Improved proper motion determinations for 15 open clusters based on the UCAC4 catalog

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Abstract The proper motions of 15 nearby \((d < 1 \text{ kpc})\) open clusters (OCs) were recalculated using data from the UCAC4 catalog. Only evolved or main sequence stars inside a certain radius from the center of the cluster were used. The results significantly differ from the ones presented by Dias et al. (2014). This could be explained by a different approach in which we take the field star contamination into account. The present work aims to emphasize the importance of applying photometric criteria for the calculation of OC proper motions.

Key words: proper motions — Galaxy: open clusters and associations: general

1 INTRODUCTION

Open clusters (OCs) are fundamental building blocks of spiral and irregular galaxies. Studies of Galactic OCs have produced a great number of important scientific results in areas such as stellar evolution and star formation (Castellani et al. 2002; Phelps & Janes 1993). Furthermore, Galactic OCs are crucial for understanding the structure and dynamics of the Milky Way. OCs and OB associations have been used to explore local structures (de Zeeuw et al. 1999; Torra et al. 2000) as well as the large-scale structure of the Galaxy (Bobylev & Bajkova 2014; Zhu 2008). They also help trace the chemical composition throughout the Galactic thin disk (Magrini & Randich 2015).

Proper motion is a key parameter describing OCs. Proper motions, distances and radial velocities are used to derive Galectocentric velocities of OCs. The latter are of fundamental significance in studies of Galactic dynamics, e.g. determination of OC orbits (Wu et al. 2009) and rotation of the Galaxy (Dias & Lépine 2005; Zhu 2007). Another important implication of OC proper motions is the calculation of membership probabilities for individual stars (Sanders 1971; Cabrera-Cano & Alfaro 1985). It has been shown that cluster parameters based on photometric membership probabilities are consistent with those based on proper motion membership probabilities, see e.g. Wu et al. (2007).

The early history of OC proper motion determinations has been outlined by Vasilevskis (1962). Up until the end of the 20\textsuperscript{th} century, proper motions of OCs were mainly derived on a case-by-case basis. The first large catalog was compiled by Glushkova et al. (1997) for 181 clusters with log(age) < 8.3. Large OC proper motion catalogs were later released by Loktin & Beshenov (2003) and Dias et al. (2001, 2002) using Hipparcos and Tycho-2 data respectively. The results, obtained by Loktin & Beshenov (2003), were also based on the Tycho-2 catalog, and are currently the ones cited in the SIMBAD database.

The UCAC4 catalog (Zacharias et al. 2013) contains proper motion data for more than 105 million objects (complete to \(R = 16\) mag). It compiles astrometric data from over 140 catalogs, including Hipparcos and Tycho-2, for the derivation of mean positions and proper motions. The astrometry is complemented by optical and near-infrared (NIR) photometry from APASS and 2MASS. Dias et al. (2014) have used UCAC4 to obtain proper motions for 1805 Galactic OCs. We have recalculated the proper motions of 15 close \((d < 1 \text{ kpc} \text{ from the Sun})\) OCs via a different method and obtained results, which are significantly different from the ones by Dias et al. (2014).
Fig. 1 left: NIR CMDs of all clusters considered in this study. All stars inside the search radii are plotted with red triangles. Filled blue circles represent highly probable cluster members (the N1 subselections), used to calculate the OC proper motions after the deletion of outlying points. Right: All sources plotted in a $\mu_\alpha \cos \delta$ vs. $\mu_\delta$ plane. Cluster members appear grouped together.
Fig. 1 — Continued.
NGC 3532

NGC 6124

NGC 6281

NGC 6405

Fig. 1 — Continued.
2 OBJECT SELECTION AND METHOD

The OCs for this work were selected from the WEBDA list\(^1\) of close OCs \((d < 1 \text{ kpc})\). Clusters closer than 300 pc were not included as there should be systematic differences between the proper motions of their members, depending on location. We chose only prominent OCs, whose color-magnitude diagrams (CMDs) exhibit typical features for OCs (main sequence (MS), turnoff point). The selected clusters are presented in Table 1.

Stars in the vicinity of each cluster were extracted by searching the UCAC4 catalog inside a given radius from the cluster center. We used the same coordinates and radii for the search as Dias et al. (2014). A 2MASS \((J - K)\) vs. \(K\) diagram was built for each cluster. Out of all the \(N_0\) stars, \(N_1\) cases were selected as very probable cluster members based on their location on the CMD. Only stars lying on the MS or evolved ones, i.e. to the right of the MS and forming a feature along an isochrone, were included in the \(N_1\) subselections (Fig. 1). Data selection was

\(^1\) See http://www.univie.ac.at/webda/dist_list.html
carried out using Virtual Observatory tools (Aladin\textsuperscript{2} and TOPCAT\textsuperscript{3}).

Outlying points in the $N_1$ subselections were removed using median absolute deviation (MAD), defined as:

$$\text{MAD}(x) = \text{median}_i (|x_i - \text{median}_j(x_j)|)$$

$$\text{MAD}(\mu) = \sqrt{(\text{MAD}(\mu_\alpha \cos \delta))^2 + (\text{MAD}(\mu_\delta))^2}$$

The value of $\text{MAD}(\mu)$ was calculated for each cluster. Sources with proper motion differing by more than 4MAD$\mu$ from the median proper motion were considered outliers and excluded from the sample, thus producing even narrower subselections consisting of $N_2$ stars. The proper motions of the clusters were finally calculated by averaging the data in the $N_2$ subselections.

3 RESULTS

Our results are presented in Table 2. The standard deviations of the proper motions in the $N_2$ subselections are in the range of 0.8 mas yr$^{-1}$–4 mas yr$^{-1}$, which is comparable to the errors given by Dias et al. (2014). However, the results significantly differ from theirs ($|\Delta \mu|$ > 2 mas yr$^{-1}$ for 9 of the 15 clusters). Very large deviations are observed for NGC 7092, NGC 3532 and NGC 2422. Higher deviations from Dias et al. (2014) are generally observed at higher absolute proper motion values (Fig. 2).

We suggest that Dias et al. (2014) may have used a large number of background stars, which could have con-

### Table 1 Open Clusters Studied in the Current Work

| Cluster | Alt. name | $\alpha$ (J2000) | $\delta$ (J2000) | $l$ | $b$ | Dist. [pc] | $(m - M)$ | $E(B - V)$ | log (age) |
|---------|-----------|----------------|----------------|-----|-----|-----------|----------|-----------|----------|
| NGC 1039 | M34 | 02:42:05 | +42:45:42 | 143.658 | −15.613 | 499 | 8.71 | 0.07 | 8.25 |
| NGC 1647 | – | 04:45:55 | +19:06:54 | 180.337 | −16.772 | 540 | 9.81 | 0.37 | 8.16 |
| NGC 1662 | – | 04:48:27 | +10:56:12 | 187.695 | −21.114 | 437 | 9.14 | 0.30 | 8.63 |
| NGC 2281 | – | 06:48:17 | +41:04:42 | 174.901 | 16.881 | 558 | 8.93 | 0.06 | 8.55 |
| NGC 2358 | – | 07:16:55 | −17:08:59 | 231.05 | −2.30 | 630 | 9.06 | 0.02 | 8.72 |
| NGC 2422 | M47 | 07:36:35 | −14:29:00 | 230.958 | 3.130 | 490 | 8.67 | 0.07 | 7.86 |
| NGC 2516 | – | 07:58:04 | −60:45:12 | 273.816 | −15.856 | 409 | 8.37 | 0.10 | 8.05 |
| NGC 2547 | – | 08:10:09 | −49:12:54 | 264.465 | −8.597 | 455 | 8.42 | 0.04 | 7.56 |
| NGC 3532 | – | 11:05:39 | −58:45:12 | 289.571 | 1.347 | 486 | 8.55 | 0.04 | 8.49 |
| NGC 6124 | – | 16:25:20 | −40:39:12 | 340.741 | 6.016 | 512 | 10.87 | 0.75 | 8.15 |
| NGC 6281 | – | 17:04:41 | −37:59:06 | 347.731 | 1.972 | 479 | 8.86 | 0.15 | 8.50 |
| NGC 6405 | M6 | 17:40:20 | −32:15:12 | 356.580 | −0.777 | 487 | 8.88 | 0.14 | 7.97 |
| NGC 6494 | M23 | 17:57:04 | −18:59:06 | 9.894 | 2.834 | 628 | 10.09 | 0.36 | 8.48 |
| NGC 7092 | M39 | 21:31:48 | +48:26:00 | 92.403 | −2.242 | 326 | 7.61 | 0.01 | 8.45 |
| IC 4725 | M25 | 18:31:47 | −19:07:00 | 13.702 | −4.434 | 620 | 10.44 | 0.48 | 7.97 |

Notes: The basic parameters are retrieved from the WEBDA database.

### Table 2 Proper Motions Calculated for 15 OCs

| Cluster | $r_v$ | $N_0$ | $N_1$ | MAD($\mu$) | $N_2$ | $\mu_\alpha \cos \delta$ | $\sigma_\alpha$ | $\mu_\delta$ | $\sigma_\delta$ | $N_{D2}$ |
|---------|------|------|------|-----------|------|----------------|--------|----------|----------|--------|
| NGC 1039 | 18.5 | 1022 | 86 | 0.92 | 72 | −0.56 | 1.03 | −6.26 | 0.82 | 783 |
| NGC 1647 | 21.0 | 848 | 87 | 1.14 | 78 | −1.13 | 1.35 | −1.27 | 1.24 | 656 |
| NGC 1662 | 11.0 | 173 | 21 | 0.99 | 19 | −1.10 | 1.42 | −0.66 | 1.21 | 151 |
| NGC 2281 | 13.5 | 439 | 46 | 0.92 | 43 | −3.92 | 0.91 | −8.21 | 0.92 | 330 |
| NGC 2358 | 11.0 | 750 | 55 | 2.83 | 49 | −1.85 | 2.56 | 0.49 | 3.10 | 618 |
| NGC 2422 | 13.5 | 1487 | 78 | 1.64 | 73 | −7.29 | 1.87 | 1.38 | 1.79 | 1293 |
| NGC 2516 | 16.0 | 941 | 134 | 2.84 | 117 | −5.48 | 3.13 | 11.14 | 3.36 | 737 |
| NGC 2547 | 13.5 | 960 | 51 | 2.55 | 48 | −4.88 | 2.80 | 3.71 | 2.96 | 644 |
| NGC 3532 | 26.0 | 11974 | 409 | 3.40 | 386 | −8.90 | 3.91 | 2.97 | 3.80 | 8705 |
| NGC 6124 | 20.5 | 1838 | 263 | 2.72 | 243 | −0.18 | 2.49 | 1.19 | 3.16 | 1633 |
| NGC 6281 | 5.0 | 280 | 33 | 2.83 | 30 | −1.92 | 2.40 | −2.51 | 3.40 | 207 |
| NGC 6405 | 11.0 | 930 | 67 | 2.05 | 61 | −1.11 | 2.33 | −3.87 | 2.12 | 737 |
| NGC 6494 | 15.5 | 1640 | 185 | 2.36 | 162 | 0.49 | 2.80 | −0.27 | 2.37 | 1342 |
| NGC 7092 | 15.5 | 2019 | 34 | 2.77 | 25 | −8.20 | 1.18 | −18.14 | 3.97 | 1464 |
| IC 4725 | 15.5 | 5812 | 124 | 2.84 | 111 | −3.46 | 2.55 | −6.01 | 3.76 | 4458 |

Notes: The last column contains the number of stars used by Dias et al. (2014).

\textsuperscript{2} See http://aladin.u-strasbg.fr/

\textsuperscript{3} See http://www.star.bris.ac.uk/mbt/topcat/
taminated their selections. We attempted to estimate the percentage of those background stars. For each cluster we examined four nearby fields, centered 40′ away (60′ away in the case of the larger NGC 3532), and with radius $r_s$, equal to the search radius for the cluster (Table 2). The median number $N_F$ of UCAC4 sources in these four fields was then calculated. The portion of field stars should be roughly $f = N_F / N_0$. For all clusters $f > 67\%$. The portion of field stars among those used by Dias et al. (2014) would be approximately $f_D = 1 - (1 - f)N_0 / N_D$. The minimum and median values of $f_D$ are 57% and 75% respectively. Although this is just a rough estimate, it shows that a considerable portion of stars used by Dias et al. (2014) are not physical members of the respective clusters.

Loktin & Beshenov (2003) have also applied photometric criteria for their selections. Our agreement with the latter is slightly better in general (median $|\Delta \mu|$ of 1.6 mas yr$^{-1}$) and much better in the case of NGC 7092 ($|\Delta \mu| = 1.52$ mas yr$^{-1}$ and 17.08 mas yr$^{-1}$ when comparing the data in Table 2 to Loktin & Beshenov (2003) and Dias et al. (2014) respectively). The proper motion diagram for NGC 7092 (Fig. 1) contains a considerable number of outlying points. The reason is that NGC 7092 is a very close cluster, located near the Galactic plane (Table 1). Most of the outliers are not in the $N_2$ subselection and do not affect the result as they lie farther than 4MAD ($\mu$) from the median value.

4 SUMMARY

Proper motions are important parameters of OCs, which help us improve our understanding of Galactic dynamics. We built NIR CMDs of 15 OCs and we used them to select stars that are very probable members. After excluding the ones with an uncommon proper motion, we used those subselections to calculate the proper motions of the clusters. Our results suggest that Dias et al. (2014) may have used selections which were contaminated by background stars. Our work shows the advantage of utilizing CMDs for the calculation of OC proper motions.

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