STELLAR OBJECTS OF EXTRAGALACTIC ORIGIN IN THE GALACTIC HALO

V.A. Marsakov, T.V. Borkova
Southern Federal University
Rostov-on-Don 344090 Russia,
marsakov@ip.rsu.ru, *borkova@ip.rsu.ru*

ABSTRACT. We identified globular clusters and field stars of extragalactic origin and investigated their chemical, physical, and kinematical properties. This objects as supposed was captured by the Galaxy at different times from debris of the dwarf satellite galaxies disrupted by its tidal forces. The results are follows. (1) The majorities of metal-poor stellar objects in the Galaxy have an extragalactic origin. (2) The masses of the accreted globular clusters decrease with the removal from the center and the plane of the Galaxy. (3) The relative abundances of chemical elements in the accreted and genetically connected stars are essentially distinguished. (4) The accreted field stars demonstrate the decrease of the relative magnesium abundanses with an increase in sizes and inclinations of their orbits. (5) The stars of the Centaurus moving group were born from the matter, in which star formation rate was considerably lower than in the early Galaxy. On the base of these properties was made a conclusion that with the decrease of the masses of the dwarf galaxies in them simultaneously decrease the average masses of globular clusters and the maximum masses of supernova SNe II. Namely latter fact leads to the decrease of the relative abundances of α-elements in their metal-poor stars.

Key words: Galaxy (Milky Way), stellar chemical composition, accreted stellar objects, halo, Galactic evolution.

Still very recently they assumed that our Galaxy was formed from the united proto-galactic cloud, and all its objects are genetically connected together. However, the numerous observations of the last years demonstrate to us compelling evidence that the Galaxy closely interacts with the less massive satellite galaxies and gradually destroying them, captured their interstellar matter, separate stars and globular clusters. In particular, we are currently observing the disruption of dwarf galaxy Sagittarius by tidal forces from the Galaxy. About ten globular clusters are associated with this galaxy. The massive globular cluster M 54 is generally believed to be the nucleus of the system. The galactic orbital elements of same else clusters also suggest that they were captured from various satellite galaxies. There are convincing proofs that even ω Cen, the largest known globular cluster of the Galaxy, which is close to the Galactic center and has retrograde orbit, was the nucleus of a dwarf galaxy in the past. The theory of dynamical evolution predicts the inevitable dissipation of clusters through the combined actions of two-body relaxation, tidal destruction, and collisional interactions with the Galactic disk and bulge. Indeed, traces of the tidal interaction with the Galaxy in the shape of extended deformations (tidal tails) have been found in all the clusters for which high-quality optical images were obtained. It is even established for ω Cen that, after the last passage through the plane of the disk, this cluster lost slightly less than one percent of its mass in the form of stars. Thus, even in the nearest solar neighborhood, we may attempt to identify stars of extragalactic origin. It is interesting to investigate the distinctive properties of stellar objects of extragalactic origin and to estimate their relative number.

It turned out that metal rich ($[Fe/H] > -1.0$) objects form the rapidly revolving and completely flattened subsystem of the thick disk. But metal-poor objects are divided into two types of populations also. Is relied that the metal-poor stars of field with the peculiar velocities are less than the critical value and globulars with the extremely blue horizontal branches form the genetically connected with the thick disk spherical, slowly rotating subsystem of their own halo with the insignificant, but the different from zero radial and vertical metallicity gradients. The high velocity field stars and globulars with the horizontal branches of intermediate color form the spherical subsystem of external accreted halo, approximately into two and one-half of times of larger size than two previous. In this case the absence in it of the metallicity gradients, the predominantly elongated orbits, the large number of stars with retrograde galactic rotation, and often small ages confirm hypothesis about their extragalactic origin.

Very important for understanding of nature of accreted globulars is one of their properties. They

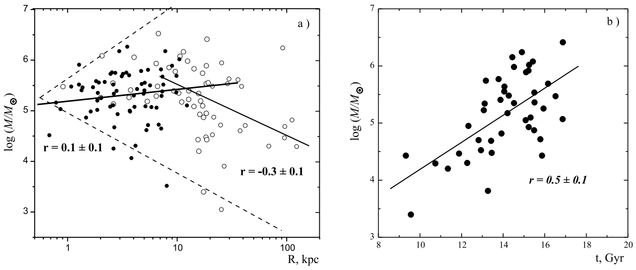

Figure 1: The relationships between the mass and the observed galactocentric distance (a), and between the mass and the age (b). The solid circles denote the genetically connected globular clusters, and open circles – the accreted ones. The solid lines are least square fits for genetically connected and accreted globulars. The dotted line in diagram (a) restrict the region of slow evolution of the globular clasters. The corresponding correlation coefficients are indicated. It is seen the good correlation for accreted clusters in both diagrams.

demonstrate the dependence of mass on the galactocentric distance (Borkova, Masakov, 2000). Solid lines in the diagram R_a – mass (Fig. 1 a) are the regression straight lines for genetically connected and accreted globulars. As we see almost all accreted clusters are into the region of the slow evolution of globular clusters the existence of which is theoretically grounded. Therefore they did not undergo the significant action of dissipation and dynamic friction; i. e., in external halo their initial mass distribution was preserved almost without the change. It is evident that the genetically connected clusters do not reveal a change in the average mass with an increase in the distance from the Galactic center. While for the accreted clusters the observed anticorrelation is different from zero far beyond ranges of errors. Simultaneously accreted clusters demonstrate the decrease of average mass, also, with the decrease of age (Fig. 1 b). The genetically connected globulars of this effect do not reveal. It seems that the globulars with small masses frequently are formed beyond the limits of the Galaxy. Moreover, the greater the dimensions of their present galactic orbit, the less their mass and the ages in average. Hence the conclusion: the globular clusters with anomalously small mass and age are formed predominantly in the such low massive satellite galaxy, which even being located at sufficiently great distances from the Galactic center, lose their globulars under the action of its tidal forces.

It is unlikely that the interstellar matter from which the stars of own and accreted halo were formed has experienced an exactly coincident chemical evolution. Therefore, it would be interesting to search for subtle differences between them that could shed light on the histories of star formation inside and outside the single proto-galactic cloud. Owing to the position of the Sun in the Galactic plane, we have an opportunity to observe the stars of all its subsystems in the immediate vicinity of the Sun and to analyze in detail their chemical composition.

According to current conception the evolution time of close binary stars that subsequently explode as SNe Ia is short, $\approx$ 1 Gyr. Exclusively higher-mass ($M > 8M_\odot$) stars exploding as type II supernovae (SNe II) are currently believed to have enriched the interstellar medium with heavy elements at earlier stages. Their characteristic evolution time is only $\approx$ 30 Myr. Almost all of the nuclei of α-elements are formed in SNe II while the bulk of iron-peak elements is ejected into the interstellar space during SN Ia explosions. Calculations show that the yield of the α-elements depends strongly on the stellar mass. Therefore, the relative abundances of α-elements ([α/Fe]) in the ejecta of SNe II with different mass can differ markedly. Hence, the variations in the upper boundary of the initial mass function for stars that exploded inside and outside the Galaxy can be estimated from the relative abundances of various elements in genetically related and accreted stars. Concurrently because of the difference between the evolution times of SNe II and SNe I we can try to trace the star formation rate for this stellar ensemble by the coordinates of the characteristic knee in its [α/Fe]–[Fe/H] diagram toward the sharp decrease in the relative abundance of the α-elements with increasing total heavy-element abundance at the onset of SNe Ia explosions, i. e., $\sim$ 1 Gyr later.

The best-studied α-element is magnesium because they exhibit several absorption lines in the visible spectral range. For the analysis, we took data from our compiled catalog of spectroscopically determined magnesium abundances (Borkova and Marsakov 2005). Almost all of the magnesium abundances in nearest stars determined by synthetic modeling of high-dispersion spectra and published before January 2004 were gathered in this catalog. The relative magnesium abundances in the catalog were derived from 1412 spectroscopic determinations in 31 publications for 867 dwarfs and subgiants using a three-pass iterative averaging procedure with a weight assigned to each primary source and each individual determination. The internal accuracy of the relative magnesium abundances for metal-poor ([Fe/H]< -1.0) stars is ε[Mg/Fe]=$\pm$0.07.

We justified the choice of the peculiar stellar velocity relative to the local standard of rest $V_{res} = 175$ km s^{-1} as a criterion for separating the nearest thick-disk and halo stars. In identifying the stars of an extragalactic origin (which were called here accreted stars), we assumed that the stars born in a monotonically collapsing single proto-galactic cloud could not be in retrograde orbits. We included all of the stars with high orbit energy, i. e. of high peculiar velocities $V_{res} > 240$ km s^{-1}, as have all stars with retrograde orbits, in the group of presumably accreted stars.

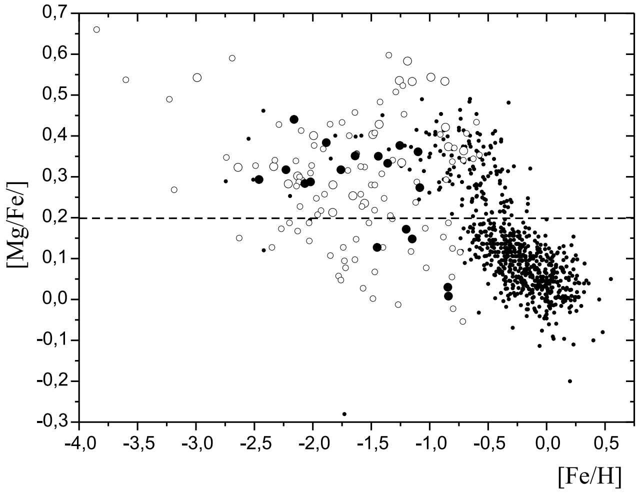

Figure 2: Metallicity vs. relative magnesium abundance for all of the stars in the catalog. The crosses, asterisks, and circles indicate thin- and thick-disk stars, own halo stars, and presumably accreted stars. The filled circles highlight the members of the Centaurus moving group among the accreted stars. The dashed line was drawn through $[Mg/Fe] = 0.2$.

Figure 2 shows the metallicity – relative magnesium abundance diagram for our catalog. It is seen that the accreted objects subsequently formed the bulk of the Galactic halo. (By this term we mean all of the objects that were born outside the single proto-galactic cloud, i. e., in the nearest satellite galaxies or in isolated proto-galactic fragments, and that subsequently escaped from them under the Galactic tidal forces.) We see also from the Figure 2 that the relative magnesium abundances in the own-halo stars are virtually independent of metallicity and that all stars of own halo lie above the dashed line drawn through $[Mg/Fe] = 0.2$. This behavior of own-halo stars suggests that, at least in the initial stage of its formation the interstellar matter in the early Galaxy either was well mixed or SNe II of the same mass exploded in all local volumes. In contrast, the presumably accreted stars exhibit a large spread in relative magnesium abundances in Fig. 2 that extends to negative [Mg/Fe]. The anomalously low relative magnesium abundances in some of the accreted stars are usually explained by an extremely low star formation rate in the dwarf satellite galaxies where these stars were born. However our analysis of the relative magnesium and europium abundances in a small sample of nearby field stars showed that large portion of the presumably accreted stars exhibited an [Eu/Mg] ratio that differed sharply from its Galactic value (Borkova and Marsakov 2004). Since the relative yield of these elements depends solely on the masses of the SN II progenitor stars where they are synthesized, we believe that a more likely mechanism of the magnesium abundance variations in accreted stars is the difference between the initial mass functions in their parent dwarf satellite galaxies. Therefore, it is interesting to try to identify genetically related stars in the accreted halo.

We identified from our catalog of the stars of moving group, which was supposedly lost by the dwarf galaxy, whose center as supposed was the cluster ω Cen. In the [Mg/Fe]–[Fe/H] diagram (see Fig. 2), all of them lie along a narrow strip. This behavior resembles the expected [Mg/Fe]–[Fe/H] relation derived in a closed model of chemical evolution, which is independent evidences for the genetic relationship between the identified stars. Hence, the low relative magnesium abundances in the metal-richest stars of this group resulted from the SN Ia explosions that began in their parent proto-galactic cloud and that ejected a large number of iron atoms into the interstellar medium and reduced the [Mg/Fe] ratio. The considerably lower metallicity of the knee point in this diagram than that in the Galaxy suggests that the stars of the Centaurus moving group were formed from matter in which the star formation rate was considerably lower than that in the early Galaxy. The high initial relations [Mg/Fe] evidences that, at least in this, presumably initially massive ($M \approx 10^9 M_{\odot}$) disrupted satellite galaxy (Tshuchiya, et al., 2003) the mean masses of the SN II progenitor stars were the same as those in our Galaxy. It is known that according to numerical simulations of dynamical processes during the interaction of galaxies (Abadi et al. 2003) the satellite galaxies are disrupted and lose their stars only after dynamical friction reduces significantly the sizes of their orbits and drags them into the Galactic plane. Less massive satellite galaxies are disrupted even before their orbits change appreciably under tidal forces. Therefore lost by them stars as a rule must be in higher and more distant orbit. Let us verify this theoretical assumption.

From Fig. 3 it is evident that only slowly rotating around the Galactic center stars with the small relations $[Mg/Fe] < 0.2$ are observed with $[Fe/H] > -1.0$. (Centaurus moving group also have the angular momentum close to zero with retrograde rotation.) Consequently we may to assume that all slow stars were born in the sufficiently massive satellite galaxies. Moreover the star formation rate in them was actually lowered, in comparison with the Galaxy, since the stars of them demonstrate less metal rich "knee point". While the overwhelming majority magnesium-poor and simultaneously metal-poor accreted stars fell within the range $|\Theta| < 50$ km s^{-1}.

From the Fig. 4 a, b, where are substituted only accreted stars, one can see well, that (1) stars with the low azimuthal velocities and the small orbital inclinations are majority. (This is understandable, because comparatively massive satellite galaxies lose many stars.) (2) Only star with small ($|\Theta| < 50$ km s^{-1}) and

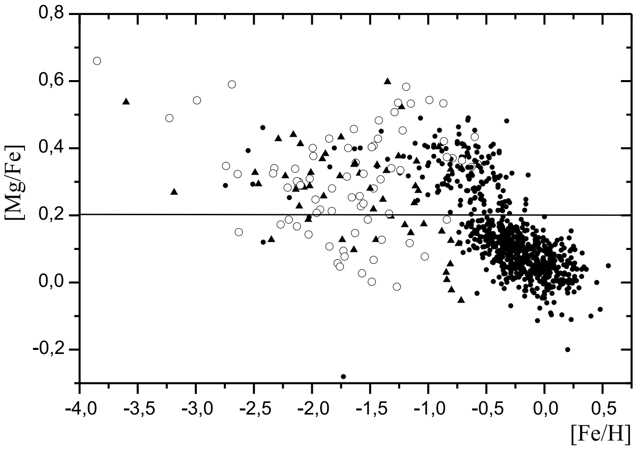

Figure 3: Relative magnesium abundances vs. metallicity. The crosses and circles indicate the genetically related stars and presumably accreted stars. The filled circles represent presumably accreted stars with azimuthal velocities in the ranges $\Theta > 50$ km s^{-1}.

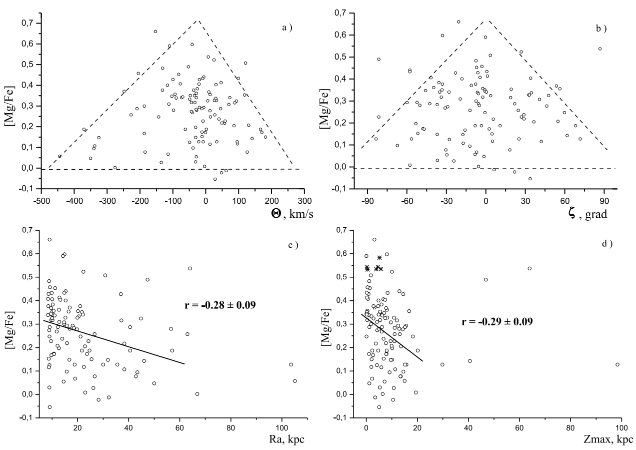

Figure 4: Relative magnesium abundances in accreted stars vs. their azimuthal velocities (a), Galactic orbital inclinations (b), maximum distances of the orbital points from the Galactic center (c) and plane (d). The dashed lines represent the envelopes of the points in the diagrams drawn by eye (upper row). The solid lines represent the regression lines for accreted halo stars (lower row).

with small orbit inclinations can have the high relative abundance of magnesium. (3) In contrast to them, the stars rapidly rotating around the Galactic center and stars with the large orbit inclinations, demonstrate in essence the low relations [Mg/Fe], uncharacteristic for such metal-poor stars. Further, (Fig 4 c, d) the negative radial and vertical gradients of the relative magnesium abundance also indicate the small relations [Mg/Fe] in the accreted stars with the extensive orbits. (These gradients reflect the sizes of the orbits, being located on which satellite galaxies lose their stars.)

Thus, sizes and inclinations of orbits in the accreted stars (and hence in their destroyed parent galaxies) increase with the decrease of the relative abundances of magnesium in them. The extensive and inclined orbits, according to the numerical simulation of the hierarchical formation of the galactic halo, as it was already said, one should expect in the debris of the low massive satellite galaxies, which are destroyed earlier than their orbit noticeably will change under the action of the tidal forces of the Galaxy. Apparently, low massive galaxies, intersecting galactic plane, lose not only stars, but also interstellar gas while crossing the Galactic plane. Star formation in them ends fairly rapidly because of the loss of interstellar matter. Therefore in them we barely see any metal rich stars. In view of this the anomalously low [Mg/Fe] ratios in the lost by them metal-poor stars are caused by the not so much low star formation rate in their parental dwarf galaxies, as the fact that in the less massive dwarf galaxies the initial stellar mass function is just truncated at the high masses. As a result, SNe II eject into the interstellar medium a smaller amount of light α-elements into the interstellar medium and the [Mg/Fe] ratios for the stars become anomalously low compared the stars of the same metallicity that are genetically related to the Galaxy.

Thus, the properties of globular clusters and field stars discovered in the work are organically fit within the framework of a single hypothesis. According to it metal-poor stars with anomalously low α-element abundances come into our Galaxy from debris of low-mass satellite galaxies in which the chemical evolution proceeded not only slowly but also with the absence of massive SNe II.

So, the results of comprehensive statistic studies testify that a significant quantity mainly of metal-poor objects, which belong at present to our Galaxy, were formed beyond its limits.

Acknowledgements. This work was supported in part by the Federal Agency for Education (projects RNP 2.1.1.3483 and RNP 2.2.3.1.3950) and by the Southern Federal University (K07T – 125)

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