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Old Star Clusters in the FSR catalogue

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ABSTRACT

We investigate the old star clusters in the sample of cluster candidates from Froebrich, Scholz & Raftery 2007 – the FSR list. Based on photometry from the 2 Micron All Sky Survey we generated decontaminated colour-magnitude and colour-colour diagrams to select a sample of 269 old stellar clusters. This sample contains 63 known globular clusters, 174 known open clusters and 32 so far unclassified objects. Isochrone fitting has been used to homogeneously calculate the age, distance and reddening to all clusters. The mean age of the open clusters in our sample is 1 Gyr. The positions of these clusters in the Galactic Plane show that 80 % of open clusters older than 1 Gyr have a Galactocentric distance of more than 7 kpc. The scale height for the old open clusters above the Plane is 375 pc, more than three times as large as the 115 pc which we obtain for the younger open clusters in our sample. We find that the mean optical extinction towards the open clusters in the disk of the Galaxy is 0.70 mag/kpc. The FSR sample has a strong selection bias towards objects with an apparent core radius of 30" to 50" and there is an unexplained paucity of old open clusters in the Galactic Longitude range of $120° < l < 180°$.

Key words: Galaxy: globular clusters: individual; Galaxy: open clusters, individual

1 INTRODUCTION

As birthplaces for the majority of stars (e.g. Lada & Lada (2003)) stellar clusters can be considered the building blocks of galaxies. The vast majority of them only reaches ages of a few Myrs after which their member stars dissolve into the general field star population. The disruption timescales are dependent e.g. on the local tidal gravitational field (interaction with nearby giant molecular clouds), the star formation efficiency in the cluster, the mass of the cluster and the efficiency of the feedback from the young stars in the cluster (jets, winds, supernova explosions). There is evidence that the disruption timescales are increasing with distance from the Galactic Center (e.g. Lamers & Gieles (2006), Goodwin & Bastian (2006), Piskunov et al. (2007)). A number of clusters, however, survive this initial infant mortality phase and become open clusters, which then can reach ages of up to several Gyrs.

These old stellar systems, including both, open and globular clusters, provide us with laboratory like conditions. All stars within such a cluster can be considered as being situated at the same distance, having the same age and metallicity. Due to their age, they are usually not associated with giant molecular clouds, thus there is a constant reddening towards all cluster members. Hence, one can fit theoretical isochrones to the cluster colour-magnitude diagram to determine the age, distance and reddening simultaneously, provided the metallicity is known.

As current catalogues of old open clusters are rather incomplete (e.g. Bonatto & Bica (2007b)), our aim is to establish a large, well defined sample of such old stellar systems and to determine its properties in a homogeneous way. This will then be used to investigate the distribution of these old clusters in the Galaxy which will improve our understanding not just of the old stellar systems, but also on issues such as the interstellar extinction law, disruption timescales of clusters, and ultimately the chemical evolution and enrichment history of the Galactic Disk.

To obtain a large sample of old clusters and analyse its properties homogeneously, we utilise the 2 Micron All Sky Survey (2MASS, Skrutskie et al. (2006)) point source catalogue and the star cluster candidate list provided by Froebrich et al. (2007a). We identify the old systems amongst their catalogue by investigation of decontaminated colour-magnitude and colour-colour diagrams and determine their parameters by fitting theoretical isochrones from Girardi et al. (2002) to the 2MASS photometry.

Our paper is structured as follows. In Sect. 2 we describe the selection of our cluster sample and the determination of its properties. This includes the automatic decontamination of foreground stars in the cluster fields, the selection and identification of the old stellar systems and the determination of their ages, distances and reddening via isochrone fits. In Sect. 3 we present our main results and discussion. We characterise the cluster sample, discuss the dis-

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tribution of clusters in the Galactic Plane and identify selection effects. Finally we present our conclusions in Sect. 4.

2 DATA ANALYSIS

2.1 The FSR sample

The sample of clusters analysed in this work is based on the FSR catalogue by Froebrich et al. (2007a). They determined a star density map based on 2MASS data (Skrutskie et al. (2006)) along the entire Galactic Plane with $|b| < 20°$. Star cluster candidates were selected as local star density enhancements and a total of 1788 objects were found. These candidates were cross referenced with the SIMBAD database. This uncovered that the FSR list contained 86 known globular clusters, 681 known open clusters and 1021, so far unknown cluster candidates. An estimate of the contamination suggested that about half of these new candidates are real star clusters. A number of these have been confirmed as real clusters since then. See Froebrich et al. (2008b) for a recent summary of FSR cluster candidates investigated so far.

2.2 Accurate cluster positions and radii

Our first aim was to determine more accurate cluster coordinates and the radius for each FSR cluster candidate. We hence extracted the 2MASS photometry for all stars in a $0.5° \times 0.5°$ sized field around each cluster. Only stars with reliable photometry (quality flag A to C in each of the JHK bands; Skrutskie et al. (2006)) were used. We then modelled the cluster candidates by two-dimensional angular Gaussian distributions applying an expectation-maximization algorithm (Dempster, Laird & Rubin (1977)) and evaluating the best fit using the Bayesian information criterion (BIC; Schwarz (1978)) by means of a code developed for the cluster search in UKIDSS GPS data (Samuel & Lucas, in preparation). This procedure provides us with the cluster centre and the size of the best-fit Gaussian and the BIC value – essentially a description of how probable it is that a given cluster candidate is a real star cluster. Objects with a BIC value less than zero are generally considered real, and a smaller BIC value indicates a higher probability to be a real cluster. The obtained central coordinates, and BIC values for each of the investigated clusters are listed in Table A1.

With the more accurate central positions for each cluster candidate we calculated radially averaged star density profiles $\rho(r)$. Those profiles were fit automatically to the function:

$$\rho(r) = \rho_{bgr} + \frac{\rho_{cen}}{1 + \left(\frac{r}{r_{core}}\right)^2}, \quad (1)$$

where ρ_{cen} and ρ_{bgr} are the central cluster and background star densities and r_{core} the radius of the cluster. Using the distances to the clusters, we later convert these radii into real sizes in parsec.

2.3 Membership probabilities

To determine the cluster properties via isochrone fitting we need to identify the most likely cluster member stars. This is in particular important in the high star density fields near the Galactic Plane, where field star contamination is important. We used the position and radius of each cluster to define a cluster region and a control field in the $0.5° \times 0.5°$ area around the cluster coordinates. Stars which were closer than three times the cluster radius to the centre are considered part of the cluster area, all stars further away than five times the cluster radius are part of the control field.

We then applied a variation of the colour-colour-magnitude (CCM) decontamination procedure from Bonatto & Bica (2007a) to the stars in the cluster area. For each star i with the apparent 2MASS magnitudes J^i, H^i, K^i and colours $J^i - H^i = JH^i$, $J^i - K^i = JK^i$ we calculate the CCM distance r_{ccm} to every other star $j \neq i$ in the following way:

$$r_{ccm} = \sqrt{\frac{1}{2}\left[J^i - J^j\right]^2 + \left[JK^i - JK^j\right]^2 + \left[JH^i - JH^j\right]^2} \quad (2)$$

The factor of 0.5 in front of the differences in the J-band magnitudes accounts for the generally larger spread of the magnitudes compared to the colours. We determine r^{10}_{ccm} as the 10^{th} smallest value over all stars $j \neq i$ and count the number N_{ccm} of stars in the control area that are within the CCM distance r^{10}_{ccm} around the values J^i, JK^i and JH^i. The probability P_{ccm} of star i to be a member of the cluster is then given by:

$$P_{ccm} = 1.0 - \frac{N_{ccm}}{10}\frac{A_{cl}}{A_{con}} \quad (3)$$

where A_{cl} and A_{con} are the areas of the cluster and control field, respectively. If P_{ccm} for a particular star is negative, then its membership probability is zero. This approach, instead of a fixed CCM cell size as in Bonatto & Bica (2007a) gives better results for the probabilities in regions of the CCM space with only a few stars, i.e. at bright magnitudes.

Alternatively one could determine the probability P_{pos} for each star to be a cluster member based on its distance from the cluster centre by assuming that the projected cluster star density profile has a given distribution $\rho_{\rm cl}(r)$ (e.g. a Gaussian or similar to Eq. 1), overlayed on a constant background star density $\rho_{\rm bgr}$. Stars outside five times the cluster radius could be used to determine the background star density $\rho_{\rm bgr}$. Based on the distance r of each individual star to the cluster centre, one could estimate its probability $P_{pos}(r)$ to be a cluster member based of the star density at this position via:

$$P_{pos}(r) = \rho_{\rm cl}(r)/\rho_{\rm bgr}. \quad (4)$$

Both probabilities P_{ccm} and P_{pos} could be combined to a total membership probability $P = \sqrt{P_{ccm} \cdot P_{pos}}$. However, we find that using the position does not give reliable results in many cases. In particular in dense (globular) clusters, where no stars are detected in 2MASS in the cluster centres, the probabilities are not reliable. Furthermore, for clusters in regions of high background star density the membership probability for most stars will drop below 20 %, despite the fact that their colours are clearly different from the field. Hence, for the purpose of this paper we solely use the membership probabilities of stars determined from the CCM considerations.

2.4 Selection of old star clusters

Utilising the individual membership probabilities for all stars in each cluster we plotted J-K vs. K colour-magnitude (CMD) and H-K vs J-H colour-colour (CCD) diagrams for each FSR cluster candidate. In Fig. 1 we show the diagrams, including the best fitting isochrone (see below) of the so far uninvestigated cluster FSR 0412 (Pfleiderer 3) as an example. One can nicely see that the cluster

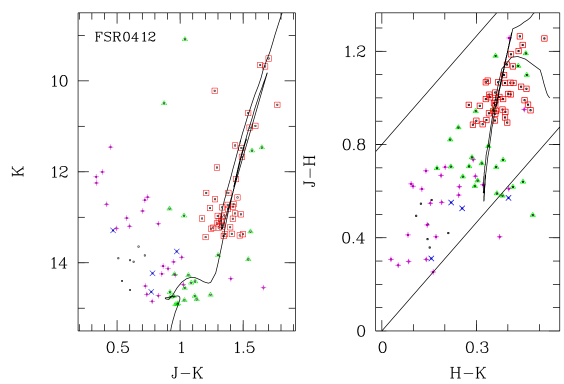

Figure 1. Example of our colour-magnitude (left) and colour-colour diagrams for the cluster FSR 0412 (Pfleiderer 3) which has so far not been investigated in detail. Red squares are stars with $P > 80\,\%$, green triangles are stars with $60\,\% < P < 80\,\%$, pink $+$-signs are stars with $40\,\% < P < 60\,\%$, blue crosses are stars with $20\,\% < P < 40\,\%$ and black dots are stars with $P < 20\,\%$. Overplotted in black is the best fitting isochrone (d = 6.1 kpc, log(age/yr) = 9.1, A_K =0.46 mag and solar metallicity). The two solid lines in the right panel enclose the reddening band for stellar atmospheres.

red giant stars are the most likely members ($P_{ccm} > 80\,\%$). Stars possessing colours in agreement with foreground dwarf stars are much less likely to be cluster members. In Appendix C we show the CMDs and CCDs for all clusters investigated in this paper.

We then inspected the 1788 CMDs and CCDs generated for the entire FSR catalogue, to decide if the high probability members are consistent with a sequence representing an old stellar cluster. In other words, we manually selected all FSR objects that either showed a Red Giant Branch (RGB) or the top of the Main Sequence (MS) and a number of giant stars. Note that this selection has been performed 'blind', without the knowledge of which object is which cluster (known or unknown) in order to ensure an unbiased selection. In total 269 of the 1788 objects were selected as candidates for old clusters and analysed in more detail for this paper.

2.5 Identification of known old star clusters

We cross-identified the list of 269 clusters with the SIMBAD[1] database. In total 63 known globular clusters are in the list, 174 known open clusters (including some already confirmed FSR objects) and 32 so far unclassified FSR cluster candidates. Some obviously old clusters, in particular some of the known globular clusters (e.g. FSR 0005 or NGC 6569, vdB-Hagen 260), are missing in our sample of old FSR clusters. This is mainly caused by the fact that they do not contain a large enough number of high probability cluster members, representing an old stellar sequence.

We obtained the distances, metallicities and reddening for the known globular clusters from the list of Harris (1996). The parameters for FSR 0040 (2MASS GC 1) are obtained from Ivanov et al. (2000) and the values for FSR 1735 are taken from Froebrich et al. (2008b). The cluster FSR 1762 (Pismis 26, vdB-Hagen 71, Tonantzintla 2) is listed as globular or cluster of stars in SIMBAD and we used its parameters from the list of Harris (1996). The clusters FSR 0190, 0584 and 1716 are also listed as globular or open cluster. In those cases we used the literature data from Froebrich et al. (2008a), Bica et al. (2007) and Froebrich et al. (2008b) and Bonatto & Bica (2008), respectively.

The open cluster parameters were obtained (as first choice) from the WEBDA[2] database for galactic open clusters. If no data was available for an open cluster we searched the literature. The main Table A1 with the cluster parameters indicates the papers used in those cases. In total we obtained data for 147 of the known open clusters. For 27 open clusters no data was available and their properties have hence been determined here, together with the parameters for the 32 so far unclassified FSR cluster candidates.

2.6 Cluster parameter determination

From our analysis so far we only determined the cluster position and radius, as well as the BIC value. In order to determine the cluster parameters such as distance, reddening and age, we need to fit an appropriate isochrone to the CMD and CCD for each cluster. We used the isochrone models from Girardi et al. (2002) for 2MASS data to perform this task. The Figures containing the CMDs and CCDs for all selected old FSR clusters in Appendix C show in general two isochrones: One with the literature values for the cluster and our best fitting isochrone. The literature isochrone is shown as dashed blue line, the best fitting isochrone from this paper is shown as a solid black line. The parameters used for our best isochrone fit for all clusters are listed in Table A1. The uncertainties of the determined parameters are discussed in Sect. 3.3.

The reddening to each cluster used in our best fitting isochrone is given as the K-band extinction in Table A1. To overplot the isochrones on the CMDs and CCDs we need to convert the K-band into the J and H-band extinction using $A_J = C_{JK} * A_K$ and $A_H = C_{HK} * A_K$. We use a conversion factor $C_{JK} = 2.618$ following Mathis (1990). In order to fit the isochrone data in the CCD as well, in general the conversion factor $C_{HK} = 1.529$ from Mathis (1990) seems too low. For the majority of clusters we hence use $C_{HK} = 1.67$. However, in some cases those values do not provide a satisfying fit, and we hence adjusted the value for C_{HK} for each cluster separately. The used values for each cluster are listed in Table A1.

3 RESULTS AND DISCUSSION

3.1 General

We have identified 269 old stellar clusters in the FSR catalogue of possible cluster candidates. For the 63 known globular clusters and 147 known open clusters we extracted parameters (distance, reddening, age) from the literature. For the remaining 27 known open clusters and 32 so far unclassified FSR cluster candidates we determine parameters here using isochrone fitting. Additionally, we determine the parameters of all clusters homogeneously by the same set of data (2MASS JHK photometry), the same data analysis method and the same set of isochrones (Girardi et al. (2002)). This will allow us, in particular for the open clusters, to analyse and compare the distribution of the parameters of our sample of old stellar clusters along the entire Galactic Plane. We will in the following only discuss the open cluster parameters, if not stated otherwise.

[1] http://simbad.u-strasbg.fr/simbad/sim-fid

[2] http://www.univie.ac.at/webda/

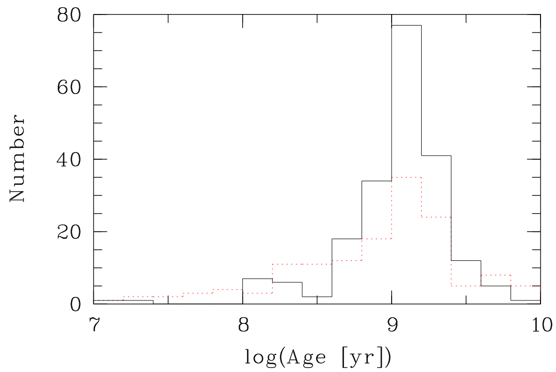

Figure 2. Distribution of the ages of the open clusters in our sample. The red dotted histogram shows the distribution of ages (from the literature) for the known open clusters. The black solid histogram shows the distribution for the ages (determined in this paper) of all open clusters in our sample. Typical age uncertainties are within the bin width of the histogram (see also Sect. 3.3).

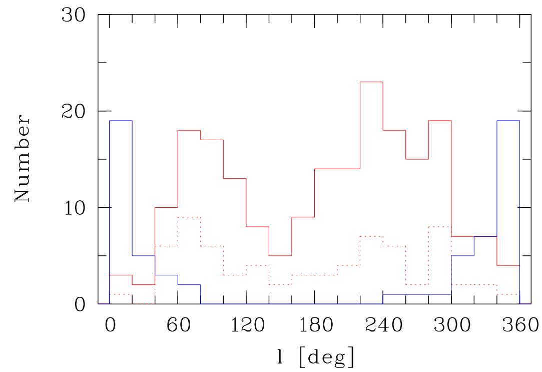

Figure 4. Histogram showing the distribution of the clusters in our sample along the Galactic Plane. In blue we show the globular clusters and in red (solid line) all open clusters, while the dotted red line shows only clusters with ages below one Gyr. The paucity of open clusters near the Galactic Centre direction is a simple selection effect caused by the high star density and thus low detection probability. The paucity between $120° < l < 180°$ is not explained.

In Appendix B we provide some notes for all newly identified old open clusters and for the known ones when their parameters differ significantly from the literature values. Here we will briefly mention some of the notable discoveries and their properties. FSR 0039 is a 1 Gyr old, highly reddened cluster. With just 4.6 kpc from the Galactic Centre it is one of the rare old inner Galaxy clusters. FSR 0313 (Kronberger 81) shows a large number of giants but no main sequence. This indicates that it might be an old, massive cluster about 10kpc from the Galactic Centre. Both, FSR 0412 (Pfleiderer 3) and FSR 0460 are very distant (6.1 kpc) and old (1.2 Gyr) clusters. Very nice examples of newly discovered clusters (or objects with parameters determined for the first time) are FSR 0134, 0177 (Kronberger 52), 0275, 0342, 0972 (NGC 2429), 1404 (vdB-Hagen 55), 1463, 1565 (Trumpler 19), 1670 (Loden 1101) which show a number of red giants and main sequence stars, while for FSR 0170, 0329 (Berkeley 92), 1521, 1559 (Teutsch 106) only red giants are detected.

3.2 Age distribution

Since we aim to investigate the old clusters in the FSR catalogue, we have to analyse the age distribution of our sample. This is shown in Fig. 2. There the red dotted histogram shows the age distribution as obtained for the known open clusters using the literature values. The black solid histogram shows the distribution of the ages determined in the paper for all open clusters. In both cases there is a clear peak at about 1 Gyr (which is also the average of the distribution), and more than 80 % of the clusters are older than 500 Myrs. This shows that our selection of clusters with a clear RGB or a main sequence and red giants, was successful in picking out old stellar systems. However, it still selects a few younger clusters. Most likely these are more massive, hence showing a larger, and thus observable number of red (super) giants earlier in their evolution. Some of the clusters with lower ages (based on the literature) have, according to our isochrone fits, an older age. This is caused by the fact that we try to include potential giant stars in the fit of the cluster isochrone, generally leading to a slightly larger age.

3.3 Comparison with literature data

For a large fraction of clusters we can compare our determined parameters with the values obtained from the literature. This will allow us to estimate the uncertainties of the isochrone fitting for the clusters without known parameters.

At first we check the position accuracy of the cluster candidates. We determine the difference of our coordinates and the literature coordinates for the known clusters. For the generally highly concentrated globular clusters the average difference is 0.5', while for the open clusters we find an average positional difference of 2'. This rather large value seems to be caused by erroneous coordinates of some not well investigated clusters in SIMBAD. See Table A1 to check the differences for each individual cluster.

Except in some cases the distance, age and reddening estimates from the literature and our isochrone fitting are in agreement. In the Appendix B we will discuss in detail the clusters with large differences in the parameters. On average the cluster distances show a scatter of about 30 % between the literature values and our estimates. For the log(age) values an agreement of about 10 % is found. The reddening values also agree to within 30 %. The 2MASS photometry does not allow the determination of the metallicity. Hence, we generally used solar values, except if a different value was available from the literature. In some cases it was, however, only possible to obtain a fit to the CMDs and CCDs with non-solar values. See Table A1 for the metallicities used for our best fitting isochrone. Please note that if the cluster has a lower metallicity than used here, the estimated reddening would be higher and the distances lower. Similarly the cluster age would be influenced systematically. However, if the metallicity is changed by less than a few tenth of a dex, then the parameters will stay within the above mentioned uncertainties. It is much more important to identify the cluster red giants and main sequence turn off with high accuracy.

3.4 Distribution in the Galactic Plane

Using the positions and determined distances to the clusters in our sample, we can investigate their distribution in the Galactic Plane.

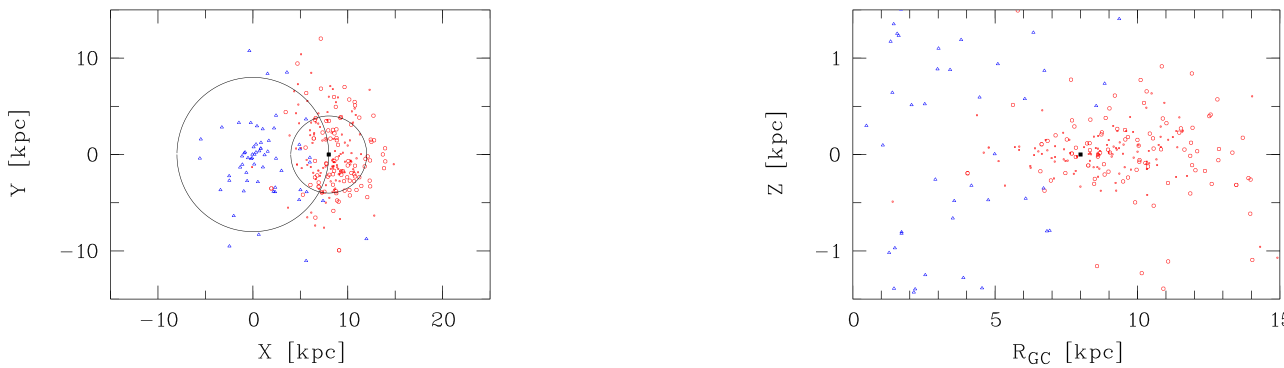

Figure 3. Left: Distribution of the clusters in the Galactic Plane based on the distances determined in this paper. Known globular clusters are shown as blue triangles, old open clusters (age above one Gyr) as red circles and younger open clusters as red dots. The distance of the Sun to the Galactic Centre is assumed to be 8 kpc and the Suns position is indicated by the black square. The two circles indicate a distance of 8 kpc (large circle) from the Galactic Centre and 4 kpc (small circle) from the Sun. Note that the three globular clusters FSR 0021 (M 54), FSR 0164 (NGC 7006) and FSR 1745 (Terzan 3) are outside the plotted area. **Right:** Distribution of the clusters perpendicular to the Galactic Plane of the Galaxy. Shown is the height Z above the Plane against the Galactocentric distance. The same symbols as in the left panel are used and for clarity only the region containing the open clusters is shown.

In the left panel of Fig. 3 we show the distribution of all clusters in the X-Y plane. As blue triangles we plot the known globular clusters, while the open clusters are plotted as red symbols (large circles for clusters with ages above 1 Gyr, small dots for clusters with ages below 1 Gyr). The plot assumes a distance of the Sun to the Galactic Centre of 8 kpc. As expected one finds most of the globular clusters concentrated towards the Galactic Centre. The open clusters are mostly found near the Suns position. This is, however, a simple selection effect, as the sample contains naturally only clusters near enough to be visible in 2MASS data.

Two details of the spatial distribution of the open clusters are, however, worth discussing in a bit more detail:

i) A histogram of the distribution of Galactic Longitude values of the open clusters in our sample (see Fig. 4) reveals two regions with a smaller than average number of clusters. This is a) the region near the Galactic Centre ($\pm 60^\circ$ away) and b) the Galactic Longitude range $120^\circ < l < 180^\circ$. In the case of a) there are two reasons for this. Firstly, the high star density towards the Galactic Centre prevents the detection and identification of stellar clusters in this area (a selection effect when establishing the sample) and secondly the fact that there are indeed fewer old stellar clusters closer than the Sun to the Galactic Centre (see below). In the case of b), there seems to be no obvious reason for the paucity of old open clusters in this region compared to the same longitude range on the opposite side of the Galactic Anticentre (i.e. the region $180^\circ < l < 240^\circ$). One explanation could be one or several large, high extinction molecular clouds in this direction, preventing the detection of clusters. However, in the all sky extinction maps from Rowles & Froebrich (2009) there is no indication of such clouds. Furthermore, the clusters which are detected in this longitude range, cover all distances between 1 and 7 kpc homogeneously, as well as extinction values between 0.0 and 0.4 mag A_K. Finally, as can be seen in Fig. 4, the effect is more pronounced for clusters with ages above 1 Gyr. Hence, this region either suffers from an unknown selection effect, or indeed there are fewer than normal old open clusters present in this part of the Galaxy.

ii) While our sample clearly contains a large number of clusters within 4 kpc from the Sun, there is a clear paucity of objects with distances to the Galactic Centre less than that of the Sun. This is a fact already noticed by Friel (1995) and replicated since then. In our sample only 3 % of the open clusters with ages above 1 Gyr are closer than 5 kpc to the Galactic Centre (only 10 % are closer than 7 kpc). In total 80 % of the old open clusters are further away than the Sun from the Galactic Centre. This clearly indicates that survival times of open clusters at smaller Galactocentric distances than the one of the Sun are significantly shortened due to the stronger tidal forces and the more frequent encounters with giant molecular clouds (e.g. van den Bergh & McClure (1980), Gieles et al. (2006; **?**)).

We also analysed the distribution of clusters below and above the Galactic Plane by fitting a Gaussian to the distribution. While the distribution of Galactic Latitudes is slightly off-centre with the peak of the distribution at $b = -0.6^\circ$ and a width of 7°, the distribution of distances Z to the Galactic Plane is almost centred ($Z = -33$ pc). In the right panel of Fig. 3 we show the distribution of all clusters perpendicular to the Galactic Plane. For clarity we zoom into the region where the open clusters are situated. The older clusters seem to be much more widely distributed perpendicular to the Galactic Plane than the younger objects. We hence analyse the full width half maximum of the distributions for clusters older and younger than 1 Gyr. We find that the 137 clusters with ages equal to or above 1 Gyr have a scale height of 375 pc. This agrees with earlier findings from e.g. Janes & Phelps (1994) utilising a much smaller sample of clusters. In contrast, the clusters in our sample which are younger than 1 Gyr have a scale height of only 115 pc. Even if our sample is inhomogeneous (see below), this is a clear indication that the older clusters have either survived longer due to their more inclined orbits, have been scattered into those, or have been formed there as part of the thick disk. The different scale height are not caused by selecting older clusters further away from the Galactic Centre than the younger clusters. The average distance to the Galactic Centre is 8.9 and 9.4 kpc for the younger and older clusters, respectively. Given the scatter in these distances of about 2 kpc, this difference is not enough to explain the different scale heights.

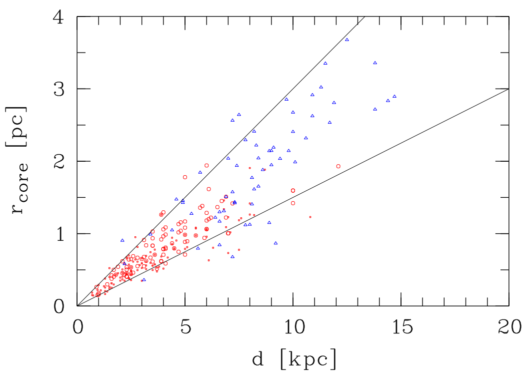

Figure 5. The apparent correlation of distance and core radius of our cluster sample, identified as one major selection effect in the FSR list. Blue triangles are the globular clusters, while large and small red circles are old (above one Gyr) and younger (less than one Gyr) open clusters. The two black lines indicate the range for the correlation as given in Eq. 5.

3.5 Reddening

The extinction towards the clusters ranges from zero to more than 0.8 mag A_K, in a handful of cases. Generally there is a trend of the extinction values with Galactic Longitude. Near to the Galactic Anticentre generally values of 0.3 mag A_K are not exceeded and away from the Anticentre region we detect more distant and reddened clusters. To account for the different distances we investigated the distribution of the reddening per kiloparsec values of our clusters. There are a handful of objects with more than 0.2 mag A_K per kiloparsec distance, which are most likely clusters behind nearby giant molecular clouds. The remaining clusters more or less show a homogeneous distribution between zero and 0.1 mag A_K/kpc. If we exclude clusters below or above the scale height (outside the main disk) of the entire sample, we find an average extinction for the entire sample of old open clusters of 0.70 mag/kpc of optical extinction (conversion of A_K into A_V following Mathis (1990)).

3.6 Selection effects and Cluster Radii

One so far not investigated issue of the FSR cluster candidate list is selection effects. The cluster selection is of course influenced by the local background star density and 2MASS completeness limit, as well as the distance to the cluster and the extinction along the line of sight.

However, we seem to have found one further important selection bias in the FSR sample. We investigate the core radius (in pc) of all clusters, determined from the fit of the radial star density profile and the estimated distance from the isochrone fitting (see Table A1 for the values of the individual clusters). We find that there is a clear correlation of the cluster core radius and its distance from the Sun (see Fig. 5). In particular, if we exclude the known globular clusters, the cluster core radii seem to follow the relation

$$r_{core}[pc] = (0.225 \pm 0.075) \cdot d[kpc] \quad (5)$$

Hence, the FSR sample does neither contain compact distant clusters nor more extended nearby objects. Both these effects are understandable when one looks back at the cluster candidate selection procedure (see Sect. 2). Stars in compact distant clusters are simply not resolved in the 2MASS data and hence might not have been picked up as local star density enhancements, and/or the number of detectable cluster members is too small to be identified as an old evolutionary sequence in the CMDs and CCDs. Similarly, nearby clusters are more extended in the sky and are hence also not picked up. Note that the average apparent cluster core radius of the old open clusters in our sample is about 40”, with a scatter of just $\pm$10”.

The identification of this selection effect in our cluster sample, also does not allow us to study the evolution of cluster radius with age and/or position in the Galaxy, as any trend might simply be caused by selection bias. If we try to account for the selection effect, we can still obtain some tentative trends for the cluster radii. i) more extended clusters seem to be found generally more often at larger Galactocentric distance; ii) larger clusters seem to be found generally at larger distances Z from the Galactic Plane. This trend has already been found by other authors (e.g. Janes et al. (1988)), Tadross et al. (2002), Schilbach et al. (**?**)).

4 CONCLUSIONS

We have analysed the entire list of cluster candidates from Froebrich et al. (2007a) by means of 2MASS photometry. We calculate more accurate cluster positions and radii. For stars within each cluster we calculate the membership probability based on a modified version of the colour-colour-magnitude approach by Bonatto & Bica (2007a). A by eye inspection of 2MASS colour-magnitude and colour-colour diagrams of high probability members has been used to identify 269 candidates for old clusters in the FSR sample.

Our sample of clusters contains 63 known globular clusters, 147 known open clusters with literature parameters, 27 known open clusters without known parameters and 32 previously unknown objects. We use isochrones from Girardi et al. (2002) to determine the age, distance and reddening for each cluster homogeneously from the 2MASS photometry. Our sample has a mean age of 1 Gyr and 80 % of the clusters are older than 500 Myrs.

The distribution of open clusters in the Galaxy shows that 80 % of the clusters with ages above 1 Gyr are further away than 7 kpc from the Galactic Centre, strengthening earlier findings e.g. from Friel (1995). Furthermore, the scale height of these old clusters is with 375 pc more than three times as large as the scale height of the younger (less than 1 Gyr) fraction in our sample, which we found to be 115 pc. This is still about twice as large as the scale height of young star clusters which is about 55 pc (Friel (1995)).

The large sample of clusters also allows us to investigate the general interstellar extinction for objects mostly not associated with Giant Molecular Clouds. For our sample of old clusters we find an average interstellar optical extinction of 0.70 mag/kpc.

We also identify a main selection effect in the FSR cluster sample, besides distance and reddening. An investigation of the cluster radii shows that the sample contains mostly clusters which have a distance to radius ratio in the range 3.3 to $6.7 \cdot 10^3$. This is caused by the fact that the sample seems to be biased towards clusters with an apparent projected core radius of 40” $\pm$ 10”.

Finally we find that there seems to be a significantly smaller than average number of old open clusters in the longitude range $120^\circ < l < 180^\circ$, which cannot be explained by any of the sample selection effects. The reason for this paucity is unknown.

Large improvements can be expected in the near future for this kind of work, as the UKIDSS GPS and Vista VVV surveys can be utilised. Their increase in limiting magnitude and in particular spatial resolution compared to 2MASS will allow us to improve on the parameter determinations, as well as to build up a cluster sample with less selection effects, e.g. circumventing the core radius selection effect.

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APPENDIX A: MAIN TABLE

Table A1: Summary table of the properties of the old stellar clusters analysed in this paper. We list the FSR catalogue ID, the coordinates, BIC value and core radius, the cluster properties as used in the isochrone fit in this work, the WEBDA or literature cluster parameter, the separation and classification of the known clusters in SIMBAD, and finally other common names for the clusters. The parameters for the isochrone fit used in this paper include the distance to the cluster, its age, the K-band extinction, the metallicity and the reddening law. The WEBDA and literature values are the distance of the cluster, its age, the reddening and metallicity. To plot the literature isochrone for the known globular clusters we use an age of 12 Gyrs. For clusters marked with a *, please read the notes in Appendix B for details on the isochrone fits.

FSR	Coordinates				this paper					Literature[1]				SIMBAD		other
ID	l	b	BIC	r_{core}	d	log(age)	A_K	[M/H]	C_{HK}	d	log(age)	E(B-V)	[M/H]	r	Class	Names
	[deg]	[deg]		[pc]	[kpc]	[yr]	[mag]	[dex]		[kpc]	[yr]	[mag]	[dex]	["]		
0003	0.069	−17.2926	−289.4	2.4	8.20	10.00	0.05	−1.28	1.97	8.2	—	0.04	−1.12	23	GlC	NGC 6723
0004	0.130	+11.0276	−146.6	1.6	8.20	10.20	0.23	−2.28	1.63	8.2	—	0.59	−2.05	17	GlC	NGC 6287
0006	0.982	+8.0110	−2.5	2.1	9.00	10.20	0.30	−1.28	1.74	9.0	—	0.89	−1.17	43	GlC	NGC 6325
0007	1.541	−11.3652	−40.3	1.9	9.00	10.20	0.03	−0.68	1.67	9.0	—	0.09	−0.96	39	GlC	NGC 6652
0008	1.729	−10.2619	−36.5	2.3	7.80	10.20	0.06	−0.68	1.67	7.8	—	0.17	−0.71	35	GlC	M 69, NGC 6637

Table notes:
[1] Data for the globular clusters has been taken from Harris (1996) and the data for the open clusters from the WEBDA database, except when indicated otherwise by a footnote.

APPENDIX B: NOTES ON INDIVIDUAL CLUSTERS

In the following we will discuss details to some clusters. These are either the objects with parameters determined here for the first time, or clusters with literature values that do not fit the 2MASS data. If the clusters is known already, then its other common names are given beside the FSR number.

FSR 0039: This seems to be a newly discovered old open cluster just 4.6 kpc from the Galactic Centre. The sequence in the CMD and CCD suggest we see a number of red giants, including red clump stars. There is no detectable main sequence in the 2MASS data, hence the age of 1 Gyr is an upper limit. The cluster seems highly reddened with $A_K = 1.22$ mag, but at a distance of 3.5 kpc and a Galactic Longitude of just 10° this is no surprise.

FSR 0050: The CMD and CCD sequence suggest that this is an about 5 Gyr old open cluster. There are not many red giant stars to determine the properties accurately, however the isochrone fit seems to fit the top of the main sequence the giants well. If confirmed, this object as well would be an inner Galaxy old open cluster with only 5.6 kpc distance to the Galactic Centre.

APPENDIX C: COLOUR-MAGNITUDE AND COLOUR-COLOUR DIAGRAMS

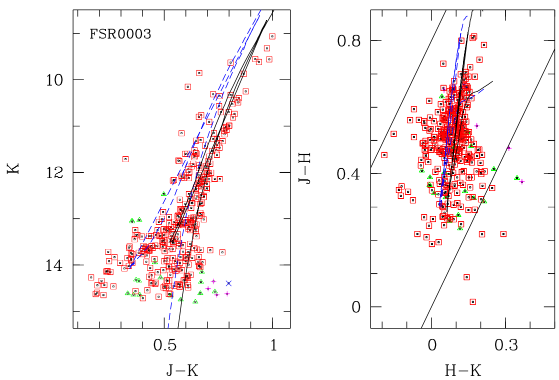

Figure C1. Example of our colour-magnitude (left) and colour-colour diagrams for the cluster FSR 0003 (NGC 6723). Red squares are stars with $P > 80\,\%$, green triangles are stars with $60\,\% < P < 80\,\%$, pink +-signs are stars with $40\,\% < P < 60\,\%$, blue crosses are stars with $20\,\% < P < 40\,\%$ and black dots are stars with $P < 20\,\%$. Overplotted in black is the best fitting isochrone (see Table A1 for the parameters). The two vertical lines enclose the reddening band for stellar atmospheres.