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SOME PROBLEMS OF OPEN CLUSTER INVESTIGATION

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Some problems of the investigation of open clusters and studies of the structure and kinematics of the Galaxy based on cluster parameters are discussed, as a result of three decade investigations made by the scientific staff of Kourovka astronomical observatory.

KEY WORDS Open clusters: age, luminosity function; galaxy: structure, kinematics

1 INTRODUCTION

In the last decades a great body of observational data for stars in open cluster (OCL) fields have been selected. The effectiveness of the treating these data defines a possibility of using them in the OCL investigations as well as in the studies of stellar evolution, star formation processes, structure, kinematics and dynamics of our and other galaxies.

We discuss only two important trends of investigations. This is an estimation of OCL parameters from the photometric data including the study of OCL luminosity functions, and the galactic studies making use of cluster parameters. These fields of research are traditional for the scientific staff of Kourovka astronomical observatory.

As most of the existing data is gathered in the UBV photometric system, our discussion refers to this system as well as other ones.

2 THE ESTIMATION OF OCL PARAMETERS

The objective and the main problem in the OCL parameter estimation is a construction of the set of well-grounded numerical procedures which allow one, using the data of various photometric systems, to reliably and objectively estimate these parameters. These estimates must be obtained in close scales, which permit one to construct the homogeneous catalogues of cluster parameters that we need both for summarizing the information on OCL and for carrying out galactic studies. As we determine OCL distances, colour excesses, ages and abundances, we find a lot of problems which cannot be discussed in a concise paper, that is why we consider a few basic aspects which influence estimating the main parameters of OCLs.

2.1 The Determination of Colour Excesses

In the estimation of colour excess of OCL we come across some troubles connected with both a variety of characteristics of cluster stars and the presence of double and multiple stars. Interstellar reddening in cluster fields often varies from star to star, that is why one has to determine this value for every star separately. The difficulties in this case are different for particular photometric systems, but there are some common problems. For single stars the main problem is that every type of stars has its own sequence of dereddened stars (SDS) on two-colour diagrams we use for reddening determination. In particular there is no photometric system which permits the extraction double stars when differential reddening is present, because the position of SDS depends at least on the mass ratios of components. It should be noted that here we regard doubles all stars as not resolved in the observations.

It is well-known (Straizis, 1977) that the position of SDS depends on the luminosity (or luminosity class) and abundance of stars. The problem of luminosity exists for stars of all spectral classes. This problem is partly solved for red giants (Loktin 1993, 1996) for UBV-system, the SDS being approximated by the polynomials including the dependence on M_V and [Fe/H]. The calibration of the SDS position is performed using bright field red giants with known absolute stellar magnitudes and abundances. For the same photometric system for blue stars with $(B-V)_0 < 0^m\!.0$ a dependence of the SDS position on the luminosity is given by the polynomial approximation of the tables of (Straizis, 1977) where for stars of the fifth luminosity class we have

$$(B-V)_{0,B} = Q \cdot (0.591 + Q \cdot (1.0635 + Q \cdot (1.67 + 0.9 \cdot Q))) - 0.01, \quad (1)$$

and to take account of the luminosity dependence we use correction

$$\Delta = 0.007 - 0.0101 \cdot M_V - 0.012 \cdot M_V^3 + 0.0092 M_V^2 \cdot Q, \quad (2)$$

and dereddened colour index is equal to

$$(B-V)_0 = (B-V)_{0,B} + \Delta \quad (3)$$

Figure 1(a,b) shows composite HR-diagrams for several young OCLs, on Figure 1a colour excesses are determined without luminosity correction, whereas on Figure 1b all excesses are calculated using equations (1)–(3). Because of the insufficiency of the observational data, there is no opportunity of taking account of the influence of luminosity and abundance in the colour excess determination for red

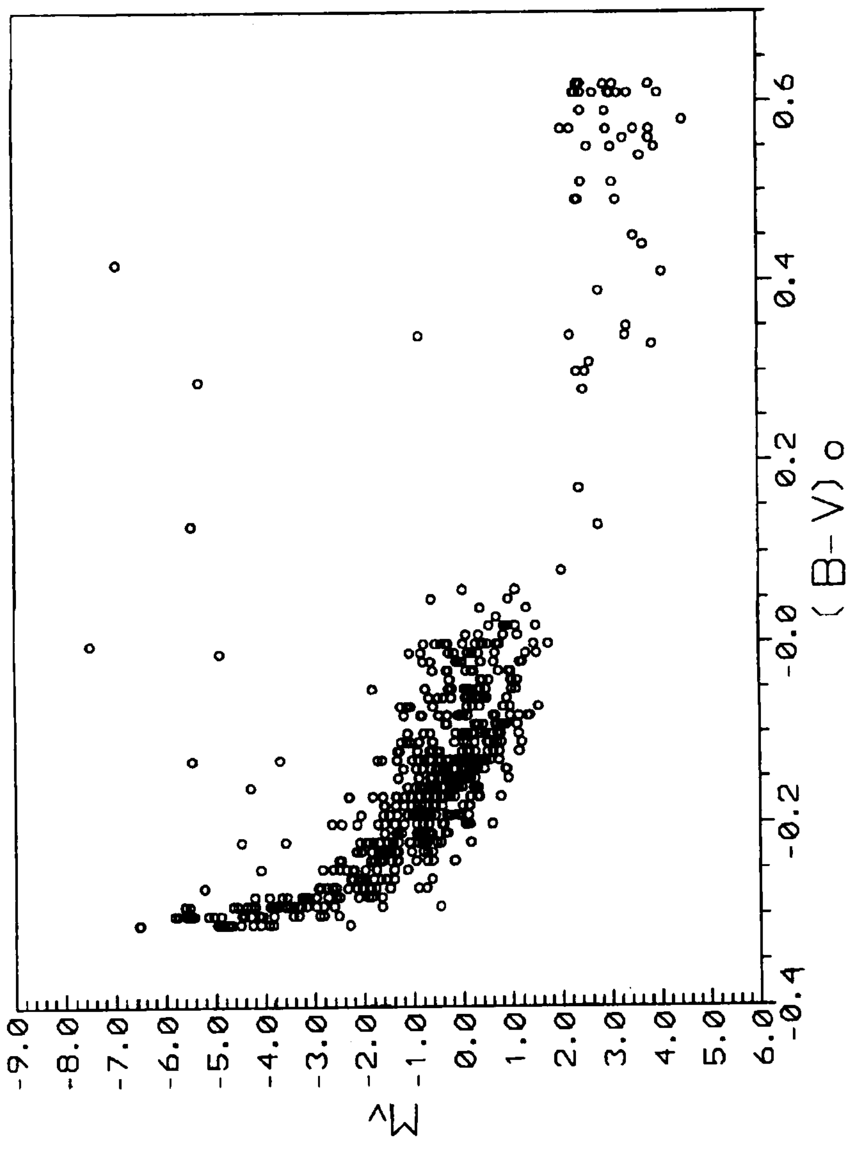

Figure 1a The composite HR-diagram for a group of young open clusters. The colour excesses are calculated without luminosity correction.

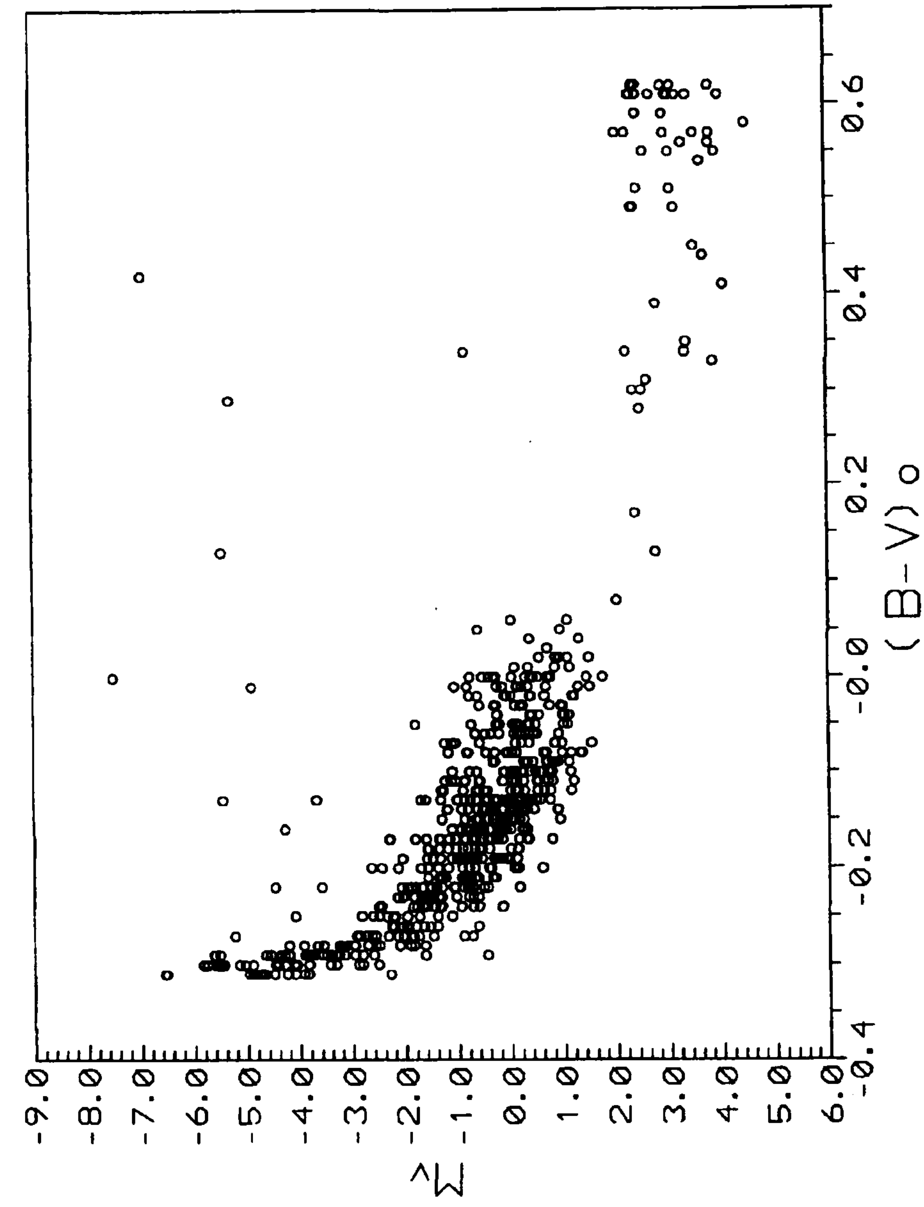

Figure 1b The same as on Figure 1a, but the luminosity correction is used for reddening calculations.

supergiants. The abundance effect for F- and G-type stars can be taken into account by seleting the appropriate SDS; e.g. such as calibrations of Cameron, 1985, but the luminosity effect can be hardly eliminated due to the difficulty of luminosity determination for this type of stars.

One can mention a possibility of elaborating the method of reddening determination using the colour index $(U-B)$, which gives one more independent estimate of the colour excess for cluster stars. Using the tables from (Straizis, 1977) an approximating polynomial is built for blue stars $(B-V) < 0^m.0)$ of the V luminosity class

$$(U-B)_0 = Q \cdot (1.2536 + Q \cdot (0.0178 + 0.022 \cdot Q)) - 0.01. \quad (4)$$

Such a polynomial may be built for redder stars. These polynomials may be used for cluster stars reddening determination, because approximately known luminosities of cluster stars allow us to choose the appropriate branch of many-valued dependence of the colour index on Q.

2.2 Ages and Distance Moduli of Open Clusters

There are lot of problems connected with age determinations for open clusters. First of all the conception of cluster age itself is rather uncertain, because clusters really consist of stars of various ages (Zakharova, Svechnikov, 1973a, 1973b). But the parameters of age distribution of cluster stars are unknown because there is no method for determining individual ages of cluster members. That is why we cannot attribute a sensible value of the definite age to a particular cluster if we even agree to count out stellar ages from one typical point of the evolutionary track, for example from the moment a star enters the Main Sequence (when pre-main-sequence stars have negative values of ages!). Now the most useful method of OCL age determination is best suited to the appropriate theoretical isochrone and concerns the isochrone age of a cluster. Usually no attention is paid to take account of an influence of double stars and dispersion of the age in the fitting procedure. The scantiness of this method is obvious. As for distance determination the best fit of appropriate isochrone gives reliable results but requires taking account of the effects mentioned above as was shown in our redetermination of OCL parameters from UBV data (Loktin, Matkin, 1994). Now we are carrying out the numerical experiments on an influence of double stars and age dispersion on the HR-diagrams which, we hope, will help to refine the method of cluster parameter estimation.

2.3 The Parameters of Red Giant Concentration Centres

One of the typical features of the HR-diagrams of many of the OCLs is noticeable red giant concentrations (clumps) near the Herzschprung gap, which allow a fast and sufficiently reliable determination of colour excesses, distance moduli and ages of such OCLs using two-colour photometry (Vasilevsky, 1969). This procedure requires calibration dependencies of the colour indices and absolute stellar magnitudes of concentration centres and cluster ages on some parameter independent of reddening and easily determinable from the HR-diagram. In (Vasilevcky, 1969) the difference between colour indices of concentration centres and main sequence (MS) turn-off points

$$g = (B - V)_{K,0} - (B - V)_{T,0} = (B - V)_K - (B - V)_T, \quad (5)$$

was proposed as such a parameter where the indices K and T respectively refer to the concentration centre and the turn-off point of the clister MS, $(B - V)_T$ being determined as a minimum colour excess of the smoothed MS, but not individual stars. The index "0" denotes dereddened values of colour indices.

The calibration expressions for the cluster ages t, absolute stellar magnitudes $M_{K,0}$ and colour indices $(B - V)_{K,0}$ of concentration centres versus the parameter g were evaluated for the first time in 1972 (Vasilevsky, 1969). In 1981 Mermilliod (Mermilliod, 1981), using 75 OCLs, determined the mean values of photometric parameters of concentration centres and the MS turn-off points and the mean ages for 14 age groups of clusters ($\log t = 7.3 \div 8.9$). But in Mermilliod's work (1) all interval of cluster ages was not considered, (2) the parameter g was not used and (3) only 16 of 75 clusters used in (Mermilliod, 1981) show pronounced concentrations of red giants on the HR-diagrams, though others contain no more than 2–3 giants. That is why the problem of calibration of colour indices and absolute stellar magnitudes of red giant concentration centres using larger volume than in (Vasilevsky, 1969; Mermilliod, 1981) of photometric data remains urgent.

By now about 80 HR-diagrams of clusters containing red giants concentrations have been published. For most of these clusters the ages, colour excesses and distance moduli are redetermined in (Loktin, Matkin, 1994). On the base of that data the following new calibration expressions are determined

$$(B - V)_{K,0} = g - 0.25 \ln (g - 0.44) - 0.15, \quad (6)$$

$$M_{K,0} = 1.23 - 1.69 \cdot g^2, \quad (7)$$

$$\log t = 9.93 - 1.45 \cdot g \quad (8)$$

with root mean square deviations $\pm 0\overset{m}{.}06$, $\pm 0\overset{m}{.}37$ and ± 0.14 respectively.

Appreciable deviations of some values of $(B - V)_{K,0}$, $M_{K,0}$ and $\log t$ from the mean dependencies for particular clusters would be explained by an influence of abundance deviations, but the statistical analysis shows that the parameters of red giants concentrations are slightly affected by the abundance factor.

The comparison of dependencies of colour indices, absolute stellar magnitudes of red giants concentration centres on g evaluated in this paper with the results of (Mermilliod, 1981) shows good agreement which means that cluster reddenings and distances from (Loktin, Matkin, 1994) coincide well with data in (Mermilliod, 1981).

Unfortunately the dependencies evaluated above are usable only for the values $g > 0.7$, because for the oldest clusters absolute magnitudes and colour indices of red giant concentration centres become insensitive to the values of g. May be it is the reason for rejection, by computer routine, of such reliable clusters as M67, NGC 752, NGC 6819, IC 4651. The problem of absolute stellar magnitudes and colour indices of red giants concentration centres for clusters with $g < 0.7$ draws special attention and will be discussed elsewhere.

2.4 Luminosity and Mass Functions

One of the main characteristics of the open cluster is its luminosity function (LF) which contains information not only about the stellar content of the cluster but reflects features of the dynamical evolution of OCL and star formation. LM provides a possibility of investigating the initial mass function (IMF), the differences between IMF of various clusters and between cluster IMF and that of some regions of the galactic disc.

Observational LF allow one to reconstruct the initial luminosity function (ILF) and IMF using the set of standard procedures. The mass-luminosity relation and bolometric corrections should be known for the construction of IMF. The shape of LF and hence ILF may be distorted by the influence of unresolved photometrically double stars. There exist two methods of evaluation of the mass-luminosity relation. The first one is a determination of star masses and luminosities of the components of double stars, the second one is a comparison of star positions on the HR-diagram using theoretical evolutionary tracks of stars of various masses. It should be mentioned that up to now there is no mass-luminosity relation, homogeneous in the sense of method used and observational data, for a sufficienly wide interval of masses. In such a way the problem of reconstruction of IMF appears to be connected with the problem of improvement of the mass-luminosity relation and bolometric corrections scale. The problem of the influence of unresolved double strars on the shape of LF requires careful discussion, though there exist some publications where this effect is shown to depend on the distribution of mass ratios of the components. For stars with masses larger than solar one the effect is small (Malkov, Piskunov, 1988).

There is no hitherto reliable theoretical predictions of the parameters of IMF, that is why it is important to get observational information on LF for many of the rich OCLs. If the period of star formation in clusters is much less than the cluster age, the LF of main sequence stars is identical to the initial luminosity function (if we do not take into account the dynamical evolution of the cluster). On the other hand, if the period of star formation is comparable with the cluster age, then for the evaluation of IFM we must know the age distribution of cluster stars. Besides, most of the open clusters consist of small number of stars, which face us with a severe problem of membership aggravated by the situation of clusters in regions of the Milky Way.

For the last three decades we have been carrying out the photometric investigations of open cluster luminosity functions. The main feature of these investigations was the attention to the homogeneity of the observational data and methods used. In all cases wide fields around cluster cores were examined, which led to the minimum effect of mass segregation natural for old clusters. There were evaluated LFs of more than 20 clusters (Barkhatova, Zakharova, 1987; Zakharova, 1989; Barhatova *et al.*, 1985) with distances from the Sun mainly from the interval 1.5–2 kpc, the interval of absolute stellar magnitudes from -3^m to $+5^m$.

One of the problems we have to solve is the problem of universality of LF of open clusters and the estimation of parameter α of Salpeter's presentation of IMF (Salpeter, 1955). The Pirson and Kolmogorov statistical criteria were used to compare luminosity functions. If one excludes from consideration the parts of LFs corresponding to evolved stars and the parts distorted by dynamical evolution, the remaining interval of LF must correspond to LF unchanged since the cluster formation. By comparing these unevolved parts of LF of various clusters or cluster LF with that of field stars one can consider the differences between cluster LFs to solve the problem of universality of ILF. The interval of magnitudes of unevolved parts of cluster LFs is small, that is why we considered functions using all observed intervals of magnitudes assuming that in all clusters the luminosity functions evolve identically. In this case we have to consider clusters with close ages, that is why we divided all our clusters into four age groups. For yonger groups the differences between cluster LFs appear to be random, but for the older ones there occur non-random differences. For a long life-time of such clusters their LFs may alter both due to random causes and dynamical evolution. The mean value of Salpeter's function parameter α for our clusters is equal to -1.43 ± 0.08. We cannot exclude the hypothesis of the universality of ILF for clusters with $\log t < 9$ but this problem must be discussed further using more clusters, especially rich ones.

The number of cluster luminosity functions have to be increased. To diminish random errors, one may try to construct combined cluster IMF using homogeneous sets of data. It is interesting to investigate the effect of mass segregation and to relate this effect with cluster age, abundance and other cluster parameters. It is important lastly to get new knowledge on the possible variations of open cluster ILFs in time and space.

3 OPEN STAR CLUSTERS IN OUR GALAXY

3.1 The Structure and Kinematics of the Galactic Disc

For the galactic research we have been creating and currently updating the homogeneous catalogue of photometric parameters of 367 open clusters recalculated from the published data in UBV, $uvby\beta$ and DDO systems, the first version of this catalogue is published in (Loktin, Matkin, 1994). Large sample of clusters, a homogeneity of the cluster parameters re-evaluated using the general method, existence of estimates of the radial velocities for 173 clusters of our sample allow one to solve the problems of the structure and kinematics of the galactic disc.

The frequency distribution of ages of open clusters is shown on Figure 2. This distribution allows one to discuss the possibility of existence of several generations of open clusters in the solar neighbourhood and serve as a base for division of the cluster sample into age groups. The division into groups will be studied in more detail in the future taking account of a statistical significance of the distribution minima. The distribution of young clusters ($\log t < 7.3$) projected onto the galactic plane is shown on Figure 3 clearly seen to be concentrated. Young clusters are

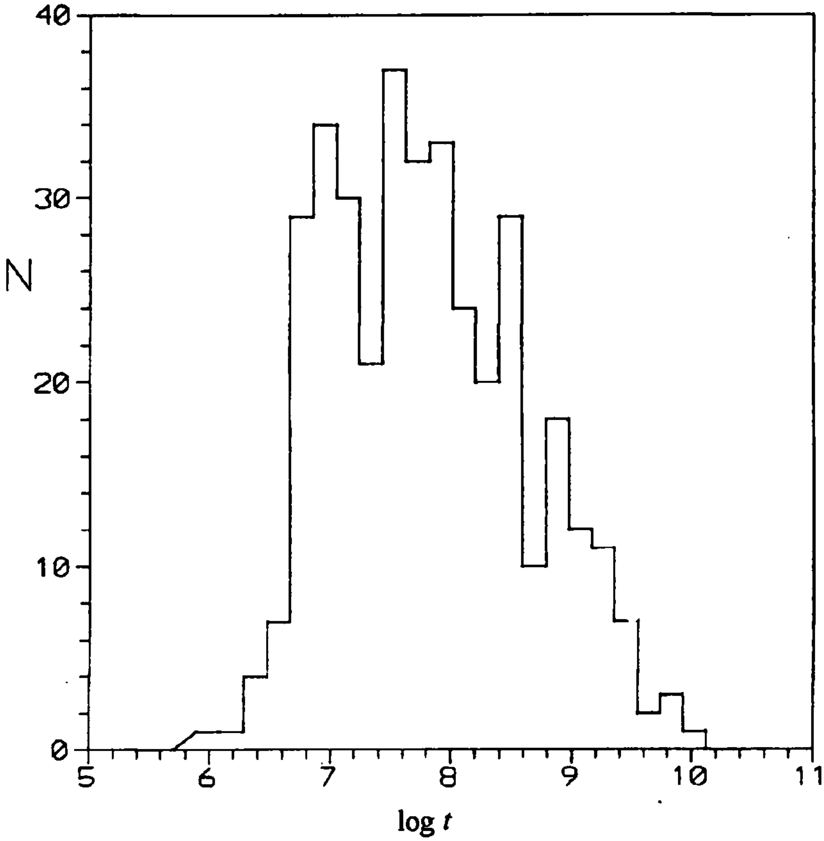

Figure 2 Frequency distribution of ages for open clusters of our catalogue.

clearly seen to be concentrated near three well known fragments of spiral structure near the Sun (see, for example, Becker, Fenkart, 1971). On this figure larger symbols correspond to better quality of data for particular cluster. It is worth noting that there is no cluster with high quality data in the interarm space, except NGC2362 ($X = -0.8$ kpc, $Y = -1.3$ kpc). One can conclude that the majority of open clusters are born in the regions near the spiral arms and the spiral wave in the galactic disc is the main triggering agent of star formation. This conclusion make it urgent to investigate properties of the spiral pattern. We are providing such investigation. For example, the space position of Perseus and Sagittarius arms are discussed, using the position of young stars and predictions of the spiral wave theory (Gerasimenko, 1983, 1993). Some parameters of the Galactic spiral wave are determined using the positions and ages of open clusters from the catalogue (Loktin, Matkin, 1994): the pitch angle $i = 8^\circ\!.2$, the angular velocity of the spiral pattern $\Omega_p = 22^\circ\!.4$ km/c/kpc, the spiral pattern of the Galaxy is four-arm (Loktin, Matkin, 1992). We continue such a work with the new version of the catalogue.

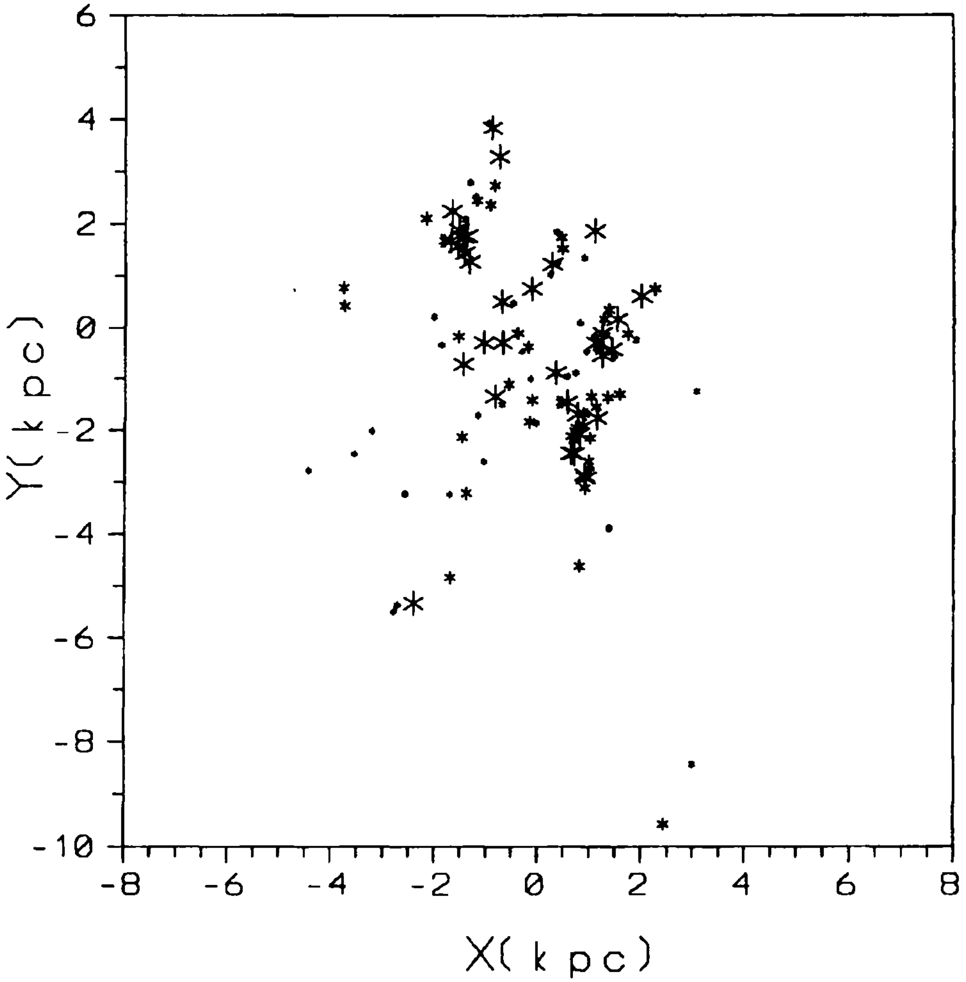

Figure 3 The distribution of open clusters projected on to the galactic plane. The size of symbols is a measure of the quality of data used.

The traditional branch of kinematical investigations is a verification of the Oort constant A and the distance of the Sun from the galactic centre R_0. With the use of the catalogue (Loktin, Matkin, 1994) and the Kamm method we have got such estimates of these parameters: $A = (14.8 \pm 0.9)$ km/s/kpc and $R_0 = (8.2 \pm 0.3)$ kpc (Gerasimenko, 1995).

3.2 Metallicity Function of the Galaxy

On the base of the Catalogue of open clusters and associations and its supplements which by now contains the information on 1265 open clusters, 160 globular clusters and 60 associations, we are investigating the features of abundance distributions in stellar groupings of various ages.

In this catalogue 160 OCLs have abundance estimates. Most of publications include these estimates for few clusters. The publications containing these estimates for many clusters are rare and in most cases they are compillative. The most extensive data one can get from the works of Lynga, 1987; Barkhatova, 1988; Strobel, 1991; Cayrel de Strobel, 1992.

For the statistical analyses of cluster chemical abundances a comparison was made of collected values of [Fe/H], [M/H], [A/H] determined from photometric indices and spectroscopic observations. The comparison of abundance scales allows one to create a homogeneous abundance scale for 126 open clusters. On the base of this scale the abundance frequency distribution for open clusters was constructed. Most of the OCLs proved to have values of [Fe/H] laying on the interval from −0.3 to +0.3, and the distribution has three maxima near the values of [Fe/H]+0.05, -0.15 and −0.6 (Pilskaya, Wiebe, 1993). The same work was done for metallicity scale of globular clusters (GCL).

The existing abundance estimates both of open and globular clusters show an essential scatter caused not only by errors in the observations and treatment of the data but by an intrinsic star-to-star scatter in clusters. It is worth noting that for the statistical chemical analysis of stellar groupings not a physical meaning of the idea of matallicity is essential but a uniformity of the determination of the parameter connected with the star heavy element abundance by a monotonous single-valued function. Our homogeneous abundance scales for OCLs and GCLs take account of this idea.

The data on cluster abundances are now insufficient to estimate the statistical significance of details of abundance distribution. But it is interesting to mention that maxima of the histograms built for a variety of objects provided by various authors (Marsakhov, Suchkov, 1985, Zinn, 1990) coincide, and the maximum for low metallicity open clusters coincides with the high metallicity maximum of the abundance distribution of globular clusters.

Our results permit us to conclude that the distribution of the metallicity of open clusters is threemodal and is connected with that of globular clusters. These results demand further interpretation taking into account the details of spatial distribution and motion of clusters, their membership in higher order aggregates.

4 CONCLUSIONS

Taking into account the urgency of investigation of open clusters for the studies of the structure and evolution of the Galaxy, the stellar evolution theory, the evolution of clusters as stellar aggregates, we enumerate some main problems and aims of these investigations.

First of all it is the photometry of wide cluster fields including various causes of errors and disturbing effects such as the influence of background stars, unresolved binaries, the influence of abundance variations on the parameter calibrations

(ZAMS, two-colour diagrams), dispersion of ages and abundances between stars of one cluster. In turn the main targets of photometrical investigations are the determination of precise cluster distances, chemical abundance estimation, the study of photometric diagrams and luminosity functions and the connection of their features with cluster ages, values of [Fe/H] and position in the Galaxy.

Nowadays we are remaking the complex of computer routines for redetermination of open cluster parameters using the published data in various photometric systems, which provide an expansion of the sample and making better the quality of parameter estimates owing to a more complete use of photometric information. It is worth to expand the number of clusters with luminosity functions determined by single method with the aim to construct a reliable initial mass function. To solve this problem one has to study the spatial mass segregation of cluster stars on LF. It is worth noting that the stellar evolution theory allows one to reconstruct the evolved part of LF for old clusters which may serve as a check of the predictions of the theory and to take into account the contribution of white dwarfs in cluster IMF.

For the investigation of kinematics and spatial distribution of open clusters in the Galaxy (galactic rotation, the distance of the Sun from the galactic centre, the parameters of spiral structure) the main problem is improvement of the data on distances, radial velocities and proper motions for distant clusters. This would provide us a representative sample and allows us to take into account the selection effects for the comparison of age and abundance distributions of open clusters, which may allow one to interpret the shape of these distributions and solve the problem of probable star formation bursts in the solar vicinity in the past.

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