On the morphology of open clusters probed by ASteCA using Gaia data

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Resumen / Analizamos la morfología de más de 1000 cúmulos abiertos dispersos en el tercer y cuarto cuadrante de la Galaxia, obteniendo estimaciones de sus elipticidades bidimensionales proyectadas y ángulos de rotación. Ambos parámetros están muy ligados al proceso de formación y evolución dinámica de estos objetos. Empleamos un método de inferencia bayesiana combinado con un modelo de perfil de King generalizado a través de nuestra herramienta de Análisis Automatizado de Cúmulos Estelares (ASteCA). Los datos provienen de la última versión de Gaia hasta la fecha (DR3) hasta una magnitud de G=19. El análisis de cientos de cúmulos sintéticos indica que nuestro enfoque es considerablemente más preciso y robusto que el método habitual de ajustar una elipse a un subconjunto de miembros seleccionados a través del método de descomposición de valores singulares.

Abstract / We analyze the morphology of over 1000 open clusters scattered in the third and fourth quadrants of the Galaxy, obtaining estimates for their projected two-dimensional ellipticities and rotation angles. Both parameters are closely linked to the formation process and dynamical evolution of these objects. We employed a Bayesian inference method combined with a generalized King profile model through our Automated Stellar Cluster Analysis (ASteCA) tool. The data come from the latest Gaia release to date (DR3), up to a magnitude of G=19. Analysis of hundreds of synthetic clusters indicates that our approach is considerably more precise and robust than the usual method of fitting an ellipse to a subset of selected members using the singular value decomposition method.

Keywords / methods: statistical — galaxies: star clusters: general — open clusters and associations: general — techniques: photometric — parallaxes — proper motions

1. Introduction

Open clusters (OCs) are gravitationally bound stellar systems characterized by containing from tens to thousands of members. The analysis of these objects is essential in the research of the structure and dynamic evolution of galaxies, as well as in the study of the stellar evolutionary process.

The morphology of star clusters is intricately linked to the internal gravitational interactions among their member stars . In their early stages, young OCs often retain traces of substructures inherited from their parent molecular clouds (Alves et al., 2020). As OCs age, the equilibration of kinetic energy through two-body relaxation has a direct consequence on the distribution of stars within a cluster (Kroupa, 1995; de La Fuente Marcos, 1996). These interactions shape the spatial distribution of stars within the cluster, influencing its density and radial distribution. Additionally, external factors such as stellar evaporation and disturbances like the Galactic tidal force, differential rotation, and encounters with molecular clouds can further influence the external spatial structure of the cluster and, in some cases, lead to its dissolution (Dinnbier & Kroupa, 2020; Tarricq et al., 2022).

In this work, we analyze the morphology of 1037 open clusters scattered throughout the third and fourth galactic quadrants, obtaining estimates of their projected two-dimensional ellipticities and rotation angles. Both parameters are closely related to the formation process and dynamic evolution of these objects. To do this, we employ a Bayesian inference method combined with a generalized King profile model through our Automated Stellar Cluster Analysis (`ASteCA`) tool (Perren et al., 2015). The data come from the latest Gaia release to date (DR3, Gaia Collaboration et al. (2023)) up to a magnitude of G=19.

To evaluate the results of this study, a comparative analysis was carried out by cross-matching the data obtained with the results of Hu et al. (2021) for 639 OCs in common. The results of the Bayesian method employed in this work were compared with the results obtained by these authors through an analysis of hundreds of synthetic clusters.

2. Methods

To estimate the parameters of the King Profile (King, 1962), we applied the maximum likelihood estimation method used in Pieres et al. (2016) and extended by us

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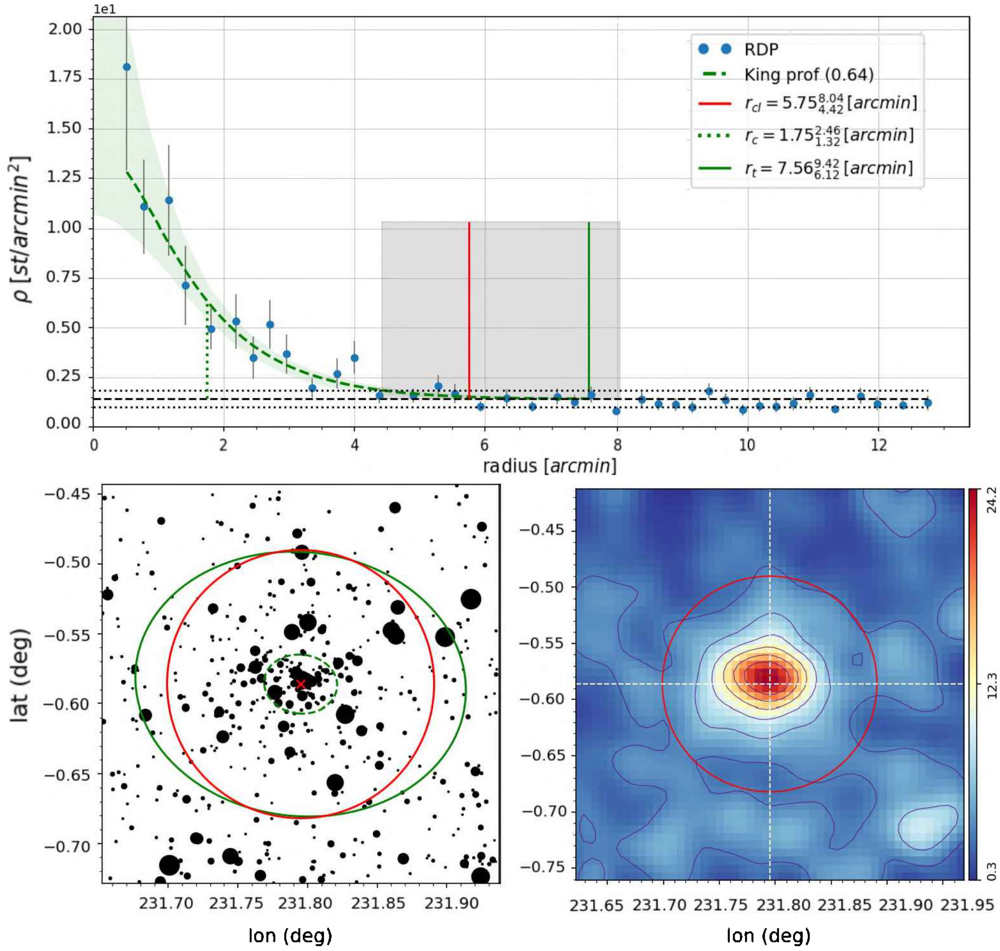

Fig. 1. Results of applying ASteCA to the open cluster Haffner 9, with detailed plot descriptions provided on the body of the article.

to process elliptical and rotated clusters. In the mentioned article, the probability that star i belongs to the complete model (King profile) with radii r_c* and r_t** and centered at (x_c, y_c) is expressed as follows:

$$l_i = \rho_{cl}(r_i) + \rho_{fl} \quad (1)$$

where ρ_{fl} is the field density value and $\rho_{cl}(r_i)$ is the surface density profile at a distance r_i from the cluster center:

$$\rho_{cl}(r_i) = k\left(\frac{1}{[1+(r_i/r_c)^2]^{1/2}} + \frac{1}{[1+(r_t/r_c)^2]^{1/2}}\right) \quad (2)$$

In the case of elliptical clusters, r_i is equivalent to the major semi-axis of a rotated ellipse with a given ellipticity (ell) and rotation angle (θ):

$$r_i(ell,\theta) = \left(\frac{[(x_i-x_c)\cos\theta+(y_i-y_c)\sin\theta]^2}{1-ell^2} + \frac{[(x_i-x_c)\sin\theta-(y_i-y_c)\cos\theta]^2}{1-ell^2}\right)^{\frac{1}{2}} \quad (3)$$

*Core radius, degree of concentration in the core of the cluster

**Tidal radius, limit of the cluster where stars are lost due to the gravitational pull of the host galaxy

To estimate the parameters r_c, r_t, ell and θ we use Bayesian inference on the model represented by the log-likelihood sum over all stars.

The ASteCA package first uses a two-dimensional Gaussian kernel density estimator to determine the center coordinates of the cluster. After this step, the *emcee package* (Foreman-Mackey et al., 2013) is employed to explore the $[r_c, r_t, ell, \theta]$ parameters space and estimate the distribution of each parameter.

3. Results

Figure 1 shows the result of applying ASteCA on the open cluster Haffner 9. The plot on *the top panel* shows the elliptical radial density profile of the cluster region. The dashed green line represents the King profile fit, while the shaded green area indicates its 16th–84th uncertainty region. The core radius (r_c) is denoted by a dashed green line, and the tidal radius (r_t) is shown as a solid green line. Additionally, the red vertical line represents the radius r_{cl} obtained through fitting a circular density profile (Eq. 2). The values of these parameters, along with their 16th-84th uncertainties, are displayed in the top right corner of this panel.

The bottom panels show: in the left plot, the coordi-

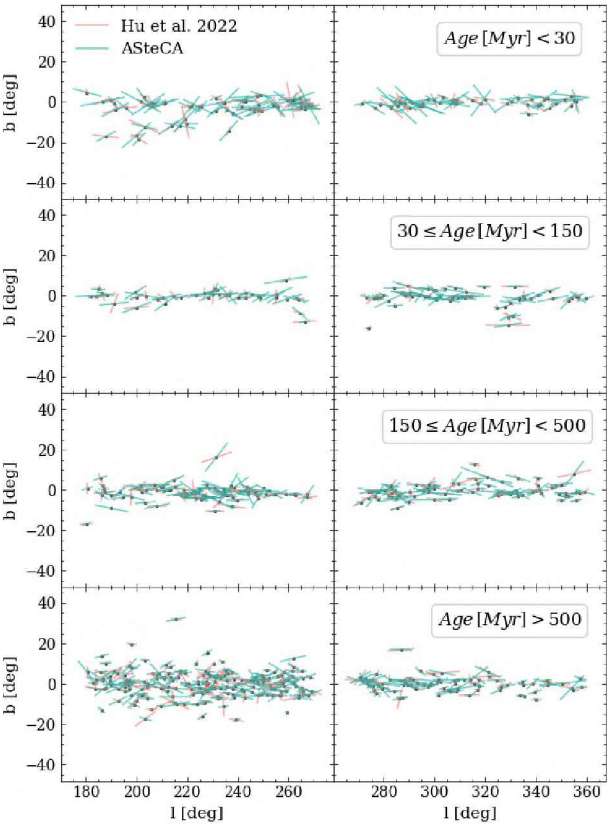

Fig. 2. Ellipticity and rotation angle estimated by ASteCA (cyan) and Hu et al. (2021) (orange)

nate space of the cluster, and in the right plot a density map. The green ellipse corresponds to the ellipse of the fitted parameters $[r_c, r_t, ell, \theta]$, and the red circle represents the fit of a circular density profile.

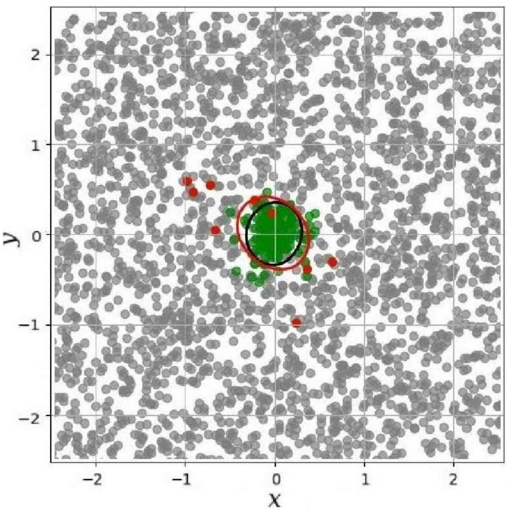

Fig. 3. An example of a synthetic cluster used to analyze how the presence of outliers affects ellipticity estimation in ASteCA and the SVD method.

To evaluate the results of this study regarding the ellipticity (ell) and position angle (θ) parameters, a comparative analysis was conducted by cross-matching our obtained data with the findings of a previous study by Hu et al. (2021). In this study, the authors conducted a detailed analysis of the structure of 1256 OCs distributed throughout the Galaxy. They utilized the database provided by Cantat-Gaudin et al. (2020), considering all stars with membership probability greater than 0 for each cluster. Using density estimation techniques and ellipse fitting with the Singular Value Decomposition (SVD) method, they characterized the spatial distribution and shape of OCs in the Galactic coordinate system.

Figure 2 presents the results of the comparative analysis for ell and θ parameters of the 639 OCs in common between Hu et al. (2021) and our work. In cyan, values obtained using ASteCA are displayed, and superimposed in orange are those obtained by Hu et al. (2021). Each OC is positioned on the graph based on its galactic coordinates and is represented by inclined lines, where the slopes align with the obtained orientation, and the length indicates the magnitude of the ellipticity estimated in each study. Additionally, the OCs from the cross-match are divided into four ascending age ranges, with the youngest ones in the first row and the oldest ones in the last row.

Most OCs present a more elongated shape in the direction parallel to the Galactic plane than in the direction perpendicular to the Galactic plane, which is in agreement with what has been found in other studies (Bergond et al., 2001; Zhai et al., 2017; Pang et al., 2021). On the other hand, while the cluster population according to their ages is not homogeneous, it is possible to observe that the ellipticity is generally higher in young clusters than in clusters of advanced ages. This aligns with findings from other studies (Chen et al., 2004; Zhai et al., 2017) regarding the morphology of OC cores. As clusters age, they become increasingly influenced by internal dynamic effects where low-mass stars reach the outer regions of the cluster, while simultaneously, the cluster core contracts. Since in this study, ASteCA conducts an analysis based on radial density, the more dispersed stars are excluded from the structural analysis, and therefore, the obtained results are more related to the core morphology rather than the entirety of the cluster.

Comparing the results of the fit performed by Hu et al. (2021) using the SVD method with those obtained in this work through ASteCA's Bayesian inference, significant differences in ellipticity and rotation angle are observed for some OCs. For this reason, a comparative analysis of both methods was carried out using a set of 250 synthetic clusters. These synthetic clusters contain between 10-25% of non-member stars (outliers) that replace the member stars and are distributed in a wider region around the cluster, up to 1.5 times the tidal radius. The objective of this comparison was to analyze how the presence of outliers affects the ellipticity estimation in both methods (SVD vs ASteCA's Bayesian inference).

An example of a synthetic cluster is shown in Fig. 3. The green dots represent the real members, the red dots correspond to the outliers, and the gray dots rep-

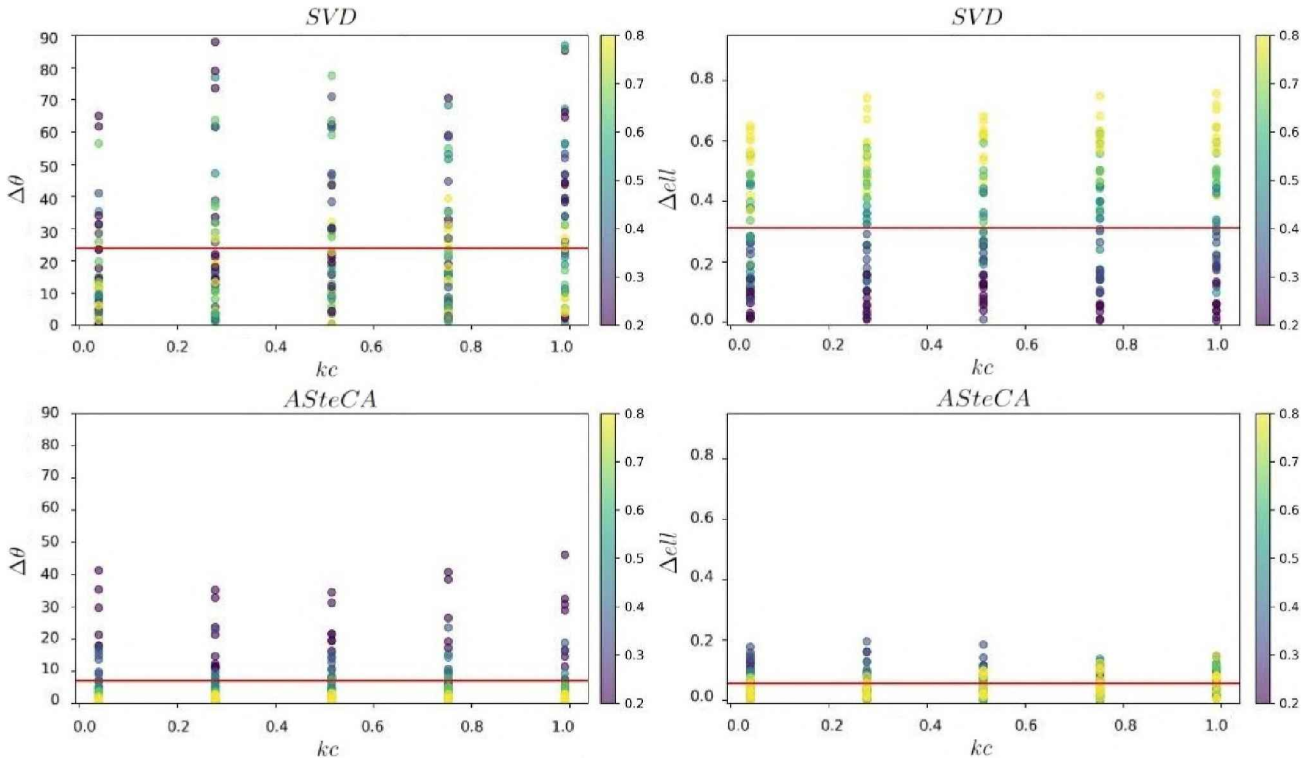

Fig. 4. Differences between real and estimated values of θ and ellipticity for SVD (top) and ASteCA (bottom) methods, presented against King's concentration (kc). Red lines indicate mean values, and dots are colored by real ellipticity.

resent the field stars. In the SVD method used by Hu et al. (2021) only the green and red dots are fitted, i.e., without considering the field stars. In this case, the red ellipse shown in the figure is the fitted ellipse. In contrast, in the ASteCA method, King's profile models both field stars and cluster members, taking them into account during the fitting. For this method, the fitted ellipse corresponds to the ellipse marked in black.

It can be observed that the SVD method is considerably affected by the presence of outliers in its ellipticity estimation. In addition, it is evident that OC with higher ellipticities are more susceptible to this influence compared to those with lower ellipticities. From these results we can assure that the method used in this work is more precise than the method used in Hu et al. (2021). This is true even for OCs with almost all their members correctly identified.

Figure 4 shows the results obtained from this comparative analysis. *The top panels* corresponds to the SVD method, while *the bottom panels* corresponds to ASteCA. *The left panels* shows the difference between the real and estimated values of θ, while *the right panels* represents the difference between the real and estimated values of ellipticity. All the plots are presented as a function of King's concentration (kc), expressed as the logarithm of the ratio of the tidal radius to the core radius (r_t/r_c). The red line indicates the mean value of each quantity and the dots are colored according to the real ellipticity.

4. Conclusions

We analyze the morphology of more than 1037 open clusters scattered throughout the Galaxy, obtaining estimates of their two-dimensional ellipticities and projected rotation angles. We employ a Bayesian Bayesian inference method combined with a generalized King profile model through our ASteCA tool. Analysis of hundreds of synthetic clusters indicate that our approach is considerably more accurate and robust than the usual method of fitting an ellipse to a subset of selected members by singular value decomposition.

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