A search for open cluster Cepheids in the Galactic plane

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\begin{abstract}
We analyse all potential combinations of Galactic Cepheids and open clusters (OCs) in the most up-to-date catalogues available. Isochrone fitting and proper-motion calculation are applied to all potential OC–Cepheid combinations. Five selection criteria are used to select possible OC Cepheids: (i) the Cepheid of interest must be located within 60 arcmin of the OC’s centre; (ii) the Cepheid’s proper motion is located within the 1\(\sigma\) distribution of that of its host OC; (iii) the Cepheid is located in the instability strip of its postulated host OC; (iv) the Cepheid and OC distance moduli should differ by less than 1 mag; and (v) the Cepheid and OC ages (and, where available, their metallicities) should be comparable: \(\Delta \log(t) < 0.3\). Nineteen possible OC Cepheids are found based on our near-infrared (NIR) analysis; eight additional OC–Cepheid associations may be genuine pairs for which we lack NIR data. Six of the Cepheids analysed at NIR wavelengths are new, high-probability OC Cepheids, since they lie on the near-infrared (NIR) period (\(P\))–luminosity relation (PLR). These objects include TY Sct and CN Sct in Dolidze 34, XX Sgr in Dolidze 52, CK Sct in NGC 6683, VY Car in ASCC 61 and U Car in Feinstein 1. Two additional new OC Cepheids lack NIR data: V0520 Cyg in NGC 6991 and CS Mon in Juchert 18. The NIR PLR for our confirmed sample of OC Cepheids is \(M_J = (-3.12 \pm 0.29) \log(P_{\text{day}} - 1) - (2.17 \pm 0.29)\) mag, which is in good agreement with the best NIR PLR available for all Galactic Cepheids.

Key words: methods: data analysis, stars: variables: Cepheids, open clusters and associations: general, distance scale
\end{abstract}

1 INTRODUCTION

Cepheids are the brightest pulsating variable stars. They obey tight period–luminosity relations (PLRs). The existence of such a PLR was first found approximately a century ago based on photographic observations of 25 Cepheids in the Small Magellanic Cloud (Leavitt et al. 1912). For nearly one hundred years, many researchers have been trying to establish and improve the relationship, mostly using one of three common methods: (i) trigonometric parallaxes (Feast and Catchpole 1997; Benedict et al. 2007), (ii) Baade–Wesselink-type methods or, equivalently, surface-brightness techniques (Gieren et al. 1997; Storm et al. 2011) and (iii) main-sequence or isochrone fitting. The latter method, when applied to single-population star clusters, can be used as an independent constraint on the distances, ages and reddening values of Cepheids in clusters, which thus enables its use as external calibrator of the PLR. The key to the application of this method resides in selecting high-confidence member stars of the relevant open clusters (OCs).

Since Irwin (1955) first matched the OC Cepheids S Nor and U Sgr with NGC 6087 and M25, respectively, and following Feast (1957), who first established stellar cluster membership based on radial-velocity measurements, many researchers have contributed to this field (e.g., van den Bergh 1957; Efremov 1964; Tsarevsky et al. 1966; Turner 1986, 2010; Turner et al. 1993; Baumgardt et al. 2006; Hovle et al. 2003; An et al. 2007; Majaess et al. 2008). To date, approximately 30 OC Cepheids have been found and confirmed. This number is increasing as the available OC samples are increasing. A good summary of the way in which calibration of the Cepheid PLR is performed using the OC and Baade–Wesselink methods was published by Tammann et al. (2003); current efforts focus on high-precision membership research pertaining to OCs based on, e.g., data obtained as part of the VISTA Variables in the Vía Láctea (VVV) survey (Majaess et al. 2011, 2012). An eight-dimensional search for bona fide Cepheids was undertaken by Anderson et al. (2013), based on a careful perusal of the existing literature. They found five new OC Cepheids.

In this paper, our aim is to improve the completeness
of the existing body of OC Cepheids. We calculate proper motions using original data rather than literature values for each cluster of interest, with as main aim to find more OC–Cepheid associations with similar proper motions. OC properties are also estimated independently based on colour–magnitude-diagram (CMD) analysis and isochrone fitting so as to improve the quality of the ages, reddening values and distances contained in existing OC catalogues. In contrast to most previous Cepheid PLR studies, we use near-infrared (NIR) observations to reduce the impact of extinction, resulting in the determination of a reliable J-band PLR.

In Section 2, we discuss our analysis of the OC and Cepheid catalogues used in this study, as well as the five selection criteria applied to find our OC Cepheids. The isochrone-fitting results, as well as crucial reddening checks and our preliminary sample of possible OC Cepheids, are covered in Section 3. We report and discuss the confirmed, new, rejected and uncertain OC Cepheids, as well as the issues affecting the completeness of our method, in Section 4. In Section 5 we summarize our main conclusions.

2 METHOD

In this section we describe the data and method used to select possible OC Cepheids. In general, we select OC Cepheid candidates by comparing the Cepheids’ positions with respect to the nearest OC centres and assess the similarity of their proper motions, combined with the Cepheids’ loci in the cluster CMDs. Five criteria are used: (i) a Cepheid must be located within 60 arcmin of an OC’s centre; (ii) the Cepheid’s proper motion must be consistent with the 1σ proper-motion distribution of its host OC; (iii) the Cepheid lies in the instability strip of its associated OC; (iv) the difference between the Cepheid and OC distance moduli (DMs) \( \Delta(m - M)_0 < 1.0 \) mag; and (v) the difference between the Cepheid and OC ages, \( \Delta \log(t \text{ yr}^{-1}) < 0.3 \). In Sections 2.3 to 2.10, we outline the details of our method.

2.1 The open cluster catalogue

This study is partially based on the DAML02; version September 2013) OC catalogue. DAML02 contains approximately 2100 clusters, for which it includes entries related to the cluster centre coordinates, size, proper motion and metallicity, if measured. For each cluster, we compared the centre position with those of the nearby Cepheids and obtained a sample of probable OC members. For most OCs, we used the DAML02 OC centre and size to select our initial samples of member stars. For some clusters characterized by small apparent diameters (< 6 arcmin), we used the positions of the bright Cepheids, combined with the cluster size, to select stars, provided that the bright Cepheids are located close to the cluster centres (< 0.5 arcmin). These small clusters are not very obvious compared with the field stars, so that our use of the Cepheid coordinates as a proxy for the cluster centres allows us to more robustly select possible OC members. We also used the WEBDA1 database as reference. It provides a large amount of information for OCs, including their ages, distances, reddening values and CMDs in different passbands.

Thus, we obtained the positions of our sample OCs from DAML02. Photometric data pertaining to these OCs were obtained from the homogeneous Two Micron All-Sky Survey (2MASS) and the UKIRT Infrared Deep Sky Survey (UKIDSS). NIR data are more suitable to study OCs in the disc of our Milky Way galaxy than optical data, because NIR observations can be used to limit the effects of differential reddening. The limiting J-band magnitude of the 2MASS Point Source Catalog (Cutri et al. 2003) is \( J \approx 15.5 \) mag, which is not sufficiently faint for some clusters. Therefore, for faint clusters, where available we added UKIDSS data to the 2MASS data at the faint end. UKIDSS performed a northern sky survey of 7500 deg², reaching up to 3 mag fainter than 2MASS. Specifically, the catalogue we used is the UKIDSS Data Release 6 Galactic Plane Survey (Lucas et al. 2003).

2.2 The Cepheid catalogue

The Cepheid catalogue contains the All Sky Automated Survey (ASAS) Catalogue of Variable Stars, the General Catalogue of Variable Stars (GCVS) and the catalogue published by Tammann et al. (2003). The latter includes 324 Cepheids; it was derived from Berdnikov et al. (2000) and a systematic trend in colour excesses was removed by Tammann et al. (2003). The Berdnikov et al. (2000) catalogue is a homogeneous database containing BVI photometry in the Cape (Cousins) photometric system for hundreds of Galactic Cepheids; the colour excesses, \( E(B-V) \), are from Fernie (1994) and Fernie et al. (1993). The Tammann et al. (2003) catalogue contains good reddening values and distances, so this catalogue has been used to check the confidence of our reddening values, which we derived independently from isochrone fitting (see Sect. 3.2). The ASAS Catalogue of Variable Stars contains more than one thousand Cepheids, some of which are newly found or poorly studied. Although only V-band data are available for most Cepheids in this catalogue, its period information is good and it contains complete light-curve data, which is sufficient to find new OC Cepheids. The GCVS contains approximately 600 Cepheids.

From these databases we obtained positions for a list of Cepheids to match to nearby OCs. Cepheid distances can be estimated using the Cepheid PLR from Sandage et al. (2006) if the reddening, apparent magnitude and period (\( P \)) are known, giving absolute magnitudes, \( M_V = (3.087 \pm 0.085) \log(P \text{ day}^{-1}) + (0.914 \pm 0.098) \) mag. We compared the Cepheid and OC distances to constrain our sample of possible OC Cepheids. To limit the effects of reddening, we used JHK-band data to obtain the mean magnitudes for a subset of the Cepheids. JHK-band mean magnitudes in the South African Astronomical Observatory (SAAO) system are available for 229 Cepheids (van Leeuwen et al. 2007). We transformed their photometry to that of the 2MASS JHK system using the recommended transformation equations. The differences between the OC NIR colour excesses and the Cepheids’ optical colour excesses are

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1 http://www.univie.ac.at/webda/

2 http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4b.html
small and the prevailing extinction law \( E(J-H) = 0.325(E(B-V)) \). These OC NIR colour excesses can be adopted to help estimate the Cepheid distances.

### 2.3 Position selection

A position cross-match was done between the OC centres and Cepheid positions. Approximately 2100 OCs and more than 1000 Cepheids were used. We adopted a maximum (projected) separation of 60 arcmin to select OC–Cepheid combinations. This resulted in 600 possible associations. The probability of finding genuine OC Cepheids at distances in excess of one degree from a given cluster centre is very small or even negligible. We first concentrated on the roughly one hundred Cepheids which are located within 20 arcmin from the nearest cluster centres and performed proper-motion and distance selection for each object individually. For the Cepheids which were located at 20–60 arcmin from their associated cluster centres, we first compared the magnitude of the cluster stars and the Cepheids in the context of the cluster CMDs. We excluded those Cepheids which were fainter than the equivalent cluster stars. Faint Cepheids are unlikely OC Cepheid candidates, because in a given stellar population Cepheids are brighter than the associated main-sequence stars.

### 2.4 Distance selection

Combined with position selection, distance selection is a very effective approach to select OC Cepheids. If the distance and position of a star are known, its 3D position can be determined. To perform distance selection, we need to calculate the distances to our sample Cepheids and OCs independently. For the Cepheids, we used the best observational PLR to calculate their absolute \( V \)-band magnitudes \( (Sandage et al. 2004) \). The \( V \)-band mean apparent magnitude is available for all of our Cepheids, so if we know the reddening, we can derive the DM for the Cepheid of interest. \( Fernie (1994) \) provided \( E(B-V) \) for some Cepheids. For the others, we used the \( E(J-H) \) colour excess based on our isochrone fits and converted it to \( E(B-V) \). Although this step may introduce a significant uncertainty (because the visible reddening affecting the Cepheids and OCs may not be the same), this will not prevent us from performing a robust distance selection and thus finding possible OC Cepheids. This is so, because across the small OC fields, the differential change in the associated colour excess is much smaller than our distance selection criterion (see below). OC DMs were obtained from isochrone fitting, independent of the distances to the Cepheids. The typical apparent diameter of many OCs is of order 10 arcmin. However, some very bright OC Cepheids can be located at 30 arcmin or more from the cluster centres.

We thus obtained a list of probable OC Cepheids, ordered by their projected separation to the corresponding cluster centres. For separations greater than 20 arcmin, Cepheids that were too faint were removed (see Section 2.3). If they are fainter than the cluster’s main-sequence stars, these objects must be background Cepheids. Inspection of finding charts (using the \textsc{Aladin} viewing tool) and 2MASS magnitudes were also used to exclude these bright OC/faint Cepheid associations.

Because of the relatively bright limiting magnitude and the limited photometric precision of 2MASS, the CMDs of some 100 OCs do not exhibit tight main sequences, which is particularly an issue for clusters with small numbers of members. We excluded these clusters from our analysis, since the error in the DM \( > 1 \) mag, we imposed \( |DM_{clus} - DM_{Cep}| \leq 1.0 \) mag to compare the DMs of our OC–Cepheid combinations and select possible OC Cepheids. The distances to Galactic OCs are mostly 500–3000 pc, or \( \langle m - M \rangle_0 \approx 8.5-12.5 \) mag, so that if the difference in DMs between a cluster and an apparently associated Cepheid is greater than 1.0 mag, the probability that these objects are physically associated with one another is very small indeed. Upon completion of this step, our sample contained 45 possible OC–Cepheid associations.

To confirm the reliability of our distance estimates based on isochrone fitting, in Table 1 and Fig. 1, we compare our newly derived distances with those of \( \text{An et al. (2007)} \), \( \text{Anderson et al. (2013)} \), \( \text{Tammann et al. (2003)} \) and \( \text{Dias et al. (2014)} \). \( \text{An et al. (2007)} \) used a multi-passband \( BVI_{c}JHK_s \) combination to derive their distance estimates. For six of their OCs in common with our sample, our distance estimates fall at (for NGC 6087) or within the mutual 1\( \sigma \) uncertainties \( \text{Anderson et al. (2013)} \) provide an up-to-date summary of literature-based distance estimates. A comparison of our distances with their best estimates, which are based on careful analysis of the uncertainties affecting the various literature values, shows excellent mutual consistency for each OC in common. Similarly, a comparison of our results with the homogeneous data set of \( \text{Tammann et al. (2003)} \) (cf. Section 2.2) shows a negligible mean difference of \(-0.07 \pm 0.17 \) mag (in the sense of the Tammann catalogue data minus our values), where the uncertainty represents the standard deviation of the data points. Finally, the \( \text{Dias et al. (2014)} \) catalogue includes distances to 94.0% of Galactic OCs. Although this data set therefore serves as a useful comparison benchmark, these latter authors do not provide uncertainties and some of their isochrone fits appear relatively poor. Figure 1 suggests a small but systematic offset of 0.35\( \pm 0.34 \) mag between the Dias et al. (2014) distances and our results and, by extension, with respect to the other comparison samples. The latter are all consistent with our results within the 1\( \sigma \) uncertainties (with the exception of ASCC 61).

### 2.5 Proper-motion selection

Proper-motion selection is a powerful tool to separate OC members from foreground or background stars. We compared the average cluster proper motions with those pertaining to the apparently associated Cepheids to further constrain our OC Cepheid sample. The proper-motion data we used were obtained from the \textsc{PPMXL Catalogue} \( \text{Roemer et al. 2010} \), which is a full-sky survey down to

\(^3\) We do not consider our distance to Lyngå 6 as very reliable because of the small number of points in the 2MASS CMD this value is based on; \( \text{An et al. (2007)} \) do not provide a \( JHK_s \)-based distance for the same reason.
Table 1. Comparison of OC absolute distance moduli

| Open cluster | This paper | An et al. (2007) | Anderson et al. (2013) | Tammann et al. (2003) | Dias et al. (2014) |
|--------------|------------|------------------|------------------------|-----------------------|-------------------|
| Dolidze 34   | 11.85 ± 0.25 |                  |                        |                       | 10.76             |
| Dolidze 52   | 10.77 ± 0.24 |                  |                        |                       | 10.60             |
| NGC 6683     | 11.62 ± 0.24 |                  |                        |                       | 10.79             |
| ASCC 61      | 11.19 ± 0.23 |                  |                        | 11.14 ± 0.20          | 11.63             |
| Feinstein 1  | 10.88 ± 0.23 |                  |                        |                       | 10.75             |
| NGC 7790     | 12.58 ± 0.35 | 12.46 ± 0.11     | 12.46 ± 0.01           | 12.69                 | 12.31             |
| NGC 6087     | 9.84 ± 0.11  | 9.65 ± 0.06      | 9.65 ± 0.03            | 9.85                  | 9.74              |
| IC 4725      | 8.90 ± 0.13  | 8.93 ± 0.08      | 8.93 ± 0.02            | 9.07                  | 8.74              |
| vdBergh 1    | 11.11 ± 0.24 |                  |                        | 11.08 ± 0.07          | 11.22             |
| NGC 129      | 11.16 ± 0.24 | 11.04 ± 0.05     | 11.11 ± 0.02           | 11.22                 | 11.13             |
| Collinder 394| 9.35 ± 0.16  |                  |                        | 9.38 ± 0.10           | 9.11              |
| Turner 2     | 11.22 ± 0.13 |                  |                        | 11.26 ± 0.10          | 11.26             |
| Trumpler 35  | 11.43 ± 0.18 |                  |                        | 11.58 ± 0.18          | 11.60             |
| Ruprecht 175 | 10.23 ± 0.18 |                  |                        |                       | 10.52             |
| NGC 5662     | 9.24 ± 0.13  | 9.31 ± 0.06      | 9.31 ± 0.02            | 9.17                  | 8.98              |
| ASCC 69      | 9.74 ± 0.23  |                  |                        | 10.0 ± 0.20           | 9.44              |
| Collinder 220| 11.48 ± 0.24 |                  |                        | 11.63 ± 0.20          | 10.83             |
| NGC 6067     | 11.18 ± 0.23 | 11.03 ± 0.08     | 11.03 ± 0.01           | 11.19                 | 11.27             |
| Berkeley 58  | 12.39 ± 0.35 |                  |                        | 12.40 ± 0.12          | 12.16             |

Figure 1. Comparison of our newly derived distances with those of An et al. (2007), Anderson et al. (2013), Tammann et al. (2003) and Dias et al. (2014).
V = 20 mag, containing some 900 million objects. 2MASS contains about 400 million objects; the PPMXL Catalogue provides proper-motion data for all 2MASS objects. The resulting, typical individual mean errors of the proper motions range from 4 mas yr\(^{-1}\) to more than 10 mas yr\(^{-1}\). The PPMXL Catalogue provides an effective way to study cluster membership because of the large database that reaches sufficiently faint magnitudes.

In order to reduce contamination by non-members, we first plotted the CMDs of our OCs and selected stars along their main sequences for our proper-motion selection (see Figure 3 and Table 2). Next, we plotted the proper-motion distribution of the OC of interest; the locus dominated by the cluster members is usually very obvious. We used these stars to obtain an initial estimate of the average proper motion for the cluster and its 1\(\sigma\) standard deviation, so as to select genuine OC members. We then reapplied our proper-motion selection to all stars in the cluster's average proper motion. Figure 2 shows an example of our proper-motion selection. The black dots are the stars selected after the first application of our selection criteria, while the blue dots are the stars located within the 1\(\sigma\) discus

### 2.6 Instability-strip selection

OC Cepheids must be located inside the instability strip. Cepheids whose proper motions result from the cluster's average proper motion. Figure 2 shows an example of our proper-motion selection (see the Appendix for the relevant figures for all other OC-Cepheid combinations discussed in this paper). The black dots are the stars selected after the first application of our selection criteria, while the blue dots are the stars located within the 1\(\sigma\) range after the second selection step. The red triangles represent the Cepheids' proper motions. We compared the loci of the red triangles to the range of blue asterisks to select the most likely OC Cepheids. One of the Cepheids in this example is located inside the 1\(\sigma\) radius, whereas the other Cepheids' loci is found at approximately 1.4\(\sigma\). The latter object is considered a possible OC Cepheid.

1\(\sigma\) deviations. Cepheids found beyond 2\(\sigma\) from the ridge line were excluded from further consideration. Since the magnitudes and colours of Cepheids change periodically, we used the mean magnitudes and colours. We added the mean magnitudes of the Cepheids used in our example cluster (cf. Fig. 2 as red diamonds to Fig. 3). All Cepheids selected in our previous selection steps satisfy our instability-strip selection criteria.

### 2.7 Age selection

The ages of cluster Cepheids should be comparable to those of their host OCs. Although this is not necessarily a hard-and-fast rule, matching Cepheid and OC ages provides at least some moderately useful additional constraints. All Galactic OCs are young, with ages usually between 10\(^6\) and 10\(^9\) yr. Cepheid ages can be calculated based on their pulsational oscillation frequencies (Bono et al. 2003). For fundamental-mode Cepheids, \(log(t \text{ yr}^{-1}) = (8.31 \pm 0.08) - (0.67 \pm 0.01) \log(P \text{ day}^{-1})\), while for first-overtone Cepheids, \(log(t \text{ yr}^{-1}) = (8.08 \pm 0.08) - (0.39 \pm 0.04) \log(P \text{ day}^{-1})\). Fundamental-mode and first-overtone Cepheids have ages around \(log(t \text{ yr}^{-1}) = 7.6\) at \(log(P \text{ day}^{-1}) = 1.0\). OC ages are usually calculated based on isochrone fitting. We used the ages listed for some OCs in the WEBDA database as reference to check the reliability of our isochrone fits (see Fig. 4).
Figure 3. Example of isochrone fitting to the CMD of the OC Dolidze 34 (cf. Fig. 2). The black dots are stars brighter than $J_{\text{2MASS}} = 12$ mag. The red dots are from the UKIDSS database, showing stars fainter than $J_{\text{2MASS}} = 12$ mag, down to the limiting magnitude of the proper-motion catalogue. The 2MASS and UKIDSS cluster stars were selected based on proper-motion constraints. The blue dots are fainter stars located within 3 arcmin from the cluster centre, which we use to show a continuous main sequence. The solid red line is the best-fitting isochrone for solar metallicity. The green dashed line is the central ridge line of the Cepheid instability strip from Tammann et al. (2003); the red and blue dashed lines are the red and blue edges of the Cepheid instability strip, respectively. The blue diamond and triangle show the loci of two Cepheids in the 2MASS catalogue, while the red symbols represent their mean $(J - H)$ colour and $J$ magnitude, respectively.

The age uncertainties associated with isochrone fitting can be of order $\Delta \log(t \ \text{yr}^{-1}) = 0.2 - 0.3$ for OC ages around $10^8$ yr. We adopted as age-selection criterion an age difference between the Cepheids and their postulated host OCs of $\Delta \log(t \ \text{yr}^{-1}) \leq 0.3$; if $\Delta \log(t \ \text{yr}^{-1}) > 0.3$, a more careful check of our CMDs would be required. All 37 OC Cepheids in our constrained sample satisfy this criterion.

2.8 Radial-velocity and iron-abundance selection

Additional selection criteria applied to our sample of potential OC Cepheids include radial-velocity and iron-abundance selection. Radial velocities and iron-abundance data are available for only a few OCs in the catalogues. The DAML02 (version 3.4) radial-velocity data we used for our OCs come mostly from Dias et al. (2014) and Kharchenko et al. (2013), whereas the radial velocity data for the Cepheids are from Storm et al. (2011) and Furnie et al. (1995). Since more than half of the OCs’ radial velocities are calculated based on fewer than three stars, we used $\sigma_{\text{RV}} = 10/(\sqrt{N})$ km s$^{-1}$ as our selection criterion (Anderson et al. 2013).

Anderson et al. (2013) carried out a detailed analysis of every OC–Cepheid combination available to them. Therefore, we use their iron abundance results as reference in the next section.

3 RESULTS

3.1 CMD analysis

CMD analysis was done for each OC in our sample. We used 2MASS $JHK_s$ photometry for our colour–magnitude analysis, applying an additional selection criterion in which we only considered stars with photometric errors of less than 0.2 mag. For a number of our OCs, UKIDSS data are also available. In these cases, 2MASS data were adopted for stars brighter than $J = 12$ mag, and UKIDSS data for fainter stars. We converted the UKIDSS $JHK_s$ photometry to 2MASS $JHK_s$ magnitudes using (Hewett et al. 2006):

$$J_{\text{2MASS}} = J - 0.01 + 0.073(J - H);$$

$$H_{\text{2MASS}} = H - 0.069(H - K);$$

$$K_{\text{2MASS}} = K + 0.073(H - K).$$

These conversion equations apply to main-sequence stars. For those OCs whose CMDs revealed well-defined cluster sequences, we determined the distances, reddening values and ages by fitting the cluster sequences with Padova isochrones (Bressan et al. 2012) in the 2MASS $JHK_s$ photometric system. If the cluster metallicity was not known, we adopted solar-metallicity isochrones. This method is identical to that adopted by Kronberger et al. (2006), who used isochrone fitting to find new OCs in the 2MASS catalogue. We also used the $(J - H)$ vs $(H - K_s)$ colour–colour diagram to check the validity of our reddening values (see Section 3.2). In Figure 3, we show an example of an isochrone-fitting result based on a $J$ vs $(J - H)$ CMD (see the Appendix for the equivalent figures for our other OCs). From isochrone fits to this particular CMD we determined the cluster parameters, $\log(t \ \text{yr}^{-1}) = 7.9 \pm 0.3$, $E(J - H) = 0.36 \pm 0.02$ mag and an apparent DM of $(M - M_\odot) = 12.80 \pm 0.20$ mag. Using the relevant extinction law (Rieke et al. 1985), $A_J = 2.64E(J - H)$, the absolute DM yields $(m - M)_\odot,J = 11.85 \pm 0.25$ mag.

3.2 Reddening check

Correcting for reddening is very important to improve the accuracy of our OC properties. If we know a cluster’s reddening and age, we can accurately derive its distance based on isochrone fitting. Colour–colour diagrams were used to obtain the appropriate colour excesses. For main-sequence cluster stars, we took the intrinsic colours, $(J - H)_0$ and $(H - K_s)_0$, from Turner (2011). Wang et al. (2014) determined a universal NIR extinction law for the Galactic plane, $E(J - H)/E(J - K_s) = 0.64$, $E(J - H)/E(H - K_s) = 1.78$. Combining the intrinsic colours with this extinction law, we derived the $(J - H)$ vs $(H - K_s)$ relationship, shown as the
Wang et al. (2014), giving a colour excess of colours adopted (Turner 2011) and the NIR extinction law of stars with $J < \text{proper-motion selection}$. To exclude field stars we only include red dots are from 2MASS and UKIDSS, respectively, based on Figure 5. Colour–colour diagram of Dolidze 34. The black and the WEBDA database.

Figure 4. Comparison of our derived ages with those taken from the one-to-one relation. The error bars associated with the distance estimates based on our isochrone fits contain the uncertainties in both the DM and the $J$-band extinction, $A_J$. The error bars associated with the Cepheid distances include the uncertainties in both the PLR and the $V$-band extinction. The latter is often too large to lead to a reliable PLR.

If we assume that most OCs are negligibly affected by differential reddening effects because of their small sizes, the associated OC Cepheids will – to first order – have the same reddening. The Tammann et al. (2003) Cepheid catalogue includes $E(B-V)$ reddening corrections, while we obtained the equivalent NIR values for our OCs based on isochrone fitting. The reddening corrections in Tammann et al. (2003) were derived from Fernie (1994) and Fernie et al. (1995), which represents the largest body of $E(B-V)$ values for Galactic Cepheids available to date. Tammann et al. (2003) applied a small systematic correction, $E(B-V)_{\text{corr}} = (0.951 \pm 0.012)E(B-V)_{\text{Fernie}}$. We converted our $E(J-H)$ reddening estimates to $E(B-V)$ values using $E(J-H) = 0.33E(B-V)$ (Rieke et al. 1985). Figure 5 shows our CMD-based reddening estimates vs Cepheid reddening values from

blue line in the colour–colour diagram of Fig. 5. We found that this relationship represents the ridge line defined by our data points. As an example, Fig. 5 illustrates this procedure for Dolidze 34, which is characterized by a colour excess, $E(J-H) = 0.36 \pm 0.02$ mag. (See the Appendix for the equivalent figures for our other sample OCs.)

If we assume that most OCs are negligibly affected by differential reddening effects because of their small sizes, the associated OC Cepheids will – to first order – have the same reddening. The Tammann et al. (2003) Cepheid catalogue includes $E(B-V)$ reddening corrections, while we obtained the equivalent NIR values for our OCs based on isochrone fitting. The reddening corrections in Tammann et al. (2003) were derived from Fernie (1994) and Fernie et al. (1995), which represents the largest body of $E(B-V)$ values for Galactic Cepheids available to date. Tammann et al. (2003) applied a small systematic correction, $E(B-V)_{\text{corr}} = (0.951 \pm 0.012)E(B-V)_{\text{Fernie}}$. We converted our $E(J-H)$ reddening estimates to $E(B-V)$ values using $E(J-H) = 0.33E(B-V)$ (Rieke et al. 1985). Figure 5 shows our CMD-based reddening estimates vs Cepheid reddening values from

Figure 6. Comparison of our newly determined NIR reddening values with their optical counterparts from Tammann et al. (2003). The solid line represents the relation, $E(J-H) = 0.33E(B-V)$.

Tammann et al. (2003). This figure shows that our reddening estimates are robust.

3.3 Possible open cluster Cepheids

Application of our five selection criteria resulted in a sample of 37 possible OC Cepheids. Note that we have not included a number of probable first-overtone Cepheids such as QZ Nor and V1726 Cyg (Tammann et al. 2003). Figure 7 shows a comparison of Cepheid and OC DMs. The solid line is the one-to-one relation. The error bars associated with the distance estimates based on our isochrone fits contain the uncertainties in both the DM and the $J$-band extinction, $A_J$. The error bars associated with the Cepheid distances include the uncertainties in both the PLR and the $V$-band extinction. The latter is often too large to lead to a reliable PLR.

To reduce the effects of differential reddening between the Cepheids and their postulated host OCs, and to avoid introducing errors through application of a reddening conversion from NIR to visible wavelengths, we opted to use the NIR mean magnitudes. $JHK$-band mean magnitudes in the SAAO system are available for 229 Cepheids (van Leeuwen et al. 2007). Among our sample of possible OC Cepheids, these mean magnitudes are available for only 22 of the 37 Cepheid candidates; three of these 22 Cepheids were excluded because they did not satisfy our NIR selection criteria (see below). The remaining 19 OC Cepheids are included in Table 1 and their corresponding CMDs, colour–colour and proper-motion diagrams are provided in the Appendix. The ages, reddening values and DMs for these OCs based on isochrone fitting are also included in Table 1. Thirteen of these 19 Cepheids are confirmed OC Cepheids and the other six are very likely OC Cepheids, because their distances and proper motions span the same ranges as those of their host OCs. These latter Cepheids are TY Sct and CN Sct in Dolidze 34, XX Sgr in Dolidze 52, CK Sct in NGC 6683, VY Car in ASCC 61 and U Car in Feinstein 1. Figure 8 shows the PLR based on this sample of OC
3.4 OC Cepheid candidates without NIR observations

For completeness, Table 2 includes an overview of the selection matches for the 15 OC Cepheid candidates for which we do not have access to NIR data. We will now briefly discuss the extent to which these objects are genuine OC Cepheids.

3.4.1 Confirmed Cepheids

3.4.1.1 Berkeley 58 and CG Cas

Confirmed CG Cas as a member of Berkeley 58, although their proper motions disagree to some extent: the proper motion of CG Cas is found within the 1.5σ range of genuine Berkeley 58 members. Its DM and reddening are $(m - M)_{0,V} = 12.40 \pm 0.12$ mag and $E(B-V) = 0.70 \pm 0.03$ mag, respectively, which is within 1-2σ of our NIR determinations, i.e., $(m - M)_{0,J} = 12.39 \pm 0.35$ mag and $E(J-H) = 0.23 \pm 0.02$ mag, respectively. The CG Cas–Berkeley 58 combination meets all four other selection criteria.

3.4.1.2 NGC 7790 and CEA Cas, CEB Cas

NGC 7790 was studied in detail by [An et al. (2007)]. They derived $(m - M)_{0,V} = 12.46 \pm 0.11$ mag and $E(B-V) = 0.48 \pm 0.02$ mag, compared with our determinations of $(m - M)_{0,J} = 12.58 \pm 0.31$ mag and $E(J-H) = 0.14 \pm 0.02$ mag, respectively. Like CF Cas, CEA Cas and CEB Cas satisfy all five selection criteria for NGC 7790. CF Cas and CEBab Cas were shown to be NGC 7790 members by [Majess et al. (2013)].

3.4.1.3 Kharchenko 3 and ASAS J182714–1507.1

[Anderson et al. (2013)] first suggested that ASAS J182714–1507.1 may be a genuine member of the OC Kharchenko 3. These authors showed that the ages, distances and proper motions of both Kharchenko 3 and ASAS J182714–1507.1 are mutually consistent. [Dias et al. (2014)] lists $(m - M)_{0,V} = 11.64$ mag and $E(B-V) = 0.72$ mag, compared with our determinations of $(m - M)_{0,J} = 11.51 \pm 0.37$ mag and $E(J-H) = 0.26 \pm 0.025$ mag, respectively. ASAS J182714–1507.1 satisfies all five criteria needed to confirm it as a member of Kharchenko 3.

3.4.2 New Cepheids

3.4.2.1 NGC 6991 and V0520 Cyg

V0520 Cyg is located at approximately 7 arcmin from the centre of NGC 6991. In the cluster’s CMD, V0520 Cyg is found near the instability strip’s ridge line. We derive $E(J-H) = 0.24 \pm 0.02$ mag, log$(t$ yr$^{-1}) = 8.2 \pm 0.3$ and $(m - M)_{0,J} = 11.17 \pm 0.35$ mag. DAML02 lists log$(t$ yr$^{-1}) = 9.11$ for NGC 6991 and an apparent diameter of 24 arcmin. This close pair was overlooked for many years because of errors affecting the OC catalogue. [Anderson et al. (2013)] excluded this OC–Cepheid pair from their compilation because of the relatively large differences in ages, proper motions and radial velocities contained in the old version of the DAML02 database. However, the latest release of the database includes improved proper-motion and radial-velocity measurements, supporting our identification of NGC 6991 and V0520 Cyg as a genuine OC–Cepheid pair.

The proper motion of NGC 6991 is $(\mu_\alpha, \mu_\delta) = (-0.46 \pm 3.11, -1.54 \pm 3.23)$ mas yr$^{-1}$, which is in good agreement with $(\mu_\alpha, \mu_\delta) = (-1.5, 1.94)$ mas yr$^{-1}$ (Dias et al. 2014). The proper motion of V0520 Cyg, $(\mu_\alpha, \mu_\delta) = (-1.6, -3.2)$ mas yr$^{-1}$, is in excellent agreement with that of NGC 6991. The radial velocity of NGC 6991 is $v_r = -21.77 \pm 5.77$ km s$^{-1}$ (Dias et al. 2014) – based on three stars – which is comparable with that of V0520 Cyg, $v_r = -23.0$ km s$^{-1}$. The apparent discrepancy in age between the OC and the Cepheid is most likely owing to the difficulty in performing robust isochrone fitting in the crowded 2MASS field.

3.4.2.2 Juchert 18 and CS Mon

CS Mon is located at about 14 arcmin from the centre of Juchert 18. We derive $E(J-H) = 0.17 \pm 0.015$ mag, log$(t$ yr$^{-1}) = 8.1 \pm 0.3$ and $(m - M)_{0,J} = 12.35 \pm 0.24$ mag. Juchert 18 and CS Mon perfectly satisfy our five selection criteria. The [Kharchenko et al. (2013)] isochrone-fitting result leads to a very old cluster, log$(t$ yr$^{-1}) = 9.02 \pm 0.04$. On the other hand, when we use UKIDSS data instead of the shallower 2MASS data for the faint stellar population, the CMD is better represented by that of a young OC.
3.4.3 Uncertain cluster Cepheids

3.4.3.1 Trumpler 9 and ASAS J075503−2614.3
Anderson et al. (2013) suggested that the status of ASAS J075503−2614.3 as a member of Trumpler 9 is inconclusive, because their proper motions and ages are discrepant. However, we find that the DMs and ages both meet our selection criteria and that the proper motions agree to within 1.6σ. It would be crucial to obtain the radial velocities of both Trumpler 9 and ASAS J075503−2614.3 (although the latter is rather faint) to ascertain the Cepheid’s OC membership.

3.4.3.2 Ruprecht 65 and AP Vel
Ruprecht 65 and AP Vel satisfy our proper-motion and age criteria. We estimate a Cepheid proper motion of µ Vel satisfy our proper-motion and age criteria. We estimate 3.4.3.2 Ruprecht 65 and AP Vel satisfy our proper-motion and age criteria. We estimate 3.4.3.2 Ruprecht 65 and AP Vel satisfy our proper-motion and age criteria. We estimate 3.4.3.2 Ruprecht 65 and AP Vel satisfy our proper-motion and age criteria. We estimate

3.4.3.3 Czernik 8 and UY Per
Turner (2011) suggested that UY Per might be a member of Czernik 8. However, Anderson et al. (2013) questioned this conclusion, since UY Per’s proper motion is much faster than that of the cluster. We estimate a Cepheid proper motion of (µα,µδ) = (−6.1, 12.9) mas yr−1, which is 3.4σ away from the mean proper motion of Czernik 8, (µα,µδ) = (−1.28 ± 2.94, −0.39 ± 3.01) mas yr−1. The DMs and ages satisfy our selection criteria; the radial velocity of Czernik 8 is not available. We conclude that UY Per’s membership status of Czernik 8 is inconclusive.

3.4.4 Rejected cluster Cepheids

3.4.4.1 Ruprecht 79 and CS Vel
The probability that CS Vel may be a member of Ruprecht 79 is less than one per cent (Anderson et al. 2013). Our results also show that the ages, proper motions and radial velocities of Ruprecht 79 and CS Vel do not agree very well. The proper motion of CS Vel is (µα,µδ) = (−1.4, −8.6) mas yr−1, which is 2σ away from the mean proper motion of Ruprecht 79, (µα,µδ) = (−5.66 ± 4.67, 4.04 ± 4.93) mas yr−1. The radial velocity of CS Vel is v_r = 26.95 km s−1 (Anderson et al. 2013), and that of Ruprecht 79 is v_r = 21.4 ± 3.6 km s−1 (Rastorguev et al. 1992). Finally, the age of Ruprecht 79 is log(t yr−1) = 7.0 ± 0.3, which places it within the 2–3σ range of that of CS Vel, log(t yr−1) = 7.8 ± 0.1.

3.4.4.2 Ruprecht 119 and ASAS J162811−5111.9
Ruprecht 119 and ASAS J162811−5111.9 satisfy both our proper-motion and age criteria. We estimate E(J−H) = 0.15 ± 0.03 mag and (m − M)0, J = 10.52 ± 0.28 mag. The OC–Cepheid DM difference is 0.7 mag, which casts doubt on the assertion that this may be a genuine OC–Cepheid pair. The radial velocity of ASAS J162811−5111.9 is 4σ from the average radial velocity of Ruprecht 119. ASAS J162811−5111.9 is thus an unlikely member of Ruprecht 119.

3.4.4.3 Sher 1 and FN Car
Sher 1 and FN Car satisfy the proper-motion and age criteria. We estimate E(J−H) = 0.13 ± 0.04 mag and (m − M)0, J = 12.66 ± 0.51 mag, but a DM difference of 0.7 mag. FN Car is located at about 7 arcmin from the centre of Sher 1; the apparent diameter of Sher 1 is 1 arcmin (Dias et al. 2014). These results imply that FN Car is an unlikely member of Sher 1.

3.4.4.4 ASCC 64 and HK Car
Sher 1 and FN Car satisfy our proper-motion and age criteria. However, the difference in DM is about 1.5 mag, which invalidates this association as a genuine OC–Cepheid pair.

3.4.4.5 NGC 5999 and ASAS J155149−5621.8
NGC 5999 and ASAS J155149−5621.8 satisfy the proper-motion criterion. Based on a detailed analysis, we derive a difference in DM of approximately 1.4 mag and and age difference, Δ log(t yr−1) = 0.4, i.e., too large to conclusively identify this association as a genuine OC–Cepheid pair.

4 DISCUSSION

4.1 Confirmed Cepheids based on NIR observations
For all confirmed OCs, our best-fitting DMs are consistent to within 0.1 mag with the corresponding determinations in the literature.

4.1.0.6 BB Sgr and Collinder 394
BB Sgr was first confirmed as a member of Collinder 394 by Turner & Pedreros (1985). Its DM and reddening are (m − M)0, V = 9.04 ± 0.08 mag and E(B−V) = 0.25 ± 0.01 mag, respectively (Turner & Pedreros 1985), which is within 1–2σ of our NIR determinations, (m − M)0, J = 9.35 ± 0.16 mag and E(J−H) = 0.095 ± 0.005 mag, respectively. The BB Sgr–Collinder 394 combination meets all five selection criteria.

4.1.0.7 WZ Sgr and Turner 2
WZ Sgr was first confirmed as a member of Turner 2 by Turner et al. (1993).
who derived its DM and reddening, \((m - M)_{0,V} = 11.26\) mag and \(E(B - V) = 0.56\) mag, respectively, which compare very well with our results, \((m - M)_{0,J} = 11.22 \pm 0.11\) mag and \(E(J - H) = 0.18 \pm 0.01\) mag. WZ Sgr and Turner 2 also satisfy all five selection criteria.

### Table 2. Isochrone-fitting results for our OC Cepheid candidates

| Cluster       | \(E(J - H)\) (mag) | \(\log(t)\) [yr] | \(\mu\) (mag) | \(\mu_0\) (mag) | Cepheid          | \(\langle J \rangle\) (mag) | \(M_J\) (mag) | \(\log(P)\) [day] |
|---------------|--------------------|------------------|---------------|---------------|-----------------|-----------------------|-------------|------------------|
| Dolidze 34    | 0.36 \pm 0.02      | 7.9              | 12.8          | 11.85 \pm 0.25 | TY Sc          | 7.225                 | -5.575      | 1.043            |
| Dolidze 52    | 0.36 \pm 0.02      | 7.9              | 12.8          | 11.85 \pm 0.25 | CN Sc          | 7.821                 | -4.979      | 1.000            |
| NGC 6683      | 0.18 \pm 0.015     | 7.6              | 11.4          | 10.77 \pm 0.24 | XX Sgr         | 6.441                 | -4.959      | 0.808            |
| ASCC 61       | 0.08 \pm 0.01      | 8.0              | 11.4          | 11.19 \pm 0.23 | VY Car         | 5.408                 | -5.992      | 1.277            |
| Feinseit 1    | 0.12 \pm 0.01      | 7.9              | 11.2          | 10.88 \pm 0.23 | U Car          | 4.138                 | -7.062      | 1.589            |
| NGC 7790      | 0.14 \pm 0.02      | 7.9              | 13.0          | 12.58 \pm 0.35 | CF Cas         | 8.595                 | -4.405      | 0.688            |
| NGC 6087      | 0.06 \pm 0.005     | 8.0              | 10.0          | 9.84 \pm 0.11  | S Nor          | 4.678                 | -5.322      | 0.989            |
| IC 4725       | 0.18 \pm 0.01      | 7.8              | 9.0           | 8.90 \pm 0.13  | U Sgr          | 4.531                 | -4.769      | 0.829            |
| vdBerg 1      | 0.26 \pm 0.015     | 7.9              | 11.8          | 11.11 \pm 0.24 | CV Mon         | 7.341                 | -4.459      | 0.731            |
| NGC 129       | 0.165 \pm 0.015    | 7.8              | 11.6          | 11.16 \pm 0.24 | DL Cas         | 6.556                 | -5.044      | 0.903            |
| Collinder 394 | 0.095 \pm 0.005    | 8.0              | 9.6           | 9.35 \pm 0.16  | BB Sgr         | 5.048                 | -4.552      | 0.822            |
| Turner 2      | 0.18 \pm 0.01      | 8.0              | 11.7          | 11.22 \pm 0.13 | WZ Sgr         | 5.258                 | -6.442      | 1.339            |
| Trumpler 35   | 0.33 \pm 0.01      | 7.8              | 12.3          | 11.43 \pm 0.18 | RU Sc          | 5.950                 | -6.350      | 1.294            |
| Ruprecht 175  | 0.065 \pm 0.01     | 7.8              | 10.8          | 10.23 \pm 0.18 | X Cyg          | 4.421                 | -5.979      | 1.215            |
| NGC 5662      | 0.10 \pm 0.01      | 8.0              | 9.5           | 9.24 \pm 0.13  | V Cen          | 5.023                 | -4.477      | 0.740            |
| ASCC 61       | 0.08 \pm 0.01      | 8.0              | 11.4          | 11.19 \pm 0.23 | SX Car         | 7.262                 | -4.138      | 0.687            |
| ASCC 69       | 0.06 \pm 0.01      | 8.0              | 9.9           | 9.94 \pm 0.23  | S Mus          | 4.503                 | -5.397      | 0.985            |
| Collinder 220 | 0.12 \pm 0.015     | 8.1              | 11.8          | 11.48 \pm 0.24 | UW Car         | 7.311                 | -4.489      | 0.728            |

### Table 3. Constraints for OC Cepheid candidates without NIR data. ‘1σ’: within 1σ; other values refer to the specific loci.

| Cluster | Cepheid          | DM     | PM    | RV    | Age |
|---------|------------------|--------|-------|-------|-----|
| Trumpler 9 | ASAS J075503−2614.3 | 1σ     | 1.7σ  | 1σ    | 1σ  |
| Lynga 6    | TW NOR           | 1σ    | 1σ    | 1σ    | 1σ  |
| NGC 6991   | V0520 Cyg       | 1σ    | 1σ    | 1σ    | 1σ  |
| Sher 1     | FN Car           | 1σ    | 1σ    | 1σ    | 1σ  |
| Ruprecht 65 | AP Vel          | 1σ    | 1σ    | 1σ    | 1σ  |
| Juchert 18 | CS Mon           | 1σ    | 1σ    | 1σ    | 1σ  |
| Ruprecht 119 | ASAS J162811−5111.9 | 1σ     | 1σ    | 4.1σ  | 1σ  |
| NGC 5999   | ASAS J155149−5621.8 | 1σ | 1σ    | 1.2σ  | 1σ  |
| Czernik 8  | UY Per           | 1σ    | 3.4σ  | 1σ    | 1σ  |
| Berkeley 58 | CG Cas          | 1σ    | 1.4σ  | 1σ    | 1σ  |
| NGC 7790   | CEA Cas          | 1σ    | 1σ    | 1σ    | 1σ  |
| NGC 7790   | CEB Cas          | 1σ    | 1σ    | 1σ    | 1σ  |
| Ruprecht 79 | CS Vel           | 1σ    | 2.0σ  | 1.5σ  | 2.0σ |
| Kharchenko 3 | ASAS J182714−1507.1 | 1σ     | 1σ    | 1σ    | 1σ  |
| ASCC 64    | HK Car           | 1.5σ  | 1σ    | 1σ    | 1σ  |

### 4.1.0.8 V Cen and NGC 5662

V Cen was first suggested as a member of NGC 5662 by Turner (1980). With \((m - M)_{0,V} = 9.10 \pm 0.08\) mag and \(E(B - V) = 0.31 \pm 0.01\) mag, its optical values are consistent with our NIR determinations, \((m - M)_{0,J} = 9.24 \pm 0.11\) mag and \(E(J - H) = 0.10 \pm 0.01\) mag, respectively. V Cen and NGC 5662 also satisfy all five selection criteria.

### 4.1.0.9 CV Mon and van den Bergh 1

The membership probability of CV Mon of the OC van den Bergh 1 was studied in detail by Turner et al. (1998). It is characterized by \((m - M)_{0,V} = 11.08 \pm 0.03\) mag and \(E(B - V) = 0.75 \pm 0.02\) mag, which is again similar to our results, \((m - M)_{0,J} = 11.11 \pm 0.21\) mag and \(E(J - H) = 0.26 \pm 0.015\) mag. The CV Mon–van den Bergh 1 pair also meets all five selection criteria.

### 4.1.0.10 RU Scτ and Trumpler 35

The membership probability of RU Scτ of the OC Trumpler 35 was studied in detail by Turner (1980). We determined \((m - M)_{0,J} = 11.43 \pm 0.16\) mag and \(E(J - H) = 0.33 \pm 0.01\) mag, which is consistent with \((m - M)_{0,V} = 11.60 \pm 0.12\) mag and \(E(B - V) = 1.03 \pm 0.02\) mag from Turner (1984). In the context of our instability-strip selection, RU Scτ is located at 1.5σ from the ridge line.

### 4.1.0.11 X Cyg and Ruprecht 175

The X Cyg membership probability of Ruprecht 175 was studied in detail by
We find \((m - M)_{0, J} = 10.23 \pm 0.16\) mag and \(E(J - H) = 0.065 \pm 0.01\) mag, which is marginally similar (given the uncertainties quoted) to their determinations, \((m - M)_{0, V} = 10.43 \pm 0.04\) mag and \(E(B - V) = 0.25 \pm 0.02\) mag, respectively. X Cyg and Ruprecht 175 satisfy all five selection criteria.

### 4.1.0.12 S Nor and NGC 6087

S Nor and NGC 6087 were studied in detail by Turner (1986). Their determinations, \((m - M)_{0, V} = 9.78 \pm 0.03\) mag and \(E(B - V) = 0.19 \pm 0.12\) mag are again similar to our results, \((m - M)_{0, J} = 9.84 \pm 0.11\) mag and \(E(J - H) = 0.06 \pm 0.005\) mag. S Nor and NGC 6087 satisfy all five selection criteria.

### 4.1.0.13 CF Cas and NGC 7790

CF Cas and NGC 7790 were studied in detail by An et al. (2007). They found \((m - M)_{0, V} = 12.46 \pm 0.11\) mag and \(E(B - V) = 0.48 \pm 0.02\) mag, compared with our determinations of \((m - M)_{0, J} = 12.58 \pm 0.31\) mag and \(E(J - H) = 0.14 \pm 0.02\) mag, respectively. CF Cas and NGC 7790 satisfy all five selection criteria.

### 4.1.0.14 U Sgr and IC 4725

U Sgr and IC 4725 were also studied in detail by An et al. (2007), who determined \((m - M)_{0, V} = 8.93 \pm 0.03\) mag and \(E(B - V) = 0.39 \pm 0.03\) mag. These values are consistent with our results (in particular the DM), \((m - M)_{0, J} = 8.90 \pm 0.11\) mag and \(E(J - H) = 0.18 \pm 0.010\) mag. U Sgr and IC 4725 also satisfy all five selection criteria.

### 4.1.0.15 SX Car and ASCC 61, S Mus and ASCC 69, UW Car and Collinder 220, V379 Cas and NGC 129

These four OC Cepheids were first found by Anderson et al. (2013). Here, we confirm their membership of their postulated host clusters. All of these Cepheids meet all five selection criteria to be associated with their proposed host OCs. We calculated the respective NIR DMs and colour excesses, which are all consistent with the values found by Anderson et al. (2013). As regards the other new OC Cepheid proposed by Anderson et al. (2013), ASAS J182714–1507.1, its V-band DM and proper motion are identical to those of its host cluster (see also Table 2). However, we do not have access to its NIR photometry, so that we cannot more robustly confirm this OC-Cepheid pair.

### 4.2 New Cepheids

#### 4.2.0.16 Dolidze 34 and TY Set, CN Set

TY Set is located at approximately 4 arcmin from the centre of Dolidze 34, while CN Set is found at about 10 arcmin from the cluster centre. Dolidze 34 is a poorly studied OC. We obtained \(E(J - H) = 0.36 \pm 0.02\) mag, \(log(t \text{ yr}^{-1}) = 7.9 \pm 0.2\) and \((m - M)_{0, J} = 11.85 \pm 0.21\) mag. Except for the DM, these values are close to those listed by Kronenberg et al. (2004), \(E(B-V) = 1.041\) mag, \(log(t \text{ yr}^{-1}) = 7.95\) and \((m - M)_{0, V} = 10.76\). The proper motion of TY Set is similar (to within 1σ) of that of Dolidze 34; the proper motion of CN Set is found within 1.3σ of the cluster’s mean proper motion. In addition, the age of CN Set, \(log(t \text{ yr}^{-1}) = 7.64 \pm 0.1\), is consistent with that of the host OC, \((m - M)_{0, V} = 7.9 \pm 0.2\). CN Set lies in the cluster’s instability strip, while TY Set is located at 1.5σ from the instability strip’s central ridge line.

#### 4.2.0.17 Dolidze 52 and XX Sgr

Dolidze 52 is also poorly studied. We determine a best-fitting reddening of \(E(J - H) = 0.24 \pm 0.015\) mag and a DM, \((m - M)_{0, J} = 10.77 \pm 0.21\) mag. XX Sgr is located at approximately 15 arcmin from the centre of Dolidze 52, while its proper motion is consistent with the cluster’s to within 1σ.

#### 4.2.0.18 NGC 6683 and CK Set

CK Set is located at about 20 arcmin from the centre of NGC 6683. Its proper motion is similar to the average proper motion of NGC 6683. In the cluster’s CMD, CK Set is found near the instability strip’s ridge line. We derive \(E(J - H) = 0.18 \pm 0.02\) mag, \(log(t \text{ yr}^{-1}) = 8.0 \pm 0.2\) and \((m - M)_{0, J} = 11.62 \pm 0.21\) mag. DAML02 lists \(log(t \text{ yr}^{-1}) = 7.0\) for NGC 6683 and an apparent diameter of 3 arcmin. This discrepancy is the reason why this potential OC Cepheid is usually excluded by other authors. However, based on our CMD, NGC 6683 could be consistent with an older age, while the apparent diameter of the cluster could be as large as 10 arcmin, which is supported by the locus of the main-sequence ridge line of stars located within 10 arcmin of the cluster centre. The radial velocity of NGC 6683 is \(V_r = 4.0 \pm 10.0\) km s\(^{-1}\) (Fernie et al. 2013), based on only one star – which is comparable with that of CK Set \(V_r = -0.4\) km s\(^{-1}\) (although the large error bar makes this comparison rather meaningless).

#### 4.2.0.19 Feinstein 1 and U Car

U Car is found at \(\sim 1^\circ\) from the centre of Feinstein 1, which corresponds to approximately twice the cluster’s size. The reddening, age and DM derived here are similar to the equivalent data provided in DAML02. The DMs of U Car \(-(m - M)_{0, V} = 11.07 \pm 0.32\) mag – and Feinstein 1 \(-(m - M)_{0, J} = 10.88 \pm 0.21\) mag – are also similar; the proper motion of U Car, \(\mu_{\alpha, \text{Cep}} = -4.8\) mas yr\(^{-1}\), \(\mu_{\delta, \text{Cep}} = 2.4\) mas yr\(^{-1}\), is found within the 1σ range of the cluster’s central proper motion, \(\mu_{\alpha, \text{cl}} = -3.80\) mas yr\(^{-1}\), \(\mu_{\delta, \text{cl}} = 2.15\) mas yr\(^{-1}\) (adopting a radius of 8.7 arcmin). Anderson et al. (2013) obtained \(\delta V_r = -15.13\) km s\(^{-1}\) \(\equiv 1.6\sigma\); their cluster radial velocity was proposed by Kharchenko et al. (2007) on the basis of one star only, which prompted Anderson et al. (2013) to state that this cluster needs more study. The radial velocity of Feinstein 1 which we adopted is \(V_r = 2.20 \pm 5.0\) km s\(^{-1}\), as derived by Dias et al. (2014) based on four stars. This is, within the uncertainties, consistent with the value for U Car, \(V_r = 0.21\) km s\(^{-1}\).

#### 4.2.0.20 ASCC 61 and VY Car

VY Car and SX Car are both located near the outer edge of the OC ASCC 61. Their proper-motion and DM measurements imply that they are robust cluster members. Anderson et al. (2013) suggested that SX Car may be an OC Cepheid, while they considered VY Car’s status inconclusive because the latter Cepheid’s age is found in the 2σ range. We obtained
Δlog(t yr\(^{-1}\)) = 0.5, while VY Car is selected as a cluster member on the basis of the proper-motion and DM measurements.

4.3 Uncertain cluster Cepheid

4.3.0.21 ASCC 64 and XZ Car XZ Car is located approximately 17 arcmin from the centre of ASCC 64, which is somewhat outside the cluster radius: the cluster’s diameter is 21.6 arcmin (Kharchenko et al. 2005). XZ Car meets the proper-motion, age and instability-strip selection criteria. The radial velocities of ASCC 64 and XZ Car are \(v_r = 1.15 \pm 5.77\) km s\(^{-1}\) (Dias et al. 2014) and 3.14 km s\(^{-1}\), respectively. However, the cluster’s DM, \((m - M)_{0, J} = 11.24 \pm 0.21\) mag, is approximately 1 mag smaller than that of XZ Car, \((m - M)_{0, J} = 12.26 \pm 0.10\) mag. Anderson et al. (2013) quote a difference in radial velocity of ∆\(v_r = −11.465\) km s\(^{-1}\); their OC proper motion was taken from Kharchenko et al. (2007), which is based on only one star. The difference in parallax is ∆π = 0.305 mas, which is more than twice as large as \(σ_π = 0.136\) mas, so that they consider this a low-possibility OC Cepheid.

4.4 Rejected cluster Cepheid

4.4.0.22 NGC 4349 and R Cru R Cru is located at roughly 16 arcmin from the centre of NGC 4349, which is well beyond the size of this cluster (5 arcmin diameter). The age of NGC 4349 is log(\(t\) yr\(^{-1}\)) = 8.6, its reddening is \(E(J - H) = 0.10 \pm 0.02\) mag and the best-fitting DM is \((m - M)_{0, J} = 11.04 \pm 0.25\) mag, values which are identical to those of Majaess et al. (2012). R Cru is located above the cluster’s instability strip, and its PLR DM is less than 9.8 ± 0.1 mag, which implies that R Cru is a foreground Cepheid, located of order 1 kpc closer to us than NGC 4349.

4.5 Reddening and data limitations

V-band mean magnitudes are available for most Cepheids. However, NIR mean magnitudes are available for only a small subsample. This means that we need to investigate the reddening affecting each Cepheid instead of using the average reddening values towards their host OCs. This is because at optical wavelengths, differential reddening across some of our clusters may be significant, sometimes reaching 0.5–1.0 mag in the V band. Such an uncertainty would seriously affect our distance selection. In the NIR, this concern can be alleviated, because the differential reddening would be reduced to at most 0.2–0.3 mag, which is comparable with the typical error in our DMs. For most clusters, we use 2MASS data for our isochrone fits. Unfortunately, some clusters exhibit unclear main sequences, which particularly applies to some of the new Cepheids associated with small OCs. In addition, some clusters’ main sequences yield large error bars in our isochrone fits, preventing us from confirming some other OC Cepheids (e.g., Berkeley 58, Turner 9). However, for some northern OCs, UKIDSS data is available, while for some southern OCs we have access to VVV data. If these observations are added to 2MASS at the faint end, the isochrone-fitting results are much improved. Majaess et al. (2011) combine 2MASS and (as yet proprietary) VVV data, which results in a more obvious main sequence for the OC Lyngå 6, and hence an improved membership assessment of TW Nor in Lyngå 6. Majaess et al. (2012) use VVV data to undertake a detailed study of NGC 4349; they robustly show that R Cru is not a member of NGC 4349.

4.6 Proper-motion and radial-velocity limitations

Proper motions and radial velocities provide very tight constraints on likely OC members. The PPMXL Catalogue provides reliable proper motions for all stars in the regions occupied by our sample OCs. However, it is sometimes difficult to exclude field stars from our calculations of the clusters’ average proper motions. In other words, the errors in the clusters’ proper motions are sometimes large and thus may render the proper-motion constraints we employed invalid. This difficulty is also linked to the photometric uncertainties inherent to the data used. Average radial velocities and their errors for our sample clusters are listed in the DAML02 OC catalogue, originally based mostly on the compilations of Dias et al. (2014) and Kharchenko et al. (2013). However, radial velocities have only been calculated for fewer than 1000 OCs, and more than half of these radial velocities are based on fewer than three stars. This clearly leads to large uncertainties in our radial-velocity database.

5 CONCLUSIONS

We have analysed all potential combinations of Galactic Cepheids and OCs in the most up-to-date catalogues available. Isochrone fitting and proper-motion calculation were done for every potential OC–Cepheid combination. Five selection criteria were used to select possible OC Cepheids: (i) the Cepheid of interest must be located within 60 arcmin of the OC’s centre, (ii) the Cepheid’s proper motion is located within the 1σ distribution of that of its host OC, (iii) the Cepheid is located in the instability strip of its postulated host OC, (iv) the Cepheid and OC DMs should differ by less than 1 mag, and (v) the Cepheid and OC ages should be comparable: ∆log(\(t\) yr\(^{-1}\)) < 0.3. A comparison of the reddening values derived from our isochrone fits with the reddening values of Tammann et al. (2003) shows that our results are reliable. The NIR PLR is obtained for a confirmed sample of about 19 OC Cepheids, \(M_j = (−3.12 \pm 0.29)\log(P\ \text{day}^{-1}) − (2.17 \pm 0.29)\) mag, which is in excellent agreement with the best NIR PLR available for all Galactic Cepheids \(M_j = (−3.030 \pm 0.022)\log(P\ \text{day}^{-1}) − (2.306 \pm 0.020)\) from Ngocw (2012).

Nineteen possible OC Cepheids are found based on our NIR analysis; eight additional OC–Cepheid associations may be genuine pairs for which we lack NIR data. However, the distance accuracy of our isochrone fits is limited by the data quality, reddening and membership probabilities of the OCs. Six of these Cepheids are new, high-probability OC Cepheids, since they lie on the NIR PLR. These objects include TY Sct and CN Sct in Dolidze 34, XX Sgr in Dolidze 52, CK Sct in NGC 6683, VY Car in ASCC 61, and U Car in Feinstein 1. Two additional new OC Cepheids lack NIR data: V0520 Cyg in NGC 6991 and CS Mon in Juchert.
18. However, many new OC Cepheids are still waiting to be found with the availability of better proper-motion data, large samples of radial-velocity data and high-precision and large-area NIR data. In addition, aided by Gaia, trigonometric parallaxes of many Galactic Cepheids will be obtained in the next few years, and direct calibration of the PLR will be possible.

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APPENDIX A: GRAPHICAL REPRESENTATIONS OF THE LOCI OF THE OTHER OPEN CLUSTER CEPHEIDS IN OUR DIAGNOSTIC DIAGRAMS
Figure A1. CMDs of our sample OCs and the loci of their associated Cepheids.
Figure A2. Colour–colour diagrams of our sample OCs and the loci of their associated Cepheids.
Figure A3. Proper motion diagrams of our sample OCs and the loci of their associated Cepheids.