Analysis of binary star cluster candidates with Gaia DR2

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Abstract. Two star clusters can be located near each other as a result of either simultaneous birth or system encounters, and thus are called a binary star cluster system. We analyzed three candidates of binary cluster: ASCC 16-ASCC 21, NGC 6716-Collinder 394, and NGC 2547-Pozzo 1 based on Gaia DR2. Each pair have physical separations of 13 pc, 13 pc, and 42 pc. In order to constrain the binarity of the candidates, we investigated their morphology, age estimates, photometric mass, and kinematics.

1. Introduction
The interest in binary star clusters started relatively recent after Bhatia and Hatzidimitriou [1] identified 69 pairs of binary star clusters in Large Magellanic Cloud (LMC) with projected separations of less than 18 pc. Such and subsequent studies revealed that the fraction of star clusters in pairs in the Magellanic Clouds were about 10% [e.g., 2, 3].

In the Milky Way, the existence of binary star clusters has been known retrospectively since antiquity with the existence of h + χ Persei, although it remained as the only known such system until Subramaniam et al. [4] published a list of candidate pairs in the Galaxy with physical separations of less than 20 pc. The existence of binary star clusters in the Galaxy was then revisited by de la Fuente Marcos and de la Fuente Marcos [5], who identified 34 pairs of binary candidates with physical separations of less than 30 pc.

The two clusters in a binary system may originate from the same molecular cloud, or from distinct clouds and formed via tidal capture. The lifetime of binary star cluster systems is relatively short. There are three possible fates of such systems: mergers, disruptions, and separations. There are several factors at play, such as the mass ratio of the system, initial separation of the pair, orbital eccentricity, and orbital inclination with respect to the galactic tidal field. Pairs with tight orbits tend to end in mergers or disruptions, while pairs with wide orbits typically become separated due to the galactic tidal field [6–8].

A cluster in a binary system might experience tidal distortions due to its companion [9]. This is an important evidence of the pair being a true binary instead of a chance alignment, particularly for pairs in the Magellanic Clouds since we cannot determine their true physical separations. Such distortions in cluster morphology can be analyzed from isodensity maps [e.g., 10, 11].

This work attempts to provide characterization of binary star cluster candidates in the Galaxy with astrometric and photometric data obtained by Gaia DR2. Three candidate pair of binary
Table 1. Cluster parameters according to Cantat-Gaudin et al. [14]. The table shows cluster names, equatorial coordinates (\(\alpha, \delta\)), proper motions in \(\alpha\)– and \(\delta\)–direction (\(\mu_{\alpha*}, \mu_\delta\)), the number of member stars (\(N\)), average parallax (\(\overline{\varpi}\)), distance (\(d\)), age (\(\log \tau\), taken from Bossini et al. [15]), and physical separation between the clusters (\(s\)).

| Cluster | \(\alpha, \delta\) | \(\mu_{\alpha*}, \mu_\delta\) | \(N\) | \(\overline{\varpi}\) | \(d\) | \(\log \tau\) | \(s\) |
|---------|-------------------|-----------------|------|-----------------|------|----------------|------|
| ASCC 16 | 081.198, +01.655  | 1.355, -0.015   | 220  | 2.838           | 348.8| 7.085          | 13   |
| ASCC 21 | 082.179, +03.527  | 1.404, -0.632   | 131  | 2.866           | 345.5| 7.063          |       |
| Collinder 394 | 283.092, -20.229 | -1.459, -5.882  | 183  | 1.388           | 705.9| 8.032          |       |
| NGC 6716 | 283.616, -19.888 | -1.476, -6.013  | 86   | 1.405           | 697.3| 7.932          | 11   |
| NGC 2547 | 122.525, -49.198  | -8.609, 4.262   | 233  | 2.853           | 387.2| 7.432          |       |
| Pozzo 1  | 122.374, -47.335  | -6.516, 9.530   | 390  | 2.853           | 346.9| 7.117          | 42   |

Star cluster systems are chosen in this study: ASCC 16-ASCC 21, NGC 6716-Collinder 394, and NGC 2547-Pozzo 1. For each pair, we examine the clusters’ morphology, mass estimates, and kinematics in order to assess the nature of its binarity.

2. Data analysis

2.1. Gaia Data Release 2

Gaia is an on-going mission aiming at providing data on positions and motions of more than one billion of stars in Milky Way. Gaia Data Release 2 provides celestial position (\(\alpha, \delta\)), proper motion (\(\mu_{\alpha*}, \mu_\delta\)), and \(G_{\text{mag}}\) band photometry (330–1050 nm), of 1.7 billion sources. Two other photometry bands, \(G_{\text{BP}}\) (330–680 nm) and \(G_{\text{RP}}\) (680–1050 nm) are available for around 1.4 billion sources. In addition, Gaia also provides the average velocities of 7 million sources as observed for 22 months [12, 13].

2.2. Analysis

The three candidates chosen are ASCC 16-ASCC 21, NGC 6716-Collinder 394, and NGC 2547-Pozzo 1. According to the Galactocentric coordinates from Cantat-Gaudin et al. [14], hereafter CG18, each pair have separations of 13 pc, 11 pc, and 42 pc, respectively. The cluster parameters according to CG18 are presented in table 1.

For each pair, a cone search on Gaia DR2 is queried to obtain the astrometric and photometric data of stars in the region. The radius of each cone search region is adjusted based on the size of each cluster and the separation between the two clusters in each pair so that each region contains two clusters as a whole.

We perform quality cuts in astrometric data by taking only stars with the ratio of parallax to parallax error \(\varpi/\sigma_\varpi > 10\) and the ”astrometric excess noise” \(< 1\) mas, as suggested by Lindegren et al. [16] (Appendix C).

These regions contain stars that are bound to clusters (cluster members) and stars that are unbound (field stars). Members of a star cluster are supposed to be concentrated in spatial space (in this case, \(\alpha, \delta, \varpi\)) as well as in kinematic space (\(\mu_{\alpha*}, \mu_\delta\)). In order to minimize the contamination of field stars and quantify the probability of a star belonging to a cluster, we use a non-parametric method with kernel density estimation. This method has been widely used in distinguishing member stars from field stars [e.g. 17].

In principle, we measure the local density value around a point \(x_i\) in a region using a kernel function \(K(x)\), with \(x = (x^1, x^2, ..., x^n)\) is the coordinate of the point in \(n\)–dimensional space, which can be represented by

\[
\Psi(x_i) = \sum_{j=1}^{N} K(x_j),
\]
where \( K(x) \), using symmetric Gaussian kernels, would take up the form

\[
K(x) = \prod_{k=1}^{n} \frac{1}{h \sqrt{2\pi}} \exp\left(-\frac{1}{2} \frac{(x_{k} - x_{i,k})^2}{h^2}\right),
\]

(2)

with \( h \) as the smoothing parameter.

For each pair, the application of the method is as follows. We set two circles around the cluster centers in spatial space \((\alpha, \delta)\) according to CG18. The stars contained in each circle are expected to be members of the respective clusters plus some number of field stars. Kernel estimation is then applied to obtain the distribution of cluster members on 2-dimensional kinematic space \((\mu_{\alpha}, \mu_{\delta})\). Smoothing parameter is calculated with Silverman’s rule,

\[
h = \left(\frac{4}{k+2}\right)^{1/(k+4)} \sigma N^{-1/(k+4)},
\]

(3)

where \( \sigma \) is the average marginal variance, defined as \( \sigma^2 = \Sigma \sigma_i^2 / k \), being \( \sigma_i \) \( (i = 1, \ldots, k) \) the standard variation of sample coordinates. We denote these distributions of cluster members, still contaminated by field stars, as \( \Psi_{\text{c+f}}^{\text{kin}} \).

To obtain the distribution of field stars, the same steps are applied to sample stars contained in five circles located at the outskirts of the field of view, where we would expect the contribution from cluster members is minimal. The field star distribution, \( \Psi_{\text{f}}^{\text{kin}} \) is taken as the average of the five sample regions. Therefore, the ‘clean’ distribution of cluster members would be \( \Psi_{\text{c}}^{\text{kin}} = \Psi_{\text{c+f}}^{\text{kin}} - \Psi_{\text{f}}^{\text{kin}} \). The probability of a star belonging to a cluster is taken as, for each space, \( P_{\text{kin}} = \Psi_{\text{c}}^{\text{kin}} / \Psi_{\text{c+f}}^{\text{kin}} \). These steps are repeated for 1-dimensional parallax distribution.

Since we treat the kinematic space and parallax independently, there are stars with high membership probability on parallax space, but low membership probability on kinematic space. To eliminate field contamination in spatial space, we consider stars with probability in kinematic space \( P_{\text{kin}} = 0 \) and probability in parallax space \( P_{\text{par}} > 0.5 \) as the field stars. Kernel density estimation is then applied to the whole region to obtain \( \Psi_{\text{c+f}}^{\text{sp}} \) and to the field stars to obtain \( \Psi_{\text{f}}^{\text{sp}} \). The smoothing parameters for this step is set to be equivalent to 2 pc for each pairs. The ‘clean’ distribution is also \( \Psi_{\text{c}}^{\text{sp}} = \Psi_{\text{c+f}}^{\text{sp}} - \Psi_{\text{f}}^{\text{sp}} \) and the probability is \( P_{\text{sp}} = \Psi_{\text{c}}^{\text{sp}} / \Psi_{\text{c+f}}^{\text{sp}} \).

Finally, we consider the stars with \( P_{\text{fin}} = P_{\text{kin}} P_{\text{par}} P_{\text{sp}} > 0.5 \) as members of a cluster.

3. Results and discussion
3.1. Membership results and morphology

The membership analysis performed gives slightly different parameters for each cluster, as can be seen in table 3.1. The result of membership analysis for each pair of clusters can be seen in figure 3.

In the case of NGC 2547–Pozzo 1, the kinematics of the two clusters are significantly different, so the resulting members are segregated automatically by their kinematics. In contrast, for ASCC 16–ASCC 21 and particularly Collinder 394–NGC 6716, the kinematics between the two clusters in each pair are almost indistinguishable. Therefore, we assign the stars manually according to the nearest cluster centroid. In figure 4, we see that Collinder 394–NGC 6716 barely appears to be two separate clusters. However, figure 5 which is the result of field decontamination in spatial space, reveals that there are indeed two centroids in the region.

Figure 6 also reveals the projected morphology of the clusters. ASCC 21 appears to be somewhat irregular in shape and is less concentrated than its companion ASCC 16. Collinder 394 and NGC 6716 seems to be elongated to each other, suggesting tidal distortion due to each
Table 2. New cluster parameters based on membership analysis.

| Gugus     | α, δ (deg) | µα*, µδ (mas yr⁻¹) | N (P > 0.5) | ε (mas) | d (pc) | log τ (yr) | s (pc) |
|-----------|------------|---------------------|-------------|---------|--------|------------|--------|
| ASCC 16   | 81.147, +1.690 | 1.344, -0.181 | 320 | 2.824 | 354.061 | 7.00 | 14 |
| ASCC 21   | 82.160, +3.551 | 1.410, -0.512 | 245 | 2.859 | 349.693 | 7.00 |
| Collinder 394 | 283.075, -20.251 | -1.517, -5.870 | 239 | 1.414 | 706.963 | 8.30 | 14 |
| NGC 6716  | 283.572, -19.885 | -1.463, -6.602 | 180 | 1.439 | 695.106 | 8.30 |
| NGC 2547  | 122.377, -47.328 | -6.475, 9.5624 | 264 | 2.867 | 348.810 | 7.10 | 46 |
| Pozzo 1   | 122.536, -49.175 | -8.584, 4.268 | 270 | 2.539 | 393.784 | 7.50 |

Figure 1. The membership analysis results of (a) ASCC 16–ASCC 21, (b) Collinder 394–NGC 6716, (c) NGC 2547–Pozzo 1. For all panels, the horizontal axis is right ascension in degrees and the vertical axis is declination in degrees. Red triangles and blue circles are member stars of the respective clusters in each panel as denoted in the legends, while gray dots are field stars.

3.2. Age and photometric mass estimates

For each cluster, we perform visual fitting on the color–magnitude diagram with PARSEC isochrones in order to estimate cluster age and mass. We adopt solar metallicity Z = 0.0152 for all clusters. Extinction in G mag magnitude A_G and reddening E(G_BP - G_RP) are derived from one free parameter, E(B − V), and calculated as

\[ A_G = R_G \times E(B − V), \]
\[ E(G_{BP} - G_{RP}) = (R_{BP} - R_{RP}) \times E(B − V), \]

where \( R_G = 2.740 \), \( R_{BP} = 3.374 \), and \( R_{RP} = 2.035 \) [19, 20].

The color-magnitude diagrams of clusters and the corresponding isochrone models are shown in figure 3. We find that ASCC 16 and ASCC 21 are a young pair of clusters with ages of 10 Myr, while Collinder 394 and NGC 6716 are an old pair of clusters at about 200 Myr. The third candidate has apparent age difference; NGC 2547 is about 30 Myr old while Pozzo 1 is about 12 Myr old. The age estimates are presented in table 3.1.

Young and similar ages between clusters in a pair, such as ASCC 16–ASCC 21 and to a lesser extent NGC 2547–Pozzo 1, suggest that both clusters are formed from the same molecular
Figure 2. Contour maps representing projected number density of ASCC 16–ASCC 21 (left), Collinder 394–NGC 6716 (center), and NGC 2547–Pozzo 1 (right). For all panels, the horizontal axis is right ascension in degrees and the vertical axis is declination in degrees. The plus and cross symbols mark cluster centers.

Figure 3. Color-magnitude diagrams of (a) ASCC 16–ASCC 21, (b) Collinder 394–NGC 6716, (c) NGC 2547–Pozzo 1. For all panels, the horizontal axis is color $G_{BP} - G_{RP}$ and the horizontal axis is absolute magnitude $M_G$. The symbols are as in figure 1. The dashed (---) and chain (—) lines are isochrone models.

cloud and may be a candidate for primordial binary cluster. Meanwhile, the primordiality of old cluster pairs such as Collinder 394–NGC 6716 is less clear since the similar ages might be due to coincidence if the system is formed via tidal capture. If the information on the metallicity of clusters is available, similar metallicity would support the idea of cluster pairs being primordial since clusters formed from the same molecular cloud is expected to share similar composition.

The isochrone models also provide mass estimates for stars according to star brightness and color. By interpolating the data to the model, we obtained the distribution and the total photometric mass of each cluster. The total photometric masses are reported in table 3.

3.3. Jacobi radii
The gravitational influence of a cluster against the Galactic tidal field can be approximated by Hill sphere, which can be characterized by its Jacobi radius. Jacobi radius of clusters in solar
Table 3. Parameters derived from isochrone fitting and cluster kinematics: photometric mass $M_{\text{phot}}$, tidal radius $r_J$, and the difference in tangential velocity $\Delta v_t$. Also included in this table are pair separation $s$, escape velocity $v_{\text{esc}}$, and radial velocity obtained by Soubiran et al. \[21\] along with the selected number of stars for the calculation $N_{\text{sel}}$.

| Cluster       | ASCC 16 | ASCC 21 | Collinder 394 | NGC 6716 | NGC 2547 | Pozzo 1 |
|---------------|---------|---------|---------------|----------|----------|---------|
| $M_{\text{phot}}$ ($M_\odot$) | 248     | 182     | 301           | 210      | 215      | 192     |
| $r_J$ (pc)    | 8.6     | 7.8     | 9.2           | 8.2      | 8.2      | 7.9     |
| $s$ (pc)      | 13.722  | 13.556  | 46.298        | 4.48     | 13.95    | 4.6     |
| $\Delta v_t$ (km s$^{-1}$) | 0.54    | 0.19    | 6.92          | 0.52     | 0.58     | 0.27    |
| $v_{\text{esc}}$ (km s$^{-1}$) | 0.52    | 0.58    | 0.27          |          |          |         |
| $N_{\text{sel}}$ | 15      | 9       | 3             | 2        | 20       | 27      |

neighborhood can be calculated in terms of Oort constants $A$ and $B$ as

$$r_J = \left( \frac{GM}{4A(A-B)} \right)^{1/3},$$

where $G$ is the gravitational constant, $A = 15.3 \pm 0.4$ km s$^{-1}$ kpc$^{-1}$ and $B = -11.9 \pm 0.4$ km s$^{-1}$ kpc$^{-1}$ \[22\]. The Jacobi radii calculated are shown in table 3.

The Jacobi radii of clusters in a binary systems can be compared to the separation between the two clusters as a hint of its cluster–cluster interaction strength. de la Fuente Marcos and de la Fuente Marcos \[6\] proposed a handy classification scheme for binary star cluster candidates based on their physical separations ($s$) and Jacobi radii ($r_J$).

Cluster pairs

- **Detached**, $r_{J1} + r_{J2} < s$
- **Interacting**, $r_{J1} + r_{J2} > s$
  - Weak, $r_{J1}$ and $r_{J2} < s$
  - Semi-detached, $r_{J1}$ or $r_{J2} < s$
  - Contact, $r_{J1}$ and $r_{J2} > s$.

According to the scheme, ASCC 16–ASCC 21 and Collinder 394–NGC 6716 are classified as semi-detached pairs, while NGC 2547–Pozzo 1 as a detached one. This is consistent with the pairs’ morphology presented in Section 3.1.

3.4. Escape velocity

Another aspect to examine the candidate pairs is checking whether the clusters are gravitationally bound to each other. The clusters relative space velocity to each other $\Delta v$ provides a hint about the bond of the pair by comparing it to the system’s escape velocity,

$$v_{\text{esc}} = \sqrt{\frac{2G(M_1 + M_2)}{s}},$$

where $M_1 + M_2$ is the total mass of the clusters and $s$ is the separation between each other. Note that this formula is only a simplification, since a cluster is not a point mass object and dynamical friction is a key factor in close encounters. Nonetheless, the difference in tangential velocity and escape velocity calculated for each pair and is reported in table 3.

To calculate the relative space velocity of clusters, information on the radial velocity of the clusters is also needed. However, we found that Gaia DR2 does not provide adequate radial velocity data for the member stars of all six clusters. Only several stars in each cluster have their radial velocities measured, and most of them have large uncertainties. In table 3, we
include radial velocity differences taken from Soubiran et al. [21] for all six clusters, which are also calculated from Gaia DR2 and suffers from the same small sample problem.

Looking only at the difference in tangential velocity, it appears that Collinder 394–NGC 6716 is below the system’s escape velocity. However, their radial velocity difference is very large, resulting in a total velocity exceeding the escape velocity. The other pairs also seem to suffer from large radial velocity differences compared to their tangential velocity differences and escape velocities. Nevertheless, more data on radial velocity is needed to constrain the possibility of the pairs being gravitationally bound.

4. Summary
In this work, we examined three candidate cluster pairs in the Galaxy in order to constrain their possible binarity. We investigated the morphology of the clusters, derived their ages and mass estimates, and the relative kinematics.

We found that ASCC 16–ASCC 21 is a candidate binary cluster system with a separation of 13 pc. Both clusters are young and share the same age, 10 Myr, suggesting that they are of the same origin. Collinder 394–NGC 6716 is a strong candidate for a binary star cluster. The clusters are 13 pc from each other, share the same age of 200 Myr, and their morphology indicates that they might be interacting. These two candidate pairs also have small tangential velocity difference, although more information about the radial velocity is needed to assess the possibility of the pairs being gravitationally bound. Meanwhile, the third candidate, NGC 2547–Pozzo 1, is unlikely to be a bound binary system with a separation of 46 pc and having large velocity difference, despite sharing the young and similar ages of 30 Myr and 12 Myr which might suggest a common origin.

Appending the data from stellar radial velocity surveys such as RAVE would be very helpful in analysing the kinematics of candidate cluster pairs. Furthermore, examining the metallicity of cluster pairs will also reveal hints about their formation, as clusters formed from the same molecular cloud will be similar in composition.

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