Properties of Star Clusters – III: Analysis of 13 FSR Clusters using UKIDSS-GPS and VISTA-VVV

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ABSTRACT

Discerning the nature of open cluster candidates is essential for both individual and statistical analyses of cluster properties. Here we establish the nature of thirteen cluster candidates from the FSR cluster list using photometry from the 2MASS and deeper, higher resolution UKIDSS-GPS and VISTA-VVV surveys. These clusters were selected because they were flagged in our previous studies as expected to contain a large proportion of pre-main sequence members or are at unusually small/large Galactocentric distances. We employ a decontamination procedure of \(JHK\) photometry to identify cluster members. Cluster properties are homogeneously determined and we conduct a cross comparative study of our results with the literature (where available). Seven of the here studied clusters were confirmed to contain PMS stars, one of which is a newly confirmed cluster. Our study of FSR1716 is the deepest to date and is in notable disagreement with previous studies, finding that it has a distance of about 7.3 kpc and age of 10 – 12 Gyr. As such, we argue that this cluster is a potential globular cluster candidate.

Key words:
open clusters and associations: individual; galaxies: star clusters: individual; stars: fundamental parameters; stars: statistics; methods: statistical; stars: pre-main-sequence

1 INTRODUCTION

Star clusters are the building blocks of the Galaxy and are tracers of both stellar and Galactic evolution. Individually they act as laboratories, demonstrating how stellar systems comprised of various masses work and interact as member stars share similar properties (distance, age, reddening and metallicity). Collectively clusters provide insight into the chemical and structural evolution of the Galaxy.

When a large sample of clusters is available, objects of interest such as massive clusters, old clusters near the Galactic Centre and/or young clusters containing a large proportion of Pre-Main Sequence (PMS) members become available for detailed study. Over the last decade the rate of cluster discovery has significantly increased. This can be attributed to the advent of multiple large scale Near-Infrared (NIR) and Mid-Infrared (MIR) surveys, such as GLIMPSE (Benjamin et al. 2003), 2MASS (Skrutskie et al. 2006), UKIDSS-GPS (Lucas et al. 2008), VISTA-VVV (Minniti et al. 2010), WISE (Wright et al. 2010). Resultantly, large photometric-only cluster candidate catalogues have become readily available e.g. Mercer et al. (2005), Froebrich et al. (2007), Borissova et al. (2011), Camargo et al. (2015).

Unfortunately, difficulties lie in ascertaining the nature and fundamental properties of these candidate clusters in the absence of spectroscopic and/or astrometric data. Additional difficulties are found in the heterogeneous nature of the catalogues themselves which are often compiled from the literature (e.g. WEBDA† or DAML02 (Dias et al. 2002)). It has been argued that incongruity between individual cluster properties is not problematic, so long as the reliability of the values and/or methods used to derived them is considered (e.g. Paunzen & Netopil (2006), Netopil et al. (2015)). However, this is impractical for the compilation of a large cluster catalogues, and ultimately any global analyses undertaken therewith would need to be treated with great care due to the resulting heterogeneity of cluster property values. To ensure the validity of large scale analyses undertaken with cluster samples, it is therefore essential that their properties are homogeneously derived, so that any uncertainties in the determined values are systematic. Consistency of properties derived by different authors is a primary concern, particularly for clusters that are sparsely populated and less well defined on the field (i.e. lack prominent features such as a strong Main Sequence (MS), giants etc.). Attempts have been made

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1 https://www.univie.ac.at/webda/
by the community to statistically address this issue by developing methodologies that homogeneously derive the properties of cluster samples, but as these rely on modelled cluster sequences and/or positional data, the accuracy of individual cluster property values remains questionable (Monteiro et al. (2010), Kharchenko et al. (2012), Perren et al. (2015)).

Our aim in this series of papers has been to homogeneously investigate the fundamental properties and large scale distribution of Galactic open clusters. In Buckner & Froebrich (2013) (Paper I, hereafter) we established a foreground star counting technique as a distance measurement and presented an automatic calibration and optimisation method for use on large samples of clusters with NIR photometric data only. We combined this method with colour excess calculations to determine distances and extinctions of objects in the FSR list cluster sample from Froebrich et al. (2007) and investigated the H-band extinction per kpc distance in the Galactic Disk as a function of Galactic longitude. In total, we determined distance estimates to 771, and extinctions values for 775, open cluster candidates from the FSR list.

In Buckner & Froebrich (2014) (Paper II, hereafter) we investigated the relationship between scale height and cluster age. We homogeneously derived cluster ages and developed a novel approach to calculate cluster scale heights, which significantly reduced established constraints on sample size. Applying our scale height method to the homogeneous MWSC catalogue by Kharchenko et al. (2013), the DAML02 list by Dias et al. (2002) and the WEBDA database, we were able to trace the scale height evolution of clusters in detail for the first time, finding a marked increase in scale height at 1 Gyr. We also determined the parameters of 298 open cluster candidates, of which we confirmed 82 as real clusters for the first time.

Following that analysis, it became apparent that some objects in the FSR list warranted further investigation as they were either suspected to contain a large proportion of PMS members, or (ii) have unusually small/large Galactocentric distances and/or distances from the Sun with respect to the remainder of the FSR list. For the former, deeper magnitude photometry is necessary to confirm that these clusters’ members are predominantly PMS, and to derive accurate properties for the clusters as only their brightest member stars were visible above the 2MASS K-band detection limit.

For the latter, clusters were found to be either within 5 kpc of, or around 13 kpc away from, the GC or have a distance from the Sun in excess of 10 kpc (the FSR List peaks at a distance of about 3 kpc). Inclusion of deeper, higher resolution photometry will therefore make visible the dimmer cluster members which are on the MS but below the 2MASS detection limit, thus enabling more accurate isochrone fits to be made and ultimately the clusters’ distances can be confirmed or revised.

Based on our Paper II study, 19 clusters in the FSR list sample were flagged as potentially having a large proportion of PMS members, and 5 clusters were flagged as having notable Galactocentric distances. Of these photometry from the UKIDSS-GPS and VISTA-VVV surveys was available for 13 of the clusters: FSR0089, FSR0188, FSR0195, FSR0207, FSR0301, FSR0636, FSR0718, FSR0794, FSR0828, FSR0870, FSR0904, FSR1189 and FSR1716.

2 ANALYSIS METHODS

In this section we present our cluster sample, and our analysis methods which are based on photometric archival data and isochrone fitting.

2.1 Cluster Selection

Following our analyses of the FSR list clusters in Papers I & II with 2MASS photometry, it became apparent that some objects warranted further investigation. These clusters were either (i) suspected to contain a large proportion of PMS members or (ii) have unusually small/large Galactocentric distances and/or distances from the Sun with respect to the remainder of the FSR List. For the former, deeper magnitude photometry is necessary to confirm that these clusters’ members are predominantly PMS, and to derive accurate properties for the clusters as only their brightest member stars were visible above the 2MASS K-band detection limit.

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2.2 Photometry and Cluster Radii

Cluster’s central coordinates are taken from Froebrich et al. (2007). The core radius of each cluster, \(r_{\text{cor}}\), is determined from a radial star density profile fit of the form:

\[
\rho(r) = \rho_{\text{bg}} + \rho_{\text{cen}} \left[ 1 + \left( \frac{r}{r_{\text{cor}}} \right)^2 \right]^{-1}
\]

Where \(r\) is the distance from the cluster centre; \(\rho(r)\) the projected radial star density; \(\rho_{\text{bg}}\) is the projected background star density which is assumed constant; and \(\rho_{\text{cen}}\) the central star density above the background of the cluster.

JHK photometry was extracted from the UKIDSS-GPS, VISTA-VVV and 2MASS NIR point source catalogues in a circular 0.3° area around the clusters’ central coordinates. The apparent core radii for our selected clusters is < 0.01°, thus an area of 0.3° satisfactorily encompasses the members of each cluster.

To optimise the quantity and quality of photometry used in

\[2\text{ Assuming a Solar Galactocentric distance of } R_{\text{GC}}^\odot = 8.00 \text{ kpc} \]
this study, we make the following selections. For the deep, high resolution VISTA-VVV and UKIDSS-GPS surveys we select all objects that have been given a mergedClass classification of -1" (i.e. object has a probability of $\geq 90\%$ of being a star; Lucas et al. (2008)), and that have photometry available in each of the $JHK$ filters, down to their limiting $K$-band magnitudes of 18.1 mag and 17.8 mag respectively. As we will use the 2MASS photometry for bright sources only (see Sect. 2.4), we select the highest photometric quality with a Qflag of "AAA", (i.e. detected by the $JHK$ filters with a $S:N$ of greater than 10 and corrected photometric uncertainties of less than 0.11 mag; Skrutskie et al. (2006)) down to a $K$-band magnitude of 12.0 mag.

2.3 Cluster Membership Identification

Ideally cluster members should be automatically identified through their colours and magnitudes. This should be done without the need to fit isochrones to Colour Magnitude or Colour-Colour diagrams or relying on manual, subjective selection of cluster members. This series of papers uses an approach that is based on the works of Bonatto & Bica (2007b) and Froebrich et al. (2010), known as the Photometric Decontamination Technique (PDT). The PDT is the approach of choice as it determines the likelihood that a star projected onto a cluster is a member based on its position in CCM space.

To distinguish true members from interloping field stars we define the cluster area, $A_{cl}$, as a circular area around the centre of a cluster within which the majority of members are expected to be contained. The radius of this cluster area is two times the cluster core radius ($2 \times r_{cor}$). We also define a control area, $A_{con}$, as a ring around the centre of a cluster within which all stars are expected to belong to the field population. The inner radius of this ring is five times the cluster core radius ($5 \times r_{cor}$) and the outer radius is 0.3°. For a discussion of the validity of our cluster and control area selections the reader is referred to the relevant sections in Papers I and II.

To determine the likelihood, $P_{cl}^i$, that star $i$ is a cluster member we start by estimating the CCM distance, $r_{CCM,cl}^{i,j}$, between star $i$ and every other star $j$ ($i \neq j$) in the cluster area using the following equation:

$$r_{CCM,cl}^{i,j} = \sqrt{\frac{1}{2} (J_i - J_j)^2 + (JK_i - JK_j)^2 + (JH_i - JH_j)^2}$$

(2)

where $i$ and $j$ identify all stars in the cluster area, $J$ refers to the $J$-band magnitudes of the stars, and $JK$ and $JH$ to the respective colours of them. This combination of colours and magnitudes has been shown to be the most effective in separating cluster members from field stars over a wide range of cluster ages (Bonatto et al. 2004, Bonatto & Bica 2007b).

We then identify the CCM distance $r_{CCM,cl}^{i,N}$ for star $i$ that corresponds to the $N^{th}$ nearest neighbour in CCM space in the cluster area. For our analysis here we set $N = 15$. As shown in Paper I, the specific choice value of $N$ is essentially arbitrary and does not significantly affect the identification of the most likely cluster members. It essentially defines the balance between the ‘resolution’ in CCM space at which potential cluster members can be separated from field stars and the $S:N$ of the determined membership likelihood. In other words increasing $N$ will lead to a higher $S:N$ for $P_{cl}^i$ but cluster features (such as the MS) traced by the most likely cluster members in CCM space will be less well defined.

We then determine the CCM distance $r_{CCM,con}^{i,j}$ between star $i$ in the cluster area and every other star $j$ in the control area adopting Eq. (2) where now $j$ identifies all stars in the control area. We then count the number of stars $N_{CCM,con}^{i,N}$ in the control area that have $r_{CCM,con}^{i,j} < r_{CCM,cl}^{i,j}$. From this we can estimate the likelihood that star $i$ is a member of the cluster by:

$$P_{cl}^i = 1.0 - \frac{N_{CCM,con}^{i,N}}{N_{CCM,con}} A_{cl}. \quad (3)$$

where $P_{cl}^i$ is the Membership Probability Index (MPI) of star $i$; and $A_{cl}$ and $A_{con}$ are the areas covered by the cluster and control fields, respectively. In principle, $P_{cl}^i$ can have a negative value due to statistical fluctuations of the number of field stars in the control and cluster area. Thus it is in fact not a true probability and hence has been named a probability index instead. As a negative value simply means that a star is very unlikely to be a member of the cluster, all negative $P_{cl}^i$ values are set to zero.

In principle stellar members can be statistically identified from (and photometric MPIs augmented by) positional data as it is reasonable to expect there to be less contamination from interlopers towards a cluster’s centre, thus the likelihood that a star $i$ is a member of the cluster increases with decreasing radial distance ( Dias et al. 2012, Krone-Martins & Moitinho 2014). However, membership probabilities derived in this way should be treated with caution as they can be unreliable for clusters that are: (i) dense, as stellar crowding in their central regions will make accurate membership determination difficult; (ii) projected onto high density stellar field, as not clearly distinguished from the field, and a significant proportion of true members may be outside the determined cluster radius; (iii) young, as these clusters may not necessarily be circular in projection and have substructure (e.g. Sanchez & Alfaro 2009, Gregorio-Hetem et al. 2015). As the clusters studied in this work each fall into one or more of these categories, we do not use spatial probabilities to identify members. For a full discussion the reader is referred to Paper II and Froebrich et al. (2010).

2.4 Construction of CCM Diagrams

Cluster $J-K$ vs. $K$ Colour-Magnitude Diagrams (CMD) and $H-K$ vs $J-H$ Colour-Colour Diagrams (CCD) were constructed using photometry from the UKIDSS-GPS/VISTA-VVV surveys for point sources at $K < 12$ mag, and 2MASS for point sources brighter than $K \geq 12$ mag. To ensure no point sources at $K \sim 12$ mag which appear in both UKIDSS-GPS/VISTA-VVV and 2MASS were plotted twice, we cross-referenced the surveys and removed point sources accordingly. Stellar memberships for each cluster were determined as described in Sect. 2.3 and overplotted on the diagrams. We define the extinction law for each cluster from the reddening free parameter $Q$ for each star in the cluster area, where

$$Q = JH - (\chi \cdot HK) \quad \text{and} \quad \chi = \frac{E(J-H)}{E(H-K)} \quad (4)$$

As described in Paper I, a value of $Q \leq -0.05$ mag by more than 1 $\sigma$ (estimated from the photometric uncertainties) denotes a Young Stellar Object.

It has been shown in the literature the value of $\chi$ typically varies between 1.55 (Mathis 1990) and 2.00 (Straizys & Lau galys 2008). Using the methods described above and in Sect. 2.5 we identify each clusters most likely members and make manual isochrone fits assuming a value of $\chi = 1.55$ until a satisfactory fit.
is made. In cases where our assumed value of $\chi$ is clearly too low (or high) we vary the conversion factors, $C_{KH}$ and $C_{JH}$, until the best fit for the cluster is found. Where

$$\frac{A_K}{A_H} = C_{KH} \quad \text{and} \quad \frac{A_J}{A_H} = C_{JH} \quad \text{therefore} \quad \chi = \frac{C_{JH} - 1}{1 - C_{KH}} \quad (5)$$

and $A_J$, $A_H$, $A_K$ are the NIR $J$-, $H$- and $K$-band extinctions respectively.

### 2.5 Isochrone Fitting

The clusters studied in this paper lack spectroscopic measurements, without which there is no way of determining their metallicities. In Paper II we showed that the median metallicity of clusters in the WEBDA catalogue is $Z = 0.02$ (i.e. Solar), hence it is reasonable to assume a Solar metallicity for open clusters in the Solar Neighbourhood in cases where their metallicity is unknown. It should be noted that systematic uncertainties caused by using a (slightly) incorrect metallicity are small. For example, if a Solar metallicity is incorrectly assumed for an open cluster of $-0.4 < [Fe/H] < 0.2$ there will be an intrinsic uncertainty comparable to $\log(\text{age/yr}) \sim 0.1$.

We fit Solar metallicity Geneva [Lejeune & Schaerer 2001] or PMS [Siess et al. 2000] isochrones to the highest probability cluster members on the CMDs and CCDs, utilising our homogeneously determined distance, extinction and age values from Paper II as a starting point for the fits.

### 3 RESULTS

In this section we present and discuss in detail the findings of our analysis of each cluster using the methods outlined in Section 2. In addition, we conduct a cross comparative study of our results with the literature (where available). A summary of the properties and nature of each cluster can be found in Table [A1].

#### 3.1 FSR0089

A confirmed cluster candidate of the FSR list, located in the first Galactic Quadrant. In Paper II FSR0089 was flagged as one of clusters with the largest Solar distance with $d = 10.50$ kpc. Figure [2] shows an old cluster with a well defined MS, turn-off and giants. The cluster has a Solar distance of $d = 4.90$ kpc, age of 1 Gyr and extinction of $A_H = 0.61$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.55$.

The revised age and extinction values are in general agreement with those derived in Paper II, but the cluster’s distance estimate has halved. As such, FSR0089 is no longer one of the furthest clusters in the sample. The cause of the distance discrepancy is that the majority of cluster sequence was below the 2MASS detection limit, which impacted on accuracy of the distance estimate; it is a good example of the necessity for deeper magnitude photometry when deriving cluster properties through isochrone fitting.

FSR0188 has been previously studied by [Kharchenko et al. 2013] as part of the MWSC catalogue using 2MASS photometry. The authors determined the cluster to be younger, nearer and redder than the revised values suggest. Figure [2] shows the CCM diagrams of the cluster with two sets of isochrones over-plotted: those depicting the revised values, and those given by [Kharchenko et al., 2013]. Clearly, the revised values are a better fit for the cluster’s sequence, the majority of which is below the 2MASS detection limit. Again, the most likely cause of the discrepancy with the MWSC catalogues values is their misidentification of field stars as cluster members (in particular the giants).

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#### 3.3 FSR0195

A confirmed cluster candidate of the FSR list, located in the first Galactic Quadrant. In Paper II FSR0195 was flagged as having a (potentially) large number of PMS members. Figure [2] shows a young open cluster with a PMS track. The cluster has a Solar distance of $d = 3.50$ kpc, age of 30 Myr and a $H$-band extinction of $A_H = 1.25$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.57$. These revised age value is consistent with our value determined in Paper II. This revised distance is approximately 1.5 times greater than that derived in Paper II, as the addition of dimmer stars below the 2MASS detection limit has enabled its value to be more accurately constrained.

The parameters of FSR0195 have previously been derived by [Kharchenko et al. 2013] who found the cluster to have smaller extinction and distance values but a markedly larger age estimate of 2.2 Gyr. Fig. [2] clearly shows that the cluster is much younger than this value and therefore the values given by the MWSC catalogue are inaccurate. FSR0195 is a good example of the need for deep, high resolution photometry when deriving clusters’ fundamental properties.

#### 3.4 FSR0207

A previously known cluster (IC4996), located in the first Galactic Quadrant in the Cygnus constellation. Figure [2] shows a young open cluster with a PMS track. The redetermined properties of FSR0207 are $d = 1.40$ kpc, age of 10 Myr and $A_H = 0.25$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.22$. These revised values are in general agreement with the values derived in Paper II.

The presence of PMS stars in FSR0207 has previously been
Analysis of 13 Clusters

Figure 1. (Left) Colour-Magnitude and (Right) Colour-Colour diagrams of FSR0089. Photometric membership probabilities are determined for stars within $2 \times r_{cor}$, with $N = 15$ and are represented as follows: $P_{cl} > 80\%$ red squares; $60 \leq P_{cl} < 80\%$ green stars; $40 \leq P_{cl} < 60\%$ blue diamonds; $20 \leq P_{cl} < 40\%$ purple triangles; $P_{cl} < 20\%$ black plus signs. The parallel black lines in the Colour-Colour plot represent the reddening band of the cluster. The horizontal dashed black line marks the 2MASS $K$-band completeness limit at the cluster’s coordinates. The solid black and dashed turquoise/black isochrones represent the best fit, as determined in this study and the MWSC catalogue respectively. The triple-dot-dash blue isochrone represents the best fit as determined by [Froebrich et al., 2008].

Figure 2. As in Figure 1 but for FSR0188.

Figure 3. As in Figure 1 but for FSR0195.
confirmed through photometric and spectral analysis (see e.g. Delgado et al. 1999, Delgado et al. 1998, Zwintz et al. 2004, Zwintz & Weiss 2006, Bhavya et al. 2007)). Using SIMBAD we searched the cluster area of FSR0207 for bright stars which are likely members of the cluster, finding there is a $\beta$ Lyr type eclipsing binary (MPI = 0.59) and a B3 type star (MPI = 0.71). A spectroscopic study by Mathew & Subramaniam (2011) showed that the age of the B3 star is 8 Myr, which is consistent with our derived cluster age.

A search of the literature reveals that the cluster has been extensively studied and it is generally agreed to have an age of $\sim$ 10 Myr, Solar distance of $\sim$ 1.90 kpc and H-band extinction of $\sim$ 0.35 mag, i.e. further and more reddened than the revised values presented here suggest (see Table A1). However, it should be noted that authors predominantly used an extinction law of $\chi = 1.60$ and UBVRI photometry to derive these values. IRAS maps have shown there to be an IR dusty shell surrounding the cluster which is associated with the nearby Berkeley 87 (Lozinskaya & Repin 1999), so the UKIDSS-GPS $JHK$ photometry utilised here has a distinct advantage, revealing the dimmer stars in the cluster sequence which are crucial to accurately fit modelled cluster sequence isochrones to the CCM diagrams of FSR0207 (and derive the cluster’s fundamental properties).

### 3.5 FSR0301

A previously known cluster (Berkeley 55), located in the second Galactic Quadrant in the Cygnus constellation. Figure 3 shows a young open cluster with a PMS track. The scattering of the brightest objects at the top of the MS could be real or could be caused by misidentification of members. The cluster’s properties are determined as $d = 2.25$ kpc, age of 50 Myr and $A_H = 0.87$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.55$. These revised values are in general agreement with the values derived in Paper II, albeit giving a slightly larger age but smaller extinction for the cluster.

FSR0301’s revised age is good agreement with Negueruela & Marco (2012) who conducted an in depth study of the cluster using UBVIHK photometry and z-band spectra. Other studies determined the cluster to have a significantly smaller Solar distance and to be much older at $\sim$ 300 Myr (Tadross 2008, Maciejewski & Niedzielski 2007) and the MWSC catalogue, which is most likely a result of member misidentification. However, the CCM diagrams clearly show this 300 Myr isochrone is too old for the cluster, which is a notably poor fit to the cluster sequence below $K \approx 13$ mag. Furthermore, Negueruela & Marco (2012) showed that the brightest stars on the MS are B4 - 6, which confirms the cluster’s age to be greater than 40 Myr but less than 100 Myr.

### 3.6 FSR0636

A cluster previously known in the literature (King 6), located in the second Galactic Quadrant in the Local Spiral Arm. In Paper II FSR0636 was flagged as having a (potentially) large number of PMS members. Figure 6 shows a young open cluster with a PMS track. The cluster has a Solar distance of $d = 0.72$ kpc, age of 60 Myr and extinction of $A_H = 0.33$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.52$. These revised age and extinction values are consistent with those previously determined in this series.

To date there have been three studies of FSR0636 in the literature and all are in general agreement with the revised distance values but conclude the cluster to be much older at $\approx$ 250 Myr (Ann et al. 2002, Maciejewski & Niedzielski 2007, Kharchenko et al. 2013). As demonstrated in Figure 6, although a 250 Myr isochrone can be fitted to the cluster, it fails to fit the cluster sequence for objects with $K > 14$ mag entirely, which fit a much younger 50 Myr isochrone. Furthermore, the earliest stars on the MS are B-stars of type B5 - 7 (Straižys & Langalys 2007), i.e. the cluster has an age of less than 100 Myr. Note, the MWSC derives an extinction of $A_H = 0.19$ i.e. markedly smaller than the accepted literature value, resulting from their use of a different extinction law ($\chi = 2.00$) to that of the other literature studies ($\chi = 1.60$).

### 3.7 FSR0718

A cluster previously known in the literature (Berkeley 15), located in the second Galactic Quadrant in the Auriga constellation. In Paper II FSR0718 was flagged as having a (potentially) large number of PMS members. Figure 7 shows a young open cluster but without a PMS track it was assumed to have. The cluster has a Solar distance of $d = 2.40$ kpc, age of 80 Myr and extinction of 3 http://simbad.u-strasbg.fr/simbad/
Figure 5. As in Figure 1 but for FSR0301. The dot-dash orange and triple-dot-dash blue isochrones represent the best fit as determined by Tadross (2008) and Maciejewski & Niedzielski (2007) respectively.

Figure 6. As in Figure 1 but for FSR0636. The dot-dash orange and triple-dot-dash blue isochrones represent the best fit as determined by Ann et al. (2002) and Maciejewski & Niedzielski (2007).

Figure 7. As in Figure 1 but for FSR0718. The triple-dot-dash blue line represents a 300 Myr isochrone with the same distance and extinction as determined by this study.
$A_H = 0.45$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.88$. These revised age and extinction values are consistent with those previously determined in this series, albeit with a slightly smaller extinction and larger age.

The properties of FSR0718 are strongly disputed in the literature, but most authors derive an age in excess of $>300$ Myr. This is much older than the revised value, which is most likely a result of misidentification of field stars (outside of $2 \times r_{cor}$) as cluster members. To demonstrate, the reader is referred to the cluster’s CCM diagrams in Figure 7, where it is shown that if there were giant members at $K \leq 12$ mag and $0.9$ mag $\leq [J - H] \leq 1.3$ mag, the cluster would have an age in excess of $\sim 300$ Myr. As observed by Tapia et al. (2010) further analysis in needed to discern the earliest member spectral types in FSR0718 for absolute clarification of the cluster’s age.

3.8 FSR0794
A previously known and extensively studied cluster (NGC 1960/M36), located in the second Galactic Quadrant in the Auriga constellation. Figure 8 shows a young open cluster with well defined MS and PMS tracks. The cluster’s properties are redetermined as $d = 1.20$ kpc, age of 10 Myr and $A_H = 0.35$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 0.75$. These revised age and distance values are in agreement with those derived in Paper II, but the extinction value is significantly larger caused by a change in the extinction law for the cluster. The brightest member of the cluster listed in SIMBAD is a B2 type star (MPI = 0.95), which is consistent with our derived age value for FSR0794.

This cluster has been extensively studied in the literature and the majority of determined properties values agree with the here revised values, albeit with a higher extinction value due to our use of a different extinction law than the majority of the literature. As such, FSR0794 is a good candidate to demonstrate the reliability of our isochrone fitting procedure to accurately establish cluster properties.

3.9 FSR0828
A cluster candidate of the FSR list, located in the second Galactic Quadrant. In Paper II FSR0828 was flagged as having the greatest Galactocentric distance in the sample at $R_{GC} = 13.0$ kpc. Figure 9 shows an old cluster with a well defined MS (below the 2MASS detection limit), turn-off and giants. The cluster’s properties are re-
determined as $d = 3.20$ kpc, age of 2 Gyr and $A_H = 0.22$ mag. As such, FSR0828 no longer has the largest Galactocentric distance in the sample. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.55$. These revised values make the cluster nearer and older than the values derived in Paper II suggest, but are in good agreement with the literature.

3.10 FSR0870

A previously known cluster (NGC 2129), located in the third Galactic Quadrant in the Gemini constellation. Figure 10 clearly show a very young open cluster with a PMS track. The cluster’s properties are redetermined as $d = 1.45$ kpc, age of 10 Myr and $A_H = 0.62$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.65$. These revised values make the cluster older, redder and nearer than determined in Paper II. The brightest member of the cluster listed in SIMBAD is a B2 type star (MPI= 0.75), which is consistent with our derived age value for FSR0870.

The nature of FSR0870 has been a subject for debate since its discovery. An early study by Cuffey (1938) placed the cluster at a distance of $\sim 0.6$ kpc from the Sun, but a study by Pena & Peniche (1994) cast doubt on the cluster’s existence when the authors created a histogram of the distances of 37 stars in the direction of FSR0870 using $uvby - \beta$ photometry and concluded it was an asterism, despite a previous radial velocity study by Liu et al. (1991). Their conclusion prompted further studies which utilised proper motions and photometry confirm whether FSR0870 is real or an asterism (e.g. Baumgardt et al. (2000), Carraro et al. (2006)). It is now generally accepted that FSR0870 is a real Solar metallicity cluster, at a distance of $\sim 2$ kpc, age of $\sim 10$ Myr and extinction of $A_H \sim 0.40$ mag. However, it should be noted that the majority of the MS is below the 2MASS (and previous studies) detection limit.

3.11 FSR0904

A cluster candidate located in the third Galactic Quadrant. Figure 11 shows a young open cluster without the PMS track it was suspected to have. The cluster’s properties are redetermined as $d = 1.50$ kpc, age of 80 Myr and $A_H = 0.30$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.52$. These revised values are in general agreement with the values derived in Paper II, albeit with slightly higher age, lower extinction and distance, estimates due to the majority of the MS falling below the 2MASS detection limit. The brightest star in the cluster area (listed in SIMBAD) is a B1 star, that would suggest that the cluster is much younger than our derived value. However it has a relatively low MPI of 0.55, so it is uncertain whether this star is a true cluster member or a field star and a spectroscopic analysis is required to determine whether it is a cluster member (which is outside the scope of this paper).

There have been three previous studies of FSR0904, and whilst all have derived values for the clusters properties by fitting isochrones to 2MASS photometry, they have produced conflicting values. The revised values are in agreement with those derived by Camargo et al. (2010), but conflict with those of Glushkova et al. (2010) and the MWSC catalogue.

Glushkova et al. (2010) found the cluster to be a factor of $\sim 10$ older than the revised values suggest, with a significantly smaller extinction and distance. This discrepancy is caused by misidentification of cluster members by the authors (i.e. field stars outside $2 \times r_{cor}$ as giants - see Figure 11), which was compounded by the majority of the MS not being visible to the authors when they determined the cluster’s properties (as it is below the 2MASS detection limit). Members were identified as objects that lay along the isochrone fitted to the CCM diagrams and which formed the cluster’s spatial density peak. Obviously, this approach is subjective to the authors interpretation of the CCM diagrams and subsequent choice of isochrone. Furthermore, assessing membership based on spatial positioning has been shown to be unreliable, especially for young clusters (such as FSR0904) which do not appear circular in projection, those projected onto a high density field star background, or with significant stellar crowding (for a full discussion see e.g. Froebrich et al. (2010), Buckner & Froebrich (2013)). Although Glushkova et al. (2010) identified the majority of members on the top of the MS with reasonable accuracy, the misidentification of field stars as the cluster’s giants, in combination with ‘missing’ the majority of the cluster sequence (due to 2MASS detection limits), has resulted in the authors significantly overestimating FSR0904’s age and underestimating its extinction and distance.

Figure 10. As in Figure 1 but for FSR0870.
Figure 11. As in Figure 1 but for FSR0904. The triple-dot-dash blue isochrone represents the best fit as determined by Glushkova et al. (2010).

Figure 12. As in Figure 1 but for FSR1189. The dot-dash orange and triple-dot-dash blue isochrones represent the best fit as determined by Segura et al. (2014) and Lim et al. (2011) respectively.

3.12 FSR1189

A previously known cluster (NGC 2353), located in the third Galactic Quadrant near the Canis Major OB1 association. Figure 12 shows a moderately young open cluster with a PMS track. The cluster’s properties are redetermined as $d = 1.20$ kpc, age of 90 Myr and $A_H = 0.11$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.55$. These revised values are in agreement with the values derived in Paper II.

The revised values are also in consensus with the literature. This age also agrees with the assessment of Fitzgibbon et al. (1990) and Lim et al. (2011), that FSR1189 is unrelated to the much younger ($\sim 3$ Myr), but similarly distanced, Canis Major OB1 association. The revised extinction estimate is a factor of 2 larger than that given by various authors, but is accurate according to the isochrone fits shown in Figure 12. Literature studies have predominantly analysed FSR1189 using visual UBV photometry (see e.g. Moitinho (2001)), whilst this work has conducted the analysis using NIR JHK photometry.

3.13 FSR1716

A confirmed cluster candidate of the FSR list, located in the fourth Galactic Quadrant. In Paper II FSR1716 was flagged as one of the nearest clusters to the GC in the FSR list at $R_{GC} = 4.3$ kpc. Figure 13 shows a very old open or possible globular cluster candidate. The cluster’s properties are redetermined as $d = 7.30$ kpc, age of 10-12 Gyr and $A_H = 0.57$ mag. After testing different variations we found the extinction law that best fits the cluster is $\chi = 1.72$. These revised values make the cluster older, further away but less reddened than the values in Paper II suggest. The revised values make FSR1716 both the oldest cluster in the sample and nearest to the GC with $R_{GC} = 4.1$ kpc.

Deriving the age of old clusters is difficult. Unlike younger clusters (for which the isochrone can be fitted to the MS stars, turnoff and potentially a few giants) the CCM diagrams of the oldest clusters have only one detectable age defining feature: the position of the Red Giant “Clump” (RGC) i.e. horizontal branch stars expected to have degenerated into a clump near the Red Giant Branch. Unfortunately in many instances this feature fails below, or is very close to, the detection limit of the photometry being employed to analyse the cluster, and its position has to be guesstimated by each author based on their individual interpretations of the CCM dia-
Figure 13. As in Figure[1] but for FSR1716. The triple-dot-dash blue isochrones represent the best fitting open cluster isochrone as determined Froebrich et al. (2010).

grams. If FSR1716 had an age \(< 10\) Gyr we would expect to detect the MS turn-off stars but as Figure[13] clearly shows this is not the case. Instead there appears to be a prominent RGC at \(K \sim 15 - 15.5\) mag, evidencing its status as an older cluster.

To derive an age estimate for FSR1716 we determine the exact position of the RGC, derived as the weighted mean of the membership probabilities of stars in the cluster area, determined to be \(K = 15.3\) mag. To confirm, we plot a histogram of the \(K\)-band magnitude of stars with a MPI of \(> 0.4\) in the cluster area and all stars in the control field (normalised to the cluster area). Figure [14] clearly shows that there is a significant peak in the histogram of cluster members at \(K \sim 15\) mag (which is independent of bin size) above that of the histogram of control field stars. Furthermore, there is a \(\sim 5.5\) magnitude difference between the top of the RGB and the peak. Thus we interpret the peak as \(K \sim 15.3\) mag as the RGC. Finally, we find a second significant peak at \(K \sim 13\) mag (independent of bin size) which we interpret as the Asymptotic Giant “Clump” i.e. Asymptotic Giant Branch stars at the onset of helium shell burning (Alves et al. (2002), Froebrich et al. (2007)).

The revised property values presented here were determined by fitting an isochrone to the CCM diagrams of FSR1716, using the measured position of the RGC as a reference point. Our age value of FSR1716 agrees with the assessment that it is a potential globular cluster candidate.

**4 CONCLUSIONS**

We selected thirteen FSR list clusters from Buckner & Froebrich (2014) and analysed their properties using deep, high resolution photometry from the UKIDSS-GPS and VISTA-VVV surveys. These clusters were selected for our sample as they were either (i) suspected to either contain a significant number of PMS stars or (ii) had a previously determined notable Galactocentric distance. Of these, seven were confirmed to contain PMS stars, one of which is a confirmed new cluster candidate. Notably, the analysis identified FSR1716 as a globular cluster candidate with a distance of about 7.3 kpc and an age of 10 – 12 Gyr.

For the majority of our selected clusters this was the first analyses of them which used deep, high resolution photometry, and as such their derived properties differed substantially from literature estimates. For the majority of these clusters there was a marked discrepancy between the properties derived in this study (and the literature) with those listed in the MWSC catalogue, which is most likely caused by the nature of these clusters the pipeline employed by the authors of the MWSC catalogue to homogeneously derive cluster properties using 2MASS photometry, as they assumed a constant extinction law (\(\chi = 2.00\); Kharchenko et al. (2012)). This, compounded by the absence of deep, high resolution photometry, has resulted in some erroneous values for individual clusters.

It is important to determine the properties of the remaining FSR list clusters and confirm the nature of the new cluster candi-
dates which could not be studied in this series of papers due to a lack of available deep, high resolution photometry. Unfortunately, to date surveys such as those used in this study (UKIDSS-GPS and VISTA-VVV) are only complete for a fraction of FSR list clusters. Mass estimates for the clusters of the catalogue would enrich the understanding of observed cluster distributions in the Galactic Plane.

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APPENDIX A: A TABLE OF CLUSTERS

Table A1: Details the refined properties of the clusters studied. For each cluster the table lists its ID, class (PMS, OC or GIC), type (known open cluster or new cluster candidate), Galactic coordinates (l,b), age, distance in parsec, $H$-band extinction value, and the literature source of these values.

| ID         | Type     | Class | ID | Type | Class | Age  | d   | $A_H$ | Reference |
|------------|----------|-------|----|------|-------|------|-----|-------|-----------|
| FSR0089    | New      | OC    |  7.0 | 5.70 | 10.00 | 5.40 | 100.0 | 0.50 | 1         |
| MWSC2997   | New      | OC    |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 2         |
| FSR0188    | New      | OC    |  7.0 | 5.80 | 10.00 | 5.50 | 100.0 | 0.50 | 3         |
| MWSC3228   | New      | OC    |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 4         |
| FSR0195    | New      | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 5         |
| MWSC3298   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 6         |
| FSR0207    | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 7         |
| MWSC3297   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 8         |
| IC 496     | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 9         |
| FSR0301    | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 10        |
| MWSC3490   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 11        |
| Berkeley 55| Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 12        |
| FSR0636    | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 13        |
| MWSC0277   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 14        |
| King 6     | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 15        |
| FSR0718    | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 16        |
| MWSC0453   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 17        |
| Berkeley 15| Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 18        |
| FSR0794    | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 19        |
| MWSC0594   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 20        |
| NGC 1960   | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 21        |
| M 36       | Known    | PMS   |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 22        |
| FSR0828    | New      | OC    |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 23        |
| MWSC0687   | New      | OC    |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 24        |
| Koposov 43 | New      | OC    |  7.0 | 5.50 | 10.00 | 5.50 | 100.0 | 0.50 | 25        |

Continued on next page
Table A1 – continued from previous page

| ID            | Type      | Class       | l   | b   | Age [log(age/yr)] | d [pc] | \(A_H\) [mag] | Reference          |
|---------------|-----------|-------------|-----|-----|------------------|--------|--------------|--------------------|
| FSR0870       | Known     | PMS         | 186.61 | 0.15 | 7.00             | 1450   | 0.62         | 1                  |
| MWSC0704      | Known     | PMS         | 7.30  | 0.15 | 7.48             | 1600   | 0.40         | 2                  |
| NGC 2129      | Known     | PMS         | 7.00  | 0.15 | 7.00             | 1651   | 0.48         | 3                  |
| FSR0904       | New       | OC          | 191.03 | -0.78 | 7.90             | 2200   | 0.35         | 4                  |
| MWSC0731      | New       | OC          | 7.30  | 0.15 | 7.80             | 1427   | 0.40         | 5                  |
| SA61           | New       | OC          | 7.30  | 0.15 | 8.80             | 2200   | 0.35         | 6                  |
| FSR1189       | Known     | PMS         | 224.67 | 0.40 | 7.95             | 1200   | 0.11         | 7                  |
| MWSC1152      | Known     | PMS         | 8.00  | 0.15 | 8.72             | 1200   | 0.10         | 8                  |
| NGC 2353      | Known     | PMS         | 8.10  | 0.15 | 8.88             | 1200   | 0.08         | 9                  |
| FSR1716       | New       | OC/GIC?     | 329.79 | -0.59 | 10.00-10.10     | 7300   | 0.57         | 10                 |
|               |           | OC          |       |      | 9.10             | 8000   | 0.57         | 11                 |
|               |           | GIC         |       |      | > 9.30           | 5000   | 0.57         | 12                 |
|               |           |             |       |      | 9.30             | 7000   | 0.57         | 13                 |
|               |           |             |       |      | 9.85             | 8000   | 0.57         | 14                 |
|               |           |             |       |      | 10.08            | 2300   | 0.57         | 15                 |
|               |           |             |       |      | 9.23             | 2396   | 0.57         | 16                 |
|               |           |             |       |      |                  |        |              |                    |
| TABLE NOTES   |           |             |       |      |                  |        |              |                    |
|              | 1 This Paper; 2 Buckner & Froebrich (2014); 3 Bonatto & Bica (2007a); 4 Froebrich et al. (2008); 5 Kharchenko et al. (2013); 6 Vansevicius et al. (1996); 7 Delgado et al. (1998); 8 Bhavya et al. (2007); 9 Lynga (1995); 10 Negueruela & Marco (2012); 11 Tadross (2008); 12 Maciejewski & Niedzielski (2007); 13 Ann et al. (2002); 14 Lata et al. (2004); 15 Sujatha et al. (2004); 16 Yapia et al. (2010); 17 Sharma et al. (2006); 18 Samer et al. (2000); 19 Barkhatova et al. (1985); 20 Bell et al. (2013); 21 Kpososov et al. (2008); 22 Carraro et al. (2006); 23 Tripathi et al. (2013); 24 Koposov et al. (2008), paper misidentified cluster as FSR 0848; 25 Camargo et al. (2010); 26 Glushkova et al. (2010); 27 Lim et al. (2011); 28 Fitzgerald et al. (1990); 29 Segura et al. (2014); 30 Froebrich et al. (2010); 31 Bonatto & Bica (2008) |