Young Open Star Clusters: The Spatial Distribution of Metallicity in the Solar Neighborhood

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Abstract

We perform a comparative analysis of the spatial distribution of young (< 50 Myr) open star clusters and field Cepheids with different metallicities. A significant fraction of young clusters are shown to have low metallicities atypical of field Cepheids. Both types of objects exhibit approximately equal (in magnitude) negative radial metallicity gradients, while their azimuthal metallicity gradients differ outside the error limits and have opposite signs. Among the stellar complexes identified by young clusters, the most metal–poor clusters are grouped in the Perseus complex. It is the clusters of this complex that are responsible for the radial and azimuthal metallicity gradients among young clusters. The described properties are indicative of a weak mixing of interstellar matter before the onset of star formation there. Significant differences between the spatial distributions of open clusters and field stars with different metallicities suggest different conditions required for the formation of these types of objects.

Keywords: open star clusters, field Cepheids, stellar complexes, chemical composition, Galaxy.

1 Introduction

Previously (Gozha et al. 2012a, 2012b), we showed that the population of open star clusters is heterogeneous and is divided into two groups differing by their mean parameters, properties, and origin. The first group includes the Galactic clusters that were formed mainly from the interstellar matter of the thin disk, have nearly solar metallicities ([Fe/H] > −0.2), and possess almost circular orbits a short distance away from the Galactic plane, i.e., typical of the field stars of the galactic thin disk. The second group includes the peculiar clusters formed through the interaction of extragalactic objects (such as high velocity clouds, globular clusters, or dwarf galaxies) with the interstellar matter of the thin disk, which, as a result, derived abnormally low (for field thin–disk stars) metallicities and/or Galactic orbits typical of objects of the older Galactic subsystems. Analyzing the orbital elements, we also showed in the above papers that the bulk of the clusters from both groups were formed within a Galactocentric radius of ≈ 10.5 kpc and closer than ≈ 180 pc from the Galactic plane, but owing to their high initial velocities, the peculiar clusters gradually took up the volumes occupied by the objects of the thick disk, the halo, and even the accreted halo (i.e., the corona) of the Galaxy.

In this paper, we are interested in the spatial distribution of heavy elements in the interstellar medium in the solar neighborhood before the onset of star formation there. Open star clusters are perhaps the most suitable objects for such a study. Several factors contribute to this. First, clusters are visible at considerable distances, and these distances are determined fairly accurately. Second, the ages of clusters are determined much more reliably than those of isolated field stars. Third, among the clusters, there are many very young ones that could not go far away from their birthplaces because of their young ages. That is why they clearly trace the segments of spiral arms that are giant
stellar complexes. And, finally, fourth, the metallicities can often be determined for FG stars of even very distant clusters not only by photometric methods but also by spectroscopic ones.

Short–lived long–period Cepheids are equally good tracers of spiral arms and typical representatives of stellar complexes. Since the metallicities are known for a considerable number of these objects, the spatial metallicity distributions for field stars and clusters can be compared. Based on Cepheids, Lepine et al. (2011) detected an azimuthal metallicity gradient that turned out to be comparable in magnitude the radial one. This means that the metallicities of field stars located at the same Galactocentric distances exhibit appreciable systematic variations of the chemical composition, indicative of a weak mixing of the interstellar medium. As a result, these authors conclude that the radial metallicity gradient in the thin disk detected by many objects in the solar neighborhood points only to the existence of a statistical trend, and its values can differ in different directions from the Galactic center. The goal of this paper is to perform a comparative analysis of the spatial distributions of heavy elements in the solar neighborhood among young open clusters and field Cepheids and to investigate properties of clusters inside giant stellar complexes.

2 Initial data

Previously (Gozha et al. 2012a), we described the catalog of fundamental astrophysical parameters that we compiled based on the most recent published data for 593 Galactic open clusters with known total velocities or metallicities1(The catalog is accessible in electronic form at http://vizier.ustrasbg.fr/cats/J.PAZh.hlx). This catalog contains 226 clusters younger than 50 Myr; the distances are known for all of them, and the masses and metallicities are known for 192 and 57 clusters, respectively. Since the overwhelming majority of sample clusters are within 3 kpc of the Sun, these parameters were determined for them with an accuracy sufficient for statistical studies. The errors of all the parameters used are described in detail in the paper cited above.

A list containing 276 field Cepheids with known variability periods, distances, and space velocity components was taken from Berdnikov et al. (2003). We calculated the ages of these stars from the formula $\log t = 8.16 - 0.68 \log P$, where $t$ is the age in years and $P$ is the Cepheid period in days. The list contains 207 Cepheids younger than 50 Myr. Spectroscopic determinations of the iron abundances for 77 young Cepheids were found in the papers of one group of authors (Andrievsky et al. 2002a, 2002c, 2004; Luck et al. 2003; Kovtyukh et al. 2005).

Recall that in our previous papers (Gozha et al. 2012a, 2012b) we determined the membership of stars and clusters in a particular Galactic subsystem from the Galactic orbital elements. As a generalized orbital characteristic, we used the parameter proposed by Chiappini et al. (1997), $(Z_{\text{max}}^2 + 4e^2)^{1/2}$, where the eccentricity ($e$) is a dimensionless quantity and the maximum distance of the orbital points from the Galactic plane ($Z_{\text{max}}$) is measured in kiloparsecs. Figure 1a shows the age $-(Z_{\text{max}}^2 + 4e^2)^{1/2}$ diagram. It can be seen from this diagram that almost all of the sample clusters with high eccentric orbits (i.e., by definition from Gozha et al. (2012a), those satisfying the criterion $(Z_{\text{max}}^2 + 4e^2)^{1/2} > 0.35$) turned out to be younger than 20 Myr. This implies that the last formation burst of such gfsah clusters began precisely 20 Myr ago. Unfortunately, the ratios [Fe/H] are known only for four of the 27 young fast clusters (see Fig. 1b), and all of them have a nearly solar metallicity. According to Vande Putte et al. (2010), such clusters were formed due to globular cluster impact on the Galactic disk, but, on the other hand, almost all metal–poor ([Fe/H] $< \approx 0.25$) young clusters are in flat, nearly circular orbits. According to Vande Putte et al. (2010), such clusters were formed from the interstellar matter that fell from the outer parts of the Galaxy (or was captured from disrupted companion galaxies).

Analysis shows that the most probable age of our young clusters is $\approx 10$ Myr (see Fig. 2b), while their most probable velocity relative Local Standard of Rest is $V_{\text{LSR}} \approx 18$ km s$^{-1}$ (see Fig. 1c, where the five fastest clusters are not shown). As a result, the mean displacement of the clusters relative to their birthplaces turned out to be less than 200 pc, i.e., approximately of the same order of magnitude as the error in the distances to these clusters, $\approx 20\%$ (see Gozha et al. 2012a). This implies that
clusters are quite suitable for a statistical analysis of the distribution of chemical elements in the solar neighborhood. Since these displacements were found to be several times larger for fast clusters, they are already far from their birthplaces even for a young age.

Figure 1d shows the distribution of young clusters in difference between the current position of the cluster \((R_G)\) and the mean radius of its \(R_m\) normalized to \((R_a - R_p)\). (In view of the fact that the orbital parameters we use were calculated by Vande Putte et al. (2010) as the means over 15 Gyr, the current positions of several clusters were found to be less than the tabulated perigalactic radii \((R_p)\) or greater than the apogalactic radii \((R_a)\) of their orbits, i.e., the ratios \(|(R_G - R_m)/(R_a - R_p)| > 0.5\) for them.) Since the ages of our clusters are much less than their revolution periods around the Galactic center, the part of the orbit where the cluster was formed can be determined from the histogram. It can be seen from the diagram that the clusters are formed predominantly near the apogalactic radii of their orbits (the ratios are > 0.4 for one third of the clusters), more rarely near the perigalactic radii, and even more rarely near the mean orbital radii. This manifests itself to an even greater extent for fast clusters with high eccentric orbits (the gray histogram in Fig. 1d). Such clusters are formed mainly near the maximum radii of their orbits (the ratios are > 0.4 for more than half of the clusters). This means that they acquire an initial momentum from extragalactic objects moving toward the Galactic center.

**COMPARATIVE ANALYSIS OF THE PROPERTIES OF YOUNG OPEN CLUSTERS AND FIELD CEPHEIDS.**

Previously (Gozha et al. 2012a), we showed that the metallicity distributions for open clusters and nearby thin-disk field F-G stars of all ages differ significantly. Let us now compare the distributions for objects at approximately equal distances from the Sun-young clusters and field Cepheids. Figure 2a presents the metallicity functions for these objects. There is an almost complete coincidence of the distribution features with the histograms in Fig. 2c from Gozha et al. (2012a). In particular, a clear excess of metal–poor clusters compared to field Cepheids is observed. Similarly, the main maximum of the \([Fe/H]\) distribution for young clusters has a metallicity larger than the solar one, while for field Cepheids it is slightly smaller than the solar one.

Although the objects of both groups are young, their age distributions differ: the maximum for clusters is observed near 10 Myr, while for Cepheids it is later approximately by 30 Myr. This is because a massive star takes some time to evolve to the pulsational instability strip and to become a Cepheid. On the other hand, young clusters experience a strong gravitational influence from the spiral density wave that formed them and, therefore, dissipate quickly. As a result, the relative number of clusters decreases sharply already after 20 Myr. Nevertheless, the number of objects of both types within our chosen range (< 50 Myr) turns out to be approximately the same and is sufficient for statistically significant estimations.

For both types of objects, Fig. 3a presents the age-metallicity relations within 50 Myr. We see that a significant fraction of young clusters also turn out to be below the lower envelope for field Cepheids (see the dashed curve in the diagram drawn by eye). This provides convincing evidence for both significant inhomogeneity of the chemical composition of the interstellar medium in the Galactic plane in the solar neighborhood and a different history of chemical evolution of the matter from which the metal-poor clusters were formed. Although the Galactocentric distance-metallicity diagrams (Fig. 3b) presented on the next panel demonstrate approximately identical, within the error limits, radial metallicity gradients for both groups of objects, the relation for clusters lies, as would be expected, well below that for field stars. In contrast, the azimuthal gradients for field stars and clusters differ radically (see Fig. 3c, where the y coordinate is positive in the direction of Galactic rotation). Whereas young Cepheids exhibit an increase in metallicity in the direction of Galactic rotation, confirming the conclusions by Lepine et al. (2011), young clusters exhibit a decrease. The negative azimuthal metallicity gradient for clusters is provided exclusively by the objects lying below the lower envelope for field Cepheids on the age-metallicity diagram (Fig. 3a). If these clusters are removed from the diagram, then the relations for the remaining metal–rich clusters and field Cepheids will coincide completely. If the same clusters are removed from the previous panel, then the radial
gradient for young clusters will become zero, within the error limits.

**SPIRAL ARMS AND STELLAR COMPLEXES.**

It is generally believed that star formation in the thin Galactic disk is stimulated mainly by spiral density waves. According to present views, the segments of spiral arms detected in the solar neighborhood are giant stellar complexes (Efremov 2011). Young star clusters and field Cepheids confirm this with confidence. Figure 4a presents the distributions of young (younger than 50 Myr) open clusters and equally young field Cepheids in projection onto the Galactic plane. It can be seen from the figure that although the formation of both types objects is assumed to be stimulated in a common process, the regions with enhanced densities for them do not coincide. Arbitrary boundaries between these regions (see the curves on the diagram drawn by eye) that are located along the usually identified spiral arms can even be drawn. Although the objects being studied are young and went not far away from their birthplaces, this separation does not necessarily suggest that the clusters and field stars were born independently of one another. Recall that the mean age of the Cepheids in our sample ($33 \pm 11$ Myr) is greater than that for the sample of young clusters ($17 \pm 12$ Myr). As a result, for $t < 50$ Myr, 70% of the clusters turn out to be younger than 20 Myr, while the fraction of such objects among the Cepheids is only 12%. Some authors (see, e.g., Ivanov 1983) point out that, for example, the clusters on the inner wing of the Carina-Sagittarius arm are systematically younger than those at the outer edge, as is required by the wave theory of spiral structure. The difference between the spatial distributions of clusters and field stars observed in Fig. 4a is most likely also due to the wave nature of the spiral structure, when conditions favorable for the formation of clusters and field stars are created at the collision front of the interstellar medium overtaking the density wave. After several tens of Myr, the number of clusters at the outer edge of the wave decreases considerably, while the Cepheids dominate for such an age.

However, as has already been pointed out, the clusters and field Cepheids exhibit a significant difference in heavy–element abundances. It can be seen from Fig. 4a that the relative number of metal-poor Cepheids on the diagram (the crosses on the diagram are Cepheids with $[\text{Fe/H}] < 0.0$) gradually decreases from left to right and from bottom to top. On the other hand, the metal-poor clusters (i.e., those lying below the lower envelope for field Cepheids in Fig. 3a), with amore or less uniform distribution over the entire diagram, form a clump in its upper left corner (see the closed circles in Fig. 4b). It is this clump (which is the Perseus stellar complex, see below) that is responsible for the negative radial and azimuthal metallicity gradients for young clusters (on the panels of Fig. 3, the clusters of the Perseus complex are indicated by the filled circles). The metal–rich clusters also form a clump but at the center of the diagram (the open circles in Fig. 4b). In other words, the spatial distributions of young open clusters with different metallicities are very nonuniform. Occasionally, clusters of different metallicities are close neighbors within the same complex (see the filled and open circles in Fig. 4b).

The ovals drawn by eye in Fig. 4b indicate five regions with enhanced cluster densities usually associated with the stellar complexes that are the segments of the Perseus, Cygnus, Sagittarius, Carina, and Local-system spiral arms. The distributions of most physical parameters for the identified groups of clusters differ from one another statistically insignificantly, but there are also some differences. In particular, the clusters of the Local system clearly show a bimodal age distribution with a rather narrow dominant peak at $t = 11 \pm 1$ Myr including two thirds of the clusters and a very distant lower peak at $t = 37 \pm 1$ Myr (Fig. 5a). As can be seen from the same figure, the age distribution for all clusters exhibits a sharp decrease in the number to 20 Myr years and then the decrease continues much more slowly. The mean mass of the Local-system clusters also turned out to be lower, outside the error limits, than the mean over all young clusters (see Fig. 5b). Themetallicities for all (except one) clusters of the Local system are as high as those for Cepheids.

Another statistically significant feature is a radical difference between the metallicity distributions for the clusters of the Perseus complex and all of the remaining young clusters (see Fig. 5c). These clusters are the most metal–poor ones among the young clusters, and their orbits are almost flat and circular.
The Perseus group also contains six fast clusters (the metallicity was determined only for one of them and it is solar); they are distributed mainly along the periphery of the complex (see the asterisks in Fig. 3b), while seven of the twelve metal–poor clusters form a dense core in the middle of the group. Five fast clusters are also observed in the Carina complex, with three of them lying near its boundary. There are no clusters with high eccentric orbits in the Cygnus and Sagittarius complexes at all, and only two are present in the Local system, while the remaining (about fifteen) fast young clusters are scattered over the entire field of the diagram. Such a chaotic distribution of fast clusters suggests that exclusively spiral density waves were unlikely to be responsible for their formation.

CONCLUSIONS

Thus, we see that the population of young open clusters is heterogeneous. In particular, some of them have exhibited very large space velocities and high eccentric orbits since the earliest age (see Fig. 1a). This unequivocally points to a nonrelaxational nature of these velocities. In addition, some of young clusters have low metallicities atypical of thin-disk field stars (Fig. 3a), although the orbits of such clusters are flat and almost circular. Such a low metallicity is most naturally explained by the fall of matter with a different history of chemical evolution on the Galactic disk and the predominant formation of precisely open clusters rather than field stars from this matter. This fall (from the outer regions of the Galaxy or from disrupted dwarf companion galaxies) occurred not too long ago, because the interstellar matter did not have time to be sufficiently mixed before the starburst in it. In addition, both young clusters and field Cepheids exhibit a chemical composition inhomogeneity, when objects of the same type with different heavy–element abundances coexist at the same place (Fig. 4). A large–scale inhomogeneity of objects in chemical composition is also observed, when the clusters and Cepheids show opposite (in sign) azimuthalmetallicity gradients that are comparable in absolute value to the approximately equal (in magnitude) negative radial metallicity gradients exhibited by both types of objects. For young clusters, both gradients are attributable exclusively to the existence of the metal–poor Perseus complex, while for field Cepheids, they are due to a gradual increase in the relative number of metal-rich stars in the directions of Galactic rotation and the Galactic center. Note that both types of objects are good tracers of spiral arms, suggesting the existence of a global mechanism triggering star formation, spiral density waves. The observed displacement of the clusters and Cepheids, respectively, to the inner and outer edges of the arms is most likely due to the slightly greater mean age of the Cepheids and the wave nature of the spiral structure. Thus, the described properties are indicative of a difference between the conditions in the interstellar medium required for the formation of open clusters and field stars. To extend our views of the degree of inhomogeneity of the interstellar matter, the history of its chemical evolution, and the origin of open star clusters, data on the abundances of the chemical elements synthesized in various processes in the atmospheres of open-cluster stars are needed. Unfortunately, a detailed chemical composition has been determined only for about 60 open clusters and only for one young cluster.

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Figure 1: (a) Age–\((Z_{\text{max}}^2 + 4e^2)^{1/2}\) diagram, where \(Z_{\text{max}}\) is the maximum distance of the orbital points from the Galactic plane expressed in kiloparsecs and \(e\) is the orbital eccentricity; (b) \((Z_{\text{max}}^2 + 4e^2)^{1/2}.[\text{Fe/H}]\) diagram; (c) the distribution in total residual velocities; (d) the distribution in relative distances from the mean radii of their orbits \((R_G - R_m)/(R_a - R_p)\) for open clusters younger than 50 Myr. The dashed lines on the first two panels correspond to the critical value of the parameter \((Z_{\text{max}}^2 + 4e^2)^{1/2} = 0.35\); the gray histograms on panels (c, d) indicate the clusters for which this parameter > 0.35.
Figure 2: The distributions of young \( t < 50 \) Myr \) open clusters (hatched) and field Cepheids (gray histograms) in metallicity (a) and age (b).
Figure 3: Metallicity for young ($t < 50$ Myr) open clusters and field Cepheids versus age (a), Galactocentric distance (b), and distance along the y coordinate (azimuthal distance). The circles are clusters, the filled circles are clusters of the Perseus complex, and the snowflakes are Cepheids. The dashed curve on panel (a) is the lower envelope for field Cepheids drawn by eye. The lines on panels (b) and (c) are the linear regressions for clusters (solid) and Cepheids (dashed). The radial and azimuthal metallicity gradients are shown on the corresponding panels.
Figure 4: (a): The distribution of young clusters and Cepheids in projection onto the Galactic plane, where the circles are clusters, the filled circles are metal-poor clusters lying below the dashed line in Fig. 3a, the crosses are metal-poor Cepheids with $[Fe/H] < 0.0$, the snowflakes are metal-rich Cepheids, and the pluses are Cepheids with unknown metallicities. The nearly vertical curves drawn by eye are the left envelopes of the regions with an enhanced cluster density, while the middle and right curves are simultaneously the right envelopes for the regions with an enhanced density of field Cepheids. (b) The same for clusters, the closed circles are metal-poor clusters, the open circles are metal-rich clusters, the asterisks are fast clusters, and the dots are clusters without metallicity. The ovals drawn by eye are places of enhanced cluster density-the stellar complexes with their names.

Figure 5: The distributions of all young open clusters and only Local-system clusters (hatched histograms) in age (a) and mass (b); (c) the metallicity functions for all young clusters and only for Perseus-complex clusters (gray histogram).