Study of the open cluster Alessi-Teutsch 9 (ASCC 10) using multiband photometry and Gaia EDR3

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Abstract There is a growing interest in the automated characterization of open clusters using data from the Gaia mission. This work evidences the importance of choosing an appropriate sampling radius (the radius of the circular region around the cluster used to extract the data) and the usefulness of additional multiband photometry in order to achieve accurate results. We address this issue using as a case study the cluster Alessi-Teutsch 9. The optimal sampling is determined by counting the number of assigned members at different sampling radii. By using this strategy with data from Gaia EDR3 and with observed photometry in 12 bands spanning the optical range from 3000 to 10000 Å, we are able to determine the properties of the cluster. The spatial distribution of stars show a two-component structure with a central core of radius ∼ 12 − 13 arcmin and an outer halo extending out to 35 arcmin. With the derived cluster distance (654 pc) we obtain that the number density of stars is ≃ 0.06 star/pc³, making Alessi-Teutsch 9 one of the less dense known open clusters. The short relaxation time reveals that it is a dynamically relaxed and gravitationally bound system.

Keywords methods: data analysis – open clusters and associations: general – open clusters and associations: individual: Alessi-Teutsch 9

1 Introduction

Open clusters (OCs) are very important components of our Galaxy. A detailed knowledge of their properties, such as distance, age, metallicity or reddening is necessary for a proper understanding of the structure and evolution of the Milky Way (see e.g. the review by Krumholz et al. 2019). With the advent of the ESA’s Gaia space mission (Gaia Collaboration et al. 2016), its second data release (DR2, Gaia Collaboration et al. 2018) and, more recently, the Early Data Release 3 (EDR3, Gaia Collaboration et al. 2021), astronomers have an homogeneous source of data with unprecedented astrometric precision and accuracy that have allowed to increase the census of known OCs and to improve the determinations of their properties. In the last years, the number of papers using data from Gaia and different techniques (from simple visual inspection to supervised or unsupervised machine learning techniques) and reporting the discovery of new OCs has increased notoriously (Castro-Ginard et al. 2018; Cantat-Gaudin et al. 2019; Ferreira et al. 2019; Liu and Pang 2019; Sim et al. 2019; Castro-Ginard et al. 2020; Casado 2021; He et al. 2021; Ferreira et al. 2021; Hunt and Reffert 2021; Xiang et al. 2021). An important requirement to be able to carry out reliable studies of the Galactic cluster population is that OC parameters are derived in a homogeneous manner. The inhomogeneous analysis combining different data sets and/or methods may lead to discrepant or biased results, as has been noted by Netopil et al. (2015) and Carraro et al. (2017). In this sense, the high quality...
of the Gaia data allows the systematic and homogeneous derivation of OC parameters with very good precision (e.g. Soubiran et al. 2015, Bossini et al. 2019, Cantat-Gaudin and Anders 2020, Cantat-Gaudin et al. 2020, Agarwal et al. 2021, Tarrio et al. 2021).

There are, however, two important issues that must be taken into account in deriving cluster parameters, especially when performing massive data processing. The first one refers to the size of the sample used to extract the data to work with. This is a very important first step that usually is decided in advance to data processing. As discussed in Sánchez et al. (2010), if the radius of the circular area around the cluster used to extract the data (the sampling radius, \( R_s \)) is much smaller than the actual cluster radius (\( R_c \)) then the cluster is obviously subsampled. In order to avoid this situation, usually a “large enough” \( R_s \) is selected. The problem is that if \( R_s \gg R_c \) then the contamination by field stars affects the determination of memberships and, consequently, the determination of the cluster properties, including the radius itself (Sánchez et al. 2010). Ideally a relatively high \( R_s \) value should not affect the membership determination, but depending on membership assignment criteria and/or measurement errors the contamination by field stars could become significant and, in any case, it tends to be higher as \( R_s \) increases. Without a previous knowledge of an approximate value of the cluster radius it is difficult to choose the optimal sampling radius \( R_s \approx R_c \). This is probably one of the reasons for the large discrepancies in \( R_s \) reported in the literature because, independently on the used membership assignment method, selected members tend to be spread over the sampled area and the a posteriori determination of \( R_c \) based, for instance, in a radial star density profile, can be biased by the previous selection of \( R_s \) (see discussions in Sánchez et al. 2010, 2018, 2020). For the case of the OC presented in this work (Alessi-Teutsch 9), previously calculated radius values range from 25.7 arcmin (Sampedro et al. 2018) to 31.8 arcmin (Kharchenko et al. 2013), but more discrepant values can be found for other clusters (see for instance Fig. 5 in Sánchez et al. 2020).

The second relevant consideration relates to the limitation of using only Gaia photometry, which may be motivated in part by the high quality (and also homogeneity) of the Gaia data. However, using only the relatively large width Gaia bands can result in degeneracy problems and/or lead to strong systematics when inferring OC parameters (Andrae et al. 2018). The obvious solution would be to complement Gaia photometry with multiband photometry from other surveys such as SDSS (York et al. 2000) or 2MASS (Skrutskie et al. 2006) as done, for example, in Tadross (2018). The larger the set of used photometric bands, the more accurate the estimated stellar parameters without the need of resorting to spectroscopy but, as mentioned above, some caution is required when combining several passbands from different photometric systems.

Based on these considerations, we have started a project to observe and characterize OCs using the 80 cm JAST80 telescope at the Observatorio Astrofísico de Javalambre (OAJ) in Teruel, Spain. The telescope has a panoramic camera (T80Cam) with a large-format CCD of 9200 × 9200 pixels providing an effective field of view of 1.4 × 1.4 deg\(^2\) that is particularly useful for wide field OCs. Moreover, it hosts a set of 12 optical filters, originally defined for the J-PLUS survey (Cenarro et al. 2019), spanning the entire optical range. Here we report the results of the pilot campaign for the cluster Alessi-Teutsch 9 (Dias et al. 2002, Kharchenko et al. 2005), also known as ASCC 10 and MWSC 275 (Bica et al. 2019). Alessi-Teutsch 9, located in the second Galactic quadrant (\( l = 155.61\) deg, \( b = -17.79\) deg) (Kharchenko et al. 2005), is a relatively large cluster for which apparent radii in the range \( 25 - 32 \) arcmin have been reported in works previous to the Gaia era (Kharchenko et al. 2005, 2013, Dias et al. 2014, Sampedro et al. 2017). The mean cluster proper motion, based on less precise catalogues as PPMXL (Roester et al. 2010) or UCAC4 (Zacharias et al. 2013), had disagreeing values in the ranges \( \sim -3.4 \) – \( -1.7 \) mas yr\(^{-1}\) in right ascension and \( \sim 2.2 \) – \( -1.0 \) mas yr\(^{-1}\) in declination (Kharchenko et al. 2005, 2013, Dias et al. 2014, Sampedro et al. 2017, Cantat-Gaudin et al. 2018b) and, consequently, the number of assigned members have varied in the range \( 10^3 - 10^4 \). More recently and using data from Gaia DR2, Cantat-Gaudin et al. (2018a) (see also Cantat-Gaudin and Anders 2020, Cantat-Gaudin et al. 2020) located the cluster proper motion centroid at \( (-1.737, -1.368) \) mas yr\(^{-1}\) with a total of 71 probable members. The method used by Cantat-Gaudin and Anders (2020) applies k-means clustering to search for groupings in proper motions and parallaxes. As other authors, a relatively high initial sampling radius was intentionally assumed and, even though they reported that the radius containing half the members is 33.5 arcmin, the assigned cluster members spread over a radius of \( \sim 70\) arcmin.

In this work we combined 12-band photometry from OAJ for Alessi-Teutsch 9 with Gaia EDR3 data to show (1) the importance of a previous identification of the optimal sampling radius and (2) the advantage of incorporate multiband photometry for a precise and accurate estimation of OC properties. Section 2 describes the observed and used data sets. In Section 3 we determine
the optimal sampling radius, which is used in Section 3 to determine reliable membership criteria and to select the final list of cluster members. Spectral energy distributions for the members, based on OAJ photometry, are derived in Section 5. The cluster properties are presented and discussed in Section 6 and, finally, the main conclusions are summarized in Section 7.

2 Observations and data

2.1 OAJ

Observations were made on February 23 and 24, 2020, with the T80Cam panoramic camera attached to the JAST80 telescope at OAJ (Cenarro et al. 2014). The total field of view is 1.4 × 1.4 deg² and the pixel scale is 0.55 arcsec/pixel. The set of filters covers the optical range, from 3500 to 10000 Å (see Cenarro et al. 2014), and they are presented in Table 1. The cluster properties are presented and discussed in Section 6 and, finally, the main conclusions are summarized in Section 7.

| Name     | λ (Å) | FWHM (Å) | N_{exp} (s) | T_{exp} (s) |
|----------|-------|----------|-------------|-------------|
| uJAVA    | 3485  | 508      | 12          | 603         |
| J0378    | 3785  | 168      | 12          | 813         |
| J0395    | 3950  | 100      | 12          | 843         |
| J0410    | 4100  | 200      | 12          | 408         |
| J0430    | 4300  | 200      | 12          | 378         |
| gSDSS    | 4803  | 1409     | 12          | 93          |
| J0515    | 5150  | 200      | 22          | 631         |
| rSDSS    | 6254  | 1388     | 18          | 204         |
| J0660    | 6600  | 138      | 12          | 588         |
| iSDSS    | 7668  | 1535     | 13          | 138         |
| J0861    | 8610  | 400      | 12          | 978         |
| zSDSS    | 9114  | 1409     | 12          | 528         |

3 Optimal sampling radius

In previous works (Sánchez et al. 2010, 2018, 2020) we have been developing and improving a method for objectively calculating the optimal $R_s$ value for OCs. The method is based on the behavior of the stars in the proper motion space as $R_s$ increases and it is not affected by how its stars are spatially distributed. For a given $R_s$ value, the first step is to identify the cluster overdensity in the proper motion space. For this, radial density profiles are derived for all the available stars in the proper motion space, that is assuming each star as the centre of the overdensity. In each case, an overdensity “edge” is also determined as the point at which the profile changes from a steep to a shallow slope. At this point, average densities are calculated both for the overdensity (the circular region from the starting point to the edge) and for the “local field” (a ring adjacent to the overdensity region). The ring width is chosen such that its area is the overdensity area but with the condition that the minimum number of stars in the ring is 100. These calculations are done for all the starting points (stars) and the cluster overdensity is identified as the one having the highest density contrast between the overdense region and the local field. The core of the method, in its latest version, consists of measuring how much the density of stars in the cluster overdensity increases ($\Delta D_{od}$) as $R_s$ increases. This change is compared with the change in the local field density ($\Delta D_{lf}$), for which a ring surrounding the overdensity is used. The key point is the assumption that $\Delta D_{od} > \Delta D_{lf}$ when $R_s < R_c$ because both field stars and cluster stars are being included inside the overdensity. However, when $R_s \geq R_c$, we expect that $\Delta D_{od} \approx \Delta D_{lf}$ (see details in Sánchez et al. 2020).

The application of this method to Alessi-Teutsch 9 using data from the Gaia EDR3 catalog gives the result shown in Figure 1. Direct application to the full data (red symbols) does not yield a clear result probably because of the relatively low density of stars in Alessi-Teutsch 9 compared to the field stars. Normally, this kind of problems can be solved by applying some kind of data filtering. At this point it is not necessary to use the full sample of stars because the goal is not

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1The exact center is irrelevant because it is recalculated from the final member selection.
yet to find members but only to make a reliable estimate of the cluster radius. If we rule out stars with errors in proper motion higher than 0.3 mas yr$^{-1}$ (the median of the error in the Gaia EDR3 catalog for this sample) then the result improves notoriously (blue symbols in Figure 1) and the point at which $\Delta D_{od} \approx \Delta D_{lf}$ becomes apparent. The valley in the curve observed around $R_s \sim 20$ arcmin could be related to variations in the spatial distribution of cluster stars, but this cannot be stated until the final selection of members has been completed. According to the previous discussion, it is clear that the cluster radius is close to the value $\sim 40$ arcmin and, therefore, this would be the optimal sampling radius.

4 Cluster member selection

From this point we remove any filtering option and get all the stars available in the Gaia EDR3 catalogue. Even though the cluster radius seems to be slightly smaller than 40 arcmin (Figure 1), here we use a conservative sampling radius of $R_s = 40$ arcmin. With this sampling we make a first iteration to determine candidate cluster members based on their proper motions, parallaxes and photometric properties.

4.1 Kinematic candidates

Apart from determining the optimal $R_s$, the used algorithm also yields the position of the overdensity in the proper motion space. In this first iteration the overdensity was found at $(-1.76, -1.44)$ mas yr$^{-1}$ and its radial star density profile in the proper motion space is shown in Figure 2. A Gaussian function with standard deviation $\sigma = 0.10$ mas yr$^{-1}$ fitted very well the overdensity profile, then we select as kinematic candidate members the 125 stars falling inside the $3\sigma = 0.30$ mas yr$^{-1}$ neighbourhood.

4.2 Parallactic candidates

Figure 3 shows the parallax distribution for the kinematically selected stars. We performed a least-square fit to the distribution using two (field and cluster) Gaussian functions that yielded a cluster mean parallax of $\text{plx} = 1.512$ mas with a standard deviation of $\sigma_{\text{plx}} = 0.090$ mas (blue line). From here, the parallax selection criterion $\text{plx} \pm 3\sigma_{\text{plx}}$ yields 67 candidates.

4.3 Photometric candidates

The colour-magnitude diagram for the 67 previously selected stars is shown in Figure 4. The cluster main sequence is clearly visible. In order to select photometric candidates we have also plotted isochrones generated using PARSEC v3.4r (Bressan et al. 2012). The distance can be estimated by adding $+0.017$ mas to

2http://stev.oapd.inaf.it/cgi-bin/cmd
the mean cluster parallax $\text{plx} = 1.512$ mas for taking into account the global parallax zero point of Gaia EDR3 (Gaia Collaboration et al. 2021), which gives a distance of 654 pc. Additionally, we assume solar metallicity and Gaia band extinction coefficients given by Wang and Chen (2019). The best fitted isochrones, determined mainly by eye, were those with extinction around $A_G = 0.6$ mag and ages in the range $\log T = 8.4 - 8.6$ Myr (black and blue lines in Figure 4). Given that, at this point, we are working with only one cluster and few photometric bands, it is not necessary to use a more sophisticated fitting procedure that will probably lead to similar results (e.g. Jeffery et al. 2016). The obtained age range is smaller than the age given by Kharchenko et al. (2013) (8.72 Myr) and higher than the recent estimation by Dias et al. (2021) (8.19 Myr), but it is in agreement with the values reported by Bossini et al. (2019) (8.60 Myr), Zhang et al. (2019) (8.45 Myr) and Cantat-Gaudin et al. (2020) (8.42 Myr). As photometric selection criterion we use an isochrone of 8.5 Myr shifted $\pm0.2$ mag in $(G_{BP} - G_{RP})$ (red lines in Figure 4), which yields 60 stars.

4.4 Cluster member selection

Once established the best kinematic, parallactic and photometric membership criteria, we repeat the strategy of spanning the sampling radius $R_s$. This is the procedure originally suggested in Sánchez et al. (2010) for a reliable estimation of the actual cluster radius regardless of the membership assignment method. The expected behaviour is that the number of members $N_m$ increases as $R_s$ increases until the point $R_s = R_c$ and then $N_m$ remains nearly constant (for the ideal case of a “perfect” membership assignment) or increases but at slower rate (for more realistic situations with some contamination by field stars). Actually, what we do is not just to determine the member stars but also to estimate the number of spurious members, i.e. the expected number of field stars fulfilling the membership criteria. For this, we use the “local” field stars defined as those stars falling in a concentric ring around the proper motion overdensity. The calculated local field density of stars allows us to estimate the proportion of field star contamination in the overdensity and in the final number of assigned members. Then, we estimate $N_m$ as the number of stars fulfilling the membership criteria minus the expected number of spurious members. Figure 3 is the plot of $N_m$ versus $R_s$ for Alessi-Teutsch 9 using data from Gaia EDR3. Open circles refer to the number of members estimated by using exclusively kinematic criteria (proper motions), which is the strategy previously used in Sánchez et al. (2010, 2015, 2020). Although the curve is somewhat noisy, the expected change of slope is clearly observed around $R_s = 35$ arcmin. If the full set of membership criteria is used (solid circles) then the change of slope is less pronounced but still visible at the same point. This result is consistent with Figure 1 but now we can undoubtedly assign the value $R_c = 35$ arcmin to the cluster radius. According to our results, the number...
of stars fulfilling the membership criteria are 55 from which we expect that \( N_m = 45 \).

5 Spectral energy distributions

The physical properties of the stars can be derived by fitting theoretical spectra to their Spectral Energy Distributions (SEDs). In order to create a well sampled SED (over a wide wavelength range), usually it is assembled or complemented with photometric information from different catalogues. In these cases, great care must be taken when cross-matching different catalogues and combining different photometric systems. An advantage of using OAJ data rather than cross-matching different catalogues is that we have homogeneous multiband photometry in 12 filters spanning the entire optical range. The SEDs of the 55 selected stars were analyzed using the Virtual Observatory SED Analyzer (VOSA) tool developed by the Spanish Virtual Observatory (Bayo et al. 2008). VOSA has a friendly interface that allows the user to choose different models and parameter ranges to find the spectrum that best reproduces the observed data.

For the fitting procedure we used the ATLAS9 Kurucz ODFNEW/NOVER models (Castelli et al. 1997). Given that the fitting process is quite insensitive to some parameters, such as surface gravity (Bayo et al. 2008), we fixed both metallicity and surface gravity around the expected values, i.e. solar metallicity and \( \log g = 4 \). Additionally, we adopted the previously obtained distance (654 pc) to all the stars. Both the effective temperature \( T_{\text{eff}} \) and the visual extinction \( A_V \) were considered as free parameters. Even though not all the stars had valid magnitudes in the 12 photometric bands, their SEDs were well-fitted by the models and converged to valid (physically reasonable) solutions. Figure 6 shows the results for two examples: the best and the worst obtained fit. \( T_{\text{eff}} \) and \( A_V \) values were inferred for the 55 stars from the fit of their SEDs. Effective temperatures are all in the range \( T_{\text{eff}} = 3500 - 13000 \) K. The mean \( A_V \) value is 0.65 mag (the median is 0.60 mag) with a standard deviation of 0.19 mag. Our mean visual extinction is higher than the value reported by Cantat-Gaudin et al. (2020) (0.43) and smaller than that by Dias et al. (2021) (0.82), but it agrees with the extinction estimated by Cantat-Gaudin et al. (2020) (0.63). There are 41 stars with extinctions and temperatures calculated using only Gaia DR2 photometry by Andrae et al. (2018). For these 41 stars, the mean extinction reported in Gaia’s G band is \( A_G = 0.66 \text{mag} \) (standard deviation 0.23 mag). However, effective temperatures reported in Gaia DR2 are systematically smaller than the ones derived in this work by using multiband photometry from OAJ, as can be seen in Figure 7. The data points that deviate the most from the 1:1 line in Figure 7 correspond to the hottest stars \( (T_{\text{eff}} > 10^4 \text{K}) \) and this is because Andrae et al. (2018)’s calculations were restricted to the range 3000 – 10000 K.

6 Properties of the open cluster Alessi-Teutsch 9

The full list of cluster members, including properties resulting from SED fitting, is provided in Table 2 (fully available online). The mean properties of Alessi-Teutsch 9 derived directly from the selected members are summarized in Table 3 where a comparison is also made with other works, especially the most recent studies using data from Gaia DR2 (Bossini et al. 2019, Cantat-Gaudin and Anders 2020, Cantat-Gaudin et al. 2020). Out of these 55 members, 45 are listed in the catalogue of Cantat-Gaudin and Anders (2020), although only 37 were assigned as probable members \( (p > 0.5) \). If we restrict to stars brighter than \( G = 18 \) mag, the constraint imposed by Cantat-Gaudin and Anders (2020), then we get 49 members from which 45 (92%)

\[ \text{We carried out some tests keeping metallicity and surface gravity as free parameters and the results did not differ significantly from those reported here.} \]
Fig. 6 Two examples of fitted SEDs. Dashed lines are the original observed photometric data, solid circles with error bars indicate dereddened data points and solid lines are the best fitted Kurucz model. Left panel corresponds to the best result for which \( T_{\text{eff}} = 13000 \) K and \( A_V = 0.6 \) mag whereas right panel is the worst case with \( T_{\text{eff}} = 6000 \) K and \( A_V = 0.6 \) mag.

Table 2 List of star members of the open cluster Alessi-Teutsch 9 and their derived properties including equatorial coordinates (J2000), proper motions, parallaxes, magnitudes and colors in the \textit{Gaia} bands, visual extinctions, effective temperatures, bolometric luminosities, and stellar masses and radii.

| RA$_{\text{J2000}}$ | DE$_{\text{J2000}}$ | \( \mu_\alpha \cos \delta \) | \( \mu_\delta \) | \( p \times \) | \( G \) | \( B - R \) | \( A_V \) | \( T_{\text{eff}} \) | \( L_{\text{bol}} \) | \( M \) | \( R \) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| (deg) | (deg) | (mas/yr) | (mas/yr) | (mas) | (mag) | (mag) | (mag) | (K) | (\( L_\odot \)) | (\( M_\odot \)) | (\( R_\odot \)) |
| 51.870058 | 34.983293 | -1.720 | -1.398 | 1.4843 | 13.910 | 1.067 | 0.60 | 6000 | 1.35 | 0.42 | 1.07 |
| 51.915978 | 35.023862 | -1.776 | -1.462 | 1.4968 | 11.943 | 0.501 | 0.60 | 8000 | 8.66 | 0.84 | 1.52 |
| 51.806890 | 34.944837 | -1.857 | -1.639 | 1.5207 | 12.362 | 0.681 | 0.60 | 7250 | 5.72 | 0.83 | 1.51 |
| 51.788046 | 34.984700 | -1.757 | -1.639 | 1.5207 | 12.362 | 0.681 | 0.60 | 7250 | 5.72 | 0.83 | 1.51 |
| 51.909316 | 34.914086 | -1.702 | -1.351 | 1.6150 | 19.350 | 2.727 | 0.75 | 3500 | 0.01 | 0.04 | 0.35 |

Note: here we show only a portion for guidance regarding table form and content. The full version is available online.

are in common with their catalogue. The 4 remaining stars are fainter than \( G = 17 \) mag but showing no particularities in spatial positions, proper motions, parallaxes or their errors and they likely come from the different methods used or from the differences in proper motions and parallaxes between \textit{Gaia} DR2 and EDR3. However, the sampling radius used by Cantat-Gaudin and Anders (2020) is around twice ours. If we use \( R_s = 70 \) arcmin instead of \( R_s = 35 \) arcmin we obtain a total of 79 stars fulfilling membership criteria, a number very similar to the 71 members reported by Cantat-Gaudin and Anders (2020). In this case, the estimated number of spurious members is 19, which means a field star contamination of 24%. Then, it is reasonable to assume that about a quarter of Cantat-Gaudin and Anders (2020)'s members are actually spurious. Using an unsuitable sampling radius may obviously affect the estimate of some important parameters, such as for instance the total cluster mass. Other parameters could be less affected. For Alessi-Teutsch 9, using \( R_s = 70 \) arcmin, cluster’s center shifted by \( \sim 4 \) arcmin, proper motion centroid by \( \sim 0.01 - 0.02 \) mas yr\(^{-1}\) and distance remained unchanged. However, depending on the nature of the data and on the details of the used method, these differences could be more significant and hence the importance of a reliable previous determination of the optimal sampling radius.

Figure 8 shows the spatial distribution of the 55 member stars. It appears quite irregular although a central concentration of stars can be discerned. The corresponding radial density profile is plotted in Figure 9. The small “valley” seen around \( r \sim 15 \) arcmin roughly agrees with that observed in Figure 1 and indicates an apparent lack of stars in this region. Given the relatively low number of members, this feature is likely a random fluctuation. What does seem clear is a two-component structure in the radial profile: a more concentrated core of radius \( R_{\text{core}} \sim 12 - 13 \) arcmin and an outer halo extending out to \( r = R_c \). These values are consistent with the relation \( R_c \sim 3R_{\text{core}} \) found by Maciejewski and Niedzielski (2007). We analysed sepa-
Fig. 7 Comparison between effective temperatures reported in Gaia DR2 and those derived in this work for the 41 stars with data in common. Solid line is the 1:1 relation.

Fig. 8 Spatial distribution of Alessi-Teutsch 9 members relative to the cluster’s center.

Cluster mean proper motion derived in this work differs by less than $\sim 0.1 \text{ mas yr}^{-1}$ from that calculated by Cantat-Gaudin and Anders (2020), that is the typical proper motion uncertainty in the sample. The differences with earlier works (Kharchenko et al. 2013; Dias et al. 2014; Sampedro et al. 2017) are much larger ($> 1 \text{ mas yr}^{-1}$) but this is not surprising since these studies were carried out with less precise data from the PPMXL or UCAC4 catalogues. The number of assigned members in these catalogues previous to Gaia is unrealistically high ($\sim 10^3$) likely because of the same reason: larger proper motion errors imply larger overdensity areas and a higher number of kinematic candidates.

Regarding the cluster distance, our result (654 pc) lies in between the estimates by Kharchenko et al. (2013) and Bossini et al. (2019) and close to the result of Cantat-Gaudin and Anders (2020) (see Table 3). At this distance, the cluster linear radius is 6.7 pc and the corresponding number density of stars would be $\Sigma_c \approx 0.06 \text{ star/pc}^3$. This makes Alessi-Teutsch 9 one of the less dense known OCs. Star density is a parameter difficult to determine accurately because it depends on the actual cluster radius, which is an uncertain parameter as already discussed in this work (see also Sánchez et al. 2018, 2020). We cross-matched Cantat-Gaudin and Anders (2020)’s catalogue with de Sánchez et al. (2020)’s catalogue of reliable OC radii and we found 334 clusters in common, of which only one had a star density smaller than Alessi-Teutsch 9 (Ruprecht 45 with $\sim 0.04 \text{ star/pc}^3$). The corresponding relaxation time, the time necessary for the cluster to reach a Maxwellian velocity distribution, can be cal-

### Table 3 Mean parameters of Alessi-Teutsch 9

| Parameter                      | This work | Other works | Ref. |
|--------------------------------|-----------|-------------|------|
| Right ascension (deg)          | 51.8261   | 51.8700     | (1)  |
| Declination (deg)              | 34.9361   | 34.9810     | (1)  |
| $\mu_\alpha \cos \delta$ (mas yr$^{-1}$) | $-1.801$  | $-1.737$    | (1)  |
| $\mu_\delta$ (mas yr$^{-1}$)   | $-1.427$  | $-1.368$    | (1)  |
| Number of members              | 55        | 71          | (1)  |
| Distance (pc)                  | 654       | 672         | (1)  |
| $\log(\text{age})$ (Myr)       | 8.5       | 8.42        | (2)  |
| $A_V$ (mag)                    | 0.65      | 0.63        | (2)  |
| Radius (arcmin)                | 35        | 31.8        | (4)  |
| Total mass ($M_\odot$)         | 35.8      |             |      |
| Total luminosity ($L_\odot$)   | 992       |             |      |

References: (1) Cantat-Gaudin and Anders (2020); (2) Cantat-Gaudin et al. (2020); (3) Bossini et al. (2019); (4) Kharchenko et al. (2013); (5) Dias et al. (2021); (6) Zhang et al. (2019); (7) Dias et al. (2014); (8) Sampedro et al. (2017).
Fig. 9  Radial spatial density profile for the cluster Alessi-Teutsch 9. The bins are 5 arcmin wide and the vertical error bars are estimated by assuming Poisson statistics.

Calculated as \[ T_E = \frac{0.06 \, N_m^{1/2} R_h^{3/2}}{G^{1/2} \, m^{1/2} \, \log(0.4N_m)} \] (1)

being \( N_m \) the number of cluster members, \( R_h \) the half-mass radius and \( m \) the mean mass of the cluster stars (\( G \) is the universal gravitational constant). Taking \( m = 0.5 \, M_\odot \) and assuming that \( R_h \approx R_c/2 \) we get \( T_E \approx 40 \) Myr, which means that Alessi-Teutsch 9 is a (very) relaxed system. Additionally, based on the diagnosis criterion proposed by Gieles and Portegies Zwart (2011), we can say that Alessi-Teutsch 9 is gravitationally bound because its crossing time, which is of the same order of magnitude as \( T_E \) (Spitzer and Hart 1971), is significantly smaller than its age. Note that choosing an unsuitable value of \( R_c = 70 \) arcmin (and \( N_m = 79 \)) yields \( T_E \approx 130 \) Myr. Reliable estimates of important characteristic times (e.g. dynamical relaxation time, crossing time or evaporation time) can be obtained only if reliable measurements for the radius, number of members or total mass are available.

7 Conclusions

This paper describes a pilot study that implements a novel approach to determine the properties of an OC in a reliable way. For a given set of membership criteria, the number of estimated cluster member should be plotted as a function of the sampling radius. The point at which the slope of the curve flattens indicates

the actual cluster radius and both member stars and cluster properties should be derived at this point. By using this strategy, we used data from Gaia EDR3 to study the cluster Alessi-Teutsch 9 and we obtained a radius of 35 arcmin and 55 member stars, from which we expect that \( \sim 10 \) are spurious (field stars fulfilling the membership criteria). We complemented this data with observed 12-bands photometry to determine the final cluster properties (Table 3). Our results show that Alessi-Teutsch 9 is a bound, dynamically relaxed cluster having a very low number density (\( \sim 0.06 \) star/pc\(^3\)) and a two-component structure with an outer halo and a central core of radius \( \sim 12 - 13 \) arcmin.

Currently, there is a prevailing approach to determine OC properties with totally automated techniques (see Gao 2018; Yontan et al. 2019; Gad 2020; Agarwal et al. 2021, for recent examples). For these cases, we highlight the importance of choosing an optimal sampling radius previous to any calculation. Additionally, it is important to complement the large width Gaia bands with photometry in multiple narrow or medium bands such as the 12 filters used in this work. However, addressing this last issue is not straightforward because it involves dedicated observations in multiple filters per each cluster. In this sense, the forthcoming data from the Javalambre-Physics of the Accelerated Universe Astrophysical Survey (J-PAS, Benítez et al. 2014) could be very useful. J-PAS will cover at least 8000 deg\(^2\) using a unique set of 56 optical filters and these data can be used to apply the proposed approach to OCs falling within the survey area.

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\(^4\)This equation actually refers to the relaxation time at the half-mass radius, because \( T_E \) varies through the cluster.
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Conflicts of interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.
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