Heterogeneity of the Population of Open Star Clusters in the Galaxy

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Abstract

Based on published data, we have compiled a catalogue of fundamental astrophysical parameters for 593 open clusters of the Galaxy. In particular, the catalogue provides the Galactic orbital elements for 500 clusters, the masses, central concentrations, and ellipticities for 424 clusters, the metallicities for 264 clusters, and the relative magnesium abundances for 56 clusters. We describe the sources of initial data and estimate the errors in the investigated parameters. The selection effects are discussed. The chemical and kinematical properties of the open clusters and field thin-disk stars are shown to differ. We provide evidence for the heterogeneity of the population of open clusters.

Keywords: open star clusters, chemical composition, kinematics, Galaxy (Milky Way)

1 Introduction

Open star clusters are traditionally considered to be typical representatives of the Galactic thin disk and are used to analyze the various aspects pertaining to the structure, chemical composition, dynamics, formation, and evolution of this subsystem. It is believed that since such parameters as the distances, metallicities, and ages are determined for clusters much more accurately than they are for single field stars, open clusters trace better the properties of the Galactic disk (Piskunov et al. 2006). These stellar systems have a low central concentration, are rather weakly gravitationally bound, are continuously subjected to a force from massive clouds of interstellar gas, and, therefore, are very short-lived systems (Pfalzner 2009). Nevertheless, clusters with ages of more than 1 Gyr are also encountered among them. Unfortunately, the absence of young hot stars, high dispersiveness, and often a small number of stars in dynamically highly evolved old open clusters produce a significant observational selection against them. Such clusters are more difficult to distinguish against the background of field stars, and this is one of the reasons why so few of them are known. This effect is rather difficult to take into account, but it should be taken into consideration in the conclusions drawn from the properties of observable open clusters.

In recent years, open clusters have ceased to be regarded as a homogeneous population, i.e., as having been formed exclusively from the interstellar matter genetically related to the previous populations of thin-disk stars. For example, Marsakov et al. (1990) showed more than two decades ago that the field thin-disk stars and open clusters occupy slightly overlapping regions in the age-metallicity diagram, and the open clusters at the same age, on average, have a lower metallicity. As a result, it turned out that low-metallicity ([Fe/H] < −0.2) open clusters are being formed very intensively even at present, while virtually no field stars with such a metallicity are born now. As a consequence, the following conclusion was reached: "the excess of low-metallicity clusters most likely results from the fall of a metal-poor gas to the disk and the succeeding starburst (for example, due to the interaction with the Magellanic Stream)".
Numerous studies point to the absence of a correlation between the properties of open clusters and field thin-disk stars. For example, in contrast to the field stars by which a monotonic radial metallicity gradient is usually detected (see, e.g., Cescutti et al. 2007), Twarog et al. (1997) showed for open clusters that the metallicity decreases with increasing Galactocentric radius with a jump-like transition to $\Delta [\text{Fe/H}] \approx -0.3$ near 10 kpc. In more recent papers (see, e.g., Friel et al. 2002; Yong et al. 2005; Magrini et al. 2009), it was shown that there is not a jump but a sharp decrease in the slope of the gradient when passing through 12 kpc, which was explained by satellite accretion onto the outer disk. Yong et al. (2005) investigated the abundances of several chemical elements in five old distant open clusters and, in particular, concluded that the clusters in the outer Galactic disk could well be formed through the stimulation of star formation by a series of captures of interstellar matter from dwarf galaxies. Generally, estimates show that about 10% of the field thin-disk stars owe their origin to open clusters (see, e.g., Piskunov et al. 2006). (This is without allowance for the numerous "embedded" clusters being born with single stars in regions of current star formation and being rapidly disrupted.) However, having reconstructed the initial mass function of open clusters, Roser et al. (2010) recently concluded that clusters provided the formation of about 40% of the field stars in the entire evolution time of the Galaxy; not all of them must necessarily turn out to be thin-disk stars. For example, Kroupa (2002) showed how the fast stars leaving the clusters mainly in the period of their formation from the parent molecular cloud could thicken the Galactic disk and even form a thick disk.

In their comprehensive paper, Wu et al. (2009) analyzed in detail the kinematics and Galactic orbits of 488 open clusters. They found the dispersions of all cluster velocity components to increase monotonically with age and hypothesized that this resulted from the action of dynamical Galactic disk heating effects. They also drew attention to the heterogeneity of the population of open clusters: in particular, they concluded from their comparison of the orbital eccentricities for clusters and thick-disk giants that 3.7% of the clusters in their sample belong to the thick disk. In addition, they showed that the distribution of clusters in heavy-element abundances is bimodal with a dip near $[\text{Fe/H}] \approx -0.2$, although they pointed out that such a distribution could result from metallicity incompleteness of the cluster sample. Nevertheless, Vande Putte et al. (2010) adopted this property as evidence for lower-metallicity clusters being isolated by assuming an "unusual" origin for them. Owing to the appearance of new extensive catalogues of highly accurate data, by investigating the eccentricities of the Galactic orbits ($e$) and the maximum distances of the orbital points from the Galactic plane ($Z_{\text{max}}$) for 481 clusters and the metallicities for a hundred and a half clusters, Vande Putte et al. (2010) revealed about ten objects of an extragalactic origin as a result of the interaction of high-velocity clouds with the gas disk. They deemed the clusters in which at least one of the two investigated orbital elements was abnormally high for thin-disk objects and the metallicity was low ($[\text{Fe/H}] < -0.2$) to be such clusters. They deemed the remaining low-metallicity open clusters that exhibited no deviations of the orbital elements from the mean ones for the bulk of the clusters to have originated from the interstellar matter that fell from the outer parts of the Galaxy (or was captured from disrupted satellite galaxies). In addition, they assumed several clusters with a nearly solar metallicity but with high eccentricities or $Z_{\text{max}}$ to have been produced by the interaction of globular clusters with the disk. The possibility of the formation of open clusters with different orbits and metallicities by the listed mechanisms triggering star formation was also demonstrated by theoretical modeling (Comeron and Torra 1992; Wallin et al. 1996; Martos et al. 1999; Levy 2000).

In their recent paper, Lepine et al. (2011) explained the abrupt decrease in the metallicity of open clusters at a Galactocentric distance exceeding the solar one by 1 kpc found by Twarog et al. (1997) by the existence of a corotation ring-shaped gap in the gas density, which isolates the inner and outer gaseous regions of the Galaxy from each other. (According to their calculations, it is at this distance that the rotation velocities of the spiral density wave and the Galactic disk coincide.) As a result, the inner and outer regions of the Galactic disk chemically evolve independently, leading to a break in the radial metallicity gradient at this Galactocentric distance. In their opinion, the processes near the corotation radius also give rise to clusters with eccentric orbits. However, they point out that
some of the clusters in the outer disk are most likely extragalactic in origin.

These studies are devoted to a comprehensive statistical analysis of the relationships between the physical, chemical, and spatial–kinematical characteristics of open clusters and nearby field stars aimed at revealing clusters of different natures as well as characteristic parameters and patterns in the various populations of Galactic open star clusters. An extensive catalogue of all the available parameters of open clusters is primarily needed to accomplish the formulated task.

2 Initial data

We took the latest version 3.1 (November 2010) of the catalogue compiled by Dias et al. (2002) as the main source of data for open clusters. This is currently the most complete catalogue of open star clusters that is continuously updated and supplemented with data from the most recent publications. The shortcomings of the catalogue include the principle of its construction based on the compilation of data by many authors that used different criteria, calibrations, techniques, and instruments. At the same time, the authors of the catalogue neither analyze nor average the data but select the most accurate (from their viewpoint) parameter determinations. As a result, the cluster parameters in the catalogue turned out to be inhomogeneous. However, Paunzen and Netopil (2006), who used the averaged values in their study, showed the results obtained from the data of their catalogue and the first version of the catalogue by Dias et al. (2002) to have the same statistical significance. Since our goal is a comprehensive statistical analysis of the chemical, physical and spatial–kinematical properties of the population of open clusters, we deemed it possible to take the data from this most voluminous catalogue as a basis while supplementing it with other necessary cluster parameters.

Positions and Velocities.

The version of the catalogue by Dias et al. (2002) that we use presents data for 2140 clusters; the distances were determined for 1309 clusters, while the proper motions and radial velocities are simultaneously known for 485 clusters. Since we use the Galactic orbital elements calculated by Wu et al. (2009), Vande Putte et al. (2010), and Magrini et al. (2010) for 500 clusters, we took the distances, proper motions, and radial velocities for them from the corresponding papers (for more details, see below). Based on the available data, we calculated the rectangular coordinates \((x, y, z)\) and the space velocity components \((V_R, V_\Theta, V_Z)\) in cylindrical coordinates corrected for the solar motion relative to the local standard of rest (LSR), where \(V_R\) is directed to the Galactic anticenter, \(V_\Theta\) is in the direction of Galactic rotation, and \(V_Z\) is directed toward the North Galactic Pole. We took the solar motion relative to the LSR to be \((U, V, W)_\odot = (11.1, 12.24, 7.25)\) km s\(^{-1}\) (Schonrich et al. 2010), the solar Galactocentric distance to be 8.0 kpc, and the LSR rotation velocity to be 220 km s\(^{-1}\). The mean relative error of the distances for all clusters was found by Wu et al. (2009) to be \(\approx 20\%\). The results by Paunzen and Netopil (2006) are also consistent with this estimate; they showed the error to be less than 20\% for 80\% of the 395 clusters for which three or more independent distance determinations were found. The space velocities are generally determined only for clusters in which the radial velocities and proper motions for more than five stars can be measured. We calculated the mean error of the velocity components using data from Vande Putte et al. (2010) to be \(\approx 10.0\) km s\(^{-1}\).

Galactic Orbital Elements.

For 488 clusters with all three velocity components, we provided the orbital eccentricities \((e)\) and the maximum distances of the orbital points from the Galactic plane \((Z_{max})\) calculated for them by Wu et al. (2009) from these data. We took the same parameters for nine more clusters (NGC 433, NGC 1513, Collinder 220, Loden 807, NGC 6249, Berkeley 81, IC 1311, NGC 7044, Berkeley 99) from Vande Putte et al. (2010) and for three more clusters (NGC 6253, NGC 6404, NGC 6583) from Magrini et al. (2010). (Since Magrini et al. (2010) used a solar Galactocentric distance slightly different from that of the other two papers in their calculations, 8.5 kpc against 8.0 kpc, we reduced the radii provided by them by 0.5 kpc.)

Analysis of the errors in the orbital elements of open clusters given in the original papers showed...
that they depend mainly on the errors in the distances to them. Therefore, the largest errors are generally obtained for the clusters farthest from the Sun. If the ten distant clusters with the largest uncertainties in their orbital elements (marked by the asterisks in the table) are excluded from our analysis, then the mean error in the apogalactic orbital radii and its dispersion for the remaining clusters will be $e(R) = 0.35$ and $\sigma(e) = 0.21$ kpc. The corresponding values for the perigalactic orbital radii are $(0.31$ and $0.06)$ kpc, for the maximum distances from the Galactic plane are $(0.09$ and $0.04)$ kpc, and for the eccentricities are $0.02$ and $0.01$. (Our analysis showed that the errors of all orbital elements for clusters closer (farther) than 1 kpc from the Sun are smaller (larger) than these values, on average, by a factor of 1.5 - 2. In contrast, the relative errors of the most informative orbital elements, $e$ and $Z_{max}$, can reach 100% for the most distant clusters.)

**Cluster Ages**

The cluster ages are not always determined with confidence. In the latest version of the catalogue by Dias et al. (2002), they are given for 1269 open clusters. The ages of distant clusters, for which the metallicities are unknown (the solar metallicity is assigned to them) and the main-sequence turnoff points are not identified, turn out to be least accurate. According to the estimates by Kharchenko et al. (2005a), the errors of the cluster ages on a logarithmic scale turn out to be, on average, $\epsilon_{\log t} \approx 0.20 - 0.25$ in this case. Paunzen and Netopil (2006) showed that the ages for only 11% of the 395 clusters with three or more independent age determinations have errors less than 20%, while the errors for 30% of the clusters exceed 50%. They also argue that the individual age determinations given in the first version of the catalogue by Dias et al. (2002) also have similar error statistics. In contrast, in the latest version of the catalogue that we use, the ages were determined slightly more accurately. We see from the above estimates that the absolute errors increase with age.

**Physical Cluster Parameters**

We took the physical parameters of the clusters from three catalogues of the same team of authors, where these parameters are successively estimated by analyzing the spatial distribution of stars in the clusters. The mass is the most important characteristic of a cluster that determines many aspects of its subsequent existence. We took the masses for 424 clusters from the catalogue by Piskunov et al. (2008), where they were estimated from the mean sizes of their semiaxes based on King’s empirical model. The mean error of the logarithm of the mass is about 0.28, which corresponds to a mean relative error of $\approx 11\%$. We calculated the central concentrations $C = \log(r_{cl}/r_{co})$, where $r_{cl}$ is the angular radius of the cluster and $r_{co}$ is the angular radius of its central core, for 424 clusters based on data from Kharchenko et al. (2005a, 2005b). These authors use a catalogue of 2.5 million stars to determine the angular radii and rely on the counts of stars brighter than $12^m$. The measurement errors of the corresponding radii are not given in their papers, but, according to the estimates of the accuracy of the King radii by the same authors (see Piskunov et al. 2007, 2008), the relative errors for the overwhelming majority of clusters lie within the range from 10% to 50%. The ellipticities, the ratio of the difference between the semimajor and semiminor axes to the semimajor axis, for 424 clusters were taken from the catalogue by Kharchenko et al. (2009). The mean absolute error of the ellipticity in the catalogue turned out to be rather large, $\approx 0.21\%$, i.e., the mean relative error is $\approx 60\%$.

**Metallicities.**

The largest number of metallicity determinations is given in Dias et al. (2002), 179, and Paunzen et al. (2010), 188. (We excluded two clusters from the table in Paunzen et al. from consideration, because, according to the conclusion reached by Dias et al. (2002), Berkeley 42 is a globular cluster, while Ruprecht 46 is an asterism.) In version 3.1 of their catalogue, Dias et al. provided the most reliable (from their viewpoint) values of [Fe/H] from various sources determined both spectroscopically and photometrically. Paunzen et al. (2010) simply averaged the photometric metallicity determinations of different authors. The [Fe/H] determinations for 110 clusters are given in both papers and correlate between themselves well enough. Assuming the spectroscopic metallicity determinations to be more reliable, we included the spectroscopic values from Dias et al. (2002) in the first place, the averaged photometric values from Paunzen et al. (2010) in the second, and, subsequently,
all of the values that fell into only one of the lists. For NGC 188 and Berkeley 39, instead of the metallicities (Friel et al. 2002) given in the catalogue by Dias et al., we used their new values obtained by Friel et al. (2010) based on high-resolution spectroscopy. We used the values of [Fe/H] for NGC 1193 from the same paper. Furthermore, we added the metallicity determinations for several clusters from Akkaya et al. (2010), Magrini et al. (2010), Pancino et al. (2010), and Fossati et al. (2011). In total, our list contains 264 clusters with known metallicities. The mean error in the metallicity that we determined using the data from these papers is $\varepsilon_{[Fe/H]} \approx 0.10$. Our checking showed that the distribution of discrepancies between the photometric and spectroscopic determinations for the same clusters also exhibits exactly the same dispersion.

**Relative Magnesium Abundances**

We managed to find 81 $[\text{Mg/Fe}]$ determinations for 56 clusters in 43 sources from 1981 to 2011. (We used only the sources in which the authors themselves analyzed the accuracies of their determinations in different stars and provided the cluster-averaged magnesium abundances.) In total, the magnesium abundance was determined in 551 cluster stars (in one paper for Be 21 and three for NGC 2682, the number of stars was not specified). The maximum number of stars measured in the cluster is 115 (Hyades), with a mean value of 10 stars and a median value of 4 stars. The determinations for NGC 1193 and Berkeley 31 were made only from one star. The abundances for ten clusters were determined in more than one source, with the maximum number of sources being 10 (NGC 2682). For these clusters, we averaged the determinations with a weight inversely proportional to the errors declared by the authors. The mean error of the relative magnesium abundance calculated from the uncertainties of individual determinations declared in the sources is $\varepsilon_{[\text{Mg/Fe}]} \approx 0.07 \pm 0.01$. Comparison of the determinations by different authors for clusters with several determinations (35 determinations from 29 sources) showed a slightly larger dispersion: $\sigma_{[\text{Mg/Fe}]} = 0.10 \pm 0.01$. At the same time, no systematic shifts between the determinations of different teams of authors exceeding this dispersion were found. The ratios $[\text{Mg/Fe}]$ found and a list of the sources used are given in the table.

For our studies, we compiled a catalogue containing 500 clusters with the calculated orbital elements and 264 clusters with the estimated metallicities. Since these lists partly overlap, the final catalogue contains 593 clusters. The table lists all of the above-described parameters found for them. Column 1 of the table gives the cluster name; columns 2 and 3 give the Galactic coordinates ($l$, $b$). The heliocentric distances $d$, coordinates ($x$, $y$, $z$) in a right-handed Cartesian coordinate system, and Galactocentric distances $R_G$ of the clusters are listed in columns 4 - 8. The next three columns contain the calculated velocity components ($V_R$, $V_\Theta$, $V_Z$) in a cylindrical coordinate system. The following columns provide the Galactic orbital elements of the clusters ($e$, $Z_{max}$, $R_a$, $R_p$). The cluster ages are listed in column 16. The physical parameters $lg(M/M_\odot)$, $lg(r_{cl}/r_{co})$, and the ellipticities are presented in the succeeding three columns. The values of [Fe/H] and references to the source are collected in columns 20 and 21, respectively. The relative magnesium abundances $[\text{Mg/Fe}]$ and their sources are presented in columns 22 and 23. The interpretation of the numbers of the references to [Fe/H] and [Mg/Fe] is appended to the catalogue. The membership in Galactic subsystems is given in the last column of the catalogue. Here, the following notation is used: 1 – the thin disk, 2 – the thick disk, 3 – the halo.

**Field Stars**

In addition to the catalogue of open clusters, we used three more lists of field stars. The first

| Name     | $l$       | $b$       | $d$     | $x$   | $y$   | $z$   | $R_G$ | $V_R$  | $V_\Theta$ | $V_Z$  | $e$  | $Z_{max}$ | $R_a$ | $R_p$ |
|----------|-----------|-----------|---------|-------|-------|-------|-------|--------|------------|--------|------|------------|-------|-------|
| NGC 6520 | 2.8811    | -2.8435   | 1900    | 1895  | -94   | 6.11  | 15.6  | -8.7   | 0.07       | 0.11   | 6.3  | 6.4        |       |       |
| NGC 6583 | 9.2825    | -2.5336   | 2100    | 2070  | 338   | 5.94  | -4.8  | 215.6  | 10.1       | 0.093  | 0.132| 6.56       | 5.36  |       |
| NGC 6791*| 69.9585   | 10.9039   | 5853    | 1970  | 5399  | 8.17  | -88.0 | 217.0  | 10.1       | 0.093  | 0.132| 6.56       | 5.36  |       |
| NGC 7789 | 115.5319  | -5.3849   | 1795    | -770  | 1613  | 8.92  | 21.1  | 158.3  | 7.8        | 0.32   | 0.17 | 9          |       | 4.6   |
| NGC 188  | 122.8431  | 22.3841   | 2047    | -1027 | 1590  | 9.20  | -8.2  | 211.4  | -14.7      | 0.07   | 0.79 | 9.3        | 8.1   |       |
is the list containing, in particular, the metallicities, Galactic orbital elements, and ages for 2255 thin–disk stars from Marsakov et al. (2011). It is a sample of nearby (< 70 pc from the Sun) F-G stars the probability of whose membership in the thin disk is higher than that in the thick one. The sample was drawn from the photometric catalogue by Holmberg et al. (2009) based on the criteria for selection into the thin disk described by Koval’ (2009). This sample is essentially complete for thin-disk F2 – G5 stars within 70 pc of the Sun. Comparison of the photometric metallicities from this catalogue with the spectroscopic values of [Fe/H] from the catalogue by Borkova and Marsakov (2005) revealed no systematic shifts outside errors of ε[Fe/H] ≈ ±0.10 (Marsakov et al. 2011). About 10% of the stars with errors in the ages > 3 Gyr were removed from the original list; as a result, the mean error in the final sample was ⟨t⟩ = ±1.0 Gyr.

The second sample contains 219 nearby thin-disk stars selected from our summary catalogue of spectroscopic iron and magnesium abundance determinations (Borkova and Marsakov 2005) based on similar criteria. Almost all of the magnesium abundances in dwarfs and subgiants of the solar neighborhood determined by the method of synthetic modeling of high–dispersion spectra that were published before January 2004 were collected in the catalogue. The internal accuracies of the catalogued metallicities and relative magnesium abundances were ε[Fe/H] = ±0.07 and ε[Mg/Fe] = ±0.05, respectively.

The third catalogue is the list containing 135 field Cepheids with the distances and spectroscopic iron abundance determinations compiled from data from the papers of one group (Andrievsky et al. 2002a - 2002c, 2004; Luck et al. 2003). The typical error of the metallicity in Cepheids declared by the authors is ε[Fe/H] < ±0.1.

### 3 HETEROGENEITY OF THE POPULATION OF OPEN CLUSTERS

Observational Selection.

Recent publications suggest that the currently available catalogues of optically visible open clusters are complete within 850 pc and, possibly, even 1 kpc (Piskunov et al. 2006). The sample of clusters with the calculated orbital elements turns out to be approximately a factor of 4 smaller in size, but, nevertheless, it is deemed representative relative to all of the observed Galactic clusters (Wu et al. 2009). Figure 1a shows the central part of the “Galactocentric distance projected onto the Galactic plane - distance from the Galactic plane” diagram for all of the optically visible clusters (Dias et al. 2002), while the open circles highlight the clusters of our catalogue. The brightest feature for both catalogues is the semicircular region of an enhanced density of points. We clearly see that within ±1 kpc (designated by the two vertical dotted lines) from the solar orbital radius, a high density of points extends up to |z| ≈ 0.15 kpc, while this density begins to rapidly drop outside this range. The effect is attributable to an enhanced interstellar reddening in the Galactic plane, which makes it difficult to determine the distances to clusters lying near this plane. It can also be seen from the diagram that the clusters in our catalogue are observed at progressively larger distances from the Galactic plane with increasing Galactocentric distance (the most distant clusters are outside the diagram). The lower density of points in the upper left corner of the diagram is not associated with observational selection, because the reddening is low at high Galactic latitudes even in the inner disk regions and, therefore, the distances to high clusters are determined fairly reliably.
This suggests that although the selection effects make it difficult to reveal clusters lying near the Galactic plane, they, nevertheless, do not prevent the detection of very distant clusters. Therefore, we have the right to use our catalogue to analyze the properties of open clusters with different spatial-kinematical parameters. In particular, it can be seen from the figure that the maximum values of $|z|$ also increase with Galactocentric distance. This is because the gravitational potential in the Galactic plane decreases in this case.

**Galactic Orbital Elements.**

It is generally believed that the open star clusters are born from the interstellar matter distributed in the form of a thin layer in the Galactic plane. The scale height of this layer in the solar neighborhoods is variously estimated to be within the range 50 - 75 pc (see, e.g., Malhotra 1994; Vergely et al. 1998; Weiss et al. 1999). Since this matter moves around the Galactic center almost in circular orbits, the open clusters should be expected to follow them as well. However, several clusters are in highly eccentric orbits that often rise high above the Galactic plane, which is indicative of their "unusual" origin (Vande Putte et al. 2010). In order to separate the clusters of different natures from one another, let us assume that only the clusters with circular low orbits were formed from the interstellar matter of the Galactic thin disk, for example, under the action of spiral density waves producing a shock wave traveling parallel to the Galactic plane, while the clusters with eccentric high orbits were formed through the action of other mechanisms on this matter. The idea that all clusters are formed in identical processes from an interstellar medium whose turbulence decreases with time serves as an alternative to this assumption. However, the latter assumption is in conflict with the theoretical calculations suggesting that the time of free collapse of a dissipating rotating protogalactic cloud into a flat disk is less than 0.4 Gyr; therefore, the clusters with the highest eccentric orbits must be the oldest. In fact, as can be seen from the table, the clusters with $Z_{\text{max}} > 8$ kpc have ages less than 2 Gyr, i.e., they are several times less than the age of the thin-disk subsystem. In addition, the velocity dispersions in clusters turn out to be considerably higher than those in field thin-disk stars (for more details, see below). Conceptually, this must suggest greater turbulence of the interstellar medium at the instant the clusters were formed from it and, hence, their older age. These inconsistencies force us to reject the alternative in favor of the originally advanced hypothesis suggesting the existence of open clusters of an unusual origin.

The thin–disk stars are known to be characterized by low residual velocities relative to the LSR and by almost circular orbits all points of which do not rise high above the Galactic plane. Nearby stars can be stratified with confidence into Galactic subsystems by their space velocity components relative to the LSR (see, e.g., Koval’ et al. 2009). However, for more distant objects whose heliocentric distances are comparable to the solar Galactocentric distance, it is more reliable to determine their membership in a subsystem from Galactic orbital elements. The eccentricity ($e$) and the maximum distance of the orbital points from the Galactic plane ($Z_{\text{max}}$) (see, e.g., Marsakov and Borkova 2005; Vande Putte et al. 2010) are the most informative (in this respect) orbital elements. The indicator composed of the same orbital elements and proposed by Chiappini et al. (1997), $(Z_{\text{max}}^2 + 4e^2)^{1/2}$, where $Z_{\text{max}}$ is measured in kpc, turned out to be very convenient. Figure 1b presents the $Z_{\text{max}} - e$ diagram for all clusters of our catalog. The almost circular region with a higher density in the lower left corner of the diagram engages our attention. The clusters in this region can be separated by the boundary value of $(Z_{\text{max}}^2 + 4e^2)^{1/2} = 0.35$ (see the solid curve in the diagram): the density of points in the diagram outside this radius is an order of magnitude lower than that in the central region of the concentration. Most (> 80%) of the open clusters are inside the curve, implying that they reflect the kinematical properties typical of Galactic–disk objects. Figure 1c shows the distribution of the selected clusters in their current distance from the Galactic plane taken in absolute value. (Recall that Wu et al. (2009) analyzed the incompleteness of the sample of clusters with known orbital elements and reached the conclusion about the legitimacy of using it to estimate the characteristic parameters of this population.) The derived distribution was fitted by an exponential law: $n(z) = C e^{-Z/Z_0}$, where $Z_0$ is the scale height. The scale height for this subsample of clusters turned out to be approximately the same as that for the interstellar medium in the solar neighborhoods, $Z_0 = (65 \pm 4)$ pc. (Within
1 kpc, where the sample may be considered essentially complete, the clusters with such circular low orbits show $Z_0 = (70 \pm 12)$ pc, i.e., the same value, within the error limits.) The selection conditions suggest that the clusters of this subgroup were formed from a kinematically cold interstellar medium. However, all stars of the Gould Belt and the comparatively young Hyades–Pleiades star stream, which is believed to have resulted from the perturbation of the interstellar medium by spiral density waves, satisfy these constraints. In other words, the criterion $(Z_{2\text{max}} + 4e^2)^{1/2} < 0.35$ turns out to correspond well to the young stellar population of the thin disk, and we believe the clusters satisfying it to be typical of the Galactic disk. Therefore, it seems natural to assume that all clusters of this kinematically cold group were formed from the matter reprocessed exclusively in genetically related stars of the Galaxy, i.e., from the matter of a single protogalactic cloud. However, it follows from Figs. 2a and 2b that this is not quite the case. These figures show the $Z_{\text{max}} - [\text{Fe/H}]$ and $e - [\text{Fe/H}]$ diagrams, respectively. The filled circles highlight the "kinematically cold" clusters satisfying the criterion $(Z_{2\text{max}}^2 + 4e^2)^{1/2} = 0.35$. We see that such clusters fill a wide metallicity range. Thus, it turns out that there are such clusters whose low metallicities are atypical of the local field thin-disk stars even among the clusters with flat circular orbits. The clusters with eccentric high orbits show a tendency for their metallicity to decrease starting from the solar one as both orbital elements increase (in Fig. 2a, three clusters with $Z_{\text{max}} > 8$ kpc are outside the diagram and are disregarded when constructing the regression line). Such dependences may suggest that an increasing fraction of interstellar matter with a low metallicity is involved in the formation of clusters with increasingly eccentric high orbits. The general appearance of Figs. 2a and 2b differs from the analogous diagrams from Vande Putte et al. (2010), because low–metallicity ([Fe/H] < −0.4) clusters with circular low orbits are absent in the latter paper. The reason is that all these clusters are distant and lie essentially in the Galactic plane, where the interstellar extinction, which makes it difficult to determine the photometric metallicity used by these authors, is great. We took the data for these clusters from Paunzen (2010) and version 3.1 of the catalogue by Dias et al. (2002) published already after the paper by Vande Putte et al. (2010).

**Metallicities.**

Wu et al. (2009) used the metallicity as an indicator for revealing clusters of an unusual origin. Let us examine the distribution of the open clusters in heavy-element abundances in our catalogue. Figure 2c shows the metallicity function for 264 clusters. The solid curve indicates the fit to the histogram by the sum of two Gaussians. The Gaussian parameters determined by the maximum likelihood method showed that the probability of erroneously rejecting the hypothesis about the description of the distribution by one Gaussian against the alternative of its representation by the sum of two Gaussians is $< 5\%$ (for the method, see Martin 1971). As a result, we see that the population of open clusters turns out to be heterogeneous in metallicity as well, and it can be divided into two groups by $[\text{Fe/H}] \approx −0.12$. The group with an approximately solar metallicity shows a low dispersion, while the low–metallicity group occupies a fairly wide $[\text{Fe/H}]$ range. For comparison, Fig. 2c also plots the histogram for nearby field thin-disk stars with the photometric metallicities from Marsakov et al. (2011). For convenience, both histograms were normalized to the total numbers of corresponding objects. We see that the metallicity functions for the clusters and field stars differ in general appearance. In particular, the metallicity range for the clusters is slightly larger toward negative values. Nevertheless, the principal maximum of the metallicity distribution for the clusters is more to the right and lies near $[\text{Fe/H}] = +0.05$, whereas for the field stars $[\text{Fe/H}] = −0.12$ (i.e., where the dip is observed for the clusters). However, as we see, there is a second, lower–metallicity maximum near $[\text{Fe/H}] = −0.27$ for the clusters. (Note that if $[\text{Fe/H}]$ for the field stars and open clusters are reduced to the solar Galactocentric distance by correcting them for the radial metallicity gradient and by assuming the mean orbital radii to be their birthplaces, then the shape of the histograms being compared in Fig. 2c will not change fundamentally.)
4 THE AGE DEPENDENCE OF THE SPATIAL-KINEMATICAL AND PHYSICAL PARAMETERS OF OPEN CLUSTERS

Heliocentric Distances

Let us examine the extent to which evolutionary changes in clusters affect their detectability among the field stars. Figure 3a shows the "age–heliocentric distance" diagram for all of the known open clusters. We see that the field is filled very nonuniformly and a dense cluster of points in the shape of a triangle is observed in the lower left corner of the diagram, while the upper right corner is almost empty. The existence of the upper inclined straight-line boundary separating the dense cluster of points in the lower left corner of the diagram from the remaining points is caused, on the one hand, by an enhanced brightness of young hot stars in the clusters: the younger the cluster, the greater the distance at which it can be distinguished against the background of Galactic field stars. On the other hand, the existence of this boundary is attributable to an intensive disruption of clusters reducing their total luminosity. Although young hot stars in clusters vanish with age, a sufficient number of red giants appear instead of them; therefore, the cluster luminosity increases again. As a result, we see the most distant clusters in the range 1 - 5 Gyr. (However, it should be noted that the z coordinates are generally also larger for distant clusters (see Fig. 1a), so that interstellar reddening does not hinder the distance determination for them.) At the same time, however, an intense loss of cluster stars through dynamical processes begins to have an effect at an even older age, and, in the long run, they all dissipate completely. The dissipation process continues over the entire cluster lifetime, causing their number in the Galaxy to decrease exponentially with time.

Residual Velocity Components.

The velocity dispersions of field Galactic-disk stars are known to increase with age. For all residual velocity components of the stars relative to the LSR, this dependence is well described by a power law of the form $\sigma_v \sim t^{0.25}$ (see, e.g., Koval’ et al. 2009). The "heating" of the disk stars by spiral density waves is believed to be most likely responsible for this increase. Let us estimate the extent to which the velocity dispersion of more massive objects, which the open clusters are, depends on the age. In contrast to nearby stars, to analyze the properties of such distant objects as open clusters, it is more appropriate to use the space velocity components in cylindrical coordinates. Figure 3b shows the "age-azimuthal velocity" diagram for the clusters of our catalogue. (To save space in the diagram, the $V_R$ and $V_Z$ velocity components are not presented, but morphologically they have an appearance very similar to Fig. 3b.) The region distinguished by an enhanced density of points is in the shape of a triangle (see the dashed lines drawn by eye) with the vertex lying on the line of the mean azimuthal velocity for these clusters and with an abscissa of $\approx 1$ Gyr. Just as in Fig. 3a, the existence of the inclined density boundaries in the diagram is attributable the decrease in cluster luminosity with age. Note that, in this case, the total scatter of velocities is essentially independent of the age, suggesting that the cluster space velocities (as in the case of field stars) do not increase with time. However, the velocity dispersions actually increase rapidly with age, reaching $(\sigma_{\Pi}, \sigma_{\Theta}, \sigma_Z) = (49, 115, 58)$ km s$^{-1}$ for the oldest clusters (see the dashed lines in Fig. 3c), whereas the limiting dispersions, on average, for considerably older nearby field thin-disk stars are significantly lower $(\sigma_{V}, \sigma_{V}, \sigma_{W}) = (44, 27, 21)$ km s$^{-1}$ (see Koval’ et al. 2009). To construct Fig. 3c, we divided all clusters of our catalogue into seven age subgroups decreasing in number (from 155 for the youngest ones to 13 for the oldest ones). The number decreased monotonically in order that it could be possible to clearly trace the behavior of the cluster velocity component dispersions in the entire range of ages occupied by them nonuniformly. It is generally believed that the increase in velocity dispersion with age for clusters is caused either by relaxation effects (see, e.g., Wu et al. 2009) or by a decreasing (with time) degree of turbulence of the interstellar medium in the thin disk. We see from Fig. 3b that the progressive decrease in the density of points near the average line in the diagram, which roughly corresponds to the circular velocity of the Galaxy at the solar Galactocentric distance, causes the dispersion to increase. This is most likely because clusters with nearly circular orbits are intensively disrupted as a result of their long stay near massive clouds of interstellar matter (see, e.g., Danilov...
and Seleznev 1994) and spiral density waves (Mishurov and Acharova 2011) concentrating near the Galactic plane.

Some decrease in dispersion within the first several hundred Myr, which is especially noticeable for the \(V_{\Theta}\) velocity component, also engages our attention in Fig. 3c. This effect is most likely caused by the observational selection effect associated with the differential rotation of the Galactic disk and the high luminosity of the young clusters visible at significantly differing Galactocentric distances. To test this assumption, Fig. 3c presents the age dependences of the velocity dispersions for the clusters lying within 1 kpc of the Sun. Recall that the original sample of clusters within this range may be considered essentially complete (see Piskunov et al. 2006). (We divided this sample into six age ranges; in the youngest group, there were several times more stars than in the oldest one, where there are only 11 of them.) As we see, the dispersions of all velocity components for nearby clusters at \(t < 1\) Gyr actually do not depend on the age, within the uncertainty limits. Note that the low dispersions in the oldest group were obtained, because it contains no very old clusters (see Fig. 3a) and clusters lying high above the Galactic plane, and precisely they provide high velocity dispersions.

**Physical Parameters**

In Fig. 4a, the masses of open clusters are plotted against their age. (The three oldest clusters are not shown in the diagram.) We see that this plot slightly differs in appearance from the plots of spatial-kinematical parameters against the age. Here, the scatter is largest for the youngest clusters and decreases with age, which allows the inclined upper boundary to be drawn. The location of the lower boundary is virtually independent of the age. As a result, it turns out that the most massive clusters are among the youngest ones, and the upper cluster mass boundary sinks with increasing age. The dots inside circles designate the clusters lying within 1 kpc of the Sun. We see that they fill rather uniformly the entire field in the diagram, except for the upper left corner, where the most massive, youngest, and, as we see, most distant clusters are found. This suggests that not the distance selection causes the inclination of the upper envelope observed in the diagram, but it is entirely attributable to evolutionary changes in clusters. The central concentration and ellipticity distributions in Figs. 4b and 4c exhibit no age dependences.

In Fig. 4d, the dispersions of the physical clusters parameters are plotted against the age. We see that the mass dispersion decreases within the first \(\sim 200\) Myr and then increases again. Such a behavior probably stems from the fact that one of the two mechanisms prevails for clusters of different ages. On the one hand, from their very birth, the open clusters begin to lose their stars; that is why the upper limit on their mass decreases. On the other hand, as the age increases, the low-mass clusters begin to be disrupted completely with acceleration; therefore, the mean mass of the survived clusters turns out to be higher. As we see, the ellipticity and central concentration dispersions remain within the range of age-independent uncertainties. Thus, evolutionary changes are detected only for the total integrated mass of the clusters.

In the next paper (Gozha et al. 2012), we will formulate the principles of identification of open clusters of different natures and investigate the properties of both populations.

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Figure 1: (a) "Position projected onto the Galactic plane - height above the Galactic plane" diagram for open clusters: the filled and open circles represent the clusters from the catalogue by Dias et al. (2002) and our catalogue, respectively. (b) "Maximum distance of the orbital points from the Galactic plane - orbital eccentricity" diagram for the clusters of our catalogue; the part of the circumference with the radius \((Z_{\text{max}}^2 + 4e^2)^{1/2} = 0.35\) separates out the region of an enhanced density of points in the diagram. (c) The distribution of clusters satisfying the criterion \((Z_{\text{max}}^2 + 4e^2)^{1/2} < 0.35\) in current distance from the Galactic plane taken in absolute value; the solid curve indicates an exponential fit to the distribution and the scale height with its uncertainty is indicated.

Figure 2: Cluster metallicity versus maximum distance of the orbital points from the Galactic plane (a) and versus orbital eccentricity (b); (c) the metallicity distributions of open clusters (hatched) and field thin-disk stars (gray color). The filled and open circles represent the clusters satisfying the criterion \((Z_{\text{max}}^2 + 4e^2)^{1/2} < 0.35\) and the remaining clusters of the catalogue, respectively; the lines represent the regression lines for the open circles; the correlation coefficients are indicated. The curve in panel (c) is the fit to the [Fe/H] distribution of clusters by the sum of two Gaussians.
Figure 3: Heliocentric distances for all optically visible open clusters (a), azimuthal space velocity components (b), and dispersions $\sigma_{\Pi}, \sigma_{\Theta}, \sigma_{Z}$ of the cluster velocity components (c) versus age. In panel (b), the open circles and the dots inside circles are the clusters of our catalog and those lying within 1 kpc of the Sun; the horizontal dashed line indicates the mean rotation velocity of the clusters around the Galactic center; the inclined dashed lines are the straight lines separating the region of an enhanced density of points in the diagram that were drawn by eye. In panel (c), the dashed and solid polygonal lines indicate the dispersion variations for the clusters of our catalogue and those lying within 1 kpc of the Sun, respectively; the errors of the dispersions are shown.
Figure 4: Masses (a), central concentrations (b), ellipticities (c), and dispersions of these three parameters (d) versus age for open clusters. The dots inside circles highlight the clusters lying within 1 kpc of the Sun. In panel (a), the dashed lines indicate the upper and lower envelopes drawn by eye.