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# The Hipparcos mission and galactic open clusters

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**Abstract.** We present some results of a study of the galactic open cluster population. This study is based on the all-sky catalogue ASCC-2.5 compiled from Tycho-2, Hipparcos and other catalogues. Screening the ASCC-2.5 resulted in the identification of 520 known clusters and the detection of 130 new ones. A uniform combined kinematic-photometric cluster membership was established for these objects and new uniform scales of cluster structure (angular sizes), kinematics (average proper motions and radial velocities), photometry (reddening and distance) and evolution (age) were established. Two parts of our more extended open cluster population study (some details on the spatial and age distributions of open clusters) are presented here.

*Keywords* : Open clusters and associations: general

## 1. What open clusters are and what they teach us

Open clusters are groups of Population I stars that have formed together. This is a key property, which makes open clusters one of the basic objects attracting steady interest of astronomers. Due to the approximately same distance of cluster members from the observer, and due to their uniformity in chemical abundance, open clusters represent excellent empirical reference sequences which are a baseline for many present-day scales and calibrations (e.g. for distances, reddening, age, abundance). Together with their globular counterparts open clusters are traditional laboratories well suited for studies of stellar evolution (tracks, isochrones). One should note, that the understanding of star cluster colour-magnitude diagrams gave the decisive impetus to the development of present-day theories of stellar evolution. Our present knowledge of star formation

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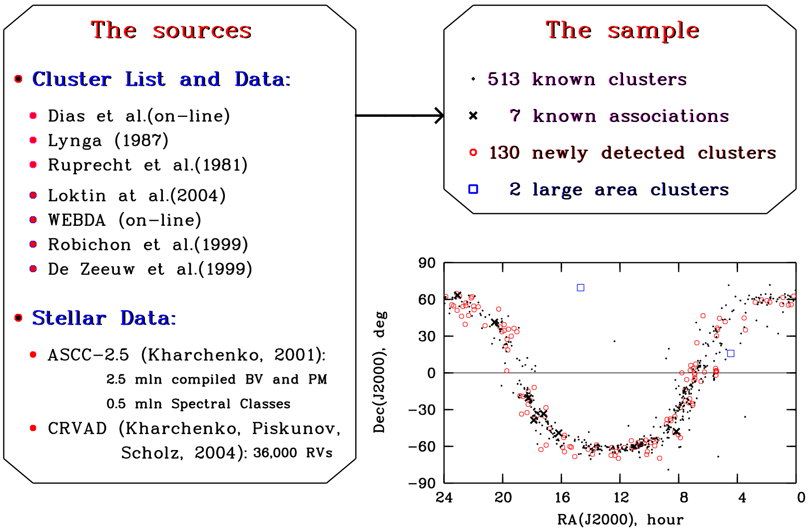


**Figure 1.** Data basis of the present study. The data sources are shown in the left panel, the summary of the sample objects in the right upper panel, their distribution over the sky in the right bottom panel.

(luminosity functions, the IMF) is also obliged to the study of young clusters. One can expect, that the complete understanding of star formation should come along with further accumulations of observed data on young stellar clusters and young star formation complexes.

## 2. Short overview on open cluster studies

### 2.1 Open clusters in the pre-Hipparcos era

Although open clusters are known to astronomers since ancient times, and despite of many efforts having been devoted to open cluster research (concentrating however on only a few tens of clusters) the population of clusters was not studied in a systematic way until Hipparcos data became available.

The latter statement can be illustrated by the following example. A total of 1200 clusters were known by 1988 (Lyngå 1987, Lund Catalogue hereforth[1]). About 400 of them had accurate, but heterogeneous UBV photometry, and distances, reddening, ages, derived from the photometric data. For about 1200 apparent diameters (eye-estimated from charts or defined by the size of detector's field of view) only about 100 clusters were studied in a systematic way (Danilov &

[1]The present-day continuation of this effort is an on-line catalogue by Dias et al. (2002) containing inhomogeneous data on somewhat less than 1700 clusters.

Seleznev 1993). Kinematics being the most traditional field in open cluster studies was also hampered by proper motions and radial velocities (RVs) in heterogeneous systems, with only very few clusters having absolute proper motions reduced to the fundamental system. Less than 100 clusters reduced by van Schewick (1971) had proper motions in the FK4 system and RVs. Space velocities were available for a few tens of clusters only. Nothing was known about the completeness of samples of clusters even in the solar neighbourhood (up to 1 kpc), which strongly prevented us to study them as a single population. In the seventies of the last century there was no sound data to study the population of stellar associations, extended clusters and loose groups (except nearby OB associations).

First of all, these difficulties were due to the fact that data on various clusters were strongly inhomogeneous since they were obtained by different instruments, detectors and techniques with no effort to homogenize them into a single system.

### 2.2 Open clusters and present-day all-sky catalogues

After the completion of the Hipparcos mission high-precision homogeneous all-sky data on stellar positions and proper motions became available, with the Tycho-experiment delivering accurate and homogeneous photometry data. The catalogues Hipparcos and Tycho-1 (ESA 1997) and Tycho-2 (Høg et al. 2000) contain data on 2.5 million stars up to 12-13 visual magnitude, with uniform coordinates and $B_T, V_T$ photometry.

The other catalogue ASCC-2.5 (2.5 mln stars up to 12-14 mag, having $B, V$-magnitudes reduced to Johnson's system, and compiled proper motions), based on Hipparcos/Tycho data, but appended with respect of star list has been compiled by Kharchenko (2001).

It should be mentioned here that the 2MASS catalogue (Cutri et al. 2003) is also of high importance to the study of open clusters. It contains accurate positions and near IR-photometry $J, H, K_s$ for 470 million stars down to about 17 $J$-magnitude. Due to its all-sky nature, accurate data, and IR-photometry this catalogue has good prospects for upcoming studies of heavily embedded clusters.

The first efforts to look at these data in open cluster research led to a discovery of new objects both in the Solar Neighborhood, and at large distances from the Sun. Bica et al. (2003a) had compiled a list of 276 embedded infrared star clusters and stellar groups from the literature. They recently appended it resulting from a search in the 2MASS all-sky release Atlas with data on 346 new compact, remote and embedded objects associated with nebulae (Bica et al. 2003b, Dutra et al. 2003). In contrast to this, only nearby clusters were discovered in the visual range. In the Hipparcos catalogue, Platais et al. (1998) have detected several nearby, very loose and extended clusters and associations, whereas Alessi et al. (2003), based on Tycho-2, discovered 11 new clusters, which reside withing 0.8 kpc from the Sun. References to a few tens of other new cluster candidates identified in Tycho-2 can be found in the Dias et al. (2002) webpage.

### 2.3 Open clusters and the ASCC-2.5 catalogue

This talk summarizes the first results of our open cluster population study, based on the ASCC-2.5 catalogue. In certain respects it is in a row with the above studies. Unlike these, however, we wanted and were able to benefit from such aspects as cluster sample completeness and data homogeneity in our project. Taking ASCC-2.5 as baseline has several advantages compared to the Tycho 1/2 catalogue. First of all the ASCC-2.5 contains stars which are missing in Tycho-2, then the photometric data are reduced to the commonly adopted $B, V$ system of Johnson, and last it is enhanced by some data useful in open cluster studies (comprising about 0.5 million stellar spectral classes and about 40 000 radial velocities, see Fig. 1).

Completeness of data plays the most important role in a population study of the details of cluster distribution. The other issue is the homogeneity of the data. Whenever open clusters were used for population studies (the spatial distribution, cluster lifetime etc.) the data were based on individual (and hence nonuniform) observations. Even such present-day lists of cluster parameters like that of Loktin et al. (2004) - being uniform in its general approach and in applied technique - are based on non-uniform photometric collections, without involving any membership criteria.

The major goals of the current project are the following:

a. To $identify$ as many known open clusters and associations as possible, and to $find$ as many new clusters as possible in the ASCC-2.5;

b. To *derive* a uniform set of parameters of these clusters (membership, coordinates, radii, proper motions, radial velocities, ages, reddening, distances);

c. To *determine* the parameters of the galactic disk population of open clusters;

d. To *study* selected stellar groups.

The steps (a) and (b) are currently completed and this presentation describes some of their results. Step (c) is nearing completion. In this talk we consider some of the aspects of the cluster population study. A complete overview of the results will be presented elsewhere.

Our sample contains 520 already known clusters (listed on the webpage of Dias et al. 2002, and in the list of associations of Ruprecht et al. 1981) which we identified in the ASCC-2.5, and 130 new open clusters which we recently detected in the ASCC-2.5 data (Kharchenko et al. 2005b). The searching technique was tuned to identify all clusters with their brightest members being no fainter than $V = 9.5$ mag. This sample of 650 open clusters is homogeneous in various aspects: it is based on a uniform data set (i.e. the catalogue ASCC-2.5), on a uniform approach of membership selection (kinematic and photometric criteria, see Kharchenko et al. 2004b), and on a uniform technique of the determination of cluster parameters (Kharchenko et al. 2005a). For each cluster of our sample, we determined the distance and spherical position (i.e. the location

**Table 1.** Summary of cluster parameters.

| Parameter | Previously known (out of 1700) | Revised or confirmed (out of 520) | New determination (out of 520) | New determination (out of 130) |
|---|---|---|---|---|
| Combined $3\sigma$ membership | – | – | 32260 | 6203 |
| Distance | 760 | 320 | 200 | 130 |
| Reddening | 760 | 320 | 200 | 130 |
| Size | 170 | 515 | 5 | 130 |
| Proper motion | 458 | 219 | 301 | 130 |
| Radial velocity | 258 | 159 | 94 | 69 |
| Age | 637 | 325 | 195 | 130 |

in the 3D space), reddening, size (including the core and corona radii), kinematics (the mean proper motions in the Hipparcos system), and the cluster age from individual ages of members near the Main Sequence turn-off. On the basis of the new cluster membership determination, we derived radial velocities and spatial velocity vectors for 359 clusters of our sample. The two nearest clusters, the Hyades and Collinder 285 (the UMa cluster), are missing in our list. Due to their proximity to the Sun, they occupy large areas on the sky and require a specific technique of membership determination. For the sake of completeness we added these clusters to our sample, which therefore comprises 652 objects. The basic data used for compilation of our list are shown in Fig.1. In Table 1 we summarise the data contained in our sample and compare it with the most abundant present-day census of open cluster data present in the webpage of Dias et al. (2002).

Table 1 indicates a considerable increase of available cluster data almost for all data classes due to uniform outcome from the current project. For about a half of our clusters there are literature data we can compare to our determinations. The comparison with most uniform previously published data set of Loktin et al. (2004) shows that our ages, reddening and distance values are in good agreement. The cluster sizes could be compared to on-line data collection of Dias et al. (2002). As we find literature data are strongly (by about factor of two) underestimated if compared to our determinations. This can be understood if one minds, that Dias et al. provide eye-estimated cluster sizes from Palomar charts, and our radii are based on star counts of the most secure cluster members.

## 3. Spatial parameters of our sample of clusters

In order to estimate the spatial completeness of the sample, we studied the distribution of clusters in the Galactic $(X, Y)$ plane and computed their surface density $\Sigma$ as a function of the projected distance $d_{xy}$ from the Sun. The corresponding histogram is shown in Fig. 2. With exception of a considerable excess at $d_{xy}$ = 0.35...0.55 kpc, the distribution is almost flat up to $d_{xy}$ = 0.85 kpc. At larger distances, the surface density $\Sigma$ of clusters is steadily decreasing. Assuming a uniform density model for the distribution of clusters in the solar neighbourhood, we can interpret this

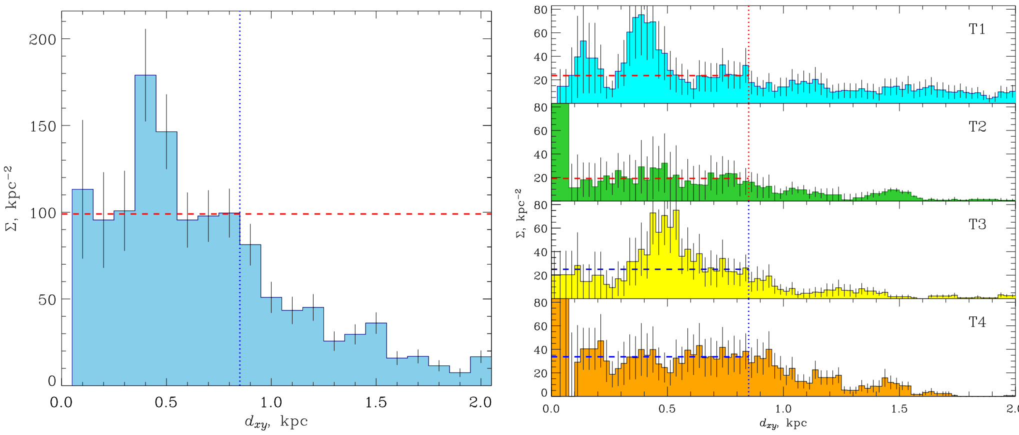


**Figure 2.** The surface density distribution of our sample of open clusters. The left panel refers to all clusters, the right one to sub-samples of different ages. The dotted vertical lines indicate the completeness limit, the dashed horizontal lines are average background levels. The bars are Poissonian errors.

behaviour as evidence for an increasing incompleteness of our sample at projected distances larger than 0.85 kpc. We adopt $d^c_{xy}$ = 0.85 kpc, as the completeness limit of our sample.

The detection of the completeness limit allows us to derive parameters of the open cluster population such as local density, distribution perpendicular to the Galactic plane, and the total number of clusters currently existing in the Galaxy. On the other hand, the enhancement of the observed cluster density at $d_{xy}$ = 0.35...0.55 kpc is too significant to be attributed to random fluctuations in the spatial distribution of open clusters in the solar neighbourhood. Assuming a density of 100 ± 10 clusters per square kpc to be typical of the "cluster field" around the Sun, we would expect 56 ± 8 clusters at $d_{xy}$ = 0.35...0.55 kpc. However, 91 clusters are counted in this region. This leads to the question: does this enhancement describe a general property of the local galactic structure or is this excess caused by a particular group (groups) of open clusters with a common evolutionary history?

In order to understand the nature of this feature we construct the surface density distribution for samples of different ages. Altogether, four cluster generations were considered: T1, the 269 youngest clusters with ages $\log t \leq 7.9$, T2, 101 moderately young clusters in the age interval $\log t = (7.9, 8.3]$, T3, 132 intermediate age clusters with $\log t = (8.3, 8.6]$, and T4, 150 older clusters with $\log t > 8.6$. The age ranges were selected such that the representation of the density distribution pattern gave the largest contrast possible. For each sample we construct the histogram of the surface density, smoothed with a five-point rectangular filter (see Fig. 2).

As we find from a detailed spatio-kinematical analysis described elsewhere, the above density fluctuations can be attributed to the existence of a number of cluster complexes of different ages having 20-30 clusters each, and of a number of smaller cluster groups. Each complex turned out to be as large as 1 kpc, its members show the same kinematic behavior, and a narrow (within the observed errors) age spread. The youngest of these cluster complexes ($\log t < 7.9$) is apparently a signature of Gould's Belt, known so far, in general, as an aggregation of field stars, gas and associations (see e.g. the review by Pöppel 1997).

The distribution along the $Z$-axis is usually described in terms of the barometric formula given by the equation

$$D(Z) = D(Z_0) \exp\left\{-\frac{|Z - Z_0|}{h_Z}\right\}$$

with parameters $Z_0$, corresponding to the position of the symmetry plane for given sample, the scale height $h_Z$, and the density at $Z_0$. To determine the distribution parameters we use 259 clusters located within the completeness radius. A non-linear fit of the data to the integrated form of the barometric formula gives $Z_0 = -22 \pm 4$ pc, and $h_Z = 56 \pm 3$ pc.

We find the total density of clusters in their plane of symmetry as $D(Z_0) = 1015$ kpc$^{-3}$; the total surface density is then equal to $\Sigma = 114$ kpc$^{-2}$. This value considerably exceeds (by a factor of about 5) the surface density of open clusters inferred from Janes et al. (1988), giving only $\Sigma = 24.9$ kpc$^{-2}$. Evidently, this difference is due to the large incompleteness of data, which is typical for the Lund catalogue. Although the current sample is more complete than the other collections of open clusters in the literature, incompleteness is the inevitable price of any magnitude limited survey. For example, our sample contains 552 clusters within 2 kpc. If the surface density would not vary within this distance range one would expect observing about 800 more clusters. Thus, in spite of intensive observations the wider Solar neighborhood (up to 2 kpc) was not even half exploited with respect to open clusters.

Using the surface density $\Sigma$ derived above, and assuming, that it does not vary with galactocentric distance, we are able to estimate the total number of clusters $N_{tot}$ in the Galaxy:

$$N_{tot} = 2\pi\Sigma \int_0^{R_G^{lim}} \exp\left(-\frac{R_G - R_{G\odot}}{h_l}\right) R_G \, dR_G.$$

Here $R_G$ is the distance from the center of the Galaxy, $R_G^{lim}$ is the radius of the Galactic disk, and $h_l$ is the scale length of the disk, taken from Bahcall and Soneira (1980) as $h_l = 3.5$ kpc. With $R_G^{lim} = 15$ kpc we find that the total number of open clusters in the Galaxy is equal to 93 000.

## 4. The formation rate and lifetime of clusters

One of the first extensive studies of the distribution of open cluster ages in relation to cluster lifetime was carried out by Wielen (1971). For the age statistics he used data from the catalogues of Lindoff (1968), and Becker and Fenkart (1971). Later studies on this subject by Janes and Adler (1982), Pandey and Mahra (1986), Janes et al. (1988), Battinelli and Capuzzo-Dolcetta (1991) and others use the approach proposed by Wielen (1971), but are based on more extended cluster lists of Janes and Adler (1982), and on the different versions of the Lund catalogue. Since the current study is based on uniform cluster data (with distances and ages for

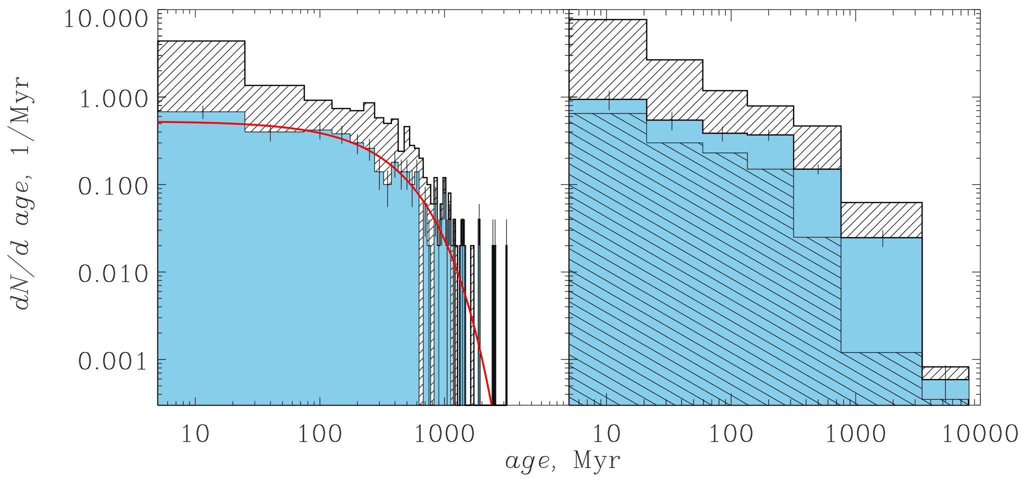


**Figure 3.** The age distribution of open clusters. Left panel: the hatched histogram shows the total sample distribution, the filled histogram is the "completeness field sample" (complex non members with $d^c_{xy} \leq$ 0.85 kpc), the fitted age distribution (see text) is shown by a solid curve. Right panel: comparison of the Wielen (1971) age distribution with our data binned according to his age scale. The designations are the same as in the left panel. Wielen's data are shown as a hatched histogram in the foreground. Vertical bars correspond to statistical errors of counting.

**Table 2.** Comparison of cluster formation rates and lifetimes derived in the present study and published in the literature.

| No | *CFR* $\mathrm{kpc^{-2}Myr^{-1}}$ | $\tau$ Myr | $N_{cl}$ | Sample | Note |
|---|---|---|---|---|---|
| 1 | 0.25±0.03 | 322±31 | 195 | field clusters, $d_{xy}$ < 0.85 kpc | |
| 2 | 0.10±0.01 | 256±12 | 652 | total sample | |
| 3 | 0.10 | 231 | 70 | Wielen (1971) | 1 |
| 4 | 0.18 | 144 | 112 | Pandey & Mahra (1986) | |
| 5 | 0.25 | 100 | 213 | Janes et al. (1988) | |
| 6 | 0.45 | 14 | 100 | Batinelli & Capuzzo-Dolcetta (1991) | 2 |

**Notes:** 1 – Becker & Fenkart sample; 2 – sampling: $d \leq$ 2kpc & $V_{integr} \leq -4.5$ mag.

about 50% of the clusters, unavailable before), including many new clusters, and makes use of a uniform scale of cluster ages, it is reasonable and adequate to revisit this topic.

Let $dN(t) = \psi(t)\,dt$ be the number of clusters formed in some interval of time $t, t + dt$ ($\psi(t)$ is the cluster formation rate, (CFR), which then decays with a probability $p = 1/\tau$, where $\tau$ is a typical lifetime of these objects. Now, if $N(a)$ is the actual number of clusters observed at age $a$, and $t_1 = t + a$, ($t_1$ being the present instant of time), one can relate $N(a)$ to the CFR via the equation

$$N(a) = N(t_1 - a)\, e^{-a/\tau} = \psi(t_1 - a)\, e^{-a/\tau}. \tag{1}$$

If clusters would never disperse ($\tau = \infty$), their age distribution would reflect the temporal behaviour of the cluster formation rate. In contrary, for a constant CFR the age distribution $N(a)$ is controlled by the decay process. In the general case the observed distribution of cluster ages depends on both factors, and in principle there is a possibility to fix both processes. Since the observed open cluster age span (a few Gyr) is much shorter that the Galactic disk age (over 10 Gyr), and since there is no observed indication of strong time variations of the local rate of star formation, the hypothesis of a rate of cluster formation independent of time seems to be reasonable. Wielen (1971) has postulated that the CFR was constant during the lifetime of the disk and found from the cluster age distribution that the cluster half-lifetime $t_{1/2}$ (decay time of one half of the once formed clusters)[2] is equal to 160 Myr, and the CFR $\psi_0 = 0.1$ kpc$^{-2}$Myr$^{-1}$. The other authors, mentioned above, using updated (sometimes to about factor two) cluster samples got generally the same or smaller lifetime scales. Comparison of cluster age parameters with their positions with respect to the Sun and cluster richness class led these authors to the reasonable conclusion, that the lifetimes increase outward in the Galactic disk and with richness class.

In the left panel of Fig. 3 we show distributions of our clusters with age. A constant spacing of 50 Myr was used to construct the age density distributions $\Delta N/\Delta a$. In order to eliminate biases related to the influence of the nearby cluster complexes mentioned in Sec. 3, we exclude these clusters from the completeness sample ($d_{xy} \leq 0.85$ kpc). After this procedure we are left with 195 field clusters. One can see, that the total sample is biased with respect to young clusters, resulting in a steeper average slope of this relation. The curve represents the result of a nonlinear fitting of the completeness sample to the equation (1). One can observe good agreement between the empirical points and the fitted relation over the whole range of available ages. The parameters of the fit are shown in lines 1 and 2 of Table 2.

In the right panel of Fig. 3 we show for comparison the age distributions together with the Wielen (1971) findings for the Becker & Fenkart (1971) sample. One can see that the slope of Wielen's sample is in better agreement with that referring to our total sample. Also, it shows a pronounced deficiency with respect to completeness for older clusters, which are more important for lifetime determination. This explains the smaller value of cluster lifetime derived by Wielen (1971) from his sample, also shown in Table 2. The values of $\tau$ from various authors presented in Table 2 are recomputed from $t_{1/2}$, which is usually published in the literature.

More pronounced deviations are found for lifetimes derived by authors working with the Lund Catalogue. We interpret the disagreement with Pandey and Mahra (1986), and Janes et al. (1988) as the consequence of an increase of the number of clusters older than 250 Myr in our present data. For example, compared to the Lund Catalogue, our list of clusters older than 250–600 Myr, which reside within 0.85 kpc from the Sun, has been increased due to the newly discovered clusters by a factor of 6. These figures are far in excess of the overall moderate rise

[2]one can draw from eq. (1) that $t_{1/2} = -\tau \ln 1/2 \approx 0.7\,\tau$.

of newly discovered clusters by a factor of 1.5 (if one compares 1150 clusters listed in the Lund Catalogue and about 1700 clusters referred to in Dias et al. 2002). The very low value of $\tau$ derived by Battinelli and Capuzzo- Dolcetta (1991) is due to a similar, but even stronger selection effect. Since they sampled only the brightest clusters, their sample is overabundant in young objects, and the lifetime of clusters is strongly underestimated.

The footprints of selection effects are also seen from data on the CFR values shown in Table 2. Unlike $\tau$, which highly depends on the completeness of older clusters, the CFR is influenced by the overall incompleteness effect. The decreased value for the CFR for our total sample clearly correlates with the increase of the data incompleteness (cf. Fig. 2). The literature data indicate an overall incompleteness of the Wielen (1971), and to some degree of the Pandey and Mahra (1986) samples. The higher completeness of the latter data is not surprising, since they are already based on the Lund catalogue. Due to the same reason, good agreement between our CFR value and the data of Janes et al. (1988) is expected – we have basically the same list of clusters – the 5th edition of the Lund Catalogue. We interpret the considerable disagreement in the CFR values, derived by us and by Battinelli and Capuzzo-Dolcetta (1991) as a consequence of their underestimation of ages of their clusters. It is well known, that the turn-off age calibrations of young clusters (a few tens of Myr or younger) are biased due to steep Main Sequences of early-type stars towards the younger ages. When neglecting this bias, one can underestimate the age span within a sample of young clusters, and hence overestimate their abundance.

## 5. Conclusions

Starting from a homogeneous sky-survey, we determined a number of uniform (based on a unique data set and approach) astrophysical parameters of 650 Galactic open clusters. For about half of these clusters the cluster membership, proper motion, distance, reddening, and age were determined for the first time. Angular sizes of the cluster cores and coronas have been newly determined. This is the area where the full-sky coverage of the ASCC-2.5 is very helpful. It makes the size determination free from selection effects, such as limited field, star counts or visual inspection of the sky without taking into account membership criteria, and others. Despite of the relatively bright limiting magnitude of the sky survey we used we find that the angular sizes of the cluster coronas are systematically larger than in earlier determinations in the literature.

Although the spatial distribution of clusters on scales comparable to inter-arm distances ($d \approx$ 2 kpc) is compatible with a model of a constant surface density, the distribution is not uniform. There are two main factors influencing the observed distribution in the optical. At first, the cluster can form groups which are revealed in the age distribution as well as in the space and velocity distributions. We found three cluster complexes in the Solar neighbourhood affecting significantly the apparent density pattern. The vertical distribution of the cluster sample turned out to be extremely flat, with a scale height of about 50…60 pc, and it does not depend on age at least for cluster ages up to 1 Gyr. We found the symmetry plane of open clusters to be $Z_0 = -22 \pm 4$ pc, and the total density of clusters in the symmetry plane is $D(Z_0) = 1015$ kpc$^{-3}$.

From the parameters of spatial distribution, we estimated a total number of $10^5$ open clusters currently in the Galactic disk.

Cluster lifetime and formation rate obtained from the age distribution of field clusters within the completeness area are found to be 322±31 Myr and 0.23 ± 0.03 $\mathrm{kpc}^{-2}\mathrm{Myr}^{-1}$, respectively. Assuming a typical open cluster of the Pleiades type, one derives the total surface density of disk stars passed through the phase of open cluster members to be about $4 \times 10^6$ $\mathrm{kpc}^{-2}$. Compared to the local density of disk stars of about $7 \times 10^7$ $\mathrm{kpc}^{-2}$, one obtains that the input of open clusters into the total population of the Galactic disk is about 6%.

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