Open clusters and the galactic disk

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It is textbook knowledge that open clusters are conspicuous members of the thin disk of our Galaxy, but their role as contributors to the stellar population of the disk was regarded as minor. Starting from a homogenous stellar sky survey, the ASCC-2.5, we revisited the population of open clusters in the solar neighbourhood from scratch. In the course of this enterprise we detected 130 formerly unknown open clusters, constructed volume- and magnitude-limited samples of clusters, re-determined distances, motions, sizes, ages, luminosities and masses of 650 open clusters. We derived the present-day luminosity and mass functions of open clusters (not the stellar mass function in open clusters), the cluster initial mass function CIMF and the formation rate of open clusters. We find that open clusters contributed around 40 percent to the stellar content of the disk during the history of our Galaxy. Hence, open clusters are important building blocks of the Galactic disk.

1 Introduction

Open clusters constitute an important part of a process transforming gas and dust into stars. They are observed as the most prominent parts in the regions of active star formation, or as tracers of the ceased star formation process in the general Galactic field. However, the role they are playing in this process has still not been fully understood. In spite of their prominence, there had been indications that classical open clusters contribute only 10% or even less input to the total stellar population of the Galactic disk. This discordance can be explained either by an early decay of a considerable fraction of newly formed star clusters (see e.g. Miller & Scalo 1978; Piskunov et al. 2006; Wielen 1971) or by an insufficient knowledge of cluster formation statistics. In this context, one should note that the most important items of cluster formation like the distribution of cluster masses at birth (i.e., the initial mass function of star clusters) and the cluster formation rate were still poorly known a decade ago.

In principle, basic parameters like distance, motion, age, and metallicity can be determined for an open cluster more accurately than for a single field star. Indeed, they are better tracers of large scale structures of the Galactic disk population than field stars. Nevertheless, the most comprehensive studies of the Galactic cluster population are about 20 years old (Janes et al. 1988, Lyngå 1982). They were based on the best data available at that time, the Lund Catalogue of Open Cluster Data (Lyngå 1987, hereafter, the Lund Catalogue) and its subset of clusters with 3-colour photometry (Janes & Adler 1982). Although these studies represent an important step in our understanding of the general properties of the cluster population, they suffer from incompleteness of the cluster samples and from inhomogeneity of the cluster parameters.

About 1200 clusters were known in the Lund catalogue by 1988. Only 400 of them had accurate, but heterogeneous UBV photometry, and photometric distances, reddening and age values. Although for almost all clusters apparent diameters were given in the Lund catalogue (estimated by eye from sky charts or defined by the size of detector field of view), only about 100 clusters were studied in a systematic way on the basis of star counts (Danilov & Seleznev 1994). Currently, the on-line list of open cluster data by Dias et al. (2002, DLAM hereafter), which can be considered as a continuation of the Lund Catalogue, contains by a factor of 1.5 more clusters than its predecessor, but the degree of completeness of this list is still unknown. Since the cluster data in the DLAM list are taken from literature, the set of the derived parameters differ from cluster to cluster. Also, the parameters themselves are based on heterogeneous observations and different methods of cluster definition and of parameter determination. Whenever using these data for cluster population studies, one is confronted with problems caused by uncertain cluster statistics and data heterogeneity.

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In the following sections we describe our approach to construct a representative sample of open clusters in the solar neighbourhood, derive a homogeneous set of cluster parameters, especially age, mass and luminosity which are basic for estimating the role of open clusters as building blocks in the evolution of the Galactic disk. A previous review on this topic was given by Zinnecker et al. (2009) at IAU Symposium 254.

2 A volume- and magnitude-limited sample of open clusters

The first goal in this cooperation which started in 2003 was the construction of a sample of Galactic open clusters whose properties and biases are known (as good as possible). In this approach we started from the very beginning, namely from a magnitude-limited catalog (sky survey), the All-Sky Compiled Catalogue of 2.5 million stars (ASCC-2.5\footnote{ftp://cdsarc.u-strasbg.fr/pub/cats/I/280B}). The latest version of ASCC-2.5 (Kharchenko & Röser 2009) gives absolute proper motions in the ICRS, Johnson B, V and 2MASS J, H, K\textsubscript{s} as well as spectral types and radial velocities if available. The catalog is to 90% complete down to V = 11.5. ASCC-2.5 was used to identify known open clusters and compact associations from the Lund Catalogue (Lynga 1987), the Dias et al. (2002) on-line data collection, and the Ruprecht et al. (1981) list of associations. Cluster membership of stars was determined based on kinematic and photometric criteria. In the ASCC-2.5 we found 520 of about 1700 known clusters (Kharchenko et al. 2005a), and discovered 130 new open clusters (Kharchenko et al. 2005b).

From this full sample of 650 clusters in the ASCC-2.5 we extract 2 important sub-samples: a volume-limited sample of 256 open clusters complete to a distance of 850 pc from the Sun, see Piskunov et al. (2006) and Fig.\ref{fig:density} and a magnitude-limited sample complete down to apparent integrated magnitude $I_V = 8$, with 440 clusters above this completeness limit. For details of the construction of the magnitude-limited sample see Piskunov et al. (2008b). Finally, we must keep in mind the evolutionary status of open clusters included in our sample. Since cluster membership is based on the proper motion data mainly obtained in the optical spectral range, we consider our sample as representative of optical clusters or “classical” open clusters. Embedded objects are not included in this sample since their members usually are fainter (in the visual) than the limiting magnitude of the ASCC-2.5. Therefore, we assume the beginning of the transparency phase after the removal of the bulk of the placental matter to be a starting point of the evolution of a classical open cluster. The corresponding age $t_0$ is defined by the lowest age of our clusters, that is, about 4 Myr.

Fig. 1 Distribution of the surface density $\Sigma$ of open clusters versus distance $d_{xy}$ from the Sun projected onto the Galactic plane. The dotted line indicate the completeness limit, the dashed horizontal line correspond to the average density of “field clusters”. The peak at $d_{xy} = 0.4$ to 0.5 is due to a population of young clusters mainly connected to Gould’s belt. The bars are Poisson errors derived from cluster counts. From Piskunov et al. (2006) where a detailed analysis can be found.

2.1 Distribution in the Galactic Disk

Having reliably determined membership of stars in open clusters, the distances from the Sun together with the interstellar extinction to the cluster was derived (Piskunov et al. 2006). The symmetry plane of the clusters’ distribution is determined to be at $Z_0 = -22 \pm 4$ pc, and the scale height of open clusters is only $56 \pm 3$ pc. The total surface density (Fig.\ref{fig:density}) and volume density in the symmetry plane are $\Sigma = 114$ kpc$^{-2}$ and $D(Z_0) = 1015$ kpc$^{-3}$, respectively. We estimate the total number of open clusters in the Galactic disk to be of order of $10^5$ at present.

3 Astrophysical parameters of open clusters

3.1 Age distribution of open clusters

Ages of open clusters in the Galaxy can be determined from the fitting of theoretical isochrones to the loci of member stars in the CMD. It should be kept in mind that this makes the basic difference to the age determination of open clusters in other galaxies. Our method of age determination is described in detail in Kharchenko et al. (2005a). Ages were determined for 506 out of 520 clusters, of which 196 are first estimates. Our values for cluster ages are in good agreement with earlier results by Loktin et al. (2001) and Loktin (2004).

In the upper panel of Fig.\ref{fig:age_density} the distributions of clusters versus age are shown for the total sample as well as for those
within the completeness area. Since young clusters contain, in general, more luminous stars, they can be observed at larger distances (beyond 850 pc) and their proportion in the total sample is somewhat higher than that of older clusters. Hence the total sample is biased towards young clusters. Such a bias has a strong impact onto the determination of cluster formation rate and lifetime. Therefore we determined these parameters from the volume-limited sample.

In the bottom panel of Fig. 2 we show the same distributions together with results from Wielen (1971) based on the Becker & Fenkart (1971) sample. The pronounced deficiency of older clusters in the latter sample is the reason for the smaller mean lifetime derived by Wielen (1971) of 231 Myr compared to the 327±25 Myr for our volume-limited sample.

3.2 Integrated magnitudes and colours of open clusters

In the past decades quite a number of authors determined the integrated colours and magnitudes of MW open clusters. Among them we mention Gray (1965), Piskunov (1974), Sagar et al. (1983), Spassova & Baev (1985), Pandey et al. (1989), Battinelli et al. (1994) and Lata et al. (2002). In many cases, however, the underlying data are strongly inhomogeneous since the photometric observations of different clusters were obtained with different instruments and detectors, and the data reduction was carried out with different methods by different authors. Frequently, the integrated magnitudes and colours were only “by-products” of studies aiming primarily at constructing photometric sequences (e.g., sets of photometric standards, or cluster CMDs), where the data completeness is not essential.

In Fig. 3 we show the colour-absolute magnitude diagrams for 650 clusters in the solar neighbourhood. At first sight, it looks rather surprising that, in the optical, most of the open clusters in the solar neighbourhood appear rather blue even if they are not as young as, e.g., open clusters in galaxies with active star formation. Piskunov et al. (2009) discuss this finding and show that this blue colour must be expected in clusters with masses less than about 10^4 M☉ where due to the discreteness of the IMF red giants do pop up only for a short period during a cluster’s lifetime. Hence, the usually adopted SSP models are not suited to reproduce the colours of the open clusters in the solar neighbourhood.

3.3 The luminosity function of Galactic open clusters

Even in the close vicinity of the Sun, the only previous attempt to construct the luminosity function of open clusters (van den Bergh & Lafontaine 1984) is based on a sample of 142 clusters that is to 2/3 complete within 400 pc.
Fig. 4 Luminosity function of Galactic open clusters based on 440 local clusters brighter than the completeness limit $I_V$ of the sample. The bars are Poisson errors, the dashed line shows a linear fit for the brighter part of the histogram ($I_M < -2.5$) where $a$ is the corresponding slope. The arrow indicates the limit of integrated absolute magnitudes reached for open clusters in the LMC (see Larsen 2002). Figure from Piskunov et al. (2008b).

Fig. 4 (from Piskunov et al. 2008b) shows the present-day luminosity function (CPDLF) constructed from the magnitude-limited sample of 440 clusters. At brighter magnitudes the CPDLF follows a power law with an exponent $\alpha$ in $dN/dL \propto L^{-\alpha}$ which comes out as $\alpha = 2.02 \pm 0.02$. This is comparable to the slope in extragalactic clusters (see e.g. Larsen 2002). Notice, that for Galactic star clusters the CPDLF can be observed much deeper than for clusters in other galaxies. For the Large Magellanic Cloud (LMC), the faint limit is reached already at about $I_M = -5$, and it is much brighter in more distant galaxies (Larsen 2002). As a consequence of going deeper we find a turnover in the CPDLF between $I_M = -3$ and $-2$, and an apparent decrease at fainter magnitudes. This turnover is a real phenomenon, since the luminosity function is obtained from the distribution of clusters within the completeness limit.

3.4 Masses and the mass function of Galactic open clusters

Mass is one of the fundamental parameters of star clusters which, from an observational point of view, is difficult to determine.

There are at least three independent methods for estimating cluster masses, each with advantages and disadvantages. The simplest and most straightforward way is to count cluster members and to sum up their masses. This requires a complete census of cluster members (down to the lowest masses). The real situation is, however, far from being ideal: incompleteness comes from either the limiting magnitude or the limited field of view or both. The extrapolation of the observed mass spectrum to “unseen” cluster members by choosing some inappropriate IMF can lead to unjustified and unpredictable modifications of the observed cluster mass, i.e. to biases. Nevertheless, due to its simplicity, the method is currently widely used (see Danilov & Seleznev 1994; Lamers et al. 2005; Tadross et al. 2002).

Another method is based on the virial theorem: the mass of a cluster is determined from the stellar velocity dispersion. It does not require the observation and membership determination of all cluster stars. The application of the method is, however, limited to sufficiently massive stellar systems (globular clusters and dwarf spheroidals) with dispersions of internal motions large enough to be measurable. For open clusters, the typical velocity dispersion is about or less than 1 km s$^{-1}$, so, only for a few clusters with the most accurate proper motions and/or radial velocities, attempts have been undertaken to derive “virial masses” (see the references in Piskunov et al. 2007).

The third method uses the interpretation of the tidal interaction of a cluster with the parent galaxy, and requires knowledge of the tidal radius of a cluster. It gives so-called ‘tidal masses’, and goes back to the fundamental paper by King (1962). Considering globular clusters which, in general, have elliptical orbits, King (1962) differentiates between the tidal and the limiting radius of a cluster. For open clusters revolving at approximately circular orbits, one can expect the observed tidal radius to be approximately equal to the limiting one, although a probable deviation of the
CPDMF follows a power law with an exponent that is independent of the results of the two methods mentioned above. As tidal masses grow with \( r_t \) cubed, their precision is strongly influenced by the uncertainties of the \( r_t \) determination. For details of the application of King’s model the reader is referred to Piskunov et al. (2007) and Piskunov et al. (2008a).

For 236 clusters of our sample we could determine core and tidal radii directly from the fitting of King profiles to the density profile of cluster members. The distribution of the corresponding cluster masses is shown in the upper part of Fig. 5 where the filled histogram shows the distribution within the completeness area. Most of the clusters have tidal masses between 50 and 5000 \( m_\odot \), and for about half of the clusters, the masses were obtained with a relative error better than 50%. To obtain a mass estimate for all the 650 clusters we calibrated the semi-major axis \( A \) (of the observed stellar density distribution) of the clusters using the tidal radii of the sub-sample of 236 clusters. The resulting mass distribution is shown in the lower part of Fig. 5. Although the masses are of moderate accuracy the large cluster sample should lead to reliable statistical evaluation.

The corresponding present-day mass function CPDMF is shown as the upper curve in Fig. 6. Notice that in Fig. 6 we show the logarithmic mass function in the form \( \eta_t = dN/d\log M_c \) while in the further discussion (and to compare with other authors) we refer to the mass function \( dN/dM_c \). On its high-mass part (\( \log M_c > 3.3 \)) the CPDMF follows a power law with an exponent \( \alpha = 1.66 \) between \( \log M_c \approx 3.3 \) and the cut-off at about \( \log M_c \approx 5 \). The low-mass part (\( \log M_c \leq 3.3 \)) can also be fitted by a power-law with \( \alpha = 0.82 \pm 0.14 \). With time, the slope of the high-mass part increases, for clusters with \( \log t \leq 8.5 \) we find \( \alpha = 2.13 \), and for \( \log t \leq 9.5 \), the CPDMF, \( \alpha \) increases to 2.17. So, at every age the cluster mass function shows the same basic features, i.e., a quasi-linear high-mass portion, and a non-linear portion at lower masses. The low-mass portion changes from an approximately flat distribution at \( \log t = 6.9 \) to a clearly non-linear behaviour displaying a broad maximum with a peak at about 100 \( m_\odot \) for the CPDMF and a decline towards lower masses.

With the same completeness arguments as for CPDLF we infer that this maximum of the CPDMF and the decline towards lower masses is real and not due to an observational bias. Moreover, the maximum in the CIMF at about 1000 \( m_\odot \) and the decline shortward is also real, as the detection probability of young clusters of, say, a few hundred \( m_\odot \) is larger than that of old clusters, because the former contain brighter stars.

The steepening of the time-integrated mass function is a direct consequence of the mass-loss of clusters due to dynamical evolution together with the cut-off at the high-mass end of the CIMF. When the clusters grow older the high-mass cut-off shifts towards lower masses. Hence, the number of clusters in the higher mass bins increases more slowly or does not increase at all. This leads to a steepening as well as a shift of the maximum to lower masses.

According to present belief, the classical gas-free open clusters stem from a population of clusters which are surrounded by the remnants of the molecular cloud in which
their stars have formed (Lada & Lada 2003) have compiled a catalogue of about 100 embedded clusters within 2.4 kpc from the Sun. The sample contains some optical objects and is partly overlapping with our data. Using models of the luminosity function, Lada & Lada (2003) scaled the IR counts within the areas studied, estimated cluster masses, and constructed an embedded cluster mass function (ECMF) shown in Fig. 7. Typically, the clusters are distributed over a mass range from 50 to 1000 $M_\odot$ and follow a power law of the form $dN/dM \propto M^{-\alpha}$, where $\alpha \approx 1.7$ to 2.0. There are striking similarities between the ECMF and the CIMF: Both follow a power law with about the same exponent $\alpha \approx 1.7$, which hints that both groups come from a universal parent distribution. Also, both show cut-offs. The high-mass cut-off of the ECMF coincides remarkably well with the low-mass cut-off of the CIMF. Lada & Lada (2003) also determined the embedded cluster formation rate to be about $2 - 4$ kpc$^{-2}$Myr$^{-1}$ which is about 10 times larger than our open cluster formation rate of 0.4 kpc$^{-2}$Myr$^{-1}$ determined from the CIMF in Fig. 6. The latter low rate led Lada & Lada (2003) to the conclusion that about 10% of the embedded clusters do survive to become classical open clusters. Hence it is not surprising that the CIMF in Fig. 6 has a break at about 1000 $M_\odot$. On the other hand, one could ask why in Fig. 7 the embedded counterparts of the classical open cluster more massive than about 1000 $M_\odot$ are absent. In fact only a few of them have been detected in a recent work by Ascenso (2008). An answer to this question may have already been given by Kroupa & Boily (2002). They found that (initially embedded) clusters that form in total mass $M > N < 10^5$ stars (so-called type II clusters) lose their gas within a dynamical time as a result of the photoionizing flux from O stars. Sparser (type I) clusters get rid of their residual gas on a time-scale longer or comparable to the nominal crossing time and thus evolve approximately abutadiabatically. For Kroupa & Boily (2002) this effect works on the transformation of the mass function of embedded clusters (ECMF) to the ‘initial’ mass function of bound gas-free star clusters (CIMF). They estimate that the resulting ICMF has, for a featureless power-law ECMF, a turnover near $10^{4.5} M_\odot$ and a peak near $10^3 M_\odot$. This explains both the absence of high-mass clusters in the ECMF and the low number of low mass clusters in the CIMF. The latter being related to ‘infant mortality’.

### 4 Evolution of open clusters and their contribution to the disk population

The driving forces in the modification of the cluster mass function with time lies in the evolution of the individual clusters during their life-time: mass-loss both from stellar evolution of massive stars and from dynamical evolution affecting preferentially low-mass stars.

This mass-loss of clusters is determined from comparing the average mass of the newly formed, youngest clusters $M_c \approx 4.5 \cdot 10^3 M_\odot$ with the average cluster mass from the whole sample ($M_c \approx 700 M_\odot$) (Piskunov et al. 2008). The typical mass-loss occurring in open clusters during their evolution amounts to about 3-14 $M_\odot$ Myr$^{-1}$. In the earliest phase of the cluster evolution this mass loss primarily occurs from stellar evolution of massive stars and even from the expulsion of massive stars from the cluster. Schilbach & Röser (2008) have traced back the trajectories of so-called ‘field’ O-stars and found that the overwhelming majority had their origin in young open clusters. They found that the mass-loss rate from ejected O-stars alone amounts to about $1.5 M_\odot$ Myr$^{-1}$ during the first 6 Myr of a cluster life. To get this number, a typical O-star mass of 20 $M_\odot$ was assumed.

Provided that the cluster formation history has not changed dramatically in the solar neighbourhood during the evolution of the Galactic disk, we estimate the contribution of mass from open clusters to the thin disk of the Galaxy, or, to be more precise, the fraction of mass in the thin disk from stars that have spent part of their lifetime being members of classical open clusters.

With an assumed lifetime of the thin disk of 10 Gyr, an average mass of open clusters from the CIMF of 4500 $M_\odot$ and a cluster formation rate of 0.4 kpc$^{-2}$Myr$^{-1}$ we estimate this contribution to be

$$\Sigma = 18 M_\odot \text{pc}^{-2}.$$  

This has to be compared to the present total surface density in form of stars of the Galactic disk in the solar neighbourhood that, according to Holmberg & Flynn (2004) is $35 \pm 6 M_\odot \text{pc}^{-2}$. As part of this mass is reprocessed (mass-loss from massive stars) one finds (Just 2009) that the amount of
mass in stars ever formed in the thin disk must have been $48 \pm 6 M_\odot$ pc$^{-2}$ to explain the present-day Holmberg & Flynn value. With these numbers about 37% of the observed surface density of the thin disk comes from open clusters.

This is considerably higher than the previous estimates for the input of open clusters to the observed stellar population of the Galactic disk that is quoted as about 10% (see Miller & Scalo 1978; Piskunov et al. 2006) or even less than 10% (Wielen 1971).

5 Summary and outlook

Summing all this up, it is fair to say that this work on the population of open clusters in the solar neighbourhood that started from an all-sky survey has found that open clusters are larger, more massive, live longer and contribute more to the thin stellar disk of the Galaxy than was believed a decade before.

Although much progress in our knowledge of the statistical properties of the open cluster population has been made in the past decade, there is still a long way to go. The sample discussed here allows us to draw general conclusions, but in some cases the derived parameters are erroneous because of a severe undersampling of the cluster membership due to the bright magnitude limit of the ASCC-2.5 survey. New questions have appeared, such as: is the local cluster population representative for the whole disk? how to discern open clusters from compact associations? are these separate populations or can the latter be seen as the high-mass end of the cluster population? What exactly do we mean by "the mass of a cluster"? Tidal, virial and star-counted masses may not necessarily measure the same mass. To get more insight into this problem, one must carefully define what a "cluster member" is. This becomes especially important near the boundary of a cluster and consequently influences our understanding of "mass".

Progress on some of these topics may be expected from an exploitation of the new deep survey catalogue PPMXL (Roeser et al. 2010), and, on a somewhat longer timescale from Gaia.

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