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Analysis of the presence of mass segregation in NGC 2516

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Resumen / Analizamos el fenómeno de segregación de masa sobre el cúmulo abierto NGC 2516, donde las estrellas con los mayores valores de masa se distribuyen, en promedio, más cerca del centro del cúmulo. Para ello aplicamos dos métodos que permiten detectar y cuantificar este fenómeno. El cúmulo se procesa previamente con nuestro algoritmo de estimación de miembros pyUPMASK, para eliminar las estrellas de campo contaminantes. El resultado es un conjunto limpio y completo de estrellas miembro, hasta G=19 mag. A continuación, utilizamos nuestro paquete ASteCA para estimar las masas individuales de las estrellas miembro y su probabilidad de ser un sistema binario. Los dos métodos aplicados indican una segregación de masa leve para las cinco estrellas más masivas. Se encuentra que los sistemas binarios se distribuyen hacia afuera en promedio en comparación con las estrellas individuales. Analizamos estos resultados en el contexto de la dinámica de los cúmulos estelares.

Abstract / We analyze the phenomenon of mass segregation on the open cluster NGC 2516, where stars with the largest mass values are expectedly distributed on average closer to the center of the cluster. For this, we apply two methods that allow us to detect and quantify this phenomenon. The cluster is previously processed with our pyUPMASK member estimation algorithm, in order to remove contaminating field stars. This results in a clean and complete set of member stars, up to G=19 mag. We then use our ASteCA package to estimate the individual masses of the member stars and their probability of being a binary system. The two methods applied indicate a slight mass segregation for the five most massive stars. The binary systems are found to be distributed outward on average compared to the individual stars. We analyze these results in the context of stellar cluster dynamics.

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

1. Introduction

In many star clusters it has been found that massive members concentrate closer to the center compared to lower mass members. This phenomenon is usually attributed to mass segregation, and its origin is hypothesized to be due to dynamic effects (dynamical segregation) or as a result of the cluster's formation process (primordial segregation, Dib et al., 2010; Allison et al., 2009, 2010). Open clusters are known to host binary systems, and since they have a greater mass on average than single stars they are of great importance in the study of mass segregation and internal cluster dynamics.

The nearby open cluster NGC 2516 (RA: 119.527, DEC: -60.800) deg is a widely studied cluster located at ∼400 pc, characterized by an extensive main sequence and a clearly detached binary sequence which makes it of great interest in the study of mass segregation. In this work, we apply two methods on NGC 2516 that allow us to detect and quantify this phenomenon.

There is a discrepancy between the previous results on the study of mass segregation on NGC 2516. In Bonatto & Bica (2005) mass segregation is detected by analysing the spatial variation of the slopes of the mass function. In Dib et al. (2018) the authors apply the two methods used in this work and find for both a slight mass segregation for the 10 most massive stars without considering binary systems. Finally in Pang et al. (2021) applying the same methods and assuming that all stars in their sample are individual stars, they find no evidence of mass segregation for NGC 2516.

2. Methods

The data is obtained from the Gaia EDR3 survey and processed with our pyUPMASK member estimation algorithm (Pera et al., 2021) to remove contaminating field stars. This results in a clean and complete set of member stars. We then use our ASteCA package (Perren et al., 2015) to estimate its fundamental parameters, the individual masses of the member stars, and their probability of being a binary system.

To detect mass segregation we use two methods. The Λ-method (Allison et al., 2009), is based on comparing the minimum spanning tree (MST) path length of massive stars with the average length of N sets of random stars. The Γ-method (Olczak et al., 2011), is an improvement of the former and proves to be much more robust when applied to stellar systems with a high binary fraction. The ratio between the MST for the N most massive stars and that corresponding to

Poster contribution

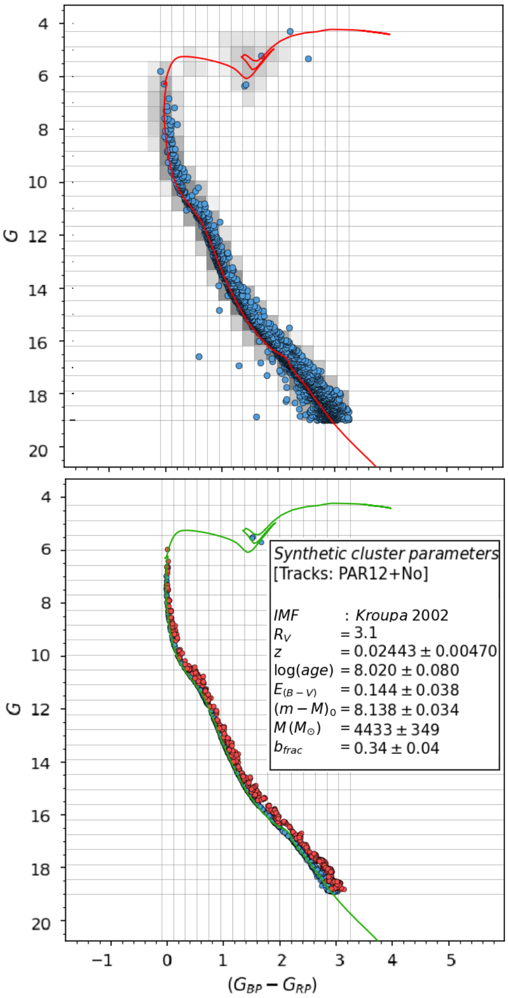

Figure 1: ASTECA synthetic cluster fitting process. *Top:* observed CMD. *Bottom:* best synthetic cluster fit (red points indicate binary systems). The estimated fundamental parameters are shown in the insert on the right. Red and green lines represent the isochrone associated with the shown synthetic cluster.

the random sets defines the minimum spanning ratio (MSR). For both methods, an MSR value significantly greater than 1 implies mass segregation.

To generate the minimum spanning trees we used the MISTREE Python package (Naidoo, 2019) applied to the 3D Cartesian stellar coordinates corrected with the Bayesian method described in Pang et al. (2021). This correction mitigates the errors introduced when individual distances are obtained by simple parallax inversion.

3. Results

Fig. 1 shows the cluster parameters provided by ASTECA through a fitting process based on the generation of synthetic clusters from theoretical isochrones (Bressan et al., 2012). The cluster members are previously selected using our PYUPMASK package.

The results obtained for Λ_{MSR} and Γ_{MSR} under these conditions are shown in Fig. 2. Each point in the figure represents the MSR value as a function of the N_{MST} (from 3 to 100) most massive stars. It can be seen that both methods indicate a slight mass segregation in the 5 most massive stars, more clearly perceived for the Γ-method. These results differ from those found in Pang et al. (2021), where they do not consider binary systems and find no evidence of mass segregation. On the other hand, the values found for the MSRs are similar to those found in Dib et al. (2018), where they use the same two methods used in this work.

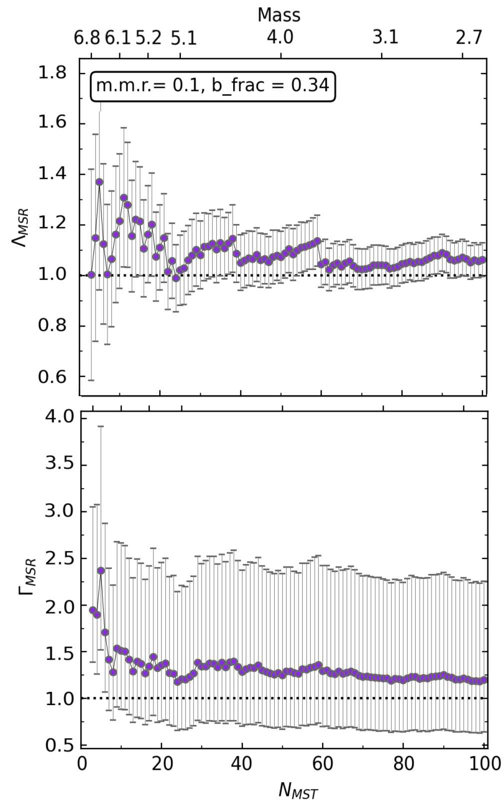

Figure 2: MSR vs. N_{MST}. *Top:* Λ-Method (Allison et al., 2009). *Bottom:* Γ-Method (Olczak et al., 2011)

The dynamic evolution of the clusters is shaped by the two-body relaxation that allows the exchange of energy between the stars and leads the systems to a state of partial equipartition of energy. Therefore, to understand if the observed segregation is due to dynamical effects, we need to compare the half-mass relaxation time (t_{rh}) -time required for the star to lose all memory of its initial orbit- with the age of the cluster (Binney & Tremaine, 2008):

$$t_{rh} = \frac{0.17N}{\ln(\lambda N)} \sqrt{\frac{r_h^3}{GM}} \tag{1}$$

We estimate a value of $t_{rh} \sim 1300$ Myr and a cluster age of ~ 100 Myr. The estimate of the cluster relaxation time gives a value much larger than the cluster age, which means that the dynamical evolution of the cluster did not have enough time to produce an equipartition of energy between the cluster members. Therefore this allows us to conclude that the segregation found in NGC 2516 corresponds to a primordial segregation and not to a dynamical segregation (Raboud & Mermilliod, 1998). Furthermore, if we calculate the mass segregation time for a star of mass m, within a stellar cluster composed of stars with average mass $< m >$ (Spitzer, 1969):

$$t_{seg}(m) \simeq \frac{< m >}{m} t_{rh} \qquad (2)$$

+we find that $t_{seg}(m_{max}) \sim$ 200Myr which indicates that no star belonging to the cluster should be segregated, which reaffirms our conclusion that the segregation found must be primordial.

In Geller et al. (2013) the authors analyze the LMC cluster NGC 1818, a cluster with age and mass values similar to those of NGC 2516. They discuss the evolution of the radial dependence of binary frequency and the contribution of dynamic binary disruption and mass segregation. In order to compare their results with NGC 2516 we analyze the distribution of the binary population within the cluster. Fig. 3 shows the binary fraction over all stars as a function of the radius from the cluster center (in units of half-mass radii). To obtain these values we define concentric rings and calculate the number of binary systems divided by the total stars within that area. From the comparison we can conclude that the distribution of the binaries present in NGC 2516 corresponds more to an age of a crossing time, than to a half-mass relaxation time. At this time, the binary frequency decreases toward the cluster core due to the disruption of the wide binaries. In addition, the stars do not have enough time to mix throughout the cluster, so there is no dynamic mass segregation.

In Fig. 4 we show the cumulative distribution function (CDF) as a function of radius for binary and simple systems. Each subgroup is in turn subdivided into two mass ranges. As can be seen, binary systems are generally distributed outward from the cluster compared to the population of simple systems. Therefore, we do not observe a preferential segregation of binary systems, but rather the opposite.

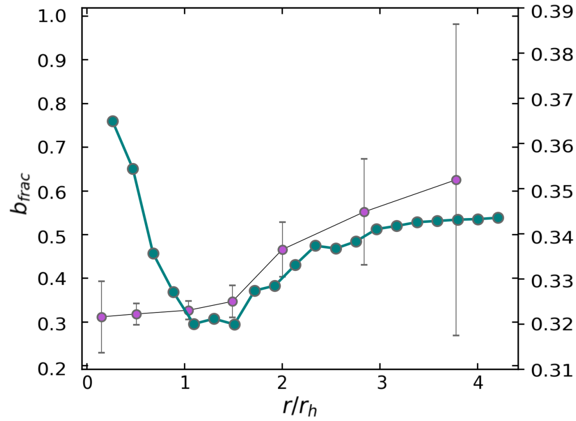

Figure 3: Binary fraction over all stars as a function of radius. The left y-axis corresponds to the magenta curve and measures the binary fraction in concentric rings. The right y-axis corresponds to the green curve and measures the cumulative binary fraction.

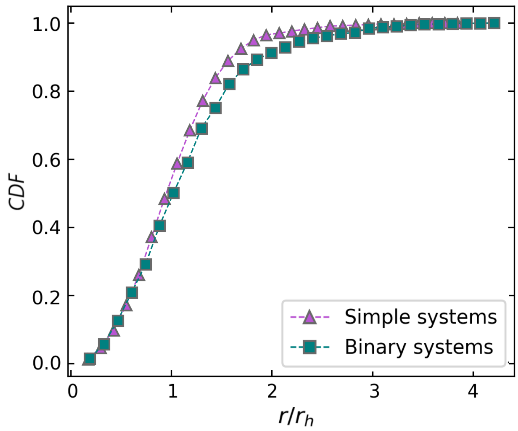

Figure 4: Cumulative radial distribution function of simple and binary population.

4. Conclusions

We analyzed the presence of mass segregation in the open cluster NGC 2516 by applying two methods that allow us to detect and quantify this phenomenon. For both methods we found a slight mass segregation for the five most massive stars. Comparing the cluster age with the half-mass relaxation time estimated in this work, we can conclude that the observed segregation corresponds to a primordial segregation and not to a segregation due to dynamical effects. In addition, we studied how the binary frequency is distributed within the cluster. Comparing our results with those of Geller et al. (2013), we found that the binary distribution corresponds more to an age of a crossing time, than to a half-mass relaxation time. At this time, no dynamical mass segregation is observed and binary frequency decreases toward the cluster core due to the disruption of the wide binaries. We were also able to detect no preferential mass segregation in binary systems.

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