papers did not provide errors of their [Sc/Fe] determinations, and in those cases we set the uncertainties equal to 0.1 dex when computing the weighted averages. To homogenize the data, we reduced the [Sc/Fe] determinations to the solar abundance from Asplund et al. (2009). Note that as a result we obtained an impressive list of relative [Sc/Fe] abundances in the atmospheres of RR Lyraes and we found no other published list of comparable size.

Table 1 lists the compiled scandium abundances and the averages that we computed. Column 1 gives the name of the star. Column 2 gives the [Fe/H] values for 68 RR Lyraes of our catalog (Marsakov et al., 2018a) and for nine RR Lyraes from Sneden et al. (2017), six of which are not included into our catalog and three other stars lack chemical-composition determinations in Marsakov et al. (2018a): these RR Lyraes are marked by the asterisk in the Table. The next column gives the final [Sc/Fe] values. The last column gives the references to the [Sc/Fe] data sources. The literature used to determine [Fe/H], [Ti/Fe], and [Y/Fe] is listed in catalog (Marsakov et al., 2018a).

For comparison, we used several samples of field stars with known metallicities and relative scandium, titanium, and yttrium abundances. We adopted the data for 7066 nearby dwarfs, subgiants, and turn-off stars of disk subsystems from Buder et al. (2019). Catalog by Reddy et al. (2006) served as the source of [Fe/H] and [Sc/Fe] for 171 F–G-type dwarfs located within 150 pc from the Sun, which in most cases belong to the thick Galactic disk (with [Fe/H] ≈ −1.0). The catalog from Venn et al. (2004) lists metallicities, relative titanium and yttrium abundances for 781 field stars spanning a wide range of metallicities coincident with the metallicity range for field RR Lyraes. We adopted the relative abundances of the elements considered in 435 Cepheids from Luck (2018).

4 ERRORS OF THE DETERMINATION OF RELATIVE ABUNDANCES OF CHEMICAL ELEMENTS

In the spectra of RR Lyraes – periodic pulsating variables – the most symmetric and sharp lines, which are best suited for elemental abundance determinations, form near the phase of minimum light and maximum radius of the star (φ ≈ 0.35), when shocks do not propagate across the atmosphere (e.g., Sneden et al., 2011). Most of the spectra used for analyzing the lines of the elements considered in the original studies were acquired near the quiescent phase of minimum light. However, the relative abundances of most of the chemical elements, including those studied in this paper, are shown to be practically independent of phase (unlike the temperature and surface gravity) (see Pancino et al., 2015, and references therein).

Table 2 gives the statistical information about the abundances of the elements considered in this paper and their errors. The second column gives the number of RR Lyraes with known relative abundances of the corresponding element. The next column gives the mean error computed from the uncertainties quoted in the original papers. The fourth column gives the standard deviation of the computed weighted mean relative abundances for the cases of two or more determinations of the abundance of each element for a particular star. This standard deviation provides an estimate for the external agreement of [el/Fe] determinations by different authors. As is evident from the Table, the standard deviation of the computed weighted average values is smaller than the average errors quoted by the authors of the original papers. We plot the histograms of the deviations of published abundances for scandium, titanium, and yttrium from the corresponding computed weighted averages in Fig. 1. Unfortunately, the number of overlapping determinations is small, especially for yttrium. The resulting distributions are single-peaked and can be described by the normal law, and this fact allows us to view errors as random. Hence our computed weighted average abundances of scandium, titanium, and yttrium and the single determinations of relative abundances of these elements compiled from original papers can be considered reliable and can be used to analyze the behavior of [el/Fe] in RR Lyrae type variables.
5 COMPARATIVE ANALYSIS OF THE RELATIVE ABUNDANCES OF SC, TI, AND Y IN METAL–RICH FIELD STARS OF VARIOUS TYPES

To clarify the causes of anomalously low [Sc/Fe], [Ti/Fe], and [Y/Fe] abundance ratios, we compare the abundances of the said elements in metal-rich RR Lyraes and other groups of stars, both stationary and variable. This will also allow us to see how justified are the explanations of the behavior of [el/Fe] of the selected elements in the above papers. Fig. 2 shows the positions of RR Lyrae type variables (the large red circles) on the [Fe/H] - [el/Fe] diagrams for scandium (panels a,d, and g), titanium (panels b,e, and h), and yttrium (panels c,f, and i). The vertical dashed line drawn through [Fe/H] = −1.0, subdivides stars into two groups by metallicity. As is evident from the figure, in all panels in Fig. 2 RR Lyraes are located along the strip, which in the domain [Fe/H] > −1.0 goes below the domains occupied by the comparison stars (see below). A clear dependence of [Sc/Fe], [Ti/Fe], and [Y/Fe] on [Fe/H] is immediately apparent so that the abundances of all the elements considered decrease with increasing metallicity.

The positions of comparison stars are shown in all panels in Fig. 2. In Figs. 2a, 2b, 2c we added 7066 nearby dwarfs, subgiants, and turnoff stars of the disk subsystems from Buder et al. (2019). All stars of this large catalog except four stars with known [Sc/Fe], ten stars with [Ti/Fe], and ten stars with [Y/Fe], have [Fe/H] > −1.0. The large number of metal-rich stars is what makes it convenient to compare the behavior of metal-rich RR Lyraes with the stars of this catalog. Most of the metal-rich RR Lyraes in the [Fe/H]–[Sc/Fe] (Fig. 2a) and [Fe/H]–[Y/Fe] (Fig. 2c) diagrams lie below the domain occupied by stars from Buder et al. (2019). The only exceptions are two stars – KP Cyg and TV Lib, which lie inside the domain of comparison stars. However, we already wrote about the peculiarities of the abundances of other elements and about the anomalously high velocity of the rotation of these stars about the Galactic center in our earlier paper (Marsakov et al., 2018a). Metal-rich RR Lyraes in the “[Ti/Fe] – [Fe/H]” diagram (Fig. 2b) lie below the comparison stars, and only four metal-rich RR Lyraes are located inside the compact region occupied by stationary field stars. Note scandium and yttrium abundances are determined only from lines of ionized Sc II and YII atoms, whereas the titanium abundances are in most of the cases determined by averaging the measurements based on lines of neutral and ionized titanium (Ti I and Ti II) (see discussion below).

Figures 2d, 2e, 2f shows the refined positions of the [el/Fe] ratios of stars and field RR Lyraes in the low metallicity domain. In Fig. 2d we had to plot, for comparison, the [Sc/Fe] ratios for 171 nearby F-G-type dwarfs from catalog by Reddy et al. (2006), which include only 15 metal-poor objects. On the other hand, Figs. 2e, 2f shows 781 field stars from Venn et al. (2004) spanning the same metallicity range as field RR Lyraes (we could not find scandium abundance determinations by these authors). We can see that in the [Fe/H] < −1.0 interval the loci of RR Lyraes and comparison stars coincide in panels (d–f) of Fig. 2. On the other hand, at higher metallicities, like in the case of the comparison with the data from Buder et al. (2019), the relative scandium, titanium, and yttrium abundances in most of the RR Lyraes are lower than in stationary comparison stars beyond the quoted errors.

It was repeatedly argued that anomalously low abundances of some elements in metal-rich RR Lyraes are found because stationary stars are used for comparison. Such peculiarities were believed to be due to pulsations of the atmospheres of variable stars. Let us now see how the [Sc/Fe], [Ti/Fe], and [Y/Fe] ratios depend on metallicity for RR Lyraes compared to similar dependencies for Cepheids, which represent a different type of radially pulsating variables. Panels (g–i) in Fig. 2 show 435 Cepheids from Luck (2018). All these Cepheids (except one) are metal rich and populate rather compact regions on the diagrams. As is evident from the figures, Cepheids are located significantly above the strip of metal-rich RR Lyraes (this is especially apparent for scandium and yttrium). The average relative abundances for Cepheids are ⟨[Sc/Fe]ceph⟩ = 0.33 ± 0.01, ⟨[Ti/Fe]ceph⟩ = 0.13 ± 0.01, ⟨[Y/Fe]ceph⟩ = 0.20±0.01, whereas the average relative abundances of the same elements in stationary comparison stars are either equal to the corresponding solar values or higher by 0.1 dex, whereas in the
metallicity interval occupied by Cepheids ([Fe/H] > −1.0) the relative abundances in field RR Lyraes are equal to ⟨[Sc/Fe]_{RRL}⟩ = −0.34 ± 0.04, ⟨[Ti/Fe]_{RRL}⟩ = −0.08 ± 0.04, ⟨[Y/Fe]_{RRL}⟩ = −0.44 ± 0.06. It is clear that the differences between the abundances in RR Lyrae type variables with [Fe/H] > −1.0 and the corresponding abundances in Cepheids far exceed observation errors. We do not believe that such low relative abundances of the elements considered in metal-rich RR Lyraes could be due to the fact that these stars are pulsating variables.

6 INFLUENCE OF NLTE EFFECTS ON THE DETERMINATION OF ELEMENTAL ABUNDANCES

It is conceivable that the differences between abundances of metal-rich RR Lyraes and comparison stars could be due to nLTE effects. Thus Asplund (2005) argue that giants are more subject to deviations from LTE than, e.g., dwarfs. However, our comparison stars also include giants, and Cepheid surface gravities are often weaker than those of RR Lyraes. Note that the [Sc/Fe], [Ti/Fe], and [Y/Fe] ratios in Cepheids are much higher than in RR Lyraes of similar metallicities.

Deviations from LTE are also believed to have stronger effect on lines of neutral atoms than on ion lines (e.g., Bergemann, 2011; Hansen et al., 2011). The authors of the papers that served as data sources for relative abundances [el/Fe] used only lines of ionized elements Sc II and YII to determine the scandium and yttrium abundances, and computed the [Ti/Fe] ratios using both neutral and ionized titanium lines (Ti I and Ti II). The authors of most of the original papers determined the [Ti/Fe] ratios by as averages of [Ti I/Fe] and [Ti II/Fe]. We used a similar procedure in the cases where the paper provided separate [Ti I/Fe] and [Ti II/Fe] measurements and then computed the weighted average of the data provided by different sources. An analysis of the data from the papers used in this study shows constant offset between [Ti I/Fe] and [Ti II/Fe], so that the abundances inferred from Ti I are usually higher than those inferred from Ti II. For and Sneden (2010); For et al. (2011); Pancino et al., (2015) obtained a similar result. For and Sneden (2010); For et al., (2011) suggested that such an offset is likely to be due to the uncertainty of log gf values for Ti I lines. Bergemann (2011) strongly suggest that [Ti/Fe] ratios for giants should be computed using solely the data for Ti II lines, however, they also point out that nLTE effects on the Ti I abundance shows up mostly in stars with low metal abundance. Our sample of metal-rich RR Lyraes include cases of slight differences between the relative abundances of Ti I and Ti II, which are mostly within the errors. Note that the above pattern persists even if we use only [Ti II/Fe] abundance ratios.

Apparenty, the uniqueness of the chemical composition of metal-rich RR Lyraes cannot be explained by nLTE effects.

7 EUROPIUM, ZIRCONIUM, AND LANTHANUM ABUNDANCES

As is well known, SNe II eject r-process elements and, in particular, europium, along with α-elements. That is why the relative abundances of this easily measured element behave like α-elements as a function of metallicity, allowing the behavior of the [el/Fe]– [Fe/H] dependence to be more reliably determined from only one type of chemical elements. Unfortunately, no europium or other r-element abundances could be found for any field RR Lyrae with [Fe/H] > −1.0. At the same time, europium abundances are reliably determined for other metal-rich variables Cepheids. The [Eu/Fe] ratios in Cepheids are the same as in field dwarfs and giants (Marsakov et al., 2013). What is the case of the lack of data about europium abundances in metal-rich RR Lyraes? Perhaps the authors of original papers did not attempt to determine these abundances. However, it might be possible that the europium abundance in metal-rich RR Lyraes is too small for its abundances to be determined. Note that r-process elements form in type II supernovas with masses 8 – 10M⊙, whereas more massive supernovas mostly eject α-elements (see, e.g., Woosley et al., 1994). We can therefore assume that the matter from which metal-rich RR Lyraes formed was enriched mostly by massive SNe II.
We also pointed out the lack of the abundances of such s-elements as lanthanum and zirconium in metal-rich RR Lyraes in our catalog (Marsakov et al., 2018a). On the other hand, La and Zr abundances have been determined in equally metal-rich Cepheid variables and proved to be high. Note that europium, lanthanum, and zirconium abundances are known for some metal-poor RR Lyraes. Further studies are needed to clarify the cause of the lack of the determinations of the abundances of these elements in metal-rich RR Lyraes.

8 CONCLUSIONS

Thus the anomalously low relative abundances of scandium, titanium, and yttrium in metal-rich Galactic RR Lyraes cannot be explained by the errors of their determination. These low abundances can neither be explained by effects arising in non-stationary atmospheres of the stars considered. Such low abundances are unlikely to be due to effects associated with deviations from local thermodynamical equilibrium. We also do not understand the lack of data about europium, lanthanum, and zirconium abundances in metal-rich RR Lyraes.

It appears that RR Lyraes inherited the aforementioned abundances of the elements considered from the parent interstellar matter. Earlier we showed that low residual velocities and close-to-solar chemical composition of metal-rich RR Lyraes indicate that they belong to the subsystem of the thin Galactic disk. This implies such a small age of these stars that they could have reached the horizontal branch only in the case of high initial helium abundances (Marsakov et al., 2018a). Based on the above, it is conceivable that metal-rich field RR Lyraes must have formed from interstellar matter with the chemical evolution history different from that of the parent interstellar matter of most of the field stars in the solar vicinity. We suggested in our previous papers that such helium-rich stars could have come to the solar neighborhood as a result of radial migration from central regions of our Galaxy, where such stars have already been found (Marsakov et al., 2019a), or as a result of the capture of a massive companion dwarf galaxy during early stages of the evolution of our Galaxy (Marsakov et al., 2020).

ACKNOWLEDGMENTS

We are grateful to T.V. Mishenina for reading the manuscript and valuable advice.

FUNDING

The research was financially supported by the Southern Federal University, 2020 (Ministry of Science and Higher Education of the Russian Federation).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Figure 1: Distribution of the deviations $\Delta[\text{el/Fe}]$ of published values from the corresponding weighted averages for relative abundances of scandium (a), titanium (b), and yttrium (c). The histograms are described by Gaussians. The standard deviations are given on all panels.

Figure 2: Relative abundances of scandium, titanium, and yttrium as a function of metallicity for Galactic-field RR Lyrae type variables (the large red circles). Comparison stars: small gray dots—nearby dwarfs, subgiants, and turn-off stars from Buder et al. (2019) (a–c); gray snowflake symbols—nearby F–G-type dwarfs of the disk subsystems from Reddy et al. (2006) (d); gray straight crosses—stars of various subsystems from Venn et al. (2004) (e, f); gray slanted crosses—cepheids from Luck (2018) (g–i). Vertical dashed lines separate metal-rich and metal-poor stars. Also shown are error bars of weighted average [el/Fe] estimates for RR Lyraes.
Table 1: Metallicities and relative scandium abundances in Galactic-field RR Lyrae type variables
(References: 1 – Andrievsky et al. (2010), 2 – Chadid et al. (2017), 3 – Clementini et al. (1995), 4 – Clementini et al. (2000), 5 – Di Fabrizio et al. (2002), 6 – For and Sneden (2010), 7 – For et al. (2011), 8 – Govea et al. (2014), 9 – Hansen et al. (2011), 10 – Kolenberg et al. (2010), 11 – Liu et al. (2013), 12 – Preston et al. (2006a), 13 – Preston et al. (2006b), 14 – Roedder et al. (2014), 15 – Sneden et al. (2017).)

| Star          | [Fe/H], dex | [Sc/Fe], dex | References | Star          | [Fe/H], dex | [Sc/Fe], dex | References |
|--------------|-------------|--------------|------------|--------------|-------------|--------------|------------|
| SW And       | -0.22       | -0.40        | 3, 11      | V Ind        | -1.45       | -0.02        | 2          |
| CI And       | -0.43       | -0.28        | 11         | SS Leo       | -1.75       | 0.03         | 2          |
| WY Ant       | -1.88       | 0.10         | 2, 7       | ST Leo       | -1.31       | -0.10        | 2          |
| XZ Aps       | -1.79       | 0.06         | 2, 7       | CM Leo       | -1.93       | 0.36         | 5          |
| BS Aps       | -1.48       | 0.00         | 2, 7       | TV Lib       | -0.43       | 0.12         | 11         |
| AA Aql       | -0.32       | -0.22        | 11         | RR Lyr       | -1.49       | 0.03         | 3, 10, 11  |
| SW Aqr       | -1.38       | -0.17        | 2          | CN Lyr       | -0.04       | -0.32        | 11         |
| BR Aqr       | -0.69       | -0.45        | 11         | IO Lyr       | -1.35       | -0.03        | 11         |
| DN Aqr       | -1.76       | 0.01         | 2          | KX Lyr       | -0.42       | -0.36        | 11         |
| FV Aqr       | -2.59       | 0.25         | 14         | Z Mic        | -1.51       | -0.03        | 2, 7       |
| X Ari        | -2.51       | 0.28         | 2, 3       | RV Oct       | -1.64       | -0.02        | 2, 7       |
| ASAS J085254-0300.3 | -1.53 | 0.12         | 8, 15      | UV Oct       | -1.75       | -0.01        | 2, 7       |
| ASAS J101332-0702.3* | -1.73 | -0.12        | 15         | V 413 Oph    | -0.75       | -0.27        | 11         |
| ASAS J132225-2042.3* | -0.96 | -0.27        | 15         | V 445 Oph    | 0.11        | -0.46        | 2, 3, 11   |
| ASAS J143322-0418.2* | -1.48 | -0.02        | 15         | AO Peg       | -1.26       | 0.00         | 11         |
| ASAS J203145-2158.7* | -1.17 | -0.68        | 15         | AV Peg       | -0.19       | -0.43        | 2          |
| ASAS J162158+0244.5 | -1.84 | 0.12         | 8, 15      | DH Peg       | -1.31       | -0.01        | 11         |
| RS Boo       | -0.21       | -0.37        | 11         | HH Pup       | -0.93       | -0.71        | 2          |
| ST Boo       | -1.73       | 0.05         | 3          | V 701 Pup    | -2.90       | 0.31         | 8, 15      |
| BPS CS 22881-039 | -2.72 | 0.20         | 6, 9, 13, 14 | SV Scl*   | -2.28       | 0.03         | 15         |
| BPS CS 22940-070 | -1.41 | 0.08         | 6, 14      | VY Ser       | -1.78       | 0.05         | 2, 3, 11   |
| BPS CS 30317-056 | -2.85 | 0.16         | 9          | AN Ser       | 0.00        | -0.51        | 2          |
| BPS CS 30339-046 | -2.70 | 0.12         | 14         | V 456 Ser    | -2.64       | 0.10         | 14         |
| YZ Cap       | -1.50       | -0.01        | 8, 15      | T Sex        | -1.55       | 0.13         | 15         |
| RR Cet       | -1.48       | 0.13         | 2, 3, 11   | RU Sex*      | -2.1        | 0.17         | 15         |
| UU Cet       | -1.36       | 0.02         | 3, 11      | V 440 Sgr    | -1.16       | -0.11        | 3, 11      |
| CU Com       | -2.38       | 0.24         | 4          | V 1645 Sgr   | -1.94       | -0.01        | 2, 7       |
| W Crt        | -0.75       | -0.24        | 2          | MT Tel*      | -2.58       | 0.3          | 15         |
| Y Crv*       | -1.39       | -0.03        | 15         | W Tuc*       | -1.76       | 0.02         | 2          |
| DM Cyg       | 0.03        | -0.48        | 11         | TYC 4887-622-1 | -1.79   | 0.10         | 8, 15      |
| KP Cyg       | 0.15        | -0.02        | 1          | TYC 6644-1306-1 | -1.78   | 0.25         | 8, 15      |
| DX Del       | -0.31       | -0.35        | 2, 11      | TYC 8776-1214-1 | -2.72   | 0.11         | 8, 15      |
| CS Eri       | -1.70       | -0.13        | 15         | CD Vel       | -1.67       | 0.02         | 2, 7       |
| SX For       | -1.80       | -0.02        | 2          | ST Vir       | -0.85       | -0.24        | 2          |
| TY Gru       | -1.88       | 0.03         | 7, 12      | UU Vir       | -0.86       | -0.59        | 2          |
| BO Gru       | -1.83       | 0.00         | 8, 15      | AS Vir       | -1.68       | -0.07        | 2, 7       |
| TW Her       | -0.35       | -0.35        | 11         | AU Vir*      | -2.04       | 0.32         | 15         |
| VX Her       | -1.46       | -0.13        | 3, 11      | DO Vir       | -1.57       | 0.09         | 11         |
| DT Hya       | -1.23       | 0.00         | 2, 7       | -           | -           | -           | -          |
| Element | Number of stars | Average quoted error | Standard deviation of the quoted mean |
|---------|-----------------|----------------------|---------------------------------------|
| Fe      | 100             | 0.14                 | 0.12                                  |
| Sc      | 77              | 0.14                 | 0.07                                  |
| Ti      | 83              | 0.13                 | 0.05                                  |
| Y       | 43              | 0.11                 | 0.07                                  |