SUBSYSTEMS OF THE GALACTIC HALO, THEIR STRUCTURES AND COMPOSITIONS

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ABSTRACT. It is shown that general populations of globular clusters and metal-poor field stars are components at least of three subsystems occupying different volumes in the Galaxy. The thick disk and proto-disk subsystems are genetically associated with the Galaxy. The age distributions of these two subsystems do not overlap. It is argued that heavy-element enrichment and the collapse of the proto-galactic medium occurred mainly in the period between the formation of the proto-disk halo and thick disk subsystems. The largest third subsystem has no metallicity gradient, most of its objects have retrograde motion in the Galaxy, some of them have unusually low content of α-elements, and their ages are comparatively low in average, supporting the hypothesis that the objects in this subsystem had an extragalactic origin.

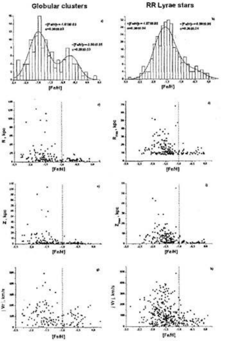

Figure 1: Relations between metallicity and other parameters of GCs and field RR Lyraes. A Sharp jump near [Fe/H]≈-1 is seen in all panels.

Quite recently the Milky Way was supposed to forms from single proto-galactic cloud. However, recently published observations demonstrate that some galactic objects have obvious extragalactic origin. In particular, the most direct evidence is provided by the Sagittatius dwarf spherical galaxy, which is now in the process of tidal destruction in the halo (Ibata et al. 1994). There are five globular clusters associated with this galaxy. Furthermore, one of the most significant results was the discovery of a large clump of field stars, which is part of the tidal tail of the Sgr galaxy (Ivesic et al. 2000). It should be noted that the existence of several populations among globular clusters (GC) and high velocity field stars belonging to different subsystems of the Galaxy follows from the discreteness of their distributions on metallicity and angular moment. Even the earliest metallicity functions revealed a gap near [Fe/H]=-1.0, which divides the populations of these objects into two discrete groups: a metal-poor, spherically symmetric, slowly rotating halo subsystem and a metal-rich, rather rapidly rotating, thick-disk subsystem (Marsakov & Suchkov 1977, 1978, Zinn 1985). Halo globular clusters were further shown to separate into two groups with different horizontal-branch (HB) morphologies. These subgroups, whose distributions are both spherical, differ in their kinematics and the spatial volume they occupy (Mironov & Samus 1974, Zinn 1993). Halo clusters, which have redder HBs for a given metallicity (i.e., with horizontal brunches showing a considerable number of stars on the low-temperature side of the Schwarzschild gap) are predominantly outside the solar circle, have a large velocity disper-

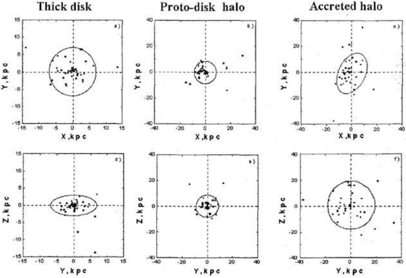

Figure 2: The spatial distributions for metal rich GCs (the first column), metal-poor GCs with extremely blue HBs (the second column), and metal-poor GCs with reddened HBs (the third column). The closed curves are upper envelopes drawn by eye.

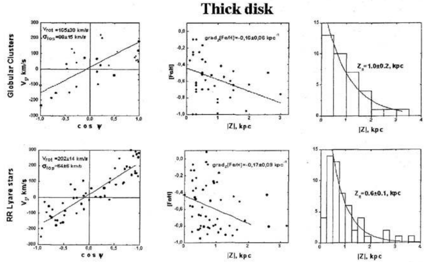

Figure3: Properties of metal-rich populations. The first column shows the kinematical diagrams, where ψ is the angle between the line of sight on the object and the vector of rotation about Z-axis, and V_S is objects line-of-sight velocity relative to an observer at rest at the position of the Sun. The straight lines are regression fits, whose slopes yield the subsystem's rotation rate. The second column shows the relations between metallicity and distance from the Galactic plane. The slope of the regression line yields the metallicity gradient. The third column shows the distributions of GCs and field RR Lyrae stars in Z. The curves approximate the histograms with an exponential laws with scale heights Z_o.

Table: Characteristic parameters of subsystems RR Lyrae field stars and globular clusters

Parameter	Thick disk		Proto-disk halo		Accreted halo	
	RR Lyrae	*GC*	RR Lyrae	*GC*	RR Lyrae	*GC*
Number	30	37	68	30	76	47
<[Fe/H]>	-0.57 ± 0.05	-0.56 ± 0.05	-1.54 ± 0.04	-1.71 ± 0.05	-1.59 ± 0.04	-1.60 ± 0.07
$^{\sigma}$[Fe/H]	0.28 ± 0.03	0.28 ± 0.03	0.36 ± 0.03	0.26 ± 0.03	0.29 ± 0.03	0.35 ± 0.05
<Θ>, km/s	198 ± 9	165 ± 38	104 ± 10	77 ± 33	-40 ± 12	-23 ± 54
σ_{Θ}, km/s	51 ± 7	88 ± 15	84 ± 7	129 ± 19	101 ± 8	140 ± 18
<*e*>	0.23 ± 0.03	0.13 ± 0.04	0.54 ± 0.03	0.53 ± 0.06	0.75 ± 0.03	0.59 ± 0.06
limR_{max}, kpc	13	7	18	10	40	20
limZ_{max}, kpc	2	3	10	10	22	20
Z_o, kpc	0.74 ± 0.05	1.0 ± 0.02	3.1 ± 0.1	2.5 ± 0.5	6.4 ± 0.5	8.5 ± 1.5
$grad_R$[Fe/H], kpc^{-1}	-0.03 ± 0.04	-0.01 ± 0.02	-0.00 ± 0.01	-0.03 ± 0.02	-0.00 ± 0.01	-0.03 ± 0.01
$grad_Z$[Fe/H], kpc^{-1}	-0.23 ± 0.10	-0.16 ± 0.06	-0.02 ± 0.01	-0.03 ± 0.02	-0.00 ± 0.01	-0.03 ± 0.01
<*t*>, Gyr		12.5 ± 0.5		15.5 ± 0.5		13.8 ± 0.3
σ_t, Gyr		1.4 ± 0.3		0.8 ± 0.2		1.4 ± 0.2
[Mg/Fe]	0.26 ± 0.02		0.35 ± 0.02		0.29 ± 0.03	
$\sigma_{[Mg/Fe]}$	0.17 ± 0.01		0.14 ± 0.02		0.15 ± 0.02	

sion, lower rotational velocities, and smaller ages than clusters with blue HBs, which are concentrated inside solar circle. (Da Costa & Armandroff 1995). This difference can be explained if the older proto-disk halo subsystem shares a common origin with the thick-disk, whereas the clusters of another subsystem − accreted halo − were captured by the Galaxy from intergalactic space during later stages of its evolution (Zinn 1993).

The presence of two populations with different histories in the low-metallicity halo was suggested by Hartwick (1987). He argued that two components were needed to model the dynamics of field RR Lyrae variables with metallicities [Fe/H]<-1: one spherical and somewhat flattened inner component, that is dominant at galactocentric distances less than radius of the solar circle. Study of a large sample of stars in a deep survey in the direction of the North Galactic Pole demonstrates that stars further than 5 kpc from the plane of the disk tend to have retrograde orbits (Majewski 1992). (A retrograde rotation is a pretty convincing argument for an origin largely independent of the Galaxy.) Further evidence for the presence of objects with an extragalactic origin among field stars is the identification of objects with relatively young ages and low abundances of heavy elements (so that they should have been older, according to abundance age indicators). The subsystem of accreted globular clusters sometimes is named the "young halo" for precisely this reason. On average, high-velocity field subdwarfs with highly eccentric orbits (e>0.85) are younger than subdwarfs with similar metallicities but less eccentric orbits (Carney 1996). Carney derived the isochrone ages of subdwarfs based on Stromgren photometry. Hanson et al. (1998), who also used abundances of α-elements as age indicators, likewise concluded that metal-poor red giants in retrograde orbits were relatively young. ([α/Fe] is known to be low for younger objects formed from matter already enriched in the injects of type 1a supernovae, whereas the higher relative abundances of α-elements in older stars are due to type 11 supernovae.) However, observations of field RR Lyrae stars and blue horizontal-branch stars were used in (Lauden 1998) to estimate the number rations of these objects in different directions from the Sun. Blue horizontal-branch giants dominate among stars close to the Galactic center and Galactic plane, whereas the numbers of variable stars and giants were approximately the same at greater distances. These stars have similar metallicities, suggesting that the inner, bluer population of the Galaxy is older than the outer population.

Thus, the existence of two subsystems in the metal-poor halo is no doubt, but it is very difficult to identify all objects, which are the debris of dwarf galaxies, with direct observations. Fortunately, all reliable identified accreted globular clusters posses a distinctive inner feature: the morphology of their horizontal branches. Therefore, to determine characteristics of different halo subsystems we suppose that the Galaxy accretes only metal-poor globulars, which have reddened HB for a given metallicity. And on the contrary, only metal-poor globulars with extremely blue HB belong to the proto-disk halo subsystem. Objects of this subsystem formed together with the Galaxy as a whole. When protogalactic cloud appreciable contracted, metal-rich globular clusters was born and formed younger, something flattening thick disk subsystem.

Objects belonging to the thick disk can be reliably distinguished based on metallicities. Figure 1a shows the distribution of heavy-element abundance for all Galactic globular cluster from catalogue with spectroscopic determination of [Fe/H] of Harris (1996). The solid curve shows an approximation of the histogram using a superposition of two Gausian curves with parameters estimated using a maximum-likelihood method. It is seen that the entire globulars population can be divided into two metallicity groups, separated by a well-defined gap at [Fe/H] =-1.0. The metallicity function of field RR Lyrae stars in Fig. 1b can also be described by two normal curves at high confidence level. The mean values and dispersions of the metallicities in the groups coincide with the corresponding parameters for globular clusters within the errors (see Table). The breakdown of both (the globular clusters and the field stars) populations into two subsystems separated by [Fe/H]≈-1.0 is further supported by the fact that diagrams in Fig. 1 (c-d, e-f) demonstrate an abrupt change of spatial locations and velocity distribution when the metallicity crosses precisely this boundary value of [Fe/H]. Note that we can observe only nearest field stars and therefore in Figures 1c and 1e we use calculated orbital parameters (apogalactic distances and the maximum distance of the orbit from the Galactic plane) for determination of spatial distributions. The present spatial distribution of globular clusters in Fig. 2a,d demonstrates that subsystem of metal-rich ([Fe/H]>-1.0) objects is concentrated toward both the center and the Galactic plane, and its shape can be very roughly described as an ellipsoid of revolution slightly flattened along the Z-axis. The flattening is caused by rapid rotational velocity of this subsystem (see Fig. 3a,d). Present position of metal-rich globulars and field stars indicate high negative vertical metallicity gradients (Fig. 3b,e) and relatively small scale heights. Taking into consideration coincidence of main characteristics of metal rich globulars and field RR Lyraes (see Fig. 3 and Table) we have to conclude that both populations belong to the same subsystem of the Galaxy, named the thick disk.

Let us now consider the metal-poor objects. Figures 2b-e,c-f show the spatial distributions of the two groups that selected according to horizontal branch color. We can see that the globular clusters of our proto-disk halo are appreciable concentrated toward the galactic center, and their galactocentric distribution is enclosed by a sphere of radius ≈9 kpc. The distribution of intended accreted clusters in the YZ plane fits well inside a circle of radius ≈19 kpc. The accreted clusters occupy a much smaller area in the XY plane, and their distribution can be described by an elongated figure with semi-axis equal to 18 and 10 kpc. The semi-minor axis is perpendicular to the Z-axis and makes an angle of about 30° to the X-axis. That is subsystem of the metal-poor clusters with reddened horizontal branches occupy a slightly flattened spherical value which is a factor of ≈2 larger than for the clusters with extremely blue HB.

Properties of these subsystems of metal-poor globular clusters differ also. Kinematical diagrams in Fig. 4a,d show that subsystem of globular clusters with extremely blue horizontal branches exhibits a fairly well defined prograde rotation, whereas subsystem of clusters with reddened horizontal branches indicates retrograde rotation (see Table). Hence most clusters with reddened HB are really accreted objects. Metallicity gradients for both subsystems were negligible but non-zero. Fig. 4c,f shows that scale heights of these subsystems differ dramatically.

It is much more difficult to identify field stars that have an extragactic origin, i.e. those belonging to the accreted halo. According to the hypothesis that the proto-galaxy collapsed monotonically from the halo to the disk, suggested by Eggen et al. (1962), stars genetically related to the Galaxy cannot have retrograde orbits. Only the oldest halo stars may be an exemption, since they could have retrograde orbits due to the natural initial velocity dispersion of proto-stellar clouds. On the other hand, some stars formed from extragalactic fragments and captured by the Galaxy may have prograde orbits. In any case, such stars should have fairly large peculiar spatial velocity relative to the Local Standard of Rest. We used for this study the largest catalogue of RR Lyrae variables compiled by Dambis & Rastorguev (2001). The catalogue contains 262 stars with published photoelectric photometry, metallicities, radial velocities, and absolute proper motions. The diagram in Fig. 5a shows that there is a transition from prograde to retrograde orbits around the galactic center near V_{pec}≈280 km/s. We also can see in the rest diagrams in Fig. 5 that all orbital parameters demonstrate the break of their relations and abrupt increase in their dispersions in the vicinity the same threshold peculiar velocity. Fig. 5f shows that RR Lyraes with velocities near the threshold lever might have any orbital inclination up to orthogonal to the galactic plane, whereas the range of "permitted" inclinations continuously becomes narrower when velocity moves away from this threshold level in both sides. For this reason, we adopt V_{pec}>280 km/s as the critical value for distinguishing stars of the accreted halo. We suppose that stars with lower peculiar velocities have a galactic origin and belong to the proto-disk halo, and to the thick disk halo subsystems. Apparently, this kinematical criterion is not entirely unambiguous: some stars of proto-disk halo may have larger peculiar velocities. Evidence for this is provided, in particular, by the increase in the star density immediately to the right of the threshold level in our diagrams. However, we decided to retain a simple criterion, in order not to artificially coiffeuse the situation.

The spatial velocities of the stars can be used to obtain estimates for a numbers of characteristics for subsystems, if we can first reconstruct the star's galactic orbits. The orbital elements were computed using the Galactic model of (Allen & Santillan 1991),

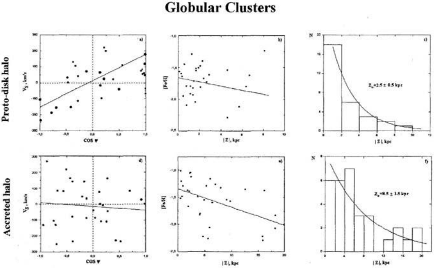

Figure 4: Properties of metal-poor subsystems of GCs with blue HBs (top row), and with redden HBs (bottom row). Notations are the same as in Fig. 3.

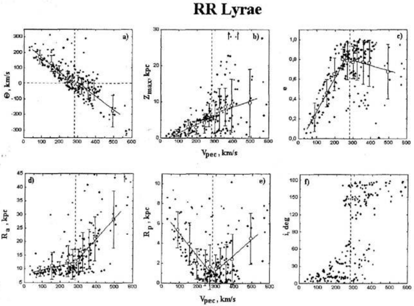

Figure 5: Relations between peculiar velocity and other characteristics of the RR Lyraes. The large open circles with error bars are mean values and dispersions of the corresponding parameters in narrow intervals of V_{pec}. The straight lines are the least-square fits for the stars lying both on the left and on the right of $V_{pec} \approx 280$ km/s (the vertical dotted lines).

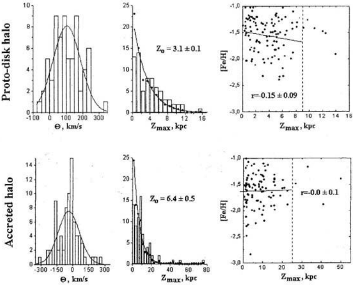

Figure 6: Properties of metal-poor subsystems of RR Lyraes with low peculiar velocity (top row) and high peculiar velocity (bottom row). The first column shows histograms in the rotation velocities. The second column shows the distribution of Z (see text for details), and the curves approximate the reconstructed distributions with exponential law The third column shows relations between maximum height above the galactic plane and metallicity.

which includes a spherical bulge, disk, and extended massive halo. Fig. 6 (see also Table) shows that the vertical metallicity gradients (Fig. 6 c-f) and the distributions of RR Lyrae stars in the two metal-poor subsystems as a function of their rotation velocities and distances to the Galactic plane differ drastically. (Note, that to compute the scale height using Z_{max} we must first to reconstruct the "real", instantaneous Z-distribution for all stars according to probability density of its location at different Z. The filled dots in the histograms (Fig. 6c,f) are the reconstructed distributions in Z.)

Age is one of the most uncertain parameters. In particular, Hipparcos data requires substantial revision of GC distances. As a result, the ages of even the most metal-poor (i.e., oldest) clusters do not exceed ≈10 Gyr (see, e.g., Reid 1997). However, we adopted the old scale here, because the refinement of the age-scale zero point based on the new data is probably now only in its initial stage, and we are primarily interested in relative parameters. The data of the comparative catalogue of homogeneous age dating of 63 globular clusters by Borkova & Marsakov (2000) shows, that the globulars of different subsystems have different ages also. Fig. 7a demonstrates the age distribution of globular clusters, which have a common origin with the Galaxy. It is seen that age distributions of the thick disk and proto-disk halo clusters do not overlap. It follows from Fig. 7a and from the Table the age dispersion for the proto-disk halo clusters is nearly equal to the error in ages themselves. The thick disk cluster ages exhibit a much larger scatter. In other words, the halo clusters formed almost simultaneously, whereas the corresponding processes in the thick disk required at least several billion years. The age gap between subsystems, if any, might be swamped by the errors in the estimated ages. From the comparison of Fig.7b and 7a it is seen that the ages of the clusters with reddened horizontal branches (Fig. 7b) demonstrate large spread, and mean age of their age distribution is smaller than that for the proto-disk halo clusters.

Figure 8 demonstrates that field stars of different subsystems differ also in content of α-elements. As a surrogate of α-elements content may be accepted magnesium abundance. We compile all known to us published spectroscopic determination of [Mg/Fe] with non-LTE models, led these data into the united scale, and compute stellar spatial velocities using Hipparcos parallaxes (it is used only stars with error of parallax <25%). In any interstellar cloud star formation process en-

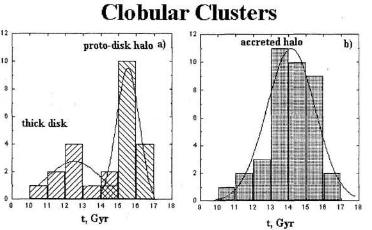

Figure 7: The age distribution of the globular clusters of (a) Galactic origin and (b) accreted by the Galaxy. Different shadings are used to show the thick disk and prot-disk halo clusters. The curves are Gaussian fits to the corresponding histograms. Data was taken from (Borkova & Marsakov, 2000).

rich their gas with the ejects from Type II, then Type Ia supernovae, and each would yield a distribution similar to Figure 8. Wyse & Gilmore (1988) has discussed the possible utility of [α/Fe] as a chronometer. If the model for Type la supernovae are a good quite, once there has been a burst of star formation it should take roughly 1 Gyr for the first Type la supernovae to appear, although timescales ranging from 0.5 to 3 Gyr have been suggested by Yoshii et al (1996). Thus, the simplest interpretation of Fig. 8 is that the Galaxy took only about ≈1 Gyr to rise from primordial chemical abundances to [Fe/H]≈-1. According to the chemical evolution calculations of Travaglio et al (1999) the thick disk population formed in the early Galaxy during an interval of ≈1.1 Gyr to 1.6 Gyr after the beginning of the protogalactic collapse. (Note, that this time interval is in some disagreement with age dispersion for the thick disk clusters, determined with the help of theoretical isochrones (see Fig.7a).) Gilmore & Wise (1998) have suggested that the very low [α/Fe] values for metal-poor stars could be produced by very slow, perhaps episodic, star formation. Only small galaxies, whose chemical enrichment history was quite different from that of the Galaxy, might be recognized by unusual locations in this diagram. Nissen & Schuster (1997) noted that while some of the halo stars followed the same trend in [α/Fe] as did the disk stars, some of the halo stars were clearly deficient in [α/Fe]. These deficiencies also seemed to be related to the maximum distance these stars from the galactic plane, their maximum distance from the Galactic center, and their high spatial velocities. This last point is illustrated in our Fig. 8. We can see in the diagram that overwhelming number of fast metal-poor stars (V_{pec}>280 km/s) have magnesium content that appear to be appreciably lower than those of majority of stars having similar metallicities (see also Table). Probably, some victims have star formation that was slow enough to permit inclusion of SN Ia ejecta into the star-forming gas, and also produce relatively low metallicity. Thus, the content of α-elements can be used as additional inner criterion for distinguishing accreted objects.

Here, we compare the characteristics of the metal-poor subsystems. The parameters of the corresponding halo subsystems differ somewhat. In particular, the metallicity dispersion of the proto-disk halo derived from the globular clusters is lower than that of the outer halo. The field stars show the opposite pattern (see Table). However, the differences are comparable to the formally computed uncertainties, indicating that any conclusions about differences between these parameters have low statistical significance. The vertical gradients in the proto-disk halo for both the RR Lyrae stars and the globular clusters almost coincide, but the radial gradients differ (see Table). In the accreted halo, both gradients are absent for the field RR Lyrae stars but are non-zero for the clusters. However, both gradients for the globular clusters in the accreted halo are due exclusively to metal-richer objects close to the galactic center (R~7kpc). Distant RR Lyraes were not included in

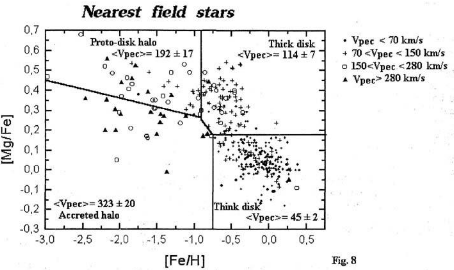

Fig. 8

Figure 8: Abundance ratio [Mg/Fe] versus [Fe/H] for nearby field stars. Drawn by eye straight lines divide panel into four sections, which mainly occupied stars of different subsystems of the Galaxy. Mean pecular velocities of stars into each panel are denoted (km/s). Ranges of star's peculiar velocities are denoted.

our sample. In any case, values of all corresponding gradients coincide within the uncertainties. In this study, we have identified the halo subsystems based on spatial velocity. Therefore, the differences between the proto-disk halo and accreted halo in any kinematical parameter for field stars should be more prominent. The velocity dispersions for the subsystems of globular clusters are obviously overestimated due to the larger distance uncertainties and, as a result, are much higher than the values for field RR Lyrae stars. The radial size of the proto-disk halo is approximately a factor of 1.8 larger for the field stars than for the clusters, whereas the two scale were the same within the errors. Recall that we can estimate the radial sizes of RR Lyrae subsystems only from their maximum distances from the galactic center, which leads to appreciable overestimates of these sizes. Note, that in order to obtain correct estimates of sizes of galactic subsystems based on data for nearby stars, it is necessary to take into account the kinematical selection effect, which leads to a deficiency of stars with large R_a and Z_{max} in the solar neighborhood.

Thus, we can see generally good agreement between characteristics of corresponding subsystems of field RR Lyrae stars and Galactic globular clusters distinguished using different criteria. This evidences for that populations of both the clusters and the field stars are not uniform and compose three different subsystems of the Galaxy: the metal-rich thick-disk, related to it by its origin the inner proto-disk halo, and the outer accreted halo. Analysis of these patterns suggests the following scenario for the early evolution of our Galaxy. The first stellar objects were formed when the proto-galactic cloud had already collapsed to the size of the modern Milky Way. The proto-disk halo formed over a short time interval. The radial and vertical metallicity gradients in this oldest known Galactic subsystem provide evidence that the first heavy-element enrichment of the gas-dust medium took place before the clusters and field stars of this subsystem formed. Both, the spatial and chemical characteristics change abruptly as we move to the thick-disk subsystem. The formation of stars in these subsystems was apparently separated by a substantial time lag, which shows up only as a gap in the age distribution. This time lag enabled the gas and dust clouds to become appreciable enriched in heavy elements (which had time to mix) and to collapse to much smaller sizes before the new generation of stars and clusters began to form. As a result, a rather flat, metal-rich, thick-disk subsystem formed. The appreciable collapse of the proto-disk cloud after the formation of the halo subsystem resulted in an increase of the rotational velocity and a rapid flattening of the future subsystem. Strong negative vertical metallicity gradient in the thick-disk testify to continuing collapse of this subsystem to the Galactic plane in their formation time. Differences in age, metallicity, and spatial distributions indicate that heavy-element enrichment and collapse of the proto-Galaxy occurred mainly in period between the formation of the proto-disk halo and thick disk subsystems. The collected result indicate that outer halo subsystem is characterized by a large size an absence of appreciable metallicity gradients, predominantly large orbital eccentricities, a large number of objects on retrograde orbits, and, on average, younger ages for its objects, supporting the hypothesis that object in this subsystem had an extragalactic origin.

More detail about subsystems of metal-poor populations of the Galaxy can be seeing in (Borkova & Marasakov, 2000, 2002).

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