Star Clusters: From the Milky Way to the Early Universe
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Structure of the open cluster Collinder 463 revealed by Gaia astrometry

Dmitrij Semionov

Center for Physical Sciences and Technology Vilnius, Saulėtekio al. 3,
LT-10257 Vilnius.Lithuania
email: dmitrij.semionov@ftmc.lt

Abstract. In this work we present our new estimates of the fundamental parameters of the open cluster Collinder 463, based on Gaia astrometric and PanSTARRS photometric data. In addition to updating previously available parameter values we highlight the existence of an extended stellar "halo" which is closely related to the presently known star cluster.

Keywords. open clusters and associations: individual (Collinder 463)

1. Introduction

Open clusters are important actors in the evolution of Galactic stellar populations. Their dynamical disruption alters stellar populations of the Galactic disk over a significant timespan and distance. Signs of these processes such as extended stellar halos and tidal tails are found in open clusters of various ages and in different environments (e.g. Davidge 2012; Carrera *et al.* 2019; Yeh *et al.* 2019). This may provide an insight into conditions around the time of their birth or a last significant interaction with other objects, passage of the Galactic plane, spiral arm molecular complexes etc.

Recently made available Gaia DR2 data provide an outstanding wealth of homogeneous astrometry for exploring dynamics of individual open cluster stars, inviting a closer look at some rarely revisited clusters. One such object is the isolated open cluster Collinder 463 (Cr463, C0144+717). The most recent work by Bossini *et al.* (2019) places this cluster at a distance of 805 pc (distance modulus 9.53) with intervening extinction of $A_V = 0.836^m$, its stellar population is assumed to have solar metallicity and the derived age is 270 Myr.

2. Astrometry

We start by selecting stars in Collinder 463 vicinity that have Gaia 5-parameter astrometric solution and Gaia and PanSTARRS photometry. Having found that the relative parallax error has the most impact on fundamental cluster parameter determination, we use it to constrain the selection by empirically setting an upper relative parallax error limit at 5 % (Fig. 1), discarding most of the field stars and erroneous data at the cost of rejecting some fainter cluster stars.

We have iteratively refined cluster center coordinates and a mean proper motion (PM) by fitting probable member distribution within 30′, 1° and 3° regions. The obtained values $\alpha_{2000} = 27^\circ.11 \pm 0.015$; $\delta_{2000} = 71^\circ.72 \pm 0.015$ and $\mu_\alpha = -1.73 \pm 0.01$ mas/yr; $\mu_\delta = -0.30 \pm 0.005$ mas/yr are close to those established by Bossini *et al.* (2019). However, we estimate the distance to the cluster to be 880 +60 / −30 pc (distance modulus 9.72) which is significantly more than previously published values.

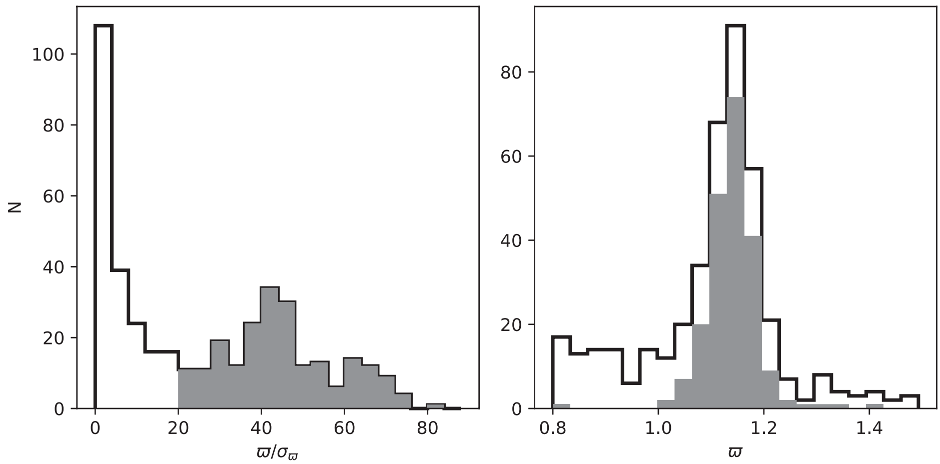

Figure 1. Parallax (right) and relative parallax error (left) of selected stars within the 1° radius from Collinder 463 center and with relative proper motion < 0.4 mas/yr. Shaded area represents the change after removing objects with > 5 % relative parallax error.

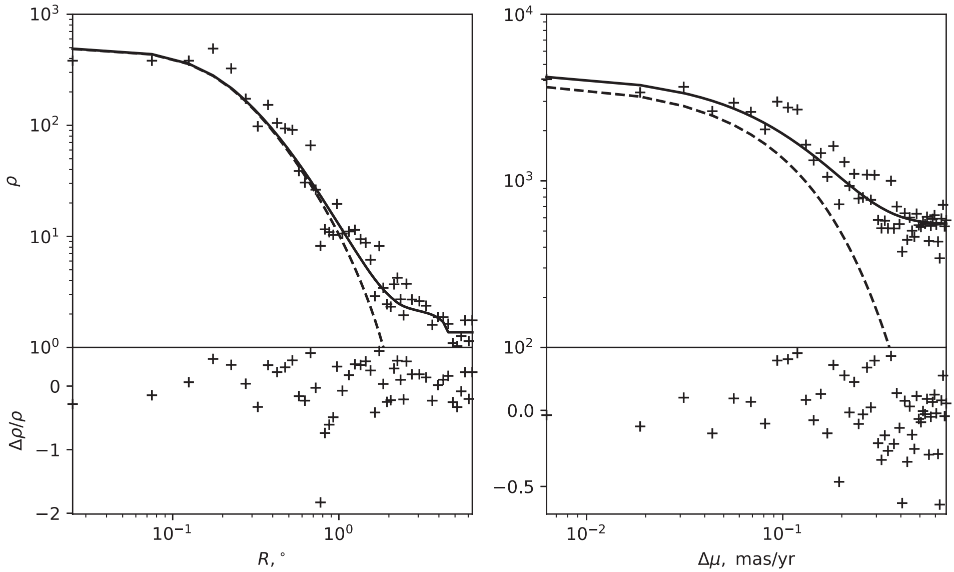

Figure 2. Stellar radial density profile (left) and proper motion distributions (right) of Collinder 463 likely members. Solid lines show the best fit solutions using a modified King profile for radial distribution and an exponential law for relative proper motion. Dashed lines show the respective models without halo and background contributions.

The distribution of individual cluster member PMs with respect to the mean cluster value is well described by a single exponent law with a background offset (Fig. 2). We chose a limiting deviation from the mean PM of 0.4 mas/yr (corresponding to 1.6 km/sec velocity) as a point where the density of cluster members falls below the average density of field stars. While this limit could be too restrictive in the outer halo region for high velocity stars, it allows us to select the central cluster stars with higher confidence.

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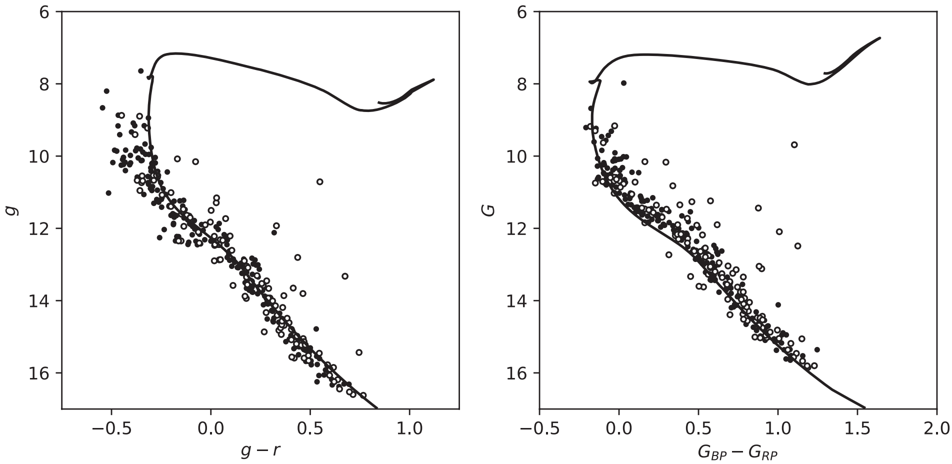

Figure 3. De-reddened color-magnitude diagram of Collinder 463 using PanSTARRS (left) and Gaia DR2 (right) photometry. Circles show stars within 1° (filled) and 3° (open) from the cluster center, with proper motion within 0.4 mas/yr from the mean value and a parallax error <5 %. The solid lines represent a PARSEC isochrone for $\log t = 8.2$ and solar metallicity.

The radial density profile of stars, selected by parallax and PM, exhibits a complex form with distinct "cluster" and "halo" regions, extending to ≈1° and 3° (15 and 45 pc) respectively. Of several radial density distribution profiles, commonly used for analisys of Galactic open clusters (Seleznev 2016; Carrera *et al.* 2019), we have found that Collinder 463 is best described by a modified King profile (Danilov & Putkov 2012) with core, tidal and halo radii of $0.22° \pm 0.02$, $3.0° \pm 0.4$ and $4.25° \pm 0.8$ (3, 45 and 70 pc, Fig. 2). The halo radius is the least defined of the three, showing only a weak dependence on the centering but having a significant scatter when fitting using MCMC methods. A similar profile shape is retained when stars with larger parallax/PM errors are included, however an asymmetric shape of the distribution of outer halo stars must be fully taken into account.

3. Photometry

Using the updated distance modulus value we have performed a de-reddening of selected Collinder 463 stars in Gaia and PanSTARRS photometric systems. Due to the large area, covered by cluster and its halo, using a single extinction value may not be advisable and, as is apparent from the $E(B-V)$ color excess map, produced by the Planck mission and available at NASA/IPAC Infrared Science Archive, cluster stars could exhibit a broad range of extinction values ($E(B-V) \in (0.2^m; 0.7^m)$).

Under assumption that the interstellar extinction in the direction of the cluster is described by a standard law ($R_V = 3.1$) and its amount beyond the cluster is negligible we have assigned to each probable cluster member an A_V value, computed from the Planck color excess map. Obtained results are shown on Fig. 3, overlayed with PARSEC isochrone (Bressan *et al.* 2012; Evans *et al.* 2018) for $\log t = 8.2$ and a solar metallicity.

Despite the uncertainties inherent in such method and absence of stars evolved away from the Main Sequence in Gaia DR2 data, making an accurate determination of age and metallicity difficult, the result suggests a slightly super-solar metallicity and a younger (100–160 Myr) age than argued for in previous publications. It also confirms that most of the interstellar matter causing the extinction detected by the Planck mission in the direction of Collinder 463 is located between the Sun and the cluster.

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4. Discussion

As can be seen from Fig. 3, the region beyond $R = 1°$ still contains a significant number of stars that could be former members of the Collinder 463 cluster, having similar PM, parallax, photometric colors and extinction estimate. An overdensity of stars with such properties can be traced as far as $R = 4.25°$. The surface density distribution of these "halo" stars is different from that of the "cluster" stars (cf. Fig. 2).

Following Cantat-Gaudin *et al.* (2018) we have applied Minimum Spanning Tree tests to the PMs and coordinates of "halo" stars, confirming most of them as likely cluster members. Application of multi-parameter clustering analysis to PMs and parallax values of stars beyond $R = 3°$ radius resulted in several new possible candidate members at projected distances up to 100 pc. Furthermore, "halo" stars as a group exhibit noticeable outward motion which could be expected in an expanding cloud of unbound stars being dispersed in the course of dynamical evolution of their parent cluster.

This highlights the difficulty in determining the outer extent of the open cluster using star count or integral light in round appertures, subject to the uncertain background level and a possible asymmetry of the cluster. A more rigorous procedure is being developed, replacing star counting with kernel density estimator and multi-parameter membership probability determination based on both astrometry and photometry data.

Modeling the distribution of "halo" stars with respect to the "cluster" stars that are most likely still gravitationally bound and follow Boltzmann velocity distribution would provide us with means to reconstruct the dynamical evolution of Collinder 463 and its surroundings. However, lack of reliable stellar radial velocities prevents us from updating cluster orbital parameters and attempt to relate extent and orientation of the observed asymmetric halo, surrounding Collinder 463, with its orbital plane.

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