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Distant globular clusters with anomalously small masses

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Abstract

We found that 10 metal-poor globular clusters are greately distinguished for anomalously small masses on the "destruction rate–mass" plain. As it turned out, these poor clusters, situated 15 kpc farther from the Galactic centre, are somewhat younger than the bulk of the metal-poor globulars, and have anomalously red horizontal branches. All these clusters are supposed to belong to the "young halo" subsystem, i.e. they are supposed to have been captured by the Galaxy at different stages of their evolution. We discovered a significant correlation between the ages found from isochrones and masses of globulars which lie at galactocentric distances greater than the radius of the solar orbit. At the same time, deficiency of distant massive clusters is noticeable with increasing distance from the galactic centre. So we see unticorrelation between the galactocentric distance and masses of distant clusters. Both relations are negligible for the inner clusters of the Galaxy. We assume that favourable conditions for violent dissipation with considerable loss of mass are realised inside the protoglobulars which formed far from the Galactic centre.

Van den Berg (1998, 2000) payed attention to the fact that all known to him "young" globular clusters with ages by ≈ 3 billion years younger than the oldest clusters of the same metallicity lie at galactocentric distances $R >$ 15 kpc and have masses smaller than the average. That is why he assumed that the initial mass spectra of globular clusters formed in the outer halo of the Galaxy displace with time towards smaller masses. Independently, we (Borkova, Marsakov, 2000) have found that the average mass of clusters located within the radius of the solar circle somewhat increases, while in the outer halo it decreases noticeably with growing galactocentric distance. The clusters of the outer halo have markedly smaller masses than those of the thick disk, even among the youngest objects (see Fig. 12 and Table 2 in the papers by Borkova and Marsakov, 2000). In the present paper this phenomenon is discussed in more details and an attempt to explain it is made.

As initial data we have used the compiled catalogue of the measured characteristics of the globular clusters of the Galaxy (Harris, 1996) and the summary catalogue of basic parameters for 145 clusters compiled on its basis by Borkova and Marsakov (2000) with involvement of other sources. For the present paper we have recalculated the parameters on the basis of a new version of the catalogue by Harris (1996) compiled for 1999 June 22, where the distances and luminosities of clusters of the inner region of the Galaxy were mostly revised. We found the masses from integral stellar magnitudes of clusters using a constant mass-to-light ratio $M/L_V = 3$, where the mass M and luminosity L_V are expressed in solar units. It should be borne in mind, however, that the constancy of the ratio M/L_V is not satisfied in all the cases. In particular, the drop in luminosity of clusters with a given mass will be observed in the case of poor population of their red giant branch. Similarly, the mass of a cluster distant from the galactic centre may be underestimated due to a considerable fraction of small-mass stars preserved from tidal destruction. Fig. 1a shows a relationship between the galactocentric distance and the mass of clusters. The dashed line restricts the region of slow evolution of globular clusters the existence of which is theoretically grounded in the paper by Surdin and Arkhipova (1998). The upper line corresponds to the critical value of mass resistent to the effects of dynamical friction that leads to deceleration of a massive stellar cluster moving through the field stars and to its destruction at the centre of the Galaxy under the action of tidal forces, while the lower one corresponds to the effects of dissipation from tidal "shocks" when the cluster flies through the galactic plane. It can be stated with high probability that the clusters lying on the diagram outside of this region are at the end of their lifetime. The solid lines in Fig. 1a represent straight regressions for the regions inside and outside the solar circle ($R_\odot = 8.5$ kpc). The corresponding correlation coefficients are shown in the figures. It can be seen that in the inner region the inspected data do not reveal variation of the average mass of clusters with increasing distance from the galactic centre. However, in the outer region of the Galaxy the observed anticorrelation is different from zero beyond the errors ($r = 0.3 \pm 0.1$). The application of the t criterion has shown that correlation between the mass and the galactocentric distance of globular clusters in the outer halo takes place at a confidence level of about 95 % despite the small value of correlation coefficient. The slope of the regression does not decrease, and the correlation coefficient remains beyond the errors even if six the most remote points are excluded from the diagram. According to Surdin and Arkhipova (1998), such distant clusters did not undergo a considerable dissipation and dynamical friction. This is why the initial mass distribution in the outer halo remained almost unaffected. Thus, a question arises why the deficiency of massive globular clusters increases in the outer halo with increasing galactocentric distance (the lower right angle in the diagram is practically empty).

The present-day theory of dynamical evolution of globular clusters offers a possibility of estimating the mass loss rate of a large number of clusters. In particular, Gnedin and Ostriker (1997) calculated the destruction rate of 119 clusters of galaxies caused by the combined action of two–body relaxation, tidal destruction, and shocks with the disk and bulge. The authors disregarded the energy increase of the clusters caused by their interaction with giant molecular clouds, following the conclusions made by Chernoff et al. (1986). The tangential components of velocities of each cluster, which were lacking for the calculation of the galactic orbits were derived by Gnedin and Ostriker (1997) statistically from the kinematic model for the galactic globular cluster system. In the recently published paper by Dinesku et al. (1999) the destruction rate for 38 globular clusters with the measured tangential and radial components of space velocities were computed. On the whole, the authors note a good agreement with the results of Gnedin and Ostriker (1997). That is why, in order to use as many clusters as possible, we considered to make use of the calculation results of destruction rates derived by Gnedin and Ostriker (1997). Fig. 1b presents the relation between the mass of clusters and the total destruction rates ν. The light symbols denote the clusters situated at a distance of $R > 15$ kpc from the galactic centre. It can be seen that a sufficiently reliable decrease of the average mass with increasing destruction rate is observed. However, rather a narrow sequence consisting of 10 distant clusters parallel to the main one separates sharply. Their masses are approximately an order of magnitude smaller than the average masses of clusters at the same values of ν. The 10 clusters are shown in Fig. 1 by open triangles. Only one cluster with an anomalously small mass (Pal 3) fell in the sample of Dinesku et al. (1999), and in the diagram destruction rate — mass, plotted from the data of this paper, it lies lower than the main relation by the same value.

It is interesting that three of the isolated clusters of anomalously small mass are usually believed to belong to the Sagittarius dwarf spheroidal galaxy. These are the clusters Arp 2, Ter 7 and Pal 12. They are closely spaced and located at a distance of about 18 kpc from the centre of the Galaxy. Apart from them, there are located another two clusters from the same galaxy, Ter 8 and NGC 6715. They did not fall into our group of clusters of anomalously small mass. Although the mass of Ter 8 is the same as that of the three isolated clusters, but its destruction rate has not been found. The mass of the cluster NGC 6715 is two orders of magnitude larger. A group of five clusters with $R \approx 100$ kpc and $log(M/M_{\odot}) \approx 4.5$ is distinguished in Fig. 1, but in fact, they are spaced by a few dozen kiloparsec. Such a distant, but massive cluster NGC 2419 has a very low central density which is more characteristic of small-mass clusters, ($log(\rho) = 1.5$), with an average density logarithm for all clusters of the Galaxy approximately equal to three. For the clusters of anomalously small mass that we have selected this value is ~ 0.2.

Check the ages of the clusters included in this group and the existence of clusters with masses above the average among the "young" clusters in the entire sample. It is of interest to see if there is any time variation of the average mass of the clusters inside and outside the solar circle separately. For this purpose, we make use of the ages from the paper by Borkova, Marsakov (2000) where, based on the ages of 47 sources taken from literature and 336 individual determinations reduced to the unified scale, the weighted mean estimates of ages for 63 globular clusters are computed. In averaging, a two-stage iteration procedure with assigning weight both to each of the used source of ages of the clusters and to each individual determination of individual age. The internal accuracy of the obtained estimates is equal to ± 0.9 billion years. In the present paper, in addition to the original list, we have computed the ages of another 14 clusters. The diagrams $t - log(M/M_{\odot})$ are displayed in Fig. 2. Mass variation as a function of age is not observed in the inner region of the Galaxy. The correlation coefficient within the errors is equal to zero, see the figures in Fig. 2a. In the outer region the correlation turns out to be rather high ($r = 0.6 \pm 0.1$), it remains significant ($r = 0.4 \pm 0.1$) even if four the youngest clusters are disregarded (i.e. the points far away from the centre of distribution). It should be noted that for the most frequently used method, when the ages of globular clusters are estimated from the luminosity of the stars of the turnoff points, the difference in ages between the clusters with different content of heavy elements depends strongly on the adopted relation between luminosity and metallicity of the horizontal branch stars. This is why, the younger age of comparatively metal-rich globular clusters is still in question. The method of estimation of ages from the effective temperatures of the turnoff point stars, which assumes coincidence of the positions of the red giant branches of clusters of the same metallicity, can be used to obtain only the difference in ages between the clusters being compared. In this case, the relative ages prove to be more reliable. The ages of the clusters of anomalously small mass distinguished in Fig. 1b have been obtained by both methods in about ten and a half papers. And both the methods suggest their age to be smaller as compared with the majority of metal-poor clusters.

The presence of an explicit correlation between mass and age in the outer halo suggests a time shift of the initial mass spectrum of globular clusters towards small masses. Indeed, massive enough clusters in Fig. 2b appear only at $t \sim 12$ billion years. However, attention should be drawn to the fact that in the range of ages (12–14 billion years) clusters are observed in a wide range of masses and all the clusters of this age with relatively great masses (NGC 362, 1851, 3201, 6981, IC 4499, and Rup 106) lie in the range of galactocentric distances $(9 \div 18)$ kpc, whereas small-mass clusters (Pal 3, 4, 5, 13, 14, Arp 2, and Pyxis) are situated at far greater distances $(18 \div 102)$ kpc. It means that at the same age the decisive factor that causes the small mass of clusters is their distance from the galactic centre.

So, the decreasing of the average mass of globular clusters with diminishing age is observed only in the outer regions of the Galaxy. The inner clusters do not reveal such an effect. Note that 10 distant clusters of anomalously small mass selected by us proved to be younger and with an average metallicity $< [Fe/H] >= -1.36 \pm 0.14$ possess anomalously red horizontal branches (except for Arp 2) non-typical for globular clusters genetically related with the Galaxy. All of them belong to the subsystem of the "young halo", i.e. they were assumingly captured by the Galaxy at different stages of their evolution (see Zinn (1993), Da Costa and Armandroff (1995)).

It looks as if only far from the centre of the Galaxy, conditions are created that lead to formation of globular clusters with anomalously small masses. The farther from the centre of the Galaxy the more frequently these conditions are realized: almost all the (five out of six) clusters with $R > 60$ kpc have masses several times smaller than the average over the Galaxy. Probably, here the predicted by Agekian (1962) process of violent dissipation of globular clusters turns to be efficient, as a result of which they may lose the greater part of their masses during a short lifetime. It is caused by the fact that at the stage of condensation of a massive diffuse cloud of a protocluster, every star formed inside it tends to its centre due to the cloud attraction. When passing by the centre of inertia of the cluster, part of the stars have time to accelerate so much that they leave it. In this case the percentage of stars "evaporated" from the cluster depends on the degree of original sphericity of the protocluster. Only the protoclusters, formed at a considerable distance from any massive objects, including those formed at a considerable distance from the Galaxy centre, can get a "regular" shape. The existence in the outer halo of older clusters quite rich in stars can be explained in this case by the fact that these clusters (located, mainly, much closer to the galactic centre than the younger ones) formed under the condition of close interaction with other massive objects and at the stage of the protocloud could not acquire a regular spherical shape. (The known very distant massive cluster NGC 2419 is not only an older one, but its central density, as has already been noted, more corresponds to a density of low-mass clusters.) In contrast to them, younger clusters were captured by the Galaxy from a relatively poorly populated, more distant region of the intergalactic space, where they lost a considerable part of mass at the initial stage of evolution. Within such an explanation, the deficiency of massive clusters at large galactocentric distances becomes clear. This explanation is somewhat hindered by the large range of metallicities of our clusters of anomalously small mass ($-1.8 < [Fe/H] < -0.6$). However, two clusters with $[Fe/H] > 1.0$ belong to Saggitarius and one more, the youngest one having at the same time the smallest mass, Pal 1, can be referred with the same degree of probability both to globular clusters and open clusters (Van den Berg, 2000). The remaining six small-mass clusters have metallicities close to $[Fe/H] \approx -1.6$ with $\sigma_{[Fe/H]} \approx 0.1$.

Certainly, each of the correlations discussed here turns out to be of little evidence because of the small number of the observed clusters and large errors in determination of their parameters. Nevertheless, since the distances, masses, ages, radial velocities and morphological composition of the horizontal branches of clusters are determined independently, the assembly of all the results suggests that in the outer halo an isolated group of mass globular clusters really exists. To draw a reliable conclusion if the deficiency of small-mass young globular clusters at the Galaxy periphery is related to the initial mass function variation of these objects with the age, or to the existence of violent dissipation in their evolution, it is necessary to measure proper motions of distant clusters. The elements of galactic orbits computed on their basis make it possible to define the supposed sites of their formation and estimate reliably the destruction rate of every cluster.

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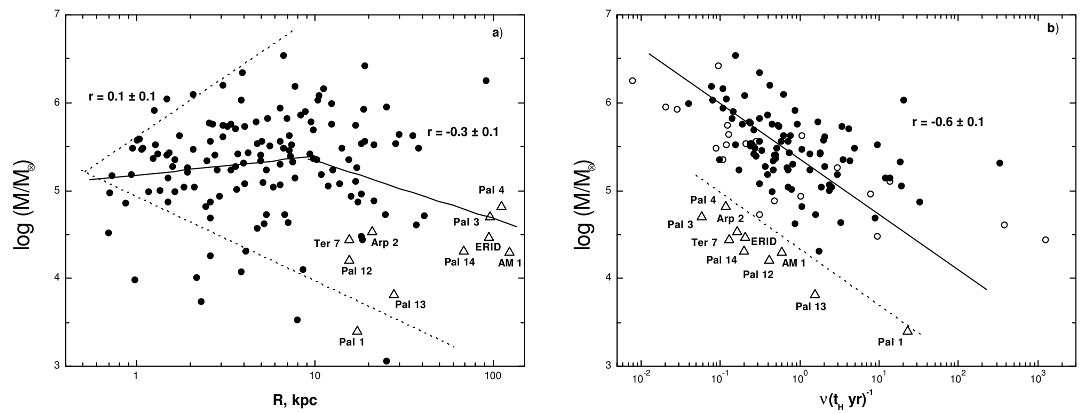

Figure 1: The relationship of the mass and the observed galactocentric distance R — (a), and that of the mass and the total dissipation velocity ν taken from Gnedin, Ostriker (1997) — (b). The dotted line in diagram (a) shows the "cone of survival" according to the paper by Surdin and Arkhipova (1998). The thin lines are the stright lines of the regression in the regions inside and outside the solar orbit radius, while r are the corresponding correlation coefficients. The open triangles are for the clusters lying below the dotted line in diagram (b). The values of ν in diagram (b) are expressed in units reverse to Hubble time adopted for convenience to be equal to 10 billion years. The open symbols (circles and triangles) denote the clusters lying farther than 15 kpc from the centre of the Galaxy. The solid line is a regression stright line for the main sequence of clusters, and the dotted line parallel to it separates the sequence of clusters of anomalously small mass shown by open triangles. Their names are beside them.

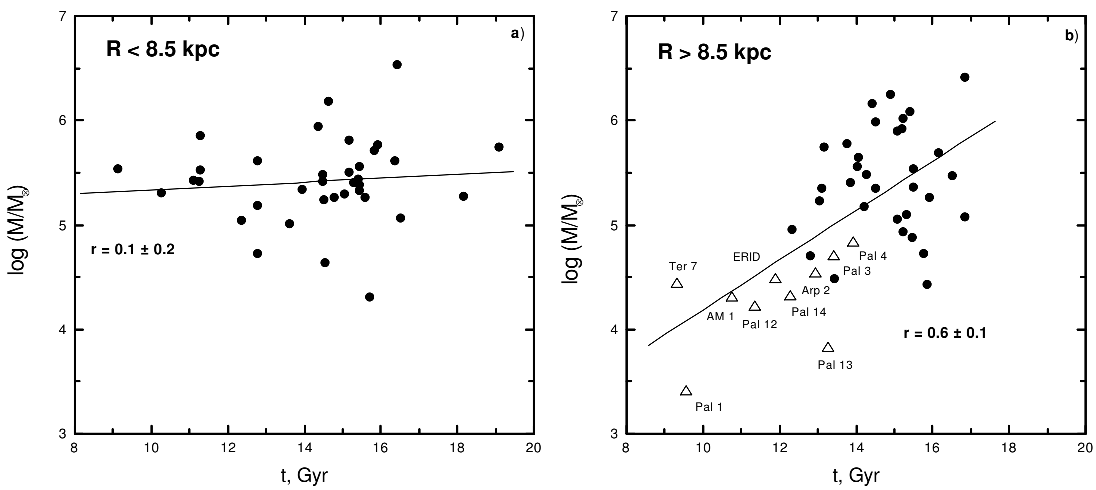

Figure 2: The mass–age relationship for the clusters lying inside (a) and outside (b) the solar circle. The stright lines are root-mean-square regressions, r are the corresponding correlation coefficients. The open triangles in diagram (b) show the clusters of anomalous mass the same as in Fig. 1b.