10.1515/astro-2017-0199

Baltic Astronomy, vol. 24, 24–29, 2015

ABUNDANCES OF CHEMICAL ELEMENTS IN OPEN STAR CLUSTERS AS INDICATORS OF THEIR NATURE

V. A. Marsakov[1], M. L. Gozha[1], V. V. Koval'[1] and L. V. Shpigel'[2]

[1] *Southern Federal University, Bolshaya Sadovaya 105/42, Rostov-on-Don, 344006, Russia; marsakov@sfedu.ru*

[2] *Institute of Astronomy of the Russian Academy of Sciences, Pyatnitskaya 48, Moscow, 119017, Russia*

Received: 2014 November 23; accepted: 2014 December 19

Abstract. Applying a compilled catalog, we find that the relative abundances of α-elements in open clusters and in field stars of the thin disk of the Galaxy show different dependencies on metallicity, age and parameters of their Galactic orbits. The distinctions are explained by different nature of open clusters and field stars. We confirm the conclusions, reached earlier from the analysis of the parameters of Galactic orbits, that some clusters may have formed from the impact of metal-poor high-velocity clouds on the interstellar matter of the thin disk. Arguments are also adduced in favor of the formation of metal-rich high-velocity clusters from the interaction of metal-rich intermediate-velocity clouds formed from returning gas of the Galactic “fountain” with the interstellar medium of the thin disk.

Key words: stars: red giants – Galaxy: disk – open clusters: abundances, kinematics

1. INTRODUCTION

Relative abundances of chemical elements [α/Fe] in stellar atmospheres carry information about the chemical evolution of the interstellar medium from which the stars were formed. According to modern concepts, the bulk of α-elements are ejected into the interstellar medium as a result of Type II supernova explosions. A number of atoms of iron-peak elements are also formed during Type II supernova events. The bulk of iron-group elements are produced in explosions of less massive Type Ia supernovae. The evolution time of massive stars does not exceed ~ 30 Myr, and massive explosions of Type Ia supernovae occur only within about 1–1.5 Gyr; thus, from this time onwards, the relative [α/Fe] abundances decrease with further metallicity increase for new generations of stars. Therefore, the relative abundances of α-elements in stars of different age can track the history of star formation in star-gas systems.

Open star clusters, typical representatives of the thin disk of the Galaxy, are often used for the analysis of its spatial structure and chemical properties. However, studies of their Galactic orbital parameters and metallicity indicate that the population of open clusters is not homogeneous and, among them, there are clusters formed partially out of the interstellar matter that had fallen from external

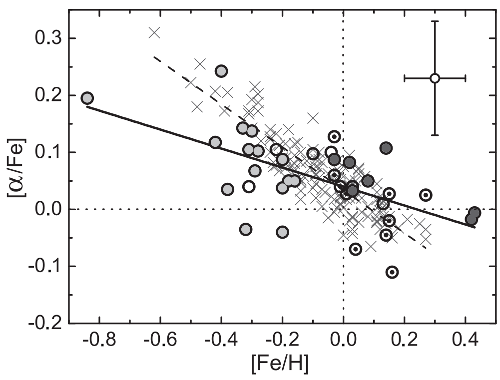

Fig. 1. Relative abundances of α-elements vs. metallicity diagram for field giants (oblique crosses) and open clusters (circles). The clusters with circular, low $Z_{\max}$ orbits are indicated by circled dots; the clusters with eccentric, high $Z_{\max}$ orbits are represented by filled symbols: light-gray circles are for metal-poor ([Fe/H] < -0.1) clusters and dark-gray circles for metal-rich ([Fe/H] > -0.1) ones; the hollow circles denote unclassified clusters. The solid and dashed lines are the regression lines for the clusters and field giants, respectively. The error bar for the clusters is shown in the upper right corner.

volumes of the Galaxy (see Vande Putte et al. 2010; Gozha et al. 2012a,b and references therein). Therefore, it is interesting to compare the behavior of the relative abundances of chemical elements in clusters and field stars; they can differ from each other.

2. INITIAL DATA

We adopted the catalogue of fundamental parameters of open clusters[1] as the main source of data for the open clusters. This catalogue was compiled by us on the basis of the latest published data. We supplemented these data with relative abundances of four α-elements (O, Mg, Si and Ca) in the stars of 38 clusters. These relative abundances are taken from 72 sources published from 1994 to 2013. The uncertainties in the relative abundances of these elements declared in the sources are in the range $\varepsilon[\alpha/\mathrm{Fe}] = 0.06 - 0.09$.

For comparison, we used the abundance determinations of the same elements in 171 field red giants from Mishenina et al. (2006, 2007, 2013). In the cited papers, the uncertainties of abundance determinations for all elements are less than 0.15 dex. Distances and proper motions for all of these stars can be found in the new *Hipparcos* catalogue (van Leeuwen 2007), and radial velocities were taken from a variety of literature sources. Using these data, we calculated the parameters of Galactic orbits in a model Galaxy potential by Flynn et al. (1996). We calculated ages of the red giants (in years) using the formula that estimates the lifetime within the main sequence for stars with solar metallicity:

$$\log t = 10 - 3.6 \log(M/M_{\odot}) + \log^2(M/M_{\odot}). \qquad (1)$$

[1] The catalogue is available in electronic form at http://vizier.u-strasbg.fr/cats/J.PAZh.htx

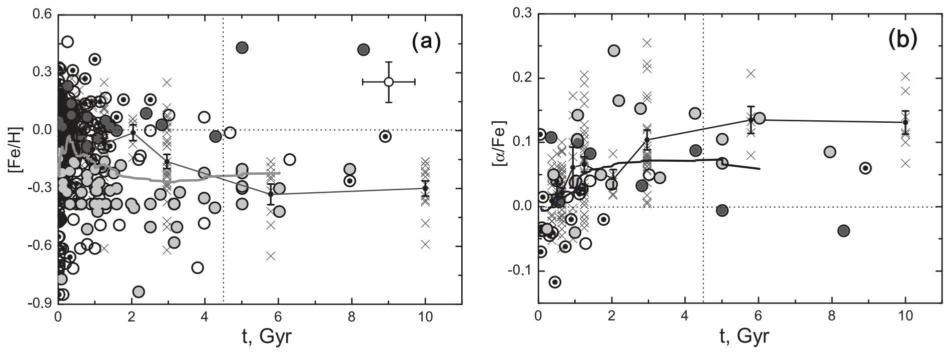

Fig. 2. Metallicity [Fe/H] and relative abundance of α-elements vs. age. The solid curve is the dependence for the open clusters, smoothed using sliding averages, and the polygonal line is that for the field giants. Dots with error bars are the average values of abundance for the field giants in the various age intervals. The symbols are the same as in Fig. 1.

3. DEPENDENCIES OF THE RELATIVE ABUNDANCE OF α-ELEMENTS ON METALLICITY, AGE AND ORBITAL PARAMETERS

The dependencies of average relative abundances of four α-elements on metallicity for the open clusters and field giants are displayed in Fig. 1. It demonstrates that the clusters with [Fe/H] < -0.1 show too low [α/Fe] ratios and the metal-richer ones show slightly higher ratios compared to field stars. At low metallicities, the clusters are deficient; thus, we observe that the entire population is divided into two groups. This feature is caused only by the behavior of the clusters with eccentric, high $Z_{\max}$ orbits, while the "Galactic" clusters, i.e. those with circular, low $Z_{\max}$ orbits, lie almost entirely in the region occupied by the field stars.

Fig. 2a shows the metallicity vs. age plot for the open clusters and field red giants. For the giants, we are able to find only the lower age limit from their mass-age relation, which in the original sources is given only to the first decimal place; thus, the diagram became discrete. To compare the behavior of the "age – metallicity" dependencies for the open clusters and field giants, it is preferable to approximate the relations with polygonal lines connecting the mean metallicities in nine intervals along the age axis for the field giants and with smoothed curves based on sliding averages for the open clusters. The behavior of the field red giants in Fig. 2a is consistent with that of the field dwarfs (see Marsakov et al. 2011); there is a systematic decrease in the mean metallicity for ages up to 5 Gyr, whereas the relation becomes flat with further increase in age. It appears from the figure that, in general, there is no correlation between age and metallicity for the clusters, though the average metallicity varies in a complex way with increasing age. Unlike the "age – metallicity" relation for the field stars, which reflects evolutionary changes in the chemical composition of the interstellar medium in the thin disk, for star clusters it is due to the distinction in the lifetime of clusters with different orbits (see Gozha et al. 2012b).

The "age vs. relative abundance of α-elements" diagram for the open clusters and field giants is presented in Fig. 2b. The figure shows that for the younger objects of both types the relative abundances of α-elements are, on average, solar. Then both relations show the tendency of α-elements to increase with increasing

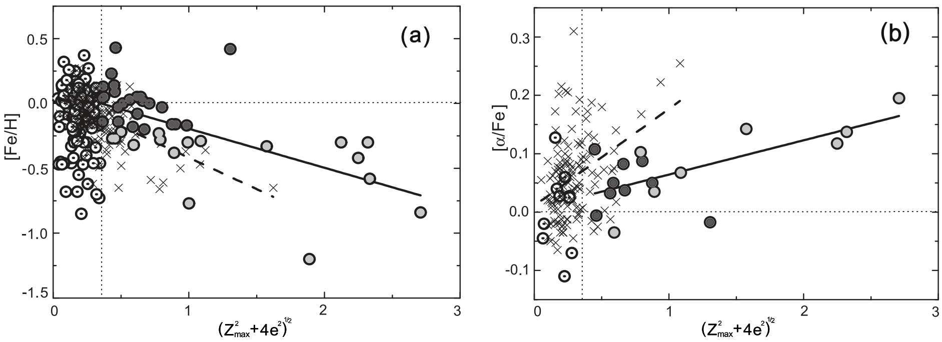

Fig. 3. Metallicity [Fe/H] and relative abundance of α-elements vs. the orbital parameter $(Z^2{}_{\max} + 4e^2)^{1/2}$. The symbols are as in Fig. 1. The thin horizontal line represents solar abundance; the vertical line marks the division of the clusters into "galactic" and "peculiar" at $(Z^2{}_{\max} + 4e^2)^{1/2} = 0.35$.

age up to about 2 Gyr; however, the increase in $[\alpha/\mathrm{Fe}]$ for clusters stops at about $+0.07$ dex, while that for field giants continues to ~ 4.5 Gyr and stops having reached $[\alpha/\mathrm{Fe}] \approx +0.13$ dex.

Fig. 3 shows the dependence of metallicity and relative abundances of α-elements in the clusters and field stars on the orbital parameter $(Z^2{}_{\max} + 4e^2)^{1/2}$, where $Z_{\max}$ is measured in kiloparsecs. In both panels, the boundary separating the clusters with large values of this orbital parameter, atypical of the thin-disk field stars according to Gozha et al. (2012a,b), is marked with a vertical line. As in the previous two figures, the clusters with eccentric, high $Z_{\max}$ orbits are shown by filled symbols: light-gray circles represent the metal-poor clusters and dark-gray circles are for metal-rich ones. Direct regressions for "peculiar" clusters with $(Z^2{}_{\max} + 4e^2)^{1/2} > 0.35$ are plotted in the diagrams as solid lines. The slopes of the relations for the clusters and field stars (dashed lines) diverge from one another, with the difference far beyond the error limits. As is evident from the diagrams, the dependencies of chemical abundance on this kinematical parameter are produced by the clusters with eccentric, high $Z_{\max}$ orbits. Moreover, our analysis shows that a greater contribution to the above orbital parameter comes from the maximum distance $Z_{\max}$ that a star (cluster) can reach from the Galactic plane and not from eccentricities of the orbits.

4. DISCUSSION

Our analysis shows that the relative abundances of α-elements in the stars of open clusters and those in the field stars exhibit different dependencies not only on metallicity but also on age, galactocentric distance, and parameters of Galactic orbits. The detected distinctions testify, with a high probability, to a difference in histories of chemical evolution of the interstellar matter from which these objects were formed. The vast majority of field stars of the thin disk may be genetically related, as they were formed from interstellar matter of this subsystem of the Galaxy; and the dependencies of the relative abundances of chemical elements in the stars on the parameters mentioned above reflect the chemical evolution. On the other hand, among the clusters considered, only the "Galactic" clusters, i.e. which are metal-rich ($[\mathrm{Fe/H}] \geq -0.2$) and move on circular, low $Z_{\max}$ orbits

$((Z^2{}_{\max} + 4e^2)^{1/2} < 0.35)$, might have been formed from the same material as the field stars according to Gozha et al. (2012b). This assumption is confirmed by the fact that, in all of the diagrams (Figs. 1–3), the "Galactic" clusters lie mainly within the regions occupied by field stars of the thin disk. At the same time, young clusters with circular, low $Z_{\max}$ orbits and with metallicities atypically low for field stars of the thin disk could have been formed, for example, from the matter of the Magellanic Stream, mixed partly with interstellar medium of the thin Galactic disk. However, detailed chemical analysis of the atmospheres of stars of all these very distant clusters is complicated, since their red giant branches have not yet formed, and their dwarf stars are too faint to obtain detailed spectroscopic information.

The clusters with eccentric orbits that climb high above or below the Galactic plane demonstrate the behavior different from the field stars practically in each of the diagrams considered. For example, the abundances $[\alpha/\text{Fe}]$ are, on average, lower for the clusters with $[\text{Fe/H}] < -0.1$ than for field giants of the thin disk (see Fig. 1). All such metal-poor clusters with known space velocities move on eccentric, high $Z_{\max}$ orbits (plotted as light-gray circles in the figures). However, we see that the clusters with such orbits, even at higher metallicity, have, on average, slightly smaller $[\alpha/\text{Fe}]$ ratios, whereas a significant decrease in $[\alpha/\text{Fe}]$ ratios with increasing [Fe/H] is observed for the field stars. As a result, the relative abundances of α-elements in such metal-rich clusters are higher than in the field giants of the same metallicity. The clusters with high values of orbital parameters, both metal-poor and metal-rich ones, are mostly older than 1 Gyr (see Fig. 2b). Finally, significant correlations of metallicity [Fe/H] and relative abundance of α-elements with the orbital parameters are observed for the clusters with $(Z^2{}_{\max} + 4e^2)^{1/2} > 0.35$: the more the orbits differ from circular and the higher the outermost points of their orbits rise above the Galactic plane, the lower are the metallicities and the higher are the $[\alpha/\text{Fe}]$ ratios (Fig. 3a,b). It is possible that, at their birth, such clusters get a mixture of matter of different chemical composition, proportional to the impulse. It should be noted that, differently from field stars, the current Galactocentric positions of the "peculiar" clusters are not related to the places of their birth, but are associated only with their initial velocities, which depend on the initial velocities of the high-velocity clouds they were formed from (Gozha & Marsakov 2013). All these facts support the conclusion that the metal-poor clusters with eccentric, high $Z_{\max}$ orbits really originate from a mixture of matter not only poorer in metals but also with a lowered relative abundance of α-elements; for example, they could be formed in collisions of high-velocity clouds with the interstellar medium of the thin disk. It seems that the dependence of metallicity on velocity is characteristic of the high-velocity clouds themselves: the metal-poorer clouds get to the Galactic disk from higher distances and therefore they cross the Galactic plane with higher velocities.

The existence of metal-rich clusters with eccentric, high $Z_{\max}$ orbits is usually associated with collisions of globular clusters or nuclei of disrupted dwarf galaxies with interstellar matter of the thin disk (see Vande Putte et al. 2010 and references therein). However, their relative abundances of α-elements are higher than in the field stars of the same metallicity and this fact makes us to assume that the birth of such clusters can be also triggered by metal-rich intermediate-velocity clouds which were formed from returning gas of the so-called Galactic "fountain". It is believed that the clouds with intermediate velocities contain genuine gas of the Galaxy, while the high-velocity clouds consist of primordial gas. A number of observations confirm enhanced abundances of oxygen (an α-element) in such clouds due to their formation as a result of Type II supernova explosions.

Thus, for open clusters, features of relative abundances of chemical elements produced in various processes of nuclear fusion confirm the conclusion based on the analysis of the parameters of their Galactic orbits, namely, that some clusters were formed as a consequence of impacts of metal-poor high-velocity clouds with interstellar matter of the thin Galactic disk. Moreover, the low ratios of α-elements and elements of rapid neutron capture in the open clusters with eccentric orbits indicate that these high-velocity clouds were formed from interstellar matter in which the star formation rate was lower than that near the Galactic plane. On the other hand, the formation of metal-rich clusters with eccentric, high Zmax orbits can be caused by clouds with intermediate velocities, which represent genuine gas of the Galaxy; and their enhanced relative abundances of α-elements, in comparison to field stars, can be inherited from a considerable portion of matter of these clouds coming from Type II supernovae.

ACKNOWLEDGMENTS. The work of V. A. Marsakov was supported by the Ministry of Education and Science of Russian Federation in the frame of the project part of state task No. 3.961.2014/K. The work of V. V. Koval' was carried out within the basic project part of state task No. 213.01-11/2014-5 (No. 26.63) of the Ministry of Education and Science of Russian Federation. M. L. Gozha performed the work under a grant No. 213.01-2014/013-VG from the Southern Federal University.

REFERENCES

Flynn C., Sommer-Larsen J., Christensen P. R. 1996, MNRAS, 281, 1027
Gozha M. L., Borkova T. V., Marsakov V. A. 2012a, Astron. Lett., 38, 506
Gozha M. L., Koval' V. V., Marsakov V. A. 2012b, Astron. Lett., 38, 519
Gozha M. L., Marsakov V. A. 2013, Astron. Lett., 39, 171
Marsakov V. A., Koval' V. V., Borkova T. V., Shapovalov M. V. 2011, Astron. Rep., 55, 667
Mishenina T. V., Bienayme O., Gorbaneva T. I. et al. 2006, A&A, 456, 1109
Mishenina T. V., Gorbaneva T. I., Bienayme O. et al. 2007, Astron. Rep., 84, 1
Mishenina T. V., Pignatary M., Korotin S. A. et al. 2013, A&A, 552, 128
Vande Putte D., Garnier T. P., Ferreras I. et al. 2010, MNRAS, 407, 2109
van Leeuwen F. 2007, A&A, 474, 653