OMEGA CENTAURI: GLOBULAR CLUSTER, STELLAR STREAM – DWARF GALAXY

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ABSTRACT. Data from our compiled catalogs of the spectroscopic determinations of the abundances of α-elements in the stars of field and globular clusters of the Milky Way are used to investigate the chemical evolution of the ω Cen globular cluster and of the same name moving group. It is established that the dependences of the relative abundances of α-elements on the metallicity for the stars of both the ω Cen moving group and the globular cluster coincide, which with the great probability testifies as genetic connected and belonging both to dwarf galaxy-satellite galaxy, the decomposed under the action of tidal forces of the Galaxy. It is simultaneously discovered that the metallicity functions of the stream and globular cluster demonstrate identical spread, but the positions of the maximums of distributions are spread to Δ[Fe/H] ≈ -0.5 (with the peak on the smaller metallicity in globular cluster). The following conclusions are made: 1. The descending branch of the "[Fe/H] – [α/Fe]" dependence of the ω Cen globular cluster is formed by the young metal-rich stars, which was captured from the parental dwarf galaxy. 2. The stars of the ω Cen globular cluster are absent in the same name moving group – are there located only the stars of their parental galaxy. 3. The star formation rate in the ω Cen dwarf galaxy was always considerably lower than in the our Galaxy, about which they testify the small metallicity of characteristic knee ("break point") to [Fe/H] ≈ -1.3 and steeply incidence in the relation [α/Fe] with further increase in the metallicity.

Key words: stellar chemical composition, the ω Cen globular cluster, the Centauri stellar stream, dwarf galaxy evolution.

The present situation

The ω Cen globular cluster is the most massive ($\approx 5 \cdot 10^6$ M$_\odot$) and the most uncommon cluster from approximately hundred sixty ones, which belong at present to our Galaxy. It occupies the area considerably more than lunar disk – a tidal radius is equal to $57'$. This cluster proves to be sufficiently old dynamically (value of central concentration $c = 1.61$), although with so large mass and sizes the time of two-body relaxation in it is one of the large for the globular clusters and is compared with Hubble time. The distributions of star density and velocities of stars along cluster radius cluster testify about the high probability of existence in its nucleus of such exotic object as black hole with a mass on the order of $4 \cdot 10^4$ M$_\odot$, characteristic, faster, for the nuclei of galaxies. All these qualities, and also described below chemical and kinematical properties, make to assume that this cluster was in the past the nucleus of dwarf galaxy-satellite, captured by our Galaxy and destroyed by the action of its tidal forces.

In system with the large initial mass, such as is observed in the ω Cen globular cluster, it is possible to assume sufficiently prolonged chemical evolution. And actually, the distribution of cluster stars on the photometric metallicity revealed not only the clearly expressed peak near [Fe/H] ≈ -1.6 but also the long tail, which is stretched up to [Fe/H] ≈ -0.5 with the possible peak in the environment [Fe/H] ≈ -1.2. Studies showed that the stars of metal rich tail occur $\approx 20\,\%$, moreover they more strongly are concentrated to the cluster center and prove to be kinematically colder, than the bulk of more metal-poor stars. Simultaneously, the most metal-poor population demonstrates well known anomalously high ellipticity in the direction East-West, while more metal-rich stars, on the contrary, occupy the volume, elongated in the direction North-South. Moreover, if star with [Fe/H] < -1.2 reveal the distinctly observed rotation, the more metal-rich stars is not noted rotation. The proper motions of more metal-rich stars also indicate the dynamics different from the bulk of the cluster stars. The described shape and kinematic differences difficult to pack in the framework of hypothesis about the formation of all stars of this system from united isolated proto-cloud. Therefore, became completely popular hypothesis assuming that the extremely metal-rich ([Fe/H] > -0.8) population, which comprises is less than $5\,\%$ all stars of cluster, completely it can prove to be the separate captured cluster. From other side, some authors assume that the model of heterogeneous chemical evolution with three flashes of star formation can explain a variation in the chemical composition in the cluster also.

Photometric data for more than 220 000 ω Cen stars demonstrate the very wide red giant branch, which indicates the significant spread of ages among the cluster stars. The ages of the chosen on metallicity stellar groups ($\langle$[Fe/H]$\rangle \approx -1.6$, -1.2 and < -0.5) proved to be equal to 15 ± 3, 13 ± 3 and 8.5 ± 2 Gyr, respectively. The spread of ages can come out, in particular, as a result of indicated above scenario of the capture of the small metal-rich cluster (however then it becomes obscure – as where it could be formed so metal-rich globular cluster), so also as a result the prolonged evolution of the united isolated system.

The analysis of the detailed chemical composition of cluster stars gives additional information. At the present time the different authors determined the abundances of different chemical elements (as a whole of approximately 20) more than for two and one-half hundred red giants of the ω Cen. The greatest number of determinations is obtained for α-elements, since precisely they contain the most significant information about the early stages of formation and evolution of stellar system. In particular, it is shown that the relative α-elements abundances among the ω Cen stars do not change with an increase in the metallicity up to [Fe/H]≈ -1.0 and are equal to [α/Fe]≈ 0.3. Then is observed the "characteristic break" of the dependence and the [α/Fe] relations begin to systematically decrease approximately to the solar value up to [Fe/H]≈ -0.5. Specifically, this dependence must come out in the case of the closed model of chemical evolution. Actually, according to contemporary ideas the α-elements are formed practically exclusively in the stars with masses > 8 $M_{\odot}$, being exploded after characteristic time on the order of 30 Myr as a second type supernovas. With the explosions the same stars eject a small quantity of iron atoms. However, the basic mass of the elements of iron peak is produced with the flashes of the close pairs of the smaller mass stars, which are exploded as supernovas of the type SNe Ia after the characteristic time ≈ 1 Gyr. When an epoch of this type supernova explosion begins in the system, the relative abundance of α-elements begins to decrease in the interstellar medium (and in the young stars). The presence of the characteristic knee ("break point") in the dependence [α/Fe] – [Fe/H] among the ω Cen stars evidences about the sufficiently large duration of the evolution of this system.

The Omega Centauri globular cluster not is lonely in its orbital motion around the Galactic center – the Centauri moving group, which consists of the field stars, accompanies it. As now they assume, there are several types of the moving group, which are distinguished by their origin. In particular, the results of the numerical simulation showed that the orbits of sufficiently massive satellite galaxies constantly decrease in the sizes and are moved into the Galactic plane by dynamic friction (Abadi et al., 2003). In the course of time such galaxies, after acquiring very eccentric orbits, the practically parallel to the Galactic disk, begin be intensively destroyed with the tidal forces of the Galaxy with their each passage of peri-galaktic distance, losing stars with the clearly determined orbital energies and the angular momentum. Therefore, if observer is located between apo-galaktic and peri-galaktic radii of this orbit, then tidal "tail" from the destroyed galaxy will be observed as a stellar "moving group" with the small vertical velocity components and the wide, symmetrical and frequently bimodal distribution of the radial velocities. In our recent work we (Marsakov and Borkova, 2006) isolated the stars of the Centauri moving group from the author's compiled catalog of the spectroscopic determinations of the magnesium abundances (representative of α-elements) in ≈ 800 close field F–K-dwarfs (Borkova and Marsakov, 2005). It turned out that revealed 18 stars of moving group actually demonstrate the sufficiently narrow sequence [Mg/Fe] – [Fe/H], characteristic for the genetically connected stars. Moreover the position of the "break point" of the relative magnesium abundance to [Fe/H]≈ -1.3 indicate that star formation rate in their parental galaxy was lower than in the Milky Way. Moreover star formation in this galaxy continued so for long, that its most metal-rich stars reached the value of the relation [Mg/Fe]< 0.0, i. e., even are less than in the Sun.

Thus, the variation of the relative magnesium abundances on the metallicity in the stars of globular cluster and moving group ω Cen is sufficiently similar, but to make the statistically significant conclusion about their genetic connection is impossible because of the low statistics for the stars of the moving group and small number for them of uniform determinations of the abundances of other α-elements, except magnesium. Furthermore the question remains open: are the moving group stars the remainders of the dwarf galaxy or only its nucleus, i. e., ω Cen globular cluster? Therefore the purpose of this work is the refinement of fine structure of both diagrams and fulfillments their comparative analysis on the basis of the created summary catalogs of the spectroscopic determinations of the abundances of four α-elements separately for the stars of the cluster and the moving group.

The observational data

To investigate the moving group we used the yet not published new version of our compiled catalog of

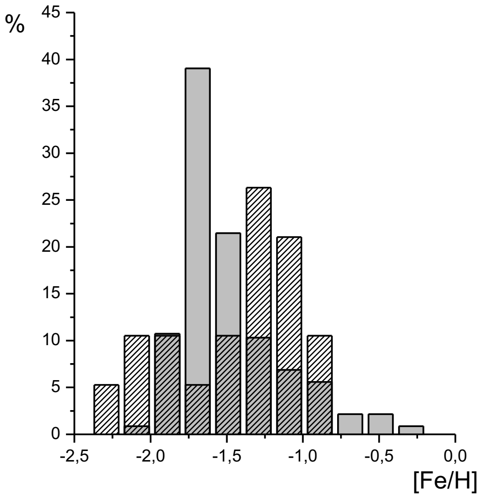

Figure 1: Distributions of stars of the Omega Centauri globular cluster grey column and the Centauri moving group (shaded column) according to the iron abundance.

the spectroscopic determinations of α-elements (magnesium, silicon, calcium and titanium) abundances, obtained by the different authors for the close field stars. In the work is used the three-pass iterative averaging procedure of the reduction of the atmospheric parameters, abundances of iron and elements of α-process with assignment of a weight both to each primary source and to each individual determination. As a result the greatest weight obtained determinations in the best way coincided with the majority of other determinations. With the determination of the atmospheric parameters and abundances of iron are used about 4700 determinations from 136 publications. The relative abundances of α-elements were obtained for $\approx$ 2000 stars on the basis of approximately 2800 determinations for each element from 81 publications. The estimated completeness for data sources with the volume is more than 5 stars to April 2008 exceeds 90 %. The internal errors in determination of the parameters the following: $\varepsilon T_{eff} = 60°$ K and 140° K; ε(log g) = 0.12 and 0.24; ε[Fe/H] = 0.06 and 0.09 for the stars with the metallicity [Fe/H] is more and less than -1.0, respectively. For the relative abundances of magnesium, calcium and silicon the corresponding values are equal to 0.07 and 0.10, whereas for titanium error in entire range of metallicity is equal to 0.15. Distances and components of space velocities for all stars are determined according to the data of contemporary high-precision astrometric and spectroscopic observations. Furthermore, for the catalog stars are calculated the elements of galactic orbits on the basis of the three-component model of the Galaxy, which consists of the disk, bulge and the massive extended halo.

For investigating the chemical composition of globular clusters we composed the compiled catalog, which uses all published spectroscopic determinations of the abundances of different chemical elements in the accessible globular clusters stars. The abundances of four α-elements and iron for more than two and one-half hundred giants of the ω Cen globular cluster were published in 4 papers. For each investigated star the atmospheric parameters and abundances of chemical elements are determined, as a rule, only once; therefore almost all given in our final list data are initial, i. e., undergone no correction. The internal accuracy of the determination of the relative abundance of each α-element we estimated by equal to $\approx$ 0.18, and the average relative abundances of all measured α-elements – $\approx$ 0.12.

Analysis of stellar chemical composition of the Centauri flow and of the Omega Centauri globular cluster

Let us compare the metallicity functions of Omega Centauri globular cluster and Centauri moving group, which arose by the hypothesis from the same destroyed dwarf galaxy. We isolates the stars of the Centauri moving group, being based on recommendations Mesa et. al., (2004), from our compiled catalog of spectroscopic determinations of α-elements abundances in field stars on the azimuthal and vertical components of their space velocities ($-50 < \Theta < 0$ km s^{-1} $|W| <$ 65 km s^{-1}, respectively). In our catalog such stars was located with 19. From the [Fe/H] – [α/Fe] diagram (Fig. 3) it is evident that all stars were arranged along the sufficiently narrow strip, which with the small metallicity ([Fe/H] ≤ -1.3) demonstrates the approximately constant quantity of the relation [α/Fe] $\approx$ 0.35, but then, with an increase in the metallicity beginning from this point, is observed a sharp drop in the relative abundance of α-elements up to the Solar one (more detail see below). This behavior is very similar to the expected dependence of the [α/Fe] on [Fe/H] relation, obtained in the closed model of chemical evolution, what is the independent evidence in favor of the genetic connection of the chosen stars. The distribution of the ω Cen globular cluster stars according to the spectroscopic determinations of the iron abundances into them and analogous distribution for the moving group stars are given in Fig. 1, where for convenience in the comparison of the distributions of different number scale along the Y-axis is given in the percentages of the total number of stars in the appropriate sample. From the comparison of distributions it is evident that the metallicity function of one object is the mirror image of another. In this case the ranges of metallicity completely coincide, whereas the maximums of distributions are spread according to the [Fe/H] scale almost by an order, i. e., far beyond the ranges of the errors in

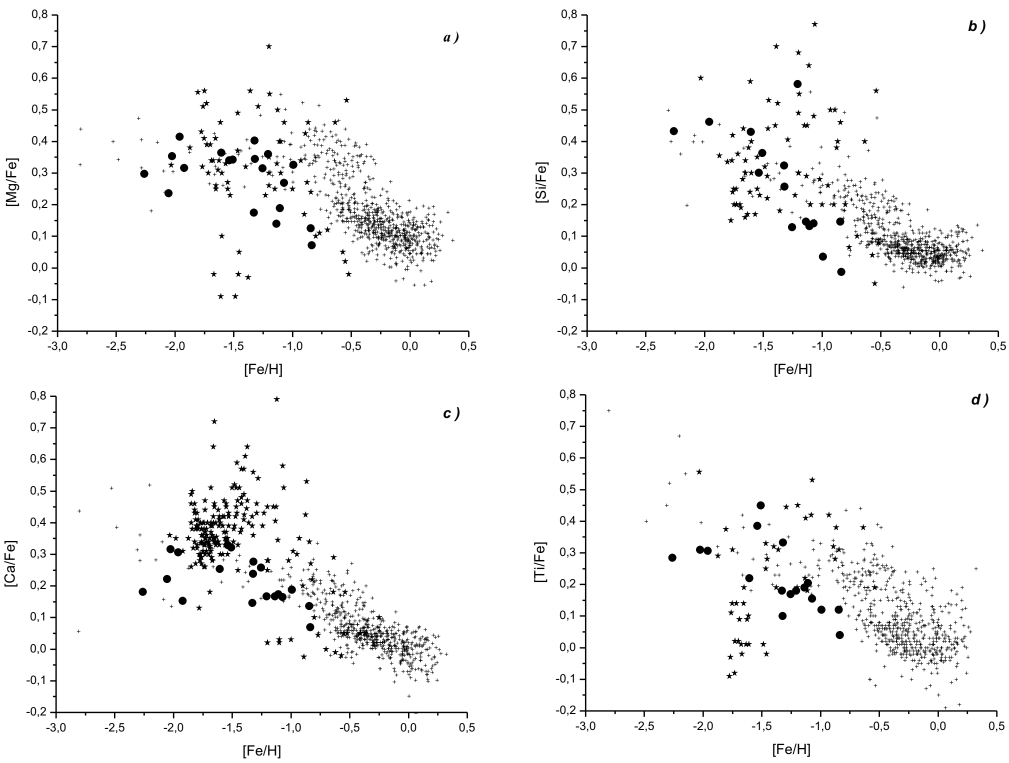

Figure 2: Metallicity – relative abundances of α-elements diagrams for magnesium (a), silicon (b), calcium (c) and titanium (g), where the star of the Centauri stream – filled circles, the ω Cen globular cluster – filled asterisk and the genetically connected field stars of the Galaxy – small crosses.

determination of this value.

The diagrams of a change in the relative abundances of four α-elements (magnesium, silicon, calcium and titanium) with an increase of the metallicity in the moving group stars and globular cluster stars are consecutively given on the panels of Fig. 2. For the comparison on all diagrams the genetically connected (i. e., formed from the matter of the united proto-galactic cloud) stars of our Galaxy are also substituted. They are selected from our compiled catalog on the local standard of rest velocity ($V_{LSR} < 240$ km s^{-1}). Stars with the higher velocities possess very high orbital energies, besides most of them demonstrates retrograde orbits, whereas precisely opposite direction of the rotation of objects around the Galactic center appears, as they assume, by the most convincing evidence against their formation from the united proto-galactic cloud. This selected stars of the Galaxy on the diagrams [Fe/H] − [α_i/Fe] of Fig. 2 for each investigated chemical element demonstrate the distinct and very similar sequences, identical special feature of which is the presence of characteristic knee in one and the same place – in the environment [Fe/H] ≈ -1.0.

The stars of the Centauri moving group in the same figure along all four α-elements also demonstrate sufficiently narrow dependences, with the clear tendency of the decrease of the relative abundance of each element with an increase in metallicity, confirming the conclusion about their genetic link. Moreover in the [Fe/H] ≈ -1.0 environment [α_i/Fe] relations in the stars of moving group they occur on the average noticeably lower than in the stars of the Galaxy - means moving group "break point" is located on the smaller metallicity. Because of a small quantity of chosen stars of the moving group and completely natural spread in the stars of the abundance of each element, is more reliable the "break point" position of group to determine an averaged abundance of all measured α- elements.

In spite of the sufficiently large number of the chemical elements abundance determinations in the atmosphere of the stars of the globular cluster ω Cen, each element on the diagrams of Figure 2 demonstrate not only disproportionately large spread, but also systematic displacement relative to the abundances of the same element in the stars of both the Galaxy and the moving group. We assume that this, it is most likely, caused by the very large distance to the cluster and by the impossibility to build the adequate models of the atmosphere for its giant stars. In favor this conclusion testifies the systematic differences in the relative abundance of titanium, obtained along the lines of ionized and neutral titanium. In order somewhat to get rid of this uncertainty, further analysis of the behavior of the dependences [α/Fe] − [Fe/H] of moving group and cluster is carried out in the averaged abundances of α-elements in their stars, moreover only three – magnesium, silicon and calcium, after excluding the abundances of titanium, the error in determination of which, as we see, much more.

In Fig. 3 different marks represented the [Fe/H] – [⟨Mg, Si, Ca⟩/Fe] diagrams for the stars of moving group, globular cluster and genetically connected stars of the Galaxy. Averaging over three chemical elements noticeably decreased the thicknesses of all three sequences, which increased the justifiability of assumption about the genetic connection of stars inside each object. Now it is distinctly evident that the characteristic "knee" for the stars of moving group begins somewhere in the environment [Fe/] ≈ -1.3, i. e., much earlier than in the Galaxy, where it is located at the point [Fe/H] ≈ -1.0. In this case the descending section of the sequence completely proved to be lying in the range with the smaller metallicity, where the genetically connected stars of the Galaxy practically be absent. This will agree with our result (Marsakov, Borkova, 2006), obtained on the basis of a study of the distribution only of one representative of α-elements – magnesium.

The picture is not so clear for the stars of globular cluster. Group of intermediate metallicity 11 stars with the anomalously high relative abundances of the α-elements (they are marked out in the figure with the being differed marks) mixes the uniqueness of interpretation. Such high relations ([α/Fe] > 0.4) for the stars of this metallicity are uncharacteristic. The analysis of the determinations of the chemical elements abundances in these stars did not reveal the systematic preferences, which facilitate their unjustified overstating; therefore status of these stars for us remains incomprehensible. It is not possible to exclude the probability that this group of stars has another origin, in any event additional studies be required for them. The remaining stars of cluster on the diagram can be conditionally divided into two parts. The first - this bulk of metal-poor stars with the high relations of ⟨[α/Fe]⟩ ≈ 0.33, and the second demonstrates the systematic decrease of this relation with an increase in the metallicity, beginning from [Fe/] ≈ -1.3. As a result, if we do not take into consideration of 13 stars with anomalously high relative abundances of α-elements, it is possible to note the very good agreement of all components of the discussed sequences of moving group and cluster.

Discussion

Thus, the behavior of the [α/Fe] – [Fe/H] dependence for the ω Cen globular cluster indicates that with the great probability both most metal-poor and most metal-rich stars can prove to be genetically connected.

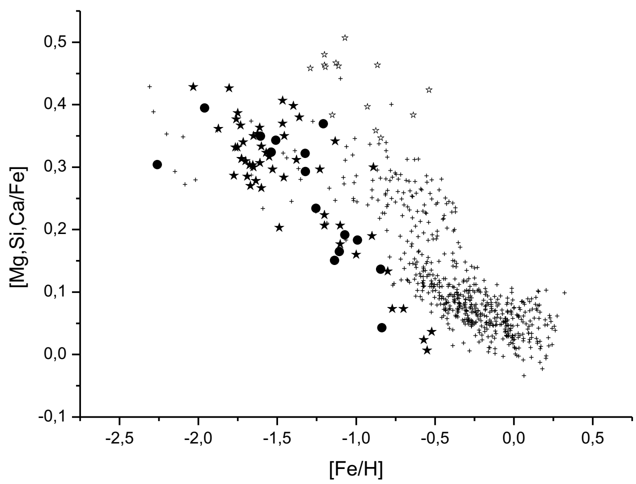

Figure 3: Metallicity – average relative α-element abundances (Mg, Si, Ca) diagram for the stars of the Centauri moving group, the ω Cen globular cluster and genetically connected field stars of the Galaxy. Designations are as in Fig. 2. Stars of globular cluster with the anomalously high relations [⟨Mg, Si, Ca⟩/Fe] are additionally isolated.

Hardly the stars of high metallicity could in it appear as a result the captured of small cluster, since then it is very difficult to explain in them the trend of the relation [α/Fe] from the metallicity. Actually, according to contemporary ideas this trend can arise only as a result of continuous star formation in the a starry-gas system, when begin to predominate the supernova explosions of the 1a type, which enrich interstellar medium exclusively with the elements of iron peak and therefore relative abundances of α-elements systematically reducing in it. To more natural assume this process in the massive stellar system (such it is ω Cen globular cluster), than in the cluster twenty times, as they assume, smaller mass. However, here apparently possibly and another explanation - precipitation to the center of the dwarf galaxy of its younger stars, irregularly caused by the tidal forces of our Galaxy. In this case it is possible to explain not only the being differed kinematics of metal-rich stars, but also another three-dimensional configuration of the volume occupied by them. (By the way, last observant fact cannot be understood within the framework the hypothesis of the formation of all stars of cluster from one proto-cloud – already only existence of correlation between the velocities dispersion and the metallicity inside the globular cluster (Norris et al., 1996; Sollima et al., 2005) some authors (Ferraro et al., 2002; Panchino et al., 2003) interpret as evidence of the accretion events, proceeding inside the parental system ω Cen.) In this case only stars of metal-poor bulk are strictly the initial population of globular cluster, which, as in all known globular clusters, it does not reveal the noticeable dispersion of chemical composition, which exceeds the errors of its determination.

The conclusion about the genetic link of the stars of moving group means that they all in the past belonged dwarf galaxy-satellite, center of which was the globular cluster ω Cen. Moreover to precisely parental galaxy, but not to globular cluster, since the cluster first of all must delegate into the stellar stream its very high velocity stars, but such, as show observations, appear most metal-poor. In the stream, as can be seen from Fig. 1 c, vice versa – are the surplus of most metal-rich stars. Observed in Fig. 3 very good agreement of the descending branches of the sequences [α/Fe] from [Fe/H] of stream and cluster, beginning from the point "knee", assumes the identical star formation rate both in the parental galaxy and in the cluster, which is highly improbable. This surprising agreement is additional evidence of in favor expressed above hypothesis about the possible capture by the central globular cluster of stars of the parental dwarf galaxy. (Certainly, for an increase in the ponderability of this assumption one should fulfill the numerical simulation of the dynamic processes, proceeding with interaction of galaxies.) The observed on the metallicity function of the moving group significant scarcity of metal-poor stars most likely could come out as a result the sufficiently continuance of interaction of the galaxy-satellite with our Galaxy, during which in the initial stages of this interaction it lost first of all its oldest, kinematically hot, i. e. metal-poor stars, which we do not observe from the Earth as a stellar stream because of a change in the course of time in its orbit. And only the slow stars of the dwarf galaxy is most gravitationally attached to the central globular cluster in essence proved to be the components of the moving group, observed now in the environments of the Sun. However, the stars of very globular cluster in this stellar stream most likely thus far be absent.

Proposing now that the united sequence [α/Fe] from [Fe/H] of stream and cluster reflects the chemical evolution of their parental galaxy, let us try to restore some of its moments. In particular, judging by the agreement of the average relative abundances of α-elements in the metal-poor stars of the Galaxy and the ω Cen dwarf galaxy, the parameters of the ejections of second type massive supernovas in these objects were not differed from each other. Further, the "break point" position of the dependence [α/Fe] on [Fe/H] with the smaller than in the Galaxy metallicity testifies that the initial star formation rate in it was substantially lower than in our Galaxy. Completely rapid reduction in the relation [α/Fe] after the "break point" evidences, that subsequently the star formation rate remained in it sufficiently low. The linearity of this drop indicates the invariability of this low star formation rate; therefore hardly correctly to speak about several flashes in it of star formation (as, however, and in the cluster itself). And finally the absence in it of stars with the metallicity $[Fe/H] > -0.5$ testify about the early exhaustion in it of interstellar gas, most probably because of the loss it as a result of interaction with our Galaxy.

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