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Empirical isochrones for single and binary stars in open clusters

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Abstract. We compose systems of empirical isochrones for single and binary stars with various components' mass ratio $q = M_2/M_1$ (M_2 – mass of the secondary component, M_1 – mass of the primary component) in order to search for unresolved binaries and multiple stars in open star clusters. We fit an empirical isochrone for single stars across the main sequence (MS) elements assigned using the HDBSCAN algorithm. Isochrones for binaries are obtained by shifting this empirical isochrone to values determined using PARSEC theoretical isochrones. We determine the parameter q for each source that lies within the corresponding intervals between the binary isochrones. We then plot a probability density distribution of the component mass ratio q and estimate the fraction of binaries in the cluster. This work is focuses on the study of close open star clusters with heliocentric distances less than 200 pc. We consider the color-magnitude diagrams (CMDs) in the Gaia photometric system and the two-index diagrams (TIDs) composed of bands in the visible and infrared wavelengths.

Keywords: open clusters and associations: general; binaries (including multiple): close

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1 Introduction

Multicolor photometry is currently the most efficient way to detect and classify unresolved binaries in stellar clusters. Malofeeva et al. (2022, 2023) proposed the new method for estimating the fraction of unresolved binaries and higher multiplicity systems, where the two-index photometric diagram was introduced. The advantage of the used (H-W2)-W1 vs W2-(BP-K) color combination is that in this diagram binary stars are more clearly distinguished from single stars even for small values of the components' mass ratio q. This is due to the fact that in the near infrared a binary star has a flux excess compared to a single star of the same mass as the primary component.

The method has got some problems. One is the ability to study the sources only in a relatively narrow range of primary component masses. This is due to the fact that in the high-mass range the theoretical isochrones for single stars, binary stars, and multiple systems nearly coincide in this diagram. In addition, the theoretical isochrones do not follow to the cluster sequence well over its entire length, especially in the region of the low-mass sources. To solve this problem, we propose to obtain the empirical isochrones individually for each cluster.

2 Empirical Isochrones and Unresolved Binary Star Fraction

To consider the problem of the unresolved binary star fraction, one should have the samples of the probable cluster members. We use the catalog of Hunt & Reffert (2023), compiled on the base of the Gaia Data Release 3 (Gaia Collaboration et al. 2023). It contains the latest and most complete data. To implement the approach of Malofeeva et al. (2022, 2023) we also need to match these samples with the 2MASS and WISE catalogs (Skrutskie et al. 2006; Wright et al. 2010).

Each cluster has a concentration of stars along the main sequence (MS) in both CMD and TID, provided that there are enough stars in the cluster. In general, we assume that this concentration along the main sequence contains only single stars, while unresolved binaries are deviated. To assign the single MS stars in the diagram, we use the HDBSCAN algorithm. In the first step we usually observe the peculiarities among the assigned points, even after filtering the points using the membership probability of $> 50\,\%$ in the TID case. Therefore, to reduce the peculiarities, we remove the outliers after the first approximation of the sample of single MS stars by a polynomial, using the distance from the point to the polynomial as a measure of a deviation. Then we conduct the second fit with new cleaned sample, and this last fit we call the empirical isochrone for the single stars of the cluster.

Isochrones for unresolved binary systems of a certain q are computed by shifting the empirical isochrone for single stars by the values specified for each cluster. These values are the average distances between the PARSEC theoretical isochrone (Bressan et al. 2012) for single stars and the theoretical isochrones for binary stars with different q in several parts of the MS (Fig. 1). We plot the theoretical isochrones for binary stars using the theoretical isochrone for single stars and a simple relationship for unresolved binary star magnitude derived from Pogson's formula (see this relationship in Malofeeva et al. 2022). We take the fundamental star cluster parameters for theoretical isochrones from the catalog of Dias et al. (2021).

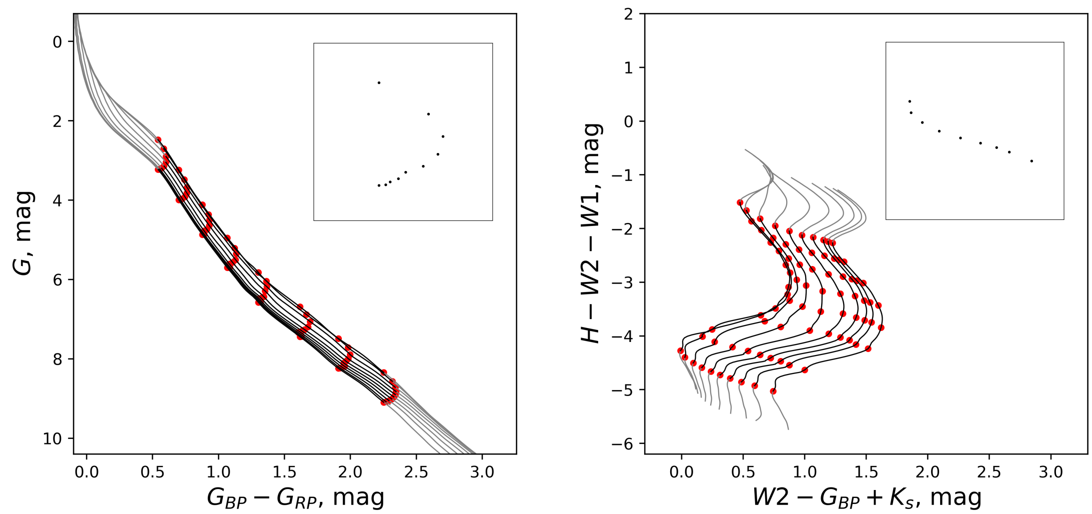

Fig. 1. An illustration of our method for determining the shift values for the empirical isochrones of binary stars. Left: PARSEC theoretical isochrones for single stars and binary stars with different q in CMD. Right: the same for TID. We use the red dots to determine the average shift values for the empirical isochrones of binary stars. These average shift values are shown in small frames with a larger scale.

Diagrams for Melotte 22 (Pleiades) with the empirical isochrones are presented in the top line of Fig. 2. We count the number of sources in the intervals between the isochrones for binary stars and calculate the specific value of the q parameter for each source. Then we use the kernel density estimator (KDE) with the Gaussian kernel to plot the distribution of the component mass ratio q. To estimate the distribution for binaries, we subtract the distribution for sources assigned as single stars by HDBSCAN from the distribution calculated from all data in a particular mass interval (the bottom line of Fig. 2). To consider the dispersion of stars at both sides of the empirical isochrone for single stars, we should introduce the “negative” q values. All distributions for binary stars have a maximum, as noted in Malofeeva et al. (2023). The mode ranges from 0.71 to 0.80 in the Gaia CMD. In the TID we observe a tendency towards a bimodal distribution with a minimum at $q \approx 0.4$. The fraction of binary stars in the cluster is extracted from the distribution by integrating it with the Simpson method. The results are shown in Table 1.

Table 1. The respective primary component mass intervals and fractions of binary stars for seven star clusters. The first column contains the names of the clusters in Hunt & Reffert (2023). Columns 2 and 3 contain the minimum and maximum primary component masses, implemented in this work. The last two columns contain a binary stars fraction estimated in TID (α_1) and in Gaia CMD (α_2).

cluster	$M_{\rm min}$	$M_{\rm max}$	α_1	α_2
IC 2391	0.15	1.55	0.17 ± 0.02	0.19 ± 0.09
IC 2602	0.18	2.27	0.07 ± 0.04	0.1 ± 0.09
Melotte 20	0.22	2.12	0.32 ± 0.04	0.15 ± 0.08
Melotte 22	0.15	1.46	0.22 ± 0.04	0.16 ± 0.07
Melotte 25	0.11	1.76	0.32 ± 0.05	0.23 ± 0.07
NGC 2451A	0.17	1.52	0.11 ± 0.07	0.25 ± 0.08
NGC 2632	0.26	1.78	0.15 ± 0.07	0.15 ± 0.08

3 Summary

In this study we present a new approach to the problem of detecting the unresolved binary stars in the open clusters using multi-color photometry. The introduction of empirical isochrones allows us to achieve a number of advantages:

1. More confident alignment of an isochrone to the main sequence.
2. Exploitation of the Malofeeva et al. (2023) method in a wider range of a primary component mass in the region of low-mass sources.

But this new approach also has the difficulty that the clustering algorithm is not able to distinguish the main sequence condensation (that is, single stars) if the star cluster contains relatively few members or the diagram looks loose.

The results for the binary star fraction show that Malofeeva et al. (2023) tends to overestimate these parameters.

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- from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium

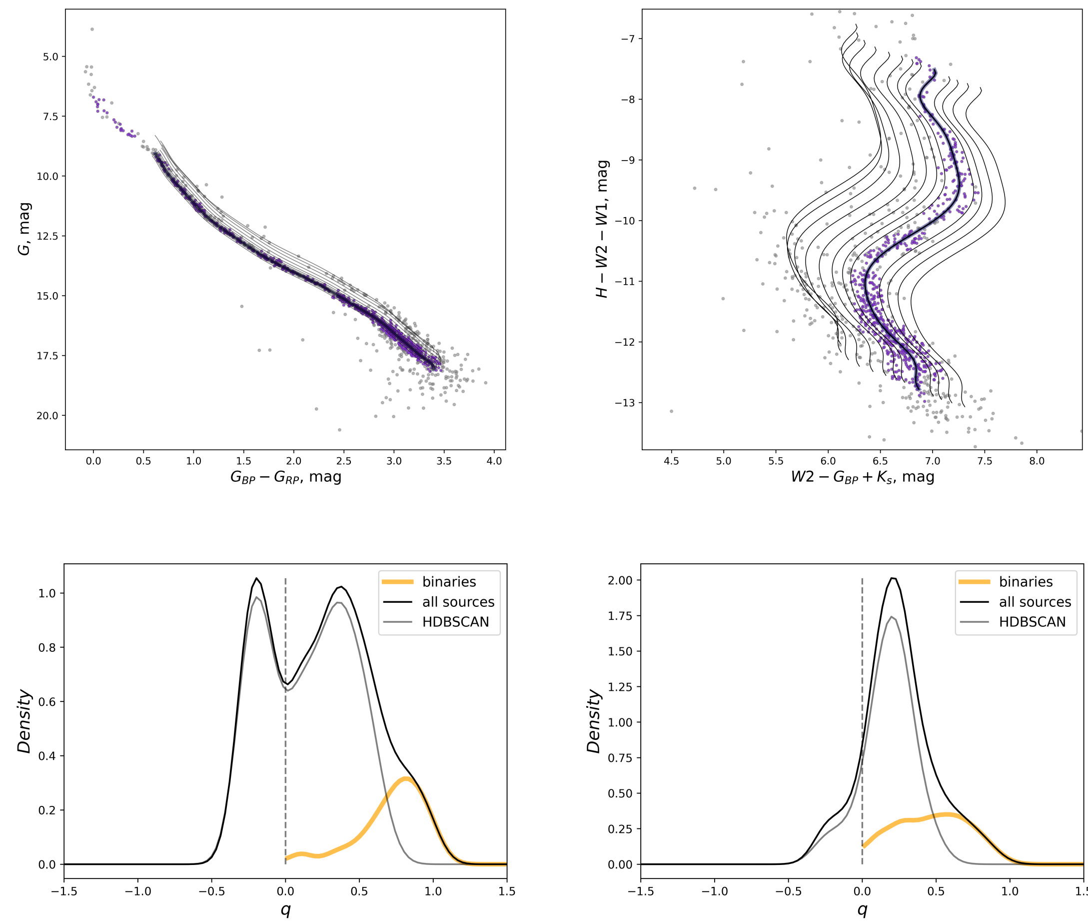

Fig. 2. Top line. Diagrams for Melotte 22. The purple dots indicate HDBSCAN assigned sources (single stars). The thick dark-blue line indicates the empirical isochrone and the thin black lines indicate the empirical isochrones of the binaries. **Bottom line**. The distribution of the component mass ratio q (thick orange line), represented as the subtraction of the distribution for single sources from the distribution for all sources of the cluster in a particular mass interval (see table 1).

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