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Systematic Difference between Eclipsing Binary Stars in Star Clusters and in Galactic Field Revealed with Gaia DR3 Data

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The recent Gaia DR3 all-sky list of candidates for eclipsing binaries including 2,184,477 sources, and the list of probable members of galactic clusters by Hunt & Reffert (2024), are used to identify eclipsing binary stars – members of star clusters, and to compare their general characteristics to those of eclipsing binaries in the galactic field. We find that the distributions over orbital frequencies notably differ from each other due to dynamic evolution of binary star orbits in galactic clusters. On the other hand, the distributions over the depth ratio of minima in clusters and in galactic field are similar, which supports the universality of pairing algorithm during binary star formation.

1 Introduction

Characteristics of the population of binary stars may serve as a key to the processes of star formation and dynamic evolution (e.g. Bate 2015, Marks et al. 2017). In particular, the probable similarities and disparities of populations of binary stars in open star clusters and in the galactic field (which, according to common belief, is largely populated by stars from disrupted clusters) is a matter of significant interest (Kouwenhoven et al. 2011, Belloni et al. 2018).

Discoveries of eclipsing binary stars have recently been exceedingly numerous due to a number of photometric sky surveys repeatedly observing the same sources (Chen et al. 2020, Heinze et al. 2018, Soszyński et al. 2016, etc.). In particular, data on more than 2 million eclipsing binaries were published as a by-product in the framework of Data Release 3 (Gaia Collaboration et al. 2023) of the ESA astrometric space project Gaia (Gaia Collaboration et al. 2016). Eclipsing binaries are detected at the extended distance scale, they are relatively easily identified among other types of variable stars, and they provide a large, uniform dataset to probe galactic populations.

In this work, we use eclipsing binaries (EBs) to probe whether their sample characteristics are basically the same or not in the galactic field and in galactic star clusters. For this task, we employ the Gaia dataset of eclipsing binary stars and the new largest uniform catalogue of galactic star clusters by Hunt & Reffert (2024).

2 Data and methods

We used the catalogue by Hunt & Reffert (2024) as the source of data on 1,291,929 probable members of galactic star clusters, and cross-identified it with the all-sky catalogue of 2,184,477 candidate EBs (Mowlavi et al. 2023) published in the frame of Gaia DR3. As long as both catalogues employ Gaia DR3 identifiers, the result of cross-match was unambigious. Thus, we found that, among Gaia EBs, 3,356 were probable cluster members. Note that galactic clusters usually do not coincide with regions of extreme stellar density in Gaia (unlike globular clusters), so one should expect that the probability of discovery and classification of an EB is unaffected by its probable open star cluster membership. Figure 1 represents the distribution of the total sample of EBs and of the subsample of EB members of star clusters over the sky. The concentration of blue crosses representing cluster members near the galactic coordinates $(l,\ b) \approx (212^\circ,\ -23^\circ)$ originates from Hunt & Reffert (2024) and obviously is caused by a technical mistake there.

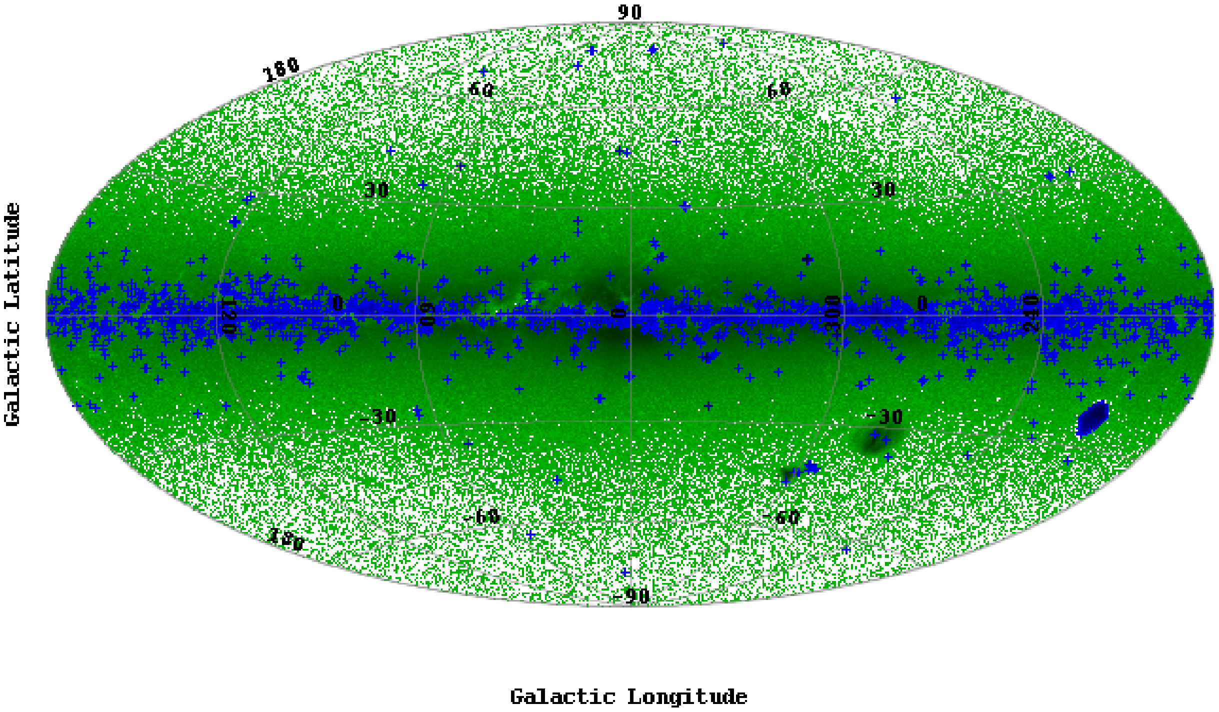

Figure 1.
Distribution of eclipsing binary stars over the sky. All Gaia DR3 candidate eclipsing binaries (green dots) and EBs classified as probable members of open star clusters (blue crosses).

Our goal is to look onto distributions of EBs over parameters least affected by external factors. These are parameters obtained from the light curve (see, e.g., discussion in Avvakumova & Malkov 2014). We choose, as the most representative and distance-independent, the distribution over proxy of period (frequency, in Gaia DR3 catalogue of EBs, in units [1/day]), and distribution over relative depth of primary and secondary minima (depths of both minima are cited in the catalogue of EBs). Frequency is presented for all EBs of the total sample. Both depth of primary minimum and depth of secondary minimum are presented in Gaia DR3 for 2,063,051 EBs, which is 94% of the total sample.

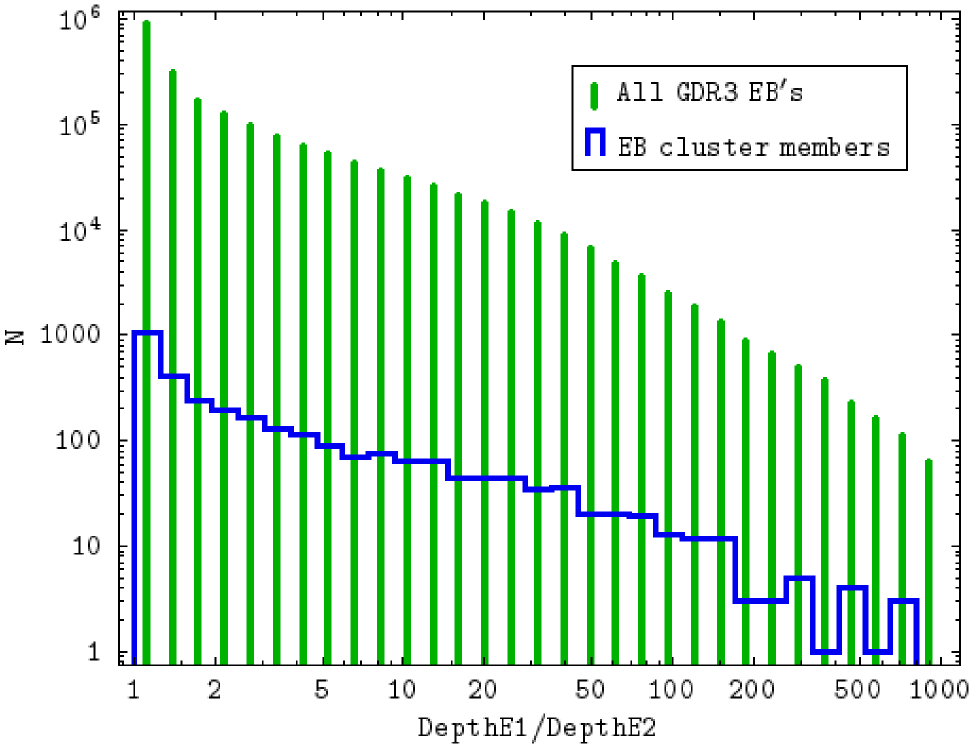

Figure 2.
The distribution of eclipsing binary stars over their ratio of depths of minima. All Gaia DR3 candidate eclipsing binaries (green) and EBs classified as probable members of open star clusters (blue).

We want to know whether characteristics of the subsample of EBs – cluster members agree with the hypothesis that this is a random selection of members of the total sample of EBs. At a glance, the distribution of the total sample of EBs over relative depth of minima is quite similar to the distribution over frequency for EBs that are cluster members (see Fig. 2). On the other hand, the distribution of the total sample of EB's over frequency notably differs from the distribution over frequency for EB's which are cluster members (see respective normalized distributions, Fig. 2). However, one may expect that the procedure of recognition of a star as an EB candidate is multiparametric and affected by a number of effects, and the distribution of the total sample over any characteristics is skewed. It is also unclear whether the number of objects in the subsample (3,356) is sufficient to make conclusions on comparison with the total sample. This is why we employ the following procedure.

We randomly select 100 test subsamples of equal volume (3,356 rows) of the complete sample of EBs. For each subsample, we construct distributions over frequency and over the ratio of depths of minima, and compare the distributions for test subsamples to each other as well as to the subsample of EBs – cluster members. We calculate the χ^2 value for each comparison. The results are described in the following section.

3 Results

Figure 3 represents the distribution of χ^2 values obtained when comparing distributions of EBs over frequency: blue symbols are star cluster member EBs vs 100 random subsamples

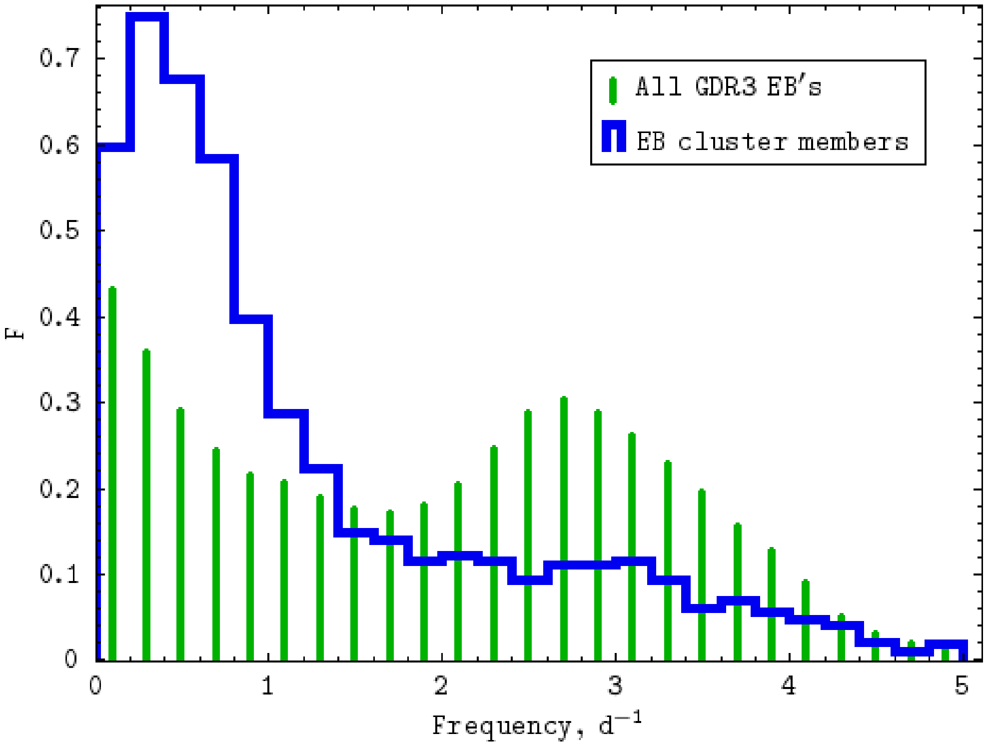

Figure 3.
The normalized distribution of eclipsing binary stars over frequency. All Gaia DR3 candidate eclipsing binaries (green) and EBs classified as probable members to open star clusters (blue).

from the total sample of GDR3 EBs; green symbols are 100 random subsamples from the total sample of GDR3 EBs vs each other. Vertical lines are as follows:

- yellow line ($\chi^2 = 1805$): χ^2 for the comparison between the total sample of GDR3 EBs with star cluster member EBs (see also Fig. 3);
- black line ($\chi^2 = 16.92$): the probability that χ^2 exceeds this critical value for compliant distributions is 5% at the accepted number of degres of freedom ($\nu = 9$);
- red line ($\chi^2 = 16.03$): the median value of χ^2 for the comparison between random subsamples of the total sample of GDR3 EBs.

We see that not all χ^2 values calculated during the comparison of random subsamples comply with each other at freedom degrees $\nu = 9$ calculated as $\nu = N_{bins} - 1$ (though, for more than a half of them, the hypothesis of compliance is not rejected at a 5% level). Actually, the distribution of these χ^2 values allows us to estimate the actual number of freedom degrees as 17. One may suggest that this is due to characteristic of multiparametric space where the dataset is defined. However, the distribution of the star cluster member EBs over frequency is obviously different and cannot be a product of random selection of sources of the total dataset. The yellow vertical line in Fig. 3 marks $\chi^2 = 1805$ for comparison of the total sample of GDR3 EBs with the subsample of cluster members.

At the same time, the distribution over relative depth of minima does not demonstrate a difference similarly obvious. The explanation of this may be as follows. The distribution over frequency reflects characteristics of the orbits of binaries while the distribution over relative depth of minima is formed by the relative astrophysical characteristics of the components of the pair. The observed systematic difference in distribution over frequen-

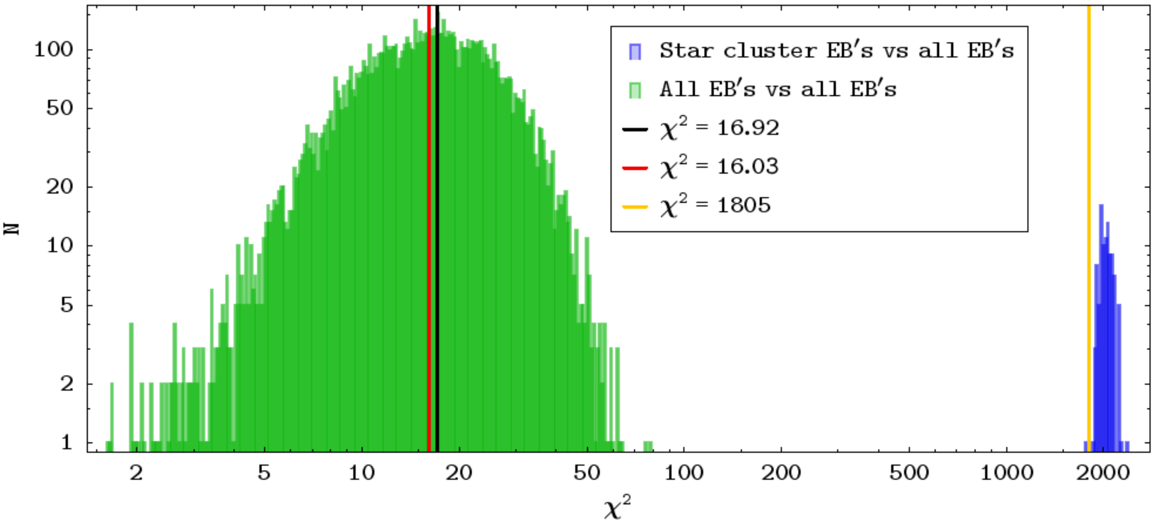

Figure 4.
χ^2 values for random subsamples from all Gaia DR3 candidate eclipsing binaries vs each other (green) and random subsamples vs EBs classified as probable members of open star clusters (blue). Vertical lines correspond to selected χ^2 values, see text for explanations.

cies is the result of dynamic evolution of orbits of binary stars being dependent on their present surroundings (a star cluster or galactic field). In clusters, harder EBs with orbital periods below a day are relatively rare; this may be due to binaries having been softened in dynamic interactions holding the cluster together. On the other hand, the similarity of distributions over the ratio of depths of minima suggests that the pairing algorithm (Kouwenhoven et al. 2009) basically does not depend on present surroundings.

4 Conclusion

The distribution of eclipsing binaries – probable members of galactic star clusters over frequencies notably differs from the distribution of the total sample of eclipsing binaries from Gaia DR3. This is due to dynamic evolution of binary star orbits in galactic clusters. On the other hand, the similarity of distributions over the ratio of depths of minima in clusters and in the galactic field supports the universality of pairing algorithm during binary star formation.

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