The Binary Fraction and Mass Segregation in Alpha Persei Open Cluster

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ABSTRACT

We have obtained membership probabilities of stars within a field of radius \( \sim 3^\circ \) around the centre of the open cluster Alpha Persei using proper motions and photometry from the PPMXL and WISE catalogues. We have identified 810 possible stellar members of Alpha Persei. We derived the global and radial present-day mass function (MF) of the cluster and found that they are well matched by two-stage power-law relations with different slopes at different radii. The global MF of Alpha Persei shows a turnover at \( m = 0.62 \, \text{M}_\odot \) with low and high-mass slopes of \( \alpha_{\text{low}} = 0.50 \pm 0.09 \) (\( 0.1 < m/\text{M}_\odot < 0.62 \)) and \( \alpha_{\text{high}} = 2.32 \pm 0.14 \) (\( 0.62 < m/\text{M}_\odot < 4.68 \)) respectively. The high-mass slope of the cluster increases from 2.01 inside 1\(^{\circ}\)10 to 2.63 outside 2\(^{\circ}\), whereas the mean stellar mass decreases from 0.95 to 0.57 \text{M}_\odot in the same regions, signifying clear evidence of mass segregation in the cluster. From an examination of the high-quality colour-magnitude data of the cluster and performing a series of Monte Carlo simulations we obtained a binary fraction of \( f_{\text{bin}} = 34 \pm 12 \) per cent for stars with \( 0.70 < m/\text{M}_\odot < 4.68 \). This is significantly larger than the observed binary fraction, indicating that this open cluster contains a large population of unresolved binaries. Finally, we corrected the mass-function slopes for the effect of unresolved binaries and found low- and high-mass slopes of \( \alpha_{\text{low}} = 0.89 \pm 0.11 \) and \( \alpha_{\text{high}} = 2.37 \pm 0.09 \) and a total cluster mass of \( 352 \, \text{M}_\odot \).

Key words: stars; luminosity function, mass function – binaries: general – open clusters and associations: individual: Alpha Per – infrared: stars

1 INTRODUCTION

The distribution of stellar masses at birth, the initial mass function (IMF), that has been found to be invariant is one of the most important dynamical properties of stellar populations. The IMF is a very important ingredient in the understanding of a large number of basic astronomical phenomena such as the formation and evolution of the first stars and galaxies. Although the determination of stellar IMF is important in many branches of astrophysics there is no direct observational determination of the IMF. What is observed is the individual or integrated light of objects. Transformation of this observable quantity into the MF thus relies on theories of stellar evolution (Chabrier 2003). Therefore, the MF provides an important test of the stellar evolution theories.

In young stellar systems, most of the low-mass stars will still be in their pre-main-sequence evolutionary stage, and the MF has not yet affected by the stellar and dynamical evolution, so one may expect to derive the global stellar IMF from their present-day MF.

Since most Galactic open clusters are disrupted on a time scale of a few hundred Myrs, most present clusters tend to be relatively young. Stars in open clusters lie roughly at the same distance with the same age, chemical abundance and reddening, at least to a first approximation. Therefore these clusters are considered as excellent laboratories for our understanding of the star formation process, stellar evolution and the dynamics of stellar systems. Especially for nearby open clusters, the selection of member stars is easy owing to average large proper motions they have.

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Another important distribution function characterizing the stellar populations is the distribution functions of semi-major axes, mass ratios and eccentricities in binary systems which seems to be quiet invariant to the physical conditions of star formation (Kroupa 2011). Observations and theoretical works indicate that stars in star clusters may be born with initially very large binary fractions and thus the majority of stars are found in binary or multiple systems (Duquennoy & Mayor 1991; Kroupa 1995a,b; Griffin & Suchkov 2003; Hambraeus et al. 2003; Kouwenhoven et al. 2005; Goodwin & Kroupa 2005; Rastegaev 2010). Indeed, many Milky Way open and globular clusters show a binary fraction with a rising binary frequency towards the cluster core, which is interpreted to be the result of mass segregation (e.g. Mathieu & Latham 1986; Geller & Mathieu 2012; Milone et al. 2012). Binary stars, either primordial or dynamically formed during close encounters between single stars, can affect the observational parameters of a star cluster, such as the velocity dispersion and the stellar MF. Therefore, characterization of the binary fraction in star clusters is of fundamental importance for many fields in astrophysics.

For example, the presence of binaries affect the dynamical mass estimation of a star cluster. The dynamical mass of a star cluster can be determined from the virial theorem, using the measured half-mass radius and line-of-sight velocity dispersion of the cluster. This dynamical mass may be a significant overestimation of the cluster mass if the contribution of the binary orbital motion is not taken into account. This is because the stars in binary systems exhibit not only motion in the gravitational potential of the cluster, but also orbital motion in the binary system. Indeed, in a cluster consisting of single stars, the velocity dispersion traces the motion of each particle, i.e. star) in the cluster potential, while in a cluster with binary stars, we do not measure the motion of each particle (i.e., the binary centre-of-mass), but of the individual binary components. These have an additional velocity component due to their orbital motion, which may result in a major dynamical mass overestimation depending on the properties of the binary population of cluster (e.g., Bosch et al. 2001; Fleck et al. 2006; Apai et al. 2007). This effect is more important if the typical orbital velocity of a binary component is of order, or larger than, the velocity dispersion of the particles (single/binary) in the potential of the cluster. The results of simulations, indicate that the dynamical mass is overestimated by a factor of two or more for low-mass star clusters, while the dynamical masses of massive star clusters are only mildly affected by the presence of binaries (Kouwenhoven & de Grijs 2008b,a, 2009).

Furthermore, the stellar MF of a star cluster is also affected by the presence of binaries. If the binarity is not taken into account in the determination of the stellar masses, the combined system will be assigned a mass that is larger than the mass of the two single stars. This causes an unrealistic flattening in the MF slope (Kroupa et al. 1991, 1993). This is because an unresolved binary consisting of two main-sequence stars has a combined colour somewhere in between the colours of the two components, and a magnitude brighter than that of a single-star main sequence at this combined colour (Kroupa & Tout 1992). The magnitude of this effect depends on the fraction of unresolved binaries and the mass distribution of the binary components.

The effect of unresolved binary and multiple systems on the MF slope is more evident in the low-mass range $m \leq 0.5 M_{\odot}$ (Kroupa et al. 1992, 1993; Kroupa 2008), while it is small in the high-mass end even for a binary fraction of 90 percent (Zonooz et al. 2014; Khalaj & Baumgardt 2013). A decrease of $\alpha$ at the low-mass end can be expected since many low-mass stars will be hidden in binaries with more massive companions.

High-quality colour-magnitude data for open clusters can be used to put constraints on the unresolved binary fraction. Since all stars in a cluster have the same metallicity and age, the intrinsic scatter in colour-magnitude data will be small and high-quality photometric data can reveal effects of binaries. A second sequence 0.75 mag brighter than the single-star main sequence is clearly observed in a number of Galactic clusters. Therefore, finding the data points near the second sequence, that are very likely to be unresolved binaries, is a useful tool for the identification of cluster binaries.

Determinations of the MF and binary fraction of star clusters of different ages allow us to verify the predictions from N-body simulations and is therefore very important for our understanding of the early evolution of binaries in star clusters. Recently, Khalaj & Baumgardt (2013) (hereafter KB13) derived the global and radial MF of Praesepe open cluster and found clear evidence for mass segregation as the high-mass slope of the radial MF increases from the inner to outer radii in Praesepe. Moreover, from an inspection of the colour-magnitude diagram (CMD) and performing a series of Monte Carlo simulations they found an overall binary fraction of $f_{\text{bin}} = 35 \pm 5$ percent for this cluster.

The present work is a follow-up paper to KB13, using the same method to investigate the MF, mass segregation and binary fraction of another nearby open cluster Alpha Persei. For this, we combine the astrometric and near and mid-infrared photometric data that have been described in Section 3. We explain the methods for selecting candidate cluster members in Section 4. We derive the MF in Section 5 and examine the effect of mass segregation in the cluster followed by the determination of the binary fraction in Section 6. A conclusion is given in Section 7.

2 PREVIOUS STUDIES

Alpha Persei is a young nearby open cluster ($d = 172.4$ pc; van Leeuwen 2009) with an age of $90 \pm 10$ Myr (Barrado y Navascués et al. 2002) and a tidal radius of 9.7 pc (Makarov 2006). The cluster members have solar metallicity (Netopil & Paunzen 2013) and the interstellar reddening towards this cluster is estimated to be $E(B-V) = 0.09 \pm 0.03$ (Netopil & Paunzen 2013). It has been reasonably well studied, despite its small proper motion and a low galactic latitude ($b = -7^\circ$). The first proper motion survey in the cluster was performed by Heckmann et al. (1956) down to $V \approx 12$ and complemented by $UBV$ photometry from Mitchell (1960). Lower mass members were identified by Stauffer et al. (1985) and Stauffer et al. (1989) on the basis of their proper motions, $UBVRI$ photometry and radial velocities. Prosser (1992) investigated the Palomar photographic plates to extract new low mass members down to $V = 18.8$. Prosser (1994) obtained addi-
tional lower mass candidates from a deeper optical survey that were assessed later using near-infrared photometry and spectroscopy (Basri & Martin 1999). The cluster has been also studied in X-rays with the ROSAT satellite (Randich et al. 1996; Prosser et al. 1996; Prosser & Randich 1998; Prosser et al. 1998).

Barrado y Navascués et al. (2002) identified a list of possible low-mass members down to 0.035 M⊙ (L ∼ 22) for Alpha Persei based on optical and near infrared photometry. They found that the MF can be fitted by a power-law, i.e. \( N(m) \sim m^{-\alpha} \), with an index of \( \alpha = 0.59 \pm 0.05 \). Deacon & Hambly (2004) identified 302 new candidate members down to about \( R = 18 \) using photometry and accurate astrometry from the SuperCOSMOS microdensitometer. Based on the high probability members, a power-law index of 0.86 was derived over the 0.15 – 1.0 M⊙ range. Makarov (2006) selected 139 possible members using the astrometric data and photometry from the Tycho-2 and ground-based catalogues. He found that only ∼ 20 per cent of members with \( K_s < 11 \) are binaries. In the magnitude range of 9.5 < \( V \) < 13.85, a minimum spectroscopic binary fraction of 32 per cent was detected among the sample selected from Heckmann et al. (1956) by Mermilliod et al. (2008). Finally, Lodieu et al. (2012b) selected 728 cluster candidates with membership probabilities higher than 40 per cent down to \( J = 19.1 \) based on the photometry and proper motions from the UKIDSS GCS-DR9. They fitted a log-normal MF (Chabrier 2003) with a goodness-of-fit \( \chi^2 = 2.275 \), characteristic mass of 0.34 M⊙ and a dispersion of 0.46 in the 0.04 – 0.5 M⊙ range.

3 THE SURVEYS

The present study is based on the proper motion and \( JHK_s \) photometric data extracted from the PPMXL catalogue (Roederer et al. 2010) combined with \( W1 \) and \( W2 \) magnitudes of the Wide-field Infrared Survey Explorer (WISE) (Wright et al. 2010).

PPMXL contains mean positions and proper motions on the International Celestial Reference System (ICRS) by combining the USNO-B1.0 catalogue (Monet et al. 2003) and 2MASS all-sky catalogue of point sources (Cutri et al. 2003) astrometry. The USNO-B1.0 is a catalogue that presents positions, proper motions and magnitudes in various optical passbands for 1,045,913,669 objects obtained during the last 50 years. The catalogue is expected to be complete down to \( V = 21 \) (Monet et al. 2003). The Two Micron All-Sky (2MASS) is a near infrared survey that uniformly scans the entire sky in three wavebands at \( J(1.25\mu m) \), \( H(1.65\mu m) \), and \( K_s(2.17\mu m) \). The observations for the survey were taken between 1997 and 2001. 2MASS photometric errors typically attain 0.10 mag at \( J = 16.2 \) and \( H = 15.0 \) (see Soares & Bica 2002). PPMXL contains about 900 million stars and galaxies, some 410 million with 2MASS photometry, from the brightest stars down to about \( V = 20 \). The typical individual mean errors of the proper motions range from 4 mas yr\(^{-1}\) to more than 10 mas yr\(^{-1}\) depending on observational history.

WISE is a NASA mission that has scanned the sky at 3.4\( \mu m \)\((W1)\), 4.6\( \mu m \)\((W2)\), 12\( \mu m \)\((W3)\) and 22\( \mu m \)\((W4)\) mid-infrared passbands in 2010. WISE contains accurate photometry and astrometry for over 300 million objects. The dataset obtained by WISE constitutes an excellent resource for finding new brown dwarfs. The \( W1 \) and \( W2 \) WISE bands have been specifically designed to identify T dwarfs from background sources. USNO-B1.0, 2MASS and WISE are full-sky surveys which have been shown to be an ideal instrument to study star clusters.

4 MEMBERSHIP DETERMINATION

We determine the stellar members of Alpha Persei using the proper motions and photometry from PPMXL catalogue and WISE survey. Alpha Persei has a tidal radius of about 9.7 pc (Makarov 2006) which corresponds to ∼ 3.3 degrees at the distance of Alpha Persei (172.4 pc; van Leeuwen 2009). Therefore, we limit our selection area to a radius of 3’3 around the centre of Alpha Persei. Our detection limit for each filter is \( J = 15.5 \), \( K_s = 15.4 \), \( W1 = 14.5 \) and \( W2 = 14.6 \), where the typical proper motion errors are ∼ 4.5 mas yr\(^{-1}\) and ∼ 8 mas yr\(^{-1}\) for bright and faint stars respectively. A comparison with Lodieu et al. (2012a,b) shows that, at these magnitude limits, PPMXL is about 90 per cent complete. \( J = 15.5 \) corresponds to \( m = 0.1 \) M⊙, which is our lower-mass limit in this study.

4.1 Astrometric selection

The internal velocity dispersions of nearby clusters (less than 200 pc) are much lower than those of field stars. As a result, one can use the velocity dispersion as a reliable tool to efficiently separate the possible stellar members of such clusters from the background stars.

We use a chi-square test, similar to KB13, to astromet-
Figure 2. The CMD of stars that satisfy our astrometric and photometric tests. The red line shows the best-fitting PARSEC isochrone. Photometrically selected stars, which are denoted by the blue dots, are located within a distance of 2.5σ from the isochrone. The black triangles are binaries (see Section 6).

Figure 3. The CMD of low-mass stars of the cluster according to the data of the WISE survey, which is obtained from a cross-matching between PPMXL and WISE data. The blue dots show stars that lie within 2.5σ of the PARSEC isochrone (green solid line). Grey dots correspond to field stars which do not belong to Alpha Persei as they fail our second photometric test. Magenta filled triangles show candidate stars of the cluster as found by Lodieu et al. (2012b). NEXTGen and BT-Settl isochrones are also shown for comparison. One can see that the PARSEC isochrone better describes the actual position of the possible stellar members of the cluster.

The value of 6.17 corresponds to a confidence level of 95.4 percent for a chi-distribution with two degrees of freedom.

In our astrometric test, we ignored stars whose proper motion errors were larger than 10 mas yr$^{-1}$ (360 stars). We found 1934 stars in the field of Alpha Persei that satisfied our chi-square criterion given by equation (1). Hereafter we refer to these stars as proper motion (PM) selected stars for convenience. Figure 1 shows these stars in a vector point diagram. One can see that our first membership criterion imposed by equation (1) has well detached the likely cluster members from the rest of the stars in the same field.

4.2 Photometric selection

In this section we perform a photometric test on our PM selected stars, using the latest version of the synthetic PARSEC isochrones (Bressan et al. 2012; Tang et al. 2014; Chen et al. 2014) and the CMD 2.7 web interface, assuming the following parameters for the cluster: age: 100 Myr (Barrado y Navascués et al. 2002); distance modulus $(m - M)_0$: 6.15 (van Leeuwen 2009); extinction $A(V)$: 0.28 (Netopil & Paunzen 2013); metallicity $Z$: 0.021. These parameters are summarized in Table 1.

| Parameter                  | Value   | Ref.  |
|----------------------------|---------|-------|
| $\mu_{\alpha, c}$         | $22.73 \pm 0.17$ mas yr$^{-1}$ | 1     |
| $\mu_{\delta, c}$         | $-26.51 \pm 0.17$ mas yr$^{-1}$ | 1     |
| 1D velocity dispersion     | $0.7 \pm 0.13$ km s$^{-1}$     | 2     |
| $(m - M)_0$                | 6.15    | 1     |
| $A(V)$                     | 0.28    | 3     |
| $Z$                        | 0.021   | 3     |
| age                        | 100 Myr | 4     |

In the CMD, we designate any PM selected star that resides within a distance of 2.5σ from the isochrone (red line in Fig. 2) as a possible member of Alpha Persei, where σ is the photometric error for each star. In total, there are 1361 PM selected stars that pass our photometric test in Alpha Persei. These stars are denoted by blue dots in Fig. 2. The PARSEC isochrone describes the position of bright main sequence ($J < 12$) stars in the CMD very well.

A possible shortcoming of such a photometric selection could be contamination by non-members in the low-mass range which is a direct consequence of the inherent uncertainties of the theoretical isochrones and the large photometric errors of the stars in this mass-range. To overcome this issue and further improve our selection, we used a second photometric test. For this test, we did a cross-match between the data of the WISE survey and the list of final members in the low mass range ($J > 9.85$). We found that 1195 of our candidate members in the low-mass range had
a counterpart in the WISE survey. In our second photometric test we use W1 and W2 magnitudes of WISE and applied a 2.5σ threshold from the PARSEC isochrone to filter out non-members. For low-mass stars, one can also use other isochrones such as NEXTGen (Hauschildt et al. 1999) or BT-Settl (Allard et al. 2011). However, a comparison of the location of the previously known members from Lodieu et al. (2012b) in a CMD, with the prediction of the theoretical isochrones showed that the PARSEC isochrone matches the actual position of the candidate stars better than NEXTGen or BT-Settl isochrones. Our final list of members contains 810 stars, shown by red dots in Fig. 3. Table 2 shows the list of the possible stellar members.

For comparison, after the astrometric test, we recover ~96 percent of all the stellar members found by Deacon & Hambley (2004) and ~66 percent of those found by Lodieu et al. (2012b), in a 3.3-degree field around Alpha Persei and for $J > 15.5$. After applying the second photometric test, these values slightly decrease to ~85 percent and 63 percent respectively.

4.3 Contamination

Using the membership selection criteria explained in sections 4.1 and 4.2, our final list of members should include most of the true cluster members. However, there might still be a number of field stars which we have erroneously been classified as members and one needs to account for such stars before deriving the underlying MF, total mass and other properties of the cluster. This is especially important for low-mass (faint) stars for which we suspect the contamination by field stars is larger than for bright stars.

To estimate the number of field stars, we use the surface density distribution of Alpha Persei beyond its tidal radius. We first determine the cluster centre. The cluster centre can be defined as the region of the highest surface brightness, or the region containing the largest number of stars. We define the cluster centre as the density-weighted average of stellar positions ($x_i$) given by the following formula from von Hoerner (1963):

$$
\bar{x}_{d,j} = \frac{\sum_{i=1}^{N} x_i \rho_i^{(j)}}{\sum_{i=1}^{N} \rho_i^{(j)}}
$$

where $\rho_i^{(j)}$ is the local density estimator of order $j$ around star $i$. In our case $j$ is equal to 10 and we use the unbiased local density estimator of Casertano & Hut (1985). Using this method, the location of density centre is:

$$
\alpha_c = 3^h 27^m 29^s, \delta_c = +48^\circ 50' 24''
$$

Fig. 4 depicts the surface density of the Alpha Persei in a radius of 9° from the density centre of the cluster. We have used 15 radial bins to derive the surface density profile. Using the surface density of the last bin, which is well beyond the tidal radius of the cluster, we estimate the surface density of field stars. We found a density of 10.02 deg$^{-2}$ for background contamination for stars with $J > 15.5$. The background contamination for bright stars ($J < 11$) is much lower (~0.4 deg$^{-2}$).

Assuming a constant surface density for field stars, one can simply multiply this value by the whole area within the tidal radius of the cluster, to get an estimate of contamination by field stars.

Using this method, we expect that out of 810 candidates found by our astrometric and photometric tests for Alpha Persei, about 469 of them to be contaminants, corresponding to a contamination level of ~58 per cent. For comparison, in Alpha Persei, Lodieu et al. (2005) reported a contamination level of about 70-80 per cent in an infrared-selected sample.
illustrates the stellar MF which is based on a maximum likelihood estimation combined with a Kolmogorov-Smirnov (K-S) test to obtain the goodness of fit and gives results which are more accurate than a least-squares method (Clauset et al. 2007). In addition, this method does not require to bin the data. We use formulae A1 and A3 in the Appendix of KB13 with a K-S test significance level of 5 percent. We only consider the main sequence stars to find the MF. The turnover point in the CMD of Alpha Persei (Fig. 2) corresponds to a stellar mass of 4.68 $M_\odot$.

Using this method we find that the MF of Alpha Persei is well described by a two-stage distribution over the 0.1 – 0.62 $M_\odot$ and 0.62 – 4.68 $M_\odot$ mass range with $\alpha_{\text{low}} = 0.50 \pm 0.09$ and $\alpha_{\text{high}} = 2.32 \pm 0.14$. The high-mass slope of our fit is consistent with a Salpeter MF slope of $\alpha = 2.35$. In the low-mass range, our result is very similar to $\alpha = 0.59 \pm 0.05$ reported by Barrado y Navascués et al. (2002), and is consistent with $\alpha = 0.86^{+0.14}_{-0.15}$ derived by Deacon & Hambly (2004) within 1.5 sigma. A comparison of our MF slopes and the results of Lodieu et al. (2012b) is given in Section 6.2. For comparison with Lodieu et al. (2012b) we first fit a single power-law to the data points given in Fig. 6, since they do not give any MF slope in the paper. We find that the MF derived by Lodieu et al. (2012b) has a MF slope of $\alpha = 0.64 \pm 0.08$ in the mass-range of 0.1 $M_\odot < M < 0.62$, which is in agreement with our $\alpha_{\text{low}}$. The value of $\alpha = 0.64 \pm 0.08$ is not reported in Lodieu et al. (2012b) and is calculated by fitting a single power-law function to the data of Lodieu et al. (2012b).

Dynamical evolution and mass segregation can have a significant effect on the shape of the present day MF of open clusters. Equilibration leads to mass-loss with the preferen-

| RA(J2000) (deg) | Dec.(J2000) (deg) | J (mag) | $K_s$ (mag) | $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $\mu_\delta$ (mas yr$^{-1}$) | Mass found previously |
|-----------------|------------------|--------|-------------|-----------------|-----------------|-------------------|
| 48.863998       | +49.674999       | 14.130 ± 0.029 | 13.204 ± 0.029 | +24.4 ± 4.1 | −29.9 ± 4.1 | 0.243 L         |
| 48.865002       | +48.810001       | 15.424 ± 0.088 | 14.852 ± 0.138 | +28.2 ± 5.6 | −24.9 ± 5.6 | 0.098 -          |
| 48.867001       | +47.568001       | 13.243 ± 0.024 | 12.360 ± 0.023 | +16.8 ± 3.9 | −24.2 ± 3.9 | 0.410 DL        |
| 48.900002       | +48.271999       | 15.467 ± 0.065 | 14.673 ± 0.088 | +16.4 ± 5.5 | −24.9 ± 5.5 | 0.098 -          |
| 54.625999       | +48.320000       | 13.037 ± 0.023 | 12.156 ± 0.022 | +21.4 ± 4.1 | −28.7 ± 4.1 | 0.450 DL        |
| 54.646259       | +48.593483       | 08.104 ± 0.020 | 08.005 ± 0.027 | +20.8 ± 0.9 | −27.0 ± 0.8 | 1.818 -         |
| 54.650002       | +47.094002       | 12.192 ± 0.021 | 11.278 ± 0.018 | +17.8 ± 4.1 | −25.0 ± 4.1 | 0.583 L         |
| 54.705002       | +48.145000       | 12.719 ± 0.023 | 11.790 ± 0.020 | +13.8 ± 4.1 | −30.3 ± 4.1 | 0.507 L         |

Table 2. Celestial coordinates, proper motions, magnitudes and the masses of the possible members of Alpha Persei as found by this study, sorted by right ascension from PPMXL. Stellar masses are derived from the $J$ magnitudes using a PARSEC isochrone. In the last column, ‘D’ and ‘L’ letters correspond to Deacon & Hambly (2004) and Lodieu et al. (2012b) respectively and show whether the members have also been designated by these studies. This table is available in its entirety in the electronic version of the journal.
Effects of mass segregation on the average mass and the MF slopes of Alpha Persei as a function of radius from the cluster centre for two different binning schemes. Mass segregation is evident regardless of the binning scheme.

| $R$ (deg) | $N$ | $m_{\text{total}}$ (M$_{\odot}$) | $m_{\text{avg}}$ (M$_{\odot}$) | $\alpha_{\text{low}}$ | $\alpha_{\text{high}}$ |
|----------|-----|-------------------------------|-----------------------------|---------------------|---------------------|
| I        |     |                               |                             |                     |                     |
| 0.00-0.66| 40  | 40.84                         | 1.02                        | 0.90 ± 0.47         | 2.61 ± 0.37         |
| 0.66-1.32| 105 | 94.14                         | 0.90                        | 0.00 ± 0.22         | 2.02 ± 0.21         |
| 1.32-1.98| 103 | 73.50                         | 0.71                        | 0.31 ± 0.20         | 2.49 ± 0.32         |
| 1.98-2.64| 107 | 73.02                         | 0.68                        | 0.70 ± 0.19         | 2.59 ± 0.27         |
| 2.64-3.30| 114 | 54.52                         | 0.48                        | 0.85 ± 0.17         | 2.52 ± 0.46         |
| II       |     |                               |                             |                     |                     |
| 0.00-1.10| 112 | 106.36                        | 0.95                        | 0.00 ± 0.23         | 2.01 ± 0.21         |
| 1.10-2.20| 172 | 124.07                        | 0.72                        | 0.49 ± 0.15         | 2.59 ± 0.21         |
| 2.20-3.30| 185 | 105.60                        | 0.57                        | 0.81 ± 0.14         | 2.63 ± 0.29         |

In this section, we explain the details of our Monte Carlo simulations to recover the underlying MF and binary fraction of the cluster.

We first make a sample of single star masses using a two-stage power-law MF (equation (3)) and convert these masses into $J$ and $K_s$ magnitudes using the PARSEC isochrones. We then pair the single stars to make binaries assuming a non-random pairing of the binary components. According to the hydrodynamical simulations of star cluster formation by Bate (2009), the multiplicity fraction is approximately proportional to the logarithm of the primary mass. As a result, we assume that the probability that a single star with mass $m_{\text{prim}}$ is the primary component of a binary, scales linearly with the logarithm of its mass, i.e. $\text{Prob} \propto \log_{10}(m_{\text{prim}})$. We also assume a flat distribution function for the mass ratio $q$. We did a Monte Carlo analysis, explained in detail in Section 6.2, to find true binary fractions and the underlying MF of Alpha Persei.
resemble the photometric errors of PPMXL at each magnitude. Using this procedure, we make a synthetic CMD of a cluster with single stars and binary systems. We then apply our photometric membership criterion (Section 4.2) on this synthetic CMD through a blind test and count the number of single stars and binaries. Photometrically, a single star is any point that lies within 2.5σ of the isochrone and a binary is any non-single star whose vertical deviation from the isochrone is less than 0.75 mag. Finally we change the low-mass and the high-mass slopes of the MF (α$_{\text{low}}$, α$_{\text{high}}$) in ranges (0.70, 1.25) and (2.00, 2.60) respectively, until we find the best match with the observed MF (using K-S test) and the observed binary fraction. For each set of the simulation parameters we have simulated 40 clusters with different random seed numbers, to reduce the errors caused by statistical fluctuations.

Fig. 8, shows the synthetic CMD of one of our simulated clusters (left panel) and the detected single stars and binaries after applying the blind photometric test. In this figure, the true binary fraction is 23 percent in the mass range 0.10 $\leq M/\text{M}_{\odot} < 4.68$, but the observed binary fraction is only $\sim$ 6 percent.

Table 4 compares the binary fractions of Alpha Persei from different studies. According to the outcome of our Monte Carlo simulations, the binary fraction of the cluster over the mass-range 0.70 $< m/\text{M}_{\odot} < 4.68$ is 34 ± 12 percent, in agreement with Mermilliod et al. (2008) results. This is comparable with $f_{\text{bin}} = 35$ percent derived for Praesepe using the same method and over the same mass-range. Over the whole mass range (0.10 $< m/\text{M}_{\odot} < 4.68$), the binary fraction is 23 ± 9 percent. In addition, we found that the unresolved binaries have a significant effect on the MF (see Table 5). As one can see, this effect is especially important for the low-mass slope of the MF (α$_{\text{low}}$) which is in agreement with the simulations of KB13 (for Praesepe) and Zonoozi et al. (2014) results (for Palomar 4). We find the total mass of Alpha Persei to be 336 $\text{M}_{\odot}$. After considering the effect of unresolved binaries and correcting the MF for the effect that the binaries have on the inferred stellar masses, the cluster mass will be equal to 352 $\text{M}_{\odot}$.

Figure 8. (Left) Synthetic CMDs of simulated binaries (red filled circles) and single stars (black open squares) for a true binary fraction of 23 percent over the whole mass range (0.1 $< m/\text{M}_{\odot} < 4.68$). The scatter of single stars is due to the added photometric errors which resemble actual photometric errors in PPMXL. (Right) The detected binaries (red filled circles) as well as single stars (blue filled circles) after applying the blind photometric test on the simulated data. As it can be seen, many of the binaries have been identified as single stars. The observed binary fraction is $\sim$ 6 percent. The PARSEC isochrone which is used in the blind photometric test, is shown by the black solid line.

Table 4. The binary fraction of Alpha Persei from other studies

| Reference                  | Binary fraction |
|----------------------------|-----------------|
| Morrell & Abt (1992)       | 14\%            |
| Makarov (2006)             | 20\% (for 28 brightest members) |
| Martín et al. (2003)       | < 9\% (brown dwarf binaries)   |
| Mermilliod et al. (2008)   | 32\% (9.5 $< V < 13.85$) |
| Our work                   | 34 ± 12\% (0.70 $< m/\text{M}_{\odot} < 4.68$) |
|                           | 23 ± 9\% (0.10 $< m/\text{M}_{\odot} < 4.68$) |

Table 5. MF of Alpha Persei before and after considering the contribution of unresolved binaries.

| mass range     | α$_{\text{low}}$, α$_{\text{high}}$ |
|----------------|------------------------------------|
| 0.10 $\leq m/\text{M}_{\odot} < 0.62$ | $+$0.5 ± 0.09, $+$2.32 ± 0.14 |
| 0.62 $\leq m/\text{M}_{\odot} < 4.68$ | $+$0.89 ± 0.11, $+$2.37 ± 0.09 |

Table 7. MF of Alpha Persei before and after considering the contribution of unresolved binaries.

7 SUMMARY

Using the available proper motions from PPMXL catalogue and photometric data from WISE survey, the photometric and proper motion membership for the Alpha Persei is derived from the analysis of the PPMXL ($J, J - K_s$) and WISE ($W_1, W_1 - W_2$) CMDs. After applying astrometric and photometric membership criteria and subtracting the background stars, 810 possible member stars (down to $J = 15.5$) are identified for Alpha Persei within its tidal radius of $3.3\circ$.

We found evidence for a break of the MF at $m = 0.62\text{M}_{\odot}$. In addition, we found that the stellar MF of Alpha Persei is well fitted by a two-stage power law in the mass range 0.1 – 0.62 $\text{M}_{\odot}$ and 0.62 – 4.68 $\text{M}_{\odot}$ with $\alpha_{\text{low}} = 0.50 ± 0.09$ and $\alpha_{\text{high}} = 2.32 ± 0.14$. This is significantly shallower than a Kroupa (2001) IMF in the low mass range with $\alpha_{\text{low}} = 2.35$.

Moreover, deriving the stellar MF in different radial bins, we found evidence for mass segregation in this open cluster. The MF of low-mass stars at different radii is well approximated by a two-stage power-law and rises with radius from a shallow slope of $\alpha_{\text{low}} = 0.00 ± 0.23$ in the region...
$r \leq 1\,\text{Myr}$ to a slope of $\alpha_{\text{low}} = 0.81 \pm 0.14$ for $1\,\text{Myr} \leq r \leq 2\,\text{Myr}$. The high-mass slope of the radial MF also rises from the inner to the outer radii, indicating the mass segregation in Alpha Persei.

Finally, a series of Monte Carlo simulations have been done to find the true binary fraction and the underlying MF of the cluster. The best-fitting model predicted by observed MF shows that the fraction of binaries is $34 \pm 12$ per cent for $0.70 < m/M_\odot < 4.68$ and over the whole mass-range $(0.10 < m/M_\odot < 4.68)$ it is $23 \pm 9$ per cent.

By summing the masses of member stars and after considering the effect of unresolved binaries we estimated the total cluster mass (in the observed stellar mass range inside the projected tidal radius) of $352 \, M_\odot$.

Having the present-day structural properties such as the global and radial MF and binary fraction for Alpha Persei and other well-studied open clusters such as Praesepe (Boudreault et al. 2012; Khalaj & Baumgardt 2013) and Pleiades (Lodieu et al. 2012a; Bouy et al. 2015), what remains to be seen is what this means for how the clusters started. Did all the clusters start from the same condition or were there variations? Did the clusters start mass segregated or are the present-day observations compatible with no primordial mass segregation? Determining the starting conditions (e.g. the initial MF-slopes, binary fractions, and primordial mass segregation at $T = 0$) under which these clusters are formed and evolved by means of the N-body simulation is our upcoming project (Zonoozi et al., in preparation). According to Kroupa (2001), the scatter introduced by Poisson noise and the dynamical evolution of star clusters produces quite well the observed scatter in the determination of the MF power-law index. As a result, the MF of open clusters is Salpeter-like down to $1\,M_\odot$ and has a steeper mass function at the high-mass end. The high-mass slope of Alpha Persei and Praesepe is statistically significant, especially at the high-mass end. Since Praesepe is an older cluster ($T = 590\,\text{Myr}$; Fossati et al. 2008) compared to Alpha Persei ($T = 100\,\text{Myr}$; Barrado y Navascu´es et al. 2002), the observed difference in the measured MF can be attributed to stellar evolution, which makes the cluster devoid of high-mass stars as the cluster ages, hence making the high-mass slope steeper and low-mass slope flatter. A similar effect can be seen when one compares the mass function of Trapezium ($T = 1.0\,\text{Myr}$; Muench et al. 2002) and Pleiades ($T = 120\,\text{Myr}$; Bouy et al. 2015). Pleiades is an older cluster and has a steeper mass function at the high-mass end.

Binaries can also play a role in the depletion of massive stars and making the high-mass slope steeper. Both Alpha Persei and Praesepe, have a binary fraction of $\sim 30 - 35$ per cent ($m > 0.7 \, M_\odot$) which can affect dynamical evolution of the clusters. Moreover, mass segregation is more evident in Praesepe. For Praesepe the high-mass slope changes from $\alpha_{\text{high}} = 2.32 \pm 0.24$ inside the half-mass radius ($\sim 1\,\text{Myr}$) to $\alpha_{\text{high}} = 4.90 \pm 0.51$ outside the half-mass radius (KB13). This change in the high-mass slope of Praesepe is significantly larger than that of Alpha Persei (Table 3). This can be due to dynamical evolution or the way in which star formation has proceeded, i.e. primordial mass segregation. N-body simulations are therefore needed to further elaborate on this.

Acknowledgements

We would like to thank the anonymous referee for his/her useful comments and suggestions which improved the quality of this work.

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MNRAS 000, 1–10 (2016)
