

# Globular Cluster as Indicators of Galactic Evolution

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We have studied the system of globular clusters (GCs) that formed in other galaxies and eventually accreted onto the Milky Way. Thus, the samples of GCs belonging to different tidal streams, obtained on the basis of the latest data from the GAIA observatory, were taken from the literature. We measured the anisotropy of the distribution of these GCs using the tensor of inertia and found that the distribution of GCs in the streams is isotropic. Nevertheless, it can be seen that some of the accreted GCs included into existing samples actually belong to the disk of the Galaxy. To clarify the origin of GCs, we investigated “the age–metallicity” relation. This dependence appeared to be bimodal and its two different branches clearly show the difference between the clusters formed in the streams and in the disk of the Galaxy. Furthermore, we have studied the influence of the large-scale environment of the Galaxy (i.e., the Local Supercluster) on the distribution of satellite galaxies and Galactic GCs. The satellite galaxies of the Milky Way are known to form an anisotropic planar structure, so we included them in our analysis too. An inspection has shown that the plane of the satellite galaxies is perpendicular both to the disk of the Galaxy and the supergalactic plane. For GCs more distant than 100 Kpc, a similar picture is observed.

**Keywords:** globular clusters, Galaxy, dwarf

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## 1. INTRODUCTION

Globular clusters (GCs) belong to the oldest objects inhabiting galaxies. According to the hierarchical theory, the galaxies are formed by merger of low-mass and then by larger mass objects [1]. When the galaxies of very different masses merge, as a rule, the lower mass galaxy disrupts gradually. As it continues its orbital motion, a tidal tail of gas, dust, stars, and GCs forms behind the galaxy, thus enriching the larger mass galaxy. This type of mergers have occurred and still occur with our Galaxy too. According to Bland-Hawthorn and Gerhard [2], about 100 satellite galaxies have accreted onto the Galaxy during the lifetime of the Universe. But out of these satellite galaxies, only massive ones contribute GCs to our Galaxy, since galaxies with stellar mass  $\leq 10^7 M_{\odot}$  have very few GCs [3]. Myeong et al. [4] argue that the clusters with the total specific energy  $E \geq -1.6 \times 10^5 \text{ km}^2 \text{ s}^{-2}$  were accreted from dwarf galaxies. Cosmological hydrodynamic simulations show that 15–40% of the stars in the halo were formed outside the Galaxy (ex-situ), that is, in dwarf satellite galaxies, and then were accreted [5, 6]. In the results of studies by different authors, the percentage of GCs formed ex-situ differs. For example, Forbes [7] claims that 54% of GCs (87 out of 160 clusters) were formed ex-situ and then accreted, while Kruijssenn et al. [8] claim that the per-

centage of accreted clusters is 43. According to Masari et al. [9], this value reaches 60%.

Thus, a significant part of the GCs of the Galaxy was accreted from the outside. Information about the origin of GCs can be preserved both in the properties of the stellar population of GCs and in the spatial distribution and dynamics of GCs themselves. In particular, it is well known that both satellite galaxies and GCs exhibit a disk-like structure perpendicular to the disk of the Galaxy (see, for instance, [10–12]). This structure may be a result of the accretion of several galaxies that arrived in our Galaxy mainly from polar directions. According to Zeldovich theory [13], formation of the large-scale structure of the Universe occurs through independent contraction or expansion of the matter in the three mutually perpendicular directions. A good example of a structure contracting in one direction and expanding in two other directions is the Local Supercluster of Galaxies, which looks like a typical Zeldovich “pancake”. This structure sets the preferred direction in the vicinity of the Galaxy, and therefore can affect the preferential direction of accretion and distribution of accreted material in our Galaxy.

Tidal streams of the Galaxy are actively discussed in the literature [14–35]. Recent measurement of the GCs proper motions using GAIA data made it possible to identify GCs belonging to specific tidal streams.

The problem regarding the difference in the physical properties of GCs formed in-situ and ex-situ was studied in detail in [36]. It was shown there that accreted GCs differ by the abundance of alpha-elements, as well as by the range of masses. The purpose of our study is to check the spatial orientation of the GCs system belonging to the streams, i.e., admittedly accreted onto the Galaxy from outside. For this, the orientation of the systems identified by different authors was juxtaposed with the disk of the Galaxy, as well as with the plane of the Local Supercluster. In addition, the “age–metallicity” relation (AMR) for GCs belonging to the streams was analyzed and the relation between GCs colors and their origin was discussed.

The paper is organized as follows. In Section 2, the studied GC samples are described and the anisotropy of their distribution is investigated. In Section, 3 the AMR for GCs is discussed. In Section 4, the influence of the Local Supercluster is measured. Conclusions are presented in Section 5.

## 2. MILKY WAY GLOBULAR CLUSTERS IN TIDAL STREAMS

In the Galaxy, 157 GCs are now known [37, 38].<sup>1</sup> As time goes by, the papers regarding new clusters in the Milky Way appear (for example, FSR 1716 [39], FSR 1758 [40, 41], VVV–CL001 [42], VVV–CL002 [43], BH 140 [44], Gran 1 [45], Pflaiderer 2 [46], ESO 93–8 [47], Mercer 5 [48], Segue 3 [49], Ryu 059, Ryu 879 [50], Kim 3 [51], Crater/Laevens 1 [52, 53], Laevens 3 [54], and BLISS 1 [55]). Although even before obtaining high-precision GAIA data, there were attempts to identify GCs belonging to the tidal streams [33, 56–58], but after the appearance of GAIA data, these attempts significantly advanced [4, 7, 9, 40, 59–62]. In this paper, we draw our attention to three studies: [9] (hereinafter, Massari), [40] (hereinafter, Myeong), and [7] (hereinafter, Forbes), which contain the most complete lists of GCs belonging to different tidal streams.

Forbes et al. list 76 clusters that belong to five progenitors—satellite galaxies. To check membership, the authors used integrals of motion (IOM), AMR, and alpha-elements dependencies. Out of these 76 GCs, nine belong to the well-known Sagittarius dwarf spheroidal galaxy (Sgr dSph), 28 belong to the Gaia-Enceladus dwarf galaxy, nine GCs—to the Sequoia dwarf galaxy, 21 clusters—to the low-energy satellite Koala, nine clusters—to a low-mass satellite, the Helmi streams. Out of the remaining 36 clusters, they are either “Low-energy” ones (25 objects) or “High-energy” ones (11 clusters). These clusters have high energies and a wide range of angular momenta, which suggests that they originated from different progenitors.

<sup>1</sup> <http://physwww.mcmaster.ca/harris/Databases.html>

Massari et al. examined 151 GCs for which they collected complete kinematic information. They concluded that 62 of these clusters were most likely formed in the Galaxy (in-situ), while the remaining clusters (89 clusters) were most likely formed ex-situ and then accreted. Basically, accreted clusters are associated with four known merger events: Gaia-Enceladus—26 GCs (+6 candidates), the Sagittarius dwarf galaxy—eight GCs, the Helmi stream (H99)—10 GCs, and the Sequoia galaxy—seven GCs. The remaining 36 clusters are classified as “Low energy” ones (25 GCs) or “High energy” ones (11 GCs). Association of the clusters with any group is uncertain, due to the partial overlap of the debris of different progenitor galaxies.

Myeong et al. considered 34 GCs, which accreted onto the Galaxy. To verify this, the authors used kinematic data of GAIA [63] in combination with photometry from DECaPS (DECam Plane Survey [64]). In opinion of Myeong et al., 6 GCs belong to the dwarf spheroidal galaxy Sagittarius, 7—to Sequoia galaxy, 21—to the Gaia Sausage. Summing up the results of three above-mentioned papers, we obtain the main list of tidal streams from which accreted a considerable fraction of GCs:

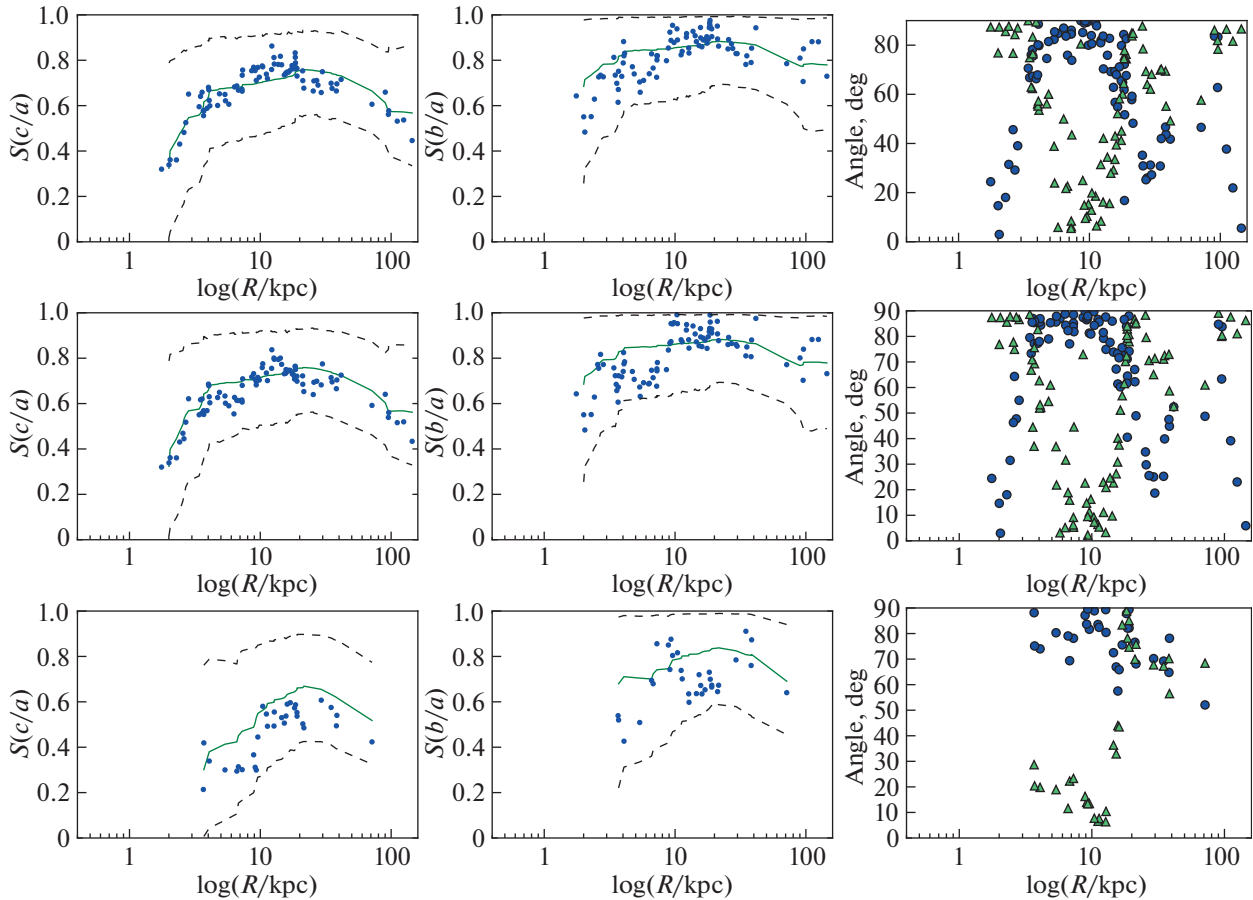
- (1) Sagittarius dwarf spheroidal galaxy with the nucleus NGC 6715 (M54).
- (2) Sequoia galaxy with the nucleus NGC 5139 ( $\omega$  Cen).
- (3) Helmi stream (H99).
- (4) Gaia-Enceladus with the nucleus NGC 1851. Other possible variations of the name of this stream—Gaia Sausage or Canis Major (CMA).
- (5) Low-energy progenitor Coala, to which Kraken may be equivalent, and also a low-energy group ( $E < -1.86 \times 10^5 \text{ km}^2 \text{ s}^{-2}$ ).
- (6) High energy group ( $E > -1.5 \times 10^5 \text{ km}^2 \text{ s}^{-2}$ ).

### 2.1. Anisotropy of the Distribution of Globular Clusters

The number of GCs belonging to different streams, according to the classification of the authors considered in this paper, is as follows: according to Forbes—87 GCs, according to Massari—89 (these clusters are located at the distance from 1.42 to 144.77 kpc from the center of the Galaxy) and according to Myeong—34 GCs (at the distance from 2.42 to 71.36 kpc).

In order to understand whether there is any difference in the distributions of GCs belonging to the streams and the objects formed in the Milky Way, we decided to check the anisotropy of the distribution of these GCs using the inertia tensor, as in [12]. The tensor is constructed as follows:

$$S_{ij} = \frac{1}{N} \sum_{k=1}^N x_i^k x_j^k, \quad (1)$$



**Fig. 1.** Galactic clusters anisotropy, quantified by the tensor of inertia for cluster samples Forbes (top), Massari (center), and Myeong (bottom). The left and middle columns show the ratios  $c/a$  and  $b/a$  as a function of the galactocentric cluster distance, respectively. Each blue dot represents the ratio of the tensor eigenvalues calculated for all clusters at the distance smaller than  $R$  from the Galactic center. Solid green line represents the median eigenvalues ratios for 10000 random samples. Dashed lines indicate the deviations  $\pm 3\sigma$  of such random distributions. The right column shows the angles, measured in degrees, between the Milky Way’s Galactic pole and the major (blue dots) and minor (green triangles) axis of the tensor of inertia. Green triangles close to  $90^\circ$ , indicate the polar plane.

where  $S$ —inertia tensor,  $N$ —the number of objects,  $x_i^k$ —the distance of  $k$ th object to the Galactic center along coordinate axis  $i$ . Standard mathematical operations for determination of the eigenvalues and eigenvectors of a tensor allow us to characterize the anisotropy of the distribution. The eigenvalues  $a$ ,  $b$ , and  $c$ , for convenience, are sorted in ascending order, so that  $a > b > c$ . The degree of anisotropy is characterized by the ratios of the eigenvalues  $c/a$  and  $b/a$ , which, in the case of an isotropic distribution, approach 1. The eigenvectors of the inertia tensor determine the orientation of the anisotropic distribution in space.

To check the statistical significance of the found parameters of the GCs system, we generated 10000 random samples with the same radial distribution and number of objects as in the data for observed objects, and measured the median value and the root-mean-square value of the ratio of the eigenvalues of the ten-

sors. Anisotropy is statistically significant if the ratio of the eigenvalues of the tensor for the real catalogs differs from the median of the random samples by more than  $3\sigma$ . Random samples are constructed by fixing the distances ( $R$ ) from the real sample and assigning random angular coordinates to the GCs.

In Fig. 1, we show the results of measuring the anisotropy for GCs using the tensor of inertia. The panels show the ratios  $c/a$  and  $b/a$  as functions of  $R$ , calculated for all GCs with a distance  $< R$ . The distributions of real objects are shown by dots, solid line represents the median result for 10000 random samples, and dashed lines represent the median  $\pm 3\sigma$ . The “angle” in these panels is measured between the normal to the Galactic plane and the minor (green triangles) or the major (blue dots) axis of distribution.

From the measurements of the anisotropy using the inertia tensor for all samples of GCs in the streams

from the three above-mentioned papers, it follows that the distribution of GCs in the streams is isotropic. Thus, none of the samples exhibit statistically significant anisotropy. In [12, p. 7, Fig. 7], for the entire sample of GCs at the distance from 2 to 10 kpc, statistically significant anisotropy is observed, which the authors associated with GCs belonging to the disk of the Galaxy, that is, formed in-situ. In this paper, we studied spatial distributions of GCs, which, according to a number of authors, belong to the tidal streams, that is, were formed ex-situ. As seen in Fig. 1, for all samples, the spatial distribution of GCs belonging to the tidal streams is isotropic. This is consistent with the conclusion of Arakelyan et al. [12] that the statistically significant anisotropy for the entire GCs sample is due to the clusters that were most likely formed in the Galaxy or have been interacting with the Galaxy disk for a very long time. It is also important that the clusters that belong to the tidal streams do not exhibit significant structure, which we might expect, first, because clustering occurs mainly along the distinguished directions associated with the walls and filaments of a large-scale structure, and, second, because anisotropic distribution is observed for satellite galaxies.

Nevertheless, it is seen in Fig. 1 that for all three samples (Forbes, Massari, Myeong) for GCs that belong to the streams, the major axis of the inertia tensor is in the disk, at the distances from about 3 to 10–20 kpc. It seems unlikely that such a situation can arise for a random isotropic GCs distribution. The distribution of the directions of the axes of the tensor as in Fig. 1, one can expect if a part of the GCs in each of the samples belongs to the disk. We demonstrate this below using random catalogs.

To check the probability of entering of the GCs from the disk into the GCs sample from the tidal streams, we generate random catalogs containing the same number of GCs as the real samples. Moreover, we take the galactocentric GC distances from the real samples. Angular coordinates are assigned randomly. To simulate a situation in which some of the clusters belong to the disk, for  $n$  clusters the height above the disk is set to zero (Cartesian coordinate  $z$ ).

Using such models, we calculated the conditional probability of obtaining a distribution similar to the right-hand column in Fig. 1, i.e., when the major axes of the tensor of inertia in the distance range from 3.5 to 20 kpc are located at an angle of more than  $70^\circ$  to the direction to the Galactic pole, provided that  $n$  clusters belong to the disk. If the distribution is isotropic, i.e.  $n = 0$ , this probability is equal to 4.5, 0.6, and 1.1% for the samples of Forbes, Massari and Myeong, respectively.

For this probability to exceed, for example, 10%, the disk must contain  $n = 6$ , 16, and 8 GCs for the Forbes, Massari, and Myeong samples, respectively. From this, we can conclude that a part of the GCs,

formed to the opinion of these authors outside our Galaxy, actually belongs to its disk. It should be noted that in [36], based on the analysis of the abundance of alpha-elements, it was shown that the group of Low energy clusters from the Massari work was most likely formed in-situ, which also indicates the inaccuracy of the in-situ/ex-situ separation in the Massari sample. In order to verify further the origin of the GCs, we use the “age–metallicity” diagram.

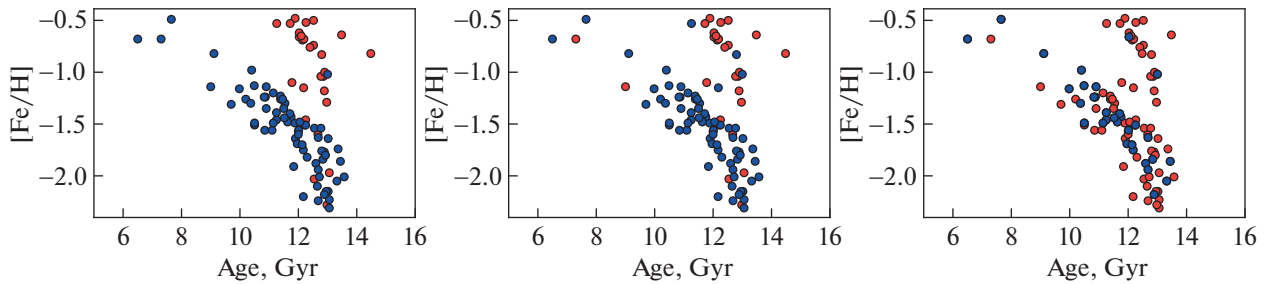
### 3. TWO BRANCHES OF THE GSs IN THE “AGE–METALLICITY” RELATION

The literature discusses the fact that the population of the GCs of the Milky Way exhibits bimodality of colors: there are blue and red clusters [65–77]. This is due to the bimodality of metallicity [73, 75, 78–87]. Blue clusters are found mostly in the halo of the Galaxy. These clusters probably previously belonged to the satellite galaxies. At the same time, red clusters are spatially concentrated towards the Galactic center and rotate with it. Blue clusters are old and metal-poor, while red clusters are younger and metal-rich. The ratio  $[\text{Fe}/\text{H}]$  peaks for blue and red clusters in the Milky Way are approximately  $-1.5$  and  $-0.5$ , respectively. Such a bimodality assumes two mechanisms of GCs formation. The authors of [76, 77, 80] argue that red clusters are formed in-situ, while blue ones were accreted either as a result of the merger of satellite galaxies with the Galaxy or as a result of tidal capture of the clusters themselves.

To understand the difference between in-situ clusters and ex-situ clusters, we plotted respective samples from Massari, Forbes, and Myeong in the “age–metallicity” diagram. The results are shown in Fig. 2.

The “age–metallicity” dependence clearly shows that GCs have two branches. The low-metals branch contains mainly clusters that belong to different tidal streams formed by the partial destruction of satellite galaxies. The clusters in this sequence show a wide variation in age and metallicity, but there are no clusters less than 6 Gyr old. The clusters of a more metals-rich branch, formed in-situ, also have a scatter in metallicity, but all clusters are more than 11 Gyr old.

It is worth noting that the in-situ clusters were formed not in the Galaxy as we know it, but in its progenitor. In the hierarchical model of the formation of galaxies, the mass of a galaxy is accumulated gradually due to mergers, and galaxies as a whole do not have a clearly defined moment of formation. Therefore, for the objects formed long ago, it is difficult to distinguish between the concepts of in-situ and ex-situ. However, specifically for our Galaxy, it is believed that it did not experience mergers with the objects of comparable mass since  $z = 2$  or less than 10.5 Gyr ago [88]. By that time, it had gained only 1/5 of its current total mass (including the dark halo). Six Gyr ago (the



**Fig. 2.** Dependence of the age of GCs on metallicity for cluster samples Forbes, Massari, and Myeong, the left, middle, and right panels, respectively. Blue dots represent ex-situ clusters and the red ones show in-situ clusters.

age of the youngest GCs), its mass was about 60% of the current one [89].

#### 4. THE ROLE OF THE LOCAL SUPERCLUSTER

In the hierarchical model of galaxies formation, accretion of the matter is controlled by large-scale flows, which are also responsible for the formation of a cellular structure—“pancakes” and filaments. In accordance with Zeldovich theory [13], a “pancake” is formed from a uniformly filled volume if compression occurs in one of the three mutually perpendicular directions, and expansion—in two other directions. Thus, the large-scale structure is associated with anisotropic motions of matter, and this anisotropy can also affect the distribution of the matter in the galaxies. Our Galaxy, together with the Local Group, is located within the Local Supercluster (LSC) [90–95], a well-visible pancake-like structure with dimensions of tens of Mpc.

We have tested the influence of the Local Supercluster on the spatial distribution of GCs, as well as dwarf satellite galaxies of the Milky Way. The satellite galaxies were a priori accreted onto our Galaxy from the outside. At the same time, they form a clear-cut flat structure [10–12]. Therefore, we did not limit ourselves to analyzing the GCs distribution, but also considered satellite galaxies. For this, the angle distributions between the axes of the tensor of inertia (1) and the plane of the Local Supercluster were obtained for dwarf satellite galaxies (27 satellites [96]) and for: (i) for the entire GC sample (157 GCs [37, 38]); (ii) for the GCs from the Forbes list; (iii) for the GCs from the Massari list, and (iv) for the GCs from the Myeong list. In Fig. 3, the “Angle” is presented as a function of galactocentric distance for the GCs and satellites of the Galaxy. The “Angle” is measured between the plane of the Local Supercluster and the minor (green triangles) or major (blue dots) axes of the distribution of GCs.

Figure 3 shows that for satellite galaxies (top row, left) at the largest distances, the major and minor axes are located in the supergalactic plane. At the same time, the minor axis is located in the disk of the Milky

Way and the major one is perpendicular to the disk. This means that the plane of satellite galaxies is perpendicular to both the disk of the Galaxy and the supergalactic plane.

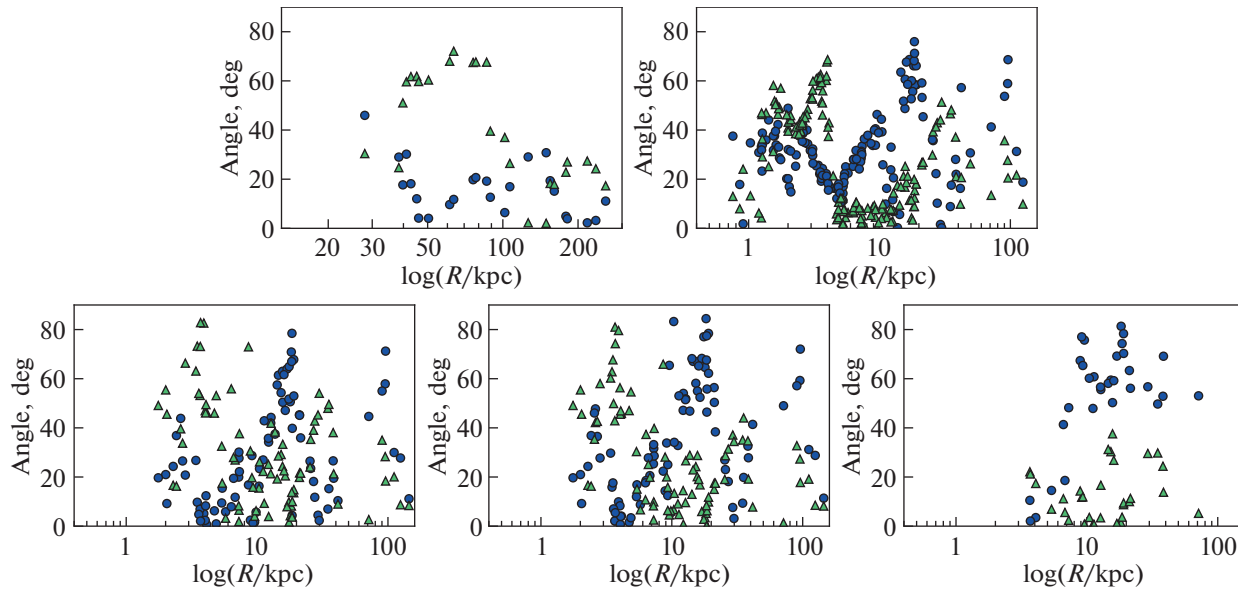
We can say the following regarding all 157 GCs (top row, on the right). At small distances, up to 4 kpc, we are not interested in the result, since these are GCs in the central part of the Galaxy. From 4 to 20 kpc, the minor axis of the system is perpendicular to the disk of the Galaxy and is in the supergalactic plane. The major axis is in the disk of the Galaxy and is perpendicular to the supergalactic plane at a distance of about 20 kpc. Thus, in the range from 4 to 20 kpc, the orientation of the GC system corresponds to the disk of the Galaxy, the influence of the Supercluster does not manifest itself. The same can be said for the clusters from streams, but only with a caveat that they have a larger noise. The minor axis shows a large scatter; this may be due to the fact that there are fewer clusters belonging to the disk of the Galaxy in the sample of objects from the streams.

At the distance of about 100 kpc, the picture for GCs resembles that of satellite galaxies for all samples, i.e., the GC system is oriented perpendicular both to the disk and the Supercluster. It is worth noting that only six clusters are observed at such distances, which is not enough for reliable conclusions.

At a distance of about 30 kpc in all samples except Myeong, the major axis is in the supergalactic plane, while the minor one makes with the large axis an angle of about  $60^\circ$  for all GCs and for Forbes sample; for the Massari sample, the angle is within  $45^\circ$ . At a distance of 25–40 kpc, there are only 10 GCs, of which 10 and 9 GCs belong to the streams of the Forbes and Massari samples, respectively. Thus, in the Forbes and Massari samples at these distances, there may be signs of the influence of the Supercluster on the orientation of the system of accreted GCs, but the reliability of this conclusion is low.

#### 5. DISCUSSION AND CONCLUSIONS

In this paper, we studied the GC system that was formed outside the Galactic disk. To do this, we took



**Fig. 3.** The “Angle” as a function of galactocentric distance for satellite galaxies for entire GCs sample (top row, left to right) and for cluster samples Forbes, Massari, and Myeong (bottom row, left to right, respectively). The “Angle” is measured between the LSC plane and the small (green triangles) or large (blue dots) axes of the distribution of GCs.

from the literature the samples of GCs that were formed in different tidal streams. We chose the works of Forbes, Massari, and Myeong, since their lists of GCs belonging to the different streams are the most complete and are based on the latest data from the GAIA observatory. Having studied a number of works, including those mentioned above, we obtained the main list of tidal streams in which GCs belonged and later were accreted: Sagittarius dwarf spheroidal galaxy (Sgr dSph), Sequoia Galaxy (Sequoia), Helmi Stream (H99), Gaia-Enceladus (possibly Gaia Sausage or CMa), the low energy group (possibly Koala or Kraken), and the High energy group.

It is believed that the accretion onto the Galaxy was anisotropic, which is manifested, for example, as a disk-like structure of satellite galaxies. We measured the anisotropy of the distribution of GCs that belonged to the streams using the tensor of inertia. The measurement result showed that no statistically significant anisotropy is observed for accreted GCs. Having obtained this result, we can state that the anisotropic structure that is observed for the complete sample of GCs (see [12], p. 7, Fig. 7) is due to the presence of many GCs in the Galactic disk, and is associated with the clusters formed in-situ.

However, in Fig. 1 for the three samples of the accreted GCs, the major axis of the tensor of inertia at a distance from 3 to 20 kpc is in the disk. This may be due to the fact that the samples contain a significant number of GCs that have formed in the disk of the Galaxy. To estimate their number, the distribution of GCs with random angular coordinates was modeled and it was shown that the probability of a random real-

ization of such a distribution, in which there are no GCs belonging to the disk, is 4.5, 0.6, and 1.1% for the Forbes, Massari, and Myeong samples, respectively. This conclusion is consistent with the conclusion of Marsakov et al. [36], who had shown that some of the clusters from the Massari catalog claimed to be ex-situ are in fact genetically related to our Galaxy.

We also checked how the clusters formed in-situ and ex-situ behave respective to the AMR (Fig. 2). Two branches can be easily distinguished; the low-metals branch contains mainly clusters belonging to different streams, and they have a large spread in the age and metallicity. At the same time, the clusters in the more metallic branch, which most likely formed in the Galaxy, have a scatter in metallicity, but their age is over 11 Gyr.

To check the likely influence of the Local Supercluster on the distribution of satellite galaxies and GCs of the Milky Way, we presented the Figures, which show the angle between the LSC plane and the axes of distribution of GCs systems or satellite galaxies, as a function of the galactocentric distance. Figure 3 (top row, left) shows that the plane of the satellite galaxies is both perpendicular to the disk of the Galaxy and to the supergalactic plane. For GCs at the distances of up to 20 kpc, only the influence of the Galactic disk is traced; at the distances of about 30 kpc, the orientation of the GCs system may coincide with the supergalactic plane, and at larger distances (more than 100 kpc), the orientation resembles that for satellite galaxies.

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