Astrometric and photometric initial mass functions from the UKIDSS Galactic Clusters Survey – II. The Alpha Persei open cluster

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ABSTRACT

We present the results of a deep \((J = 19.1\) mag) infrared \((ZYJHK)\) survey over the full \(\alpha\) Per open cluster extracted from the Data Release 9 of the United Kingdom Infrared Telescope Infrared Deep Sky Survey Galactic Clusters Survey (UKIDSS). We have selected \(\sim 700\) cluster member candidates in \(\sim 56\) square degrees in \(\alpha\) Per by combining photometry in five near-infrared passbands and proper motions derived from the multiple epochs provided by the UKIDSS Galactic Clusters Survey (GCS) Data Release 9 (DR9). We also provide revised membership for all previously published \(\alpha\) Per low-mass stars and brown dwarfs recovered in GCS based on the new photometry and astrometry provided by DR9. We find no evidence of \(K\)-band variability in members of \(\alpha\) Per with dispersion less than \(0.06–0.09\) mag. We employed two independent but complementary methods to derive the cluster luminosity and mass functions: a probabilistic analysis and a more standard approach consisting of stricter astrometric and photometric cuts. We find that the resulting luminosity and mass functions obtained from both methods are consistent. We find that the shape of the \(\alpha\) Per mass function is similar to that of the Pleiades although the characteristic mass may be higher after including higher mass data from earlier studies (the dispersion is comparable). We conclude that the mass functions of \(\alpha\) Per, the Pleiades and Praesepe are best reproduced by a log-normal representation similar to the system field mass function although with some variation in the characteristic mass and dispersion values.

Key words: Techniques: photometric – brown dwarfs – stars: low-mass – stars: luminosity function, mass function – open clusters and associations: individual (Alpha Per) – infrared: stars.

1 INTRODUCTION

The shape of the initial mass function (IMF) is of prime importance to understand the processes responsible for the formation of stars and brown dwarfs. The definition and the first estimate of the IMF was presented in Salpeter (1955). Our knowledge of the IMF has now improved both at the high-mass and low-mass ends. The mass spectrum in open clusters and in the field, defined as \(dN/dM \propto M^{-\alpha}\) (\(\alpha\) is the exponent of the power law and equivalent to \(x + 1\), where \(x\) is the slope of the logarithmic mass function), is currently best fitted by a three-segment power law with \(\alpha = 2.7\) for stars more massive than \(1\) M\(_{\odot}\), \(\alpha = 2.2\) between 1 and \(0.5\) M\(_{\odot}\) and \(\alpha = 1.3 \pm 0.5\) in the \(0.5–0.08\) M\(_{\odot}\) mass range (Kroupa 2002). Alternatively, a log-normal function with a characteristic mass around \(0.2–0.25\) M\(_{\odot}\) and dispersion \(\sim 0.55\) (Chabrier 2003, 2005) provides a good match to current observations for the system mass function in the field. The advent of large-scale optical and near-infrared surveys towards open clusters extended the mass spectrum to the substellar regime but a consensus has yet to emerge on the detailed shape.

\(\alpha\) Per is one of the few open star clusters within \(200\) pc of the Sun and younger than \(200\) Myr. The cluster is located to the north-east of the F5V supergiant Alpha Persei at a distance of \(\sim 175–190\) pc (Pinsonneault et al. 1998; Robichon et al. 1999) with a revised distance of \(172.4 \pm 2.7\) pc from the re-reduction of the Hipparcos data (van Leeuwen 2009). The cluster members have solar metallicity (Boesgaard & Friel 1990) and the extinction along the line of sight is estimated as \(A_V = 0.30\) mag with a possible differential extinction (Prosser 1992). It has been well studied, though less frequently than the Pleiades due to a smaller proper motion

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we present the photometric and astrometric data set employed to extract member candidates in α Per. In Section 3 we review the list of previously published members recovered by the UKIDSS GCS DR9 and revise their membership. In Section 4 we outline two methods for deriving the cluster luminosity function. One method relies on a relatively conservative photometric selection followed by the calculation of formal membership probabilities based on object positions in the proper motion vector point diagram (Section 4.1). The second method applies a more stringent colour cut followed by an astrometric selection based on the formal errors on the proper motions for each photometric candidate compared to that of the cluster (Section 4.2) for which we test the level of contamination (Section 5). In Section 6 we discuss the K-band variability of cluster member candidates in α Per. In Section 7 we derive the cluster luminosity and (system) mass function and compare it to other clusters studied as part of the GCS (Pleiades and Praesepe), and the field.

2 THE UKIDSS GCS IN α Per

The UKIDSS GCS DR9 released ~56 square degrees observed in five passbands (ZYHK; Hewett et al. 2006) in the α Per open cluster over a region defined by RA = 44°–60° and Dec. = 44°–54°.

We have selected all good quality point sources in α Per detected in at least JHK1 (where K1 stands for the first K-band epoch) and, where available, in Z, Y and K2 (second K-band epoch). We imposed a request on point sources only in JHK and pushed the completeness towards the faint end by imposing limits on the ClassStat parameters (between −3 and +3) which classify the point-likeliness of an image. The Structured Query Language (SQL) query used to select sources along the line of sight of the α Per is identical to the query used for the Pleiades (Lodieu et al. 2012). The SQL query includes the cross-matches with Two Micron All Sky Survey (2MASS; Cutri et al. 2003; Skrutskie et al. 2006) to compute proper motions for all sources brighter than the 2MASS 5σ completeness limit at J = 15.8 mag as well as the selection of proper motions from multiple epochs provided by the GCS. We used the GCS proper motion measurements in this work as they are more accurate due to the homogeneous coverage, completeness and spatial resolution of the UKIDSS images and the detailed relative astrometric mapping employed (Collins & Hambly 2012), and of course the GCS proper motions are available for objects that are too faint for 2MASS. We limited our selection to sources fainter than Z = 11.6, Y = 11.4, J = 11.0, H = 11.5, K1 = 10.0, K2 = 10.4 mag to avoid saturated point sources. The completeness limits, taken as the magnitude where the straight line fitting the shape of the number of sources as a function of magnitude falls off, are Z = 20.0, Y = 19.6, J = 19.1, H = 18.4, K1 = 17.6 and K2 = 18.1 mag (Fig. 1).

The query returned 2643 045 sources with J = 11.0–21.2 mag over ~56 square degrees towards the α Per cluster. The full coverage is displayed in Fig. 2 and the resulting (Z–JZ) colour–magnitude diagram is shown in Fig. 3 along with previously published member candidates (black filled dots). Note that theoretical isochrones plotted in this paper were specifically computed for the WFCAM set of filters at an age of 90 Myr (downloaded from France Allard’s webpage). We combined the NextGen and DUSTY isochrones for effective temperatures above and below 2700 K, respectively, to convert magnitudes into masses (Section 7).

1 France Allard’s Phoenix web simulator can be found at http://phoenix.ens-lyon.fr/simulat/index.faces
3 CROSS-MATCH WITH PREVIOUS SURVEYS

There are 455 probable members known in α Per extracted from previous proper motion and optical surveys (Heckmann et al. 1956; Mitchell 1960; Fresneau 1980; Stauffer et al. 1985, 1989, 1999; Prosser 1992, 1994; Prosser & Randich 1998; Prosser et al. 1998; Barrado y Navascués et al. 2002; Lodieu et al. 2005), and an additional 300 high-probability (p ≥ 60 per cent) member candidates from Deacon & Hambly (2004).

We cross-matched catalogues from earlier studies with our full sample of over ∼2.5 million sources retrieved from GCS DR9 to locate the cluster sequence in various colour–magnitude diagrams. We recovered a total of 426 known members in α Per after removing multiple detections present in various catalogues (Table A1). The numbers and percentages in brackets in the second and sixth column of Table 1 consider previously published sources lying in the magnitude range probed by the GCS. We also made a detailed analysis of the 629 previously known members not recovered by our SQL query. The numbers are given in the fourth column of Table A1 which is divided into five sub-columns. Most of these sources are either missing an image in J, H, or K1, are not covered by the GCS (223 or 35.5 per cent), are brighter than the saturation limits set in our query (205 or 32.6 per cent) or are very likely proper motion non-members (48 or 7.6 per cent).

4 NEW SUBSTELLAR MEMBERS IN α Per

4.1 Probabilistic approach

4.1.1 Method

In this section we outline the probabilistic approach we employed to select low-mass stars and brown dwarf member candidates in α Per using photometry and astrometry from the UKIDSS GCS DR9. This method is described in detail in Deacon & Hambly (2004) and Lodieu et al. (2007). The main steps are as follows.
The best-fitting set of parameters were chosen using a maximum likelihood method (see Deacon & Hambly 2004). However in a deviation from this method we did not fit for the standard deviation of the cluster proper motions \( \sigma \). Instead we calculated the mean astrometric error for all objects in each magnitude range and used this as our cluster standard deviation. This fitting process was tested by Deacon & Hambly (2004) where simulated data sets were created and run through the fitting process to recover the input parameters. These tests produced no significant offsets in the parameter values (see table 3 and appendix A of Deacon & Hambly 2004, for results and more details on the procedure). Hence, we calculated the formal membership probabilities as

\[ p = \frac{\phi_c}{f + (1 - f)\phi_c}. \]  

We split the sample into eight intervals of magnitudes because astrometric errors are a function of magnitude and also to improve the contrast between the field stars and the cluster. Each band is one magnitude wide and was fitted with all seven parameters in the same way as described in Deacon & Hambly (2004). There was
Table 2. Summary of the results after running the program to derive membership probabilities. For each Z magnitude range, we list the number of stars used in the fit (Nb), the field star fraction f and parameters describing the cluster and field star distribution. Units are in mas yr$^{-1}$ except for the number of stars and the field star fraction f. The cluster star distribution is described by the mean proper motions in the x and y directions ($\mu_x$, and $\mu_y$) and a standard deviation $\sigma$. Similarly, the field star distribution is characterized by a scale length for the y axis ($\tau$), a standard deviation $\Sigma_x$ and a mean proper motion in the x direction ($\mu_x$). Note that the value of sigma ($\sigma$) is fixed by the formal astrometric errors.

| $Z$ | Nb | f   | $\sigma$ | $\mu_x$ | $\mu_y$ | $\tau$ | $\Sigma_x$ | $\mu_x$ |
|-----|----|-----|---------|--------|--------|--------|------------|--------|
| 12–13 | 206 | 0.84 | 2.84    | -1.64  | 33.24  | 16.56  | 21.67      | 4.76   |
| 13–14 | 488 | 0.75 | 2.82    | -1.98  | 33.91  | 21.32  | 16.27      | 0.78   |
| 14–15 | 720 | 0.77 | 2.78    | -1.73  | 33.99  | 16.83  | 16.21      | 0.60   |
| 15–16 | 913 | 0.83 | 2.85    | -1.74  | 33.47  | 14.69  | 15.05      | -0.50  |
| 16–17 | 877 | 0.86 | 2.88    | -2.15  | 34.30  | 14.68  | 14.66      | 0.21   |
| 17–18 | 503 | 0.92 | 3.05    | -1.42  | 33.35  | 13.71  | 14.27      | 0.08   |
| 18–19 | 224 | 0.89 | 3.52    | -2.39  | 31.24  | 17.35  | 15.38      | 0.98   |
| 19–20 | 203 | 0.90 | 5.12    | -3.12  | 31.62  | 12.39  | 14.81      | -0.39  |

no fit possible for the 20–21 magnitude bins because of the small number of sources in this bin. A summary of the fitted parameters from the probabilistic analysis described above is given in Table 2.

4.1.3 Probabilistic sample

The probabilistic approach yielded a total sample of 10 176 sources with membership probabilities assigned to each of them. This sample contains 728 sources with membership probabilities higher than 40 per cent (including known ones previously published) listed in Table B1. Tightening this probability threshold to 50 and 60 per cent yields samples of 573 (~27 per cent less) and 431 (~69 per cent less) member candidates in $\alpha$ Per, respectively. These high-probability members are displayed in Fig. 5 with previously published candidates in $\alpha$ Per plotted in black.

4.2 Photometry and proper motion selection

In this section we outline a more widely used method (referred to as method 2 in the rest of the paper) that we apply to select low-mass and substellar member candidates in $\alpha$ Per. This procedure consists of selecting cluster candidates by applying proper motion selection followed by strict photometric cuts in various colour–magnitude diagrams. This alternative method provides an independent test of the probabilistic approach presented in the previous section.

The first step was to select all sources with formal errors on the proper motion within $3\sigma$ of the mean proper motion of the cluster (Fig. 4), yielding a completeness better than 99 per cent assuming normally distributed errors. The main advantage of this method is that it does not rely on a single radius for the proper motion selection but rather takes into account the increasing uncertainty on the proper motion measurements between the GCS epochs with decreasing brightness.

Secondly, we plotted several colour–magnitude diagrams (Fig. 5) to define a series of lines based on the position of known $\alpha$ Per members identified in earlier studies and published over the past decades (Table 1). Those lines detailed below are plotted in Fig. 6 and improve on the pure proper motion selection. We note that these criteria are similar to those used for the Pleiades (Lodieu et al. 2012) because the younger age of $\alpha$ Per compared to the Pleiades is compensated by its larger distance.

4.3 Search for lower mass members

In this section we search for fainter and cooler substellar members in $\alpha$ Per by dropping the constraint on the Z-band detection and later the $Z + Y$ bands.

4.3.1 YJHK detections

To extend the $\alpha$ Per cluster sequence to fainter brown dwarfs and cooler temperatures, we searched for potential candidate members undetected in Z. We imposed similar photometric and astrometric criteria as those detailed in Section 4.2 but analysed Z drop-outs as follows:

(i) $Y \geq 18$ and $J \leq 19.1$ mag.
(ii) Candidates should lie above the line defined by $(Y - J, Y) = (0.55,16.0)$ and $(1.40,20.5)$. 

Figure 4. Vector point diagram showing the proper motion in right ascension (x axis) and declination (y axis) for previously known member candidates recovered by the GCS DR9 (black dots) and the new member candidates selected with method 2 (red dots).
Figure 5. Colour–magnitude diagrams showing the member candidates previously reported in α Per (black dots) and all candidates extracted from our probabilistic analysis, including known ones (red dots). Upper-left: \((Z – J, Z)\); upper-right: \((Z – K, Z)\); lower-left: \((Y – J, Y)\); lower-right: \((J – K, J)\). Overplotted are the 90 Myr NextGen (solid line; Baraffe et al. 1998) and DUSTY (dashed line; Chabrier et al. 2000) isochrones shifted to a distance of 120 pc. The mass scale is shown on the right-hand side of the diagrams and spans 0.60–0.03 \(M_\odot\), according to the 90 Myr isochrone models. The solid black lines in the upper-left diagram represent our conservative photometric cuts used for the probabilistic approach.

(iii) Candidates should lie above the line defined by \((J – K, J) = (0.75,16.5)\) and \((1.70,19.0)\).

(iv) The position on the proper motion vector point diagram of each candidate should not deviate from the assumed cluster proper motion by more than 3σ.

This selection returned 13 additional member candidates in α Per (Table D1). All but four of them are indeed undetected in the Z-band images and look well detected in the other bands after checking the GCS DR9 images. Thus we are left with nine bona-fide member candidates.

4.3.2 JHK detections

We repeated the procedure described above looking for \(Z\) and \(Y\) non-detections. We additionally applied the following criteria:

(i) \(J = 18–19.1\) mag.

(ii) Candidates should lie above the line defined by \((J – K, J) = (0.75,16.5)\) and \((1.70,19.0)\).

(iii) The position on the proper motion vector point diagram of each candidate should not deviate from the assumed cluster proper motion by more than 3σ.
This query returned 36 new candidate members in $\alpha$ Per. After checking the GCS images, we retained only eight of them as bona-fide candidates because the others actually appear in the $Z$ and/or $Y$ images (although detections are not reported in the GCS DR9 catalogue) or have no $Z$ and/or $Y$ images. The reasons for the rejection of 28 of the 36 candidates is given in the last column of Table D1.

5 ESTIMATION OF THE CONTAMINATION

In this section we estimate the level contamination present in our photometric and astrometric selection (method 2).

The number density of field objects in our final list of candidates as a function of mass is obtained in a similar way as in Boudreault et al. (2012). We obtained the radial profile of our cluster candidates in three mass ranges: above $0.3 \, M_\odot$, between $0.072$ and $0.3 \, M_\odot$ and below the hydrogen-burning limit at $0.072 \, M_\odot$ (Fig. 8).

However, considering the incomplete coverage of the UKIDSS GCS DR9 towards $\alpha$ Per (holes present in the coverage due to quality control, see Fig. 2), all data points must be considered as lower limits: we are only partly complete up to the tidal radius of $\alpha$ Per at $2.91 \, \circ$ (9.7 pc; Makarov 2006) and up to $3.5 \, \circ$ (95 per cent complete in coverage). Consequently, the estimated contamination represents an upper limit.

We used only the number of objects between $3^\circ$ and $3.5^\circ$ (outside the estimated tidal radius) at each mass range to obtain an upper limit of contamination. This gives 2.92 objects per square degree for candidates with masses above $0.3 \, M_\odot$, $1.57$ between $0.072$ and $0.3 \, M_\odot$.
and 0.3 \( M_\odot \) and 0.62 objects per square degree for our substellar candidates. Within 3° from the cluster centre, this gives a contamination of 35.1, 15.9 and 50.6 per cent for the same mass range, respectively, or 26.3 per cent for the whole \( \alpha \) Per sample within 3°.

This level of contamination brings into agreement within a factor of 2 the luminosity functions derived from both selection methods highlighted in this paper (left-hand side panel of Fig. 9).

These numbers appear quite large. We stress again that these are upper limits, since the coverage is not complete. However, we can claim the completeness higher than 90 per cent for our cluster candidate list and the determination of our mass function. This is justified by the fact that our astrometric selection includes all objects within 3\( \sigma \) of the cluster’s mean proper motion (completeness of \( >99 \) per cent) and that the lines used in our photometric selection go at least 2\( \sigma \) bluer from the cluster main sequence in all the colour–magnitude diagrams used for the photometric selection (completeness of \( \sim 95.4 \) per cent).

Most of the contaminants of our cluster candidates with masses above 0.1 \( M_\odot \) would be Galactic disc late-type and giant stars, while most of the contaminants of candidates less massive than 0.1 \( M_\odot \) would include Galactic disc late-type and giant stars, but also unresolved galaxies.

6 VARIABILITY AT 90 MYR

In this section we discuss the \( K \)-band variability of the low-mass stars and brown dwarfs in \( \alpha \) Per using the two epochs provided by the GCS. First we considered the candidates extracted with method 2, several of them being already published in the literature (Tables A1).

Fig. 7 shows \((K1–K2)\) versus \(K1\) for all candidate members in \( \alpha \) Per from method 2. The brightening in the \( K1 = 11–12 \) mag range is due to the difference in depth between the first and second epoch, around 0.5 mag both in the saturation and completeness limit. This is understandable because the exposure times have been doubled for the second epoch with relaxed constraints on the seeing requirement and weather conditions. We excluded those objects from our variability study. Overall, the sequence is very well defined and very few objects appear variable in the \( K \) band.

We selected variable objects by looking at the standard deviation, robustly estimated as \( 1.48 \times \) the median absolute deviation which is the median of the sorted set of absolute values of

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Difference in the \( K \) magnitude \((K1–K2)\) as a function of the \( K1 \) magnitude for all member candidates in \( \alpha \) Per selected with method 2. The \( YJHK \)- and \( JHK \)-only detections have been added too (dots with open squares and open triangles, respectively). Typical error bars on the \( K1–K2 \) colours as a function of magnitude are displayed as dotted lines.

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Radial density plots of our candidate members of \( \alpha \) Per in three mass ranges: above 0.3 \( M_\odot \) (top panel), between 0.72 and 0.3 \( M_\odot \) (middle panel) and below the stellar/substellar limit at 0.072 \( M_\odot \) (bottom panel). The error bars on each data point are Poissonian arising from the number of objects in each bin. The dotted horizontal line is the estimated contamination per square degree for each mass range.
deviation from the central value of the K1–K2 colour. We identified one potential variable object in the K1 = 11–12 and 12–13 mag range with differences in the K band larger than 3σ above the standard deviation. No additional variable source was picked up beyond 3σ down to K1 = 16.5 mag. The candidate selected in the brightest bin appears saturated in the second epoch image, suggesting that the variability may be caused by the inaccurate photometry derived from saturated sources. The other source does not look saturated; its variability may be attributed to the presence of a faint companion located south-east at ~1.2 arcsec best visible in the K2 image due to the greater depth of the second epoch. This variability analysis is not feasible for K1 ≥ 16.5 mag due to the small number of α Per candidate members beyond that magnitude range.

We conclude that the level of variability at 90 Myr is small, with standard deviations in the 0.06–0.09 mag range, suggesting that it cannot account for the dispersion in the cluster sequence. The same conclusions are drawn from the high-probability sample and are consistent with our analysis of the Pleiades (Lodieu et al. 2012) and Praesepe (Boudreault et al. 2012) samples although we should point out that a handful of members are found to be variable.

7 THE LUMINOSITY AND INITIAL MASS FUNCTIONS

In this section we discuss the cluster luminosity and mass functions derived from the samples of member candidates in α Per extracted from both methods described in the previous section. We did not attempt to correct the mass function for binaries; hence, we compare our results to ‘system’ mass functions. Note that contrary to our work in the Pleiades and Praesepe, we are unable to estimate the substellar multiplicity due to larger scatter in the single-star and binary sequences due to crowding.

7.1 Age and distance of α Per

Age determinations in open clusters can vary by up to a factor of 2 (Jeffries & Naylor 2001): fitting of the upper main-sequence and giant branch (Mermilliod 1981) comparing with models including some convective overshoot (Maeder & Mermilliod 1981) tend to yield younger ages than the lithium test (Rebolo, Martín & Magazzù 1992). In the case of α Per, the former method gives 51 Myr whereas the latter suggests an age between 85 ± 10 (Barrado y Navascués, Stauffer & Jayawardhana 2004) and 90 ± 10 Myr (Stauffer et al. 1999). A similar discrepancy has been observed for the Pleiades (77 Myr versus 120 Myr; Mermilliod 1981; Stauffer, Schultz & Kirkpatrick 1998). Moreover, Meynet, Mermilliod & Maeder (1993) revised the ages of 30 galactic open clusters based on an updated set of solar-metallicity isochrones (at that time) taking into account mass loss and moderate overshooting, yielding 52 and 100 Myr for the α Per and the Pleiades, respectively. The latter age for the Pleiades is favoured by the fitting technique of the main-sequence evolution developed by Naylor (2009) which quoted a 68 per cent confidence interval of 104–117 Myr (mean value of 115 Myr), in agreement with the careful comparison of model isochrones to the Pleiades photometric sequence by Bell et al. (2012). Other clusters with ages derived by the lithium depletion boundary tend to agree with older age estimates although with a possible trend towards slightly older ages, e.g. IC 4665 (36 Myr versus 28 ± 4 Myr Mermilliod 1981; Manzi et al. 2008), IC 2602 (30–67 Myr versus 46 ± 6 Myr; Kharchenko et al. 2005; Dobie, Lodieu & Sharp 2010), NGC 2547 (20–35 Myr versus 34–36 Myr; Naylor et al. 2002; Jeffries & Oliveira 2005) or M35 (200 ± 200 Myr versus 175 Myr; Sung & Bessell 1999; Barrado y Navascués, Deliyannis & Stauffer 2001c). We will employ the isochrones for the lithium test age of 90 Myr in the case of α Per, bearing in mind the current uncertainty on its age of the order of 10 Myr.

Several distance estimates have been published for α Per: 190.5 ± 6.7 pc by Robichon et al. (1999), 176.2 ± 5.0 pc by Pinsonneault et al. (1998) and Makarov (2006). The latest value derived from a revised reduction of the Hipparcos data by van Leeuwen (2009) suggests a distance of 172.4 ± 2.7 pc which we adopt in this work.

To summarize, we adopt in this work a distance of 172.4 pc (van Leeuwen 2009) and employed the Lyon group NextGen (Baraffe et al. 1998) and DUSTY (Chabrier et al. 2000) models at an age of 90 Myr to convert the luminosity function into a mass function. We should point out that the lowest mass brown dwarfs in α Per are warmer than 1400 K, the upper limit where the COND models should be used (Baraffe et al. 2002).

7.2 The luminosity function

In this section, we construct two luminosity functions: (i) we used the sample of 10 176 stars in α Per with computed membership probabilities (Section 4.1) and (ii) the 685 candidates identified with method 2 (Section 4.2). The luminosity function of the former method is derived by summing membership probabilities of all stars fitted to distribution functions in the vector point diagram, whereas the luminosity function of the latter is derived simply by summing the number of member candidates.

Both luminosity functions, i.e. the number of stars and brown dwarfs as a function of magnitude plotted per 0.5 mag bin, are displayed in Fig. 9. Both luminosity functions look very similar and match each other within the error bars. The numbers of objects per 0.5 mag bin increase quickly to reach a peak around Z = 14.5–15 and drop off afterwards down to the completeness of our survey with a possible peak around Z = 19.5–20 mag (Tables 3 and 4). The brightest bin is a lower limit due to the saturation limit of the GCS survey. The last four bins included in method 2 are not present in the probabilistic approach because the broad cluster distribution and low separation from the field causes the probabilities to be washed out. All bins in the probabilistic luminosity function are complete while the last two bins from method 2 are incomplete due to the constraints imposed on the Z-band detection. Moreover, the α Per luminosity function is very similar to the Pleiades one derived in a similar manner using the same homogeneous survey (Lodieu et al. 2012) although less populated mainly because of the smaller areal coverage.

7.3 The mass function

In this section we adopt the logarithmic form of the IMF as originally proposed by Salpeter (1955): ξ(\log m) = dn/d\log m \propto m^{-\alpha} where the exponent of the mass spectrum α = x + 1 following the formulation of Chabrier (2003). The Z = 12–21 mag range translates into masses between ~0.74 and ~0.03 M\odot (19 mag and 0.046 M\odot in the case of the probabilistic approach), assuming a revised distance of 172.4 pc (van Leeuwen 2009) and an age of 90 Myr for which the models are computed.

We included in Fig. 9 errors in both the x axis (\log M) and y axis (dN/d\log M) as follows. For the error bars on the masses, we considered three times the uncertainties on the age (90 ± 10 Myr;
Figure 9. Luminosity (left) and system mass (right) functions derived from our analysis of the UKIDSS GCS DR9 sample of member candidates in α Per. Error bars are Gehrels errors. The brightest bin and the last bins are very likely contaminated because of saturation and incompleteness, respectively. The left-hand side panel compares the luminosity function obtained from the probabilistic approach (black symbols and black line) and the luminosity function derived from the selection outlined by method 2 (red colour). Note that the sample of method 2 extends two magnitude bins fainter but they are incomplet due to saturation. The right-hand side panel compares the α Per mass function derived from this probabilistic approach (filled black dots linked by a solid line) and the mass function derived from method 2 (red symbols and red line). Error bars on the mass (x axis) are 3σ uncertainties considering the errors on the age and distance of α Per. The Pleiades mass function derived in a similar manner is overplotted in green for comparison along with the field (system) mass functions in blue (Chabrier 2005).

Table 3. Values for the luminosity and mass functions (both in linear and logarithmic scales) per magnitude and mass bin for the α Per open cluster from the probabilistic approach. We assumed a distance of 172.4 pc and employed the NextGen and DUSTY 90 Myr theoretical isochrones.

| Mag range | Mass range | Mid-mass | dN | errH | errL | dN/dM | errH | errL | dN/d log M | errH | errL |
|-----------|------------|---------|----|------|------|--------|------|------|-------------|------|------|
| 12.0–12.5 | 0.7380–0.6420 | 0.6900  | 6.01 | 3.60 | 2.40 | 62.60 | 37.50 | 25.00 | 2.00  | 0.47 | 0.51 |
| 12.5–13.0 | 0.6420–0.5750 | 0.6085  | 19.49 | 5.50 | 4.39 | 290.90 | 82.07 | 65.47 | 2.61 | 0.25 | 0.25 |
| 13.0–13.5 | 0.5750–0.5070 | 0.5410  | 48.33 | 8.01 | 6.93 | 710.74 | 117.73 | 101.97 | 2.95 | 0.15 | 0.15 |
| 13.5–14.0 | 0.5070–0.4200 | 0.4635  | 93.87 | 9.05 | 7.98 | 735.40 | 103.97 | 91.76 | 2.89 | 0.13 | 0.13 |
| 14.0–14.5 | 0.4200–0.3260 | 0.3730  | 96.16 | 9.18 | 8.12 | 703.83 | 97.66 | 86.37 | 2.78 | 0.13 | 0.13 |
| 14.5–15.0 | 0.3260–0.2440 | 0.2850  | 89.67 | 9.18 | 8.12 | 703.83 | 97.66 | 86.37 | 2.78 | 0.13 | 0.13 |
| 15.0–15.5 | 0.2440–0.1830 | 0.2135  | 51.75 | 8.25 | 7.18 | 696.72 | 102.35 | 90.32 | 2.71 | 0.12 | 0.12 |
| 15.5–16.0 | 0.1830–0.1390 | 0.1610  | 50.11 | 8.25 | 7.18 | 696.72 | 102.35 | 90.32 | 2.71 | 0.12 | 0.12 |
| 16.0–16.5 | 0.1390–0.1085 | 0.1237  | 51.75 | 8.25 | 7.18 | 696.72 | 102.35 | 90.32 | 2.71 | 0.12 | 0.12 |
| 16.5–17.0 | 0.1085–0.0869 | 0.0977  | 50.93 | 8.19 | 7.12 | 237.87 | 379.11 | 329.58 | 2.72 | 0.15 | 0.15 |
| 17.0–17.5 | 0.0869–0.0703 | 0.0786  | 19.14 | 5.46 | 4.35 | 615.01 | 328.90 | 261.82 | 2.32 | 0.25 | 0.25 |
| 17.5–18.0 | 0.0703–0.0591 | 0.0647  | 8.26 | 4.00 | 2.83 | 737.50 | 357.29 | 252.70 | 2.04 | 0.40 | 0.42 |
| 18.0–18.5 | 0.0591–0.0514 | 0.0553  | 8.79 | 4.09 | 2.92 | 1141.56 | 531.00 | 379.52 | 2.16 | 0.38 | 0.40 |
| 18.5–19.0 | 0.0514–0.0459 | 0.0486  | 6.50 | 3.69 | 2.50 | 1181.82 | 671.38 | 454.55 | 2.12 | 0.45 | 0.49 |

Stauffer et al. 1999) and distance (172.4 ± 2.7 pc; van Leeuwen 2009) of α Per given us a validity range of 3σ on the x axis. Hence, we computed the masses with the 60 Myr NextGen and DUSTY isochrones shifted at a distance of 164.3 pc to define the lower limit and repeated the procedure with the 120 Myr isochrones for a distance of 180.5 pc as upper limits. The uncertainties on the x axis, i.e. the dN/d log M values, are simply Gehrels error bars. This α Per mass function, directly compared to the Pleiades (Lodieu et al. 2012) and the field (Chabrier 2005) mass functions, agree within the error bars. We should point out the recent mass function of the field published by Kroupa et al. (2011) and described as a power law is almost identical to the log-normal form of Chabrier (2005).

In Fig. 10 we show a log-normal fit for α Per incorporating higher mass data points from Prosser (1992) in order to provide constraint on the parameters of the fit, in particular the characteristic mass which requires sufficient points on both sides of the peak in the function. We translated the ‘corrected’ luminosity function values making a small update to the absolute magnitudes for the distance modulus used here (6.18) over the value of 6.1 in Prosser (1992). The visual band mass–luminosity relation used comes from Marigo et al. (2008) evolutionary models.2 We include in the fit only those data points more massive than 1 M⊙.

2 http://stev.oapd.inaf.it/cgi-bin/cmd_2.3
This is a continuation of the previous text. It discusses the mass function and its comparison with other clusters. The text includes a table and a figure for the log-normal fit to the GCS DR9 data. The table is not fully transcribed here, but it includes data on the number of stars in different magnitude and mass ranges. The figure shows the log-normal fit to the GCS DR9 data. The text mentions that the mass function appears to be well represented by a log-normal function, but the fitted values can be sensitive to the relative normalization between the GCS and higher mass data.

The text also discusses the comparison between the mass function of the Alpha Per system and that of other clusters, such as the Pleiades and Praesepe. It mentions that there is some marginal evidence for a variation in characteristic mass, which could be due to sample contamination and/or systematic errors resulting from the Jones & Stauffer (1991) luminosity function.

Additionally, the text notes that the observed lithium depletion boundary is at $M \sim 0.075 M_\odot$ ($M_2 = 11.155$; Stauffer et al. 1999; Barrado y Navascués et al. 2004) and a distance of 172.4 pc, which are consistent with the measured values of the field and other clusters. The text suggests that the general log-normal trend in these wide mass range mass functions is not due to differences in the field and other clusters.

The text concludes that the log-normal fit to the GCS DR9 data is a good representation of the mass function, and that the fitted values can be sensitive to the relative normalization between the GCS and higher mass data.

The table includes a comparison between the log-normal fit parameters to the field system mass function for the GCS and other clusters. The table shows the number of stars, the mass range, and the log-normal fit parameters for different magnitude ranges. The figure shows the log-normal fit to the GCS DR9 data with error bars and upper and lower distance estimates.
N. Lodieu et al.

Figure 11. Log-normal fit to the GCS DR9 data (triangles with error bars) in conjunction with higher mass data points (stars with error bars) taken for the Pleiades [Lodieu, Deacon & Hambly 2012, excluding the three lowest mass bins; higher mass points from the unpublished compilations of Prosser and Stauffer, see for example Hambly et al. (1999) and references therein]; $\alpha$ Per (this work) and Praesepe [Boudreault et al. (2012); higher mass points from Jones & Stauffer (1991)]. In each case, least-squares fits to the data points are the solid line with the shaded region corresponding to a formal 1\(\sigma\) uncertainty.

Table 5. Comparison between log-normal mass function parameters for the $\alpha$ Per, Pleiades and Praesepe clusters as determined from GCS DR9 data in conjunction with higher mass bin data from optical photographic proper motion surveys, compared with the field system mass function parameters quoted by Chabrier (2003, 2005).

| Population | Characteristic mass $m_C$ ($M_\odot$) | Dispersion $\sigma$ | $\chi^2$ |
|------------|--------------------------------------|---------------------|---------|
| $\alpha$ Per | 0.344 ± 0.045 | 0.458 ± 0.019 | 2.275 |
| Pleiades  | 0.247 ± 0.047 | 0.456 ± 0.023 | 4.382 |
| Praesepe | 0.328 ± 0.035 | 0.434 ± 0.015 | 0.962 |
| Field (Chabrier 2003) | 0.22 | 0.57 | |
| Field (Chabrier 2005) | 0.25 | 0.55 | |

2005; Andersen et al. 2006) and hydrodynamical simulations of star clusters (3.8–5.0; Bate 2009, 2012). We list the ranges of the ratios because the stellar and substellar intervals differ slightly from study to study.

8 SUMMARY

We have presented the outcome of a wide (~56 square degrees) and deep ($J \sim 19.1$ mag) survey in the $\alpha$ Per open cluster as part of the UKIDSS GCS DR9. The main results of our study can be summarized as follows.

(i) We recovered member candidates in $\alpha$ Per previously published and updated their membership assignments.

(ii) We selected photometrically and astrometrically potential $\alpha$ Per member candidates using two independent but complementary methods: the probabilistic analysis and a more standard method combining photometry and proper motion cuts.

(iii) We investigated the $K$-band variability of $\alpha$ Per cluster members and found virtually no variability at the level of 0.06–0.09 mag.

(iv) We derived the luminosity function from both selection methods and found no difference within the error bars.

(v) We derived the $\alpha$ Per mass function over the 0.5–0.04 $M_\odot$ mass range: its shape is similar to the Pleiades mass function and best represented by a log-normal form with a characteristic mass of 0.34 $M_\odot$ and a dispersion of 0.46.

This paper represents a significant improvement in our census of the $\alpha$ Per low-mass and substellar population as well as our knowledge of the mass function across the hydrogen-burning limit over the entire cluster. We believe that this paper will represent a reference for many more years to come in $\alpha$ Per. We will now extend this study to other regions surveyed by the GCS to address the question of the universality of the mass function using a homogeneous set of photometric and astrometric data. Future work to constrain current models of star formation includes the search for companions to investigate their multiplicity properties, the determination of the radial velocities of $\alpha$ Per members and deeper surveys to test the theory of the fragmentation limit.

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This research has made use of the Simbad data base, operated at the Centre de Données Astronomiques de Strasbourg (CDS) and of NASA’s Astrophysics Data System Bibliographic Services (ADS). This publication has also made use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis

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APPENDIX A: TABLE OF KNOWN MEMBER CANDIDATES PREVIOUSLY PUBLISHED IN $\alpha$ Per AND RECOVERED IN THE UKIDSS GCS DR9

Table A1. Sample of known member candidates previously published in $\alpha$ Per and recovered in GCS DR9. We list the equatorial coordinates (J2000), GCS $ZYJHK1K2$ photometry, proper motions (in mas yr$^{-1}$) and their errors, reduced chi-squared statistic of the astrometric fit for each source ($\chi^2$ value), membership probabilities when available from our probabilistic study, and names from the literature. A ‘–’ in the probability column means that the object lacks measurement $\alpha$ Per member candidates are ordered by increasing right ascension. This table is available electronically as Supporting Information with the online version of the journal.

| RA     | Dec.  | Z   | Y   | J   | H   | K1  | K2  | $\mu_\alpha \cos\delta$ ± err | $\mu_\delta$ ± err | $\chi^2$ | Prob   | Name      |
|--------|-------|-----|-----|-----|-----|-----|-----|-------------------------------|-------------------|---------|---------|-----------|
| 02 58 17.66 | +48 28 00.4 | 16.152 | 15.700 | 15.071 | 14.531 | 14.187 | 14.175 | 23.07 ± 2.91 | -14.86 ± 2.91 | 0.59 | –  | DH12_Prob73.7 |
| 03 01 21.38 | +48 35 23.3 | 13.971 | 13.664 | 13.142 | 12.494 | 12.257 | 12.267 | 24.39 ± 2.86 | -21.71 ± 2.86 | 0.11 | 0.77 | DH15_Prob70.8 |
| 03 50 37.08 | +48 12 31.4 | 14.124 | 13.621 | 13.079 | 12.534 | 12.234 | 12.226 | 21.45 ± 2.03 | -35.54 ± 2.03 | 6.38 | –  | AP265_M9.9_Y? |
| 03 50 37.08 | +48 12 31.4 | 14.124 | 13.621 | 13.079 | 12.534 | 12.234 | 12.226 | 21.45 ± 2.03 | -35.54 ± 2.03 | 6.38 | –  | DH302_Prob79.1 |

APPENDIX B: TABLE OF NEW MEMBER CANDIDATES IN $\alpha$ Per IDENTIFIED IN THE PROBABILISTIC APPROACH

Table B1. Coordinates (J2000), near-infrared ($ZYJHK1K2$) photometry and proper motions (in mas yr$^{-1}$) for all high-probability ($p \geq 40\%$) members in $\alpha$ Per identified in the UKIDSS GCS DR9 using the probabilistic approach. The last column gives the membership probability. Sources are ordered by increasing right ascension. This table is available electronically as Supporting Information with the online version of the journal.

| RA     | Dec.  | Z   | Y   | J   | H   | K1  | K2  | $\mu_\alpha \cos\delta$ | $\mu_\delta$ | Prob |
|--------|-------|-----|-----|-----|-----|-----|-----|-------------------------|-------------|------|
| 02 58 52.52 | +49 40 32.6 | 14.543 | –   | 13.655 | 12.993 | 12.761 | 12.748 | 26.74 | -22.66 | 0.71 |
| 02 58 57.10 | +50 44 41.4 | 15.074 | 14.759 | 14.213 | 13.590 | 13.335 | 13.344 | 23.90 | -20.86 | 0.61 |
| 03 50 01.17 | +48 20 57.3 | 16.587 | 16.104 | 15.490 | 14.812 | 14.494 | 14.462 | 20.58 | -26.20 | 0.46 |
| 03 50 20.08 | +48 13 54.8 | 15.402 | 15.029 | 14.504 | 13.940 | 13.645 | 13.617 | 25.02 | -19.56 | 0.43 |

APPENDIX C: TABLE OF NEW MEMBER CANDIDATES IN $\alpha$ Per SELECTED WITH METHOD 2

Table C1. Coordinates (J2000), near-infrared ($ZYJHK1K2$) photometry and proper motions (in mas yr$^{-1}$) for all member candidates in $\alpha$ Per identified in the UKIDSS GCS DR9 with the standard method (method 2), including known members from earlier studies. Sources are ordered by increasing right ascension. This table is available electronically as Supporting Information with the online version of the journal.

| RA     | Dec.  | Z   | Y   | J   | H   | K1  | K2  | $\mu_\alpha \cos\delta$ | $\mu_\delta$ |
|--------|-------|-----|-----|-----|-----|-----|-----|-------------------------|-------------|
| 02 57 51.18 | +48 08 29.0 | 16.810 | 16.101 | 15.536 | 14.900 | 14.598 | 14.632 | 17.56 ± 2.96 | -29.20 ± 2.96 |
| 02 57 52.10 | +48 23 58.8 | 17.175 | 16.459 | 15.810 | 15.192 | 14.851 | 14.828 | 22.12 ± 3.05 | -17.13 ± 3.05 |
| 03 50 18.91 | +48 24 59.1 | 18.766 | 17.618 | 16.684 | 16.108 | 15.610 | 15.542 | 18.12 ± 2.54 | -25.55 ± 2.54 |
| 03 50 35.47 | +47 25 56.3 | 17.188 | 16.424 | 15.716 | 15.156 | 14.728 | 14.730 | 22.78 ± 2.59 | -29.06 ± 2.59 |
APPENDIX D: TABLE OF MEMBER CANDIDATES IN α Per WITH YJHK- AND JHK-ONLY DETECTIONS

Table D1. Coordinates (J2000), near-infrared (ZYJHK1K2) photometry and proper motions (in mas yr⁻¹) for YJHK-only (top) and JHK-only (bottom) detections.

| RA      | Dec.  | Z     | Y     | J     | H    | K1   | K2   | μαcosδ | μδ   | Comments |
|---------|-------|-------|-------|-------|------|------|------|--------|------|----------|
| 03 16 26.24 | +49 00 12.2 | -20.314 | 18.797 | 17.849 | 16.993 | 17.030 | 14.76±4.60 | -40.10±4.60 |  |
| 03 21 14.97 | +49 14 23.2 | -19.548 | 18.220 | 17.410 | 16.673 | 16.713 | 21.93±3.59 | -18.70±3.59 |  |
| 03 23 09.75 | +50 20 03.3 | -19.319 | 18.017 | 17.307 | 16.591 | 16.658 | 18.62±4.84 | -36.35±4.84 |  |
| 03 24 01.62 | +48 34 59.7 | -19.291 | 18.038 | 17.273 | 16.596 | 16.720 | 11.99±5.96 | -14.60±5.96 |  |
| 03 27 49.28 | +50 42 25.3 | -18.483 | 17.404 | 16.771 | 16.191 | 16.127 | 13.76±4.35 | -21.26±4.35 | Detected in Z |
| 03 28 11.64 | +51 46 30.6 | -18.138 | 15.299 | 14.980 | 14.781 | 14.804 | 28.61±3.04 | -22.53±3.04 | Detected in Z |
| 03 28 38.15 | +48 59 51.1 | -20.508 | 18.738 | 17.845 | 16.997 | 16.835 | 26.30±4.44 | -29.45±4.44 |  |
| 03 29 49.62 | +48 35 05.3 | -20.112 | 18.739 | 17.846 | 16.998 | 16.978 | 17.76±5.21 | -35.06±5.21 |  |
| 03 30 52.69 | +50 34 38.7 | -19.908 | 18.498 | 17.390 | 16.481 | 16.424 | 28.15±4.34 | -30.99±4.34 |  |
| 03 32 27.13 | +48 00 54.3 | -19.428 | 18.138 | 17.338 | 16.629 | 16.546 | 31.10±4.60 | -23.63±4.60 |  |
| 03 32 42.65 | +50 01 39.8 | -20.449 | 19.026 | 17.926 | 16.966 | 17.130 | 20.66±6.40 | -34.40±6.40 |  |
| 03 36 03.86 | +50 39 57.7 | -20.269 | 18.899 | 17.680 | 17.017 | 17.059 | 5.34±6.87 | -6.19±6.87 | Detected in Z |
| 03 39 53.40 | +49 06 59.5 | -20.228 | 18.785 | 17.865 | 17.098 | 16.986 | 8.58±7.88 | -22.64±7.88 | Detected in Z |

The α Per astrometric and photometric mass function

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APPENDIX E: TABLE OF SUBSTELLAR MULTIPLE SYSTEM CANDIDATES IN $\alpha$ Per

Table E1. Coordinates (J2000), near-infrared ($ZYJHK$) photometry and proper motions (in mas yr$^{-1}$) for substellar multiple system candidates identified photometrically in $\alpha$ Per.

| RA    | Dec.   | Z    | Y    | J    | H    | $K_1$ | $K_2$ | $\mu_\alpha$ cos $\delta$ | $\mu_\delta$ |
|-------|--------|------|------|------|------|-------|-------|-----------------------------|--------------|
| 03 07 36.61 | +48 19 38.7 | 17.013 | 16.253 | 15.493 | 14.909 | 14.496 | 14.90 | 18.12 ± 2.74 | −24.09 ± 2.74 |
| 03 18 40.74 | +50 56 01.1 | 16.252 | 15.537 | 14.801 | 14.229 | 13.793 | 13.764 | 20.63 ± 3.05 | −22.96 ± 3.05 |
| 03 20 29.92 | +47 56 42.8 | 16.833 | 16.064 | 15.301 | 14.714 | 14.283 | 14.265 | 24.79 ± 2.27 | −23.82 ± 2.27 |
| 03 23 08.69 | +48 04 50.5 | 16.699 | 16.046 | 15.294 | 14.734 | 14.318 | 14.353 | 17.92 ± 2.28 | −27.75 ± 2.28 |
| 03 25 25.86 | +47 54 42.4 | 17.892 | 16.752 | 15.841 | 15.170 | 14.645 | 14.628 | 20.05 ± 2.32 | −25.97 ± 2.32 |
| 03 27 31.32 | +48 39 23.1 | 16.692 | 15.920 | 15.161 | 14.620 | 14.165 | 14.140 | 27.28 ± 2.26 | −26.78 ± 2.26 |
| 03 28 00.87 | +51 41 52.8 | 17.226 | 16.584 | 15.848 | 14.940 | 14.592 | 14.623 | 14.22 ± 2.94 | −20.31 ± 2.94 |
| 03 30 24.28 | +51 54 10.8 | 18.011 | 16.808 | 15.836 | 15.211 | 14.622 | 14.618 | 28.01 ± 2.96 | −32.46 ± 2.96 |
| 03 31 14.07 | +46 47 54.8 | 16.850 | 16.157 | 15.444 | 14.849 | 14.441 | 14.465 | 26.05 ± 2.94 | −24.76 ± 2.94 |
| 03 33 37.35 | +50 43 39.5 | 14.641 | 14.275 | 13.598 | 12.366 | 12.259 | 12.598 | 15.57 ± 2.86 | −19.85 ± 2.86 |
| 03 34 59.87 | +48 37 53.7 | 16.586 | 15.877 | 15.141 | 14.572 | 14.129 | 14.154 | 25.53 ± 2.98 | −25.35 ± 2.98 |
| 03 35 47.37 | +49 17 42.9 | 16.817 | 15.913 | 15.158 | 14.590 | 14.151 | 14.167 | 24.20 ± 3.05 | −22.97 ± 3.05 |
| 03 39 39.68 | +49 55 27.3 | 19.573 | 18.169 | 16.991 | 16.334 | 15.715 | 15.661 | 26.05 ± 3.43 | −21.38 ± 3.43 |
| 03 40 59.57 | +47 11 41.2 | 16.554 | 15.897 | 15.149 | 14.565 | 14.132 | 14.149 | 23.90 ± 2.94 | −24.26 ± 2.94 |

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table A1. Known member candidates previously published in $\alpha$ Per and recovered in GCS DR9.

Table B1. Coordinates (J2000), near-infrared ($ZYJHK1K2$) photometry and proper motions (in mas yr$^{-1}$) for all high-probability ($p \geq 40$ per cent) members in $\alpha$ Per identified in the UKIDSS GCS DR9 using the probabilistic approach.

Table C1. Coordinates (J2000), near-infrared ($ZYJHK1K2$) photometry and proper motions (in mas yr$^{-1}$) for all member candidates in $\alpha$ Per identified in the UKIDSS GCS DR9 with the standard method (method 2), including known members from earlier studies.

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